Horticultural and juice attributes of cider apple (*Malus domestica* Borkh.) cultivars grown in Ontario, the endogenous development of yeast assimilable nitrogen in apple juice, and the effects of exogenous nitrogen supplementation on the fermentation of apple juice

by

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ABSTRACT

HORTICULTURAL AND JUICE ATTRIBUTES OF CIDER APPLE (MALUS DOMESTICA BORKH.) CULTIVARS GROWN IN ONTARIO, THE ENDOGENOUS DEVELOPMENT OF YEAST ASSIMILABLE NITROGEN IN APPLE JUICE, AND THE EFFECTS OF EXOGENOUS NITROGEN SUPPLEMENTATION ON THE FERMENTATION OF APPLE JUICE

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Apple growers in the cider industry would like to grow regionally suitable cultivars and optimize desirable juice attributes for cider. Regional conditions and orchard practices affect juice composition, including sugar, acidity, polyphenols, and yeast assimilable nitrogen (YAN). The main objectives of this research were to identify which cultivars are best suited for growth in Ontario and to determine the effect of orcharding practices on the juice YAN composition and fermentation. Horticultural and juice data were collected on 28 cultivars from initial planting in 2015 through the 2018 harvest. Cultivars that show promise for continued research in Ontario include 'Binet Rouge', 'Bramley's Seedling', 'Breakwell', 'Bulmers Norman', 'Calville Blanc d'Hiver', 'Cline Russet', 'Cox Orange Pippin', 'Crimson Crisp®', 'Dabinett', 'Enterprise', 'Esopus Spitzenberg', 'Golden Russet', 'GoldRush', 'Medaille d'Or', 'Porter's Perfection', and 'Stoke Red'. In another experiment, foliar urea spray was applied to 'Crimson Crisp®' trees to determine its effect on YAN

concentrations. It was determined that YAN concentrations in ‘Crimson Crisp®’ apple juice are stable for the month before harvest and after storage and that high levels of fertilization will lead to an increase in aspartic acids and asparagine. Fermentations of ‘GoldRush’ juice with varying diammonium phosphate and sucrose supplementation were performed to investigate YAN requirements for cider production, which showed that YAN and sugar are associated in cider fermentations and that there is an optimal proportion between the two for a fast and complete fermentation. This research will help growers select orchard and cider production practices that will result in higher quality cider.

DEDICATION

To my nephew and godson Benedict Alastair MacGregor and my niece Mirabella Iris MacGregor.

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FOREWORD

When I was growing up, cider meant one thing: the sweet brown nectar from freshly pressed apples. It was an ephemeral delicacy of the cool Michigan autumn, and it always came with a side of donuts. It was a treat for a Sunday morning or after a leisurely visit to the local U-Pick orchard. It wasn't until I was much older that I learned that hard cider existed. At first, I thought that it was something similar to a spiked punch or a hard lemonade, a sweet beverage that in my mind had been adulterated with alcohol. As I began to seriously study horticulture, however, I was exposed to a rich tradition of apple varieties that had all but disappeared for a century. This led me down a seemingly endless path of learning about historical cider production in North America, England, France, and Spain. The 21st century brought about a renewed interest in cider production and research, and I decided to ride the wave into it.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS, ABBREVIATIONS OR NOMENCLATURE

AK	‘Ashmead’s Kernel’
Ala	Alanine
Arg	Arginine
Asn	Asparagine
Asp	Aspartate
B	‘Breakwell’
BA	‘Brown’s Apple’
BN	‘Bulmer’s Norman’
BR	‘Binet Rouge’
BSe	‘Bramley’s Seedling’
CBH	‘Calville Blanc d’Hiver’
CC	‘Crimson Crisp®’
COP	‘Cox’s Orange Pippin’
CR	‘Cline Russet’
Cys	Cysteine
D	‘Dabinett’
DAP	Diammonium phosphate
E	‘Enterprise’
ES	‘Esopus Spitzenberg’
FAN	Free amino nitrogen
FR	‘Fréquin Rouge’
G	‘GoldRush’
GABA	γ-aminobutyric acid

GG	‘Grimes Golden’
Glu	Glutamate
Gln	Glutamine
Gly	Glycine
GR	‘Golden Russet’
His	Histidine
Ile	Isoleucine
KB	‘Kingston Black’
Leu	Leucine
Lys	Lysine
M	‘Michelin’
MD	‘Muscadet de Dieppe’
MO	‘Medaille d’Or’
Met	Methionine
N	Nitrogen
OCCA	Ontario Craft Cider Association
PAN	Primary amino nitrogen
Phe	Phenylalanine
PP	‘Porter’s Perfection’
Pro	Proline
SA	‘Sweet Alford’
Ser	Serine
SR	‘Stoke Red’
TCSA	Trunk cross-sectional area

Thr	Threonine
TL	‘Tydeman Late Orange’
Trp	Tryptophan
TS	‘Tolman Sweet’
Tyr	Tyrosine
Val	Valine
YAN	Yeast assimilable nitrogen
YM	‘Yarlington Mill’

LIST OF APPENDICES

1 Introduction

1.1 Cider

In Canada, the definition of “cider” is the product of the alcoholic fermentation of apple juice, which allows for additions like yeast, sugar, concentrate, and preservatives (Lametti, 2019), with no regulations on the provenance of the ingredients. Further, the Ontario Craft Cider Association (OCCA) has defined Ontario Craft Cider as a beverage that “must be produced by a craft cidery in Ontario from 100 percent Ontario grown apples or pears” (MNP LLP, 2016).

1.1.1 Cider production

Cider production has three principal phases: fruit cultivation, juice extraction, and fermentation (Figure 1.1). Juice needs to be separated from whole fruits so that yeast can propagate throughout the juice and convert its sugars into alcohol. In the orchard, apples are collected from the tree or on the ground. This will vary based on the variety, the labor force, the region, and legal and food safety regulations. The particular cultivars being used depend on the regional availability and the desired cider style. These fruits will then be cleaned and sorted before being ground or milled. Grinding was historically carried out using stone mills powered by draft animals or water or by using hammers to smash fruits (Mangas Alonso & Blanco Gomis, 2010). Modern day grinders are motorized and grind using a toothed drum. Finer grinds usually allow for the extraction of more juice, although different apple varieties can be ground more or less efficiently. The mixture of ground fruit and juice, known as pomace, is then pressed to allow for the liquid juice to separate from the apple solids. Traditional rack-and-cloth presses are still used. In these presses, ground apples are placed onto a textile-lined rack, wrapped in the textile, and stacked on top of another rack that has been prepared the same way. A press force is then applied to the top and juice is collected into an appropriate vessel. These can range from small racks to large Spanish presses, where the pomace is turned over multiple times in day-long pressing sessions. Wine-like basket presses are sometimes use on a small scale. Large cider producers will often use pneumatic French presses or belt presses to extract juice more efficiently. Unlike the extended maceration, like that done in red wine production, cider is usually macerated for a maximum of 24 hr in order to extract a greater amount of juice (Mangas Alonso & Blanco Gomis, 2010).

Once juice is extracted, it usually will be treated with compounds containing sulfites, like potassium metabisulfite, to prevent the growth of unwanted yeast and bacteria in the juice. Some producers will choose to skip sulfiting and go directly into the fermentation process. Commercial producers will typically ferment in large stainless-steel tanks, although other materials may be used, including chestnut or oak barrels or fiberglass tanks. Small-scale and home producers may carry out fermentations in buckets or carboys and traditional producers may use barrels. After the cider has gone through primary and sometimes secondary fermentation and aging, it can be packaged for storage or sale. Typical final vessels for cider include glass bottles, kegs, barrels, or cans. Different storage vessels can impact the quality of cider over time and have implications for sale and transport (Plotkowski, 2015).

Much like wine, there is extensive variation in the types of cider produced in different regions. These differences can be attributed to available apple cultivars, climatic differences, and cultural trends that affect the desired products.

British cider makes up roughly 40% of the global cider market (NACM, 2020). Legally, in the UK cider only needs to consist of 35% juice from apples and pears pre-fermentation, with the rest potentially consisting of sugar, water, and other additives (HM Revenue and Customs, 2019). Traditional ciders are made of 100% apple and/or pear juice, with “perry” being reserved to describe the product fermented from 100% pear juice. English ciders, when compared with other regions, are dry, high in bitter tannins, and low in acidity. The primary English regions for cider production are Herefordshire, Gloucestershire, and Somerset. Some common apples include ‘Kingston Black’, ‘Michelin’, ‘Bramley’s Seedling’, ‘Dabinett’, and ‘Foxwhelp’, some of which are prized for their tannins or acidity (Merwin et al., 2008).

French ciders are most commonly produced in Brittany and Normandy. Traditional styles include *cidre bouché* and *cidre fermier*. French ciders are often sweeter and lower in alcohol than those found in other regions, sometimes through characteristic low-nutrient fermentations or intentional fermentation arrests. They are also characterized by bitterness and astringency. Cider orchards in France are usually planted on standard or semi-dwarf trees, which allow for cattle grazing in the orchards. In Normandy, cider is often distilled and aged in oak to produce Calvados. Other associated products include Pommeau and countless culinary applications of cider. Some common apples for cider production include ‘‘Calville Blanc d’Hiver’’, ‘la Guillevic’, and ‘‘Muscadet de Dieppe’’ (Merwin et al., 2008).

The principle cider producing region of Spain is the Principality of Asturias, with a considerable amount of production in the Basque Country. Asturian ciders are characterized by high acidity, much of which comes from acetic acid. “Sidra natural” usually spends some of its life in chestnut barrels and is served using a traditional long pour method known as *escanciando*. It is an inexpensive common man’s beverage. Some common apples for cider production include ‘Regona’, ‘Raxao’, ‘Solarina’, and ‘Collaos’ (Plotkowski, 2015).

North American ciders range in styles. New England and New York ciders tend to be dry, bitter, and sparkling. Other producers in North America often use commodity apples to produce ciders, many of which are sweet. Ontario ciders primarily consist of the modern styles found in other parts of North America, with some ice cider production. Québec ciders include the local specialties of ice cider and fire cider, which are made through concentrating juices through natural cold or maple syrup condensers, respectively, and then fermenting the concentrates.

There is a great diversity in cider styles that derive from the use of different apples and different production methods. The American Cider Association (formerly the United States Association of Cider Makers) defines its standard cider styles as “modern ciders” made from table apples and “heritage ciders” made from multi-use or cider apple cultivars, among several specialty styles of cider and perries (USACM, 2018).

1.2 Economic considerations

Cider is a growing industry in Ontario, with a projected estimate of $57.7 million CAD in total output in 2020 (MNP LLP, 2016). However, diversity in the definitions of cider and the novelty of the industry make attempts to value craft cider as a product difficult, Reports on the economics of cider in Ontario have shown that the value of the sector is increasing. Cider makers in Ontario have identified the limited supply of inputs, including a reliable supply of cider apples, as a barrier to the sale of craft cider Further knowledge and research surrounding the production of fine cider will increase its value and contribute to its mainstream acceptance as a part of the alcoholic beverage market alongside wine, beer, and spirits. New orchards are expensive and time-consuming to plant, so planning and an increased knowledge base is essential (Galinato et al., 2015). Greater knowledge about apple varieties and the assurance of smooth fermentation will result in higher quality and higher value cider (MNP LLP, 2016).

1.3 Scientific considerations

Research related to cider has been sparse in comparison to the research efforts that have gone into beer and wine. While there has been consistent research conducted on cider in Spain, France, and England, there has been little work done on the subject in North America. With the growth of the American cider industry in the last decade, interest in funding this research has increased. The current state of research can go in multiple directions, but the most logical progression is to spend the immediate future laying basic groundwork studies and to use the body of research in wine as a guideline for the future direction of cider research while considering the difference between cider production and wine production. While the two are similar in many ways, there are important differences that require them to be treated separately.

1.4 Impetus for current research

The Cline pomology lab was approached by members of the Ontario Craft Cider Association to conduct research on apple cultivars that would be suitable for growth in Ontario. Most of the Ontario producers use dessert fruit or table fruit that, while producing serviceable cider, lacks the complexity and depth of the fruit used in foreign ciders from traditional cidermaking regions. These fruit cultivars have attributes, such as polyphenolic compounds and aroma compounds, which lend well to cider production. From this desire a collaborative research project developed in which 28 cultivars were chosen, acquired, propagated, and ultimately planted in 2015 at the Simcoe Research Station in Simcoe, Ontario. These cultivars were chosen by creating a list of available germplasm within Canada and having collaborators prioritize the list for cultivars of interest based on their reputation or potential for cider production. The apple trees were subject to analysis of their growth attributes and the characteristics of their juice. Among the juice parameters, the concentration of yeast assimilable nitrogen (YAN) plays a role in assuring that yeast can reproduce and ferment the must. This will lead to higher-quality base material for cider production and consequently to superior cider.

1.5 Tables and Figures

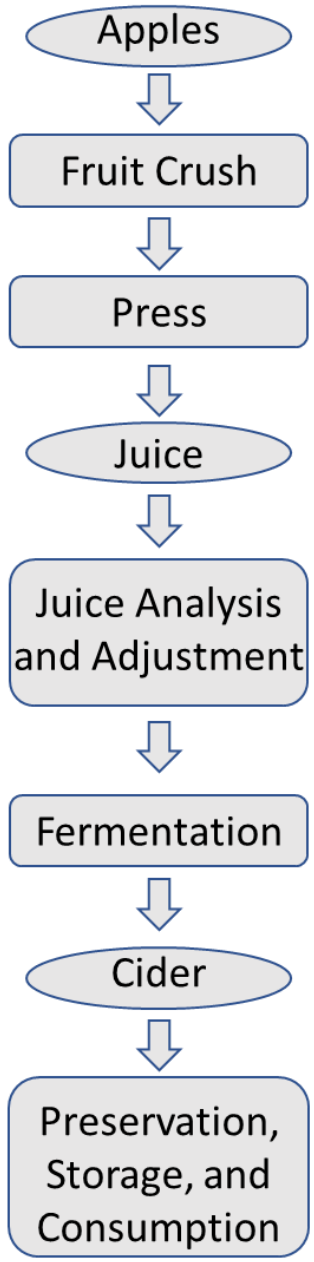

Figure 1.1 Flowchart of typical steps and procedures in cider-making. Source: Adapted from Merwin et al. (2008) and Mangas Alonso and Blanco Gomis (2010)

2 Literature Review

2.1 Introduction

Cider production starts with the cultivation of apples in the orchard, which are then juiced, fermented, and bottled. Every step in this process affects the final product, beginning with the fruit itself and including everything ranging from cellar sanitation to fermentation temperature to the type of container that is used to store and serve cider (Figure 2.1).

Apples grown for cider production have different quality and harvest parameters than those for familiar table fruit because their fruit is grown for their juice and the apples are not intended for fresh market consumption (Valois et al., 2006). In parts of Canada, culinary and dessert apples like ‘McIntosh,’ ‘Spartan,’ ‘Empire,’ ‘Northern Spy,’ and ‘Cortland’ are often used for cider to add value to lower-quality fruits. Overall there has been little research and development in cider apples in North America (Wilson et al., 2003; Provost, 2018). The apple cultivars that produce desirable characteristics for cider each have unique growth and bearing characteristics and other needs which must be accounted for when growing the fruit, including biennial bearing, pre-harvest drop, and disease susceptibility. When the apples are harvested and pressed into juice, or must, they are often blended to create new combinations of sugars, acids, tannins, nitrogen, and aromatic compounds which influence how yeast and bacteria grow and ferment the must into cider (Valois et al., 2006).

2.2 Horticultural attributes of cider cultivars

Horticultural characteristics of cider apple trees and fruit describe how the fruits grow, how the tree develops, and how it survives. These characteristics are important for understanding how the tree performs in an orchard production setting.

The period that apple trees bloom is an important parameter for determining which varieties should be planted together and if a cultivar is suitable for a particular climate zone. Most apples are not self-fertile and thus require another variety of apple nearby to act as a pollinizer. If two apple varieties are planted near each other and do not bloom at the same time, however, they cannot act as pollinizers for one another. Rather, flowers from one tree need to be receptive to pollination while the blooms from another produce pollen. Given successful pollination, the identity of the pollinizer has no effect on the fruit produced by the fruit-bearing tree (Dennis, 2003). Environmental factors that affect bloom date and length also influence fruit set. An early blooming tree has an increased risk of the flowers being damaged by frost and low temperatures during early bloom dates may inhibit pollinators (Dennis, 2003). A late bloom or protracted bloom period may increase the risk of infection of diseases, particularly fireblight (*Erwinia amylovora),* which is of particular concern to apple growers in the humid regions of eastern North America (Grove et al., 2003). Bloom and phenology is usually measured using a rating system of floral bud development ranging from silver tip stage to petal fall (Ballard, 1981). In many regions in the northern hemisphere, a typical bloom period begins at the end of April or beginning of May and may last until June (Table 2.1). The number of flowers on a tree is the number of potential fruits, a number which then must be controlled by thinning of the flowers or the fruitlets (Byers, 2003).

Precocity refers to how quickly after planting a tree begins to bear fruit(Robinson, 2003). In high-density dwarf plantings that are shorter-lived than standard or semi-dwarf orchards, precocious trees contribute a greater part of the total lifetime yield of the tree in addition to the economic importance of a faster return on investment. High-density systems have recently become popular as options for a fast turnover of fruit production (Miles et al., 2020). Rather than waiting five years for fruit production, growers may get fruit as early as the third year after planting and can begin cider production. While standard rootstock orchards produce more fruit per tree, high-density plantings are easier to harvest and produce more fruit per area and produce sooner after planting (Robinson, 2003). Some cultivars, like ‘Stoke Red’ and ‘Bramley’s Seedling’ have been noted to have slow precocity while others, like ‘Dabinett’ and ‘Yarlington Mill’ have historically produced fruit soon after planting (Table 2.2).

Tree vigour is described by measurements of tree height, tree breadth and width, and trunk cross-sectional area (TCSA). The height and breadth of the tree has long been linked with the trunk cross-sectional area and total fruit bearing surface of the tree (Barden & Neilsen, 2003). Some trees have distinctive shapes (conic, curving, etc.), habits, or spread out into the row, which may require harsher pruning for vigorous cultivars grown in high-density orchards. In addition, whether fruit are borne terminally or on spurs are important management considerations, as is the propensity to develop non-fruiting regions on the main leaders – referred to as “blind wood” (Ferree & Schupp, 2003). Traditional cider apple cultivars range in vigour from short, compact varieties like ‘Fréquin Rouge’ to large triploid trees like ‘Bramley’s Seedling’ (Table 2.2).

All apple cultivars tend towards biennial production, with some having a greater disposition than others. Reproductive buds are initiated in the summer for the following year’s crop while the current year’s crop is still on the tree, usually after fruit set. The presence of the current year’s fruit on the tree inhibits the set of reproductive buds for the following year, while the absence of fruit in one year would encourage reproductive bud setting for the following year (Dennis, 2003). This leads to apple trees bearing large quantities of fruit one year and smaller quantities the next, alternating every year unless some sort of intervention is taken. Interventions taken to mitigate extreme biennial bearing include fruit thinning and growth regulator sprays (e.g. ethephon, 1-napthaleneacetic acid, carbaryl, 6-BA) early during fruit development (Byers, 2003). Not all varieties are receptive to this amelioration, however. Cider makers may choose to purchase fruit from other sources to compensate for the shortfall or they may simply choose to press what fruit they have (Plotkowski, 2015). Asturian cider production, for example, is heavily affected by bienniality, with 40-50 million kg of fruit produced in ‘on’ years and 7-20 million kg of fruit produced in ’off’ years (Pando Bedriñana et al., 2010). The bienniality index of a cultivar is calculated by taking the absolute value of the ratio of the difference in yield between two harvests and the sum of the yield of those harvests (Hoblyn et al., 1937;

Jonkers, 1979). Some cultivars, like ‘Breakwell’s Seedling’ are inconsistent, being annual bearers in some regions and biennial in others (Table 2.3).

The total weight of a given tree’s yield is measured as the fruit are harvested (Provost, 2018). Yield varies among cultivars, even those planted in similar locations on the same rootstock (Valois et al., 2006). Many traditional apple cultivars, like ‘Kingston Black’ and ‘Brown Snout’ are known to produce low yields, while others, like ‘Bramley’s Seedling’ and ‘Michelin’, have been noted for their prolific production (Table 2.3).The total fruit borne by the tree can be divided into pre-harvest dropped fruit and harvested fruit. In Ontario, dropped fruits are usually discarded (OMAFRA, 2016). A cumulative yield over every year of a tree’s life can be determined by the sum of annual yields. The juice yield, a measure of the volume of juice extracted from a given weight of fruit, has a historical reported range from 0.15 to 0.35 mL juice g^{-1} fruit (Table 2.3) in the studied cultivars.

Crop load is an estimate of fruit number normalized for tree size and is calculated as the ratio of the number of apples on a tree relative to its TCSA. In a fruit thinning study of ‘York’ apples, trees that had higher crop loads produced fruit that were smaller, less acidic, and poorer in YAN than trees with lower crop loads. When the ‘York’ juice was made into cider, higher polyphenol concentrations were associated with a higher crop load. At some point the decreased crop load in the field reduces the yield without any benefit to fruit quality (Peck et al., 2016). The position of the fruit on the tree also plays a role in the composition of the fruit and juice. Fruits collected from the outer canopy of apple trees differ from those collected from the inner canopy. Much of these changes are attributed to light exposure (Feng et al., 2014). In the outer canopy, fruits tend to have greater fresh weights, greater soluble solids, greater phenolics, greater concentrations of sugars and sugar alcohols in the flesh and peel, and less starch in flesh and peels as compared to fruits from the inner canopies. Inner canopy fruits have greater amino acid concentrations (Feng et al., 2014).

In most Northern Hemisphere apple producing regions, cider apples are harvested between August and November, with the majority being harvested in September and October (Table 2.1). Choosing a harvest date depends on several factors. These include the weather, labor availability, the ripeness of the fruit, the intended purpose of the fruit, and the available storage capacity (OMAFRA, 2016). Ripeness in the field is usually monitored using the starch-iodine test (Blanpied & Silsby, 1992) in conjunction with a generalized rating chart and internal ethylene production. The starch index method works by halving apples transversely and dipping the flesh in an iodine solution. Iodine will turn starch a dark colour, while simple sugars will not. As apples ripen, starches break down into simple sugars. If the mesocarp of an apple fails to change colour in the presence of the iodine solution, it is considered fully ripe. Apples that are placed into controlled atmosphere storage or cold storage are often picked underripe with the expectation that they will store better by slowing ripening off the tree (Blanpied & Silsby, 1992). As yeast will not ferment the starches in unripe fruit (Mangas Alonso, 2010), cider producers will obtain the maximum amount of sugar in their juice by using fully ripened fruit and thus produce the maximum amount of alcohol in their cider.

Fruit from the apple tree falls at various times throughout the season. The first point is what is known as June drop, which is when fruitlets abscise after fruit set either in response to chemical thinners or naturally. From then until harvest fruit may drop due to wind, natural or accidental physical force, or disease (Dennis, 2003). When fruit matures, pre-harvest drop varies widely by cultivar. Some trees will drop mature fruit as soon as it is ripe, while other fruits will hang onto the tree long past maturity. This can be controlled with plant growth regulators like aminoethoxyvinylglycine (AVG, ReTain®) or 1-napthaleneacetic acid (Greene, 2003).

2.3 Juice attributes of cider cultivars

Apple cultivars for cider production are categorized by cider producers into blending classes based on their juice attributes, such as the traditional British classes of “sharp,” “sweet,” “bittersharp,” and “bittersweet” (Lea, 2015) (Table 2.9). Depending on where the fruit is grown, apple cultivars will fall into different classifications due to regional differences in fruit attributes. Furthermore, the benchmarks for the measured parameters and the classifications are defined by comparing the common apples of a region. For instance, Spanish cider production uses six classes (Mangas Alonso & Blanco Gomis, 2010) (Table 2.10) and French cider apples are often classified as sweet , bitter, acidic, or acidulated (Boré & Fleckinger, 1997). These classes are usually determined by the concentrations of acids, tannins, and sometimes sugars, all of which vary based on climate and geography. These categories are used to determine pre-fermentative blending proportions, an essential process in cider production (Mangas Alonso & Blanco Gomis, 2010). Ciders are usually made from blends of multiple cider apple cultivars, in contrast with wine, which often consists of single varieties. It has been suggested that this is because North American cider was traditionally made with surplus dessert apples or seedling apples as opposed to apples cultivated specifically for cider (Jolicouer, 2013). Some North American studies have looked at the parameters of cider apples in specific regions, such as New York (Valois et al., 2006), Virginia (Thompson-Witrick et al., 2014), Québec (Provost, 2018), and Washington (Miles et al., 2017). All of these studies, in addition to studies on table fruit, show variation among the cultivars in every measured juice attribute within the studies, even when grown in the same place (Wu et al., 2007). The variations between parameters among cultivars that are common across the studies also point to differences caused by climate, terrain, and horticultural practices. As sensory perceptions of ciders are due to the physical and chemical makeup of the cider (Le Quéré et al., 2006), the variations among regions in such attributes as sugars, acids, polyphenols, and nitrogenous compounds show how the interaction of region and cultivar can affect finished ciders.

Sugars in apple juice are primarily a mix of fructose, glucose, and sucrose with fructose being the most abundant (Mangas Alonso & Diáz Llorente, 2010; Wu et al., 2007). During fermentation, yeast will preferentially consume glucose over fructose (Magyar & Tóth, 2011). After concentration and storage, sucrose present in the juice becomes hydrolyzed into its component glucose and fructose monomers (Babsky et al.,

1986) although processing methods do not affect the sugar concentration in juices (Wilson et al., 2003). Sugar alcohols like sorbitol may also be present, but these are not fermentable (Thomas, 2004). Starches, which are the primary form of carbohydrate storage in apples before ripening, are also not fermentable. As apples ripen, the starch polymers are hydrolyzed into simple sugars (Watkins, 2003). Sugar plays a dual role in cider, both as the primary source of the perception of sweetness and as the substrate yeast ferments to produce alcohol and carbon dioxide (González San José, 2010; Mangas Alonso, 2010a). Fermentable sugar is commonly supplemented at different points in the cider-making process to boost sweetness (usually post-fermentation), alcohol (usually pre-fermentation), or carbon dioxide (post-primary fermentation, such as in sparkling ciders). Sugars are measured using several methods, including refractometry and specific gravity, the latter a measure of the density of the juice (Iland, 2004). Historical data show that specific gravity changes with respect to year of production (Alexander et al., 2016). Historical sugar concentrations in the apple cultivars in this study range from 10.9° Brix in ‘Breakwell’s Seedling’ to 18.2° Brix in ‘Brown Snout’ (Table 2.4).

Acid, like sugar, plays a dual role in cider production. Its most obvious role is its contribution to the sour taste of a cider or juice, which is related to the titratable acidity (TA). The TA is a measure of the quantity of acid molecules or functional groups that can lose protons in an acid-base titration reaction (Iland, 2004). Additionally, the pH of a juice changes the suitability of the juice as a medium for hosting yeast and other microorganisms, some of which may have detrimental effects on the cider, in addition to affecting the chemical forms of sulfite compounds that are used for microbial control (Mangas Alonso, 2010b). Wine yeast, *Saccharomyces cerevisiae*, performs well at lower pH values than many spoilage microorganisms. Titratable acidity is usually measured by titration with a strong base, while pH is usually measured using a pH meter. Historical TA measurements range from 1.86 g L^{-1} juice as malic acid in ‘Sweet Alford’ to 12.5 g L^{-1} juice as malic acid in ‘Brown’s Apple’ (Table 2.5), while historical pH measurements range from 2.95 in ‘Bramley’s Seedling’ to 4.49 in ‘Yarlington Mill’ (Table 2.6). The major organic acid found in apple juice is malic acid. Other acids commonly found in apple juice include quinic acid, citric acid, ascorbic acid, succinic acid, tartaric acid, and shikimic acid (Wu et al., 2007). During or after alcoholic fermentation there is often production of lactic acid, which is converted from malic acid by lactic acid bacteria, and acetic acid, which is converted from ethanol by acetic acid bacteria (Mangas Alonso, 2010).

Compared to cider apples grown in Europe, the culinary apples used for cider in North America are low in polyphenols (Wilson et al., 2003). Polyphenols are a class of compounds that include tannins. All polyphenols contain multiples of the aromatic organic chemical structures known as phenols. They contribute bitterness and astringency to juices and act as antioxidants (Lesschaeve & Noble, 2005). Historically they were measured with the Lowenthal-Permanganate method as tannic acid (Alexander et al., 2016; Lea, 2015). These measurements were used to establish the juice classifications of “bittersharp” and “bittersweet.” Other methods, like the Folin-Ciocalteu method, are also used to assess polyphenols, though they exhibit different sensitivities to distinct polyphenol compounds and still do not discriminate amongst them. Given this variation, comparisons made between measurements obtained through different methods cannot always be directly made (Ma et al., 2019). Polyphenol concentrations are affected by site, cultivar, growing year, storage, processing methods, and oxidation (Thompson-Witrick et al., 2014). Five classes of polyphenols have been studied in apples: catechins, procyanidins, flavan-3-ols, quercetins, and phloretins. Cider makers will sometimes supplement musts with exogeneous polyphenols, often from grapes, to increase bitterness and astringency to appeal to consumers (Martin et al., 2017; Thompson-Witrick et al., 2014). In addition to most North American cultivars having low polyphenol levels (Peck et al., 2016; Thompson-Witrick et al., 2014), there is year-to-year variation when comparing fruit from the same orchard (Alexander et al., 2016). In a study of culinary apples, the dominant phenolics were chlorogenic acid and protocatechuic acid (Wu et al., 2007). Another study simulating transport conditions with high temperature storage at 37°C, phenolic compounds in apple juice concentrate increase rather than break down (Babsky et al., 1986). Procyanidins and catechin polymers contribute to the perception of bitterness and astringency of ciders (Le Quéré et al., 2006).

It is difficult to quantify sensory impact based on polyphenol composition and total polyphenol concentration (Lesschaeve & Noble, 2005). Polyphenol perception is affected by the degree of polymerization of procyanidins (Symoneaux et al., 2014). Specifically, astringency is progressively perceived to be higher in sensory tests as the degree of polyphenol polymerization in the cider increases, though concentration played a larger role. The associated perception of bitterness, sweetness, and sourness are also affected by polyphenol concentration, but not necessarily by degree of polymerization (Symoneaux et al., 2014). Cider procyanidins, which are polymers of epicatechins, typically have lower degrees of polymerization than those in wine (Symoneaux et al., 2014). As some wine sensory studies have shown that exogenous tannin additions may not always be effective at producing the desired sensory effects (Harbertson et al., 2012), horticultural practices to increase endogenous polyphenols may be preferable. For example, polyphenols in finished cider made from trees with high crop loads were higher than those ciders made from trees with low crop loads in 'York' apples (Peck et al., 2016). Juice extraction methods also play a role in polyphenol concentration in part because of the uneven distribution of polyphenols in the fruit. For example, apple peels usually have more catechins and total polyphenols than the flesh, while phloretins are concentrated in the seeds (Mangas Alonso & Diáz Llorente, 2010; Thompson-Witrick et al., 2014). Historical polyphenol concentrations in cider apples range from 0.035% tannin in 'Esopus Spitzenberg' to 1.05% tannin in 'Medaille d'Or' (Table 2.7). In a study of culinary fruit, the greatest fraction of apple polyphenols was composed of epicatechin, followed by chlorogenic acid, coumarin, phloridizin, catechin, and caffeic acid (Wu et al., 2007).

The importance of nitrogen in apple juice lies in the fermentation process. YAN is the fraction of nitrogen in a fermentation medium that is biologically available to yeast, including ammonium and primary amino acids. Yeast acquire nitrogenous compounds early in fermentation and are used to synthesize other amino acids, transporter proteins, and nucleic acids for reproduction and metabolism (Bell & Henschke, 2005; Bisson, 1999). Yeast use nitrogen catabolite repression to preferentially use those nitrogenous compounds that are most easily convertible to ammonia, glutamic acid, and glutamine, such as ammonium, while excess nitrogenous compounds remain in the fermentation medium (Bell & Henschke, 2005). YAN is generally measured by enzymatic assay or formol titration. Suggestions for ideal YAN concentrations in apple juice range widely, with researchers and cider producers suggesting YAN concentrations as low as 80 mg L^{-1} YAN up to 470 mg L^{-1} YAN, similar to concentrations found in grape juice (Alberti et al., 2011; Kelkar & Dolan, 2012; G. H. Neilsen et al., 2010; Valois et al., 2006).

In a study of fruit grown for fresh-market production, the principal amino acids in apple juice were asparagine (Asn) and serine (Ser), but there was no detection of aspartate (Asp) or glutamate (Glu) (Wu et al., 2007). Blanco Gomis et al. (1990) tested the amino acid composition of the entire fruit, rather than just the juice and found that the major amino acids in ‘Collaos’ apples include Asn, Asp, glutamine (Gln), Glu, Ser, and phenylalanine (Phe). The major amino acids in ‘Raxao’ apples include Asn and Asp. The major amino acids in ‘Meana’ apples include Asn and Asp. Proline (Pro), a non-assimilable amino acid, is only present in apples in small quantities (Blanco Gomis et al., 1990). Ma et al. (2018) also reported variation in amino acid profiles among cultivars, with many cultivars having high concentrations of Asn, Asp and some showing high concentrations of Phe. Amino acids aren’t always metabolized in cider production, rather they are recycled through yeast autolysis and reuptake by other yeast cells (Suárez Valles et al., 2005).

Most apple cultivars for cider have low YAN, with historical measurements ranging from 9 mg YAN L^{-1} in ‘Yarlington Mill’ to 262 mg YAN L^{-1} in ‘Ashmead’s Kernel’ (Table 2.8). This low YAN leads cider producers to add nitrogen to must in the cidery, usually in the form of diammonium phosphate (DAP) or complex yeast nutrients, which are often made from yeast hulls and contain amino acids, vitamins, and inorganic nutrients (Jolicoeur, 2013). In orchard experiments on ‘York’ apples, YAN concentration was inversely proportional to crop load (Peck et al., 2016). In a storage experiment of apple juice concentrate, there was an 87% loss in total free amino acids after storage at 37° C for 55 days, with pronounced decreases in Glu, Asn, and Asp. This loss made formol titration an inadequate measure because amino acids that were present were bound and therefore unable to react to formaldehyde. Some of this loss seems to involve Maillard browning, in which amino acids interact with and bind to sugars (Babsky et al., 1986). In contrast to N supplementation, some cider producers manipulate N concentrations by reducing the amount of N to allow for a slower, more complex fermentation. This reduction comes from using fining agents or from keeving (natural or induced), in which nitrogenous compounds and other nutrients are removed from the juice medium by physical means. Keeving increases shelf stability by removing nutrition for yeast, though this process usually results in a high residual sugar concentration in the product, which reduces microbial stability (Le Quéré et al., 2006). Many amino acids also act as precursors to aromatic compounds in finished cider. Cysteine (Cys), methionine (Met), leucine (Leu), isoleucine (Ile), and valine (Val) are transformed into methyl-branched alcohols, acids, esters, and carbonyls. Tryptophan (Trp), Phe, and tyrosine (Tyr) can be transformed by cinnamic acid metabolism into aromatic alcohols, acids, esters, and carbonyls. Other amino acid metabolism leads to pyruvate, acetyl-CoA, and glucosinolate production (Mangas Alonso & Diáz Llorente, 2010). In the presence of some microorganisms, like *Brettanomyces* or *Lactobacillus*, the amino acid Lysine (Lys) can be converted into 2-acetyl-1,4,5,6-tetra hydropyridine, which is responsible for "mousiness," an off-flavour that is a major fault in fermented beverages (Toit & Pretorius, 2000). Attention to the amino acid precursors of aromatic compounds present in pre-fermented juice can help to optimize aromatic compounds in cider.

In addition to production by yeast through amino acid precursors, aromatic and volatile compounds are also produced in the fruit itself and by other microorganisms. These compounds are measured using analytical tools such as High-Performance Liquid Chromatography or Gas Chromatography. The primary volatile compounds present in fresh apple juice include three main groups: aldehydes, like acetaldehyde and hexanal; alcohols, like 1-butanol and 1-hexanol; and esters, like acetates, butanoates, and hexanoates (Mangas Alonso & Diáz Llorente, 2010). Volatile compounds present in fermented cider include esters, like isoamyl acetate; higher alcohols, like propanol and isobutanol; aldehydes, like acetaldehyde; and volatile acids, like acetic acid and ethyl acetate, among other compounds (Eleutério dos Santos et al., 2016; Suárez Valles et al., 2008; Ye et al., 2014). The presence of specific compounds affects the perception of other flavours as well. For example, the concentration of isobutanol affects the perception of fruity, sweet, and scented flavours among tasters (Leguerinel et al., 1988). Although aromatics are present in natural apple musts, the ciders produced from these musts have different volatile compounds than the ciders produced by synthetic musts made with individual amino acids while musts that are supplemented with amino acid mixes, like aspartate and glutamate, have higher concentrations of volatile esters, which demonstrates the importance of nitrogenous compounds in affecting flavour (Eleutério dos Santos et al., 2015). Secondary fermentations also affect aromatic and flavor compounds. Almost all Asturian ciders, for example, undergo malolactic fermentation where malic acid is converted to lactic acid by *Leuconostoc oeni*, so lactic acid is the dominant acid in that style (Pando Bedriñana et al., 2010; Suárez Valles et al., 2005). The other microorganisms responsible for secondary fermentation affect glycerol, acetaldehyde, ethyl acetate, and alcohols (Suárez Valles et al., 2008).

2.4 Nitrogen development in apples

Nitrogen, being the most limiting major nutrient in fruit production after water, plays an important role in apple and cider production (Sanchez et al., 2016). It contributes to tree growth, fruit growth, and fermentation.

The soil acts as the primary source of nitrogen for the apple tree. Nitrogen is taken up through the roots in mobile organic and inorganic forms that are found in the soil, including urea, ammonium, and nitrate (Neilsen & Neilsen, 2003). Factors affecting this uptake include soil type, drainage, pH, the presence of competitors, and the presence of microorganisms, especially nitrifying bacteria. Low soil N is associated with root growth being prioritized over shoot growth, while high soil N can lead to increased shoot growth (Westwood, 1993). Tree N status is usually measured by sampling current season leaves in the summer. Both the total nitrogen content in trees and the annual nitrogen requirements in apple orchards vary based on the cultivar being grown and the age of the orchard. This variation can be exacerbated by nitrogen cycling within the plant. In young dwarf trees, roughly 9% of total tree nitrogen is found in the fruit and roughly 40% is found in leaf tissue (Neilsen & Neilsen, 2003).

Nitrogen fertilization of apple trees can take place at different times of year. Ground applications usually occur in the late fall or in the spring, whereas foliar applications take place in the summer, after flowering (Toselli et al., 2000). When administering foliar sprays of urea, the solution should be directed towards the absorptive abaxial side of leaves. Leaves with high N status and young leaves are the most efficient nutrient absorbers (Boynton, 1954). Millard and Neilsen (1989) demonstrated that for apples with adequate N status, added N was primarily used for shoot growth and plant maintenance. Trees that have a low nitrogen status respond well to N fertilization, with increased vigour and yield compared to when it is deficient, with annual recommendations ranging from 30-100 kg N ha^{-1} (Neilsen & Neilsen, 2003).

Yeast assimilable nitrogen (YAN) refers to nitrogen sources that are biologically available to yeast. In fermentation media, YAN primarily consists of amino acids and ammonium (Bell & Henschke, 2005). The fraction of YAN that is composed of amino acids is often referred to as primary amino nitrogen (PAN) or free amino nitrogen (FAN). The most common amino acids in mature apples are Asp, Glu, Asn, Ser, Gln, and Ala (Mangas Alonso & Llorente, 2010; Wu et al., 2007), whereas ammonium is present in a low concentration in apple juice (Boudreau et al., 2018). Within the fruit nitrogenous compounds can be found in the skin, seeds, flesh, and juice. The concentrations of individual amino acids vary based on cultivar and the sum totals have been shown to decrease as the fruit matures (Figure 2.2) (Blanco Gomis et al., 1990; Ma et al., 2018). The most accurate method to determine YAN is the measurement of specific amino acids using HPLC and the direct measurement of ammonium with an ion probe. For HPLC, juice samples are prepared with ortho-phthalaldehyde (OPA) derivatization of amino acids, which reacts with a functional group on the primary amino acids and has been demonstrated to be an effective way to measure primary amino acid substances (Blanco Gomis et al., 1990).

Like in cider production, N concentration is important for wine production. Many wine producers have sought to increase endogenous nitrogen through N fertilization during the growing season. In grapes, vineyard nitrogen applications increase total N, total amino acids (especially arginine), and ammonium content whether the application is a ground fertilizer or a foliar spray (Bell & Henschke, 2005). Hannam et al. (2016) applied urea as a foliar spray to grapevines alongside soil N additions in order to measure their effects on grape juice YAN. They found that the foliar sprays are effective in increasing YAN in the late season and change the amino acid profile, with the percentage of proline as a total of the amino acids dropping in both Merlot and Pinot Gris grapes. Although proline forms a smaller fraction of apple juice N than grape juice N, these data suggest that fertilization doesn't necessarily have the same effect on all components of the nitrogen profile of juice.

2.5 Nitrogen in cider production

Researchers working on the oenological significance of YAN have pointed to the importance of yeast strain (Jiranek et al., 1995), initial N content and form (Alberti et al., 2011), and fermentation temperature and juice chemistry (Kelkar & Dolan, 2012) on the progression of fermentation. Both the sensory perception and chemical characteristics of finished cider are also significantly affected by yeast strain (Leguerinel et al., 1988). The importance of yeast strain has implications for early cider processing, as even apple pressing can greatly influence the profile of yeasts present in must for natural fermentation (Suárez Valles et al., 2008) and thus the requirements for YAN. Taillandier et al. (2007) showed that sugar consumption was more dependent on yeast strain than on N concentration and that increased nitrogen allowed the strains to consume more sugar, although this study did not compare musts with different initial sugar concentrations.

Studies on nitrogen deficiencies in fermentation focus on a few key phenomena: the duration of fermentation and the production of fermentation aromas, both desirable and undesirable. The studies of duration mainly focus on the reproduction of yeast and the speed of fermentation and include mathematical models of fermentation (Kelkar & Dolan, 2012). Duration studies focus on “stuck” or arrested fermentations where the yeast no longer metabolize sugar into alcohol, which may be because yeast cells are performing aerobic respiration instead of anaerobic fermentation or because the yeast are no longer able to reproduce (Bisson, 1999). The production of off-aromas is a major concern in cider production, particularly the production of hydrogen sulfide, which has a low sensory threshold. Hydrogen sulfide, which is the principal compound responsible for the smell of rotten eggs, is produced by yeast that are trying to generate methionine and cysteine, which are sulfur-containing amino acids. Yeast sources sulfur from inorganic sulfates and sulfites or organic sulfur in the medium (Bell & Henschke, 2005). Yeast cells need sufficient free nitrogen to use up the hydrogen sulfide they produce. If there is an excess of hydrogen sulfide produced and there is not any free nitrogen, then the hydrogen sulfide is discarded as waste and ends up in the cider or wine as an off-aroma (Jiranek et al., 1995). Mangas Alonso (2010) identified 4 factors that affect the accumulation of hydrogen sulfide in cider: the presence of elemental sulfur or sulfur compounds in the juice, deficiency in Vitamin B5, high concentrations of threonine (Thr), and low concentrations of N. Low concentrations of N can be moderated by sufficient presence of Vitamin B_5 (pantothenic acid) (Bohlscheid et al., 2011)

The production of higher alcohols is affected by fermentation temperature and speed. Over-supplementation of YAN and the inefficient use of N can also cause fermentation problems, such as the formation of biogenic amines, ethyl , and higher alcohol production or fermentations that are too fast with little flavour development (Alberti et al., 2011; S. J. Bell & Henschke, 2005; Carrau et al., 2008). Ethyl carbamate, a carcinogen and human health risk, is of particular concern because alcoholic and malolactic fermentation produce several of its precursors, including urea and citrulline (Ajtony et al., 2013; Uthurry et al., 2006). Low initial N concentrations lead to diverse aromatic results in the final cider, which in some strains results in higher quantities of esters and fatty acids, while in others produces higher concentrations of isoacids, gamma-butyrolactate, higher alcohols, and +3-methylthiol-propanol (Carrau et al., 2008).

It's important to understand the metabolic footprint of individual yeast strains; not all strains of *S. cerevisiae* are good for fermentation (Carrau et al., 2008).

Yeasts produce some amino acids and directly assimilate others. *S. cerevisiae* absorbs amino acids through their cell membrane using active transport proteins, like general amino acid permease, accumulating them in their vacuole at the beginning of fermentation. The rapid growth stage of yeast can consume all of the available YAN in a medium (Nogueira et al., 2008). Ammonium is also acquired through active transport (Eleutério dos Santos et al., 2016; Mangas Alonso, 2010a). Yeasts possess asparagine synthetase, which converts aspartic acid to asparagine (Cubillos, 2016).

Yeast responds to nitrogen supplementation, which allows for faster yeast reproduction and therefore rapid fermentation. In wine production, most N supplementations come from ammonium salts, like DAP (Gutiérrez et al., 2012). Ammonium additions in cider are practiced on a routine basis, but when this leads to N over-supplementation the fermentation length is shorter and fewer fusel alcohols are produced (Martínez-Moreno et al., 2014). Additionally, the timing DAP additions and the presence of other nitrogenous compounds may affect the ability of supplementation to prevent hydrogen sulfide production (Bell & Henschke, 2005). Certain strains of yeast are better adapted to utilizing N efficiently (Cubillos, 2016). Wine and cider makers often prefer local or autochthonous yeasts to commercial yeasts because they are proposed to be better-acclimated to local environmental conditions (Suárez Valles et al., 2008). *S. cerevisiae* prefers ammonium and glutamine as N sources, which ultimately influences the production of aromas in addition to spoilage potential (Gutiérrez et al., 2012; Mangas Alonso, 2010a). In experiments with synthetic musts, those whose N composition consists of arginine have better kinetic performance than controls while ammonium performs worse, however any increase in N concentration leads to more yeast growth (Gutiérrez et al., 2012). The population of yeast rather than the potential for "glycolytic flux" of the individual yeast cells is responsible for increased fermentation rates (Gutiérrez et al., 2012). Based on synthetic must studies, glucose transport capacity of the yeast is at its highest in the beginning of the fermentation process, regardless of the medium's initial N concentration (Palma et al., 2012). In N-limited fermentations, glucose uptake was reduced, but ammonium supplementation promotes the new synthesis of glucose transporters in yeast (Palma et al., 2012). Apples have relatively low glucose compared to fructose, so ammonium supplementation may help cider fermentations less than it helps wine fermentation. Ammonium salts can repress the consumption of amino acids (Taillandier et al., 2007), but an increased proportion of ammonium in YAN positively affects volatile acidity and glycerol until the point of over-supplementation beyond the optimal range (Martínez-Moreno et al., 2014).

N consumption during fermentation is key for keeping the populations of yeast and other microbes below a spoilage threshold post-fermentation. A low N concentration in the post-fermentation cider results in a finished product will have greater microbial stability (Nogueira et al., 2008). In contrast, the excessive addition of N before or during fermentation can lead to microbial instability in the finished product due to excess nutrition available for spoilage microorganisms in the finished cider (Gutiérrez et al., 2012). One way that many cider producers have circumvented the problem of low YAN has been to produce specific cider styles that require less YAN. One such style involves a technique is called “keeving,” in which the addition of calcium chloride salts to the juice reduces the total nutrient content by forming a calcium pectate gel and trapping proteins and yeast cells (Jolicoeur, 2013; Wilson et al., 2003). This is followed by a long, slow fermentation carried out by a relatively small yeast population. Keeving leads to biomass reduction, namely a reduction of the yeast population. A lower yeast population means that it takes the population longer to ferment the must to dryness. Other nutrient and biomass reducing techniques include clarification and centrifugation, which can result in slower fermentations that favor fruity aromas (Nogueira et al., 2008).

2.6 Conclusion

The collection of historical data outlining the horticultural and juice parameters of cider cultivars is useful to estimate the ranges of values that may be found in Ontario. The lack of Ontario-specific data that exists for the cultivars reduces the ability for cider makers and growers to make informed choices about which cultivars have the best chance of being successful in Ontario. Information collected on each cultivar will be useful to tell growers what type of juice can reasonably be expected to come from each individual cultivar, the difficulty or ease with which a cultivar will grow, expected yields for each cultivar, and expected management practices needed to take care of the cultivar during the establishment of the orchard.

Past studies in N development in apples have yet to show how N fertilization affects specific nitrogenous compounds in apple juice, which is an area of interest in cider production. Amino acid and nitrogen profile data will allow cider makers to better plan their fermentations. Fermentation studies in cider production literature have examined the effects of temperature, sugar, and initial nitrogen, but not specifically how sugar and nitrogen interact. The study of the interaction between the two in cider fermentations will contribute to establishing baseline recommendations for YAN in pre-fermentation apple juice. This collection of experiments will expand upon these research directions.

2.7 Tables and Figures

Table 2.1 Historical bloom and harvest dates of 28 apple cultivars grown for cider production.

Cultivar	Historical bloom period[z]		Historical harvest date	
Ashmead's Kernel	Early May to early June	22	Early to late October	12, 20, 29
Binet Rouge	Mid-May	11, 12, 28	Early to late October, November	17, 28, 29
Bramley's Seedling	Late April to mid-May	4, 20, 22, 32	Early September to mid-October	12, 31, 36
Breakwell	Early May to early June	22, 24, 32	Early September to early October	24, 32
Brown Snout	Late May to early June, May 24 average	22	Early to late October	12, 20, 29
Brown's Apple	Mid-May, May 14 average	8, 20, 22, 32	Mid-September to early November	1, 12, 19, 20, 24, 29, 32
Bulmers Norman	Late April to late May	8, 22	Early to mid-September	19, 29
Calville Blanc d'Hiver	Mid-season	4	Early September to early October	4, 13, 31
Cline Russet	-	-	-	-
Cox Orange Pippin	Mid to late season	1, 4, 10, 21, 31, 36	Mid-August to early October	18, 19, 26, 29, 31, 35
Crimson Crisp	Late mid-season	9	Early September to early October	6, 7, 9, 12, 18
Dabinett	Mid-May to early June, May 21 average	8, 22, 32	Early November	8, 24, 32
Enterprise	Late mid-season to late season	9, 13, 20	Mid-October to mid-November	7, 12, 13, 20, 31
Esopus Spitzenberg	Early to mid-season	30, 34	Late September to mid-October	2, 12, 13, 21, 31
Frequin Rouge	Late April to late May, May 11 average	11, 282, 28	Early September to late November	17, 28, 29
Golden Russet	Mid-April to mid-May; May 2 average	22	Late September to mid-October	5, 12, 13, 31, 36
GoldRush	Mid to late season	7	Early October to mid-November	7, 9, 12, 20, 21, 31
Grimes Golden	Late April to mid-May, May 4 average	22	Late September to early October	20, 31
Kingston Black	Late April to late May, May 15 average	16, 22, 31, 32	Late September to early November	1, 8, 31, 32
Medaille d'Or	Late May to mid-June, June 2 average	22	Late September to late November	1, 8, 19, 31
Michelin	Late April to late May, May 14 average	8, 22, 34	Mid-October to early November	1, 8, 12, 29, 31, 34
Muscadet De Dieppe	Late April to late May, May 13 average	22	Mid-September	19, 34
Porter's Perfection	Early May	8	October to late November	8, 19
Stoke Red	Late May to early June, May 31 average	8, 19, 20, 22, 26, 32	Late September to late November	1, 8, 20, 32
Sweet Alford	Early to mid-May, May 11 average	1, 8, 22, 26	Late October to early November	1, 8, 26
Tolman Sweet	Late season	5	Late September to late October	2, 5, 20, 31
Tydeman Late	Late April to late May, May 17 average	1, 4, 14, 22, 36	Late September to October	1, 4, 33, 36
Yarlington Mill	Mid-May	8, 20, 26, 32	Late September to early November	8, 19, 20, 32

[z] Historical values are reported in the column to the right of the data and are cited with the following numbers: 1) Ashridge Trees Ltd., 2020; 2) Beach et al., 1903; 3) Bradshaw, 2016; 4) Bultitude, 1983; 5) Burford, 2013; 6) Cline & Norton, 2008; 7) Cline, 2014.; 8) Copas, 2013; 9) Crosby et al., 1993; 10) Cummins, 2020; 11) Gamm Vert, 2018; 12) Grandpa's Orchard, 2020; 13) Hanson, 2005; 14) Harding, 2014; 15) Heekin, 2014; 16) Hogg, 1859; 17) Institut Francais des Productions Cidricoles, 2009; 18) Janick et al., 2006; 19) Jolicoeur, 2013; 20) Khanizadeh & Cousineau, 1998; 21) Merwin, 2008; 22) Miles et al., 2017; 23) Mohr, 1988; 24) Morgan & Richards, 2003; 25) Moulton et al., 2010; 26) NSW Department of Primary Industries, 2008; 27) Orange Pippin, 2019; 28) Pôle Fruitier de Bretagne, 2013; 29) Rothwell, 2012; 30) Seattle Tree Fruit Society, 2015; 31) Shelton, 2015; 32) Simmens, 2015; 33) Smith, 1971; 34) Summerland Varieties Corp., 2020; 35) The Ontario Department of Agriculture, 1914; 36) Wynne, 2020

Table 2.2 Historical precocity and vigour of 28 apple cultivars grown for cider production.

Cultivar	Historical precocity[z]		Historical vigour	
Ashmead's Kernel	Slow	20, 24	Moderate vigour	19, 24, 25, 29
Binet Rouge	Average to fast	17	Low to moderate vigour	28, 29
Bramley's Seedling	Slow	27	Extreme vigour	4, 10, 13, 20, 27, 32
Breakwell	-	-	Moderate vigour	24, 32
Brown Snout	Slow	20, 24	Low to moderate vigour	19, 24, 25, 29
Brown's Apple	Slow	1, 8, 24, 32	Moderate to high vigour	8, 19, 24, 32
Bulmers Norman	-	-	High vigour	8, 19, 26
Calville Blanc d'Hiver	Average	10, 13	Moderate to high vigour	4, 13, 16
Cline Russet	-	-	-	-
Cox Orange Pippin	Fast	13	Low to moderate vigour	1, 2, 4, 13, 20
Crimson Crisp	-	-	Low to moderate vigour	9, 18
Dabinett	Fast	10, 24, 26	Low to moderate vigour	8, 10, 32
Enterprise	Fast	13	Moderate to high vigour	9, 13, 20
Esopus Spitzenberg	-	-	Low to moderate vigour	3, 7, 8, 20, 21, 22
Frequin Rouge	Slow to fast	15, 17	Low to moderate vigour	28
Golden Russet	-	-	Moderate to high vigour	2, 13, 19, 20, 35
GoldRush	Fast	13, 21, 31	Low to moderate vigour	5, 9, 10, 21, 31
Grimes Golden	Fast	20	Moderate vigour	2, 20, 35
Kingston Black	Slow	1	High vigour	8, 32
Medaille d'Or	-	-	Moderate to high vigour	1, 31
Michelin	Fast	8	Low to moderate vigour	19, 29
Muscadet De Dieppe	-	-	High vigour	19
Porter's Perfection	-	-	High vigour	8, 19
Stoke Red	Slow	8, 20, 32	Low to high vigour	19, 20, 26, 32
Sweet Alford	-	-	-	-
Tolman Sweet	Moderate to fast	2	Moderate to high vigour	2, 20, 35
Tydeman Late	-	-	High vigour	4, 36
Yarlington Mill	Fast	8, 10, 20, 26	Moderate to high vigour	19, 32

[z] Historical values are reported in the column to the right of the data and are cited with the following numbers: 1) Ashridge Trees Ltd., 2020; 2) Beach et al., 1903; 3) Bradshaw, 2016; 4) Bultitude, 1983; 5) Burford, 2013; 6) Cline & Norton, 2008; 7) Cline, 2014.; 8) Copas, 2013; 9) Crosby et al., 1993; 10) Cummins, 2020; 11) Gamm Vert, 2018; 12) Grandpa's Orchard, 2020; 13) Hanson, 2005; 14) Harding, 2014; 15) Heekin, 2014; 16) Hogg, 1859; 17) Institut Francais des Productions Cidricoles, 2009; 18) Janick et al., 2006; 19) Jolicoeur, 2013; 20) Khanizadeh & Cousineau, 1998; 21) Merwin, 2008; 22) Miles et al., 2017; 23) Mohr, 1988; 24) Morgan & Richards, 2003; 25) Moulton et al., 2010; 26) NSW Department of Primary Industries, 2008; 27) Orange Pippin, 2019; 28) Pôle Fruitier de Bretagne, 2013; 29) Rothwell, 2012; 30) Seattle Tree Fruit Society, 2015; 31) Shelton, 2015; 32) Simmens, 2015; 33) Smith, 1971; 34) Summerland Varieties Corp., 2020; 35) The Ontario Department of Agriculture, 1914; 36) Wynne, 2020

Table 2.3 Historical yield attributes of 28 apple cultivars grown for cider production.

Cultivar	Historical biennial bearing[z]		Historical juice yield (mL juice g^{-1} fruit)		Historical Yield	
Ashmead's Kernel	No	25	0.24	29	7.2 kg $tree^{-1}$	3
Binet Rouge	Yes, but fruit difficult to thin	17, 28	0.15	29	20-30 T ha^{-1}	10, 12, 17, 28
Bramley's Seedling	Possible	20, 25, 30, 32	-	-	Very good production	10, 13, 21, 25, 32
Breakwell	Yes in some places, not in others	24, 25, 32	-	-	Good to very good production	24, 25, 32
Brown Snout	No	25	0.24	29	3.3 kg	3
Brown's Apple	Yes	24, 25, 32	0.33	23, 29	Good to very good production	8, 25, 26, 32
Bulmers Norman	Yes	25, 26, 34	0.31	29	Good to very good production	19, 25, 26
Calville Blanc d'Hiver	No	13	-	-	Light to good production; 2.8 kg $tree^{-1}$	3, 13, 16
Cline Russet	-	-	-	-	-	-
Cox Orange Pippin	No	13, 20, 21	Good	23	Low to moderate production	4, 13, 31
Crimson Crisp	Possible	18	-	-	Moderate production	9
Dabinett	No	25, 32	-	-	Good production, 4.0 kg $tree^{-1}$	3, 8, 10, 24, 25, 32
Enterprise	No	20	-	-	Moderate to heavy production	9
Esopus Spitzenberg	Yes	2, 13, 34	-	-	Low to moderate production, 2.2 kg $tree^{-1}$	2, 3, 21, 35
Frequin Rouge	Semi	25	0.35	28, 29	Good to very good production; 30-35 T ha^{-1}	15, 17, 25, 28
Golden Russet	Possible	5, 13, 21, 36	Medium	19	Low to very good production	2, 16, 20, 35
GoldRush	Possible	20	-	-	Moderate to good production	5, 9, 20
Grimes Golden	Yes	2, 20, 35	-	-	Good production	20, 31, 35
Kingston Black	Slight	25, 32	-	-	Low to moderate production	8, 25, 31, 32
Medaille d'Or	Yes	8	-	-	Moderate to good production	8, 25
Michelin	Yes	25	0.29	29	High production	19, 29
Muscadet De Dieppe	Yes	25	Medium	19	Low production	19, 25
Porter's Perfection	-	-	Medium	19	Low to good production	8, 19
Stoke Red	Yes	8, 20, 32	Fair to good	8, 23	Very good production	20, 32
Sweet Alford	Semi	25	-	-	Average to good production	1, 8, 25
Tolman Sweet	Possible	2, 5, 20	-	-	Very good production	2, 35
Tydeman Late	Possible	14, 36	-	-	Very good production	1
Yarlington Mill	Somewhat	8, 20, 25	Poor to medium	19, 23	Good to very good production, 10.4 kg $tree^{-1}$	3, 8, 20, 25, 32

[z] Historical values are reported in the column to the right of the data and are cited with the following numbers: 1) Ashridge Trees Ltd., 2020; 2) Beach et al., 1903; 3) Bradshaw, 2016; 4) Bultitude, 1983; 5) Burford, 2013; 6) Cline & Norton, 2008; 7) Cline, 2014.; 8) Copas, 2013; 9) Crosby et al., 1993; 10) Cummins, 2020; 11) Gamm Vert, 2018; 12) Grandpa's Orchard, 2020; 13) Hanson, 2005; 14) Harding, 2014; 15) Heekin, 2014; 16) Hogg, 1859; 17) Institut Francais des Productions Cidricoles, 2009; 18) Janick et al., 2006; 19) Jolicoeur, 2013; 20) Khanizadeh & Cousineau, 1998; 21) Merwin, 2008; 22) Miles et al., 2017; 23) Mohr, 1988; 24) Morgan & Richards, 2003; 25) Moulton et al., 2010; 26) NSW Department of Primary Industries, 2008; 27) Orange Pippin, 2019; 28) Pôle Fruitier de Bretagne, 2013; 29) Rothwell, 2012; 30) Seattle Tree Fruit Society, 2015; 31) Shelton, 2015; 32) Simmens, 2015; 33) Smith, 1971; 34) Summerland Varieties Corp., 2020; 35) The Ontario Department of Agriculture, 1914; 36) Wynne, 2020

Table 2.4 Historical soluble solids concentrations of 28 apple cultivars grown for cider production.

Cultivar	Historical Sugar	References[z]
Ashmead's Kernel	15.98° Brix; 17.6-18.0° Brix	5; 2
Binet Rouge	14.2° Brix	10
Bramley's Seedling	40-51 sg[y], 13.18° Brix; 11.1° Brix	4; 5; 8
Breakwell	10.9° Brix	8
Brown Snout	18.06° Brix; 15.4° Brix; 13.5° Brix; 18.2° Brix	12; 10; 8; 2
Brown's Apple	48 sg; 13.6° Brix; 10.8° Brix; 45-65 sg	4; 10; 8; 6
Bulmers Norman	13.6° Brix; 11.4° Brix; 14.6° Brix; 48-66 sg	10; 8; 7; 6
Calville Blanc d'Hiver	13.85° Brix; 14.70-14.96° Brix; 15.3° Brix	12; 5; 2
Cline Russet	New cultivar, no historical data available	
Cox Orange Pippin	50-75 sg; 15.32° Brix; 13.0° Brix	4; 5; 7
Crimson Crisp	14.4° Brix	2
Dabinett	13.22-13.83° Brix; 14.0° Brix; 15.1° Brix; 13.1-15.3° Brix	12; 8; 7; 2
Enterprise	13.0° Brix	11
Esopus Spitzenberg	14.9° Brix; 15.3° Brix	7; 2
Frequin Rouge	17.0° Brix; 11.7° Brix	10; 8
Golden Russet	15.14-18.05° Brix; 18.32° Brix; 16.9° Brix	12; 5; 8
GoldRush	11.52-14.30° Brix; 15.0	12; 11
Grimes Golden	14.0° Brix; 12.8° Brix	9; 8
Kingston Black	16.16° Brix; 13.4° Brix; 52-56 sg	12; 8; 3
Medaille d'Or	15.8° Brix; 58 sg	8; 1
Michelin	11.74° Brix, 14.9° Brix; 12.0; 50sg	12; 10; 3
Muscadet De Dieppe	14.7° Brix; 46-63 sg	8; 6
Porter's Perfection	13.87-14.97° Brix; 53-66 sg	12; 6
Stoke Red	12.3° Brix; 52 sg	8; 3
Sweet Alford	11.9° Brix	8
Tolman Sweet	15.0° Brix	7
Tydeman Late	No historical data found	
Yarlington Mill	15° Brix; 12.3° Brix; 12.2° Brix; 53-75 sg	9; 8; 2; 6

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Eisele & Drake, 2005; 6) Jolicoeur, 2013;7) Gottschalk et al., 2017; 8) Miles et al., 2013; 9) Raboin, 2016; 10) Rothwell, 2012; 11) Thompson-Witrick et al., 2014; 12) Valois et al., 2006

Table 2.5 Historical titratable acidity of 28 apple cultivars grown for cider production.

Cultivar	Historical TA	References[z]
Ashmead's Kernel	1.17 % malic; 10.40-10.78 g L^{-1} malic	5; 2
Binet Rouge	.15% malic	7
Bramley's Seedling	1.05-1.21% acid; 1.54% malic; 10.07 g L^{-1}	4; 5; 9
Breakwell	.64% malic; 7.82 g L^{-1}	7; 9
Brown Snout	.47 g malic acid 100 g^{-1} juice; 3.37 g L^{-1} malic; 1.05 g L^{-1} malic	13; 9; 2
Brown's Apple	.67% malic; 7.29 g L^{-1} malic; 8.0-12.5 g L^{-1} malic	4; 9; 6
Bulmers Norman	.24% malic; 2.16 g L^{-1} malic; 2.2-4.9 g L^{-1} malic	7; 9; 6
Calville Blanc d'Hiver	0.73 g malic acid 100 g^{-1} juice; .76 %-1.17 malic; 9.97 g L^{-1} malic	12; 5; 2
Cline Russet	New cultivar, no historical data available	
Cox Orange Pippin	.68-.76% acid; 0.90 % malic	4; 5
Crimson Crisp	8.85 g L^{-1} malic	2
Dabinett	.10-.16 g malic acid 100 g^{-1} juice; 2.55 g malic L^{-1}; 1.10-1.88 g L^{-1} malic	12; 9; 2
Enterprise	9.35 g L^{-1} malic	11
Esopus Spitzenberg	7.10 g L^{-1} malic	2
Frequin Rouge	2.62 g L^{-1} malic	9
Golden Russet	.46-.54 g malic acid 100 g^{-1} juice; 0.73% malic; 6.64 g malic L^{-1}	12; 5; 9
GoldRush	.61-.78 g malic acid 100 g^{-1} juice; 9.35 g L^{-1} malic	12; 11
Grimes Golden	6.6 g L^{-1} malic; 6.75 g L^{-1} malic	10; 9
Kingston Black	.67 g malic acid 100 g^{-1} juice; 6.45 g malic L^{-1}; 1.5-2.6 g L^{-1} malic	12; 9; 3
Medaille d'Or	.27% malic; 3.43 g L^{-1} malic; 2.1 g L^{-1} malic	7; 9; 1
Michelin	.24-.27 g malic acid 100 g^{-1} juice; 3.25 g malic L^{-1}; 2.5 g L^{-1} malic	12; 9; 3
Muscadet De Dieppe	2.72 g L^{-1} malic; 2.8 g L^{-1} malic	9; 6
Porter's Perfection	.70-.88 g malic acid 100 g^{-1} juice; 13 g L^{-1} malic; 8.2 g L^{-1} malic	12; 6; 3
Stoke Red	.64% malic; 6.13 g L^{-1} malic	7; 9
Sweet Alford	.22% malic; 1.86 g L^{-1} malic	7; 9
Tolman Sweet	No historical data found	
Tydeman Late	No historical data found	
Yarlington Mill	g L^{-1} malic; 1.3-4.5 g L malic	7; 10; 8; 2; 6

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Eisele & Drake, 2005; 6) Jolicoeur, 2013;7) Lea, 2015; 8) Gottschalk et al., 2017; 9) Miles et al., 2013; 10) Raboin, 2016; 11) Thompson-Witrick et al., 2014; 12) Valois et al., 2006

Table 2.6 Historical pH of 28 apple cultivars grown for cider production.

Cultivar	Historical pH	References[z]
Ashmead's Kernel	3.55; 3.03-3.25	3; 1
Binet Rouge	No historical data found	
Bramley's Seedling	2.95-3.08; 3.37; 3.26	2; 3; 4
Breakwell	3.23	4
Brown Snout	3.95; 3.87; 3.78	7; 4; 1
Brown's Apple	3.28	4
Bulmers Norman	4.04	4
Calville Blanc d'Hiver	3.28; 3.64; 3.13	7; 3; 1
Cline Russet	New cultivar, no historical data available	
Cox Orange Pippin	3.30-3.48; 3.70	2; 3
Crimson Crisp	3.37	1
Dabinett	4.39; 4.37; 4.13-4.15	7; 4; 1
Enterprise	3.76	6
Esopus Spitzenberg	3.48	1
Frequin Rouge	4.19	4
Golden Russet	3.61-3.65; 3.79; 3.67	7; 3; 4
GoldRush	3.19-3.22; 3.49	7; 6
Grimes Golden	3.57; 3.42	5; 4
Kingston Black	3.47; 3.45	7; 4
Medaille d'Or	4.19	4
Michelin	4.04-4.08; 3.98	7; 4
Muscadet De Dieppe	4.12	4
Porter's Perfection	3.31-3.36	7
Stoke Red	3.67	4
Sweet Alford	4.43	4
Tolman Sweet	No historical data found	
Tydeman Late	No historical data found	
Yarlington Mill	4.49; 4.13; 3.78	5; 4; 1

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Bradshaw, 2016; 2) Copas, 2010; 3) Eisele & Drake, 2005; 4) Gottschalk et al., 2017; 5) Raboin, 2016; 6) Thompson-Witrick et al., 2014; 7) Valois et al., 2006

Table 2.7 Historical polyphenol and tannin concentrations of 28 apple cultivars grown for cider production.

Cultivar	Historical Polyphenols	References[z]
Ashmead's Kernel	.07-.075% tannin	2
Binet Rouge	0.21% tannin	6
Bramley's Seedling	.09-.14% tannin; .12% tannin	4; 7
Breakwell	.23% Tannin; .27% tannin	6; 7
Brown Snout	310 ± 58 GAE 100 g^{-1}; .19% tannin; .21% tannin	10; 7; 2
Brown's Apple	.14% tannin; .16% tannin; .58 g/L GAE	4; 7; 5
Bulmers Norman	.27% tannin; .22% tannin; 1.8 g/L GAE	6; 7; 5
Calville Blanc d'Hiver	210 ± 16 GAE 100 g^{-1}; .07% tannin	10; 2
Cline Russet	New cultivar, no historical data available	
Cox Orange Pippin	.04-.05% tannins	4
Crimson Crisp	.11% tannin	2
Dabinett	346 ± 42 GAE 100 g^{-1}, 297 ± 63 GAE 100 g^{-1}; .29% tannin; .109-.37% tannin	10; 7; 2
Enterprise	398 mg GAE L^{-1}	9
Esopus Spitzenberg	.035% tannin	2
Frequin Rouge	.38 % tannin	7
Golden Russet	236 ± 30 GAE 100 g^{-1}, 148 ± 17 GAE 100 g^{-1}; .13% tannin	10; 7
GoldRush	150 ± 31 GAE 100 g^{-1}, 324 ± 32 GAE 100 $^{-1}$; 359 mg GAE L^{-1}	10; 9
Grimes Golden	.12% tannin; .08% tannin	8
Kingston Black	308 ± 37 GAE 100 g^{-1}; .17% tannin; 1.9 g L^{-1} tannic acid	10; 7; 3
Medaille d'Or	.64% tannin; 1.05% tannin; 4.4 g L^{-1} tannic acid	6; 7; 1
Michelin	253 ± 35 GAE 100 g^{-1}, 641 ± 68 GAE 100 g^{-1}; .16% tannin; 2.3 g L^{-1} tannic acid	10; 7; 3
Muscadet De Dieppe	.19% tannin; 1.0 g L^{-1} gallic acid	7; 5
Porter's Perfection	246 ± 16 GAE 100 g^{-1}, 328 ± 12 GAE 100 g^{-1}	10
Stoke Red	.31% tannin; .32% tannin	6; 7
Sweet Alford	0.15% tannin; .10% tannin	6; 7
Tolman Sweet	No historical data found	
Tydeman Late	No historical data found	
Yarlington Mill	.32% tannin; .20% tannin; .21% tannin; .35% tannin; 1.9 g L^{-1} GAE	6; 8; 7; 2; 5

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Jolicoeur, 2013; 6) Lea, 2015; 7) Gottschalk et al., 2017; 8) Raboin, 2016; 9) Thompson-Witrick et al., 2014; 10) Valois et al., 2006

Table 2.8 Historical yeast assimilable nitrogen concentrations of 28 apple cultivars grown for cider production.

Cultivar	Historical YAN concentrations	References[z]
Ashmead's Kernel	166.3-262.6 mg YAN L^{-1}	1
Binet Rouge	No historical data found	
Bramley's Seedling	No historical data found	
Breakwell	No historical data found	
Brown Snout	Historical YAN concentrations+A2:D34	2; 1
Brown's Apple	No historical data found	
Bulmers Norman	No historical data found	
Calville Blanc d'Hiver	45.2 ± 8.5 mg YAN L^{-1}; 86.31 g YAN L^{-1}	2; 1
Cline Russet	New cultivar, no historical data available	
Cox Orange Pippin	No historical data found	
Crimson Crisp	170 mg YAN L^{-1}	1
Dabinett	13.3 ± 1.9 mg YAN L, 45 ± 20 mg YAN L; 31.79-60.6 g YAN L^{-1}	2; 1
Enterprise	No historical data found	
Esopus Spitzenberg	113.4 mg YAN L^{-1}	1
Frequin Rouge	No historical data found	
Golden Russet	66 ± 11 mg YAN L^{-1}, 76.1 ± 9.5 mg YAN L^{-1}	2
GoldRush	13.8 ± 2.7 mg YAN L^{-1}, 36.3 ± 2.5 mg YAN L^{-1}	2
Grimes Golden	No historical data found	
Kingston Black	24.4 ± 5.6 mg YAN L^{-1}	2
Medaille d'Or	No historical data found	
Michelin	20.3 ± 1.9 mg YAN L^{-1}, 58.2 ± 9.0 mg YAN L^{-1}	2
Muscadet De Dieppe	No historical data found	
Porter's Perfection	50 ± 23 mg YAN L^{-1}, 110 ± 12 mg YAN L^{-1}	2
Stoke Red	No historical data found	
Sweet Alford	No historical data found	
Tolman Sweet	No historical data found	
Tydeman Late	No historical data found	
Yarlington Mill	8.88 mg YAN L^{-1}	1

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Bradshaw, 2016; 2) Valois et al., 2006

Table 2.9 Barker's classification of cider apples, Long Ashton Research Station (Lea, 2015).

Classification	*Acid (g malic acid L^{-1})*	*Tannin (g tannic acid L^{-1})*
Sharp	> 4.50	< 2.0
Bittersharp	> 4.50	> 2.0
Bittersweet	< 4.50	> 2.0
Sweet	< 4.50	< 2.0

Table 2.10 Spanish cider apple classification, SERIDA (Mangas Alonso and Blanco Gomis, 2014).

Classification	*Acid (g H_2SO_4 L^{-1})*	*Tannin (g tannic acid L^{-1})*
Bitter (*amargo*)	<3.29	>2.00
Sharp (*ácido*)	>4.80	<1.45
Sweet (*dulce*)	<3.29	<1.45
Bittersweet (*dulce-amargo*)	<3.29	[1.45-2.00]
Bittersharp (*ácido-amargo*)	>4.80	[1.45-2.00]
Sweet-Sharp (*acidulado*)	[3.29-4.80]	<1.45

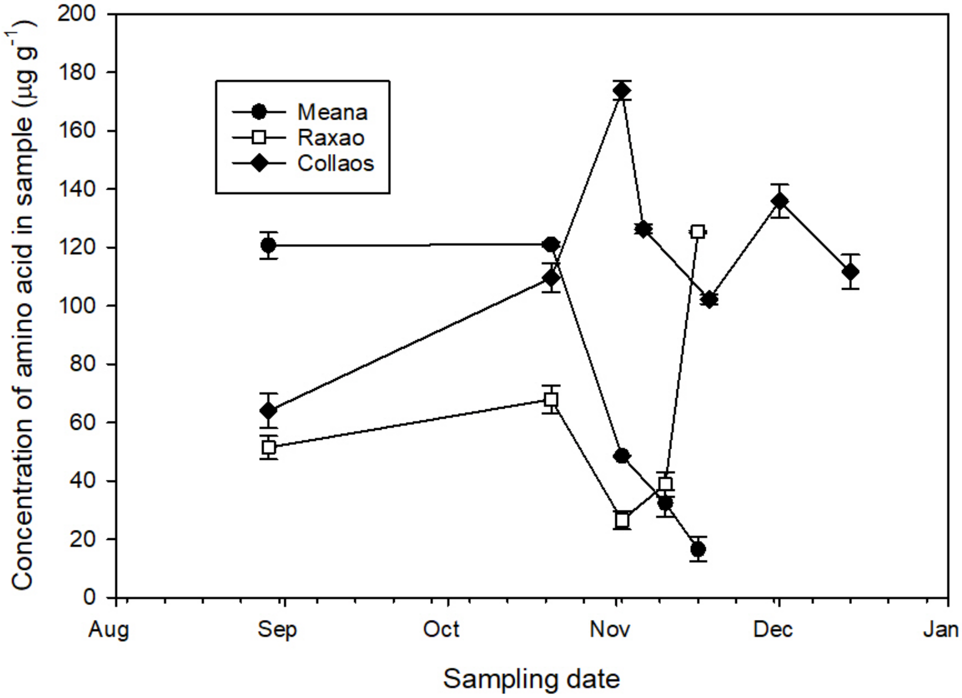

Figure 2.2 Evolution of aspartic acid in 'Meana,' 'Raxao,' and 'Collaos' apple, SERIDA, Villaviciosa, Spain. Adapted from (Blanco Gomis et al., 1990)

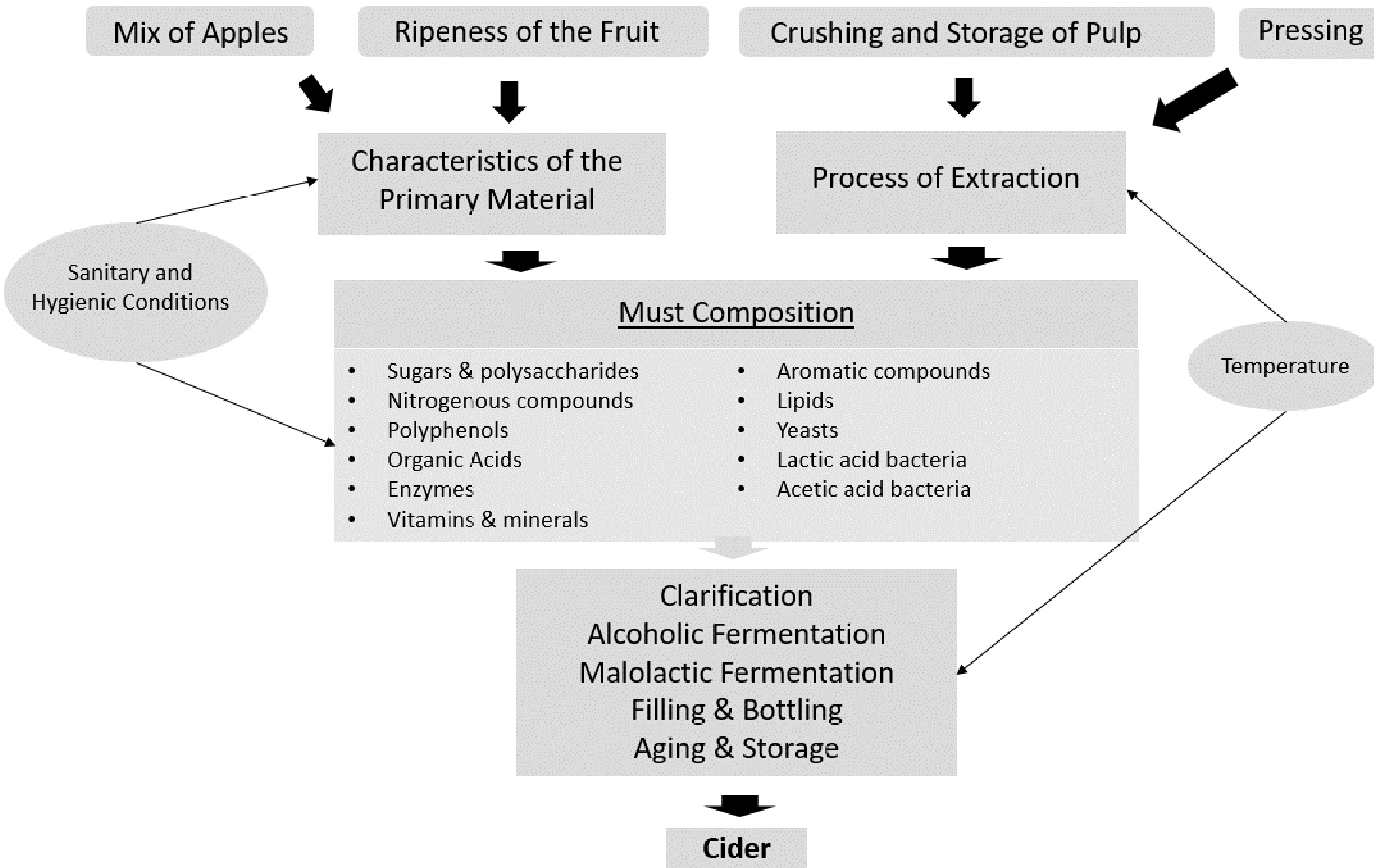

Figure 2.1 Cider production steps and the factors that influence must and cider composition. Adapted from Mangas Alonso and Blanco Gomis (2010).

3 Horticultural Attributes of Cider Cultivars

3.1 Abstract

Twenty-eight apple cultivars were selected for their potential for hard cider production in Ontario. An experiment was conducted to evaluate their horticultural potential in the province. After being planted in spring 2015, the trees were evaluated annually for their survival, tree height and spread, trunk growth, flowering dates, flower counts, fruit per tree, pre-harvest drop, crop load, fruit weight, fruit firmness, juicing extraction efficiency, and harvest dates. These horticultural attributes were sufficient to discriminate between cultivars. Additional exploratory analyses indicated a relationship between horticultural attributes and a cultivar's origin, with British cider cultivars blooming the latest, American cider apples producing the most juice, and French cider cultivars having the highest pre-harvest fruit drop. Cultivars in this study that show promise for continued research in Ontario include 'Binet Rouge', 'Bramley's Seedling', 'Breakwell', 'Bulmers Norman', 'Calville Blanc d'Hiver', 'Cline Russet', 'Cox Orange Pippin', 'Crimson Crisp®', 'Dabinett', 'Enterprise', 'Esopus Spitzenberg', 'Golden Russet', 'GoldRush', 'Medaille d'Or', 'Porter's Perfection', and 'Stoke Red'.

3.2 Introduction

3.2.1 Cider

The goal of this paper is to report and examine the relationships among the horticultural and growth characteristics of 28 apple cultivars selected for cider production in Ontario as evaluated at the Simcoe Research Station. This study was done in collaboration with Ontario craft cider producers who wished to learn more about these varieties. In Canada, the definition of "cider" is the product of the alcoholic fermentation of apple juice, which allows for additions like yeast, sugar, concentrate, and preservatives (Lametti, 2019). Further, the Ontario Craft Cider Association (OCCA) has defined Ontario Craft Cider as a beverage that "must be produced by a craft cidery in Ontario from 100 percent Ontario grown apples or pears" (MNP LLP, 2016). Cider in Ontario has been growing as a beverage category in Ontario over the last 10 years, especially craft cider (MNP LLP, 2016).

3.2.1.1 Apples

Apples grown for cider production have different quality and harvest parameters than those for table fruit because their fruit is grown for their juice and the apple is not meant for fresh market consumption. This has greatly influenced how cultivar selection has occurred in the past. Historically, cider trees were often grown on large roots (standard rootstocks or own-rooted) and many of the fruit would fall to the ground when ripe, which is not generally compatible with modern North American harvesting and juicing practices. Many contemporary cider orchards are therefore planted in high-density systems, so research that implements these systems is important for advising modern cider apple production (Merwin et al., 2008).,

Given the different origins of these cultivars and their climatic adaptations, there are other considerations about growing them in Ontario. Is the season long enough? Do they bloom too early, which predisposes the flowers to frost? Do they mature adequately in our seasons? Do they exhibit pre-harvest drop? Are they susceptible to fire blight (*Erwinia amylovora*)? It is well-known that some cultivars exhibit high degrees of bienniality and produce small and few fruit. These are attributes growers seek before investing time and money into establishing cider orchards.

In this paper we will summarize the bloom habits of 28 of these cultivars, their precocity, growth patterns, and their harvesting particularities in addition to exploring the relationships among these variables. This will provide a grower with information regarding whether the tree is worthwhile to grow. We will briefly discuss what these are, why they are important, and what they measure.

3.2.1.2 Harvesting

Cider apples have been harvested in different ways over the millennia. In Canada, most apples, including cider apples, are harvested by hand directly from the tree. In other countries, apples are collected off the ground after they fall, whether naturally or by shaking. Some orchardists use mechanical harvesting methods to collect fruit from the ground, while research on mechanical collection of fruits from the tree is being conducted currently (in our own lab). In Canada ground apples are not typically used in cider production due to food safety concerns, and while the alcohol produced by fermentation will inhibit bacterial growth, fungal growth, and patulin production (Doores, 2009), the sanitation concerns of juice press operators largely override any attempts to press dropped fruit.

When evaluating the harvest potential of a cider apple cultivar, parameters often assessed include the total number of fruit, the total weight of the fruit, the number of fruits harvested, the number of pre-harvest fruits that dropped, the weight of harvested fruits, the weight of dropped fruits, the number of fruits thinned, and the percentage of fruit set based on total number of floral clusters.

3.2.1.3 Rootstocks

Rootstocks regulate the vigor of the tree in addition to other attributes, such as soil adaptation. Some rootstocks are not compatible with certain cultivars. Modern orchards tend to use size-controlling rootstocks, which allow for smaller and closer spacing of trees and reduce the need for unwieldy and dangerous equipment like orchard ladders. Older orchards, including many of those in Europe where many of cider cultivars originated were planted on standard roots, often the cultivar’s own roots. These European cider apples tend to be rich in polyphenols, which are desirable in cider production, however many are biennial and grow vigorously, so dwarfing rootstocks are used. Visual aspects of the fruit are less important (Provost, 2018) because the cider maker is concerned about the pressed juice rather than fruit aesthetics.

3.2.2 Horticultural characteristics of apple trees

This study will focus on the horticultural characteristics of cider apple trees and fruit, excluding the consumption of the fruit. Understanding how the fruits grow, how the tree develops, and its dieback is important for understanding how the tree performs separately from its juice quality. For example, tree that produces only a few apples each year, even with perfect juice, isn't helpful to a grower.

3.2.2.1 Bloom and phenology

The period that apple trees bloom plays an important role in what varieties should be planted together and if a cultivar is suitable for a particular climate zone. Apples are largely not self-fertile and thus require another variety of apple nearby to act as a pollinizer. If two apple varieties are planted near each other and do not bloom at the same time, however, they cannot act as pollinizers for one another. Rather, blooms from one tree need to be receptive to pollination while the blooms from another produce pollen. Given successful pollination, the identity of the pollinizer has no effect on the fruit produced by the fruit-bearing tree (Dennis, 2003).

Another reason bloom date and length are important is that it influences the effect that environmental stressors have on fruit set. An early blooming tree has an increased risk of the flowers being damaged by frost. Additionally, lower temperatures during early bloom dates may inhibit pollinators. A late bloom or protracted bloom period may increase the risk of infection with fireblight (*Erwinia amylovora)* or other diseases.

Bloom and phenology are usually measured using a rating system based on the development of floral buds. The chart used for this was from Washington State University, which covers the progression from the silver tip stage right after dormancy to petal fall (Ballard, 1981).

3.2.2.2 Precocity

Precocity refers to how quickly after planting a tree begins to bear fruit. In the cider industry this ends up being even more important because of the extra time needed to put cider to market as opposed to fresh fruit. The sooner a tree bears fruit, the sooner cider can start being produced. In high-density dwarf plantings, precocious trees contribute a greater part of the total lifetime yield of the tree in addition to the economic importance of a faster return on investment when compared to standard or semi-dwarf trees. High density systems have recently become popular as options for a fast turnover of fruit production. Rather than waiting five years for fruit production, growers may get fruit as early as the third year after planting. Standard orchards produce more fruit per tree, but high-density is easier to harvest and produces more fruit per hectare and earlier after planting.

3.2.2.3 Growth habit

In a high-density system, trees with more vigorous growth may need harsher pruning. Some trees have distinctive shapes, habits, or spread out into the row. The height and breadth of the tree has long been linked with the trunk cross-sectional area and total fruit bearing surface of the tree (Barden & Neilsen, 2003). In addition, whether fruit are borne terminally or on spurs are important management considerations, as is the propensity to develop non-fruiting regions on the main leaders – referred to as "blind wood."

3.2.2.4 Bienniality

All apple cultivars tend towards bienniality, with some having a greater disposition than others. Reproductive buds are initiated in the summer for the following year's crop while the current year's crop is still on the tree, usually after fruit set. The presence of the current year's fruit on the tree inhibits the set of reproductive buds for the following year, while the absence of fruit in one year would encourage reproductive bud setting for the following year. This leads to apple trees bearing large quantities of fruit one year and smaller quantities the next, alternating every year unless some sort of intervention is taken. Interventions taken to mitigate extreme biennial bearing include fruit thinning and growth regulator sprays before bud set in the summer. Not all varieties are receptive to this amelioration, however. Cider makers may choose to purchase fruit from other sources to compensate for the shortfall or they may simply choose to press what fruit they have. Asturian cider production, for example, is heavily affected by bienniality, with 40-50000 tons of fruit produced in odd years and 7-20000 tons of fruit produced in even years (Pando Bedriñana et al., 2010). The biennial bearing index of a cultivar is calculated by taking the absolute value of the ratio of the difference in yield between two harvests and the sum of the yield of those harvests (Hoblyn et al., 1937; Jonkers, 1979).

3.2.2.5 Harvest weight (total yield)

The total weight of a given tree's harvest is measured as the fruit are harvested. Alternatively, the number of fruit can be counted and an average weight can be measured using a smaller sample of fruits. The total fruit borne by the tree can be divided into pre-harvest dropped fruit and harvested fruit. In Canada, dropped fruits are usually discarded or sold for juice. Additionally, a cumulative yield over every year of a tree's life can be determined by the sum of annual yields. Crop load, an estimate of fruit number normalized for tree size, is calculated by taking the ratio of the number of apples on a tree to its trunk cross-sectional area.

Peck et al. (2016) published the results of a tree thinning study and its effect on cider production. Trees that had higher crop loads were found to have fruit that were smaller, less acidic, and more mature when compared to trees of lower crop loads in the same orchard with the same cultivars and rootstocks. At some point the decreased crop load in the field reduces the yield without any benefit to fruit quality (Peck et al., 2016).

3.2.2.6 Harvest date

Choosing a harvest date depends on several factors. These include the weather, labor availability, the ripeness of the fruit, the intended purpose of the fruit, and the available storage capacity. Ripeness in the field is usually monitored using the starch-iodine test (Blanpied & Silsby, 1992) in conjunction with a generalized rating chart, and internal ethylene production. The starch index method works by halving apples transversely and dipping the flesh in an iodine solution. Iodine will turn starch a dark colour, while simple sugars will not. As apples ripen, starches break down into simple sugars. If the mesocarp of an apple fails to change colour in the presence of the iodine solution, it is considered fully ripe. Apples being put into controlled atmosphere storage or cold storage are often picked underripe with the expectation that they will store better. They will ripen off the tree. Cider producers want to press ripe fruit, as yeast will not ferment starches. By maximizing the ripeness of the fruit, cider producers will get the maximum amount of sugar in their juice and thus the maximum amount of alcohol in their cider.

3.2.2.7 Pre-harvest Fruit Drop

Fruit from the apple tree falls at various times throughout the season. After fertilization, the first point is what is known as June drop, which is when fruitlets abscise after fruit set either in response to chemical thinners or naturally. From then until harvest fruit may drop due to wind, natural or accidental physical force, or disease. When fruit matures, pre-harvest drop varies widely by cultivar. Some trees will drop mature fruit as soon as it is ripe, while other fruits will hang onto the tree long past maturity.

In Canada, fruit that falls to the ground is usually discarded due to disease risk from soil-associated pathogens, though it can be used for sweet (unfermented) cider in some instances when pasteurized. The cost of labour and labour availability often preclude grower interest in harvesting fruit off the ground as the financial returns are often not merited.

3.2.2.8 Effects of Horticultural Practices on Juice and Processing

Horticultural practices can affect the juice attributes of apples and may be preferable to using interventions in the cidery to modify juice attributes. For example, added polyphenols were shown in sensory tests not to be helpful in improving cider taste, so researchers made it a goal to increase endogenous polyphenols in order to achieve the desired sensory characteristics in cider (Martin et al., 2017). Crop load management is an effective tool for altering juice and cider quality, though there is a point where decreased crop load in the field reduces the yield without any benefit to fruit quality (Peck et al., 2016). Although juice polyphenol content didn't differ at harvest in the crop-load study, post-fermentation polyphenols increased with the crop load (Peck et al., 2016).

Polyphenol concentrations are affected by site, cultivar, growing year, storage, processing methods, and oxidation (Thompson-Witrick et al., 2014).

In the 2018 Agriculture and Agri-Food Canada cider apple report, six varieties of eating apples were tested in addition to the cider apples. In Québec, table apples like McIntosh, Spartan, Empire, and Cortland were often used for cider to add value to lower-quality fruits. Overall there has been little research and development in cider apples in North America (Provost, 2018). Ontario cider producers would historically use culinary and dessert apples instead of cider apples (Wilson et al., 2003).

When organic apple production was compared with integrated pest management there were no consistent trends found for either flavour or texture in apples nor were triangle tests effective at distinguishing fruit produced among the systems (Peck & Merwin, 2010). One of the advantages of cider apple production is that it possibly requires fewer fungicidal treatments, though they may be necessary to assure a profit (Provost, 2018).

3.2.3 Objectives of the study

The objectives of this study were to report the horticultural and growth characteristics of 28 apple cultivars selected for cider production in Ontario as evaluated at the research orchard in Simcoe, Ontario. The specific characteristics that will be summarized are: the phenological stages of the different cultivars, particularly the full bloom dates; the yield attributes, including the number and weight of the fruit on the trees; and the vigour of each cultivars as indicated by tree height, width, and mortality.

These data will be subject to exploratory analyses to examine relationships that exist among the horticultural attributes. It is hypothesized that differences in horticultural attributes exist among cultivars that have different geographic origins due to the difference in traits selected by growers in each region to adapt for the local climates and horticultural practices.

3.3 Materials and Methods

3.3.1 Plant materials

The main experiment consisted of 28 apple cultivars grafted onto M.9 T337 rootstock. All budwood was sourced from collectors within Ontario, Canada, and trees were propagated and grown by a commercial nursery in Warwick, Ontario. The cultivars consist of: ‘Ashmead’s Kernel,’ ‘Breakwell,’ ‘Brown’s Apple,’ ‘Bulmers Norman,’ ‘Binet Rouge,’ ‘Bramley’s Seedling,’ ‘Brown Snout,’ ‘Calville Blanc d’Hiver,’ ‘Crimson Crisp®,’ ‘Cox Orange Pippin,’ ‘Cline Russet,’ ‘Dabinett,’ ‘Enterprise,’ ‘Esopus Spitzenberg,’ ‘Fréquin Rouge,’ ‘GoldRush,’ ‘Grimes Golden,’ ‘Golden Russet,’ ‘Kingston Black,’ ‘Michelin,’ ‘Muscadet de Dieppe,’ ‘Medaille d’Or,’ ‘Porter’s Perfection,’ ‘Sweet Alford,’ ‘Stoke Red,’ ‘Tydeman Late,’ ‘Tolman Sweet,’ and ‘Yarlington Mill.’

The apple cultivars were selected by consultation with members of the Ontario Craft Cider Association, with special attention being paid to cultivars that had a historical reputation for cider production as well as those with a historically high tannin concentration. These cultivars were then sourced within Canada, as no virus-free certified budwood was available outside of Canada at the time of propagation.

In the spring of 2015 the trees were planted at the Simcoe Research Station (Simcoe, ON). They received regular treatment and care and an integrated pest management for disease and insect pests according to local recommendations (OMAFRA, 2016). The trees in this experiment were planted in a randomized complete block, with 4 blocks of 5 trees for each of 28 cultivars (Appendix 2). Data were collected from the middle three trees from each five-tree block, with the two outside trees in each block acting as guard trees. Trees were spaced 1 m within and 4.5 m between rows spacing (1667 trees ha^{-1}). At planting, the trees were headed and trained to a wire trellis in a vertical axis training system. The trellis system was equipped with drip irrigation for each tree to supplement natural rainfall.

3.3.2 Horticultural measurements

Each autumn the size of the trees were measured by recording tree width, tree height, and trunk cross-sectional area (calculated by the measured circumference or diameter of the tree) 30 cm above the ground using digital calipers (Electronic Caliper with Digital Display, Mastercraft Canada, Toronto) or tape measures. Tree mortality was accounted for in the spring and fall from 2016-2018.

In the spring of 2017 and 2018 phenology was rated three to four times per week from late April to the end of flowering in June. Flower clusters were counted on each tree at full bloom in May of 2017 and 2018 and fruits were hand-thinned to 10 cm between fruits and single fruits per cluster after June drop each year.

3.3.3 Yield measurements

In the fall of 2017 and 2018, fruit was collected from guard trees before harvest to determine maturity. Fruit maturity was assessed on five fruit selected from among the two guard trees in each block, usually consisting of two fruit from one tree and three fruit from the other. These were taken beginning two weeks before their projected harvest date based on data from other sites, although in some instances fruit were harvested ahead of the projected schedule. These five apples were weighed and photographed whole. They were then halved transversely and seeded. One fruit half from each apple was photographed, as were the seeds. Notes were taken on the seed colour and fruit colour. One half from each apple was assessed using the starch-iodine method (Blanpied & Silsby, 1992) and photographed. For each cultivar, fruit on the data trees, from the three middle trees in the set of five trees, were harvested when the guard tree fruit was measured at 40% flesh stain on the Cornell generic starch-iodine test scale (Blanpied & Silsby, 1992). At harvest, all pre-harvest drop fruit were and all harvested fruit were separately counted and weighed using an outdoor battery-operated digital scale (A&D FG-30KBM, Data Weighing Systems, Wood Dale, IL). These counts and weights were recorded for each individual data tree.

A pool of 15 apples, comprised of 5 random apples sampled from each of the three data trees, were weighed on an analytical scale (LC 3200D, Sartorius, Bohemia, NY). Thereafter, the fruit pool was ground with a fruit juicer (Model 8006, Omega, Harrisburg, PA), wrapped in cheesecloth (Grade #50, Fisher Scientific, Whitby, ON), and pressed on a custom made stainless steel rack and cloth set used in conjunction with a PowerFist hydraulic press (Princess Auto, Hamilton, ON). The juice was collected in a graduated cylinder and the volume from each pressing was measured. The volume of the juice was divided by the weight of the apples to calculate the juicing efficiency. Juice production was estimated by multiplying the harvest weight per tree by the planting density of 1667 trees ha^{-1} and juicing efficiency.

3.3.4 Statistical analyses

Explanatory statistics were analyzed using the GLIMMIX procedure in SAS 9.4 (The SAS Institute, Cary, NC). Significance was evaluated at a *p* value of 0.05 and residuals were analyzed for normality and outliers, with outliers being excluded from the data set. Post-hoc means separation was analyzed using Tukey-Kramer grouping for least square means (α=0.05). Additional statistical data can be found in Appendix 1.

To understand the relationships among variables, exploratory multivariate statistical analyses were performed using the PRINCOMP, FASTCLUS, and DISCRIM procedures in SAS 9.4 (The SAS Institute, Cary, NC). These procedures group variables using principal component analysis, cluster analysis, and discriminant analysis, respectively. The discriminant analysis clusters quantitative variables based on a classification variable, which can describe differences among known classes. The suitability of the discriminant analyses was analyzed with a χ^2 test.

3.4 Results

3.4.1 Bloom data

In 2017 the first blossoms opened on 29-April on ‘Binet Rouge’. The last cultivar to start blossoming was ‘Stoke Red’, which first opened on 21-May. ‘Calville Blanc d’Hiver’ was the first cultivar to reach full bloom, indicated by a rating of 8 on the Washington State University apple phenology chart (Ballard, 1981), on 10-May, whereas ‘Stoke Red’ was the last to reach full bloom on 29-May (Table 3.1). ‘Ashmead’s Kernel’ and ‘Esopus Spitzenberg’ were the first to finish full bloom on 19-May, whereas ‘Stoke Red’ was the last to finish full bloom on 1-June. ‘Binet Rouge’ was the first cultivar to finish the entire bloom period, with its final blossoms dropping their petals on 23-May. The last cultivars to finish dropping blossoms were ‘Brown’s Apple’, ‘Fréquin Rouge’, and ‘Stoke Red’, which dropped their final petals on 3-June. ‘Golden Russet’ had the longest overall bloom period, whereas ‘Fréquin Rouge’ had the shortest (Figure 3.1). In 2017 the number of flower clusters ranged from an average of 16 clusters on ‘Tydeman Late’ to 163 clusters on ‘Medaille d’Or’ (Table 3.5)

In 2018 the first blossoms opened on 14-May on ‘Ashmead’s Kernel’ and ‘Calville Blanc d’Hiver’. The last cultivar to start blossoming was ‘Stoke Red’, which first opened on 24-May. ‘Ashmead’s Kernel’ was the first cultivar to reach full bloom, which occurred on 16-May, whereas ‘Stoke Red’ was the last to reach full bloom on 25-May (Table 3.2). ‘Ashmead’s Kernel’ was the first cultivar to finish full bloom on 23-May, whereas ‘Stoke Red’ and ‘Fréquin Rouge’ were the last to finish full bloom on 30-May. ‘Calville Blanc d’Hiver’, ‘GoldRush’, and ‘Binet Rouge’ were the first cultivars to finish the entire bloom period, with their final blossoms dropping their petals on 25-May. The last cultivar to retain blossoms was ‘Yarlington Mill’, which had open flowers until 4-June. ‘Yarlington Mill’ had the longest overall bloom period, whereas ‘Cline Russet’, ‘Porter’s Perfection’, and ‘Stoke Red’ had the shortest (Figure 3.2). In 2018 the number of flower clusters on each tree ranged from 11 clusters on ‘Bulmers Norman’ to 147 clusters on ‘Calville Blanc d’Hiver’ (Table 3.5).

3.4.2 Harvest data

Of the cultivars evaluated, only three produced more than one fruit per tree in the second year of production (Table 3.6): ‘Muscadet de Dieppe’, ‘Binet Rouge’, and ‘Grimes Golden’. Every cultivar produced a harvestable quantity of greater than one fruit per tree by 2017 (Table 3.7), the third year of production. In 2016 the yield on every cultivar was relatively small, due to the trees being young (Table 3.6). In 2017 the total fruit weight per tree ranged from 2.1 kg in ‘Tydeman Late’ and ‘Brown Snout’ to 10.7 kg in ‘Bramley’s Seedling’ (Table 3.7), whereas in 2018 the total fruit weight per tree ranged from 0.7 kg in ‘Medaille d’Or’ to 14.3 kg in ‘Calville Blanc d’Hiver’ (Table 3.8).

In 2017 the harvested fruit weight ranged from to 0.8 kg tree^{-1} in ‘Tolman Sweet’ to 8.1 kg tree^{-1} in ‘Bramley’s Seedling’ (Table 3.7) and the harvested fruit number ranged from 6 fruit tree^{-1} in ‘Tolman Sweet’ to 67 fruit tree^{-1} in ‘GoldRush’ (Table 3.7), the pre-harvest dropped fruit weight ranged from 0 kg tree^{-1} in ‘Esopus Spitzenberg’ and ‘Tydeman Late’ to 3.7 kg tree^{-1} in ‘Yarlington Mill’ (Table 3.7), the pre-harvest dropped fruit number ranged from 0 fruit tree^{-1} in ’Tydeman Late’ to 51 fruit tree^{-1} in ‘Michelin’ (Table 3.7), and the pre-harvest dropped fruit percentage ranged from 1% in ‘GoldRush’ to 79% in ‘Michelin’ (Table 3.7). In 2018 the harvested fruit weight ranged from 0.5 kg in ‘Bulmer’s Norman’ to 13.7 kg in ‘Calville Blanc d’Hiver’ (Table 3.8), the harvested fruit number ranged from 5 fruit tree^{-1} in ‘Bulmer’s Norman’ to 73 fruit tree^{-1} in ‘Tydeman Late’ (Table 3.8), the pre-harvest dropped fruit weight ranged from 0 kg tree^{-1} in ‘Medaille d’Or’ to 8.6 kg tree^{-1} in ‘Grimes Golden’ (Table 3.8), the pre-harvest dropped fruit number ranged from 1 fruit tree^{-1} in ’Medaille d’Or’ to 61 fruit tree^{-1} in ‘Grimes Golden’ (Table 3.8), and the pre-harvest dropped fruit percentage ranged from 5% in ‘Crimson Crisp®’ to 88% of total fruit per tree in ‘Grimes Golden’ (Table 3.8).

In 2017, the first variety to be harvested was ‘Brown’s Apple’, which was picked on 29-Aug, and the last to be picked was ‘GoldRush’ on 26-Oct. The cultivar that had the shortest number of days between full bloom and harvest was ‘Brown’s Apple’ with 99 days whereas the longest was ‘GoldRush’ with 164 days (Table 3.1). In 2018, the first variety to be harvested was ‘Brown’s Apple’, which was picked on 22-Aug, whereas the last to be picked were ‘Enterprise’ and ‘GoldRush’ on 6-Nov. The cultivar that had the shortest number of days between full bloom and harvest was ‘Brown’s Apple’ with 92 days whereas the longest was ‘GoldRush’ with 173 days (Table 3.2).

In 2017, the crop load ranged from 2.0 fruits cm^{-2} TCSA on 'Tydeman Late' to 14.4 fruits cm^{-2} TCSA on 'GoldRush' (Table 3.7). In 2018, the crop load ranged from 0.5 fruits cm^{-2} TCSA on 'Bulmers Norman' to 9.4 fruits cm^{-2} TCSA on Crimson Crisp (Table 3.8). The average fruit weight of the individual apples ranged from 80 g for a 'Porter's Perfection' apple to 364 g for a 'Bramley's Seedling' apple in 2017 (Table 3.1), whereas in 2018 this ranged from 70 g for a 'Binet Rouge' apple to 267 g for a 'Bramley's Seedling' apple (Table 3.2).

3.4.3 Growth data

By 2018, the TCSA of the trees ranged from 6.9 cm^2 in Crimson Crisp to 21.2 cm^2 in 'Calville Blanc d'Hiver' (Table 3.4). By 2018, the height of trees ranged from 2.5 m in 'Fréquin Rouge' to 3.5 m in 'Binet Rouge'. The breadth of the trees ranged from 0.9 m in 'Brown Snout' to 1.8 m in 'Tydeman Late' (Table 3.4).

From planting in 2015 to the 2018 harvest, the cumulative fruit count for the cultivars ranged from 40 fruit per tree in 'Kingston Black' to 114 fruit per tree in 'Grimes Golden'. The cumulative fruit weight for the cultivars ranged from 3.8 kg per tree in 'Kingston Black' to 20.2 kg per tree in 'Calville Blanc d'Hiver' (Table 3.8). From planting in 2015 to the 2018 harvest, the survival rate at the Simcoe site ranged from 95% to 100%, with no significance associated with cultivar (Table 3.3).

3.4.4 Juice production data

In 2017, the juicing efficiency ranged from 48 mL juice per 100 g fruit in 'Muscadet de Dieppe' to 72 mL juice per 100 g fruit in 'GoldRush' (Table 3.1). In 2018, the juicing efficiency ranged from 36 mL juice per 100 g fruit in 'Muscadet de Dieppe' to 68 mL juice per 100 g fruit in Crimson Crisp (Table 3.2).

. In 2017, the estimated juice yield ranged from 780 L juice ha^{-1} in 'Tolman Sweet' to 11700 L juice ha^{-1} in 'GoldRush' (Table 3.1). In 2018, the estimated juice yield ranged from 510 L juice ha^{-1} in 'Bulmers Norman' to 14840 L juice ha^{-1} in 'Calville Blanc d'Hiver' (Table 3.2).

3.4.5 Multivariate analyses

The principal component analysis indicated that 77% of the horticultural variance among the cultivars could be attributed to 4 clusters. The first cluster explained 32% of the variance and was dominated by the total fruit weight and the total fruit number. The second cluster explained 24% of the variance and was most influenced by tree TCSA and height. The third cluster explained 11% of the variance and mostly accounted for the percentage of pre-harvest fruit drop. The fourth cluster also explained 11% of the variance and comprised the percentage of pre-harvest fruit drop and the percentage of fruit set.

The discriminant analyses showed that horticultural attributes classification by origin was successfully predicted in 59% of observations and that classification by cultivar was successfully predicted in 49% of observations. A χ^2 test at 95% confidence indicated a goodness of fit for both origin and cultivar (Table 3.10).

3.5 Discussion

3.5.1 Evaluation criteria

The goal of evaluating the horticultural attributes of these apple cultivars was not only to provide practical recommendations for choosing varieties for cider production, but to identify cultivars that are good candidates for future research on juice quality, flavour development, and horticultural improvement. In this research, five horticultural attributes were identified that could have a negative impact on a variety's performance in cider production: tree mortality, early and protracted bloom, harvest issues, biennial bearing potential, and processing issues.

While the Simcoe research site did not reveal any statistically significant differences in tree mortality among the apple cultivars, 'Michelin' exhibited higher mortality rates at off-site locations (Appendix 3). Cultivars that were particularly vigorous, taking into account TCSA, height, and width, included 'Binet Rouge,' Bramley's Seedling,' 'Calville Blanc d'Hiver,' 'Porter's Perfection,' and 'Tydeman late,' whereas those with low overall vigour included 'Brown Snout,' 'Cline Russet,' 'Crimson Crisp®,' 'Fréquin Rouge,' ‘GoldRush,’ ‘Kingston Black,’ and ‘Medaille d’Or’ (Tables 3.3, 3.4). The cultivars that were less vigorous when grown at the Simcoe Research Station than in historical studies include ‘Kingston Black,’ ‘Medaille d’Or,’ and ‘Muscadet de Dieppe,’ whereas ‘Binet Rouge’ was the only cultivar to exhibit higher vigour than suggested in historical reports (Ashridge trees Ltd., 2020; Copas, 2013; Grandpa’s Orchard, 2020; Jolicoeur, 2013; Pôle Fruitier de Bretagne, 2013; Rothwell, 2012; Shelton, 2015; Simmens, 2015) (Tables 2.2, 3.3, 3.4).

Flowers that bloom before the frost-free date are at risk of freezing, which would result in major crop loss for that year. In Simcoe, the average date has been reported to be between May 3 (OMAFRA, 2020) and May 15 (Brown & Bootsma, 1991). In 2017, five cultivars: ‘Binet Rouge’, ‘Ashmead’s Kernel’, ‘Calville Blanc d’Hiver’, ‘Golden Russet’, and ‘GoldRush’, started blooming before this date, but full bloom was reached after the last frost. In 2018 all cultivars started blooming after May 3. Cultivars, that bloom late or have a protracted bloom, however, are at greater risk for fire blight infection due to higher temperatures, which contributes to increased spread through pollinator activity over a greater period of time and to increased bacterial reproduction (Grove et al., 2003). Cultivars with bloom dates in Simcoe that are earlier than historical data suggest include ‘Brown Snout,’ ‘Calville Blanc d’Hiver,’ ‘Enterprise,’ ‘Medaille d’Or,’ and ‘Tolman Sweet,’ whereas cultivars with bloom dates in Simcoe that are later than historical data suggest include ‘Bramley’s Seedling,’ ‘Brown’s Apple,’ ‘Grimes Golden,’ ‘Porter’s Perfection,’ and ‘Yarlington Mill’ (Ashridge trees Ltd., 2020; Bultitude, 1983; Burford, 2013; Copas, 2013; Hanson, 2005; Khanizadeh & Cousineau, 1998; C. A. Miles et al., 2017; NSW Department of Primary Industries, 2008; Simmens, 2015) (Tables 2.1, 3.1, 3.2).

Many apple cultivars are prone to pre-harvest fruit drop, while others have uneven fruit ripening that require multiple picks. While pre-harvest fruit drop is welcome in regions where fruit are harvested from the ground, such as England, it is a detriment when dropped fruit are not used for cidermaking. These varieties include ‘Michelin’, ‘Grimes Golden’, ‘Ashmead’s Kernel’, ‘Breakwell’s Seedling’, ‘Brown Snout’, ‘Esopus

Spitzenberg’, ‘Fréquin Rouge’, ‘Kingston Black’, ‘Muscadet de Dieppe’, ‘Porter’s Perfection’, ‘Tolman Sweet’, ‘Sweet Alford’, and ‘Yarlington Mill’. Two cultivars, ‘Brown’s Apple’ and ‘Tydeman Late’ produced fruit that rotted and cracked while on the tree, making sorting necessary at harvest. While a bienniality index is best calculated in a mature orchard, the data from this research can be used to calculate a bienniality index with the caveat that an increase in fruit production from 2017 to 2018 may be due to tree maturity rather than bienniality. A biennial bearing index based on 3 years provides only 2 data points, and more years are required to obtain a true picture of biennial bearing. A considerable decrease in production from 2017 to 2018, such as in ‘Bulmers Norman’, is likely attributable to bienniality. Similarly, crop load is a confounding factor that influences biennial bearing. In precocious rootstocks, like M.9, fruit overset in year 2 or 3 may lead to biennial bearing early in the tree’s life, which can be controlled with thinning and precision pruning (Robinson, 2003). Five cultivars had an average difference in total fruit weight between 2017 and 2018 that was larger than the average total fruit weight of the two years: ‘Bulmers Norman’, ‘Medaille d’Or’, ‘Stoke Red’, ‘Fréquin Rouge’, and ‘Tydeman Late’. All these cultivars have historically exhibited biennial bearing (Table 2.3). Cultivars that produced lower total yields in the first three years than historical yield data suggest include ‘Binet Rouge,’ ‘Fréquin Rouge,’ ‘Michelin,’ ‘Stoke Red,’ and ‘Tolman Sweet,’ whereas cultivars that had higher than anticipated yields include ‘Calville Blanc d’Hiver,’ and ‘Cox Orange Pippin’ (Beach et al., 1903; Cummins, 2020; Grandpa’s Orchard, 2020; Heekin, 2014; Institut Français des Productions Cidricoles, 2009; Jolicoeur, 2013; Khanizadeh & Cousineau, 1998; Moulton et al., 2010; Pôle Fruitier de Bretagne, 2013; Rothwell, 2012; Simmens, 2015; The Ontario Department of Agriculture, 1914) (Tables 2.3, 3.7, 3.8).

Once harvested, cider apples must be processed to procure juice. Many cultivars are difficult to extract juice from and more have a low juicing efficiency due to their texture, composition, and state of horticultural maturity. The cultivars whose average juicing efficiency was below 60 mL 100 g^{-1} fruit include: ‘Binet Rouge’, ‘Muscadet de Dieppe’, ‘Yarlington Mill’, ‘Brown Snout’, ‘Fréquin Rouge’, ‘Sweet Alford’, ‘Tolman Sweet’, ‘Ashmead’s Kernel’, ‘Cox Orange Pippin’, ‘Dabinett’, ‘Kingston Black’, and ‘Michelin’. This could be overcome by grinding the pulp more finely, letting the apples “sweat” in storage, using press aids like rice hulls, extending the press time, or mixing the apples with other cultivars to aid processing (Merwin et al., 2008). The results of this study run contrary to historical reports of “good” juice yield in ‘Cox Orange Pippin’ and the reported medium-to-high yields for in ‘Muscadet de Dieppe,’ Fréquin Rouge,’ and ‘Michelin,’ but are consistent with reported low juice yields for ‘Binet Rouge,’ ‘Brown Snout,’ and ‘Yarlington Mill’ (Copas, 2013; Jolicoeur, 2013; Mohr, 1988; Pôle Fruitier de Bretagne, 2013; Rothwell, 2012) (Tables 2.3, 3.1, 3.2). When grown in Ontario, many cultivars were harvested in a different part of the season than historical data from other parts of the world suggest. Those that were harvested earlier than historical reports include ‘Ashmead’s Kernel,’ ‘Binet Rouge,’ ‘Brown’s Apple,’ ‘Dabinett,’ ‘Kingston Black,’ ‘Michelin,’ ‘Stoke Red,’ and ‘Sweet Alford,’ whereas the only cultivar that was harvested later than historical reports include ‘Calville Blanc d’Hiver’ (Ashridge trees Ltd., 2020; Bultitude, 1983; Copas, 2013; Grandpa’s Orchard, 2020; Hanson, 2005; Institut Français des Productions Cidricoles, 2009; Jolicoeur, 2013; Khanizadeh & Cousineau, 1998, 1998; Merwin et al., 2008; Morgan & Richards, 2003; NSW Department of Primary Industries, 2008; Pôle Fruitier de Bretagne, 2013; Rothwell, 2012, 2012; Shelton, 2015; Simmens, 2015; Summerland Varieties Corp., 2020) (Tables 2.1, 3.1, 3.2). The early harvest in the listed cultivars has implications for fruit weight and polyphenol concentration in the juice, which are associated with the length of time between full bloom and the harvest date (Figure 4.9).

3.5.2 Screening results

The cultivars were screened by removing those that were previously identified as having high tree mortality, early bloom, harvest issues, high biennial bearing potential, or low juicing efficiency. Once all of the screens were applied, few cultivars filter through as being suitable. Left were: ‘Bramley’s Seedling’, ‘Calville Blanc d’Hiver’, ‘Cline Russet’, Crimson Crisp, ‘Enterprise’, ‘Golden Russet’, and ‘GoldRush’. These cultivars all fall under the “sharp” juice classification and are mostly low in polyphenols. The extra work to grow the cultivars that were screened out may be worthwhile for some producers, and future horticultural research can work to overcome the difficulties in growing them. Other potential issues that were beyond the scope of this study include the effects of pests and diseases, like fire blight.

It is recommended that the cultivars that were passed all but one of the screening tests be considered for continued research investigation in Ontario for Ontario cider producers. These cultivars include: ‘Binet Rouge’, ‘Bramley’s Seedling’, ‘Breakwell’, ‘Bulmers Norman’, ‘Calville Blanc d’Hiver’, ‘Cline Russet’, ‘Cox Orange Pippin’, Crimson Crisp, ‘Dabinett’, ‘Enterprise’, ‘Esopus Spitzenberg’, ‘Golden Russet’, ‘GoldRush’, ‘Medaille d’Or’, ‘Porter’s Perfection’, and ‘Stoke Red’ (Table 3.11). Detailed photographs and data about each of these cultivars, along with those that aren’t recommended, are summarized in Appendix 4.

3.5.3 Associations among variables

A cluster analysis showed that the horticultural attribute data set contained several associations (Figure 3.3), including tree height with fruit weight and the number of floral clusters with the width and TCSA of the trees.

A principal component analysis of the variables TCSA, in-row width, between-row width, tree height, total fruit weight, total fruit number, floral clusters, pre-harvest drop percentage, and fruit set described the variation in the data in 4 dimensions (Figure 3.4). The 4 components, chosen based on the Jolliffe Test, were:

a) component 1: in-row width, between-row width, total fruit weight, total fruit number, and floral clusters;
b) component 2: TCSA, height;
c) component 3: pre-harvest drop percentage; and
d) component 4: pre-harvest drop percentage and fruit set.

Component pattern charts of the principal components indicate natural groups of associated variables (Figure 3.5). One cluster of variables includes floral clusters, total fruit number, and total fruit weight, while another cluster includes the growth characteristics of width (between rows and within rows), height, and TCSA.

A discriminant analysis of origin based on horticultural data indicated that North American cultivars were distinct enough from British and French cultivars to be classified as North American 87% of the time (Table 3.10). While French cultivars were classified as French 51% of the time, 42% of the French cultivars were classified as British. The British cultivars were misclassified 61% of the time, which suggests that they are not distinctive based on their horticultural attributes. The distinguishing attributes of North American cultivars are low TCSA values, high total fruit weights, low percentage of dropped fruit, and low fruit set compared to British and French cultivars.

A discriminant analysis of cultivar based on horticultural data indicated that most cultivars are not easily distinguishable when just looking at horticultural attributes, with 51% of data points being misclassified as a different cultivar. Cultivars that were classified as one another frequently due to similar horticultural characteristics include: 'Breakwell's Seedling' and 'Kingston Black;' 'Bulmer's Norman,' 'Muscadet de Dieppe,' and 'Medaille d'Or;' 'Brown Snout' and 'Kingston Black;' 'Crimson Crisp®' and 'GoldRush;' 'Cox's Orange Pippin' and 'Crimson Crisp®;' 'Cline Russet' and 'Esopus Spitzenberg,' 'Dabinett' and 'Cline Russet;' 'Fréquin Rouge' and 'Kingston Black;' 'Grimes Golden' and 'Crimson Crisp®;' 'Golden Russet' and 'Esopus Spitzenberg;' 'Porter's Perfection' and 'Binet Rouge;' 'Tydeman Late Orange' and 'Esopus Spitzenberg;' and 'Yarlington Mill,' 'Muscadet de Dieppe,' and 'Tolman Sweet.'

3.5.4 Associations based on place of origin

The 28 cultivars were picked because of their reputation or potential for cider, especially those that were traditionally grown in France, the United Kingdom, and parts of North America with a history of cider production. When separated by their country of origin, it was found that some horticultural attributes were significantly influenced by the origin of the cultivar. British varieties bloomed later than French and American cultivars, while American cultivars were harvested the latest and were on the tree the longest between bloom and harvest. American cultivars were the heaviest and produced the most juice, while French cultivars were low weight, had the lowest juicing efficiency, and had the highest pre-harvest drop percentage (Table 3.9). These associations may reflect the environments in which the cultivars are traditionally grown and their method of collection.

3.6 Summary and Conclusions

Of the 28 cultivars evaluated in this trial, all can be successfully grown in the Haldimand-Norfolk region of Ontario and other counties with similar climates, especially comparable winter temperatures. For a cider producer, the most important factors to consider will be juice extraction efficiency, yield, and mortality. Juice production estimates should be considered in conjunction with the attributes of the juice in question and whether its value can be conveyed in price, which is not necessarily an issue for orchard cider producers. Based on this research, those cultivars that show the most potential for early return on investment include: ‘Binet Rouge’, ‘Bramley’s Seedling’, ‘Breakwell’, ‘Bulmers Norman’, ‘Calville Blanc d’Hiver’, ‘Cline Russet’, ‘Cox Orange Pippin’, Crimson Crisp, ‘Dabinett’, ‘Enterprise’, ‘Esopus Spitzenberg’, ‘Golden Russet’, ‘GoldRush’, ‘Medaille d’Or’, ‘Porter’s Perfection’, and ‘Stoke Red’.

The exploratory analyses in this study indicate that differences exist among apple cultivars grown in Ontario based on the cultivar’s origin, whereas those differences become less pronounced when examined on a cultivar-specific level. In addition to long-term evaluation of these cultivars, future experiments could compare the horticultural attributes of the same cultivars grown on different rootstocks or in different regions, particularly those with different climatic and biotic pressures, such as susceptibility to fireblight (*E. amylovora*).

3.7 Tables and Figures

Table 3.1 Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017.

Cultivar	Average selected fruit weight (g)[z]		Juice extraction efficiency (mL juice g fruit^{-1})		Estimated orchard juice production at 1667 trees ha^{-1} (L juice ha^{-1})[y]	Days to harvest		Full bloom date		Harvest date	
Ashmead's Kernel	185	bcd	0.57	defghi	2100	138		11-May	lm	26-Sep	b
Binet Rouge	81	jk	0.53	ghi	2680	128	l	11-May	klm	16-Sep	m
Bramley's Seedling	364	a	0.69	ab	9270	133	ij	15-May	hijk	25-Sep	l
Breakwell	151	cdefgh	0.64	abcd	4030	111	no	20-May	cdefg	8-Sep	o
Brown Snout	85	ijk	0.61	bcdefg	1510	135	hi	23-May	bc	5-Oct	f
Brown's Apple	124	efghijk	0.62	bcdef	1920	99	p	22-May	bcd	29-Aug	q
Bulmers Norman	133	defghijk	0.68	ab	6140	112	no	19-May	efgh	7-Sep	p
Calville Blanc d'Hiver	204	bc	0.65	abcd	6110	156	b	10-May	m	13-Oct	d
Cline Russet	149	cdefgh	0.67	abc	3400	150	c	16-May	ghij	13-Oct	d
Cox Orange Pippin	181	bcd	0.53	fghi	3560	137	gh	19-May	defgh	3-Oct	h
Crimson Crisp	133	defghijk	0.68	ab	2500	137	gh	19-May	defgh	3-Oct	h
Dabinett	176	bcde	0.51	hi	3440	139	fg	17-May	fghij	3-Oct	h
Enterprise	225	b	0.65	abcd	5410	156	b	17-May	fghij	20-Oct	c
Esopus Spitzenberg	151	cdefgh	0.62	bcdef	2820	143	de	15-May	ijk	5-Oct	f
Frequin Rouge	98	ghijk	0.52	ghi	1410	132	ijk	24-May	b	3-Oct	h
Golden Russet	146	cdefghi	0.63	abcde	4530	146	d	13-May	jklm	6-Oct	e
GoldRush	154	cdefgh	0.72	a	11700	164	a	15-May	ijk	26-Oct	a
Grimes Golden	153	cdefgh	0.63	abcde	4280	143	def	14-May	ijkl	4-Oct	g
Kingston Black	114	efghijk	0.55	efghi	1080	119	m	20-May	cdef	16-Sep	m
Medaille d'Or	95	ghijk	0.67	abc	4970	131	jkl	21-May	bcde	29-Sep	i
Michelin	81	jk	0.59	cdefgh	990	131	jkl	20-May	cdefg	27-Sep	j
Muscadet De Dieppe	105	fghijk	0.48	i	1880	114	no	17-May	fghij	8-Sep	n
Porter's Perfection	80	k	0.61	cdefg	3080	140	efg	18-May	efghi	5-Oct	f
Stoke Red	93	hijk	0.64	abcd	2850	110	o	29-May	a	16-Sep	m
Sweet Alford	162	cdef	0.60	cdefgh	3480	143	de	16-May	ghij	6-Oct	e
Tolman Sweet	143	cdefghij	0.61	bcdefg	780	130	jkl	19-May	defgh	26-Sep	k
Tydeman Late	136	defghijk	0.51	hi	1760	138	hg	18-May	efghi	3-Oct	h
Yarlington Mill	136	cdefghij	0.51	ij	1590	129	kl	20-May	cdefg	25-Sep	l
P value	<0.0001		<0.0001			<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means
[y] Value calculated by multiplying the cultivar's juice extraction efficiency by the planting density and the cultivar's harvested weight (Table 3.7)

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Average selected fruit weight (g)[z]		Juice extraction efficiency (mL juice g fruit^{-1})		Estimated orchard juice production at 1667 trees ha^{-1} (L juice ha^{-1})[y]	Days to harvest		Full bloom date		Harvest date
Ashmead's Kernel	167	bcde	0.60	ab	2120	134	kl	16-May	j	27-Sep
Binet Rouge	70	j	0.45	ef	1170	109	q	18-May	fghij	4-Sep
Bramley's Seedling	267	a	0.64	ab	6810	121	n	19-May	efghij	17-Sep
Breakwell	138	defg	0.65	ab	3110	113	op	21-May	bcdef	11-Sep
Brown Snout	93	hij	0.59	ab	1060	145	f	23-May	ab	15-Oct
Brown's Apple	152	cdef	0.66	ab	4170	92	t	22-May	bc	22-Aug
Bulmers Norman	110	ghi	0.61	ab	510	97	s	22-May	bcd	27-Aug
Calville Blanc d'Hiver	262	a	0.65	ab	14840	158	b	17-May	ij	22-Oct
Cline Russet	134	defg	0.64	ab	3510	142	gh	20-May	cdefg	9-Oct
Cox Orange Pippin	158	bcdef	0.62	ab	10040	121	n	19-May	efghij	17-Sep
Crimson Crisp	165	bcde	0.68	a	10300	138	ij	19-May	efghij	4-Oct
Dabinett	192	b	0.61	ab	9860	131	l	19-May	efghij	27-Sep
Enterprise	246	a	0.65	ab	13460	172	a	18-May	ghij	6-Nov
Esopus Spitzenberg	178	bc	0.58	abc	4850	154	c	17-May	ij	18-Oct
Frequin Rouge	68	j	0.48	de	870	148	e	23-May	ab	18-Oct
Golden Russet	183	bc	0.61	ab	6470	161	b	17-May	hij	25-Oct
GoldRush	172	bcd	0.66	ab	6630	173	a	17-May	hij	6-Nov
Grimes Golden	139	defg	0.66	ab	1390	149	de	19-May	efghij	15-Oct
Kingston Black	102	ghij	0.49	cde	630	112	p	22-May	bc	11-Sep
Medaille d'Or	90	hij	0.60	ab	620	128	m	22-May	bcd	27-Sep
Michelin	96	hij	0.39	ef	990	115	o	19-May	efghij	11-Sep
Muscadet De Dieppe	130	efgh	0.36	f	570	114	op	20-May	cdefgh	11-Sep
Porter's Perfection	81	ij	0.60	ab	1780	141	hi	21-May	bcde	9-Oct
Stoke Red	76	j	0.61	ab	1660	102	r	25-May	a	4-Sep
Sweet Alford	190	bc	0.59	abc	9370	144	fg	18-May	fghij	9-Oct
Tolman Sweet	156	bcdef	0.56	bcd	1690	136	jk	21-May	bcdef	4-Oct
Tydeman Late	164	bcde	0.60	ab	10550	152	cd	19-May	defghi	18-Oct
Yarlington Mill	121	fgh	0.39	ef	830	139	ij	23-May	ab	9-Oct
P value	<0.0001		<0.0001			<0.0001		<0.0001		<0.0001

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Value calculated by multiplying the cultivar's juice extraction efficiency by the planting density and the cultivar's harvested weight (Table 3.8)

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Survival rate fall 2018	Spring 2015 TCSA[zy]		Fall 2015 TCSA		Fall 2016 TCSA		Fall 2017 TCSA		Fall 2018 TCSA		2018 relative growth		Fall 2017 crop load (no. fruit cm^{-2} TCSA)		Fall 2018 crop load (no. fruit cm^{-2} TCSA)	
Ashmead's Kernel	95%	0.76	hijkl	1.68	efghij	5.0	de	7.7	de	13.4	def	5.6	fghi	3.1	hijk	2.9	defghi
Binet Rouge	100%	1.06	bcdef	2.32	bcd	6.4	abc	9.9	bc	19.4	ab	9.5	ab	7.9	bcde	1.5	ghi
Bramley's Seedling	100%	1.33	a	2.86	a	7.5	abc	11.1	ab	21.1	a	10.0	ab	2.9	ijk	1.3	ghi
Breakwell	100%	1.12	abcd	2.08	cde	5.5	cd	8.9	cd	17.3	bc	8.4	bcd	3.7	ghijk	1.6	fghi
Brown Snout	100%	0.62	lm	1.58	hij	3.2	hi	4.4	i	8.1	ij	3.7	jklm	5.5	cdefghijk	3.5	cdefghi
Brown's Apple	100%	0.92	defghi	1.67	efghij	4.2	efgh	6.2	efgh	12.6	defg	6.4	efgh	5.3	cdefghijk	2.6	defghi
Bulmers Norman	100%	1.07	bcde	2.21	bcd	5.1	de	6.8	efgh	14.0	de	7.6	cde	7.6	bcdef	0.5	i
Calville Blanc d'Hiver	100%	1.20	ab	2.61	ab	7.2	ab	12.2	a	21.2	a	9.0	abc	2.5	jk	2.9	defghi
Cline Russet	95%	0.75	hijkl	1.38	jk	3.3	ghi	4.7	hi	8.2	ij	3.5	klm	6.1	cdefghi	3.7	cdefghi
Cox Orange Pippin	100%	0.74	ijkl	1.61	ghij	4.3	efgh	6.5	efg	9.9	fghi	3.4	klm	4.5	efghijk	7.2	abc
Crimson Crisp	100%	0.48	m	1.13	k	2.9	i	4.9	gh	6.9	j	2.0	m	3.8	ghijk	9.4	a
Dabinett	90%	0.80	ghijkl	1.58	hij	4.2	efgh	6.1	efghi	9.6	ghij	3.5	klm	5.0	cdefghijk	6.2	abcd
Enterprise	100%	0.77	hijkl	1.88	defghi	4.6	def	6.9	ef	11.9	defgh	4.9	ghijk	3.2	hijk	4.6	bcdefgh
Esopus Spitzenberg	100%	0.68	jklm	1.54	hijk	4.1	efgh	6.3	efgh	11.6	efgh	5.3	fghijk	3.1	hijk	3.7	cdefghi
Frequin Rouge	100%	0.66	klm	1.65	efghij	4.0	efgh	6.3	efgh	11.1	fghi	4.8	ghijk	5.2	cdefghijk	5.2	bcdef
Golden Russet	100%	0.61	lm	1.49	ijk	4.2	efg	6.4	efgh	12.4	defg	6.0	efghi	5.9	cdefghij	3.5	cdefghi
GoldRush	100%	0.78	ghijkl	1.63	fghij	3.7	fghi	4.8	ghi	8.4	ij	3.6	klm	14.4	a	5.6	abcde
Grimes Golden	100%	0.87	efghijk	1.87	defghi	4.3	efg	6.2	efgh	9.1	hij	2.9	lm	7.2	cdefg	8.1	abc
Kingston Black	100%	0.97	bcdefgh	2.05	cdefg	4.0	efgh	5.4	fghi	11.1	fghi	5.7	fghi	5.1	defghijk	1.3	ghi
Medaille d'Or	95%	0.91	defghij	1.60	ghij	4.2	efgh	6.0	efghi	11.2	fghi	5.2	fghijk	11.1	ab	0.8	hi
Michelin	95%	1.01	bcdefg	2.04	cdefg	4.8	de	6.8	ef	12.4	defg	5.6	fghij	8.7	bc	2.5	defghi
Muscadet De Dieppe	100%	1.04	bcdef	2.24	bcd	5.0	de	7.4	de	14.5	cde	7.2	cdef	5.4	cdefghijk	1.1	ghi
Porter's Perfection	100%	1.20	ab	2.24	bcd	6.3	bc	9.5	bc	20.0	ab	10.5	a	8.0	bcd	1.6	fghi
Stoke Red	100%	0.83	fghijkl	1.59	hij	4.0	efgh	6.0	efghi	12.5	defg	6.5	efgh	8.5	bcd	2.1	efghi
Sweet Alford	100%	1.15	abc	2.06	cdef	4.9	de	7.7	de	11.8	defgh	4.1	ijkl	4.4	fghijk	5.7	abcde
Tolman Sweet	100%	0.92	cdefghi	1.93	cdefgh	4.5	def	6.5	efg	11.1	fghi	4.6	hijkl	3.7	hijk	4.4	bcdefgh
Tydeman Late	90%	0.72	ijklm	1.57	hijk	4.5	def	8.9	cd	14.8	cd	6.7	defg	2.0	k	4.8	bcdefg
Yarlington Mill	100%	0.75	hijkl	1.91	cdefghi	4.4	def	6.7	ef	12.4	defg	5.8	fghi	6.5	cdefgh	1.7	fghi
P value		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Trunk cross-sectional area.

Table 3.4. Height and width growth of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	2015 height (m)[z]		2016 height (m)		2017 height (m)		2018 height (m)		2015 width (m)		2016 width (m)		2017 width (m)		2018 width (m)	
Ashmead's Kernel	1.5	hijk	2.4	efghij	3.0	ab	3.4	abc	0.2	efgh	1.2	abcdefg	1.3	bcde	1.4	ghij
Binet Rouge	1.9	abcd	2.9	a	3.1	a	3.5	a	0.4	abc	1.4	ab	1.7	a	1.7	ab
Bramley's Seedling	1.8	bcdef	2.4	fghij	3.0	abc	3.2	bcdefg	0.5	a	1.3	abcd	1.7	a	1.7	abcd
Breakwell	1.3	lm	1.8	no	2.4	hij	2.8	ij	0.2	defgh	0.9	hij	1.0	ghi	1.2	jk
Brown Snout	1.5	ijk	2.0	mn	2.5	ghi	2.8	ij	0.1	h	0.7	j	0.8	i	0.9	l
Brown's Apple	1.4	jkl	2.1	jklm	2.5	fghi	2.9	ghi	0.2	bcdefgh	1.0	ghi	1.3	cdef	1.5	efghi
Bulmers Norman	1.5	hijk	2.1	klm	2.7	defg	3.0	efghi	0.3	bcdefgh	1.1	fghi	1.3	bcdef	1.4	ghij
Calville Blanc d'Hiver	2.0	a	2.9	a	3.0	abc	3.3	abcdef	0.4	ab	1.3	abcde	1.5	abc	1.6	bcdefgh
Cline Russet	1.7	cdefgh	2.3	ghijk	2.8	cdef	3.0	defghi	0.4	abcde	1.1	efgh	1.2	defg	1.4	ghij
Cox Orange Pippin	1.6	fghij	2.2	ijklm	2.8	bcde	3.0	efghi	0.4	abcdef	1.1	defg	1.3	bcdef	1.5	cdefghi
Crimson Crisp	1.4	jkl	2.2	ijkl	2.8	bcde	3.0	efghi	0.3	bcdefg	1.1	defgh	1.2	defg	1.4	ghij
Dabinett	1.5	ghijk	2.1	jklm	2.7	cdefg	3.0	efghi	0.3	abcdefg	1.2	abcdef	1.3	bcdef	1.5	cdefghi
Enterprise	1.5	hijk	2.3	ghijk	2.8	bcde	3.0	fghi	0.4	abcd	1.4	abc	1.7	a	1.7	abcdef
Esopus Spitzenberg	1.8	abcde	2.7	abc	3.0	abc	3.2	bcdefg	0.4	abcd	1.4	a	1.5	abc	1.7	abcde
Frequin Rouge	1.2	m	1.7	o	2.2	j	2.5	k	0.2	defgh	0.9	hij	1.1	efgh	1.3	hij
Golden Russet	1.8	bcdefg	2.6	bcdef	3.1	a	3.4	ab	0.4	abcdefg	1.3	abcde	1.5	abc	1.5	efghi
GoldRush	1.9	ab	2.8	ab	2.9	abcd	3.2	abcdef	0.5	a	1.1	defg	1.1	fgh	1.2	jk
Grimes Golden	1.8	abcde	2.6	bcde	2.8	bcde	3.1	bcdefgh	0.4	abcde	1.2	abcdef	1.4	bcde	1.5	fghi
Kingston Black	1.3	klm	1.8	no	2.3	ij	2.5	jk	0.2	fgh	0.8	ij	1.0	hi	1.1	kl
Medaille d'Or	1.5	hijk	2.3	hijkl	2.8	cdef	3.0	defghi	0.2	gh	1.2	bcdefg	1.4	bcde	1.5	fghi
Michelin	1.8	bcdef	2.5	defghi	3.0	abc	3.3	abcd	0.2	defgh	1.2	cdefg	1.3	bcdef	1.4	ghij
Muscadet De Dieppe	1.7	efghi	2.2	ijklm	2.6	efgh	2.8	hi	0.3	cdefgh	1.0	fghi	1.2	defg	1.3	ijk
Porter's Perfection	1.7	defghi	2.5	defghi	3.0	abc	3.3	abcde	0.4	abcdefg	1.3	abcd	1.5	ab	1.6	abcdefg
Stoke Red	1.8	abcde	2.7	abcd	3.0	abc	3.1	defgh	0.3	bcdefg	1.2	abcdef	1.5	abc	1.5	defghi
Sweet Alford	1.6	fghij	2.1	klm	2.6	efgh	3.0	defghi	0.4	abcdefg	1.3	abcdef	1.4	bcd	1.7	abcdef
Tolman Sweet	1.9	abcde	2.5	cdefg	2.9	bcde	3.2	abcdefg	0.4	abcdef	1.3	abcde	1.5	abc	1.7	abc
Tydeman Late	1.8	abcde	2.5	cdefgh	3.1	a	3.2	abcdef	0.4	abcd	1.4	abc	1.6	a	1.8	a
Yarlington Mill	1.9	abc	2.6	cdefg	2.9	abcd	3.1	cdefgh	0.4	ab	1.3	abcde	1.5	abc	1.5	bcdefgh
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

Table 3.5. Yield attributes in 2017 and 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Flower clusters 2017 (no. tree^{-1})^z		Flower clusters 2018 (no. tree^{-1})		Thinned fruit 2017 (no. tree^{-1})		Thinned fruit 2018 (no. tree^{-1})		Fruit set 2017 (no. tree^{-1})		Fruit set 2018 (no. tree^{-1})	
Ashmead's Kernel	69	efghi	104	bc	9	ef	18	b	5.6	c	8	b
Binet Rouge	155	ab	39	fghij	46.75	bcdef	35	ab	10.4	c	22	b
Bramley's Seedling	92	cdefgh	28	ghij	19.5	def	45	ab	7.2	c	23	b
Breakwell	87	defgh	29	ghij	55.5	abcdef	67	ab	7.7	c	44	ab
Brown Snout	48	ghi	27	ghij	56.75	abcdef	83	ab	11.3	c	29	b
Brown's Apple	68	efghi	34	ghij	72.75	abcd	84	ab	10.4	c	21	b
Bulmers Norman	146	abcd	11	j	56.25	abcdef	34	ab	7.1	c	19	b
Calville Blanc d'Hiver	142	abcd	147	a	13.25	ef	15	b	4.3	c	8	b
Cline Russet	58	fghi	36	fghij	4.5	ef	14	b	7.7	c	16	b
Cox Orange Pippin	91	cdefgh	112	abc	19	def	69	ab	5.8	c	13	b
Crimson Crisp	65	efghi	139	ab	3.75	f	16	b	8.1	c	9	b
Dabinett	47	ghi	90	cde	23.5	cdef	65	ab	9.1	c	15	b
Enterprise	50	ghi	70	cdefg	8.25	ef	37	ab	8.8	c	15	b
Esopus Spitzenberg	46	ghi	36	fghij	12.5	ef	52	ab	8.0	c	19	b
Frequin Rouge	71	efghi	57	defgh	77.5	abc	77	ab	11.4	c	44	ab
Golden Russet	123	abcde	49	efghi	55.25	abcdef	55	ab	6.5	c	21	b
GoldRush	125	abcde	49	efghi	42	bcdef	27	ab	9.6	c	17	b
Grimes Golden	115	abcdef	95	cd	18.5	def	58	ab	8.1	c	18	b
Kingston Black	55	fghi	13	ij	31	bcdef	30	ab	8.0	c	22	b
Medaille d'Or	163	a	14	ij	58.25	abcde	2	b	8.7	c	12	b
Michelin	97	bcdefgh	26	ghij	104.75	a	84	ab	12.8	bc	40	ab
Muscadet De Dieppe	51	ghi	20	hij	78.75	ab	62	ab	14.9	bc	16	b
Porter's Perfection	162	a	31	ghij	109.5	a	93	ab	7.9	c	48	ab
Stoke Red	105	abcdefg	29	ghij	34.25	bcdef	63	ab	9.7	c	100	a
Sweet Alford	53	ghi	77	cdef	20.25	def	78	ab	9.5	c	22	b
Tolman Sweet	36	hi	50	efghi	24.5	bcdef	50	ab	11.7	c	22	b
Tydeman Late	16	i	85	cde	25	bcdef	129	a	29.0	a	27	b
Yarlington Mill	36	hi	16	hij	39.875	bcdef	22	ab	24.7	ab	49	ab
P value	<0.0001		<0.0001		<0.0001		0.0059		<0.0001		<0.0001	

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016.

Cultivar	Total fruit weight (kg tree^{-1})		Total fruit (no. tree^{-1})		Total fruit harvested (kg tree^{-1})^{z}		Total fruit harvested (no. tree^{-1})		Dropped fruit weight (kg tree^{-1})		Dropped fruit (no. tree^{-1})		Percentage of total fruit dropped		Flower clusters (no. tree^{-1})		Crop load (no. fruit cm^{-2} TCSA^{y})	
Ashmead's Kernel	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.2	abcd	2	c	1.6	c
Breakwell	0.0	b	0.8	b	0.0	b	0.1	b	0.0	ab	0.7	bc	1.3	abc	3	c	2.6	c
Brown's Apple	0.3	ab	0.7	b	0.2	b	0.4	b	0.1	ab	0.3	bc	1.3	abc	2	c	1.6	c
Bulmers Norman	0.1	b	0.3	b	0.0	b	0.0	b	0.1	ab	0.3	bc	0.9	cde	0	c	0.3	c
Binet Rouge	0.3	ab	3.4	a	0.2	b	2.1	a	0.1	ab	1.3	ab	0.7	e	5	bc	5.1	bc
Bramley's Seedling	0.0	b	0.4	b	0.0	b	0.0	b	0.0	ab	0.4	bc	0.9	cde	2	c	2.3	c
Brown Snout	0.1	b	0.5	b	0.0	b	0.0	b	0.1	ab	0.5	bc	1.1	abcd	4	bc	3.9	bc
Calville Blanc d'Hiver	0.1	b	0.5	b	0.1	b	0.5	b	0.0	b	0.0	c	1.2	abcd	11	b	11.3	b
Crimson Crisp	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.1	abcde	4	bc	3.6	bc
Cox Orange Pippin	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.2	abcd	0	c	0.0	c
Cline Russet	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.1	abcde	3	c	3.1	c
Dabinett	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.3	abc	0	c	0.0	c
Enterprise	0.0	b	0.1	b	0.0	b	0.1	b	0.0	b	0.0	c	1.5	a	1	c	0.6	c
Esopus Spitzenberg	0.0	b	0.1	b	0.0	b	0.1	b	0.0	b	0.0	c	1.4	ab	0	c	0.2	c
Frequin Rouge	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.0	cde	0	c	0.0	c
GoldRush	0.1	b	0.5	b	0.1	b	0.5	b	0.0	b	0.0	c	1.2	abcd	3	c	3.0	c
Grimes Golden	0.5	a	3.3	a	0.5	a	3.2	a	0.0	b	0.1	bc	1.2	abcd	22	a	21.9	a
Golden Russet	0.0	b	0.1	b	0.0	b	0.1	b	0.0	b	0.0	c	1.2	abcd	3	c	3.0	c
Kingston Black	0.0	b	0.3	b	0.0	b	0.1	b	0.0	b	0.2	bc	0.8	de	1	c	0.7	c
Michelin	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.2	abcd	0	c	0.2	c
Muscadet De Dieppe	0.2	ab	2.1	ab	0.0	b	0.1	b	0.2	a	2.0	a	1.1	abcde	7	bc	6.7	bc
Medaille d'Or	0.0	b	0.1	b	0.0	b	0.1	b	0.0	b	0.0	c	1.0	bcde	1	c	1.0	c
Porter's Perfection	0.0	b	0.1	b	0.0	b	0.1	b	0.0	b	0.0	c	1.2	abcd	0	c	0.4	c
Sweet Alford	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.2	abcd	0	c	0.0	c
Stoke Red	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.2	abcd	0	c	0.0	c
Tydeman Late	0.1	b	0.7	b	0.0	b	0.4	b	0.1	ab	0.4	bc	1.2	abcd	4	bc	4.0	bc
Tolman Sweet	0.0	b	0.0	b	0.0	b	0.0	b	0.0	b	0.0	c	1.3	abc	0	c	0.0	c
Yarlington Mill	0.2	b	0.9	b	0.1	b	0.5	b	0.1	ab	0.4	bc	1.3	abc	1	c	1.4	c
P value	<0.0001		<0.0001		<0.0001		<0.0001		0.0005		<0.0001		<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Trunk cross-sectional area.

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017.

Cultivar	Total fruit weight (kg tree^{-1})		Total fruit (no. tree^{-1})		Total fruit harvested (kg tree^{-1})^{z}		Total fruit harvested (no. tree^{-1})		Dropped fruit weight (kg tree^{-1})		Dropped fruit (no. tree^{-1})		Percentage of total fruit dropped		Cumulative fruit count (no. tree^{-1})		Cumulative fruit weight (kg tree^{-1})		Crop load (no. fruit cm^{-2} TCSA^{y})	
Ashmead's Kernel	3.8	cdef	24	fgh	2.2	defgh	13	hij	1.6	cdefgh	11	defgh	46	def	24	fgh	3.8	cdefgh	3.1	ghij
Binet Rouge	3.9	cdef	77	a	3.1	cdefgh	58	ab	0.9	fghij	19	bcd	25	ghij	77	a	4.0	cdefgh	7.9	bcd
Bramley's Seedling	10.7	a	32	defgh	8.1	a	24	ghij	2.6	abc	9	defgh	27	ghij	33	defgh	11.0	a	2.9	hij
Breakwell	4.5	bcdef	32	defgh	3.8	bcdef	26	efghi	0.8	fghij	6	efgh	19	ijkl	32	defgh	4.5	bcdefgh	3.7	fghij
Brown Snout	2.1	f	24	fgh	1.5	fgh	18	ghij	0.6	hij	7	efgh	23	hijk	28	efgh	2.4	gh	5.5	cdefghij
Brown's Apple	3.6	cdef	33	defgh	1.9	efgh	16	ghij	1.7	cdefg	17	cdefg	51	cde	33	defgh	3.6	cdefgh	5.3	cdefghij
Bulmers Norman	6.4	b	51	bcd	5.4	b	43	bcd	1.0	fghij	9	defgh	16	jkl	52	bcd	6.4	b	7.6	bcde
Calville Blanc d'Hiver	5.8	bcd	29	efgh	5.6	b	28	defghi	0.1	ij	1	h	3	l	29	efgh	5.8	bcde	2.5	ij
Cline Russet	3.5	cdef	25	fgh	3.0	cdefgh	22	ghij	0.5	hij	4	gh	14	jkl	25	fgh	3.5	cdefgh	6.1	cdefgh
Cox Orange Pippin	4.5	bcdef	28	efgh	4.0	bcde	25	fghi	0.5	hij	4	gh	13	jkl	28	efgh	4.5	bcdefgh	4.5	defghij
Crimson Crisp	3.2	def	19	gh	2.2	defgh	13	hij	1.0	fghij	6	fgh	34	efghi	19	gh	3.2	efgh	3.8	fghij
Dabinett	4.7	bcdef	28	efgh	4.0	bcde	26	efghi	0.6	ghij	4	gh	13	jkl	28	efgh	4.7	bcdefgh	5.0	cdefghij
Enterprise	5.1	bcde	23	fgh	5.0	bc	22	ghij	0.1	ij	1	h	5	kl	23	fgh	5.1	bcdefg	3.2	hij
Esopus Spitzenberg	2.8	ef	20	gh	2.7	cdefgh	20	ghij	0.0	j	1	h	3	l	20	gh	2.8	fgh	3.1	hij
Frequin Rouge	2.8	ef	33	defgh	1.6	fgh	18	ghij	1.2	efghi	15	defg	49	cde	33	defgh	2.8	fgh	5.2	cdefghij
Golden Russet	5.3	bcde	38	defgh	4.3	bcd	30	cdefgh	1.0	fghij	8	efgh	19	ijkl	38	defgh	5.5	bcdef	5.9	cdefghi
GoldRush	9.9	a	68	ab	9.8	a	67	a	0.1	ij	1	h	1	l	71	ab	10.5	a	14.4	ab
Grimes Golden	6.2	bc	44	cdef	4.1	bcde	29	defghi	2.2	cde	15	defg	33	efghi	44	cdef	6.2	bc	7.2	cdef
Kingston Black	2.7	ef	28	fgh	1.2	gh	11	ij	1.6	cdefgh	16	def	58	bcd	28	fgh	2.8	fgh	5.1	cdefghij
Medaille d'Or	6.1	bc	65	abc	4.5	bcd	48	bc	1.6	cdefgh	17	def	29	fghij	65	abc	6.1	bcd	11.1	ab
Michelin	4.5	bcdef	64	abc	1.0	h	14	ghij	3.5	ab	51	a	79	a	68	ab	4.9	bcdefgh	8.7	bc
Muscadet De Dieppe	3.7	cdef	40	defg	2.3	defgh	24	ghij	1.4	defgh	15	defg	43	defg	40	defg	3.7	cdefgh	5.4	cdefghij
Porter's Perfection	4.9	bcde	75	a	3.0	cdefgh	46	bcd	1.8	cdef	29	bcd	38	efgh	75	a	4.9	bcdefgh	8.0	bc
Stoke Red	4.1	bcdef	51	bcde	2.7	cdefgh	32	cdefg	1.5	defgh	19	bcd	40	defgh	51	bcde	4.1	bcdefgh	8.5	bc
Sweet Alford	4.9	bcde	31	efgh	3.5	bcdefg	23	ghij	1.4	defgh	8	defgh	27	ghij	31	efgh	4.9	bcdefgh	4.4	efghij
Tolman Sweet	3.3	def	23	fgh	0.8	h	6	j	2.5	bcd	18	cde	75	ab	24	fgh	3.4	defgh	3.7	ghij
Tydeman Late	2.1	f	16	h	2.1	defgh	15	ghij	0.0	j	0	h	3	l	16	h	2.1	h	2.0	j
Yarlington Mill	5.6	bcd	43	cdef	1.9	efgh	15	ghij	3.7	a	28	bc	66	abc	44	cdef	5.8	bcde	6.5	cdefg
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<.0001		<.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Trunk cross-sectional area.

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Total fruit weight (kg tree^{-1})		Total fruit (no. tree^{-1})		Total fruit harvested (kg tree^{-1})^z		Total fruit harvested (no. tree^{-1})		Dropped fruit weight (kg tree^{-1})		Dropped fruit (no. tree^{-1})		Percentage of total fruit dropped		Cumulative fruit count (no. tree^{-1})		Cumulative fruit weight (kg tree^{-1})		Crop load (no. fruit cm^{-2} TCSA^y)		Bienniality Index^x	
Ashmead's Kernel	6.0	efghi	39	bcdefgh	2.1	fghi	12	fg	3.9	b	27	bc	69	abc	63.3	defg	9.9	efghi	2.9	defghi	0.25	d
Binet Rouge	1.7	hij	28	defgh	1.5	hi	25	fg	0.1	e	3	d	9	gh	105.3	abc	5.7	ij	1.5	ghi	0.50	bcd
Bramley's Seedling	6.7	cdefg	27	defgh	6.4	cdef	25	fg	0.3	de	2	d	12	gh	60.1	efg	17.7	abc	1.3	ghi	0.42	bcd
Breakwell	3.2	fghij	26	defgh	2.9	fghi	21	fg	0.4	de	4	d	27	efgh	57.3	fg	7.4	ghij	1.6	fghi	0.31	cd
Brown Snout	2.1	ghij	26	defgh	1.1	hi	13	fg	1.0	de	13	cd	53	cbde	54.6	fg	4.5	j	3.5	cdefghi	0.42	bcd
Brown's Apple	4.4	fghij	32	cdefgh	3.8	fghi	26	fg	0.6	de	6	d	15	gh	64.8	defg	8.0	fghij	2.6	defghi	0.37	bcd
Bulmers Norman	0.8	j	8	h	0.5	i	5	g	0.3	e	3	d	46	cde	59.6	fg	7.2	hij	0.5	i	0.73	ab
Calville Blanc d'Hiver	14.3	a	57	abcde	13.7	a	53	abc	0.6	de	3	d	6	h	86.2	abcdef	20.2	a	2.9	defghi	0.32	cd
Cline Russet	3.6	fghij	28	defgh	3.3	fghi	25	fg	0.3	de	3	d	21	fgh	53.5	fg	7.2	hij	3.7	cdefghi	0.33	cd
Cox Orange Pippin	10.2	abcde	70	ab	9.7	abcd	66	ab	0.5	de	4	d	6	h	98.3	abcde	14.7	bcde	7.2	abc	0.46	bcd
Crimson Crisp	9.5	bcde	61	abcd	9.1	bcde	58	abc	0.3	de	3	d	5	h	79.3	abcdef	12.7	cdefg	9.4	a	0.56	abcd
Dabinett	10.2	abcde	62	abcd	9.7	abcd	57	abc	0.5	de	4	d	7	h	90.0	abcdef	14.8	bcde	6.2	abcd	0.35	cd
Enterprise	12.9	ab	56	abcde	12.4	ab	53	abc	0.5	de	2	d	5	h	78.5	abcdef	18.0	ab	4.6	bcdefgh	0.44	bcd
Esopus Spitzenberg	5.9	efghi	38	bcdefgh	5.0	efgh	29	fgc	0.9	de	8	d	21	fgh	57.8	fg	8.7	fghij	3.7	cdefghi	0.33	cd
Frequin Rouge	3.6	fghij	53	abcdef	1.1	hi	16	fg	2.5	c	37	b	74	ab	85.1	abcdef	6.4	ij	5.2	bcdef	0.70	abc
Golden Russet	7.0	cdef	42	abcdefgh	6.4	cdef	37	fbc	0.6	de	5	d	13	gh	80.8	abcdef	12.5	defgh	3.5	cdefghi	0.25	d
GoldRush	6.4	cdefgh	40	abcdefgh	6.1	defg	38	fbc	0.3	de	2	d	8	h	111.0	ab	16.9	abcd	5.6	abcde	0.35	cd
Grimes Golden	9.9	abcde	71	ab	1.3	hi	10	fg	8.6	a	61	a	88	a	114.4	a	16.1	abcd	8.1	abc	0.26	d
Kingston Black	1.2	ij	12	gh	0.8	hi	8	fg	0.4	de	4	d	35	defg	38.8	g	3.8	j	1.3	ghi	0.53	abcd
Medaille d'Or	0.7	j	7	h	0.6	hi	6	g	0.0	e	1	d	11	gh	71.3	cdefg	6.7	ij	0.8	hi	0.92	a
Michelin	2.7	fghij	31	cdefgh	1.5	hi	18	fg	1.2	cde	14	cd	45	cdef	99.7	abcd	7.6	fghij	2.5	defghi	0.46	bcd
Muscadet De Dieppe	1.7	hij	16	fgh	1.0	hi	8	fg	0.7	de	7	d	56	bcd	55.2	fg	5.4	ij	1.1	ghi	0.51	bcd
Porter's Perfection	2.1	ghij	30	cdefgh	1.8	ghi	24	fg	0.4	de	6	d	23	fgh	105.3	abc	7.0	ij	1.6	fghi	0.49	bcd
Stoke Red	1.7	hij	25	abc	1.6	hi	23	fg	0.1	e	2	d	21	fgh	75.5	bcdefg	5.8	ij	2.1	efghi	0.61	abcd
Sweet Alford	11.1	abc	67	defgh	9.6	abcd	58	abc	1.5	cd	9	d	16	gh	97.8	abcde	16.0	abcd	5.7	abcde	0.47	bcd
Tolman Sweet	6.3	defgh	45	abcdefg	1.8	ghi	12	fg	4.5	b	33	b	75	ab	69.2	cdefg	9.7	efghi	4.4	bcdefgh	0.33	cd
Tydeman Late	11.0	abcd	77	a	10.6	abc	73	a	0.4	de	4	d	6	h	92.9	abcdef	13.1	bcdef	4.8	bcdefg	0.76	ab
Yarlington Mill	2.6	fghij	22	efgh	1.3	hi	11	fg	1.3	cde	11	cd	56	bcd	66.2	defg	8.4	fghij	1.7	fghi	0.43	bcd
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

^{y} Trunk cross-sectional area.

^{x} Alternate bearing index (i) = |(year 1 yield – year 2 yield)| / (year 1 yield + year 2 yield).

Table 3.9. Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018.

Cultivar Origin	Full Bloom Date	Harvest Date	Days to Harvest	Juice extraction efficiency (mL juice g fruit^{-1})	Average selected fruit weight (g)^{z}	Pre-harvest Drop Percentage
France	139 b	255 b	115 b	0.53 c	115 b	38.5 a
North America	138 b	273 a	134 a	0.64 a	164 a	23.3 b
United Kingdom	141 a	252 b	110 b	0.60 b	145 a	30.5 ab
P value	<.0001	<.0001	<0.0001	<0.0001	<0.0001	0.01

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

Table 3.10 classification summary for the horticultural attributes of cider cultivars based on geographical origin. University of Guelph, Simcoe, Ontario, 2018.

From Origin	France	North America	United Kingdom	Total
France	66[z]	9	54	129
	51[y]	7	41.86	100
North America	1	166	23	190
	0.5	87	12	100
United Kingdom	98	106	132	336
	29	32	39	100
Total	165	281	209	655
	25	43	32	100
Priors	0.33333	0.33333	0.33333	

[z] Number of observations classified into origin
[y] Percent classified into origin

Table 3.11 Recommendations based on 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Table 3.11. Recommendations based on 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Mortality	Early or protracted bloom	Pre-harvest drop or multi-pick	Biennial bearing potential	Low juice yield	Overall recommendation
Ashmead's Kernel	Lower	Yes	Yes	Lower	Yes	No
Binet Rouge	Lower	Yes	No	Lower	Yes	Yes
Bramley's Seedling	Lower	No	No	Lower	No	Yes
Breakwell	Lower	No	Yes	Lower	No	Yes
Brown Snout	Lower	No	Yes	Lower	Yes	No
Brown's Apple	Lower	No	Yes	Lower	No	No
Bulmers Norman	Lower	No	No	Higher	No	Yes
Calville Blanc d'Hiver	Lower	Yes	No	Lower	No	Yes
Cline Russet	Lower	No	No	Lower	No	Yes
Cox Orange Pippin	Lower	No	No	Lower	Yes	Yes
Crimson Crisp®	Lower	No	No	Lower	No	Yes
Dabinett	Lower	No	No	Lower	Yes	Yes
Enterprise	Lower	No	No	Lower	No	Yes
Esopus Spitzenberg	Lower	No	Yes	Lower	No	Yes
Frequin Rouge	Lower	No	Yes	Higher	Yes	No
Golden Russet	Lower	Yes	No	Lower	No	Yes
GoldRush	Lower	Yes	No	Lower	No	Yes
Grimes Golden	Lower	No	Yes	Lower	No	No
Kingston Black	Lower	No	Yes	Lower	Yes	No
Medaille d'Or	Lower	No	No	Higher	No	Yes
Michelin	Higher	No	Yes	Lower	Yes	No
Muscadet De Dieppe	Lower	No	Yes	Lower	Yes	No
Porter's Perfection	Lower	No	Yes	Lower	No	Yes
Stoke Red	Lower	No	No	Higher	No	Yes
Sweet Alford	Lower	No	Yes	Lower	Yes	No
Tolman Sweet	Lower	No	Yes	Lower	Yes	No
Tydeman Late	Lower	No	Yes	Higher	No	No
Yarlington Mill	Lower	No	Yes	Lower	Yes	No

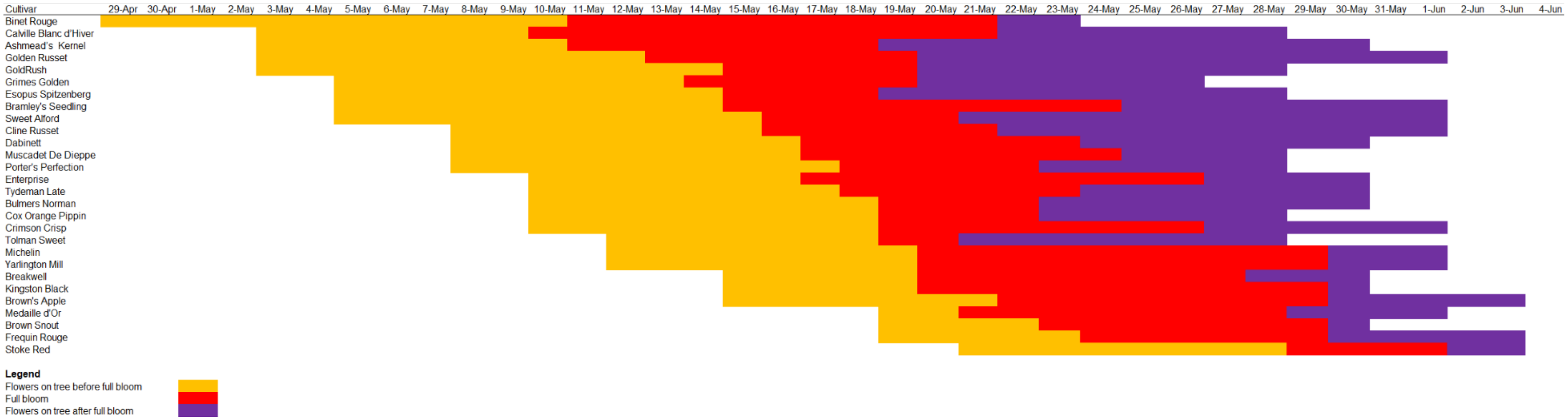

Figure 3.1. Diagram of 2017 bloom dates in 28 apple cultivars grown on M.9. rootstock for cider production. Yellow: flowers observed on the tree but the tree has not reached full bloom. Red: tree is at full bloom. Purple: flowers observed on the tree but the tree is past full bloom. University of Guelph, Simcoe, Ontario, 2017.

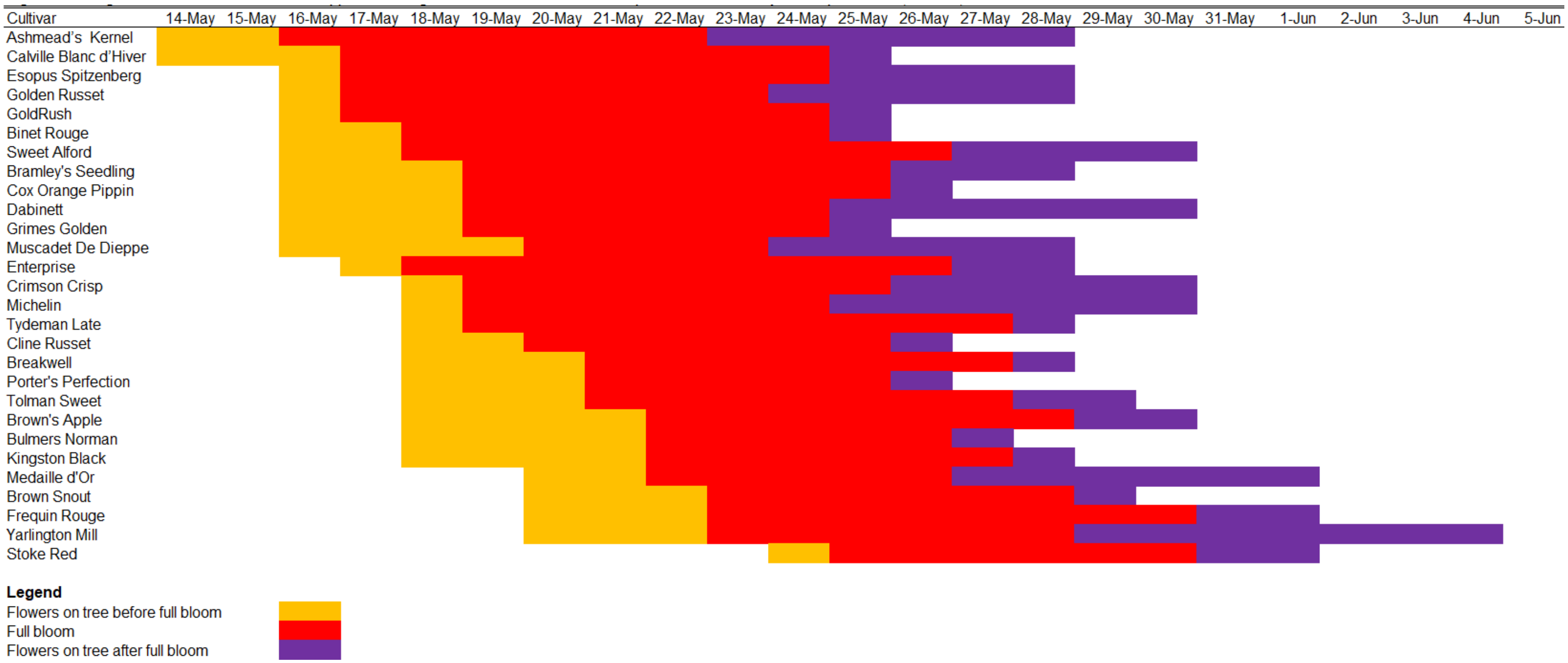

Figure 3.2 Diagram of 2018 bloom dates in 28 apple cultivars grown on M.9. rootstock for cider production. Yellow: flowers observed on the tree but the tree has not reached full bloom. Red: tree is at full bloom. Purple: flowers observed on the tree but the tree is past full bloom. University of Guelph, Simcoe, Ontario, 2018.

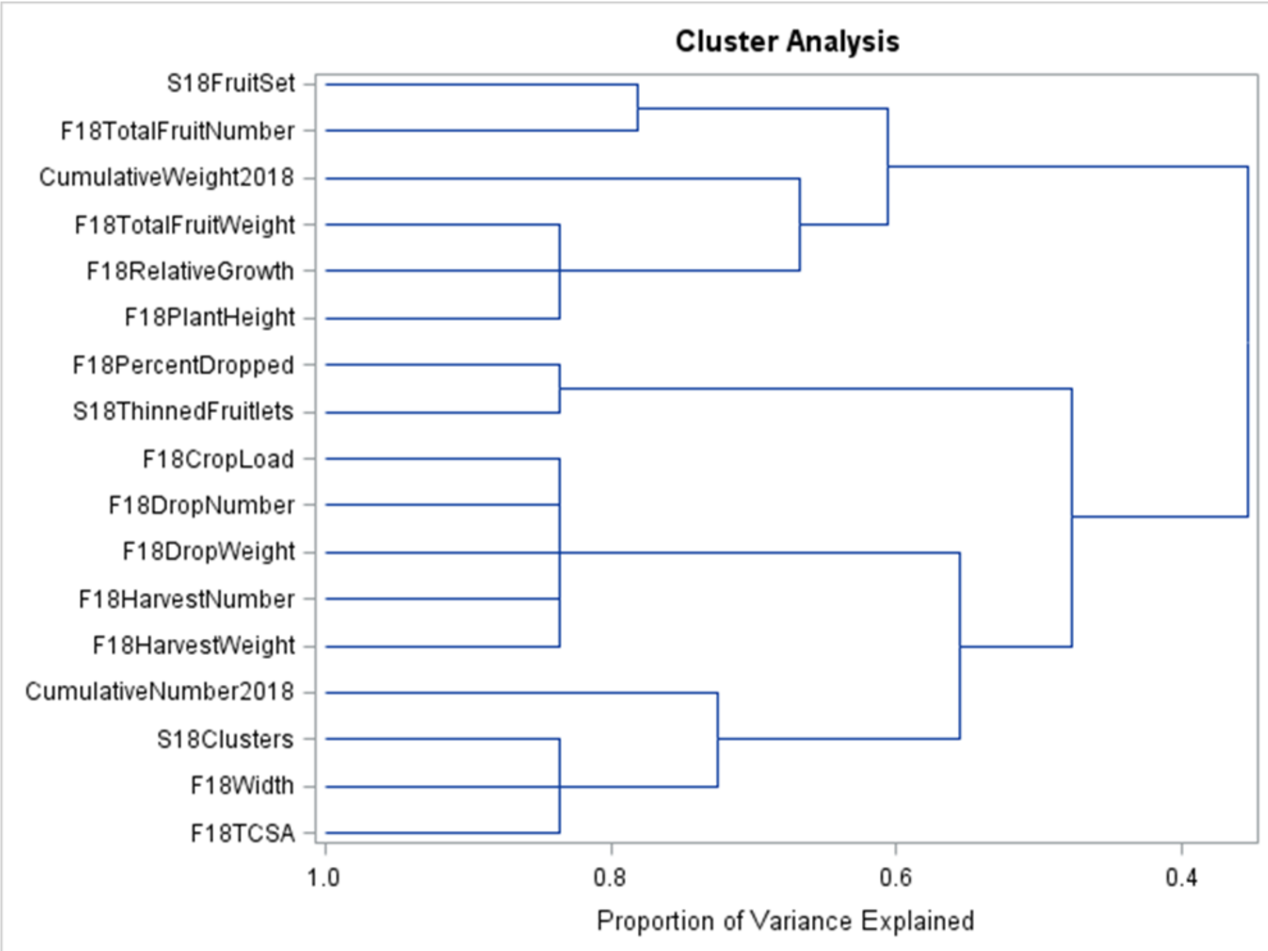

Figure 3.3 The association among horticultural attributes measured in 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

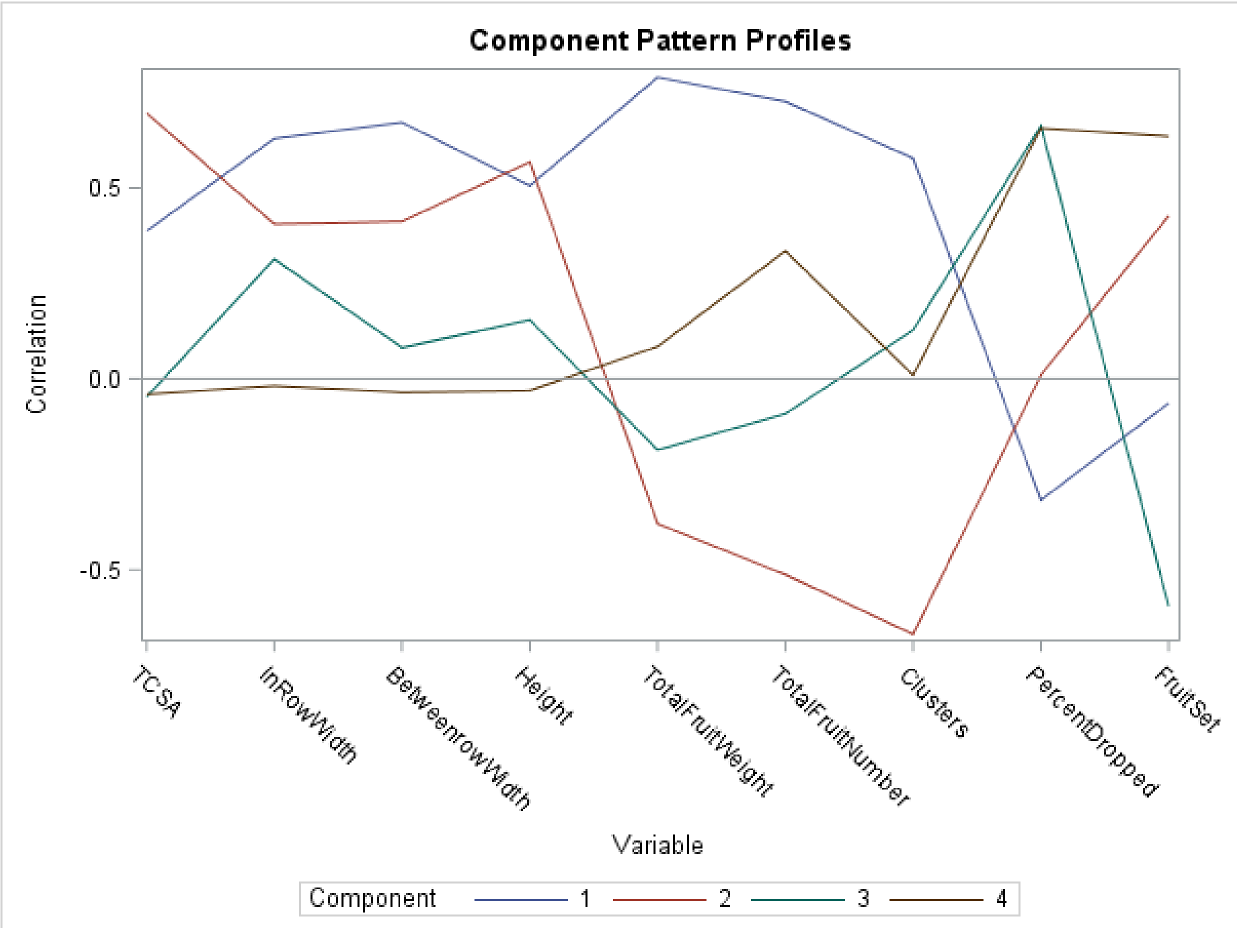

Figure 3.4 The correlation between horticultural characteristics and the principal components of the horticultural attribute data set. University of Guelph, Simcoe, Ontario, 2018.

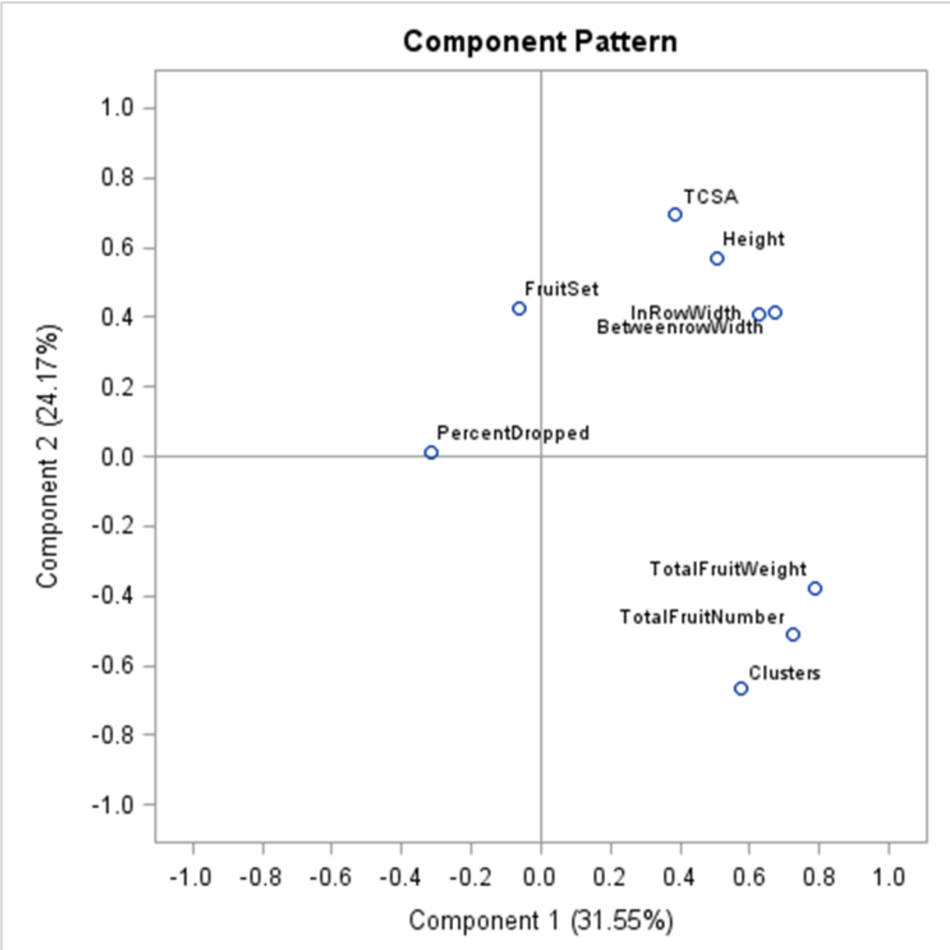

Figure 3.5 The relationship between horticultural characteristics and the principal components of the horticultural attribute data set. University of Guelph, Simcoe, Ontario, 2018.

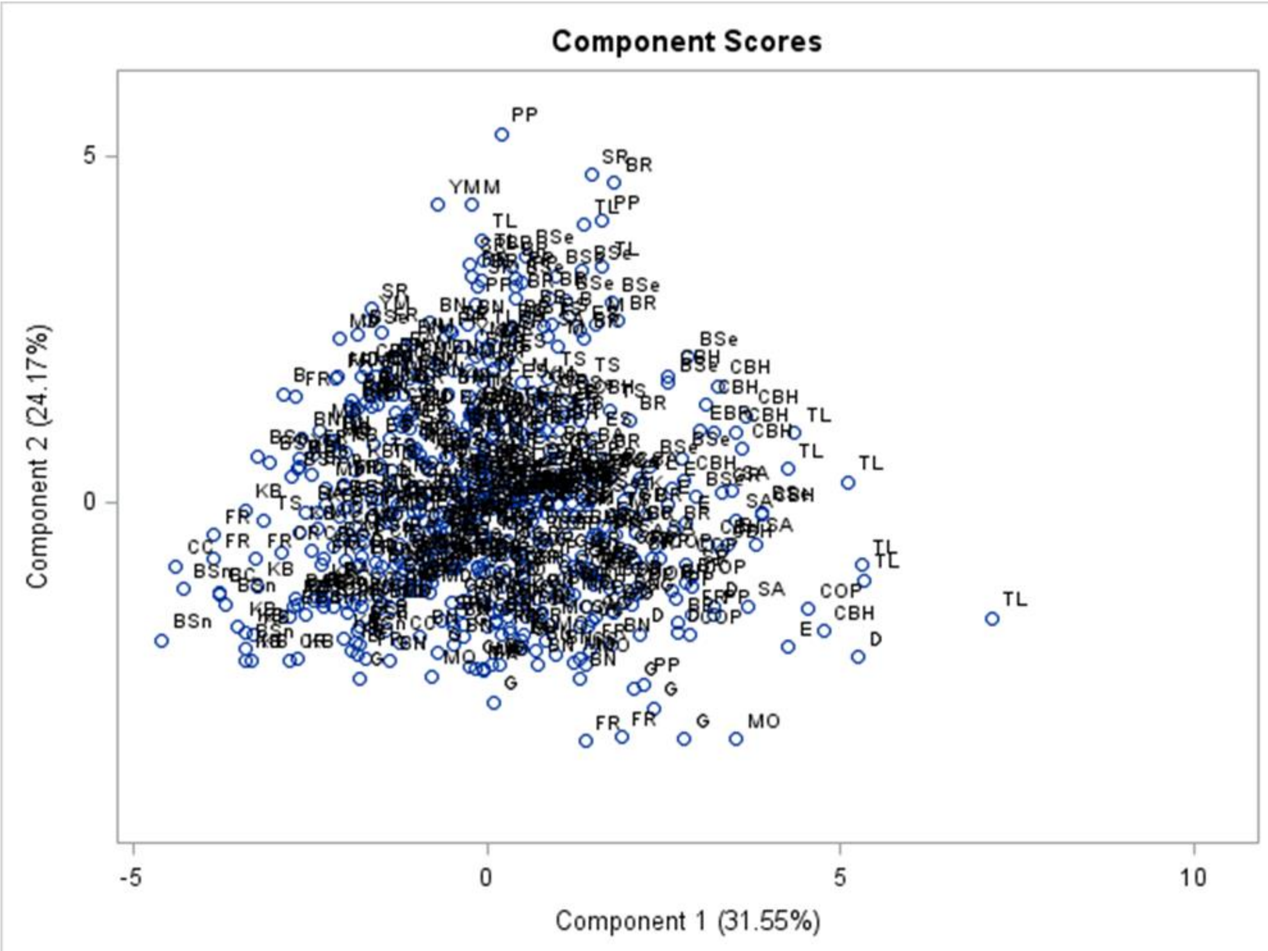

Figure 3.6 Plot of individual data points and the principal components of the horticultural attribute data set by cultivar. University of Guelph, Simcoe, Ontario, 2018.

4 Juice Attributes of Cider Cultivars

4.1 Abstract

Twenty-eight apple cultivars were selected for their potential for hard cider production in Ontario and their juice characteristics were measured in 2017 and 2018, beginning two years after planting in 2015. After being harvested and pressed, each juice sample underwent analyses to determine soluble solids, titratable acidity (TA), pH, yeast assimilable nitrogen (YAN), polyphenolic content, and firmness. Soluble solids concentration ranged from 10.6° Brix in ‘Brown’s Apple’ to 18.3° Brix in ‘Ashmead’s Kernel’. TA ranged from 31 as mg malic acid 100 mL^{-1} juice in ‘Sweet Alford’ to 191 as mg malic acid 100 mL^{-1} juice in ‘Bramley’s Seedling’. The pH ranged from 2.88 in ’Breakwell’s Seedling’ to 4.76 in ‘Sweet Alford’. YAN concentration ranged from 60 mg YAN L^{-1} juice in ‘Medaille d’Or’ to 256 mg YAN L^{-1} juice in ‘Bulmers Norman’. Total polyphenolic concentration in juice ranged from 131 µg gallic acid equivalents mL^{-1} juice in ‘Tolman Sweet’ to 1042 µg gallic acid equivalents mL^{-1} juice in ‘Stoke Red’. Firmness ranged from 6.3 N in ’Yarlington Mill’ to 11.7 N in ‘GoldRush’. The relationships between these variables were also analyzed, showing a connection between acidity and juicing efficiency as well as a relationship between polyphenol concentration, and fruit weight. Exploratory analyses indicated that juice attributes are usable to distinguish between cultivars and their origins. These data can be used by cider producers to give them ideas of what to expect in juice from these cultivars.

4.2 Introduction

4.2.1 Cider production

When making cider, producers usually blend the juices of several apple cultivars to achieve the desired physicochemical characteristics for the best fermentation and final product. Many Canadian cider makers choose apples using the cider apple classification system developed by the former Long Ashton Research Station (LARS) in the United Kingdom. This approach was useful when the system was developed at the beginning of the 20th century, however, with more accurate and complex analytical methods to determine juice components, there is greater ability to discriminate between cider juice. The LARS system is useful because most cider makers have the equipment and capabilities to conduct these analyses on their own, however other factors are important to consider when selecting apple juice for cider production. For example, pH is important for the assurance of microbial stability and sugar is the main substrate for fermentation.

The year-to year variation in polyphenols and titratable acidity also make the juice of apple cultivars somewhat difficult to categorize. A bittersharp apple juice one year may be a bittersweet the next. Ideally, classification based on many seasons would be used, but on a practical level commercial cider producers could conduct these measurements each year. Still, the point of a system of cultivar classification is to determine what is expected from the orchard. If the cider maker desires a consistent cider from year to year using 40% bitters and 60% sharps, then knowing the averages will be helpful. This study was done in collaboration with Ontario craft cider producers who wished to learn more about these varieties in order to report on the attributes of the juices extracted from cider cultivars when grown in Ontario.

The quality of fruit is related to, though distinct from the quality of cider. Fresh market apples, often because of their appearance, have consumer appeal. Superficial characteristics mean nothing for a juice, and therefore do not contribute to cider quality. The colour of the fruit mostly stays in the skin and liquid juice doesn’t retain the solid apple crispness. Juice for cider production is defined by its sugar, acid, polyphenols, and aromatics. Some descriptors for cider defined by the American Cider Association for styles include “farmyard,” “spicy,” “acetic,” “cheesy,” and “floral” (USACM, 2018). These attributes are uncommon in fresh juices made from culinary fruit. Rather, these characteristics come from polyphenols, acids, fermentation, and other factors. In cider production these are desirable attributes, and varieties are often blended to derive characteristic must properties sought by the cider maker. Sugar contributes to sweetness and alcohol; acids contribute to stability and sourness; nitrogen contributes to aroma and fermentation; and polyphenols contribute to bitterness, astringency, and flavour. These differences vary among cultivars, which is why highlighting their specific attributes is critical to the sustainability and profitability of commercial cider apple production.

Once fruit has been harvested and stored, moving from whole apples to apple juice can take multiple routes. Generally, the fruit is cleaned, crushed, and pressed, resulting in a separated mass of pomace and juice. Variations in this formula can occur at any stage. In most modern cider production, apples are cleaned in with water and sorted to discard rotten or unripe fruits and vegetative plant tissue before they end up in the juice.

Juice extraction varies based on region, resources, and scale. Most presses cannot easily or effectively extract juice from whole apples, so the fruits are milled or crushed to increase juice extraction. Grinding was historically carried out using stone mills powered by draft animals or water or by using hammers to smash fruits (Mangas Alonso & Blanco Gomis, 2010). In England, France, and North America millstones were used, which were often powered by water or horses. Modern apple grinders are usually motor-powered and use grinding teeth on a drum to break apart the fruits into small pieces to increase juice extraction. Small producers, such as home cider makers, may use small appliances like food processors, blenders, juicers, or even knives.

After it is crushed, pomace is transferred to a press where the solids will be separated from the liquids. Traditional presses that remain common include rack-and-cloth presses, in which square layers of pomace are wrapped in cheesecloth or burlap and stacked in several racks and pressed vertically; and basket presses, in which pomace is loaded into a basket and pressed vertically, sometimes with a physical pressing aid. The length of press time varies, which affects the amount of juice extracted in addition to the juice's exposure to air. Modern producers may also use pneumatic presses and continuous belt presses. Apple juice for cider production is typically not left to macerate in contact with pomace for extended periods of time, such as in red wine production. Rather the juice is immediately transferred into tanks or other storage vessels. From fresh juice, further processing for storage or directly to cider making can take place. This may include the addition of sulfites, pasteurization, or concentration (including cryo-concentration for ice cider).

Apple juice undergoes a series of compositional changes during the fermentation process. The most dramatic change comes from the conversion of sugar to alcohol. Yeast will also incorporate nitrogenous compounds and build them into proteins for its own growth. Some amino acids present will act as precursors to aromatic compounds, but the absence of sufficient nitrogen may lead to the production of undesirable volatile compounds or flavours. Acidity during alcoholic fermentation tends to remain stable, however malolactic fermentation, in which malic acid is converted to lactic acid, will reduce the acidity and increase the pH of cider while acetification will increase the acidity and reduce the pH. Focusing on the macronutrients in juice attributes aids in the prediction of the composition of the resulting cider. The compounds found in smaller concentrations, like aromatic and flavour compounds, are more greatly affected by yeast strains, weather, and other factors and are beyond the scope of this study. Once fermented, the primary and secondary metabolites in cider include carbohydrates, organic acids, amino acids, and phenolic compounds (Feng et al., 2014).

4.2.2 Juice attributes

Juice composition affects both the production and flavour of cider. Nitrogen availability, sugar concentration, and pH influence the growth and metabolism of fermentation microorganisms (Kelkar & Dolan, 2012), while titratable acidity and polyphenols have traditionally been used to classify apple cultivars for their flavour (Lea, 2015; Mangas Alonso & Blanco Gomis, 2010).

The three major sugars found in apple juice, in order of concentration, are fructose, glucose, and sucrose (Wu et al., 2007). Yeast will preferentially consume glucose over fructose and will hydrolyze sucrose into its constituent monomers before fermentation (Babsky et al., 1986; Magyar & Tóth, 2011). Non-fermentable carbohydrates present in juice include sugar alcohols, like sorbitol, and starches, which are used as carbohydrate storage as the fruit develops before being decomposed into fermentable sugars during ripening (Thomas, 2004; Watkins, 2003) In cider production, sugar's first role is as a substrate for yeast to convert to pyruvate via glycolysis and then to ethanol and CO_2 via alcoholic fermentation (Mangas Alonso, 2010a). Post-fermentation, residual sugar is the source of the perception of sweetness. in cider. Measuring sugar in juice by refractometry or specific gravity, a measure of juice density, before fermentation allows cider makers to predict alcohol production, plan how to blend ciders, and make any desired correction through exogenous sugar additions (Merwin et al., 2008).

The two main functions of acids in cider production, like those of sugar, are to influence fermentation, which is associated with pH, and to affect the flavor of the final cider, which is associated with titratable acidity (TA). The pH of a juice, the measure of the concentration of hydrogen ions, affects the survival of yeast, beneficial bacteria, like *Leuconostoc*, and spoilage microorganisms, like *Pedioccus* and *Lactobacillus*, in addition to affecting the formation of H_2S, biogenic amines, volatile acids. The pH in alcoholic fermentation media is considered to be high if it is above 3.5, below which the pH favours the growth of desirable microorganisms (Toit & Pretorius, 2000). TA, on the other hand, is a metric that describes the quantity of molecules or functional groups that can lose protons (that is, be titrated) (Iland, 2004a). These acids, primarily malic acid in apple juice, but also including citric and ascorbic acid in addition to lactic and acetic acid in finished ciders, are perceived as a sour flavor when consumed in a cider (González San José, 2010; Wu et al., 2007).

North American cider producers often rely on culinary apples for cider production, which can be low in acid and polyphenols when compared to cider apples grown in European cider regions (Cline et al., 2020; Wilson et al., 2003). Cider makers will often supplement musts with exogeneous polyphenols to compensate during the cidermaking process to add bitterness and astringency (Thompson-Witrick et al., 2014). There is also the potential to address low acidity of fruit using orchard practices. Trees that had higher crop loads were found to have fruit that were smaller and less acidic when compared to trees of lower crop loads in the same orchard with the same cultivars and rootstocks (Peck et al., 2016).

Polyphenols are a class of compounds that include tannins. All polyphenols contain multiples of the aromatic organic chemical structures known as phenols. Thompson-Witrick et al. (2014) identified five classes of polyphenols important in ciders: catechins, procyanidins, flavan-3-ols, quercetins, and phloretins. Bitterness and tactility in cider are affected by structure, polymer size, and stereochemistry (Lesschaeve & Noble, 2005). Polyphenols are also important as antioxidants. Historically polyphenols were measured with the Lowenthal-Permanganate method as tannic acid (Alexander et al., 2016). These measurements were used to establish juice classifications of "bittersharp" and "bittersweet." Other methods, like the Folin-Ciocalteu, bovine serum albumin, and dimethylaminocinnamaldehyde methods, are also used to assess polyphenols, though they may lack sensitivity or specificity to polyphenol compounds and still do not discriminate amongst the compounds the way HPLC may. Direct comparisons among these methods are made more difficult by the varying ratios seen between the methods when performed on the same samples (Ma et al., 2019).

In addition to most apple cultivars used for North American cider production having low polyphenol concentrations (Peck et al., 2016; Thompson-Witrick et al., 2014), there is significant variation between years when comparing fruit from the same orchard (Alexander et al., 2016). The major phenolics in culinary apples are chlorogenic acid and protocatechuic acid (Wu et al., 2007). Despite knowing that procyanidins and catechin polymers are known to contribute to the perception of bitterness and astringency, it is difficult to quantify sensory impact based on polyphenol composition and total polyphenol concentration (Le Quéré et al., 2006; Thompson-Witrick et al., 2014). Martin et al. (2017) investigated the idea of adding commercial tannin in order to make up for the lack of high-tannin cider apples in North America. In their sensory study, the ciders that were most highly rated on a hedonic scale were those with some tannins and moderate residual sugar concentrations (Martin et al., 2017). In addition to being affected by the competing flavours of acidity and sweetness, polyphenol perception is affected by the degree of polymerization of procyanidins (Symoneaux et al., 2014). Astringency is associated with greater polymerization of procyanidins in cider, while bitterness is higher in medium chain polymers than in short or long chains (Symoneaux et al., 2014). Adding exogenous polyphenols to influence these flavours have not been shown to be effective at improving cider taste, but horticultural and oenological methods of improving polyphenols to achieve desirable sensory characteristics show promise. On the horticultural side, increasing crop load in the orchard has been demonstrated to increase post-fermentation polyphenol concentration in ‘York’ apples (Peck et al., 2016). On the oenological side, addressing fruit processing could allow for greater polyphenol extraction from apple peels, which usually have more polyphenols than the flesh, (Thompson-Witrick et al., 2014).

While important from a plant nutrition perspective, nitrogen in cider production is most often discussed in terms of YAN and the fermentation process, Yeast assimilable nitrogen (YAN) comprises ammonium and primary amino acids, which make up the fraction of nitrogen in a fermentation medium that is biologically available to yeast. Yeast require nitrogen as a nutrient for growth and reproduction, which is key for a consistent fermentation. Amino acids aren’t used in a consumptive way in cider production, but are recycled through yeast autolysis and reuptake (Suárez Valles et al., 2005). YAN is measured by enzymatic assay, formol titration, or ammonium ion electrodes (for ammonium) (Bell & Henschke, 2005). In one study of culinary fruit, the principal amino acids in apple juice were asparagine and serine with no detection of aspartate or glutamate (Wu et al., 2007). Blanco Gomis et al. (1990) tested the amino acid composition of the entire fruit, rather than just the juice and found that the major amino acids in Collaos apples include Asn, Asp, Gln, Glu, Ser, and Phe. The major amino acids in Raxao apples include Asn and Asp. The major amino acids in Meana apples include Asn and Asp. Proline, a non-assimilable amino acid, is only present in apples in small quantities (Blanco Gomis et al., 1990).

Most cultivars for cider production produce juice with low YAN, which is often corrected by cider producers adding nitrogen in the cellar, whether it is by adding diammonium phosphate (DAP) or commercial yeast nutrient formulations (Jolicoeur, 2013). Horticultural and oenological practices also influence YAN. In contrast to N supplementation, many cider producers manipulate nitrogen concentrations the other way, reducing the amount of nitrogen to induce a longer fermentation (Le Quéré et al., 2006).

4.2.3 Other places of study

Some North American studies have looked at the juice parameters of cider apples in specific regions, such as New York (Valois et al., 2006), Virginia (Thompson-Witrick et al., 2014), Québec (Provost, 2018), and Washington (Miles et al., 2017). The variations between parameters among cultivars common across the studies point to differences in climate, terrain, and horticultural practices. These studies analyzed the juice by measuring sugars, acids, polyphenols, and nitrogenous compounds. At Washington State University, researchers compared and contrasted 'Brown Snout', 'Dabinett', 'Kingston Black', and 'Yarlington Mill' apples grown in northwest and central Washington (Alexander et al., 2016). It was observed that the growing region, cultivar, and annual variation did not influence juice soluble solids, pH, TA, or tannins (Alexander et al., 2016). Moreover, the cultivars in question did not match the LARS classification of these apples grown in Britain, but testing the attributes every year was still considered important in order to account for the particular year's juice attributes (Alexander et al., 2016).

4.2.4 Objectives of the study

The objectives of this study were to report the juice characteristics of 28 apple cultivars selected for cider production in Ontario as evaluated at the Simcoe Research Station. The specific attributes that were measured are sugar concentration, TA, pH, polyphenol concentration, and YAN concentration.

This data set will be used in an exploratory analysis to examine relationships that exist among the juice attributes across cultivars. It is hypothesized that differences in juice attributes exist among cultivars that have different geographic origins due to the difference in traits selected by growers in each region to adapt for the local climates and horticultural practices. It is also hypothesized that like the historical cider apple classifications based on acidity and polyphenols, the primary factors in classifying juice using a principal component analysis will be acidity and polyphenols.

4.3 Materials and Methods

4.3.1 Plant materials

Apple samples were collected from 28 cultivars grafted onto M.9 T337 rootstock. The cultivars consist of: 'Ashmead's Kernel,' 'Breakwell,' 'Brown's Apple,' 'Bulmers Norman,' 'Binet Rouge,' 'Bramley's Seedling,' 'Brown Snout,' 'Calville Blanc d'Hiver,' 'Crimson Crisp®,' 'Cox Orange Pippin,' 'Cline Russet,' 'Dabinett,' 'Enterprise,' 'Esopus Spitzenberg,' 'Fréquin Rouge,' 'GoldRush,' 'Grimes Golden,' 'Golden Russet,' 'Kingston Black,' 'Michelin,' 'Muscadet de Dieppe,' 'Medaille d'Or,' 'Porter's Perfection,' 'Sweet Alford,' 'Stoke Red,' 'Tydeman Late,' 'Tolman Sweet,' and 'Yarlington Mill.' Many of these apple cultivars were selected because of their reputation for tannin concentration and cider production.

4.3.2 Methods

The cider orchard was planted at the Simcoe Research Station (Simcoe, ON) in spring 2015 in a randomized complete block, with each cultivar being represented by four blocks of five trees. The three trees in the middle of each block were used for data collection with the other two trees being used as 'guards'. The orchard was managed using an integrated pest management for disease and insect pests according to local recommendations (OMAFRA, 2016). The high-density planting was on a vertical axis with trees headed and trained to a wire trellis with drip irrigation and had a spacing of 1 m within and 4.5 m between rows (1667 trees ha^{-1}). In the fall of 2017 and 2018, fruit was collected from guard trees before harvest to determine maturity using starch-iodine analysis (Blanpied & Silsby, 1992). Ripeness analyses were done by harvesting a total of five fruit from the two guard trees in each block, usually consisting of two fruit from one tree and three fruit from the other. These were anticipated to be taken beginning two weeks before their projected harvest date based on data from other sites, though some trees were harvested ahead of the projected schedule.

All fruit on the data trees, which were the three middle trees in the set of five trees, were harvested when the guard tree fruit was measured at 40% flesh stain on the Cornell generic starch-iodine test scale (Blanpied & Silsby, 1992). After harvesting, apples were either processed into juice immediately or stored at 0-1°C until processing within a week. From each of the data trees, the three centre trees in each block, all the harvested fruit was collected in a separate basket. For juicing, five representative fruit from each tree were selected from each replicate for a total of fifteen fruit per replicate. Fruit weight of the fifteen apples was recorded on an analytical scale (LC 3200D, Sartorius, Bohemia, NY), after which the fruit were sectioned to fit into the feed tube and ground in the fruit juicer (Model 8006, Omega, Harrisburg, PA) using the grinding attachment, which does not separate the juice from the pomace. The ground fruit was then placed in cheesecloth (Grade #50, Fisher Scientific, Whitby, ON) on a rack of a custom-made stainless steel rack-and-cloth set (Allingham Machining Inc., Stoney Creek, ON) used in conjunction with a PowerFist hydraulic press (Princess Auto, Hamilton, ON rack-and-cloth press . Any separated juice from the juicer was poured over the pomace before closing the cheesecloth packet. Once the cheesecloth packet was closed another steel plate was placed on top along with a pressing plate and the hydraulic press was pressed down to 17,000 kPa, released once the juice stopped running freely into a graduated cylinder, and pressed down once more to 17,000 kPa. The volume of juice extracted was recorded and used in conjunction with the fruit weight to calculate the juice extraction efficiency. The racks were washed between each use. A 50 mL aliquot of juice was set aside and frozen at -80° C for downstream polyphenol analysis. All other juice analyses were performed immediately or within a day of pressing while storing the juice at 0-1°C.

The soluble solid concentration was measured using a temperature compensating refractometer (Pocket 7105 PALBXIAcid5, Atago, Tokyo, Japan). The lens was washed with distilled water between measurements and wiped with a delicate task wiper (Kimwipes, Kimberly-Clark, Mississauga, ON).

For polyphenol analysis, a 2 mL aliquot of each juice sample was transferred to an Eppendorf tube and centrifuged for 10 minutes in a centrifuge at room temperature at 10000 rpm (Legend Micro 21, Thermo Fisher, Mississauga, ON). Thereafter, 0.5 mL of the supernatant was transferred to a new Eppendorf tube containing 1.5 g of polyvinylpolypyrrolidone (PVPP), with the rest of the supernatant reserved, the mixture of supernatant and PVPP was then centrifuged for 10 minutes. The PVPP was used to precipitate out the polyphenols in order to measure interfering compounds. The samples, along with water blanks and gallic acid standards (0-500 mg L^{-1} gallic acid in water), were plated onto a 96-well microplate (Thompson-Witrick et al., 2014). Folin-Ciocalteu reagent (Sigma Aldrich) was added to the samples on the plate. The plate was incubated for an hour before the addition of sodium bicarbonate solution and being read in the microplate reader (Epoch 2, BioTek, Winooski, VT) at 765 nm. The polyphenol concentration was calculated by using the difference between the untreated samples and samples treated with PVPP. These differences were transformed using a standard curve created by using the standard solutions.

Each time of use the pH meter (pH 700 Benchtop Meter, Oakton Instruments, Vernon Hills, IL) was calibrated using standards (Fisher Scientific, Whitby, ON) of 4.0, 7.0, and 10.0. The pH electrode was rinsed with distilled water and wiped with a Kimwipe in between measurements, which were taken directly by placing the electrode in the juice sample. The titratable acidity was measured using an autotitrator (G20 Compact Titrator, Mettler Toledo, Mississauga, ON) programmed to an endpoint of pH=8.2 using a .01 M NaOH solution. The titrator was calibrated with pH standards of 4.0, 7.0 and 8.0. 5 mL of juice was mixed with 45 mL of distilled water and run through the autotitrator. The volume of 0.01 M NaOH used as a titrant was used to calculate TA with the acid milliequivalence (meq.) factor for malic acid (Equation 1).

$$Titrable\ acidity\ \left(\frac{g}{100\ ml}\right) = \frac{\mathrm{ml\ NaOH\ x\ N(NaOH)\ x\ 0.067\ acid\ meq.factor\ x\ 100}}{ml\ juice\ titrated}$$

Equation 1: Calculation of titratable acidity based on volume of NaOH used to titrate the medium to an endpoint of pH=8.2.

The YAN concentration was measured using a formol titrator (HI84533, Hanna Instruments, Laval, QC), formol calibration standards (Hanna Instruments, Laval, QC). The instrument's pH meter was calibrated with pH standards (Hanna Instruments, Laval, QC) of 4.1, 7.1, and 8.2. The injector was calibrated using the formol calibration standards (Hanna Instruments, Laval, QC) on the low concentration setting. For each assay, 10 mL of juice was diluted with 40 mL of distilled water, and then titrated to pH=8.2. Once the solution was titrated, 4 mL of formaldehyde was added and the solution was re-titrated , which the machine reported as the formol number.

Firmness was measured by slicing off 1-2 mm of skin with a sharp razor to create flat surfaces on opposite equatorial ends of the apple. Each cut end was then placed on a Fruit Texture Analyzer (Güss Instruments, South Africa), which recorded the firmness by determining the force required to penetrate fruit flesh with an 11-mm diameter probe (Abbott et al., 1976). This was repeated for five apples for every sample on 2 lateral sides before the fruit was juiced.

4.3.3 Experimental design

The orchard at the Simcoe Research Station was planted in a randomized complete block, with 4 replications of 5 trees for each of 28 cultivars. Data were collected from the middle three trees from each five-tree block, with the two outside trees in each block acting as a buffer.

Data were analyzed using the GLIMMIX procedure in SAS 9.4 (The SAS Institute, Cary, NC). Significance was evaluated at a *p* value of 0.05 and residuals were analyzed for normality and outliers. Post-hoc means separation was analyzed using Tukey-Kramer grouping for least square means (α=0.05). Additional statistical data can be found in Appendix 1.

To understand the relationships among juice variables, exploratory statistical analyses were performed using the PRINCOMP, FASTCLUS, and DISCRIM procedures in SAS 9.4 (The SAS Institute, Cary, NC). These procedures group variables using principal component analysis, cluster analysis, and discriminant analysis respectively. The suitability of the discriminant analyses was analyzed with a χ^2 test.

4.4 Results

4.4.1 Juice attributes

In 2017, soluble solids ranged from 10.6° Brix in ‘Brown’s Apple’ to 18.3° Brix in ‘Ashmead’s Kernel’ (Table 4.1), with the 5 cultivars with the highest soluble solid contents being ‘Ashmead’s Kernel’ (18.3° Brix), ‘Golden Russet’ (17.2° Brix), ‘Tydeman Late’ (17.1° Brix), ‘Brown Snout’ (16.4° Brix), and ‘Fréquin Rouge’ (16.0° Brix). In 2018, soluble solids ranged from 11.8° Brix in ‘Brown’s Apple’ to 17.6° Brix in ‘Brown Snout’ (Table 4.2), with the 5 cultivars with the highest soluble solid contents being ‘Brown Snout’ (17.6° Brix), ‘Medaille d’Or’ (16.8° Brix), ‘Yarlington Mill’ (16.7° Brix), ‘Golden Russet’ (16.4° Brix), and ‘Fréquin Rouge’ (16.4° Brix).

In 2017, juicing efficiency ranged from 0.48 mL juice g^{-1} fruit in ‘Muscadet de Dieppe’ to 0.72 mL juice g^{-1} fruit in ‘GoldRush’ (Table 4.3). The 5 cultivars with the highest juicing efficiency in 2017 were ‘GoldRush’ (0.72 mL juice g^{-1} fruit), ‘Bramley’s Seedling’ (0.69 mL juice g^{-1} fruit), ‘Bulmers Norman’ (0.68 mL juice g^{-1} fruit), Crimson Crisp (0.68 mL juice g^{-1} fruit), ‘Cline Russet’ (0.67 mL juice g^{-1} fruit). In 2018, juicing efficiency ranged from 0.36 mL juice g^{-1} fruit in ‘Muscadet de Dieppe’ to 0.68 mL juice g^{-1} fruit in Crimson Crisp (Table 4.4). The 5 cultivars with the highest juicing efficiency in 2018 were Crimson Crisp (0.68 mL juice g^{-1} fruit), ‘Brown’s Apple’ (0.66 mL juice g^{-1} fruit), ‘Grimes Golden’

(0.66 mL juice g^{-1} fruit), ‘GoldRush’ (0.66 mL juice g^{-1} fruit), and ‘Enterprise’ (0.65 mL juice g^{-1} fruit).

In 2017, the concentration of polyphenols (corrected for interfering compounds) in juice ranged from 185 µg gallic acid equivalents mL^{-1} juice in ‘Tolman Sweet’ to 1042 µg gallic acid equivalents mL^{-1} juice in ‘Stoke Red’ (Table 4.1). The five cultivars with the highest polyphenol concentrations in 2017 were ‘Stoke Red’ (1042 µg gae mL^{-1} juice), ‘Porter’s Perfection’ (925 µg gae mL^{-1} juice), ‘Binet Rouge’ (915 µg gae mL^{-1} juice), ‘Brown’s Apple’ (781 µg gae mL^{-1} juice), and ‘Bulmers Norman’ (738 µg gae mL^{-1} juice). In 2018, the corrected concentration of polyphenols in juice ranged from 131 µg gallic acid equivalents mL^{-1} juice in ‘Tolman Sweet’ to 923 µg gallic acid equivalents mL^{-1} juice in ‘Bulmers Norman’ (Table 4.2). The 5 cultivars with the highest polyphenol concentrations in 2018 were ‘Bulmers Norman’ (923 µg gae mL^{-1} juice), ‘Binet Rouge’ (880 µg gae mL^{-1} juice), ‘Stoke Red’ (876 µg gae mL^{-1} juice), ‘Medaille d’Or’ (875 µg gae mL^{-1} juice), and ‘Porter’s Perfection’ (865 µg gae mL^{-1} juice).

In 2017, the pH ranged from 3.00 in ‘Bramley’s Seedling’ to 4.76 in ‘Sweet Alford’ (Table 4.1). The 5 cultivars with the lowest pH in 2017 were ‘Bramley’s Seedling’ (2.99), ‘Breakwell’s Seedling’ (3.08), ‘Tydeman Late’ (3.17), ‘Medaille d’Or’ (3.17), and ‘Calville Blanc d’Hiver’ (3.19). In 2018, the pH ranged from 2.88 in ‘Breakwell’ to 4.57 in ‘Sweet Alford’ (Table 4.2). The 5 cultivars with the lowest pH in 2018 were ‘Bramley’s Seedling’ (2.70), ‘Breakwell’s Seedling’ (2.88), ‘Medaille d’Or’ (3.03), ‘Cox Orange Pippin’ (3.08), and ‘Tydeman Late’ (3.12).

In 2017, the titratable acidity ranged from 31 as mg malic acid 100 mL^{-1} juice in ‘Sweet Alford’ to 176 as mg malic acid 100 mL^{-1} juice in ‘Tydeman Late’ (Table 4.1). The top 5 in 2017 were ‘Tydeman Late’ (176 as mg malic acid 100 mL^{-1} juice), ‘Breakwell’s Seedling’ (158 as mg malic acid 100 mL^{-1} juice), ‘Bramley’s Seedling’ (145 as mg malic acid 100 mL^{-1} juice), ‘Medaille d’Or’ (137 as mg malic acid 100 mL^{-1} juice), ‘Calville Blanc d’Hiver’ (132 as mg malic acid 100 mL^{-1} juice). In 2018, the titratable acidity ranged from 35 as mg malic acid 100 mL^{-1} juice in ‘Sweet Alford’ to 191 as mg malic acid 100 mL^{-1}

juice in ‘Bramley’s Seedling’ (Table 4.2). The top 5 in 2018 were ‘Bramley’s Seedling’ (191 as mg malic acid 100 mL^{-1} juice), ‘Breakwell’s Seedling’ (190 as mg malic acid 100 mL^{-1} juice), ‘Tydeman Late’ (179 as mg malic acid 100 mL^{-1} juice), ‘Medaille d’Or’ (171 as mg malic acid 100 mL^{-1} juice), and ‘Porter’s Perfection’ (138 as mg malic acid 100 mL^{-1} juice).

In 2017, the YAN concentration ranged from 60 mg YAN L^{-1} juice in ‘Medaille d’Or’ to 206 mg YAN L^{-1} juice in ‘Tydeman Late’ (Table 4.1). The 5 cultivars with the highest concentrations of YAN in 2017 were ‘Tydeman Late’ (206 mg YAN L^{-1} juice), ‘Golden Russet’ (174 mg YAN L^{-1} juice), ‘Brown Snout’ (170 mg YAN L^{-1} juice), ‘Tolman Sweet’ (155 mg YAN L^{-1} juice), and ‘Bulmers Norman’ (152 mg YAN L^{-1} juice). In 2018, the YAN concentration ranged from 82 mg YAN L^{-1} juice in ‘Kingston Black’ to 256 mg YAN L^{-1} juice in ‘Bulmers Norman’ (Table 4.2). The 5 cultivars with the highest concentrations of YAN in 2018 were ‘Bulmers Norman’ (256 mg YAN L^{-1} juice), ‘Golden Russet’ (207 mg YAN L^{-1} juice), ‘Binet Rouge’ (185 mg YAN L^{-1} juice), ‘Ashmead’s Kernel’ (169 mg YAN L^{-1} juice), and ‘Michelin’ (168 mg YAN L^{-1} juice).

Firmness was not measured in 2017. In 2018, the firmness ranged from 6.3 kg in ‘Yarlington Mill’ to 11.7 kg in ‘GoldRush’ (Table 4.2). The 5 cultivars with the greatest firmness in 2018 were ‘Golden Russet’ (11.7 kg), ‘Medaille d’Or’ (10.8 kg), ‘Binet Rouge’ (10.7 kg), ‘Tolman Sweet’ (10.0 kg), and ‘GoldRush’ (9.9 kg).

4.4.2 Multivariate analyses

The principal component analysis indicated that 83% of the horticultural variance among the cultivars could be attributed to 4 clusters. The first cluster explained 35% of the variance and was influenced most by the TA, fruit weight, and juicing efficiency (Figure 4.2). The second cluster explained 23% of the variance and its main factors were the number of days until harvest, the soluble solids, and the pH. The third cluster explained 15% of the variance and mostly accounted for YAN, soluble solids, and TA. The fourth cluster accounted for 10% of the variance and mostly consisted of YAN, juicing efficiency, and fruit weight.

The discriminant analyses showed that using juice attributes classification by origin was successfully predicted in 73% of observations and that classification by cultivar was successfully predicted in 90% of observations. A χ^2 test at 95% confidence indicated a goodness of fit for both origin and cultivar (Table 4.9).

4.5 Discussion

4.5.1 Evaluation criteria for juice

Given that any attribute of juice can be balanced by blending, a high-quality juice would be one that is rich in a specific attribute, be it one of those measured in this study or another attribute like aroma (Merwin et al., 2008). Cultivars that are rich in a specific attribute can be added to a more neutral base to create the desired concentration of that attribute. For a cider that needs more acidity, a cider maker may choose to blend in additional ‘Bramley’s Seedling’ juice while ‘Bulmers Norman’ would be a good addition for needed polyphenols. Microbial stability based on pH, alcohol potential based on sugars, and fermentation capability based on nitrogen should also be considered. The attributes of the juice must be considered in conjunction with horticultural attributes for an orchard cider maker to make the best decisions for planting in the orchard.

Historical TA measurements range from 1.86 g L^{-1} juice as malic acid in ’Sweet Alford’ to 12.5 g L^{-1} juice as malic acid in ‘Brown’s Apple’ (Jolicoeur, 2013; C. Miles et al., 2013) (Table 4.3), while historical pH measurements range from 2.95 in ’Bramley’s Seedling’ to 4.49 in ’Yarlington Mill’ (Copas, 2013; C. Miles et al., 2013) (Table 4.4). In this study, most of the apple cultivars were more acidic than the historical data, having higher TA values, though units and methodology differed among researchers. The pH values were typically in the same range as historical data, though ‘Dabinett,’ ‘Enterprise,’ ‘Golden Russet,’ ‘Medaille d’Or,’ and ‘Stoke Red’ had low pH values and ‘Fréquin Rouge’ had a high pH value when compared to other sources (Bradshaw, 2016; Eisele & Drake, 2005; C. Miles et al., 2013; Thompson-Witrick et al., 2014; Valois et al., 2006) (Tables 4.1, 4.2, 4.4).

Historical soluble solids concentrations in the apple cultivars in this study range from 10.9° Brix in 'Breakwell's Seedling' to 18.2° Brix in 'Brown Snout' (Bradshaw, 2016; C. Miles et al., 2013) (Table 4.5). Cultivars that were higher in soluble solids in this study than in historical data were 'Breakwell', 'Enterprise', 'Stoke Red', and 'Sweet Alford'. Cultivars that were lower in soluble solids in this study than in historical data were 'Muscadet de Dieppe' and 'Tolman Sweet' (Copas, 2001; Gottschalk et al., 2017; Jolicoeur, 2013; C. Miles et al., 2013; Thompson-Witrick et al., 2014) (Tables 4.1, 4.2, 4.5). The range of soluble solids concentrations in all other cultivars overlapped with historical data. When compared with historical data, most cultivars are within or close to the range of soluble solids concentrations reported elsewhere, though both 'Sweet Alford' and 'Stoke Red' had higher soluble solids concentrations in Simcoe than in other locations.

Historical polyphenol concentrations in cider apples range from 0.035% tannin in 'Esopus Spitzenberg' to 1.05% tannin in 'Medaille d'Or' (Bradshaw, 2016; C. Miles et al., 2013) (Table 4.6). The different methods of measurement make direct comparisons of historical polyphenol data to the data in this study difficult. Because polyphenol measurement methods vary so greatly, direct comparisons between historical data sources and these data can only be made when both were measured with the same methods. Of those, five cultivars had higher polyphenol concentrations in Simcoe than at other North American sites: 'Brown Snout,' 'Calville Blanc d'Hiver,' 'Golden Russet,' 'Kingston Black,' and 'Porter's Perfection.' Two cultivars had lower polyphenol concentrations in Simcoe than at other North American sites: 'Dabinett,' and 'Enterprise' (Bradshaw, 2016; Copas, 2001; C. Miles et al., 2013; Thompson-Witrick et al., 2014; Valois et al., 2006) (Tables 4.1, 4.2, 4.6).

Most cultivars for cider have low YAN, with historical measurements ranging from 9 mg YAN L^{-1} in 'Yarlington Mill' to 262 mg YAN L^{-1} in 'Ashmead's Kernel'.' All YAN measurements in this study were higher than those found in other sources, but methodology differed among the sparse historical data sources (Bradshaw, 2016; Valois et al., 2006) (Tables 4.1, 4.2, 4.7).

4.5.2 Associations among attributes

In order to understand how juice attributes were related to one another, a cluster analysis was run on the data set. Some notable attribute associations include: average fruit weight and juicing efficiency; and sugar concentration and the number of days from full bloom to harvest (Figure 4.1).

A principal component analysis of the variables days to harvest, TA, pH, soluble solids, YAN, average fruit weight, juicing efficiency, and polyphenols described the variation in the data in 4 dimensions (Figure 4.2). The 4 components, chosen based on the Jolliffe Test, were:

a) component 1: TA, fruit weight, and juicing efficiency;
b) component 2: days to harvest, soluble solids, and pH;
c) component 3: YAN. soluble solids, and TA; and
d) component 4: YAN, juicing efficiency, and fruit weight.

Component pattern charts of the principal components indicate natural groups of associated variables that are reflective of the above-listed components (Figure 4.3). Notably, polyphenols were not a major factor in any of the components, which is contrary to the hypothesis that they would be based on their use in historical classification.

A discriminant analysis (Table 4.9) of origin based on juice attribute data indicated that North American cultivars were distinct enough from British and French cultivars to be classified as North American 92% of the time. While French cultivars were classified as French 64% of the time and British cultivars correctly classified 62% of the time, which supports the prediction the juice attributes of the cultivars are distinct based on their origin. The distinguishing attributes of North American cultivars are large fruit size, long length of time to harvest, low pH, high juicing efficiency, and polyphenol values. French cultivars are often distinguished based on their low TA, high pH, low fruit weight, low juicing efficiency, and high polyphenols. British cultivars could be distinguished by their high polyphenols, low pH, and high TA.

A discriminant analysis of cultivar based on juice attribute data indicated that most cultivars are easily distinguishable when looking at combined juice attributes, with 90% of data points being classified as the correct cultivar. Cultivars that were classified as one another frequently due to similar horticultural characteristics include two sets: the set of ‘Cox’s Orange Pippin’ and ‘Dabinett’ and the set of ‘Michelin’ and ‘Muscadet de Dieppe.’ These pairs cultivars should have interchangeable juice, notwithstanding unmeasured aromatic and flavor attributes.

4.5.3 Associations based on place of origin

The 28 cultivars were picked because of their reputation or potential for cider, especially those that were traditionally grown in France, the United Kingdom, and parts of North America with a history of cider production. When separated by their country of origin, it was found that some juice attributes were significantly influenced by the origin of the cultivar. There were no differences among the average soluble solids or the YAN concentrations in the cultivars based on their origin. North American apples were the firmest, while British apples were the softest. French and English cultivars both had significantly higher polyphenol concentrations than North American ones, even when grown in North America. British apples had significantly higher TA values than American or French apples, while the French cultivars had the highest average pH. This reflects the styles of cider that have been typical of these regions. French ciders are typically naturally fermented and have biomass removed through keeving, which may be aided by the high pH. French and English ciders both have bitter and astringent properties that are associated with their high polyphenol concentrations. Producers who want to make a specific cider style should use apples that reflect that style and should be able to recreate those properties when growing the apples in North America (Table 4.8).

4.6 Summary and Conclusions

The results enumerated in this study will give cider producers and apple growers the necessary information to decide which apple cultivars they should plant to produce high-quality cider. Many cider producers choose to use traditional LARS classifications to guide their plantings and cider blends. The polyphenol concentrations were used to estimate percent tannins using a lab-developed standard curve to place the 28 cultivars on the LARS classification scale (Table 4.10, Figure 4.4), however the classification system may need to be updated to better reflect current research and understanding of juice composition. Further research should be undertaken to establish the composition of aromatics in the juices, particularly the effect of fermentation on those compounds. This research forms the basis on which further cider apple research in the region can be done. Once apple cultivars with good horticultural and juice production qualities in Ontario are planted, other aspects of orchard management can be studied for their effects on juice quality. The effects of these aspects of *terroir* on juice can help us to understand the origins of the physicochemical qualities of apple juice and better control those in the future for continued improvement in cider production.

The exploratory analyses show that differences in juice attributes exist among apple cultivars grown in Ontario based on the cultivar's origin and based on the cultivars themselves. In addition to continued evaluation at the Simcoe site, future experiment could compare the juice attributes of the same cultivars grown in different regions, particularly those with different climatic and biotic pressures.

4.7 Tables and Figures

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe

Cultivar	Titratable acidity (as mg malic acid 100 mL juice -1)[z]		Soluble solids (°Brix)		Juice pH		Juice yeast assimilable nitrogen (mg YAN L juice^{-1})		Corrected juice polyphenols (µg gallic acid equivalents mL juice-1)[y]	
Ashmead's Kernel	95	ef	18.3	a	3.45	hi	148	bcd	366	fgh
Binet Rouge	37	k	15.1	defgh	4.44	c	104	defg	915	ab
Bramley's Seedling	145	bc	12.7	jkl	3.00	n	73	fg	276	gh
Breakwell	158	b	11.4	lm	3.08	mn	69	fg	446	efgh
Brown Snout	58	ij	16.4	bcd	4.09	ef	170	ab	580	cdef
Brown's Apple	102	e	10.6	m	3.33	jk	116	cdef	781	bc
Bulmers Norman	36	k	11.7	kl	4.07	ef	152	bcd	738	bcd
Calville Blanc d'Hiver	132	cd	14.1	ghij	3.19	lm	91	fg	317	fgh
Cline Russet	60	hi	14.5	fgh	3.74	g	82	fg	230	h
Cox Orange Pippin	82	fg	15.7	cdef	3.49	hi	146	bcd	256	gh
Crimson Crisp	74	gh	13.7	hij	3.54	h	104	defg	271	gh
Dabinett	82	fg	14.9	efgh	3.50	hi	145	bcde	256	gh
Enterprise	102	e	14.2	ghi	3.41	ijk	118	cdef	246	h
Esopus Spitzenberg	97	ef	15.4	defg	3.38	ijk	113	cdef	250	gh
Frequin Rouge	32	k	16.0	bcde	4.61	b	148	bcd	515	defg
Golden Russet	85	fg	17.2	ab	3.48	hi	174	ab	380	fgh
GoldRush	92	ef	12.9	ijk	3.29	kl	82	fg	246	h
Grimes Golden	93	ef	13.8	hij	3.48	hi	81	fg	275	gh
Kingston Black	86	efg	14.0	ghij	3.49	hi	80	fg	437	efgh
Medaille d'Or	137	cd	15.3	defg	3.18	lm	60	g	557	def
Michelin	43	jk	13.0	ij	4.17	e	145	bcde	564	cdef
Muscadet De Dieppe	40	k	12.9	ijk	3.98	f	97	efg	693	bcde
Porter's Perfection	121	d	14.6	fgh	3.30	kl	104	defg	925	ab
Stoke Red	101	e	12.8	ijk	3.42	hij	78	fg	1042	a
Sweet Alford	31	k	15.7	cdef	4.76	a	82	fg	208	h
Tolman Sweet	34	k	14.6	efgh	4.45	c	155	bc	185	h
Tydeman Late	176	a	17.1	abc	3.18	lm	206	a	314	fgh
Yarlington Mill	40	k	14.1	ghij	4.30	d	83	fg	737	bcd
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Corrected juice polyphenols = uncorrected juice polyphenols - juice ascorbic acid interference

[x] Least Significant Difference calculated by averaging the differences of cultivar least square means with a tukey-Kramer adjustment for

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Titratable acidity (as mg malic acid 100 mL juice $^{-1}$)^{z}		Soluble solids (°Brix)		Juice pH		Juice yeast assimilable nitrogen (mg YAN L juice^{-1})		Corrected juice polyphenols (µg gallic acid equivalents mL juice^{-1})^{y}		Fruit firmness (kg)	
Ashmead's Kernel	108	cde	16.1	abc	3.31	ijkl	169	bcd	372	efghi	9.4	bcd
Binet Rouge	43	jk	13.8	def	4.41	ab	185	bc	880	ab	10.7	ab
Bramley's Seedling	191	a	11.9	ef	2.70	p	133	cdef	373	efghi	9.3	bcdef
Breakwell	190	a	12.8	def	2.88	o	103	def	436	efgh	7.4	ghij
Brown Snout	77	gh	17.6	a	4.01	ef	158	bcde	577	def	6.8	hij
Brown's Apple	114	cd	11.8	f	3.39	hijk	154	bcde	799	abcd	6.4	ij
Bulmers Norman	63	hi	13.3	def	4.15	de	256	a	923	a	8.3	defg
Calville Blanc d'Hiver	125	bc	12.9	def	3.21	lmn	104	def	258	ghi	6.7	hij
Cline Russet	86	fg	14.0	cde	3.53	gh	123	cdef	188	hi	8.5	cdefg
Cox Orange Pippin	110	cde	12.3	ef	3.08	mn	167	bcde	230	ghi	7.5	fghij
Crimson Crisp	86	fg	11.9	ef	3.40	hij	128	cdef	180	hi	8.7	cdefg
Dabinett	104	cdef	13.0	def	3.19	lmn	151	bcdef	188	hi	6.8	hij
Enterprise	102	def	13.9	cdef	3.54	gh	139	bcdef	225	ghi	7.8	fghij
Esopus Spitzenberg	116	cd	14.9	bcd	3.60	g	152	bcde	222	hi	9.3	bcdef
Frequin Rouge	53	ijk	16.4	ab	4.39	bc	149	bcdef	639	bcde	9.6	bc
Golden Russet	113	cd	16.4	ab	3.48	ghi	207	ab	315	fghi	11.7	a
GoldRush	123	bcd	13.8	def	3.42	hi	145	bcdef	189	hi	9.9	bc
Grimes Golden	91	efg	12.4	ef	3.44	ghi	82	f	277	ghi	8.1	defgh
Kingston Black	112	cde	14.1	cde	3.23	klm	110	def	493	efg	9.2	bcdef
Medaille d'Or	171	a	16.8	ab	3.03	no	120	cdef	875	abc	10.8	ab
Michelin	50	ijk	12.8	def	3.95	f	168	bcd	585	cde	7.8	efghi
Muscadet De Dieppe	46	ijk	14.0	cde	4.11	def	101	def	567	def	7.0	hij
Porter's Perfection	138	b	14.0	cdef	3.24	jklm	138	bcdef	865	abc	9.1	cdef
Stoke Red	120	bcd	13.6	def	3.39	hijk	148	bcdef	876	ab	7.5	fghij
Sweet Alford	35	k	13.0	def	4.57	a	98	ef	131	i	7.6	fghij
Tolman Sweet	49	ijk	13.5	def	4.26	bcd	134	cdef	228	ghi	10.0	bc
Tydeman Late	179	a	16.3	ab	3.12	mn	157	bcde	259	ghi	9.2	bcdef
Yarlington Mill	57	hij	16.7	ab	4.24	cd	132	cdef	640	bcde	6.3	j
P value	<0.0001		<0.0001		<0.0001		<0.0001		<0.0001		<0.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Corrected juice polyphenols = uncorrected juice polyphenols - juice ascorbic acid interference

Table 4.3. Historical titratable acidity of 28 apple cultivars grown for cider production compared with 2017-2018 data from this study. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Titratable acidity at Simcoe (as mg malic acid 100 mL juice $^{-1}$)	Historical TA	References[z]
Ashmead's Kernel	95-108	1.17 % malic; 10.40-10.78 g L^{-1} malic	5; 2
Binet Rouge	37-43	.15% malic	7
Bramley's Seedling	145-191	1.05-1.21% acid; 1.54% malic; 10.07 g L^{-1}	4; 5; 9
Breakwell	158-190	.64% malic; 7.82 g L^{-1}	7; 9
Brown Snout	58-77	.47 g malic acid 100 g^{-1} juice; 3.37 g L^{-1} malic; 1.05 g L^{-1} malic	13; 9; 2
Brown's Apple	102-114	.67% malic; 7.29 g L^{-1} malic; 8.0-12.5 g L^{-1} malic	4; 9; 6
Bulmers Norman	36-63	.24% malic; 2.16 g L^{-1} malic; 2.2-4.9 g L^{-1} malic	7; 9; 6
Calville Blanc d'Hiver	125-132	0.73 g malic acid 100 g^{-1} juice; .76 %-1.17 malic; 9.97 g L^{-1} malic	12; 5; 2
Cline Russet	60-86	New cultivar, no historical data available	
Cox Orange Pippin	82-110	.68-.76% acid; 0.90 % malic	4; 5
Crimson Crisp	74-86	8.85 g L^{-1} malic	2
Dabinett	82-104	.10-.16 g malic acid 100 g^{-1} juice; 2.55 g malic L^{-1}; 1.10-1.88 g L^{-1} malic	12; 9; 2
Enterprise	102	9.35 g L^{-1} malic	11
Esopus Spitzenberg	97-116	7.10 g L^{-1} malic	2
Frequin Rouge	32-53	2.62 g L^{-1} malic	9
Golden Russet	85-113	.46-.54 g malic acid 100 g^{-1} juice; 0.73% malic; 6.64 g malic L^{-1}	12; 5; 9
GoldRush	92-123	.61-.78 g malic acid 100 g^{-1} juice; 9.35 g L^{-1} malic	12; 11
Grimes Golden	91-93	6.6 g L^{-1} malic; 6.75 g L^{-1} malic	10; 9
Kingston Black	86-112	.67 g malic acid 100 g^{-1} juice; 6.45 g malic L^{-1}; 1.5-2.6 g L^{-1} malic	12; 9; 3
Medaille d'Or	137-171	.27% malic; 3.43 g L^{-1} malic; 2.1 g L^{-1} malic	7; 9; 1
Michelin	43-50	.24-.27 g malic acid 100 g^{-1} juice; 3.25 g malic L^{-1}; 2.5 g L^{-1} malic	12; 9; 3
Muscadet De Dieppe	40-46	2.72 g L^{-1} malic; 2.8 g L^{-1} malic	9; 6
Porter's Perfection	121-138	.70-.88 g malic acid 100 g^{-1} juice; 13 g L^{-1} malic; 8.2 g L^{-1} malic	12; 6; 3
Stoke Red	101-120	.64% malic; 6.13 g L^{-1} malic	7; 9
Sweet Alford	31-35	.22% malic; 1.86 g L^{-1} malic	7; 9
Tolman Sweet	34-49	No historical data found	
Tydeman Late	176-179	No historical data found	
Yarlington Mill	40-57	g L^{-1} malic; 1.3-4.5 g L malic	7; 10; 8; 2; 6

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Eisele & Drake, 2005; 6) Jolicoeur, 2013;7) Lea, 2015; 8) Gottschalk et al., 2017; 9) Miles et al., 2013; 10) Raboin, 2016; 11) Thompson-Witrick et al., 2014; 12) Valois et al., 2006

Table 4.4. Historical pH of 28 apple cultivars grown for cider production compared with 2017-2018 data from this study. University of Guelph, Simcoe, Ontario, 2018..

Cultivar	pH at Simcoe	Historical pH	References[z]
Ashmead's Kernel	3.31-3.45	3.55; 3.03-3.25	3; 1
Binet Rouge	4.41-4.44	No historical data found	
Bramley's Seedling	2.70-3.00	2.95-3.08; 3.37; 3.26	2; 3; 4
Breakwell	2.88-3.08	3.23	4
Brown Snout	4.01-4.09	3.95; 3.87; 3.78	7; 4; 1
Brown's Apple	3.33-3.39	3.28	4
Bulmers Norman	4.07-4.15	4.04	4
Calville Blanc d'Hiver	3.19-3.21	3.28; 3.64; 3.13	7; 3; 1
Cline Russet	3.53-3.74	New cultivar, no historical data available	
Cox Orange Pippin	3.08-3.49	3.30-3.48; 3.70	2; 3
Crimson Crisp	3.40-3.54	3.37	1
Dabinett	3.19-3.50	4.39; 4.37; 4.13-4.15	7; 4; 1
Enterprise	3.41-3.54	3.76	6
Esopus Spitzenberg	3.38-3.60	3.48	1
Frequin Rouge	4.39-4.61	4.19	4
Golden Russet	3.48	3.61-3.65; 3.79; 3.67	7; 3; 4
GoldRush	3.29-3.42	3.19-3.22; 3.49	7; 6
Grimes Golden	3.44-3.48	3.57; 3.42	5; 4
Kingston Black	3.23-3.49	3.47; 3.45	7; 4
Medaille d'Or	3.03-3.18	4.19	4
Michelin	3.95-4.17	4.04-4.08; 3.98	7; 4
Muscadet De Dieppe	3.98-4.11	4.12	4
Porter's Perfection	3.24-3.30	3.31-3.36	7
Stoke Red	3.39-3.42	3.67	4
Sweet Alford	4.57-4.76	4.43	4
Tolman Sweet	4.26-4.45	No historical data found	
Tydeman Late	3.12-3.18	No historical data found	
Yarlington Mill	4.24-4.30	4.49; 4.13; 3.78	5; 4; 1

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Bradshaw, 2016; 2) Copas, 2010; 3) Eisele & Drake, 2005; 4) Gottschalk et al., 2017; 5) Raboin, 2016; 6) Thompson-Witrick et al., 2014; 7) Valois et al., 2006

Table 4.5. Historical soluble solids concentrations of 28 apple cultivars grown for cider production compared with 2017-2018 data from this study. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Soluble Solids (°Brix) at Simcoe	Historical Soluble Solids	References[z]
Ashmead's Kernel	16.1-18.3	15.98° Brix; 17.6-18.0° Brix	5; 2
Binet Rouge	13.8-15.1	14.2° Brix	10
Bramley's Seedling	11.9-12.7	40-51 sg[y], 13.18° Brix; 11.1° Brix	4; 5; 8
Breakwell	11.4-12.8	10.9° Brix	8
Brown Snout	16.4-17.6	18.06° Brix; 15.4° Brix; 13.5° Brix; 18.2° Brix	12; 10; 8; 2
Brown's Apple	10.6-11.8	48 sg; 13.6° Brix; 10.8° Brix; 45-65 sg	4; 10; 8; 6
Bulmers Norman	11.7-13.3	13.6° Brix; 11.4° Brix; 14.6° Brix; 48-66 sg	10; 8; 7; 6
Calville Blanc d'Hiver	12.9-14.1	13.85° Brix; 14.70-14.96° Brix; 15.3° Brix	12; 5; 2
Cline Russet	14.0-14.5	New cultivar, no historical data available	
Cox Orange Pippin	12.3-15.7	50-75 sg; 15.32° Brix; 13.0° Brix	4; 5; 7
Crimson Crisp	11.9-13.7	14.4° Brix	2
Dabinett	13.0-14.9	13.22-13.83° Brix; 14.0° Brix; 15.1° Brix; 13.1-15.3° Brix	12; 8; 7; 2
Enterprise	13.9-14.2	13.0° Brix	11
Esopus Spitzenberg	14.9-15.4	14.9° Brix; 15.3° Brix	7; 2
Frequin Rouge	16.0-16.4	17.0° Brix; 11.7° Brix	10; 8
Golden Russet	16.4-17.2	15.14-18.05° Brix; 18.32° Brix; 16.9° Brix	12; 5; 8
GoldRush	12.9-13.8	11.52-14.30° Brix; 15.0	12; 11
Grimes Golden	12.4-13.8	14.0° Brix; 12.8° Brix	9; 8
Kingston Black	14.0-14.1	16.16° Brix; 13.4° Brix; 52-56 sg	12; 8; 3
Medaille d'Or	15.3-16.8	15.8° Brix; 58 sg	8; 1
Michelin	12.8-13.0	11.74° Brix, 14.9° Brix; 12.0; 50sg	12; 10; 3
Muscadet De Dieppe	12.9-14.0	14.7° Brix; 46-63 sg	8; 6
Porter's Perfection	14.0-14.6	13.87-14.97° Brix; 53-66 sg	12; 6
Stoke Red	12.8-13.6	12.3° Brix; 52 sg	8; 3
Sweet Alford	13.0-15.7	11.9° Brix	8
Tolman Sweet	13.5-14.6	15.0° Brix	7
Tydeman Late	16.3-17.1	No historical data found	
Yarlington Mill	14.1-16.7	15° Brix; 12.3° Brix; 12.2° Brix; 53-75 sg	9; 8; 2; 6

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Eisele & Drake, 2005; 6) Jolicoeur, 2013;7) Gottschalk et al., 2017; 8) Miles et al., 2013; 9) Raboin, 2016; 10) Rothwell, 2012; 11) Thompson-Witrick et al., 2014; 12) Valois et al., 2006

Table 4.6. Historical polyphenol and tannin concentrations of 28 apple cultivars grown for cider production compared with 2017-2018 data from this study. University of Guelph, Simcoe, Ontario, 2018.

Cultivar	Corrected juice polyphenols	Historical Polyphenols	References[z]
Ashmead's Kernel	366-372	.07-.075% tannin	2
Binet Rouge	880-915	0.21% tannin	6
Bramley's Seedling	276-373	.09-.14% tannin; .12% tannin	4; 7
Breakwell	436-446	.23% Tannin; .27% tannin	6; 7
Brown Snout	577-580	310 ± 58 GAE 100 g^{-1}; .19% tannin; .21% tannin	10; 7; 2
Brown's Apple	781-799	.14% tannin; .16% tannin; .58 g/L GAE	4; 7; 5
Bulmers Norman	738-923	.27% tannin; .22% tannin; 1.8 g/L GAE	6; 7; 5
Calville Blanc d'Hiver	258-317	210 ± 16 GAE 100 g^{-1}; .07% tannin	10; 2
Cline Russet	188-230	New cultivar, no historical data available	
Cox Orange Pippin	230-256	.04-.05% tannins	4
Crimson Crisp	180-271	.11% tannin	2
Dabinett	188-256	346 ± 42 GAE 100 g^{-1}, 297 ± 63 GAE 100 g^{-1}; .29% tannin; .109-.37% tannin	10; 7; 2
Enterprise	225-246	398 mg GAE L^{-1}	9
Esopus Spitzenberg	222-250	.035% tannin	2
Frequin Rouge	515-639	.38 % tannin	7
Golden Russet	315-380	236 ± 30 GAE 100 g^{-1}, 148 ± 17 GAE 100 g^{-1}; .13% tannin	10; 7
GoldRush	189-246	150 ± 31 GAE 100 g^{-1}, 324 ± 32 GAE 100 $^{-1}$; 359 mg GAE L^{-1}	10; 9
Grimes Golden	275-277	.12% tannin; .08% tannin	8
Kingston Black	437-493	308 ± 37 GAE 100 g^{-1}; .17% tannin; 1.9 g L^{-1} tannic acid	10; 7; 3
Medaille d'Or	557-875	.64% tannin; 1.05% tannin; 4.4 g L^{-1} tannic acid	6; 7; 1
Michelin	564-585	253 ± 35 GAE 100 g^{-1}, 641 ± 68 GAE 100 g^{-1}; .16% tannin; 2.3 g L^{-1} tannic acid	10; 7; 3
Muscadet De Dieppe	567-693	.19% tannin; 1.0 g L^{-1} gallic acid	7; 5
Porter's Perfection	865-925	246 ± 16 GAE 100 g^{-1}, 328 ± 12 GAE 100 g^{-1}	10
Stoke Red	876-1042	.31% tannin; .32% tannin	6; 7
Sweet Alford	131-208	0.15% tannin; .10% tannin	6; 7
Tolman Sweet	185-228	No historical data found	
Tydeman Late	259-314	No historical data found	
Yarlington Mill	640-737	.32% tannin; .20% tannin; .21% tannin; .35% tannin; 1.9 g L^{-1} GAE	6; 8; 7; 2; 5

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Boré & Fleckinger, 1997; 2) Bradshaw, 2016; 3) Copas, 2001; 4) Copas, 2010; 5) Jolicoeur, 2013; 6) Lea, 2015; 7) Gottschalk et al., 2017; 8) Raboin, 2016; 9) Thompson-Witrick et al., 2014; 10) Valois et al., 2006

Table 4.7. Historical YAN concentrations of 28 apple cultivars grown for cider production compared with

Cultivar	Juice formol (mg YAN L juice^{-1}) at Simcoe	Historical YAN concentrations	References[z]
Ashmead's Kernel	148-169	166.3-262.6 mg YAN L^{-1}	1
Binet Rouge	104-185	No historical data found	
Bramley's Seedling	73-133	No historical data found	
Breakwell	69-103	No historical data found	
Brown Snout	158-170	Historical YAN concentrations+A2:D34	2; 1
Brown's Apple	116-154	No historical data found	
Bulmers Norman	152-256	No historical data found	
Calville Blanc d'Hiver	91-104	45.2 ± 8.5 mg YAN L^{-1}; 86.31 g YAN L^{-1}	2; 1
Cline Russet	82-123	New cultivar, no historical data available	
Cox Orange Pippin	146-167	No historical data found	
Crimson Crisp	104-128	170 mg YAN L^{-1}	1
Dabinett	145-151	13.3 ± 1.9 mg YAN L, 45 ± 20 mg YAN L; 31.79-60.6 g YAN L^{-1}	2; 1
Enterprise	118-139	No historical data found	
Esopus Spitzenberg	113-152	113.4 mg YAN L^{-1}	1
Frequin Rouge	148-149	No historical data found	
Golden Russet	174-207	66 ± 11 mg YAN L^{-1}, 76.1 ± 9.5 mg YAN L^{-1}	2
GoldRush	82-145	13.8 ± 2.7 mg YAN L^{-1}, 36.3 ± 2.5 mg YAN L^{-1}	2
Grimes Golden	81-82	No historical data found	
Kingston Black	80-110	24.4 ± 5.6 mg YAN L^{-1}	2
Medaille d'Or	60-120	No historical data found	
Michelin	145-168	20.3 ± 1.9 mg YAN L^{-1}, 58.2 ± 9.0 mg YAN L^{-1}	2
Muscadet De Dieppe	97-101	No historical data found	
Porter's Perfection	104-138	50 ± 23 mg YAN L^{-1}, 110 ± 12 mg YAN L^{-1}	2
Stoke Red	78-148	No historical data found	
Sweet Alford	82-98	No historical data found	
Tolman Sweet	134-155	No historical data found	
Tydeman Late	157-206	No historical data found	
Yarlington Mill	83-132	8.88 mg YAN L^{-1}	1

[z] Historical values are reported in the same order as the source listing cited the following numbers: 1) Bradshaw, 2016; 2) Valois et al., 2006

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018.

Cultivar Origin	Soluble solids (°Brix)		Titratable acidity (as mg malic acid 100 mL juice $^{-1}$)^z		Juice pH		Juice formol (mg YAN L juice^{-1})		Corrected juice polyphenols (µg gallic acid equivalents mL juice^{-1})^y		Fruit firmness (kg)	
France	12.6	*ns*	74	b	3.91	ab	123	*ns*	771	a	8.7	ab
North America	12.4	*ns*	88	ab	3.59	b	126	*ns*	409	b	9.2	a
United Kingdom	12.4	*ns*	101	ab	3.56	b	136	*ns*	684	a	7.9	b
P value	0.7879		0.0006		<0.0001		0.1308		<0.0001		<0.0001	

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

^{y}Corrected juice polyphenols = uncorrected juice polyphenols - juice ascorbic acid interference

Table 4.9 Classification summary for the juice attributes of cider cultivars based on geographical origin. University of Guelph, Simcoe, Ontario, 2018.

From Origin	France	North America	United Kingdom	Total
France	30^z	10	7	47
	64^y	21	15	100
North America	3	58	2	63
	5	92	3	100
United Kingdom	32	16	79	127
	25	13	62	100
Total	65	84	88	237
	27	35	37	100
Priors	0.33333	0.33333	0.33333	

^{z} Number of observations classified into origin

^{y} Percent classified into origin

Table 4.10 Juice classifications of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

	TA		Polyphenols		
Cultivar	2017	2018	2017	2018	Classification
Ashmead's Kernel	95	108	366	372	Sharp
Binet Rouge	37	43	915	880	Bittersweet
Bramley's Seedling	145	191	276	373	Sharp
Breakwell	158	190	446	436	Sharp
Brown Snout	58	77	580	577	Sharp
Brown's Apple	102	114	781	799	Bittersharp
Bulmers Norman	36	63	738	923	Bittersharp
Calville Blanc d'Hiver	132	125	317	258	Sharp
Cline Russet	60	86	230	188	Sharp
Cox Orange Pippin	82	110	256	230	Sharp
Crimson Crisp®	74	86	271	180	Sharp
Dabinett	82	104	256	188	Sharp
Enterprise	102	102	246	225	Sharp
Esopus Spitzenberg	97	116	250	222	Sharp
Frequin Rouge	32	53	515	639	Sweet
Golden Russet	85	113	380	315	Sharp
GoldRush	92	123	246	189	Sharp
Grimes Golden	93	91	275	277	Sharp
Kingston Black	86	112	437	493	Sharp
Medaille d'Or	137	171	557	875	Bittersharp
Michelin	43	50	564	585	Sharp
Muscadet De Dieppe	40	46	693	567	Bittersweet
Porter's Perfection	121	138	925	865	Bittersharp
Stoke Red	101	120	1042	876	Bittersharp
Sweet Alford	31	35	208	131	Sweet
Tolman Sweet	34	49	185	228	Sweet
Tydeman Late	176	179	314	259	Sharp
Yarlington Mill	40	57	737	640	Bittersharp

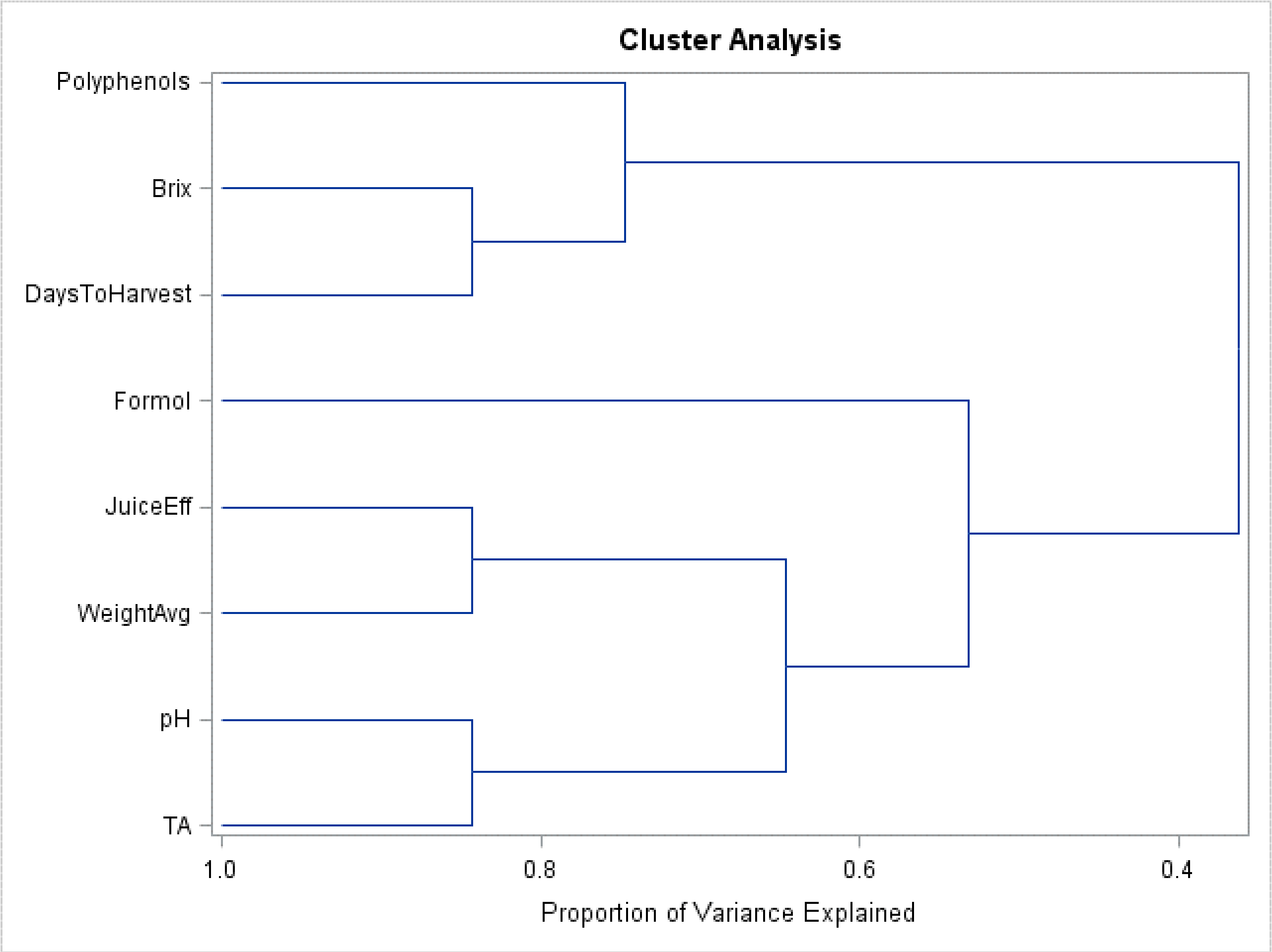

Figure 4.1 The association among juice attributes of fruits measured in 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

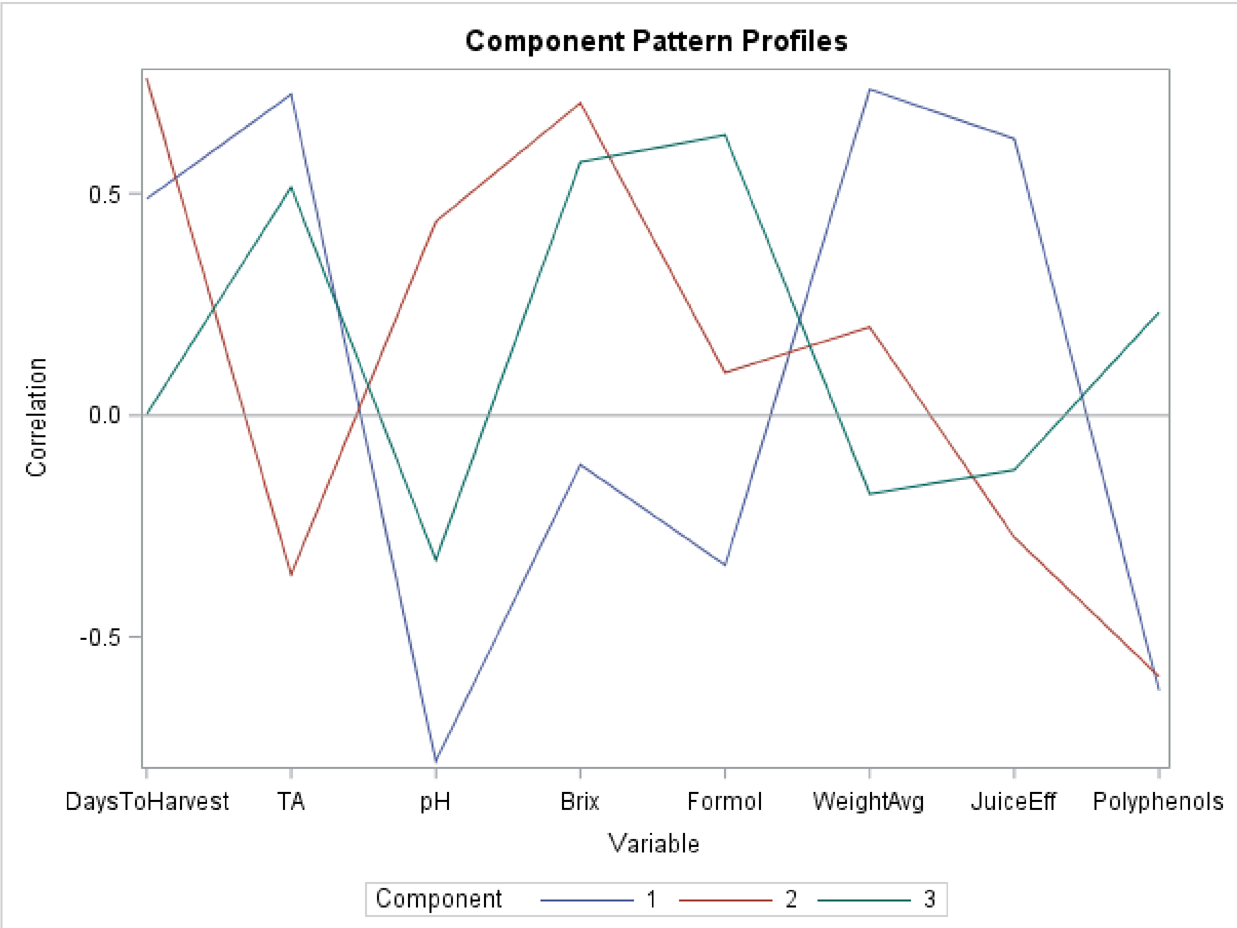

Figure 4.2 The correlation of juice attributes to principal components derived from the juice attribute data of 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

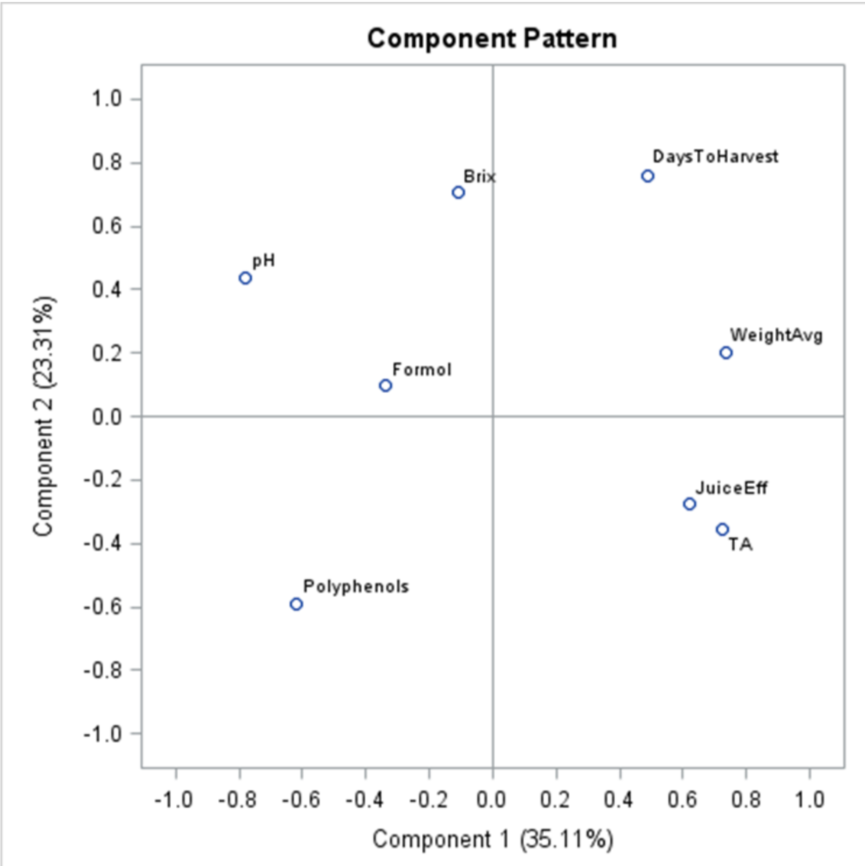

Figure 4.3 Plot of juice attributes based on the first two principal components derived from the juice attribute data of 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

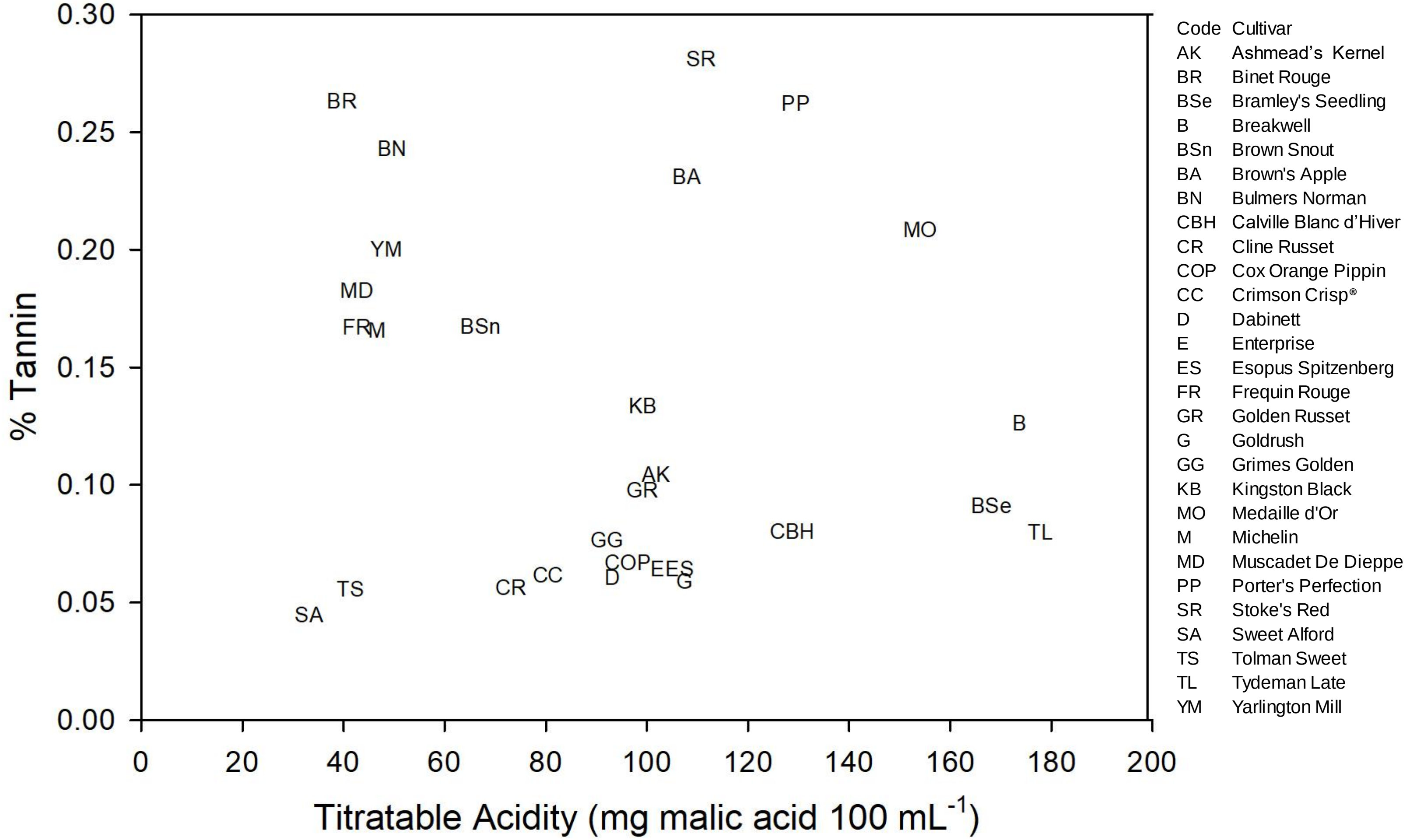

Figure 4.4 Plot of cultivars by titratable acidity and calculated tannin concentrations 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.

5 Changes in amino acid composition in apple (*Malus domestica Borkh.)* juice from fruit set to harvest, after cold-storage, and in response to summer foliar urea applications

5.1 Abstract

Insufficient biologically available nitrogen for yeast is a persistent issue facing cider makers, whose apple juice base usually does not provide adequate nutrition for a complete fermentation. Cider makers often choose to supplement their juice with additional yeast assimilable nitrogen (YAN) in the cellar to aid fermentation. The development of biologically available nitrogen in apple juice is not as well understood. In this study, juice samples from 'Crimson Crisp®' apples were taken at several sampling dates in the 2016, 2017, and 2018 growing seasons. The juice samples were then analyzed for YAN using formol titration and high-performance liquid chromatography. It was found that while the total YAN concentration in these apples drops from the period shortly after fruit set to the end of summer, it remains stable from several weeks before harvest until the date of harvest, nor does the total change after a 6-week post-harvest storage period. By contrast, the individual amino acid components of the YAN do change during this period. This information will allow producers to analyze their juice YAN concentration several weeks before harvest and better prepare for their needs in the cellar.

5.2 Introduction

One of the perennial obstacles for cider producers is N as a limited resource in apple juice. For a complete fermentation to take place with adequate speed and without producing off-flavours, the fermentation medium must have an adequate nitrogen supply that is biologically available to yeast (Bisson, 1999). This available N, which is known as YAN, consists of primary amino nitrogen (PAN) and ammonium. Proteins and small polypeptides, in addition to proline (Pro), are not easily assimilable by yeast and are thus not included in the YAN quantity (Navarre & Langlade, 2010). Proline uptake, specifically, is often inhibited by nitrogen catabolite repression by the yeast (Bell & Henschke, 2005). Suggestions for ideal YAN concentrations in apple juice range widely, with some suggesting similar concentrations to those found in grape juice. Neilsen et al. (2010) suggested 140 mg L^{-1} as sufficient for YAN in wine production, which has a higher initial sugar concentration than cider production and therefore should require a longer fermentation based on fermentation models (Kelkar & Dolan, 2012).

Amino acid components of YAN are alanine (Ala), arginine (Arg), asparagine (Asp), aspartic acid (Asp), cysteine (Cys), γ-aminobutyric acid (GABA), glutamine (Gln), glutamic acid (Glu), glycine (Gly), histidine (His), isoleucine (Ile), leucine (Leu), lysine (Lys), methionine (Met), phenylalanine (Phe), serine (Ser), threonine (Thr), tryptophan (Trp), tyrosine (Tyr), and valine (Val). Proline, a non-assimilable amino acid, is only present in apples in small quantities (Blanco Gomis et al., 1990)

Studies of apple juices made from culinary and cider fruit show variation in amino acid concentrations among cultivars. Some researchers found that the greatest fraction of amino acids was generally composed of Ala followed by Asn, Ser, Gln, and Thr (Wu et al., 2007), while others found that the major amino acids were Asn, Asp, Glu, and Ser (Burroughs, 1957).This variation among cultivars was also seen in past experiments in cider apples which tested the amino acid composition of the entire fruit, rather than just the juice(Blanco Gomis et al., 1990). The major amino acids in Collaos, Raxao, and Meana apples include Asn, Asp, with Collaos also having considerable concentrations of Gln, Glu, Ser, and Phe (Blanco Gomis et al., 1990). In addition Asn and Asp, Ma et al. (2018) found that many cultivars, like 'Northern Spy,' 'Winesap,' and 'Rome' had high concentrations of Phe.

Excess N fertilization can reduce firmness and colour while increasing storage disorders in apples (Neilsen & Neilsen, 2002). N from spring-applied fertilizer has been demonstrated to make up a greater percentage of fruit N than N from summer-applied fertilizer, with N accumulation increasing consistently in the fruit until about a month before harvest (Toselli et al., 2000). During fermentation the amino acids in the must are depleted due to consumption by yeast, but they are eventually returned to the must due to yeast autolysis (Blanco Gomis et al., 1990; Suárez Valles et al., 2005). Changes in amino acid composition continue to occur after primary fermentation and during the aging process of cider (Suárez Valles et al., 2005). The relationship between nutrient availability and the production of desirable aroma compounds is important for the selection of yeast strains (Carrau et al., 2008; B. C. Dukes & Butzke, 1998), but studies describing yeast-produced aromas don't usually consider N composition. Fewer differences are found among strains when initial N is high than when nutrient availability is an issue (Carrau et al., 2008).

YAN in apple juice is principally composed of amino acid N, with a small quantity of ammonium (Boudreau et al., 2018). The quantity and composition of YAN will change based on the apple cultivar and year-to-year variations (Blanco Gomis et al., 1990). Many cider makers choose to supplement their base juice with ammonium or a complex nitrogen source in order to ensure a complete fermentation without H_2S production. Other methods for manipulating YAN in the cidery include N extraction by keeving or the addition of N sources like wine lees (Nichols and Proulx, 2012). In order to measure YAN before additions, cider makers usually evaluate samples of non-fermented juice using enzymatic analyses or formol titration. Enzymatic analyses for YAN are done as an assay with a spectrophotometric reading. Formol titration is less expensive than enzymatic analyses, but it can be a more hazardous method because of the use of formaldehyde. The process involves neutralizing all acids in the juice, adding formaldehyde to convert simple nitrogenous compounds to acids, and then titrating the sample again. The most accurate method to determine YAN is the measurement of specific amino acids using high performance liquid chromatography (HPLC). For HPLC, juice samples are prepared with ortho-phthalaldehyde (OPA) derivatization of amino acids, which reacts with the amino functional group in the primary position of amino acids, which was suitable for the amino acid components of YAN (Blanco Gomis et al., 1990; Dukes & Butzke, 1998).

Previous work in Spain measured seasonal changes in amino nitrogen concentration in apples using whole fruit samples including seeds, skin, and mesocarp (Blanco Gomis et al., 1990). The amino acids extracted from the puréed fruit may differ from what cider makers access using standard juice extraction methods. Still, a significant seasonal variation in specific amino acids among different apple cultivars exist, with ‘Collaos,’ ‘Raxao,’ and ‘Meana’ apples all having different relative proportions of amino acids (Figure 2.2).

Many of the considerations for cider-making are identical to winemaking. The changes in amino acids in grapes throughout the growing season and in response to treatments have been well-documented, including the evaluation of YAN for the fermentation process. In grapes, there are common N development trends across many cultivars between véraison and harvest. In most grape cultivars, total N, amino acid N, and proline increase while ammonium steadily decreases, whereas Arg decreases after a quick increase (Bell & Henschke, 2005). It is believed that the change in Arg concentration in the grape juice is due its use as a transport molecule in the remobilization of the nitrogen to storage organs for future use. Other horticultural factors have been shown to change amino acid concentration, including cluster shading, elicitors, nitrogen fertilization, cultivar, and weather protection (Guan et al., 2017; Gutiérrez- Gamboa et al., 2018; Meng et al., 2018). Hannam et al. (2016) conducted a N-fertilization experiment based on grapes, which demonstrated that the application of foliar N was most effective for increasing YAN in grapes when the fruit has its greatest sink strength . After determining that a series of three foliar urea applications of 3.8 g N vine $^{-1}$ made the vine incorporate more amino acids and ammonium into the juice than the same series of urea application to the soil, the researchers applied foliar urea to grapes in three different treatments., Late-season applications of urea were the most effective at improving YAN in grape must. In the first year of the experiment, there was no treatment difference in fruit in Merlot, but in the following year there was a greater yield in the fertilized Merlot vines. In separate years, fertilization led to a decrease in TA in Pinot Gris fruit. In the fertilized vines, the juices produced has a lower proportion of proline, which is non-assimilable, therefore increasing the total YAN (Hannam et al., 2016). Past research has shown, however, that nitrogen application should only be made when factors indicate that the vineyard is lacking in N (Bell & Henschke, 2005). Nitrogen controls vine growth, but its misuse can affect the atmosphere and the groundwater (Hannam et al., 2016; Neilsen & Neilsen, 2002)

There are potential additive effects of nitrogen fertilization on YAN based on application methods (Hannam et al., 2016). Increasing N fertilization leads to higher N concentrations in the apples (Khemira et al., 1998), while in grapes, postharvest N supplementation doesn't affect fruit composition or YAN the following year, but can increase yield (Neilsen et al., 2010). N treatments in grapevines consistently affect YAN concentrations in grape juice every year, but the response varies with application rate and timing (Neilsen et al., 2010). Based on recommended YAN concentrations for wine, though, YAN only exceeds deficiency in grape juice when the vineyard receives applications of N fertilizer at a rate that exceeds twice the recommendation (Neilsen et al., 2010). This may prove true for apples as well.

Methods of N fertilization in apples include ground or foliar application (G. H. Neilsen & Neilsen, 2003). Plants respond to nutrient sprays differently based on both the nutrient and its form. Nitrogen is a common nutrient spray which is rapidly absorbed by leaves, though leaf phytotoxicity can occur at high concentrations. Other factors that affect the absorption and use of foliar nutrients include the addition of surfactants, wetting agents, the contact surface of the spray, and the position of stomate, which are on the bottom of apple leaves. Absorption takes time, and that is affected by temperature, humidity, and precipitation (Boynton, 1954). In other fruit trees, like peaches, application date has been demonstrated not to affect urea nitrogen absorption, but plays a role in allocation (Rosecrance et al., 1998).

In N isotope studies in apple trees, it was found that trees recovered 16% of applied labeled nitrogen from soil urea applications compared to 47% of that applied from foliar urea sprays (Hill-Cottingham & Lloyd-Jones, 1975). Within a growing season at the Long

Ashton Research Station in the UK, N applied to soil pre-bud break in March was found in the apples, whereas urea nitrogen applied to soil in August was not. Within a growing season, foliar-applied nitrogen from both June and August were found in apples (Hill-Cottingham & Lloyd-Jones, 1975). Khemira et al. (1998) looked at partitioning of nitrogen in apple trees from ground-applied ammonia and foliar urea sprays. Nitrogen applied to the ground as ammonia in the spring was allocated to the shoots and the fruit. Nitrogen that was applied early in the season was more likely to be partitioned into the fruit than nitrogen applied later in the season, such as the fall foliar applications. Spur-type apple trees seemed to recycle N more efficiently and retained more nitrogen than standard trees (Khemira et al., 1998).

In a N fertigation study in apples in British Columbia, Milllard and Neilsen (1989) reported that adequate N led to less translocation and that an increase in N fertilization increased leaf growth but did not affect root mass. Trees that received no N fertilization relied on N stored in the plant, which was first transported to leaves and then was relocated to the roots. Fertilized trees did not translocate their N. In the spring, N was remobilized from woody tissues to the leaves and then in the fall, N was withdrawn from the leaves and roots into woody tissues. Trees have a limited overall capacity for N uptake (Millard & Neilsen, 1989). This study was consistent with Neilsen et al. (2001), who also said that N supply must meet demand. Rather than fixed-rate applications, demand-controlled fertigation was a more efficient user of N. Applications of N later in the growing season were more efficiently used by the trees because N supplies late in the growing season were more likely to come from the soil, but early applications still resulted in greater N mobilization to the fruit (Neilsen et al., 2001).

Apple trees grown on M.9 rootstocks have low nitrogen requirements, but are also inefficient at using N. Fertigation has been shown to be better for trees than direct fertilization by ground or foliar spray because efficient delivery of nutrients like N is dependent on water management (Neilsen & Neilsen, 2002). Similar to the results of earlier work done in apples, Neilsen et al. (2010) reported that in grapes, N stores from past seasons are used early in the season and that N concentrations in fruit are higher when nitrogen is applied post-bloom because budbreak foliar urea application only increased N in vegetative tissue. Soil N applications may only be effective for some cultivar and rootstock combinations, but regardless of the crop, estimations for N percentage in the compost were usually higher than the measured percentage of N in the compost. Tree fruit production systems are not efficient at nitrogen recovery from fertilization and leaf nitrogen measurements may be inadequate measures of plant nitrogen status (Neilsen et al., 2010). Toselli et al. (2000) conducted a N partitioning experiment in apples by applying ammonium nitrate to trees either before harvest or at full bloom and found that N partitioning is affected by application time. Summer-applied N was stored in water and was eventually translocated to growing tissues in the spring, whereas spring-applied nitrogen went into the canopy (Toselli et al., 2000).

To better understand how YAN develops in apples and specifically in the juice, an experiment was conducted to evaluate how YAN changes during the growing season in addition to how the YAN composition changes in response to N fertilization.

The research objectives of this study were to develop a profile of the concentration of individual amino acids and total YAN in apples at different stages throughout the growing season and to understand the effect of orchard foliar N fertilization on the YAN concentration of apple juice/must.

The hypotheses tested in this experiment were:

1) apple trees fertilized with a foliar urea spray in a maintained orchard will produce fruit with a higher juice YAN concentration in the juice than unfertilized trees;

2) amino acid nitrogen concentration in juice will decrease as the fruit matures;

3) non-amino N concentration in juice will decrease as the fruit matures;

4) after harvest, amino acid nitrogen in juice will decrease and residual non-amino YAN concentration in juice will increase.

5.3 Materials and Methods

A mature orchard of ‘Crimson Crisp®’ apple trees on M.9 rootstock planted in a Super Spindle system at 1 m spacing in 2009 and 2012 was divided into 18 blocks of 10 trees at the Simcoe Research Station in Simcoe, ON. The map of the orchard can be seen in Appendix 2.

In 2016 beginning one week after petal fall, ‘Crimson Crisp®’ apple trees were treated with a 5.1 g N L^{-1} foliar urea spray. To conduct the foliar urea sprays, the materials used were a sprayer wand with a 14-gallon tank with a diaphragm pump (SHURflo, Minneapolis, MN) attached to a small vehicle, water, Regulaid (KALO, Overland Park, KS), pure urea pellets (46% N) (PotashCorp, Saskatoon, SK), a respirator, a Tyvek suit, nitrile gloves, and goggles. Treatments consisted of: (1) untreated, (2) three foliar urea sprays applied weekly after petal fall, and (3) six foliar urea sprays applied weekly after petal fall. The 5.1 g N L^{-1} solution was made by dissolving 600 g of urea pellets in water and filling up a clean tank to 50 L with the addition of 0.1% v/v Regulaid and applied to drip, which amounted to 0.5 L of solution per tree. Sprays were conducted on June 10, June 17, and June 29 for treatments 2 and 3, while treatment 3 also received sprays on July 6, July 15, and July 26. Apple fruits were sampled after the third spray, and every three weeks thereafter until harvest. Sampling consisted of taking 1 apple randomly from each of the ten trees, for a total of ten apples per sampling date. In 2016 these apples were labeled and stored in plastic zipper-top bags at -20° C until they were processed. Sampling dates that underwent subsequent analyses were August 30, September 14, and October 4. Before processing, fruit were thawed at 4° C in a cooler for 12-18 hr until they could be pressed. Ten thawed apples were wrapped in cheesecloth (Grade #50, Fisher Scientific, Whitby, ON), and placed on a custom-made steel rack (Allingham Machining Inc., Stoney Creek, ON). Another stainless-steel rack was placed on top and the fruit was pressed with a PowerFist hydraulic press (Princess Auto, Hamilton, ON). The juice from each sample was collected, mixed, and place into a 50 mL centrifuge tube and stored at -80° C. In 2017 the same treatment regime for spraying and sampling was followed. Sprays were conducted on June 8, June 14, and June 21 for treatments 2 and

3, while treatment 3 also received sprays on July 6, July 14, and July 20. Sampling dates were July 5, July 25, August 16, September 5, September 25, and October 3. Instead of storing fruit in the freezer, apples were pressed within a day of harvesting, except for the final harvest, which was left for 6 weeks at 4°C to look at the effect of storage. The freshly sampled apples were sectioned to fit into the feed tube of a commercial juicer (Model 8006, Omega, Harrisburg, PA), which ground the apples using the grinding attachment. The pomace was then wrapped in cheesecloth before being pressed using the hydraulic press. The juice from each sample was collected, mixed, and placed into a 50 mL centrifuge tube and stored at -80° C.

In late fall 2017, samples were thawed in batches in a water bath to 15 °C. Five mL samples were analyzed using an autotitrator (G20 Compact Titrator, Mettler Toledo, Mississauga, ON) set to a pH endpoint of 7. An equivalent amount of .1 M NaOH was added to 5 mL of thawed juice, mixed, and stored in 15 mL centrifuge tubes at -80° C until analyzed by HPLC.

In 2018, the apple tree fertilization proceeded as it did in 2017. Sprays were conducted on June 11, June 19, and June 26 for treatments 2 and 3, while treatment 3 treatment also received sprays on July 3, July 10, and July 17. Due to a lack of fruit on the trees, samples were only taken at maturity on October 1, with 10 fruit per block being pressed immediately and 10 fruit being left for 8 weeks at 4° C. The juice samples pressed in 2018 underwent HPLC analysis the same week they were pressed. In addition to HPLC analyses the juice was evaluated for sugar concentration using a refractometer (Pocket 7105 PALBXIAcid5, Atago, Tokyo, Japan), titratable acidity using an autotitrator, formol number using a formol titrator (frozen samples from 2016 and 2017 were also analyzed at this time using the formol titrator) (HI84533, Hanna Instruments, Laval, QC), and polyphenols using the Folin-Ciocalteu microplate analysis with a microplate reader (Epoch 2, BioTek, Winooski, VT).

In January-March 2018 and November-December 2018, samples were analyzed by HPLC using the methods for amino acid detection using the Agilent Zorbax Eclipse

AAA column (Henderson et al., 2000). Sodium phosphate monobasic buffer was mixed for mobile phase A while methanol/acetonitrile buffer was mixed and filtered using a vacuum flask for mobile phase B. The Agilent 1100 Series HPLC instrument (Agilent Technologies, Waldbronn, Germany) and ChemStation software (Agilent Technologies, Waldbronn, Germany) was programmed with the Agilent amino acid analysis protocol using reverse-phase chromatography and o-phthalaldehyde (OPA) derivatization. Titrated juice samples were thawed in cool water and vortexed for proper mixing. In a 1 mL Eppendorf tube 250 µL of sample was mixed with 250 µL of sodium phosphate monobasic buffer and centrifuged. The supernatant was then passed through a sterile syringe (Fisher Scientific Company, Whitby, ON) with a filter tip (Mandel Scientific, Guelph, ON). A 50 µL aliquot of the filtered solution was then loaded into a vial insert and placed into a vial. The protocol allowed for the HPLC instrument to run 12 sample vials each day in duplicate. The samples were passed through a Zorbax Eclipse AAA column (Agilent Technologies, Waldbronn, Germany) and then detected using a diode array detector at 262 nm. A standard sample of the amino acids (Agilent Technologies, Waldbronn, Germany) was run after every 5 samples to confirm calibration. The chromatograms produced were analyzed for consistency within 10% for the calibration samples, with repeats being run if necessary. For analysis, the area under the peaks on the chromatograms were integrated using ChemStation and compared with the standards to calculate amino acid concentrations in the samples. Only mature juice samples were analyzed from the 2016 harvest, while all samples from the 2017 harvest were analyzed. HPLC was used to measure Ala, Arg, Asp, Asp, Cys, GABA, Gln, Glu, Gly, His, Ile, Leu, Lys, Met, Phe, Ser, Thr, Trp, Tyr, and Val. Proline was not analyzed because it is not assimilable by yeast.

Data were analyzed using the GLIMMIX procedure in SAS 9.4 (The SAS Institute, Cary, NC). Significance was evaluated at a p value of 0.05 and residuals were analyzed for normality and outliers. Post-hoc means separation was analyzed using Tukey-Kramer grouping for least square means (α=0.05). The factors analyzed were sampling date, which included a storage period post-maturity in 2017 and 2018, foliar urea spray treatment, and the interaction between sampling date and treatment. Additional statistical data can be found in Appendix 1.

5.4 Results

The results describe the changes in amino acid concentrations in response to foliar urea fertilization treatments, sampling date, and their interaction.

5.4.1 Primary amino nitrogen

Juice total PAN was consistently affected by the number of foliar urea sprays in the 6-spray treatment each year of the study (Table 5.1, Figure 5.1). There was a significant interaction (p=*0.009*) interaction between the number of sprays and the sampling date; trees that received six sprays produced apples that consistently had higher PAN concentrations than those that received 0 or 3 sprays, 33-40% higher in each year from 2016-2018. PAN concentration decreased as the season progressed in 2017, starting at 186 mg N L^{-1} on July 5, 2017, and dropping to 63 mg N L^{-1} at maturity on September 25. Storage did not have a significant effect on total PAN concentration in 2017 or 2018. While the data between years could not be directly compared, there was considerable variation in PAN concentrations between years, with PAN at fruit maturity ranging from 104-155 mg N L^{-1} in 2016, 51-85 mg N L^{-1} in 2017, and 48-66 mg N L^{-1} in 2018.

5.4.2 Aspartic acid

There was a significant foliar urea spray treatment effect on juice aspartic acid concentrations in 2016 (p=*0.001*), but not in 2018, with Asp concentrations 27% higher in the apple juice from the trees that had received six sprays over those that received zero or three sprays (Table 5.2). There was a significant (p=*0.0134*) interaction between the number of sprays and the sampling date in 2017. Generally, trees that received six sprays produced apples that had juice Asp concentrations that were 12-40% higher than those that received zero or three sprays. Asp concentration increased as the season progressed in 2017, ranging from 627 µmol L^{-1} on July 5 to 1903 µmol L^{-1} at maturity and

2265 µmol L^{-1} after storage (Figure 5.3). In 2018, no measured factors had a significant effect on Asp concentration, with Asp ranging from 1253 µmol L^{-1} to 1677 µmol L^{-1} after storage, however the interaction of the spray treatments and storage were not significant.

5.4.3 Asparagine

The asparagine concentration in the juice was significantly affected by the number of foliar urea sprays applied to the block in 2016 (p=*0.0015*) and 2018 (p=*0.0001*) (Table 5.3), with Asn concentrations 54% and 78% higher, respectively by year, in the apple juice from the trees that had received six sprays than in those that had received zero or three sprays,. The interaction between the sampling date and the spray treatment in 2017 was significant (p=*0.0134*), with Asn concentration decreasing as the season progressed from 10656 µmol L^{-1} on July 5 to 1812 µmol L^{-}1 at maturity while staying elevated in the samples that received the 6-spray treatment (Figure 5.3). Storage did not affect the Asn concentration in 2017 or 2018 (Table 5.3).

5.4.4 Serine

The serine concentration in the juice was affected by the number of foliar urea sprays applied to the block in 2017 (p<*.0001*) and 2018 (p=*0.0005*), with Ser concentrations being 87% and 33% higher, respectively by year, in the samples that received six urea sprays than in those that received zero or three sprays, but the treatment was not significant in 2016 (Table 5.4). In 2017 the sampling date was significant (p<*0.0001*), with Ser first decreasing and then increasing towards harvest (Figure 5.3). The sampling date and the spray treatment did not have a significant interaction for Ser, nor did storage in 2017. In 2018 the Ser concentration decreased significantly (p<*0.0001*) by 27% after storage.

5.4.5 Glutamine

The concentration of glutamine was significantly affected by the foliar urea spray treatments in 2016 (p=*0.0429*), 2017 (p<*0.0001*), and 2018 (p=*0.0049*) with Gln concentrations being 15%, 19%, and 28% higher, respectively by year, in the six-spray treatment than in those that received zero or three sprays (Table 5.5). In 2017 there was a significant ($p<$*0.0001*) interaction between sampling date and spray treatments, with Gln being highest early in the season, 508 µmol L^{-1} on July 5, and decreasing towards maturation and after storage to 142 µmol L^{-1} (Figure 5.4). In 2018 storage resulted in a significant ($p<$*0.*0001) change, with Gln concentration decreasing by 69% from 138 µmol L^{-1} to 43 µmol L^{-1} after storage.

5.4.6 Alanine

The concentration of alanine was significantly affected by the foliar urea spray treatments in 2016 ($p=$*0.017*), and 2017 ($p=$*0.0005*), with Ala concentration being 16% and 24% higher, respectively by year, in the samples that had received the six-spray treatment than in those that received zero or three sprays (Table 5.6). The interaction between sampling date and spray treatment was significant ($p=$*0.0314*) in 2017, with Ala concentration fluctuating in the growing season and peaking at maturity at 168 but decreasing by 69% after storage (Figure 5.4). In 2018 storage resulted in a significant increase in Ala concentration ($p=$*0.0014*), rising 31% from 29 µmol L^{-1} to 38 µmol L^{-1}.

5.4.7 Valine

The concentration of valine was significantly affected by the foliar urea spray treatments in 2018 ($p=$*0.0006*), with Val concentration being 47 % higher in the samples that had received the six-spray treatment than in those that had received zero or three sprays, however it was not significant in 2016 or 2017 (Table 5.7). The sampling date factor was significant in 2017 ($p<$*0.0001*), with Val rising from 0 at the earliest sample date to peaking at 37 µmol L^{-1} in August and decreasing to 23 µmol L^{-1} at maturity. In both 2017 and 2018 ($p=$*0.0019*) the Val concentration decreased 43% and 29%, respectively by year, after storage (Figure 5.5). The interaction between sampling date and treatment was not significant.

5.4.8 Methionine

The methionine concentration in the samples was significantly affected by the foliar urea spray treatment in 2016 ($p=0.0071$) with Met concentrations 28% higher in the samples that received six sprays than in those that received zero or three sprays, but it was not significant in 2018 (Table 5.8). The interaction between spray treatment and sampling date was significant in 2017 ($p=0.003$), with Met concentrations decreasing as the season progressed, from 68 µmol L^{-1} on July 5 to 3 µmol L^{-1} on September 5, but then increasing to 35 µmol L^{-1} before harvest and 44 µmol L^{-1} after storage (Figure 5.5). In 2018 the Met concentration significantly ($p<0.0001$) increased by 54% from 24 µmol L^{-1} to 37 µmol L^{-1} after storage.

5.4.9 Glutamic acid

The glutamic acid concentration in the samples was significantly affected by the foliar urea spray treatment in 2016 ($p=0.0182$), with the Glu concentration being 21% higher in the samples that had received the six-spray treatment than in those that had received zero or three sprays (Table 5.9). The interaction between spray treatment and sampling date was significant in 2017 ($p=0.0005$), with Glu concentration decreasing as the season progressed from 701 µmol L^{-1}on July 5 to 247 µmol L^{-1} at maturity, but rising to 282 µmol L^{-1} after storage (Figure 5.3). During the 2017 season, Glu concentration was normally highest in those samples that received six urea sprays. In 2018 there was a significant($p=0.0003$) 17% decrease in Glu concentration in the samples after storage.

5.4.10 Histidine

Histidine was not detected in 2016 or 2018. In 2017 it was present at 89 µmol L^{-1} at the earliest sampling date but decreased significantly ($p<0.0001$) and was effectively 0 for the rest of the season (Table 5.10, Figure 5.4).

5.4.11 Arginine

Arginine was not detected in 2016 or 2018. In 2017 it was present at 51 µmol L^{-1} the earliest sampling date but decreased significantly (p<*0.0001*) and was effectively 0 for the rest of the season (Table 5.11, Figure 5.4).

5.4.12 Glycine

The glycine concentration in the samples was significantly affected by the foliar urea spray treatment in 2016 (p=*0.0024*) and 2017 (p<*0.0001*), with Gly concentrations 35% and 25% highest, respectively by year, in the samples that received the six-spray treatment than those that received zero or three sprays, but the treatment was not significant in 2018 (Table 5.12). The sampling date was significant in 2017 (p<*0.0001*), with Gly decreasing as the season progressed from 75 µmol L^{-1} to 55 µmol L^{-1} at storage and then to 40 µmol L^{-1} after storage (Figure 5.4). In 2018 there was a significant (p=*0.014*) 35% decrease in Gly concentration after storage as well. There was no significant interaction between sampling date and treatment.

5.4.13 Cysteine

The cysteine concentration in the samples was significantly affected by the foliar urea spray treatment in 2016 (p=*0.0025*), 2017 (p=*0.0043*), and 2018 (p=*0.0016*) with Cys concentrations 17%, 21%, and 24%, respectively by year, higher in the samples that received the six-spray treatment in 2016 than those that received zero or three sprays. The foliar urea spray treatment was not significant in 2018 (Table 5.13). The sampling date was significant (p<*0.0001*) in 2017, with the Cys concentration decreasing as the season progressed, from 33 µmol L^{-1} on July 5 to 14 µmol L^{-1} at maturity but increasing to µmol L^{-1} after storage (Figure 5.5). In 2018 there was a significant (p=*0.0002*) 23% decrease in Cys concentration after storage. The interaction between treatment and sampling date was not significant om 2017 or 2018.

5.4.14 GABA

The γ-aminobutyric acid concentration in the samples was significantly affected by the foliar urea spray treatment in 2017 (p=*0.005*) with GABA concentration being 43% higher, in the samples that had received six sprays than those that received zero or three sprays (Table 5.14). The foliar urea spray treatment was not significant in 2016 or 2018. In 2017 the sampling date was significant (p<*0.0001*), with GABA increasing from 6 µmol L^{-1} on July 5 to 33 µmol L^{-1} on August 16 and then fluctuating, with storage having no effect (Figure 5.5). In 2018 storage decreased the GABA concentration by 38%, a significant (p<*0.0001*) amount. The interaction between the sampling date and the spray treatment was not significant in 2017 or 2018.

5.4.15 Total YAN concentration by formol number

The total YAN concentration as determined by formol titration was significantly affected by the foliar urea spray treatment in 2016 (p<*0.0001)* and 2018 (p=*0.0007*), with YAN concentration being 38% and 29% higher, respectively by year, in those samples that had received the six-spray treatment than those that had received zero or three sprays (Table 5.15). In 2016 there was no significant difference between samples taken at the end of August and the mature harvest in October, nor was there a significant interaction between the spray treatment and the sampling date in 2016. In 2017, there was a significant (p=*0.0395*) interaction between spray treatment and sampling date, with a general decrease in YAN concentration as the season progressed from 242 mg N L^{-1} on July 5 to 85 mg N L^{-1} at maturity on September 25. On each date, the six-spray treatment samples had the highest YAN concentration. The YAN concentration stabilized early in September through harvest and storage. There was a significant (p<*0.0001*) 25% decrease in YAN concentration after storage in 2018.

1.4.2.16 Estimated residual YAN

Estimated residual YAN, comprised primarily of ammonium, was calculated by subtracting PAN (Table 5.1), which was calculated form the sum of the individual amino acids (Table 5.16), from total YAN (Table 5.15). In 2016 and 2017 there was no significant effect of spray number on residual YAN, but in 2018 the residual YAN was significantly ($p=0.0056$) higher in the samples that received the six-spray treatment (Table 5.17). In 2017 the residual YAN decreased significantly ($p<0.0001$) as the season progressed, from 57 µmol L^{-1} to 19 µmol L^{-1}, but was stable during storage. In 2018 there was a significant ($p<0.0001$) 39% decrease in residual YAN after storage. There was no significant interaction between the sampling date and the spray treatments.

1.4.2.17 Juice attributes

The juice attributes in the sample were affected by the foliar urea spray treatment and storage (Table 5.18). The titratable acidity was significantly affected by the interaction between the number of sprays and the storage ($p=0.0206$), with the highest TA being found in those samples that received 6 sprays and decreasing after storage. Sugar concentration increased slightly, but significantly ($p=0.0079$) after storage, but was unaffected by the number of sprays or the interaction between factors. Polyphenol concentration decreased significantly ($p=0.0001$) after storage, but was unaffected by the number of sprays or the interaction between factors. The pH of the samples was not significantly affected by the number of sprays the sample received, but it significantly ($p<0.0001$) increased after storage and the interaction between the spray treatments and the storage treatment was significant ($p=0.0449$). The number of sprays significantly ($p=0.0158$) affected fruit weight, with the trees receiving six sprays producing the smallest fruit. Storage significantly($p=0.0366$) reduced the fruit weight, but there was not an interaction between the spray and storage treatments. The juicing efficiency of the fruit was significantly affected by the interaction between spray treatment and storage ($p<0.0001$), with efficiency decreasing after storage in all cases, but decreasing most in the 0-spray and 3-spray treatments.

5.5 Discussion

These experiments demonstrated that without late-season N additions, total YAN in ‘Crimson Crisp®’ juice does not change in the last few weeks before harvest, nor does it change after a short period of storage, such as one that a cider maker may utilize. This is consistent with the results from Toselli et al. (2000), where N accumulation increased consistently until about a month before harvest in the fruit without late-season nitrogen additions in ‘Mutsu’ apples. On the contrary, total fruit amino N concentrations fluctuated in the final month leading to harvest in ‘Meana,’ ‘Raxao,’ and ‘Collaos’ apples, which may be due to changes in the flesh, seeds, or skin rather than the juice. The composition of YAN in extracted juice, however, changes after storage and in response to treatment with foliar urea sprays.

The first research objective of this study was to develop a profile of the concentration of individual amino acids and total YAN in apples at different stages throughout the growing season. Based on data from the 2017 study, summarized in Figure 5.1 and specifically in Figures 5.3, 5.4, 5.5, 5.6, 5.7, and 5.8, the main changes are that total amino acids decrease over the course of the growing season. This change in amino acid concentrations in the growing season in ‘Crimson Crisp®’ comes primarily from the loss of Asn while the relative concentration of Asp increases (Figure 5.2). This pattern is the same regardless of treatment, though the both residual Asn and additional Asp are the highest in the six-spray treatment. (Figures 5.7, 5.8). This change appears to depend on the cultivar, as Asp has been shown to decrease in ‘Meana’ and fluctuate in ‘Raxao’ and ‘Collaos’ apples as the fruit approaches maturity (Blanco Gomis et al., 1990). Similarly, the overall profile of amino acids at maturity is different among dessert cultivars (Wu et al., 2007). The Wu study did not differentiate between Asn and Asp or Glu and Gln, but in the results found here and in other literature, the three highest proportions of the amino acid fraction belonged to Asp/Asn, Glu/Gln, and Ser in every cultivar (Blanco Gomis et al., 1990; Burroughs, 1957; Wu et al., 2007). In the Simcoe experiment, the proportion of Asn and Asp as parts of the total varied significantly based on year and by treatment, with the 6-spray treatment being associated with a higher proportion of Asn and a lower proportion of Asp and other amino acids relative to the 0- and 3-spray treatments, which were the same (Table 5.19). Both Asn and Gln are used as transport molecules for N in plant vascular tissue, which could explain their high concentrations early in the growing season as the apples are expanding (Taiz & Zeiger, 1991). Both sulfur-containing amino acids, Cys and Met, decrease for the first part of the season and then increase before harvest and maturity. These amino acid concentrations were not reported in Blanco Gomis et.al.(1990) and were observed in low concentrations at maturity in Wu et al. (2007) and Burroughs (1957). If the concentration of Met continues to increase as fruit ripens in other cultivars, then H_2S production should be reduced during fermentation due to a reduced need for Met production by the yeast (Jiranek et al., 1995). Similarly, it means that harvesting immature or underripe apples could lead to higher H_2S production if other cultivars have similar amino acid development patterns.

The second research objective of this study was to observe the effect of orchard foliar N fertilization on the YAN concentration of apple juice/must. Only the highest spray treatment of 6 foliar urea sprays consistently had an effect on the YAN composition, primarily by increasing the relative concentration of Asn, which is a common amino acid for transport in the vascular tissue of plants along with glutamine (Pate, 1980). Within plant cells, urea is degraded into ammonia and carbon dioxide by urease, which is the only method of urea N assimilation into plants (Polacco & Holland, 1993).

The first hypothesis tested in this study was that, like the grapes studied by Hannam (2016), apple trees fertilized with a foliar urea spray will produce fruit with a higher total YAN concentration in the juice than those that did not receive foliar urea sprays. While this was observed at nearly every sampling date, it was only found for the treatment groups that received six sprays of urea, which was four times as much N as recommended by local agricultural authorities for correcting N deficiency (OMAFRA, 2016). The treatment groups that received three foliar urea sprays, also with a concentration higher than recommended for correcting tree N deficiency, usually did not produce juice with individual amino acid concentrations significantly different from those that received no foliar urea sprays, which is consistent with research by Khemira et al. (1998) that showed low percentage of N derived from foliar spray in plant tissue. Additionally, Khemira et al. observed that N responses are less pronounced in orchards with high amounts of reserved N from years of fertilization management, which may also explain why only the largest fertilization dosage produced a measurable effect. These results indicate that orchard manipulation of YAN is possible as a concept, but is not practical using the same methods used in this study.

The second hypothesis tested in this study was that amino acid N concentration in juice will decrease as the fruit matures. This prediction was supported by the data, where total PAN concentration decreased as the season progressed (Figure 5.1), regardless of treatment. Amino acid content per fruit may have stayed stable, though, as the increased size of the fruit may have diluted the amino acids that were present. This could be tested in a future experiment by sorting fruit from the same tree by size and comparing the concentrations of amino acids in the juice of the differently sized fruit.

The third hypothesis tested in this study was that ammonium concentration in juice decreases over the growing season. This prediction was supported in this study, where it was observed that the non-amino N decreased as the growing season progressed and after storage. Here it is assumed that the estimated residual YAN calculated in this study was primarily composed of ammonium, as seen in other studies (Boudreau et al., 2018; Ma et al., 2018).

The fourth hypothesis tested in this study was that after harvest, amino acid N in juice decreases and residual YAN concentration increases. The data from this experiment did not support either part of the hypothesis. Rather, total PAN did not change significantly after storage in either 2017 or 2018. In 2017, residual YAN did not change after storage, while decreasing significantly ($p<0.0001$) after storage in 2018. Similar work where stored apples were tested for PAN concentrations showed inconsistent results among cultivars, with some cultivars, like ‘Dabinett’ decreasing in PAN concentration after storage in one year and increasing the following year (Ewing et al., 2019). These inconsistencies could be related to the PAN composition on an amino acid level, as our research showed stability in some amino acids after storage, like Ser, and changes in others, like Asp.

5.6 Summary and Conclusions

By analyzing the composition of YAN in apple juice both during the growing season and after a post-harvest storage period, we were able to better understand how nitrogenous compounds in apple juice change within the fruit. Unlike winemakers monitoring the changes in N concentration in grape juice as harvest approaches, cider makers may be able to sample fruit juice well before harvest and plan accordingly without having to worry about late-season changes in total YAN or the accumulation of non-assimilable proline. This would allow cider makers time to choose if they would like to manipulate the nitrogen concentration of the juice and if they would like to use a complex nitrogen source or DAP. The patterns of changes in amino acids in the growing seasons of other apple cultivars would be needed to test the range of application.

Future research pertaining to the effects of fertilization in apple orchards on apple juice N should look at the timing of fertilizer application, the concentrations of N used, and the formulations and application methods of N fertilizer. Research pertaining to YAN in apple juice should investigate the variation in amino acid composition among different apple cultivars, particularly if the effects of storage are consistent across amino acids, and the effects of different maceration and extraction times and techniques, which could also contribute to the composition of YAN in the juice of mature fruit.

5.7 Tables and Figures

Table 5.1. Primary amino nitrogen concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Primary amino nitrogen (mg N L^{-1})[z]		Sampling Date	Primary amino nitrogen (mg N L^{-1})		Sampling Date	Primary amino nitrogen (mg N L^{-1})	
Main Effects									
Number of Sprays									
0		104	b		83	b		42	b
3		119	b		91	b		51	b
6		155	a		116	a		64	a
P Value		0.0003			<.0001			0.0013	
Harvest Date									
				5-Jul	186	a			
				25-Jul	116	b			
				16-Aug	84	c			
				5-Sep	66	d			
	4-Oct	126		25-Sep	63	d	1-Oct	54	
				3-Oct[y]	66	d	1-Oct[x]	50	
P Value		.			<.0001			0.1124	
Simple Effects									
0 Sprays				7/5/2017	181	ab			
3 Sprays					178	ab			
6 Sprays					198	a			
0 Sprays				7/25/2017	78	ef			
3 Sprays					122	cd			
6 Sprays					148	bc			
0 Sprays				8/16/2017	67	f			
3 Sprays					79	ef			
6 Sprays					106	de			
0 Sprays				9/5/2017	64	f			
3 Sprays					57	f			
6 Sprays					76	ef			
0 Sprays	4-Oct	104		9/25/2017	51	f	1-Oct	48	
3 Sprays		119			54	f		49	
6 Sprays		155			85	ef		66	
0 Sprays				10/3/2017[y]	57	f	1-Oct[x]	36	
3 Sprays					56	f		52	
6 Sprays					84	ef		62	
P Value		.			0.009			0.0654	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.2. Aspartic acid concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018	
Treatment	Sampling Date	Aspartic acid (μmol L^{-1})[z]		Sampling Date	Aspartic acid (μmol L^{-1})		Sampling Date	Aspartic acid (μmol L^{-1})
Main Effects								
Number of Sprays								
0		2361	b		1083	b		1312
3		2769	b		1056	b		1587
6		3264	a		1316	a		1531
P Value		0.001			<.0001			0.0508
Harvest Date								
				5-Jul	627	d		
				25-Jul	619	d		
				16-Aug	628	d		
				5-Sep	869	c		
	4-Oct	2798		25-Sep	1903	b	1-Oct	1449.98
				3-Oct[y]	2265	a	1-Oct[x]	1503.51
P Value					<.0001			0.376
Simple Effects								
0 Sprays				7/5/2017	617	de		
3 Sprays					586	e		
6 Sprays					678	de		
0 Sprays				7/25/2017	469	e		
3 Sprays					653	de		
6 Sprays					734	de		
0 Sprays				8/16/2017	569	e		
3 Sprays					614	de		
6 Sprays					702	de		
0 Sprays				9/5/2017	810	de		
3 Sprays					723	de		
6 Sprays					1074	de		
0 Sprays	4-Oct	2361		9/25/2017	1686	c	1-Oct	1372
3 Sprays		2769			1733	c		1253
6 Sprays		3264			2290	ab		1498
0 Sprays				10/3/2017[y]	2084	bc	1-Oct[x]	1677
3 Sprays					2029	bc		1481
6 Sprays					2681	a		1581
P Value					0.0001			0.1264

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.3 Asparagine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

Treatment	2016 Sampling Date	2016 Asparagine ($\mu mol\ L^{-1}$)[z]		2017 Sampling Date	2017 Asparagine ($\mu mol\ L^{-1}$)		2018 Sampling Date	2018 Asparagine ($\mu mol\ L^{-1}$)	
Main Effects									
0		3867	b		3676	c		1226	b
3		4429	b		4270	b		1535	b
6		6382	a		5601	a		2452	a
P Value		0.0015			<.0001			0.0001	
Harvest Date									
				5-Jul	10656	a			
				25-Jul	6159	b			
				16-Aug	4012	c			
				5-Sep	2794	d			
	4-Oct	4893		25-Sep	1812	e	1-Oct	1838	
				3-Oct[y]	1661	e	1-Oct[x]	1637	
P Value					<.0001			0.125	
Simple Effects									
0 Sprays				7/5/2017	10339	a			
3 Sprays					10254	a			
6 Sprays					11375	a			
0 Sprays				7/25/2017	3960	de			
3 Sprays					6510	bc			
6 Sprays					8006	b			
0 Sprays				8/16/2017	2892	ef			
3 Sprays					3722	de			
6 Sprays					5423	cd			
0 Sprays				9/5/2017	2408	ef			
3 Sprays					2423	ef			
6 Sprays					3550	de			
0 Sprays	4-Oct	3867		9/25/2017	1219	f	1-Oct	1526	
3 Sprays		4429			1400	f		926	
6 Sprays		6382			2817	ef		1453	
0 Sprays				10/3/2017[y]	1236	f	1-Oct[x]	1617	
3 Sprays					1313	f		2534	
6 Sprays					2433	ef		2369	
P Value					0.0134			0.0626	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.4 Serine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017		2018		
Treatment	Sampling Date	Serine (μmol L^{-1})[z]	Sampling Date	Serine (μmol L^{-1})	Sampling Date	Serine (μmol L^{-1})	
Main Effects							
Number of Sprays							
0		276		151 b		111 b	
3		308		142 b		119 b	
6		340		275 a		153 a	
P Value		0.095		<.0001		0.0005	
							1.1624
Harvest Date							
			5-Jul	273 b			
			25-Jul	224 c			
			16-Aug	222 c			
			5-Sep	262 b			
	4-Oct	308	25-Sep	287 ab	1-Oct	147 a	
			3-Oct[y]	322 a	1-Oct[x]	108 b	
P Value				<.0001		<.0001	
Simple Effects							
0 Sprays			7/5/2017	258			
3 Sprays				245			
6 Sprays				282			
0 Sprays			7/25/2017	224			
3 Sprays				283			
6 Sprays				353			
0 Sprays			8/16/2017	302			
3 Sprays				307			
6 Sprays				356			
0 Sprays			9/5/2017	269			
3 Sprays				252			
6 Sprays				300			
0 Sprays	4-Oct	276	9/25/2017	118	1-Oct	135	
3 Sprays		308		129		87	
6 Sprays		340		180		129	
0 Sprays			10/3/2017[y]	158	1-Oct[x]	109	
3 Sprays				125		177	
6 Sprays				170		128	
P Value		.		0.0859		0.1074	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.5 Glutamine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Glutamine ($\mu mol\ L^{-1}$)[z]		Sampling Date	Glutamine ($\mu mol\ L^{-1}$)		Sampling Date	Glutamine ($\mu mol\ L^{-1}$)	
Main Effects									
Number of Sprays									
0		222	b		283	b		78	b
3		222	b		287	b		87	b
6		256	a		339	a		106	a
P Value		0.0429			<.0001			0.0049	
Harvest Date									
				5-Jul	508	a			
				25-Jul	407	b			
				16-Aug	304	c			
				5-Sep	233	d			
	4-Oct	225		25-Sep	224	d	1-Oct	138	a
				3-Oct[y]	142	e	1-Oct[x]	43	b
P Value					<.0001			<.0001	
Simple Effects									
0 Sprays				7/5/2017	514	ab			
3 Sprays					464	ab			
6 Sprays					546	a			
0 Sprays				7/25/2017	298	cde			
3 Sprays					425	b			
6 Sprays					497	ab			
0 Sprays				8/16/2017	300	cd			
3 Sprays					292	cde			
6 Sprays					320	c			
0 Sprays				9/5/2017	257	cdef			
3 Sprays					213	defg			
6 Sprays					229	cdef			
0 Sprays	4-Oct	222		9/25/2017	200	efg	1-Oct	126	
3 Sprays		222			200	efg		30	
6 Sprays		256			273	cde		130	
0 Sprays				10/3/2017[y]	129	g	1-Oct[x]	44	
3 Sprays					125	g		157	
6 Sprays					171	fg		54	
P Value		.			<.0001			0.315	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.5 Alanine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Alanine (µmol L^{-1})[z]		Sampling Date	Alanine (µmol L^{-1})		Sampling Date	Alanine (µmol L^{-1})	
Main Effects									
Number of Sprays									
0		261	b		71	b		30	
3		273	ab		75	b		33	
6		310	a		90	a		38	
P Value		0.017			0.0005			0.0669	
Harvest Date									
				5-Jul	65	c			
				25-Jul	95	b			
				16-Aug	44	cd			
				5-Sep	47	d			
	4-Oct	281		25-Sep	168	a	1-Oct	29	b
				3-Oct[y]	52	cd	1-Oct[x]	38	a
P Value		.			<.0001			0.0014	
Simple Effects									
0 Sprays				7/5/2017	55	de			
3 Sprays					63	de			
6 Sprays					76	de			
0 Sprays				7/25/2017	65	de			
3 Sprays					94	cd			
6 Sprays					127	bc			
0 Sprays				8/16/2017	37	e			
3 Sprays					38	e			
6 Sprays					56	de			
0 Sprays				9/5/2017	55	de			
3 Sprays					37	e			
6 Sprays					49	e			
0 Sprays	4-Oct	261		9/25/2017	165	ab	1-Oct	26	
3 Sprays		273			167	ab		34	
6 Sprays		310			171	a		26	
0 Sprays				10/3/2017[y]	49	e	1-Oct[x]	39	
3 Sprays					50	e		34	
6 Sprays					58	de		42	
P Value		.			0.0314			0.5332	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.7 Valine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017			2018		
Treatment	Sampling Date	Valine (μmol L^{-1})[z]	Sampling Date	Valine (μmol L^{-1})		Sampling Date	Valine (μmol L^{-1})	
Main Effects								
Number of Sprays								
0		38		21			14	b
3		42		20			17	b
6		50		23			23	a
P Value		0.1268		0.0613			0.0006	
Harvest Date								
			5-Jul	0	d			
			25-Jul	21	b			
			16-Aug	37	a			
			5-Sep	36	a			
	4-Oct	43	25-Sep	23	b	1-Oct	21	a
			3-Oct[y]	13	c	1-Oct[x]	15	b
P Value		.		<.0001			0.0019	
Simple Effects								
0 Sprays			7/5/2017	0				
3 Sprays				0				
6 Sprays				0				
0 Sprays			7/25/2017	19				
3 Sprays				22				
6 Sprays				22				
0 Sprays			8/16/2017	37				
3 Sprays				35				
6 Sprays				37				
0 Sprays			9/5/2017	38				
3 Sprays				32				
6 Sprays				37				
0 Sprays	4-Oct	38	9/25/2017	19		1-Oct	18	
3 Sprays		42		20			18	
6 Sprays		50		29			27	
0 Sprays			10/3/2017[y]	12		1-Oct[x]	10	
3 Sprays				11			16	
6 Sprays				15			19	
P Value		.		0.4175			0.2532	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.8 Methionine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Methionine (µmol L^{-1})^{z}		Sampling Date	Methionine (µmol L^{-1})		Sampling Date	Methionine (µmol L^{-1})	
Main Effects									
Number of Sprays									
0		48	b		35			27	
3		50	b		34			31	
6		63	a		38			33	
P Value		0.0071			0.1304			0.3244	
Harvest Date									
				5-Jul	68	a			
				25-Jul	50	b			
				16-Aug	14	d			
				5-Sep	3	e			
	4-Oct	53		25-Sep	35	c	1-Oct	24	b
				3-Oct^{y}	44	bc	1-Oct^{x}	37	a
P Value					<.0001			<.0001	
Simple Effects									
0 Sprays				7/5/2017	70	a			
3 Sprays					64	ab			
6 Sprays					69	a			
0 Sprays				7/25/2017	42	cd			
3 Sprays					53	abc			
6 Sprays					54	abc			
0 Sprays				8/16/2017	19	efg			
3 Sprays					15	fg			
6 Sprays					7	g			
0 Sprays				9/5/2017	8	g			
3 Sprays					0	g			
6 Sprays					0	g			
0 Sprays	4-Oct	48		9/25/2017	31	def	1-Oct	22	
3 Sprays		50			29	def		32	
6 Sprays		63			45	bcd		23	
0 Sprays				10/3/2017^{y}	38	cde	1-Oct^{x}	39	
3 Sprays					40	cd		25	
6 Sprays					55	abc		40	
P Value		.			0.003			0.4687	

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

^{y}Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

^{x}Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.9 . Glutamic acid concentrations in mature Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Glutamic Acid (μmol L^{-1})[z]		Sampling Date	Glutamic Acid (μmol L^{-1})		Sampling Date	Glutamic Acid (μmol L^{-1})	
Main Effects									
Number of Sprays									
0		46	b		417	b		146	
3		57	ab		431	ab		161	
6		62	a		461	a		157	
P Value		0.0182			0.0071			0.2622	
Harvest Date									
				5-Jul	701	a			
				25-Jul	551	b			
				16-Aug	506	b			
				5-Sep	332	c			
	4-Oct	55		25-Sep	247	d	1-Oct	169	a
				3-Oct[y]	282	cd	1-Oct[x]	141	b
P Value					<.0001			0.0003	
Simple Effects									
0 Sprays				7/5/2017	715	ab			
3 Sprays					658	ab			
6 Sprays					731	a			
0 Sprays				7/25/2017	434	ef			
3 Sprays					594	bcd			
6 Sprays					626	abc			
0 Sprays				8/16/2017	499	de			
3 Sprays					504	cde			
6 Sprays					516	cde			
0 Sprays				9/5/2017	353	fg			
3 Sprays					316	fg			
6 Sprays					325	fg			
0 Sprays	4-Oct	46		9/25/2017	235	g	1-Oct	166	
3 Sprays		57			249	g		126	
6 Sprays		62			257	g		164	
0 Sprays				10/3/2017[y]	268	g	1-Oct[x]	158	
3 Sprays					264	g		177	
6 Sprays					314	fg		138	
P Value		.			0.0005			0.0546	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.10. Histidine concentrations in mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017			2018	
Treatment	Sampling Date	Histidine (μmol L^{-1})[z]	Sampling Date	Histidine (μmol L^{-1})		Sampling Date	Histidine (μmol L^{-1})
Main Effects							
Number of Sprays							
0				15			
3				14			
6				16			
P Value		.		0.7128			
Harvest Date							
			5-Jul	89	a		
			25-Jul	0	b		
			16-Aug	0	b		
			5-Sep	1	b		
	4-Oct		25-Sep	0	b	1-Oct	
	-		3-Oct[y]	0	b	1-Oct[x]	
P Value				<.0001			
Simple Effects							
0 Sprays			7/5/2017	92			
3 Sprays				87			
6 Sprays				89			
0 Sprays			7/25/2017	0			
3 Sprays				0			
6 Sprays				0			
0 Sprays			8/16/2017	0			
3 Sprays				0			
6 Sprays				0			
0 Sprays			9/5/2017	0			
3 Sprays				0			
6 Sprays				4			
0 Sprays	4-Oct		9/25/2017	0		1-Oct	
3 Sprays				0			
6 Sprays				0			
0 Sprays			10/3/2017[y]	0		1-Oct[x]	
3 Sprays				0			
6 Sprays				0			
P Value				0.9596			

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.11 Arginine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017			2018	
Treatment	Sampling Date	Arginine (μmol L^{-1})^{z}	Sampling Date	Arginine (μmol L^{-1})		Sampling Date	Arginine (μmol L^{-1})
Main Effects							
Number of Sprays							
0				9			
3				8			
6				8			
P Value		.		0.6934			
Harvest Date							
			5-Jul	51	a		
			25-Jul	0	b		
			16-Aug	0	b		
			5-Sep	0	b		
	4-Oct		25-Sep	0	b	1-Oct	
			3-Oct^{y}	0	b	1-Oct^{x}	
P Value				<.0001			
Simple Effects							
0 Sprays			7/5/2017	55			
3 Sprays				51			
6 Sprays				47			
0 Sprays			7/25/2017	0			
3 Sprays				0			
6 Sprays				0			
0 Sprays			8/16/2017	0			
3 Sprays				0			
6 Sprays				0			
0 Sprays			9/5/2017	0			
3 Sprays				0			
6 Sprays				0			
0 Sprays	4-Oct		9/25/2017	0		1-Oct	
3 Sprays				0			
6 Sprays				0			
0 Sprays			10/3/2017^{y}	0		1-Oct^{x}	
3 Sprays				0			
6 Sprays				0			
P Value				0.957			

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

^{y}Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

^{x}Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.10. Glycine concentrations in mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017		2018	
Treatment	Sampling Date	Glycine (µmol L^{-1})[z]	Sampling Date	Glycine (µmol L^{-1})	Sampling Date	Glycine (µmol L^{-1})
Main Effects						
Number of Sprays						
0		74 b		52 b		34
3		82 b		54 b		29
6		106 a		66 a		36
P Value		0.0024		<.0001		0.5145
Harvest Date						
			5-Jul	75 a		
			25-Jul	62 b		
			16-Aug	52 b		
			5-Sep	60 b		
	4-Oct	87	25-Sep	55 b	1-Oct	40 a
			3-Oct[y]	40 c	1-Oct[x]	26 b
P Value				<.0001		0.014
Simple Effects						
0 Sprays			7/5/2017	47		
3 Sprays				51		
6 Sprays				57		
0 Sprays			7/25/2017	47		
3 Sprays				60		
6 Sprays				80		
0 Sprays			8/16/2017	46		
3 Sprays				50		
6 Sprays				70		
0 Sprays			9/5/2017	42		
3 Sprays				35		
6 Sprays				42		
0 Sprays	4-Oct	74	9/25/2017	73	1-Oct	39
3 Sprays		82		73		35
6 Sprays		106		80		47
0 Sprays			10/3/2017[y]	59	1-Oct[x]	26
3 Sprays				53		23
6 Sprays				67		29
P Value		.		0.0909		0.6282

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.11 Cysteine concentrations in Crimson Crisp® apple fruit treated with 5.1 g N L^{-1} solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Cysteine ($\mu mol\ L^{-1}$)[z]		Sampling Date	Cysteine ($\mu mol\ L^{-1}$)		Sampling Date	Cysteine ($\mu mol\ L^{-1}$)	
Main Effects									
Number of Sprays									
0		35	b		21	ab		10	b
3		38	b		19	b		11	b
6		43	a		24	a		13	a
P Value		0.0025			0.0043			0.0016	
Harvest Date									
				5-Jul	33	a			
				25-Jul	23	b			
				16-Aug	19	bcd			
				5-Sep	18	cd			
	4-Oct	39		25-Sep	14	d	1-Oct	13	a
				3-Oct[y]	22	bc	1-Oct[x]	10	b
P Value		.			<.0001			0.0002	
Simple Effects									
0 Sprays				7/5/2017	33				
3 Sprays					31				
6 Sprays					35				
0 Sprays				7/25/2017	23				
3 Sprays					19				
6 Sprays					27				
0 Sprays				8/16/2017	17				
3 Sprays					18				
6 Sprays					21				
0 Sprays				9/5/2017	16				
3 Sprays					16				
6 Sprays					21				
0 Sprays	4-Oct	35		9/25/2017	12		1-Oct	11	
3 Sprays		38			13			9	
6 Sprays		43			17			12	
0 Sprays				10/3/2017[y]	25		1-Oct[x]	11	
3 Sprays					18			14	
6 Sprays					22			12	
P Value		.			0.7734			0.155	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.12. Gamma-aminobutyric acid (GABA) concentrations in mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017		2018	
Treatment	Sampling Date	GABA (µmol L^{-1})[z]	Sampling Date	GABA (µmol L^{-1})	Sampling Date	GABA (µmol L^{-1})
Main Effects						
Number of Sprays						
0		193		17 b		16
3		201		18 b		16
6		221		25 a		19
P Value		0.2192		0.005		0.0773
Harvest Date						
			5-Jul	6 c		
			25-Jul	8 c		
			16-Aug	33 a		
			5-Sep	18 b		
	4-Oct	205	25-Sep	28 ab	1-Oct	21 a
			3-Oct[y]	28 ab	1-Oct[x]	13 b
P Value		.		<.0001		<.0001
Simple Effects						
0 Sprays			7/5/2017	6		
3 Sprays				6		
6 Sprays				8		
0 Sprays			7/25/2017	0		
3 Sprays				0		
6 Sprays				23		
0 Sprays			8/16/2017	29		
3 Sprays				34		
6 Sprays				36		
0 Sprays			9/5/2017	17		
3 Sprays				17		
6 Sprays				20		
0 Sprays	4-Oct	193	9/25/2017	25	1-Oct	20
3 Sprays		201		27		11
6 Sprays		221		33		20
0 Sprays			10/3/2017[y]	27	1-Oct[x]	12
3 Sprays				25		24
						15
6 Sprays				31		
P Value				0.3402		0.7827

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.13. Yeast assimilable nitrogen (YAN) in juice of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Juice YAN (mg N L^{-1})[z]		Sampling Date	Juice YAN (mg N L^{-1})		Sampling Date	Juice YAN (mg N L^{-1})	
Main Effects									
Number of Sprays									
0		141	b		115	c		99	b
3		149	b		124	b		100	b
6		200	a		157	a		128	a
P Value		<.0001			<.0001			0.0007	
Harvest Date									
				5-Jul	242	a			
				25-Jul	166	b			
	30-Aug	167		16-Aug	121	c			
	14-Sep	162		5-Sep	95	d			
	4-Oct	161		25-Sep	85	d	1-Oct	125	a
				3-Oct[y]	82	d	1-Oct[x]	94	b
P Value		0.5374			<.0001			<.0001	
Simple Effects									
0 Sprays				7/5/2017	223	bc			
3 Sprays					247	ab			
6 Sprays					256	a			
0 Sprays				7/25/2017	141	de			
3 Sprays					155	d			
6 Sprays					203	c			
0 Sprays	30-Aug	138		8/16/2017	100	fgh			
3 Sprays		151			111	fg			
6 Sprays		212			151	d			
0 Sprays	14-Sep	140		9/5/2017	83	gh			
3 Sprays		151			87	gh			
6 Sprays		195			116	ef			
0 Sprays	4-Oct	145		9/25/2017	66	h	1-Oct	119	
3 Sprays		145			71	h		109	
6 Sprays		193			109	fg		145	
0 Sprays				10/3/2017[y]	74	h	1-Oct[x]	78	
3 Sprays					73	h		91	
6 Sprays					107	fg		111	
P Value		0.3171			0.0395			0.098	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.14 Sum of assimilable amino acid concentrations in mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016			2017			2018		
Treatment	Sampling Date	Sum of amino acids (mg N L^{-1})[z]		Sampling Date	Sum of amino acids (mg N L^{-1})		Sampling Date	Sum of amino acids (mg N L^{-1})	
Main Effects									
Number of Sprays									
0		7396	b		5922	b		3005	b
3		8472	b		6510	b		3625	b
6		11095	a		8287	a		4560	a
P Value		0.0003			<.0001			0.0013	
Harvest Date									
				5-Jul	13257	a			
				25-Jul	8282	b			
				16-Aug	5991	c			
				5-Sep	4689	d			
	4-Oct	8988		25-Sep	4528	d	1-Oct	3888	
				3-Oct[y]	4693	d	1-Oct[x]	3572	
P Value		.			<.0001			0.1124	
Simple Effects									
0 Sprays				7/5/2017	12937	ab			
3 Sprays					12687	ab			
6 Sprays					14147	a			
0 Sprays				7/25/2017	5581	ef			
3 Sprays					8714	cd			
6 Sprays					10549	bc			
0 Sprays				8/16/2017	4767	f			
3 Sprays					5654	ef			
6 Sprays					7551	de			
0 Sprays				9/5/2017	4548	f			
3 Sprays					4096	f			
6 Sprays					5423	ef			
0 Sprays	4-Oct	7396		9/25/2017	3627	f	1-Oct	3462	
3 Sprays		8472			3888	f		3506	
6 Sprays		11095			6067	ef		4697	
0 Sprays				10/3/2017[y]	4072	f	1-Oct[x]	2547	
3 Sprays					4023	f		3745	
6 Sprays					5983	ef		4423	
P Value					0.009			0.0654	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.17. Estimated residual (non-amino) yeast assimilable nitrogen (YAN) in juice of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.

	2016		2017			2018		
Treatment	Sampling Date	Residual juice YAN (mg N L^{-1})[z]	Sampling Date	Residual juice YAN (mg N L^{-1})		Sampling Date	Residual juice YAN (mg N L^{-1})	
Main Effects								
Number of Sprays								
0		42		33			57	ab
3		27		34			49	b
6		38		41			64	a
P Value		0.259		0.151			0.0056	
Harvest Date								
			5-Jul	57	a			
			25-Jul	52	ab			
	30-Aug		16-Aug	37	bc			
	14-Sep		5-Sep	32	cd			
	4-Oct	35	25-Sep	19	d	1-Oct	70	a
			3-Oct[y]	19	d	1-Oct[x]	43	b
P Value		.		<.0001			<.0001	
Simple Effects								
0 Sprays			7/5/2017					
3 Sprays								
6 Sprays								
0 Sprays			7/25/2017	63				
3 Sprays				41				
6 Sprays				53				
0 Sprays	30-Aug		8/16/2017	33				
3 Sprays				32				
6 Sprays				45				
0 Sprays	14-Sep		9/5/2017	28				
3 Sprays				29				
6 Sprays				40				
0 Sprays	4-Oct	42	9/25/2017	17		1-Oct	71	
3 Sprays		27		17			60	
6 Sprays		38		24			79	
0 Sprays			10/3/2017[y]	17		1-Oct[x]	43	
3 Sprays				17			38	
6 Sprays				23			49	
P Value				0.1376			0.5286	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y] Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x] Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.18 Juice attributes of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Treatment	2018	Titratable acidity (as mg malic acid 100 mL^{-1} Juice)^{z}		° Brix		Polyphenols (µg GAE mL^{-1})		Ascorbic acid (µg GAE mL^{-1})		pH		Fruit weight (g)		Juicing efficiency (mL juice N g^{-1}fruit)	
Main Effects															
Number of Sprays															
0		94	b	14.4		292		231		3.3		194	a	0.61	
3		92	b	14.5		306		238		3.4		193	a	0.62	
6		102	a	14.6		316		234		3.3		179	b	0.62	
P Value		0.0012		0.5135		0.3299		0.8531		0.0825		0.0158		0.5777	
Harvest Date															
	1-Oct	102	a	14.4	b	329	a	389	a	3.3	b	192	a	0.64	a
	1-Oct^{x}	90	b	14.6	a	281	b	79	b	3.4	a	185	b	0.59	b
P Value		<.0001		0.0079		0.0001		<.0001		<.0001		0.0366		<.0001	
Simple Effects															
0 Sprays	1-Oct	102	ab	14.3		322		378		3.2	b	199		0.66	a
3 Sprays		97	b	14.4		338		399		3.3	b	197		0.64	ab
6 Sprays		106	a	14.5		326		391		3.3	b	181		0.63	bc
0 Sprays	1-Oct^{x}	87	c	14.6		262		84		3.4	a	190		0.56	e
3 Sprays		87	c	14.5		274		77		3.4	a	190		0.60	d
6 Sprays		97	b	14.8		306		76		3.4	a	176		0.61	cd
P Value		0.0206		0.6241		0.1418		0.4068		0.0449		0.8971		<.0001	

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

[y]Fruit harvested on October 3, 2017 was stored at 1° C and pressed on November 14, 2017

[x]Fruit harvested on October 1, 2018 was stored at 1° C and pressed on November 28, 2018

Table 5.19 Relative concentrations of amino acids in juice of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Treatment		Proportion of Asp	Proportion of Asn	Proportion of Other Amino Acids
Year				
2016		32% c	54% a	15% c
2017		43% a	39% c	18% a
2018		38% b	46% b	16% b
P Value		<.0001	<.0001	<.0001
Number of Sprays				
0 Sprays		40% a	43% b	17% a
3 Sprays		40% a	43% b	17% a
6 Sprays		33% b	52% a	15% b
P Value		<.0001	<.0001	<.0001
Simple Effects				
2016	0 Sprays	33%	52%	16% bc
2016	3 Sprays	33%	52%	15% bc
2016	6 Sprays	30%	57%	13% d
2017	0 Sprays	47%	33%	20% a
2017	3 Sprays	45%	36%	19% a
2017	6 Sprays	38%	46%	16% bc
2018	0 Sprays	40%	43%	16% bc
2018	3 Sprays	43%	41%	16% bc
2018	6 Sprays	32%	54%	15% cd
P Value		0.0706	0.1596	0.0318

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

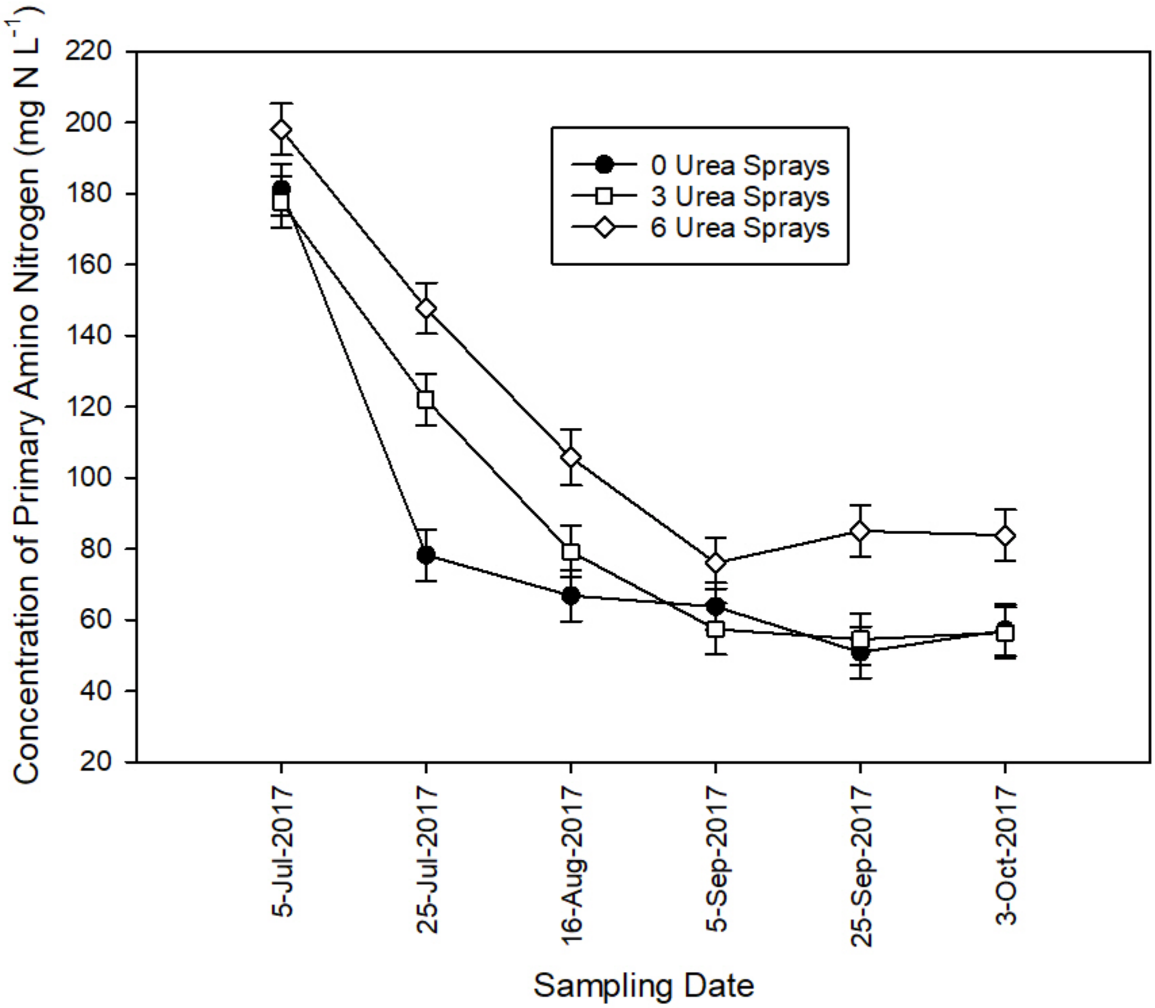

Figure 5.1. Changes in PAN concentration in 'Crimson Crisp ®' juice from mid-season through harvest and storage in 'Crimson Crisp®' apple juice based on treatment with 5.1 g N L-1 solution foliar urea sprays. University of Guelph, Simcoe, Ontario, 2017.

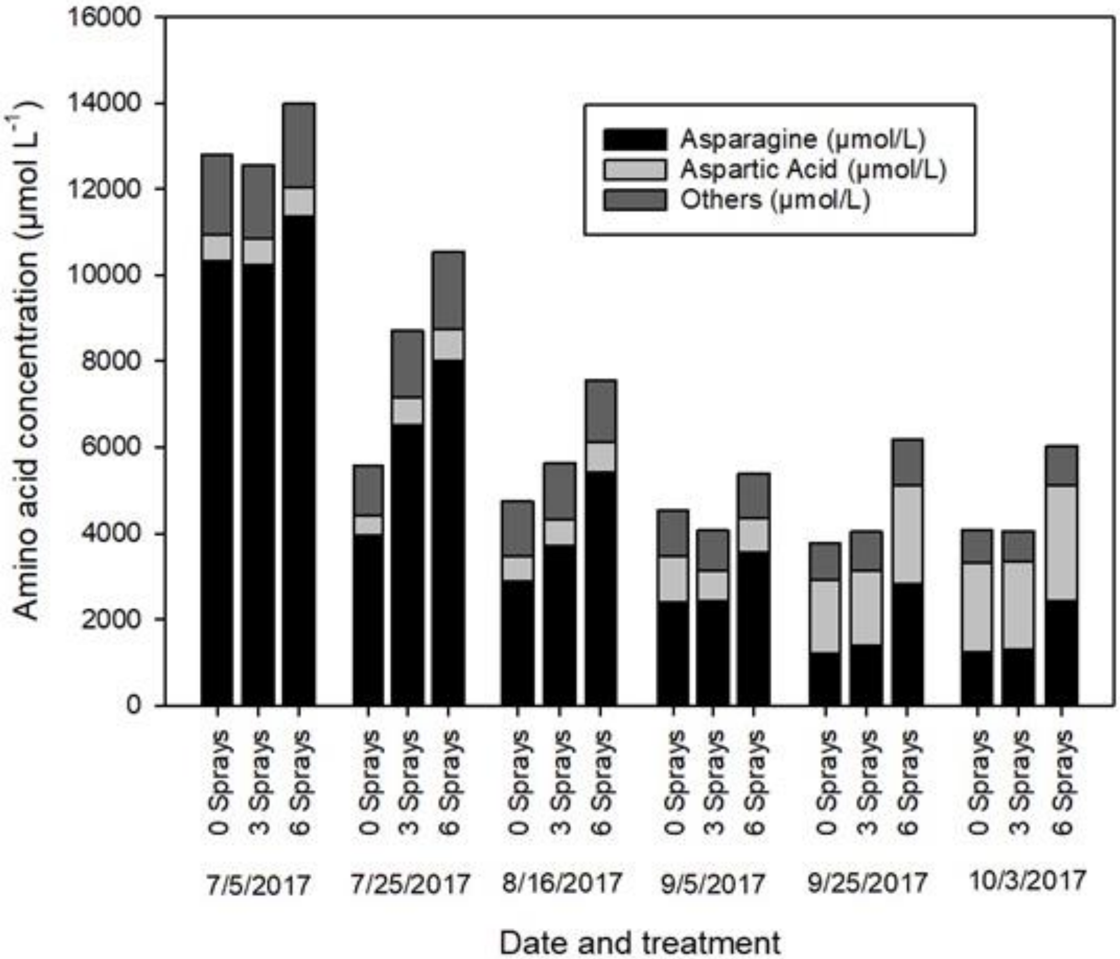

Figure 5.2. Amino acid concentrations of 'Crimson Crisp®' juice in the 2017 season arranged by date and 5.1 g N L-1 solution foliar urea spray treatment. University of Guelph, Simcoe, Ontario, 2017.

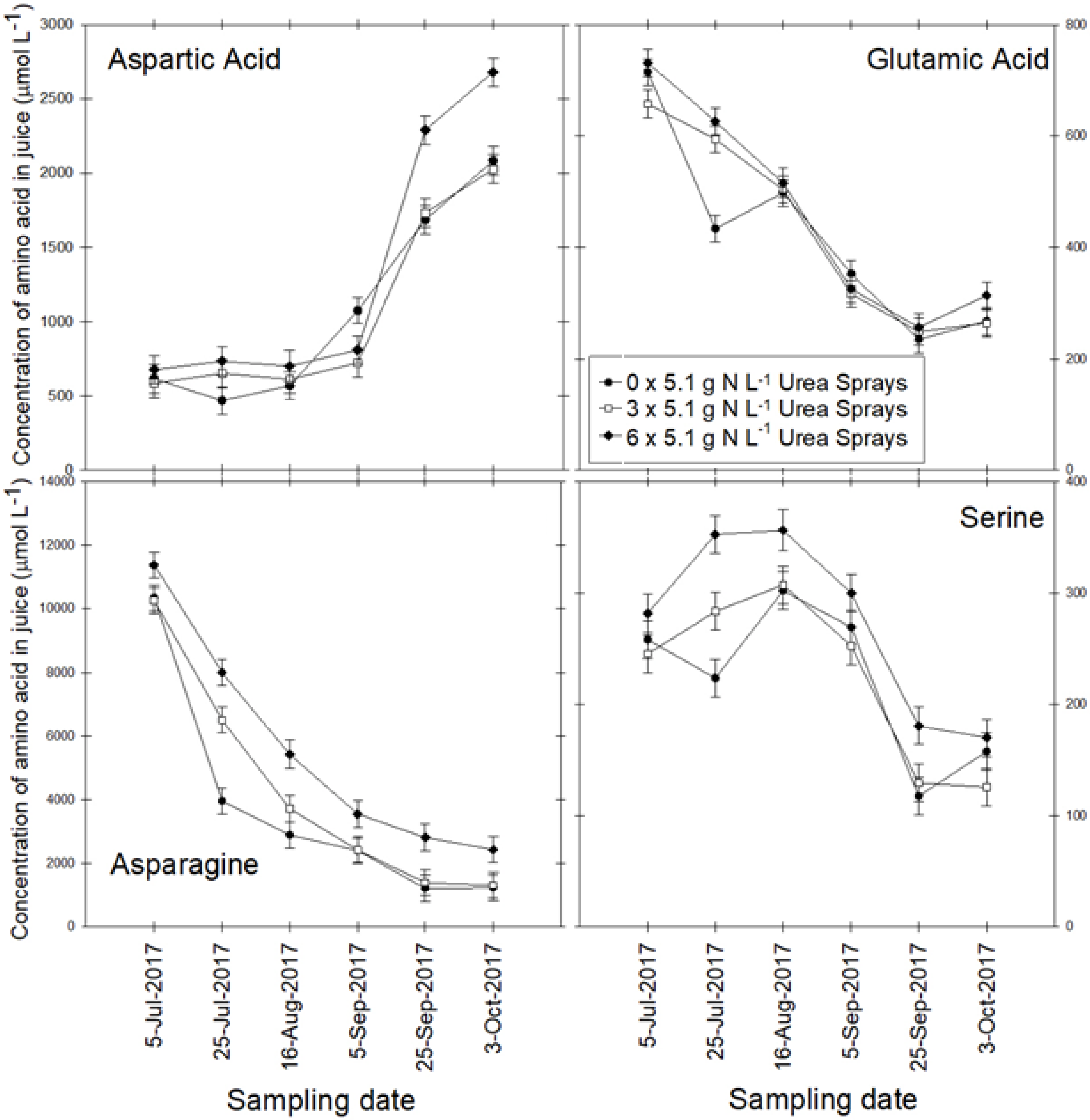

Figure 5.3 Seasonal development of Asp, Glu, Asn, and Ser in 'Crimson Crisp®' apple juice in response to 5.1 g N L^{-1} foliar urea sprays. University of Guelph, Simcoe, ON. 2017.

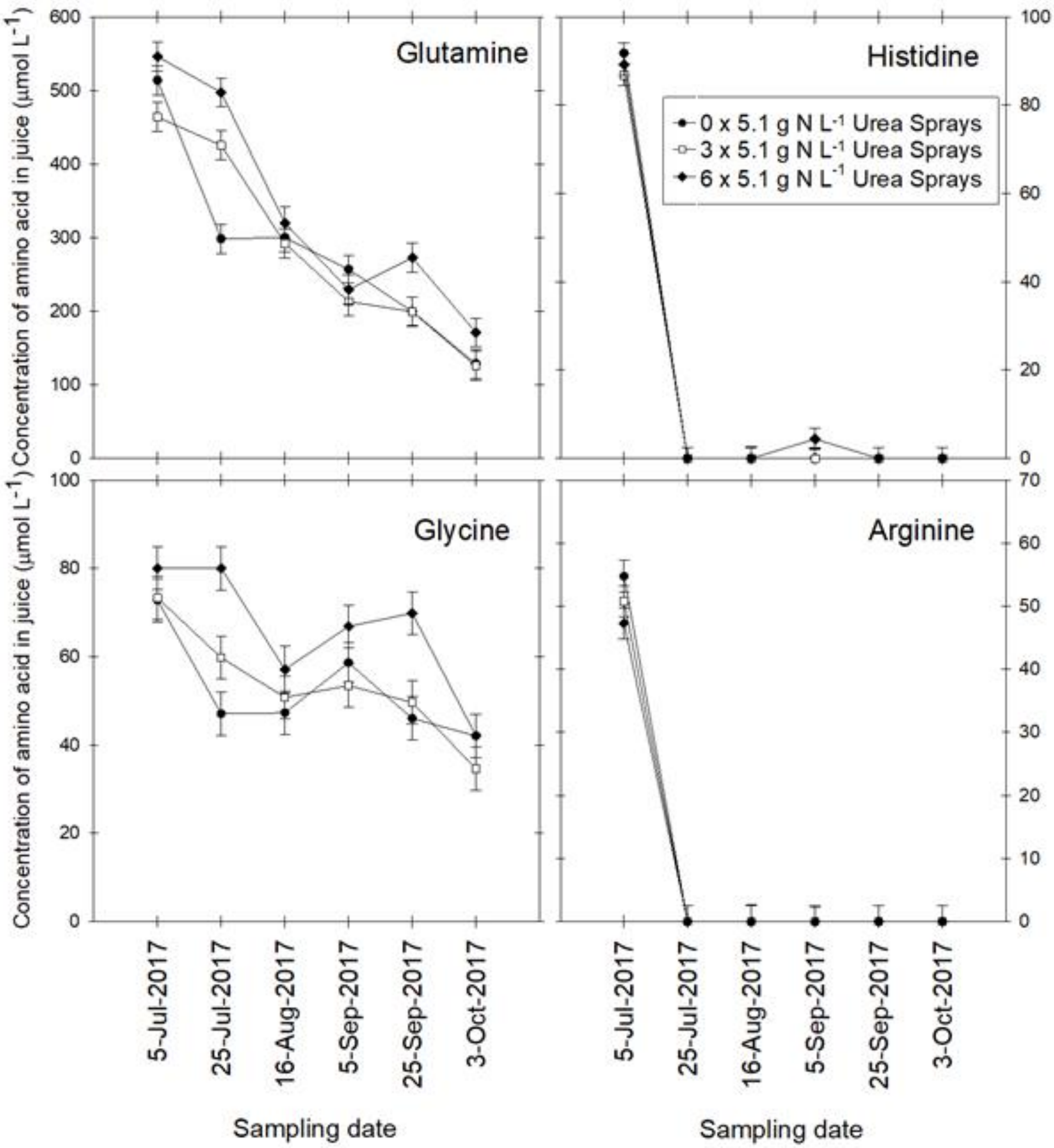

Figure 5.4 Seasonal development of Glu, His, Gly, and Arg in 'Crimson Crisp®' apple juice in response to 5.1 g N L^{-1} foliar urea sprays. University of Guelph, Simcoe, ON. 2017.

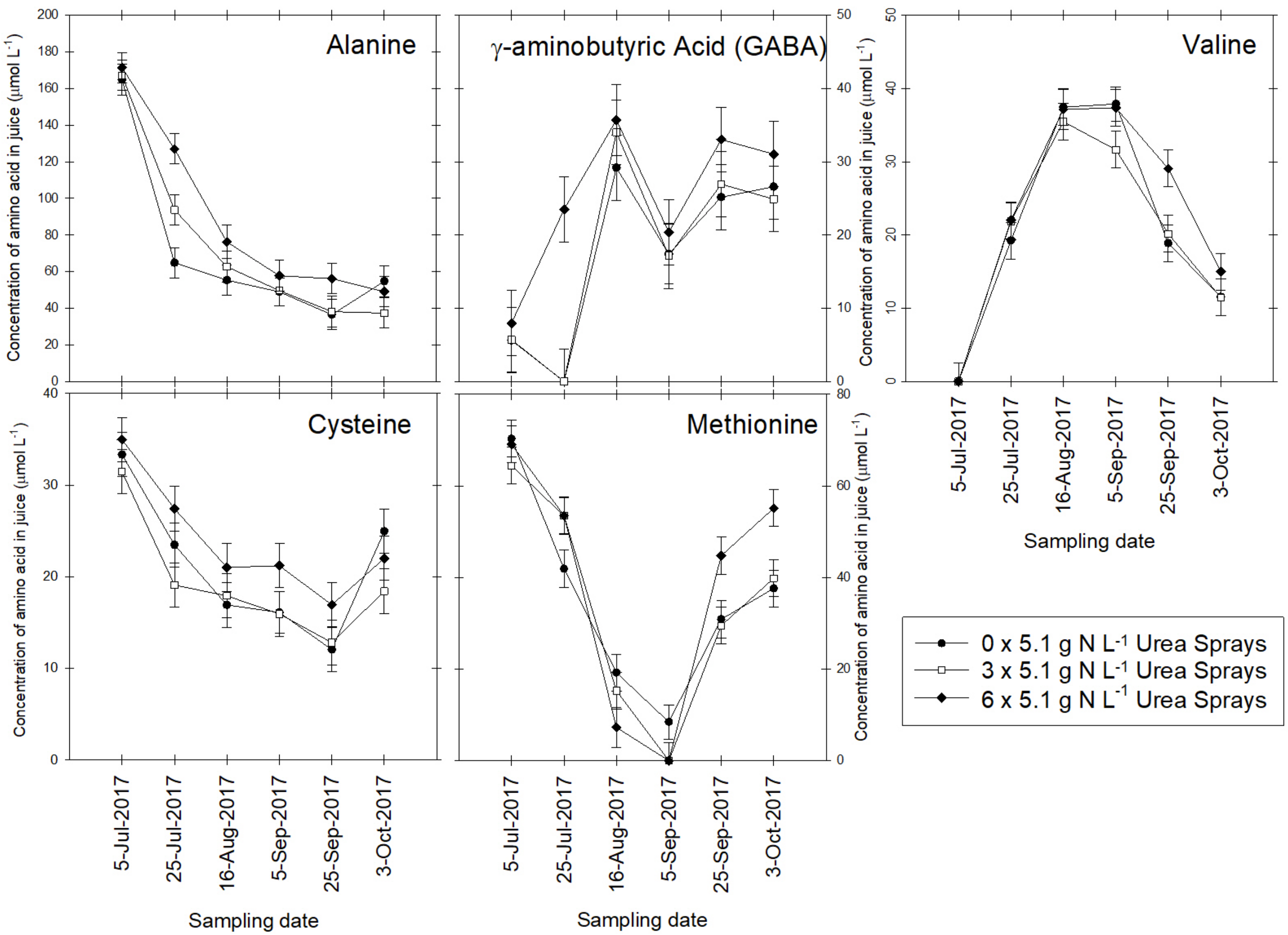

Figure 5.5 Seasonal development of Ala, GABA, Cys, Val, and Met in 'Crimson Crisp®' apple juice in response to 5.1 g N L^{-1} foliar urea sprays. University of Guelph, Simcoe, ON. 2017.

6 The proportion of initial sugar concentration and initial yeast assimilable nitrogen concentration affects the alcoholic fermentation kinetics of Davis522 yeast in a 'GoldRush' apple juice medium

6.1 Abstract

Understanding the relationship between yeast assimilable nitrogen (YAN) and sugar concentration in cider fermentations is important for planning for supplementation and ensuring complete fermentations without undesirable flavour production. It is unclear whether a specific quantity of YAN is required for a proportional amount of sugar to be fermented to a complete absence of sugar. To test this, a two-factor factorial experiment was conducted involving the fermentation of 'GoldRush' apple juice with increasing amounts of sucrose and diammonium phosphate (DAP) in conjunction with an additional experiment investigating the impact of varying proportions of YAN and sucrose. In the first experiment, measures of juice were dosed to reflect ranges of sugar from 12.9 to 18.5° Brix and DAP to reflect ranges of 70 to 170 mg N L^{-1}. In the second experiment, measures of juice were dosed with the appropriate sugar and DAP amounts to create proportions of 5.4, 9.3, and 13.1 mg N L^{-1}Brix$°^{-1}$. In both experiments, juices were inoculated with activated Davis522 yeast. To monitor fermentation progression, CO_2 loss from the fermentation vessel was determined gravimetrically daily over a 5-week period until the vessel's weight stabilized. The maximum fermentation rate, timing thereof, and the period required for complete fermentation to complete were determined. It was observed that DAP concentration and sugar concentration interact with one another in determining fermentation kinetics and that the performance of the yeast in fermentation depends on the relative concentrations of the two. This is important because it shows that apple juice can ferment well with a specific proportion of sugar to YAN, which can be controlled with juice selection and supplementation to ensure a healthy and complete fermentation.

6.2 Introduction

In formal cider evaluation, such as competition and cider judging settings, many ciders smell sulfurous and retain sweetness, even if they are labeled as dry (González San José, 2010). Both characteristics are rather common faults in cider production, particularly from home producers (Jolicoeur, 2013). These properties are often indicative of arrested or “stuck” fermentations, which occurs when the yeast population either dies or becomes inactive before all of the sugar available in the juice is consumed (Bisson, 1999). The remaining sugar explains the unwanted sweetness, but not the sulfur smell. This could be linked to YAN, the form of N that is biologically available for yeast, including N as ammonium and in primary amino acids (i.e. the proteinogenic amino acids except for proline) (Bell & Henschke, 2005). Not only is YAN required for yeast growth and reproduction, it also can prevent off-odour production, such as hydrogen sulfide production that occurs when a yeast cell attempts to produce methionine without a sufficient supply of YAN (Jiranek et al., 1995). Over-supplementation of YAN can also cause fermentation problems, such as the formation of biogenic amines, ethyl carbamate, and higher alcohols, or rapid fermentations with little flavour development (Alberti et al., 2011; Bell & Henschke, 2005). Excessive ammonium in cider production can lead to the production of higher alcohols, acetic acid, ethyl carbamate, and hydrogen sulfide (Taillandier et al., 2007). In contrast, an adequate YAN concentration allows for an increase in yeast biomass and then a higher fermentation rate (Gutiérrez et al., 2012). The initial yeast biomass has a greater effect on fermentation than the initial N concentration, but a high initial N concentration provides an environment for greater yeast biomass production. Natural fermentations, those without the addition of commercial yeasts, start off with a low biomass, particularly a low population of *Saccharomyces cerevisiae* (Gutiérrez et al., 2012). Initial yeast biomass was also considered an important factor in Kelkar and Dolan’s cider fermentation model in addition to the main factors of initial N concentration and temperature. This model demonstrated that sugar consumption and therefore ethanol production are proportional to the viable yeast cell concentration (Kelkar & Dolan, 2012). While higher temperatures lead to a more complete fermentation in the model, both low temperatures and temperatures above 240° C can inhibit fermentation and rapid temperature fluctuations can cause yeast shock (Bisson, 1999; Irastorza Iribas & Dueñas Chasco, 2010; Kelkar & Dolan, 2012; Nogueira et al., 2008).

Although N is the primary growth-limiting factor in cell growth during fermentation for both wine and cider (Gutiérrez et al., 2012; Kelkar & Dolan, 2012), producers often fail to quantify N concentrations before fermentation. Initial juice N concentrations below 100 mg L^{-1} may result in sluggish fermentations (Kelkar & Dolan, 2012). Thus, monitoring N in the juice before fermentation is important (Martínez-Moreno et al., 2014). The average of 156 mg L^{-1} total N in the apple juices studied by Alberti et al. differs from the 59-330 mg L^{-1} range detected in juices studied by dos Santos et al in 2016 (Alberti et al., 2011; Eleutério dos Santos et al., 2016). In these juices, the most common amino acids are aspartate, glutamate, asparagine, glutamine, and serine (Alberti et al, 2011; Santos et al., 2016). The optimal suggested concentration for YAN according to dos Santos is 120 mg L^{-1} total with 43% aspartate and 57% glutamate (Santos et al., 2015). This N fraction in apple juice can be affected by the age of the orchard and the extensive use of N fertilizers in the orchard (Alberti et al., 2011). In some cases, formol is used to approximate amino N due to the small fraction of ammonium in apple juice (Alberti et al., 2011).

Certain strains of yeast are better adapted to utilizing N efficiently (Cubillos, 2016). A lower N concentration in the post-fermentation cider results in a finished product that will have greater microbial stability (Nogueira et al., 2008). In contrast, the excessive addition of N before or during fermentation can lead to microbial instability in the finished product due to excess nutrition available for spoilage microorganisms in the finished cider (Gutiérrez et al., 2012). If N is to be added to the must, the timing of the supplementation must be taken into consideration. Nogueira et al. (2008) found that N consumption is rapid in the first ten days of the fermentation process, suggesting that reducing the yeast population after the initial sugar consumption phase would be favorable. In wine production, most N supplementation involves ammonium salts (Gutiérrez et al., 2012); ammonium additions in cider are done on a routine basis. Other methods of manipulating juice N include nutrient reduction using methods like clarification, centrifugation, and keeving (Nogueira et al., 2008).

Alcoholic fermentation is the anaerobic energy-producing process in which yeast convert sugars into pyruvate via glycolysis to generate ATP, culminating in the formation of ethanol and CO_2 and the regeneration of NADH. In high sugar conditions, *S. cerevisiae* will also produce ethanol in aerobic conditions, which is a phenomenon known as the Crabtree effect. Alcoholic fermentation does not use YAN as a substrate or as a cofactor. Rather, YAN is used in yeast growth and formation of the proteins necessary for the yeast to grow and reproduce (Bell & Henschke, 2005). Under the ideal conditions, yeast will grow exponentially and carry out alcoholic fermentation as their primary form of energy production. Inadequate YAN can retard the growth of yeast, leading to a slower or stopped fermentation (Bisson, 1999). Apple juice on average is lower in YAN than other fermentation media, notably grape juice (Alberti et al., 2011).

The progression of fermentation and the sensory properties of finished cider are affected by the interaction of YAN with yeast strain (Jiranek et al., 1995), the initial N concentration and form (Alberti et al., 2011), and the fermentation temperature and juice chemistry (Alberti et al., 2011; Jiranek et al., 1995; Kelkar & Dolan, 2012; Leguerinel et al., 1988). The importance of yeast strain has implications for early cider processing, as even apple pressing can greatly influence the profile of yeasts present in must for natural fermentation (Suárez Valles et al., 2005) and thus the requirements for YAN. Some commonly recommended strains, like EC1118, DV10, AWRI 350, are effective fermenters even with low YAN, but wild strains in natural fermentations vary in their needs (Irastorza Iribas & Dueñas Chasco, 2010; Jolicoeur, 2013). Taillandier et al. showed that sugar consumption was more dependent on yeast strain than on N concentration and that increased N allowed the strains to consume more sugar, although this study did not compare musts with different initial sugar concentrations (Taillandier et al., 2007).

Other cider fermentation kinetic studies have used maximum fermentation rates and total time to fermentation completion as metrics for fermentation speed in addition to using weight loss as an indicator of fermentation (Alberti et al., 2011). In Alberti et al.'s experiment, the fermentation rate was calculated as the loss of mass over time fitted to a 6th order polynomial. These studies showed that increasing YAN would increase the fermentation rate. Many cider producers ask what the ideal concentration of YAN in their juice is to allow for a complete fermentation. Natural YAN concentrations present in some apple musts have been observed to allow for complete fermentations, though YAN varies among cultivars (Alberti et al., 2011). Published literature in cider suggests YAN concentrations ranging from those as low as 100 mg N/L based (Jolicoeur, 2013) to suggestions similar to wine, close to 400 mg N^{-1} (Valois et al., 2006). Although YAN is not consumed in the actual alcoholic fermentation, it is consumed by the yeast that perform the process, meaning that for enological purposes it can be treated as a consumable substrate. This allows for a potential recommendation for initial YAN to ensure a complete fermentation. As previously indicated, this will be dependent on yeast strain and potentially on the sugar concentration found in the must.

This study will investigate the effect of the relationship between DAP additions and sugar concentrations on fermentation kinetics and examine the effect of proportion of YAN to sugar on fermentation kinetics. The experiments described in this work were conducted to test these three hypotheses:

1) as sugar concentration increases, a higher YAN concentration will be needed to ferment the cider to dryness;

2) low sugar must will be fermentable to dryness at lower YAN concentrations;

3) the proportion of YAN to sugar, that is the interaction between the two factors, has a significant effect on fermentation kinetics.

6.3 Materials and Methods

6.3.1 Source and preparation of juice

The juice used for this experiment was extracted from ‘GoldRush’ apples grown on M.9 rootstock at the Simcoe Research Station in Simcoe, ON in 2017. The trees were planted in 2015 and received regular treatment and care and a full pesticide spray regimen based on local recommendations (OMAFRA, 2015-2016 Publication 360).

Sound fruit was collected, washed, ground in a juicer (Model 8006, Omega, Harrisburg, PA), and pressed using a PowerFist hydraulic press (Princess Auto, Hamilton, ON) in conjunction with custom-made stainless-steel rack-and-cloth setup fitted with cheesecloth. Pressure up to 17,000 kPa was applied twice, with a 30 second rest in between applications. Samples of juice were collected in a clean polyethylene 10 L lidded bucket. Based on the pH of ‘GoldRush’ juice, each bucket of juice was mixed with 500 mg of potassium metabisulfite powder to sterilize the juice (Fisher Scientific, Whitby, ON). The juice was then frozen at -20°C until it was ready to use. The juice was removed from the freezer two days before experiment setup to thaw at 4° C.

For the main experiments, Davis522 yeast (*S. cerevisiae*) was used (Lallemand, Montreal, QC) based upon recommendations from Scott Labs technicians (Scott Labs Canada Niagara on the Lake, ON) for a common yeast with high N requirements. In a preliminary experiment DV10 (Lallemand, Montreal, QC) yeast was also used as it is commonly used in cider production, however it was excluded in further studies because it was found to be too efficient at consuming N.

6.3.2 Fermentation methods

To set up the experiment, juice was separated into 25 and 15 fractions in the first and second experiments, respectively. Sucrose and DAP are common additions in commercial cideries. Table sugar (Redpath, Toronto, ON) was added where required, enclosed in a sealed container with the juice, and shaken until dissolved. DAP (Fisher Scientific, Whitby, ON) was added where required, enclosed in a sealed container with the juice, and shaken until dissolved. An 80 mL portion of supplemented juice was then transferred into a 100 mL glass jar for each replicate (Wide-Mouth Glass Jars - 4 Oz, Plastic Lid, Uline Canada, Milton, ON). Additional controls of 80 mL distilled water were measured into the same style of vessel. Davis522 yeast (Lallemand, Montreal, QC) was activated at 40°C in distilled water at a rate of 30g yeast hL^{-1} water, according to package instructions and scaled down to appropriate values. Using a pipet, 0.1 mL of yeast suspension was added to each treatment. Each jar was then sealed using a #6 bored rubber bung (Kamil Juices, Guelph, ON) fitted with a 3-piece plastic airlock (Kamil Juices, Guelph, ON) filled with distilled water. Each jar was numbered and positioned randomly among plastic trays that were stored in a 15°C incubator (Low Temperature Incubator Model 307C, Fisher Scientific, Whitby, ON).

Each fermentation apparatus was weighed on an analytical scale (Sartorius Laboratory LC 3200 D, Sartorius Lab Instruments, Goettingen, Germany) immediately after inoculation, and then subsequently each day until a constant weight (loss <0.1 g day^{-1}) was recorded indicating that fermentation was complete. The time of measurement as well as the weight of each apparatus were recorded. The difference of the weights between consecutive days was recorded as weight loss and the weight loss of the water controls was averaged and subtracted from the weight loss of the fermentations to account for evaporation from the air locks to calculate the corrected loss. The corrected loss was then added together for all days to record the cumulative weight loss up to that time to measure fermentation.

A graph of time vs. weight loss for each treatment and replication was made and a 6^{th}-order polynomial curve was fitted to each line using Microsoft Excel 2013 in order to interpolate data points from the graph. Each line's first derivative was graphed using a TI-83 Plus graphing calculator (Texas Instruments, Dallas, TX), from which the maximum rate of fermentation, the time at which the maximum rate was achieved, and the time at which the rate was zero, which is when the fermentation stopped, were all determined. These values were then analyzed using SAS 9.4 (The SAS Institute, Cary, NC) with

PROC GLIMMIX, the correlation procedure, and the regression procedure. Normality of residuals and goodness of fit were analyzed for each parameter. The confidence interval used was 95%.

6.3.3 Treatments

Experiment 1

A two-factor factorial experiment was established with five sugar concentrations and five YAN concentrations. Distilled water was used as sugar and YAN controls. For the first factor the sugar concentrations used were: 12.9° Brix (natural sugar concentration of the juice), 14.3° Brix, 15.7° Brix, 17.1° Brix, and 18.5° Brix. The difference between each sugar concentration level represents a 1% change in final alcohol concentrations (Iland, 2004). For the second factor, the following DAP-based YAN concentrations used were: 70 mg N L^{-1} (natural YAN concentration of the juice) 95 mg N L^{-1},120 mg N L^{-1},145 mg N L^{-1}, and 170 mg N L^{-1}. The sugar and YAN concentrations were chosen to represent the natural range of sugar and YAN concentrations found in cider apples, respectively (Tables 4.1 and 4.2). Treatments were replicated 3 times.

Experiment 2

In the proportion-controlled experiment, another two-factor factorial experiment was set up in which the independent variables consisted of the same five sugar concentrations as those described for experiment 1: 12.9° (natural sugar concentration of the juice), 14.3°, 15.7°, 17.1°, and 18.5° Brix in addition to three proportions of YAN to sugar: 5.4, 9.3, and 13.1 mg N L^{-1} per °Brix. The 5.4 mg N L^{-1} per °Brix proportion was the natural proportion found in the juice, while the 13.1 mg N L^{-1} per °Brix proportion was the highest found in the experiment 1. Treatments were replicated 3 times.

6.3.4 Statistical analysis

Data were analyzed using the GLIMMIX procedure in SAS 9.4 (The SAS Institute, Cary, NC). Significance was evaluated at a *p* value of 0.05 and residuals were analyzed for normality and outliers. Post-hoc means separation was analyzed using Tukey-Kramer grouping for least square means (α=0.05). The factors analyzed in Experiment 1 were pre-fermentation sugar concentration, pre-fermentation YAN concentration, and their interaction for the kinetics measurements of maximum fermentation rate, time to maximum fermentation rate, and time to fermentation completion. In Experiment 2 the same kinetics measurements were analyzed with respect to the factors of pre-fermentation sugar concentration, pre-fermentation proportion of YAN to sugar, and their interaction. Additional statistical data can be found in Appendix 1.

6.4 Results

6.4.1 Experiment 1: Effects of varying sugar and YAN concentrations on the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast

The initial sugar concentration of the pre-fermentation must had a significant ($p=0.0003$) effect on the maximum fermentation rate, with the values ranging from 21 to 23 mg CO_2 evolved h^{-1}, with lower initial sugar concentrations corresponding to higher fermentation rates (Table 6.1) 9% higher than the maximum. A statistically significant effect on the time to reach maximum fermentation rate was also observed ($p<0.0001$), ranging from 119 to 132 hr, with the lowest initial sugar concentrations taking 10% less time to reach the maximum rate than the highest (Figure 6.4).

The initial concentration of YAN in the pre-fermentation must had a significant ($p<0.0001$) effect on the maximum fermentation rate, ranging from 16 to 27 mg CO_2 evolved h^{-1}, with the highest initial YAN concentrations having 41% higher fermentation rates than media with the lowest initial YAN concentrations (Table 6.1). A significant effect on the time to maximum fermentation rate was also observed ($p<0.0001$), ranging from 119 to 136 hr, where the highest initial YAN concentrations achieving the maximum rate 13% faster than those with the lowest (Figure 6.4).

When both main effects are considered, their interaction also had a significant ($p=0.0032$) effect on fermentation rate, ranging from 15 to 28 mg CO_2 evolved h^{-1}. Those values on the lower end of the range are typically those with low initial YAN concentrations while those values on the higher end of the range are typically those with high initial YAN concentrations (Table 6.1). A significant ($p=0.0045$) effect was also seen on the time to reach maximum fermentation rate, ranging from 106 to 143 hr. Those values on the faster end of the range were associated with higher initial YAN concentrations and lower initial sugar concentrations (Table 6.1, Figure 6.4).

The initial sugar concentration, initial YAN concentration, and their interaction have a significant ($p<0.0001$) impact on the time to complete fermentation (Table 6.1). As initial sugar concentration increased, the time to complete fermentation increased, ranging from 546 h in low-sugar musts to 714 h in high-sugar musts, 31% more time (Figure 6.4). As initial YAN concentration increased, the must fermented to completeness significantly ($p<0.0001$) faster, ranging from 599 h in high-YAN musts to 710 h in lower-YAN musts, 19% more time. Where the two interact ($p<0.0001$), the fastest fermentations occurred in musts with low initial sugar and high initial YAN. and that the interaction was significant.

6.4.1.1 Proportion of YAN to sugar

The relationship between the proportion of initial YAN to initial sugar concentration in the pre-fermentation must and maximum fermentation rate showed that as proportion increases, the maximum fermentation rate increases (Fig. 6.1; $R^2 = 0.8326$). The relationship between the proportion of initial YAN to initial sugar concentration revealed that as proportion increases, the time to reach the maximum fermentation rate decreases (Fig. 6.2; $R^2 = 0.4273$). The relationship between the proportion of initial YAN to initial sugar concentration and time to completion of fermentation showed that as proportion increases, the time to completion decreases (Fig. 7.3; $R^2 = 0.5013$).

6.4.2 Experiment 2: Effects of proportion of YAN to sugar on fermentation

The initial sugar concentration of the pre-fermentation must significantly ($p<0.0001$) influenced the maximum fermentation rate, which ranged from 16 to 34 mg CO_2 evolved h^{-1} (Figure 6.5). Musts with higher initial sugar concentrations had higher maximum fermentation rates that were nearly twice those of musts with the lowest initial sugar concentrations (Table 6.2). A statistically significant ($p<0.0001$) effect of initial sugar concentration on the time to maximum fermentation rate was also observed, which ranged from 101 to 133 h, where the musts with the lowest initial sugar concentrations were associated with a 24% faster time to reach maximum fermentation rate than those with the highest (Table 6.2).

The initial proportion of YAN to sugar in the pre-fermentation musts had a significant ($p=0.0151$) effect on the maximum fermentation rate, with the values ranging from 24 to 27 mg CO_2 evolved h^{-1}. The middle proportion, 9.3 mg N L^{-1} $°Brix^{-1}$, had the highest maximum fermentation rate (Table 6.2), which was as much as 10% greater than other treatments. Similarly, the initial proportion had a significant ($p=0.0006$) effect on the time taken to reach maximum fermentation rate after inoculation, ranging from 107 to 123 h. Again, the intermediate proportion treatment was the quickest to reach maximum fermentation rate (Table 6.2).

The interaction between initial sugar concentration and the initial proportion of YAN to sugar was also significant ($p<0.0001$) for both maximum fermentation rate and the time to reach maximum fermentation rate. The maximum fermentation rate ranged from 10 to 37 mg CO_2 evolved h^{-1}. The maximum fermentation rate was highest among those samples that were initially higher in sugar (Table 6.2), and were up to 3.7 times greater than other treatments. The time to maximum fermentation rate ranged from 89 to 143 h, with lower initial sugar concentrations being associated with faster times to reach maximum fermentation rate and higher initial proportions being associated with slower times (Table 6.2).

The initial sugar concentration had a significant ($p<0.001$) effect on the time to complete fermentation, with the values ranging from 585 hr to 652 hr with the musts with highest initial sugar concentrations taking up to 11% more time to complete fermentation than the others (Figure 6.5). The initial proportion of YAN to sugar had a significant effect ($p=0.01$) on the time to completion of fermentation, which ranged from 601 to 624 h, with the middle proportion of 9.3 mg N L^{-1} $^{\circ}Brix^{-1}$ exhibiting the fastest time to complete fermentation up to 4% faster than the other proportions (Table 6.2). The interaction between initial sugar concentration and the proportion of YAN to sugar was also significant ($p<0.0001$) for time to completion. The completion times ranged from 571 to 684 h. The fastest times were found with the lowest sugar concentration and highest proportion of YAN to sugar. The slowest fermentation times were found in the musts with the highest sugar and highest proportion of YAN to sugar. The musts with the lowest sugar concentration and the lowest proportion of YAN to sugar had the second-slowest fermentations. Generally, higher initial sugar concentrations and higher initial proportions of YAN to sugar extended the time to completion (Table 6.2).

6.5 Discussion

The first experiment, which varied initial sugar and initial YAN concentrations, supported the hypotheses that initial YAN is the primary factor in determining fermentation rate and yeast growth in apple juice for cider production. The first hypothesis was that as sugar concentration increases, a higher YAN concentration is needed to ferment the cider to dryness. While this experiment showed that higher sugar concentrations significantly increased the time to completion of fermentation and that higher YAN concentrations significantly decreased the time to completion, fermentation was able to progress to dryness even at low YAN concentrations and high sugar concentrations. Past research indicates that N concentrations lower than 100 mg L^{-1} may result in sluggish cider fermentations (Kelkar and Dolan, 2012). The fermentations in this experiment that began with initial N concentrations below 100 mg L^{-1} were indeed slower than those with higher initial N concentrations.

The second hypothesis, that musts with low sugar concentrations will be fermentable to dryness at lower YAN concentrations, was supported by the results, though the musts with the lowest initial sugar and lowest initial YAN concentrations took the longest to ferment completely. The observation that the fermentations in this experiment all ran to dryness, even those with the lowest initial N concentrations, supports the work of Alberti et al. (2011), who suggested that N not be supplemented in apple musts because there was usually adequate N to allow the fermentation to run to completion.

The third hypothesis, that the interaction between YAN and sugar affects fermentation kinetics, is supported by both experiments. The regression analyses in the first experiment showed that the proportion of YAN to sugar had the greatest effect on maximum fermentation speeds, but also that a higher proportion of YAN to sugar reduced the total time to completion. This pointed to the second experiment, in which the proportion of YAN to sugar was a controlled variable. A specific study of the effect of the proportion of YAN to sugar does not appear in the cider literature to date. For a cider producer, an ideal proportion of YAN to sugar would first ensure the completion of fermentation while allowing for desired flavour development, which is limited in fast fermentations like those found when YAN is over-supplemented (Alberti et al., 2011; S. J. Bell & Henschke, 2005; Carrau et al., 2008).

The results of the proportion-controlled experiment were more complex than the first experiment. Like the first experiment, every fermentation progressed to completion without difficulty. The time to reach maximum fermentation rate and time to completion increased with the initial sugar concentration. Contrary to the results from the first experiment, where the maximum fermentation rate decreased slightly, the proportion-controlled experiment showed that as the sugar concentration increased, the maximum fermentation rate increased significantly and with greater change than when the sugar concentration increased in the proportion-controlled experiment. This change is likely due to the significant interaction between the initial sugar concentration and the initial proportion of YAN to sugar.

The proportion-controlled experiment demonstrates that the “strongest” fermentations (highest maximum rate, fastest time to maximum rate, and fastest time to completion) were usually associated with the middle sugar: YAN proportion of 9.3 mg N L^{-1} : 1 °Brix, which indicates that the interaction between sugar and YAN is important and that different proportions in and of themselves can lead to different fermentation patterns. This supports the overall hypothesis that an ideal proportion of YAN to sugar exists for a given yeast strain. The fermentation of the natural juice, with no sugar or DAP additions, took on a different fermentation pattern than the other samples (Figure 6.5), indicating that the very addition of juice amendments may have an impact on yeast development.

6.6 Summary and Conclusion

This research indicates that sugar and YAN concentration do not act independently of one another in the fermentation of apple juice into cider. Although the relationship isn’t consumptive, each contributes to fermentation kinetics. Consistent with studies in wine, YAN is most important in establishing a yeast population early in the fermentation process, while sugar sustains that population as it converts the sugar into alcohol and carbon dioxide (Gutiérrez et al., 2012). Higher sugar concentration appears to increase the maximum fermentation rate, though increasing the time for that rate to be achieved. Given that there is more substrate to ferment, it is sensible that increased sugar concentrations increase the total fermentation time.

Although direct additions of YAN generally increase speed of fermentation, including the maximum rate and total time to completion, an increased proportion of YAN to sugar tends to decrease the speed of fermentation relative to other juices with the same initial sugar concentration. The significant interaction between the two implies that there is an optimal proportion of YAN to sugar for any particular yeast strain, a matter that can be pursued in the future by running similar experiments with different yeast strains and a different array of proportions.

For cider makers, this research reinforces the importance of measuring the YAN concentrations in juice before fermentation begins. When choosing to add YAN in the form of DAP or sugar to the must, cider makers should pay attention to the ratio of YAN to soluble solids, particularly as further research is done to determine the ideal proportion.

Further avenues for future research include measuring the chemical and sensory effects of the sugar and YAN factors on the fermented ciders, incorporating pH as a factor, measuring the residual N and amino acids in the cider, evaluating the effects of sugar composition (glucose to fructose ratio) on fermentation kinetics, and evaluating the specific effects of YAN composition (amino acid and ammonium concentrations) on fermentation kinetics. This is relevant in light of past research that showed that aspartate and glutamate are more readily assimilable by yeast than other nitrogenous compounds (Eleutério dos Santos et al., 2016). Though other research indicates that the source of N does not have the same degree of effect on fermentation rate and yeast growth that the concentration of N does (Gutiérrez et al., 2012). Continued studies should also investigate the role of yeast strain, microbial diversity, and other major juice attributes in YAN utilization in fermentation.

6.7 Tables and Figures

Table 6.1. Kinetics of the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast and varying concentrations of sugar and YAN. University of Guelph, Guelph, Ontario, 2019.

Treatment	Maximum Fermentation Rate (g CO_2 evolved h^{-1})^z	Time to Maximum Rate (h)	Time to Completion (h)
Main Effects			
Sugar (°Brix)			
12.9	0.023 a	119 c	546 c
14.3	0.022 ab	124 bc	665 b
15.7	0.022 bc	129 ab	690 ab
17.1	0.022 bc	130 ab	701 a
18.5	0.021 c	132 a	714 a
P Value	0.0003	<.0001	<.0001
YAN (mg N L^{-1})			
70	0.016 e	136 a	706 ab
95	0.020 d	129 ab	710 a
120	0.022 c	127 b	679 b
145	0.025 b	123 bc	622 c
170	0.027 a	119 c	599 c
P Value	<.0001	<.0001	<.0001
Simple Effects			
12.9° Brix * 70 (mg N L-1)	0.017 nop	136 abc	636 f
12.9° Brix * 95 (mg N L-1)	0.022 fghijk	115 d	646 ef
12.9° Brix * 120 (mg N L-1)	0.023 efghij	119 bcd	642 ef
12.9° Brix * 145 (mg N L-1)	0.025 bcdef	121 abcd	468 g
12.9° Brix * 170 (mg N L-1)	0.028 ab	106 d	338 h
14.3° Brix * 70 (mg N L-1)	0.017 mnop	134 abc	682 abcdef
14.3° Brix * 95 (mg N L-1)	0.021 ijkl	123 abcd	713 abcdef
14.3° Brix * 120 (mg N L-1)	0.024 defghi	119 bcd	651 def
14.3° Brix * 145 (mg N L-1)	0.024 defghi	124 abcd	638 f
14.3° Brix * 170 (mg N L-1)	0.027 abc	120 bcd	643 ef
15.7° Brix * 70 (mg N L-1)	0.017 nop	140 ab	729 abcd
15.7° Brix * 95 (mg N L-1)	0.020 klm	138 ab	729 abcd
15.7° Brix * 120 (mg N L-1)	0.022 ghijk	126 abcd	651 cdef
15.7° Brix * 145 (mg N L-1)	0.025 bcdefg	119 bcd	649 def
15.7° Brix * 170 (mg N L-1)	0.026 abcde	121 abcd	693 abcdef
17.1° Brix * 70 (mg N L-1)	0.016 op	127 abcd	741 ab
17.1° Brix * 95 (mg N L-1)	0.019 klmn	134 abc	721 abcde
17.1° Brix * 120 (mg N L-1)	0.022 hijk	133 abc	708 abcdef
17.1° Brix * 145 (mg N L-1)	0.025 abcdef	124 abcd	673 abcdef
17.1° Brix * 170 (mg N L-1)	0.026 abcd	131 abc	660 bcdef
18.5° Brix * 70 (mg N L-1)	0.015 p	143 a	740 abc
18.5° Brix * 95 (mg N L-1)	0.019 lmno	135 abc	743 a
18.5° Brix * 120 (mg N L-1)	0.021 jkl	140 ab	744 a
18.5° Brix * 145 (mg N L-1)	0.025 cdefgh	126 abcd	682 abcdef
18.5° Brix * 170 (mg N L-1)	0.028 a	118 bcd	659 cdef
P value	0.0032	0.0045	<.0001

^{z} Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

Table 6.2. Kinetics of the fermentation of 2017 ‘GoldRush’ apple juice with Davis522 yeast and varying concentrations of sugar and proportions of YAN to sugar. University of Guelph, Guelph, Ontario, 2019.

Treatment	Maximum Fermentation Rate (g CO_2 evolved h^{-1})[z]	Time to Maximum Rate (h)	Time to Completion (h)
Main Effects			
Sugar (°Brix)			
12.9	0.016 e	108 b	606 bc
14.3	0.019 d	101 b	585 c
15.7	0.027 c	107 b	605 bc
17.1	0.031 b	121 a	619 bc
18.5	0.034 a	133 a	652 a
P Value	<.0001	<.0001	<.0001
Proportion of YAN (mg N L^{-1}) to Sugar (°Brix)			
5.4	0.025 ab	112 b	615 ab
9.3	0.027 a	107 b	601 b
13.1	0.024 b	123 a	624 a
P Value	0.0151	0.0006	0.01
Simple Effects			
12.9°Brix * 5.4	0.010 f	135 ab	668 ab
12.9° Brix * 9.3	0.019 e	89 d	578 d
12.9° Brix * 13.1	0.018 e	99 cd	571 d
14.3° Brix * 5.4	0.018 e	99 cd	588 d
14.3° Brix * 9.3	0.021 de	92 cd	581 d
14.3° Brix * 13.1	0.019 e	112 bcd	586 d
15.7° Brix * 5.4	0.028 bc	101 cd	615 bcd
15.7° Brix * 9.3	0.028 bc	100 cd	580 d
15.7° Brix * 13.1	0.025 cd	120 abc	621 bcd
17.1° Brix * 5.4	0.033 ab	109 bcf	600 cd
17.1° Brix * 9.3	0.033 ab	116 abcd	597 d
17.1° Brix * 13.1	0.028 bc	139 ab	659 abc
18.5° Brix * 5.4	0.037 a	118 abcd	603 cd
18.5° Brix * 9.3	0.034 ab	137 ab	668 ab
18.5° Brix * 13.1	0.032 ab	143 a	684 a
P value	<.0001	<.0001	<.0001

[z] Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's Test of Least Square Means

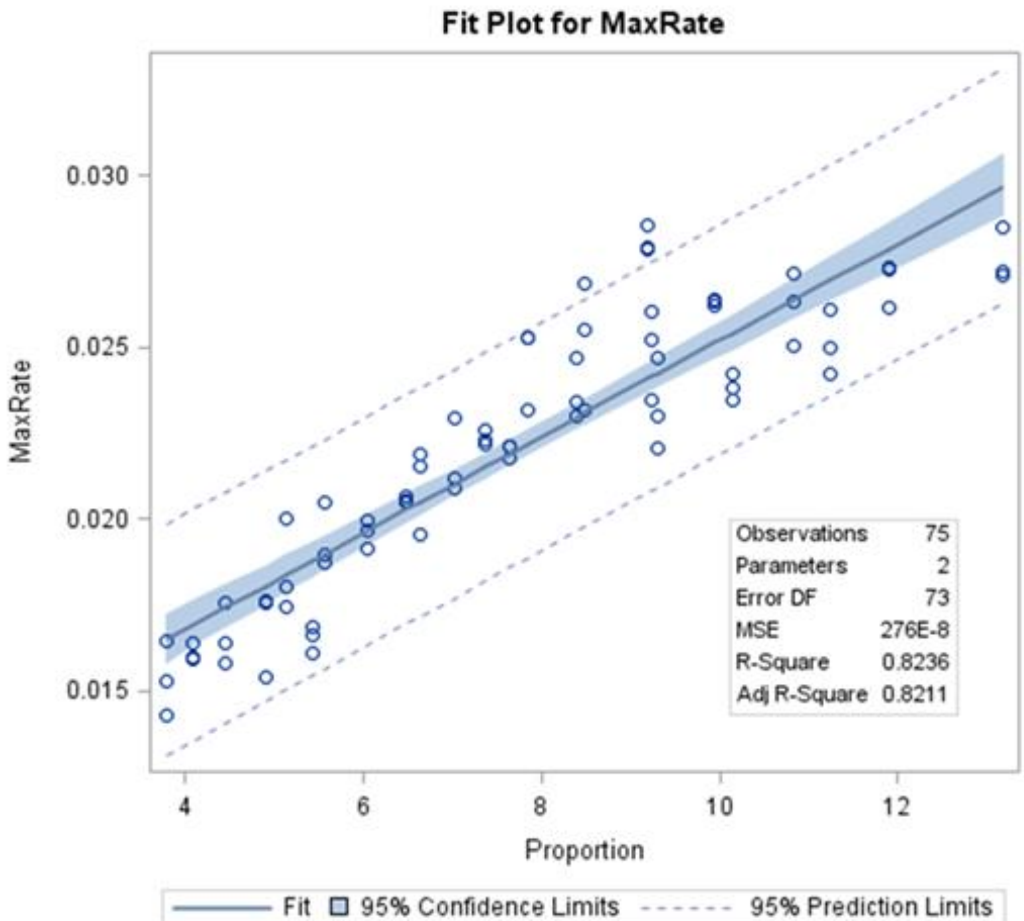

Figure 6.1 Regression line for proportion of YAN to sugar and the maximum fermentation rate (g CO_2 evolved hr^{-1} in January 2019.

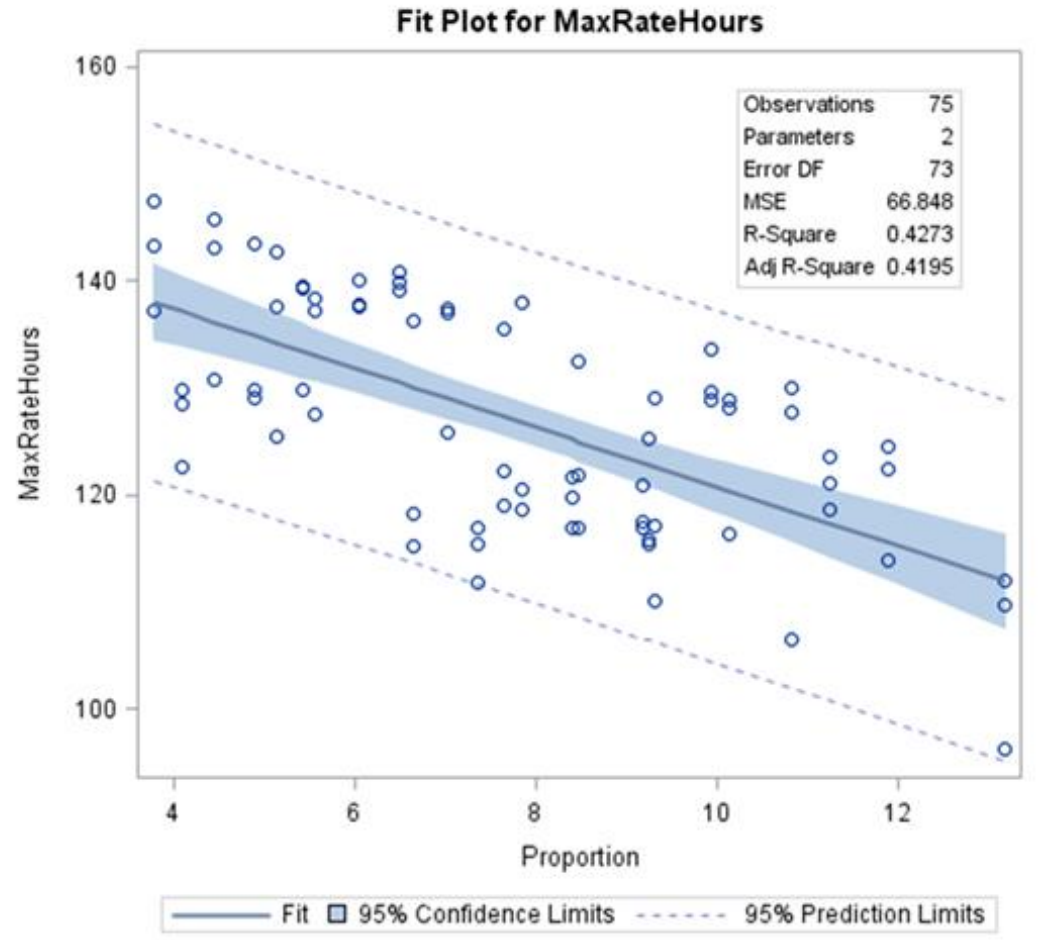

Figure 6.2 Regression line for proportion of YAN to sugar and the time to maximum fermentation rate in January 2019.

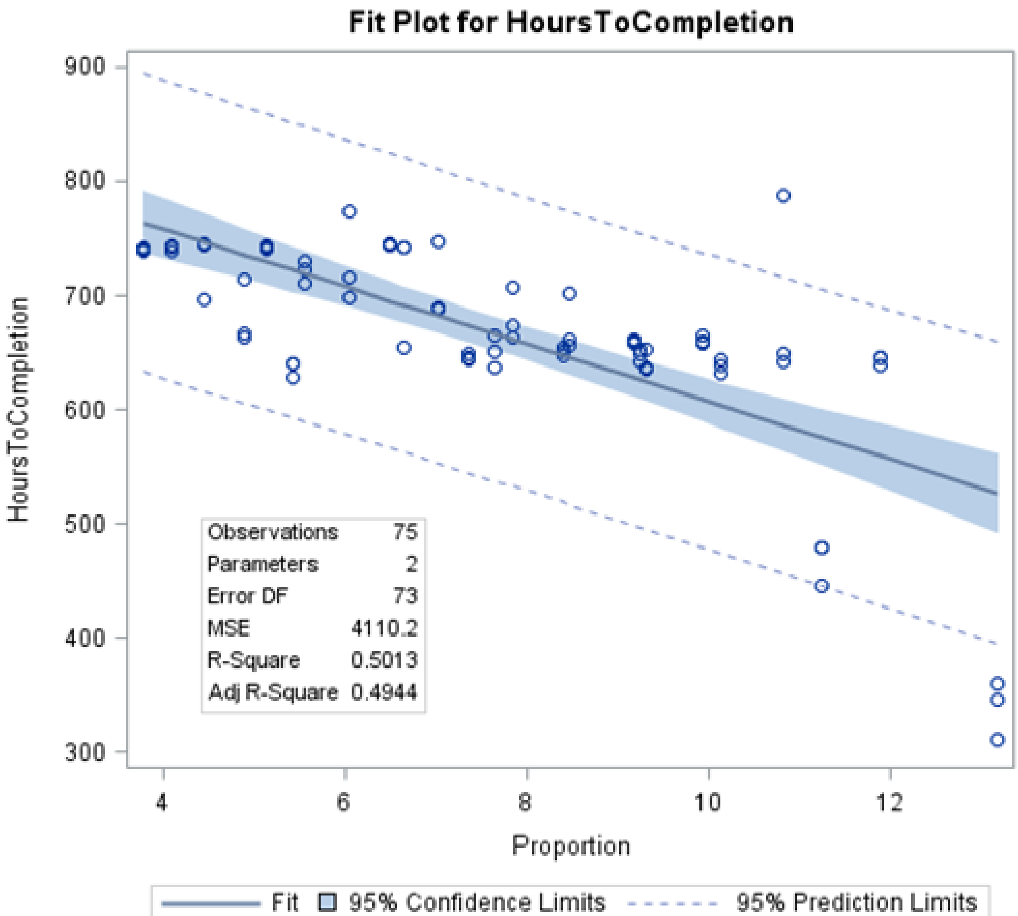

Figure 6.3 Regression line for proportion of YAN to sugar and the time to complete fermentation in January 2019.

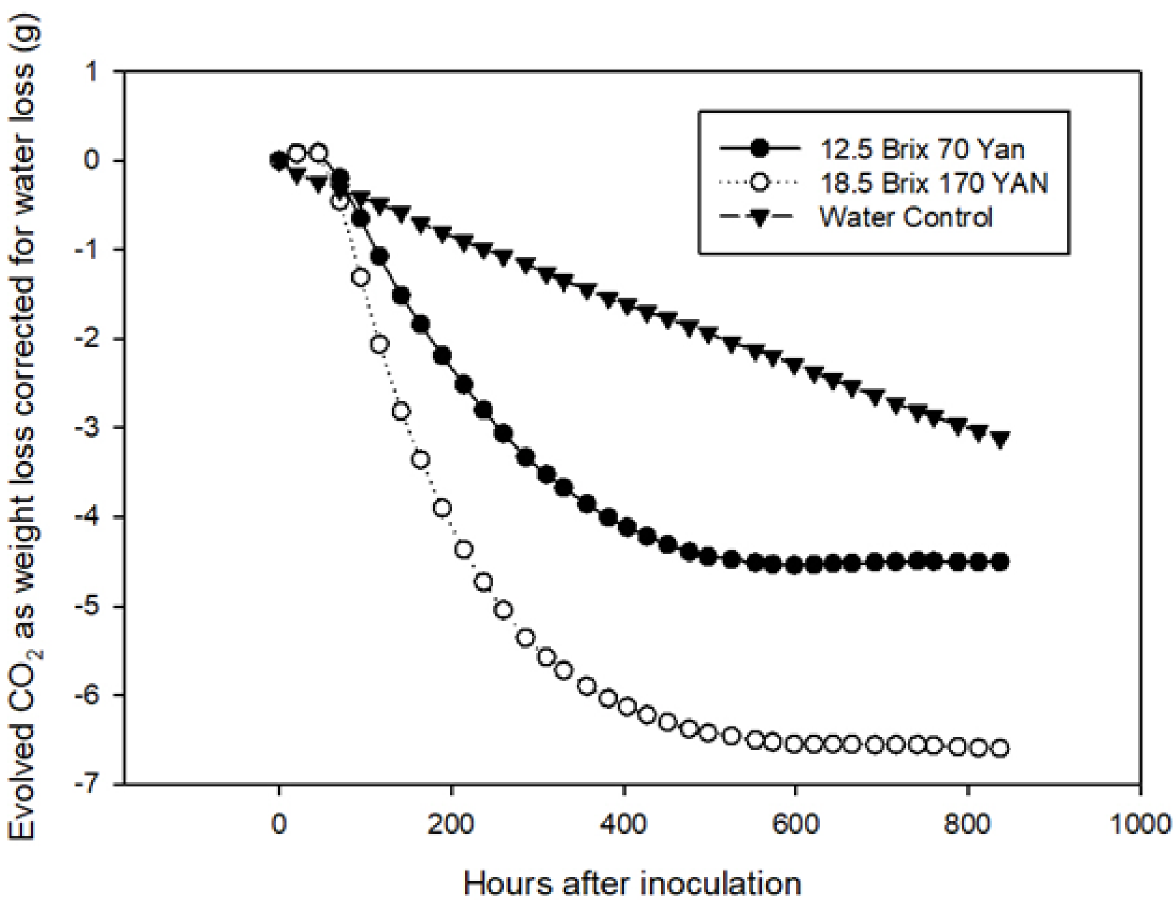

Figure 6.4 The progression of fermentation in the GoldRush musts with the lowest and highest YAN and sugar concentrations fermented with Davis522 yeast. January 2019.

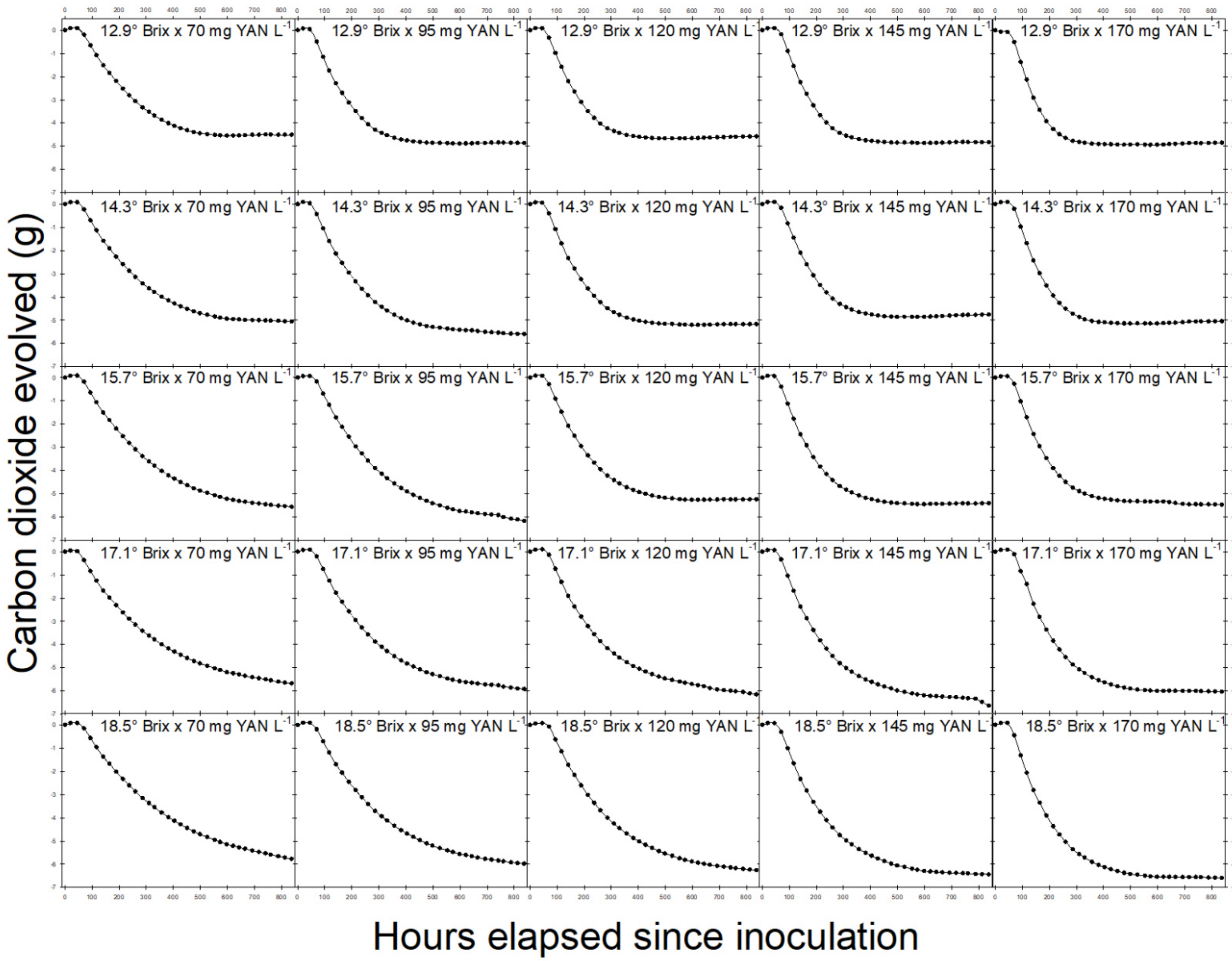

Figure 6.5 The progression of fermentation of 2017 GoldRush apple juice with Davis522 yeast based on the effects of varying sugar concentrations by sucrose supplementation and YAN concentrations by DAP supplementation.

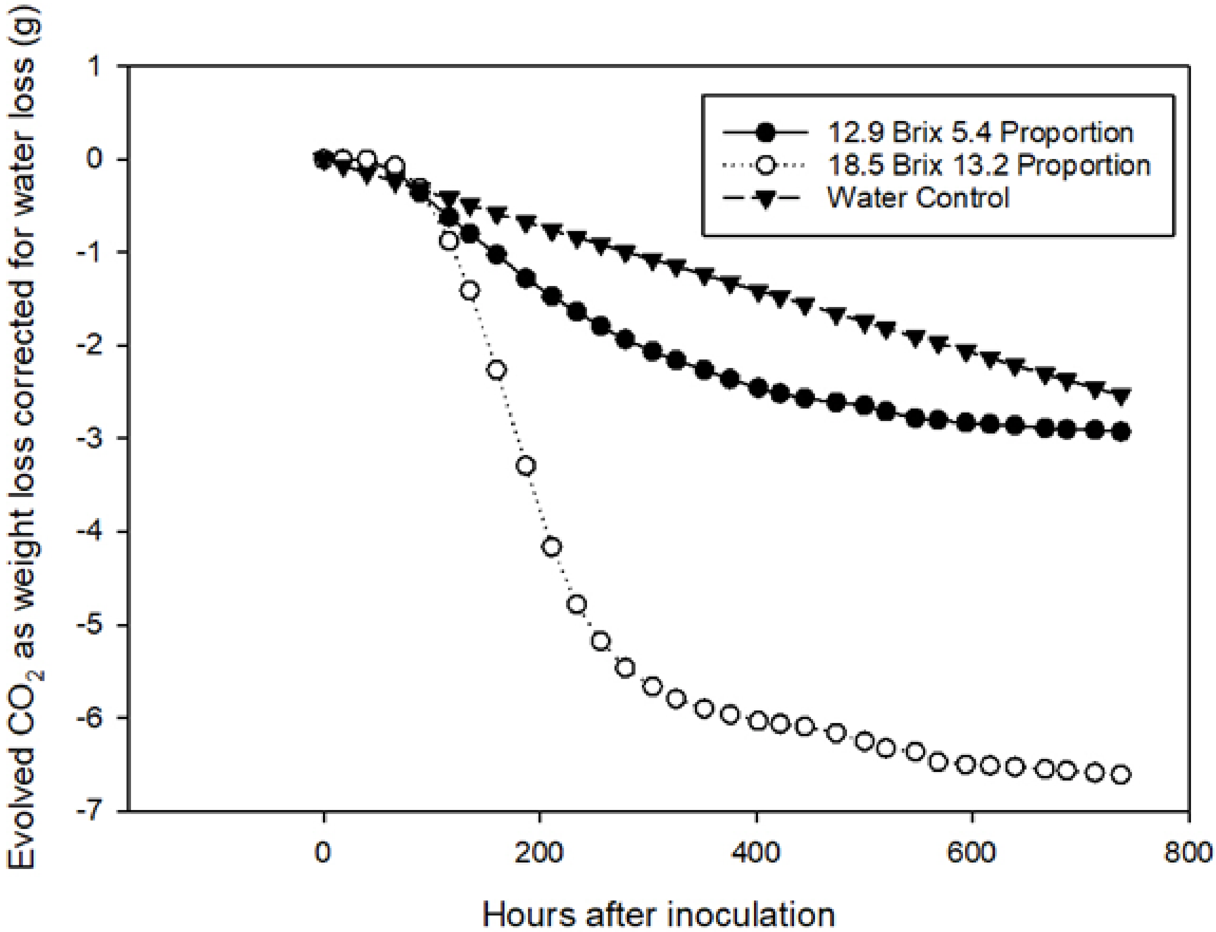

Figure 6.6 The progression of fermentation in the GoldRush musts with the lowest and highest proportions of YAN to sugar concentrations fermented with Davis522 yeast. March 2019.

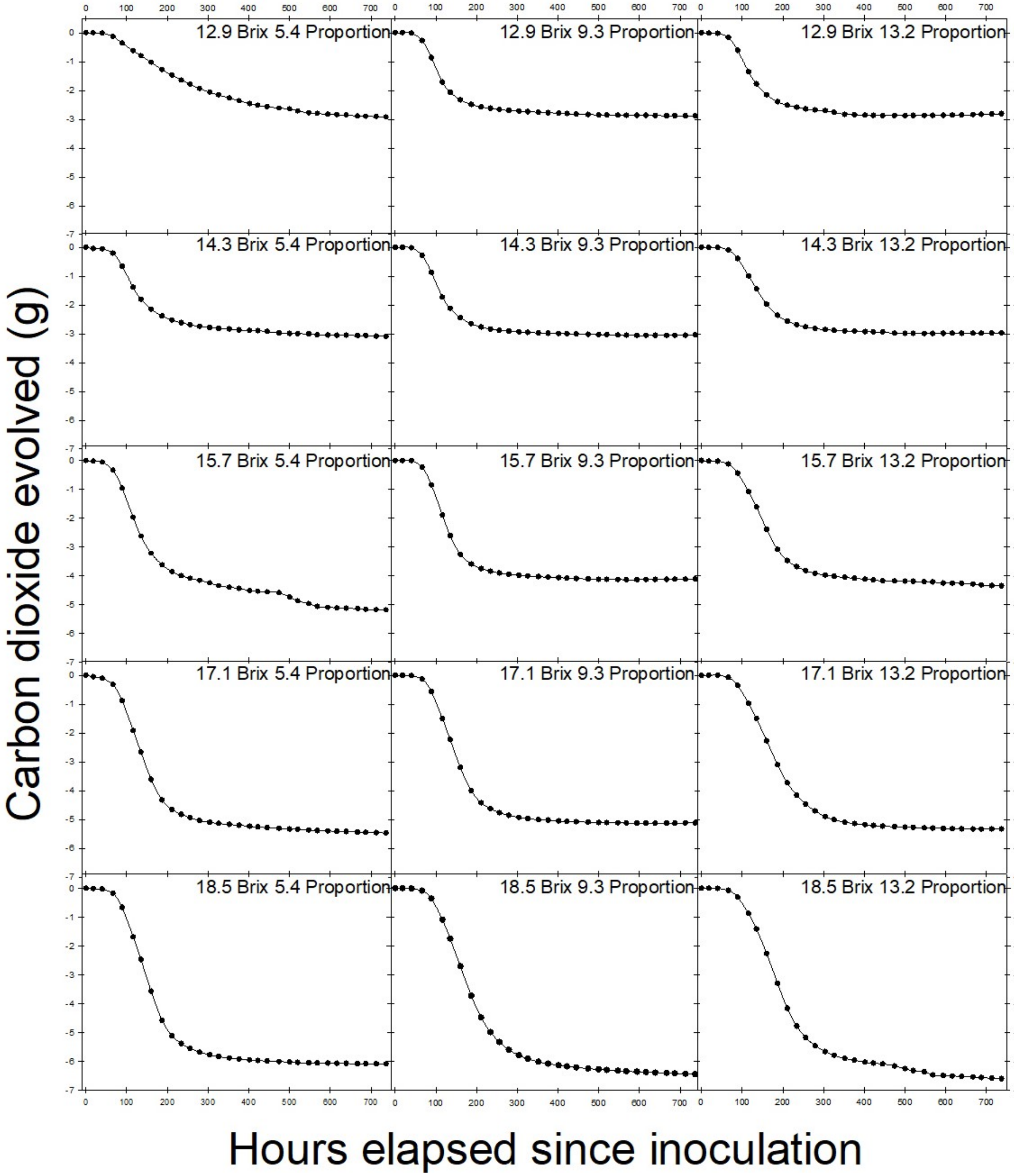

Figure 6.7 The progression of fermentation of 2017 GoldRush apple juice with Davis522 yeast based on the effects of varying sugar concentrations by sucrose supplementation and the proportion of YAN to sugar concentrations by sucrose and DAP supplementation.

7 General Discussion and Conclusion

7.1 Implications of this research

Cider as a product is the culmination of hundreds of factors. The major factors that affect its final attributes can be influenced by orchard growers and cider makers. Rather than being a simple alcoholic beverage constructed in a lab it is a complex agricultural *produit de terroir*.

7.1.1 Cultivar experiments

By choosing the correct cultivars to grow, orchardists can maximize the amount of juice they produce while maintaining the quality of fruit needed for fine cider production. By choosing the proper cultivars for juice and blending them accordingly, cider makers can craft a pre-fermentation must that hits the proper balance of nutrient and aromatic attributes that they desire to make their final cider. Future evaluations of these cultivars should include analyses of specific polyphenol and aromatic compounds and the effects of horticultural practices and the environment on the fruit, particularly yield and juice attributes. Cultivars that show promise for continued research in Ontario due to their horticultural suitability and juice characteristics include ‘Binet Rouge’, ‘Bramley’s Seedling’, ‘Breakwell’, ‘Bulmers Norman’, ‘Calville Blanc d’Hiver’, ‘Cline Russet’, ‘Cox Orange Pippin’, ‘Crimson Crisp®’, ‘Dabinett’, ‘Enterprise’, ‘Esopus Spitzenberg’, ‘Golden Russet’, ‘GoldRush’, ‘Medaille d’Or’, ‘Porter’s Perfection’, and ‘Stoke Red’.

7.1.2 Fertilization experiments

The fertilization experiments showed us how key attributes can be manipulated in the orchard by choosing how to treat the trees. Although this experiment didn’t result in a practical proposal, it worked as a proof of concept. Inorganic nitrogen in the orchard and came out with increased organic nitrogen in the juice. The total YAN concentration in ‘Crimson Crisp®’ apples drops from the period shortly after fruit set to the end of summer, but it does not change from several weeks before harvest to harvest, nor does the total change after a 6-week post-harvest storage period. High levels of foliar urea spray fertilization will lead to an increase in aspartic acids and asparagine in ‘Crimson Crisp®’ apple juice. Future research should look at the variation in amino acid composition among different apple cultivars. The effects of different maceration and extraction times and techniques could also contribute to the composition of YAN in the juice of mature fruit.

7.1.3 Fermentation experiments

The fermentation experiment demonstrated that YAN and sugar do not act independently in a fermentation system and that YAN is a nutrient class that should be regularly evaluated by cider producers. As YAN concentrations stabilize well ahead of harvest, cider producers may have a longer window to make those determinations than previously thought. When choosing to add DAP, complex yeast nutrients, or sugar to must, cider makers should pay attention to the ratio of YAN to soluble solids, particularly as further research is done to determine the ideal proportion.

Further avenues for future research include measuring the chemical and sensory effects of the sugar and YAN factors on the fermented ciders, incorporating pH as a factor, measuring the residual N and amino acids in the cider, evaluating the effects of sugar composition (glucose to fructose ratio) on fermentation kinetics, and evaluating the specific effects of YAN composition (amino acid and ammonium concentrations) on fermentation kinetics.

7.2 State and future of cider research

Now that we have identified cultivars that are suitable for cultivation Ontario, the real work of understanding how their juice and cider can be enhanced and put to market can commence. These factors can be considered when developing a sustainable and fruitful cider industry that will grow in Ontario for years to come. This work will require interdisciplinary cooperation, including the horticulturists, food scientists, microbiologists, and environmental scientists along with industry members and representatives. As the cider industry grows it can be supported and driven by scientific inquiry in a way that broadly impacts and guides community food and beverage production systems

7.2.1 Direction of research for horticultural and juice attributes of apple cultivars

The cultivars that are were studied in this research program have diverse origins, including cultivars that were traditionally grown for cider in France and England and cultivars that have been bred in modern times for disease resistance and cold hardiness. The worldwide variation in climatic regions means that direct comparisons between cultivars grown in different parts of the world can be misleading, however these data allow us to make predictions about the performance of cultivars in other regions. Based on the variation in apple tree performance among cultivars grown in different regions, the first step in assessing the suitability for cider cultivars in Ontario is to measure their horticultural performance through the collection of phenology, vigour, and yield data.

Research on cider apples includes understanding how best to grow antique and traditional cultivars, breeding for desirable technical attributes, and understanding the relationship between the origins of a cultivar and its attributes. Once suitable cultivars are identified, further horticultural research on these varieties can continue, including the analysis of novel rootstocks and the omission or use of phytosanitary inputs. Cider apple production has been reputed to require fewer fungicidal treatments than culinary apple production (Provost, 2018) and fruit quality in both integrated pest management systems and organic cropping systems have shown to be consistent (Peck & Merwin, 2010), so a study on the effects of low-input cropping systems on cider quality is a potential direction for the future.

After the base characterization of the cultivars with regards to sugar, acid, polyphenols, and nitrogen, cultivars can be identified as candidates for further research. These cultivars can be analyzed for composition of their sugar, acid, polyphenol, nitrogen, and aromatic attributes. If the attributes can be linked to apple genetics, they could be used for breeding. Used in conjunction with horticultural data, juice data can be used to recommend apple cultivars for cider production in Ontario.

7.2.2 Direction of research for nitrogen development in apples

Nitrogenous compounds develop and change in apple fruits during fruit growth and development (Blanco Gomis et al., 1990) and both foliar and soil-applied fertilizer affect those compounds (Toselli et al., 2000). Despite that, it is unclear exactly which compounds are affected by the addition of fertilizer. As nitrogenous compounds affect flavour development during fermentation, understanding how they change and can be manipulated in the orchard will allow cider producers to better plan for their fermentations. Research to be done includes measuring how nitrogenous compounds in fruit and juice change over the growing season and in response to fertilization.

7.2.3 Direction of research for cider fermentation

Although there is a great body of work related to nitrogen in wine, most of that work has not been applied to cider. Once in the winery there should be many similarities, but apple juice is still a different medium from grape juice (Kelkar & Dolan, 2012). Yeast strain and initial YAN concentration are important factors in determining whether a fermentation will proceed to dryness in cider (Alberti et al., 2011), defined as having a residual sugar concentration below 0.4% (Bisson, 1999). It is not completely clear, however, whether musts with low sugar concentration require less YAN for yeast to ferment them to dryness than musts with higher sugar concentrations. There may be a way to suggest for a particular yeast strain an ideal proportion of YAN concentration to sugar concentration.

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APPENDICES

Appendix 1 Statistical tests

Statistics information organized by table and figure:

Table 3.1. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 81

Average selected fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	24.95	<.0001

Fit Statistics

-2 Res Log Likelihood	916.04
AIC (smaller is	974.04
AICC (smaller is	1000.4
BIC (smaller is	1048.41
CAIC (smaller is better)	1077.41
HQIC (smaller is better)	1004.1
Pearson Chi-Square	51305.18
Pearson Chi-Square / DF	534.43

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.86319	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.13733	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.45934	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	3.18169	Pr > A-Sq	<0.0050

Table 3.1. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 81

Juice extraction efficiency

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	14.24	<.0001

Fit Statistics

-2 Res Log Likelihood	-336.14
AIC (smaller is	-278.14
AICC (smaller is	-251.78
BIC (smaller is	-203.77
CAIC (smaller is better)	-174.77
HQIC (smaller is better)	-248.08
Pearson Chi-Square	0.11
Pearson Chi-Square / DF	0

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.96106	**Pr < W**	0.0012
Kolmogorov-Smirnov	**D**	0.09782	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.24843	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	1.48883	**Pr > A-Sq**	<0.0050

Table 3.1. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 81

Days to harvest

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	733.92	<.0001

Fit Statistics

-2 Res Log Likelihood	380.33
AIC (smaller is	438.33
AICC (smaller is	464.7
BIC (smaller is	512.7
CAIC (smaller is better)	541.7
HQIC (smaller is better)	468.39
Pearson Chi-Square	193.5
Pearson Chi-Square / DF	2.02

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.96099	Pr < W	0.0012
Kolmogorov-Smirnov	D	0.12168	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.26099	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.53285	Pr > A-Sq	<0.0050

Table 3.1. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 81

Full bloom date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	36.3	<.0001

Fit Statistics

-2 Res Log Likelihood	380.83
AIC (smaller is	438.83
AICC (smaller is	465.19
BIC (smaller is	513.19
CAIC (smaller is better)	542.19
HQIC (smaller is better)	468.89
Pearson Chi-Square	194.5
Pearson Chi-Square / DF	2.03

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.92977	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.21396	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.76752	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	3.78521	Pr > A-Sq	<0.0050

Table 3.1. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 81

Harvest date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	96	108297	<.0001

Fit Statistics	
-2 Res Log Likelihood	-125.13
AIC (smaller is	-67.13
AICC (smaller is	-40.77
BIC (smaller is	7.23
CAIC (smaller is better)	36.23
HQIC (smaller is better)	-37.07
Pearson Chi-Square	1
Pearson Chi-	0.01

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.93693	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.17319	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.556	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	3.00935	**Pr > A-Sq**	<0.0050

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 82

Average selected fruit weight

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	87	60.41	<.0001

Fit Statistics	
-2 Res Log Likelihood	746.41
AIC (smaller is	804.41
AICC (smaller is	834.94
BIC (smaller is	875.92
CAIC (smaller is better)	904.92
HQIC (smaller is better)	833.21
Pearson Chi-Square	17268.5
Pearson Chi-	198.49

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.9587	**Pr < W**	0.0013
Kolmogorov-Smirnov	**D**	0.08429	**Pr > D**	0.0439
Cramer-von Mises	**W-Sq**	0.14464	**Pr > W-Sq**	0.0281
Anderson-Darling	**A-Sq**	1.19764	**Pr > A-Sq**	<0.0050

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 82

Juice extraction efficiency

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	86	23.09	<.0001

Fit Statistics

-2 Res Log Likelihood	-283.44
AIC (smaller is	-225.44
AICC (smaller is	-194.36
BIC (smaller is	-154.26
CAIC (smaller is better)	-125.26
HQIC (smaller is better)	-196.79
Pearson Chi-Square	0.12
Pearson Chi-	0

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.84064	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.20846	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.12693	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	6.19274	Pr > A-Sq	<0.0050

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 82

Days to harvest

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	87	2132.92	<.0001

Fit Statistics

-2 Res Log Likelihood	283.24
AIC (smaller is	341.24
AICC (smaller is	371.76
BIC (smaller is	412.75
CAIC (smaller is better)	441.75
HQIC (smaller is better)	370.03
Pearson Chi-Square	84.17
Pearson Chi-	0.97

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.96687	**Pr < W**	0.006
Kolmogorov-Smirnov	**D**	0.09344	**Pr > D**	0.015
Cramer-von Mises	**W-Sq**	0.17359	**Pr > W-Sq**	0.0118
Anderson-Darling	**A-Sq**	1.02144	**Pr > A-Sq**	0.0106

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 82

Full bloom date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	87	23.7	<.0001

Fit Statistics	
-2 Res Log Likelihood	283.24
AIC (smaller is	341.24
AICC (smaller is	371.76
BIC (smaller is	412.75
CAIC (smaller is better)	441.75
HQIC (smaller is better)	370.03
Pearson Chi-Square	84.17
Pearson Chi-	0.97

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.9166	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.21346	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.69171	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	4.03008	**Pr > A-Sq**	<0.0050

Table 3.2. Horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 82

Harvest date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	87	#######	<.0001

Fit Statistics

-2 Res Log Likelihood	-2044.27
AIC (smaller is	-1986.27
AICC (smaller is	-1955.74
BIC (smaller is	-1914.75
CAIC (smaller is better)	-1885.75
HQIC (smaller is better)	-1957.47
Pearson Chi-Square	0
Pearson Chi-	0

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.95293	Pr < W	0.0005
Kolmogorov-Smirnov	D	0.12995	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.31428	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.79337	Pr > A-Sq	<0.0050

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

Spring 2015 TCSA

Fit Statistics
-2 Res Log Likelihood -144.85
AIC (smaller is better) -84.85
AICC (smaller is better) -81.27
BIC (smaller is better) 44.50
CAIC (smaller is better) 74.50
HQIC (smaller is better) -34.31
Pearson Chi-Square 21.19
Pearson Chi-Square / DF 0.04

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 551 21.78 <.0001

Tests for Normality
Test Statistic p Value
Shapiro-Wilk W 0.951101 Pr < W <0.0001
Kolmogorov-Smirnov D 0.071899 Pr > D <0.0100
Cramer-von Mises W-Sq 0.79378 Pr > W-Sq <0.0050
Anderson-Darling A-Sq 5.007092 Pr > A-Sq <0.0050

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

Fall 2015 TCSA

Fit Statistics
-2 Res Log Likelihood 548.35
AIC (smaller is better) 608.35
AICC (smaller is better) 611.96
BIC (smaller is better) 737.37
CAIC (smaller is better) 767.37
HQIC (smaller is better) 658.79
Pearson Chi-Square 74.46
Pearson Chi-Square / DF 0.14

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 545 20.70 <.0001

Tests for Normality
Test Statistic p Value
Shapiro-Wilk W 0.975878 Pr < W <0.0001
Kolmogorov-Smirnov D 0.062418 Pr > D <0.0100
Cramer-von Mises W-Sq 0.562277 Pr > W-Sq <0.0050
Anderson-Darling A-Sq 3.242021 Pr > A-Sq <0.0050

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

Fall 2016 TCSA

Fit Statistics
-2 Res Log Likelihood 1521.62
AIC (smaller is better) 1581.62
AICC (smaller is better) 1585.27
BIC (smaller is better) 1710.43
CAIC (smaller is better) 1740.43
HQIC (smaller is better) 1631.99
Pearson Chi-Square 449.68
Pearson Chi-Square / DF 0.83

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 541 26.93 <.0001

Tests for Normality
Test Statistic p Value
Shapiro-Wilk W 0.949753 Pr < W <0.0001
Kolmogorov-Smirnov D 0.100094 Pr > D <0.0100
Cramer-von Mises W-Sq 1.238438 Pr > W-Sq <0.0050
Anderson-Darling A-Sq 7.407211 Pr > A-Sq <0.0050

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

Fall 2017 TCSA

Fit Statistics
-2 Res Log Likelihood 2021.07
AIC (smaller is better) 2081.07
AICC (smaller is better) 2084.73
BIC (smaller is better) 2209.82
CAIC (smaller is better) 2239.82
HQIC (smaller is better) 2131.43
Pearson Chi-Square 1137.51
Pearson Chi-Square / DF 2.11

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 540 32.59 <.0001

Tests for Normality
Test Statistic p Value
Shapiro-Wilk W 0.915965 Pr < W <0.0001
Kolmogorov-Smirnov D 0.121481 Pr > D <0.0100
Cramer-von Mises W-Sq 2.189355 Pr > W-Sq <0.0050
Anderson-Darling A-Sq 12.83525 Pr > A-Sq <0.0050

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

Fall 2018 TCSA

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	540	42.9	<.0001

Fit Statistics

-2 Res Log Likelihood	2663.37
AIC (smaller is	2721.37
AICC (smaller is	2724.79
BIC (smaller is	2845.83
CAIC (smaller is better)	2874.83
HQIC (smaller is better)	2770.05
Pearson Chi-Square	3753.32
Pearson Chi-	6.95

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

2017 relative growth

Tests for Normality
Test Statistic p Value
Shapiro-Wilk W 0.918043 Pr < W <0.0001
Kolmogorov-Smirnov D 0.105536 Pr > D <0.0100
Cramer-von Mises W-Sq 2.165423 Pr > W-Sq <0.0050
Anderson-Darling A-Sq 12.81539 Pr > A-Sq <0.0050

Fit Statistics
-2 Res Log Likelihood 1625.98
AIC (smaller is better) 1685.98
AICC (smaller is better) 1689.63
BIC (smaller is better) 1814.73
CAIC (smaller is better) 1844.73
HQIC (smaller is better) 1736.33
Pearson Chi-Square 547.27
Pearson Chi-Square / DF 1.01

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 540 26.44 <.0001

Table 3.3. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 83

2018 relative growth

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	539	37.18	<.0001

Fit Statistics

-2 Res Log Likelihood	2136.65
AIC (smaller is	2194.65
AICC (smaller is	2198.07
BIC (smaller is	2319.05
CAIC (smaller is better)	2348.05
HQIC (smaller is better)	2243.31
Pearson Chi-Square	1422.65
Pearson Chi-	2.64

Table 3.4. Height and width growth of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 84

2015 height

Fit Statistics
-2 Res Log Likelihood -268.14
AIC (smaller is better) -208.14
AICC (smaller is better) -204.52
BIC (smaller is better) -79.12
CAIC (smaller is better) -49.12
HQIC (smaller is better) -157.70
Pearson Chi-Square 16.64
Pearson Chi-Square / DF 0.03

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 545 28.99 <.0001

2016 height

Fit Statistics
-2 Res Log Likelihood -48.47
AIC (smaller is better) 11.53
AICC (smaller is better) 15.19
BIC (smaller is better) 140.22
CAIC (smaller is better) 170.22
HQIC (smaller is better) 61.87
Pearson Chi-Square 24.58
Pearson Chi-Square / DF 0.05

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 539 44.50 <.0001

Table 3.4. Height and width growth of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 84

2017 height

Fit Statistics
-2 Res Log Likelihood -43.96
AIC (smaller is better) 16.04
AICC (smaller is better) 19.69
BIC (smaller is better) 144.78
CAIC (smaller is better) 174.78
HQIC (smaller is better) 66.39
Pearson Chi-Square 24.84
Pearson Chi-Square / DF 0.05

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 540 25.89 <.0001

2018 height

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	540	18.6	<.0001

Fit Statistics

-2 Res Log Likelihood	118.59
AIC (smaller is	176.59
AICC (smaller is	180
BIC (smaller is	301.05
CAIC (smaller is better)	330.05
HQIC (smaller is better)	225.27
Pearson Chi-Square	33.71
Pearson Chi-	0.06

Table 3.4. Height and width growth of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 84

2015 width

Fit Statistics
-2 Res Log Likelihood -480.32
AIC (smaller is better) -420.32
AICC (smaller is better) -416.49
BIC (smaller is better) -292.87
CAIC (smaller is better) -262.87
HQIC (smaller is better) -370.38
Pearson Chi-Square 10.15
Pearson Chi-Square / DF 0.02

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 517 8.47 <.0001

2016 width'

Fit Statistics
-2 Res Log Likelihood -124.52
AIC (smaller is better) -64.52
AICC (smaller is better) -60.86
BIC (smaller is better) 64.17
CAIC (smaller is better) 94.17
HQIC (smaller is better) -14.18
Pearson Chi-Square 21.34
Pearson Chi-Square / DF 0.04

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 539 17.52 <.0001

Table 3.4. Height and width growth of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 84

2017 width

Fit Statistics
-2 Res Log Likelihood -121.28
AIC (smaller is better) -61.28
AICC (smaller is better) -57.62
BIC (smaller is better) 67.47
CAIC (smaller is better) 97.47
HQIC (smaller is better) -10.92
Pearson Chi-Square 21.53
Pearson Chi-Square / DF 0.04

Type III Tests of Fixed Effects
Effect Num DF Den DF F Value Pr > F
TrtCode 28 540 23.74 <.0001

2018 width

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	540	22.53	<.0001

Fit Statistics

-2 Res Log Likelihood	-186.54
AIC (smaller is	-128.54
AICC (smaller is	-125.13
BIC (smaller is	-4.09
CAIC (smaller is better)	24.91
HQIC (smaller is better)	-79.87
Pearson Chi-Square	19.16
Pearson Chi-	0.04

Table 3.5. Yield attributes in 2017 and 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.85

2018 flower clusters

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	537	23.33	<.0001

Fit Statistics

-2 Res Log Likelihood	5449.26
AIC (smaller is	5507.26
AICC (smaller is	5510.69
BIC (smaller is	5631.55
CAIC (smaller is better)	5660.55
HQIC (smaller is better)	5555.88
Pearson Chi-Square	686713
Pearson Chi-Square / DF	1278.8

2017 thinned fruit

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	92	8.54	<.0001

Fit Statistics

-2 Res Log Likelihood	853.23
AIC (smaller is	911.23
AICC (smaller is	939.29
BIC (smaller is	984.36
CAIC (smaller is better)	1013.36
HQIC (smaller is better)	940.75
Pearson Chi-Square	37092.38
Pearson Chi-Square / DF	403.18

Table 3.5. Yield attributes in 2017 and 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.85

2018 thinned fruit

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	91	2.06	0.0059

Fit Statistics

-2 Res Log Likelihood	983.34
AIC (smaller is	1041.34
AICC (smaller is	1069.86
BIC (smaller is	1114.15
CAIC (smaller is better)	1143.15
HQIC (smaller is better)	1070.71
Pearson Chi-Square	168946.9
Pearson Chi-Square / DF	1856.56

2017 fruit set

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	313	5.42	<.0001

Fit Statistics

-2 Res Log Likelihood	2222.32
AIC (smaller is	2280.32
AICC (smaller is	2286.47
BIC (smaller is	2388.96
CAIC (smaller is better)	2417.96
HQIC (smaller is better)	2323.74
Pearson Chi-Square	17781.13
Pearson Chi-Square / DF	56.81

Table 3.5. Yield attributes in 2017 and 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018.85

2018 fruit set

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	290	2.56	<.0001

Fit Statistics

-2 Res Log Likelihood	2961.03
AIC (smaller is	3019.03
AICC (smaller is	3025.73
BIC (smaller is	3125.46
CAIC (smaller is better)	3154.46
HQIC (smaller is better)	3061.67
Pearson Chi-Square	365835.2
Pearson Chi-Square / DF	1261.5

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016. 86

2016 total fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	3.88	<.0001

Fit Statistics

-2 Res Log Likelihood	-68.29
AIC (smaller is	-10.29
AICC (smaller is	-2.6
BIC (smaller is	92.52
CAIC (smaller is better)	121.52
HQIC (smaller is better)	31.06
Pearson Chi-Square	8.93
Pearson Chi-Square / DF	0.03

2016 total fruit number

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	5.12	<.0001

Fit Statistics

-2 Res Log Likelihood	901.12
AIC (smaller is	959.12
AICC (smaller is	966.82
BIC (smaller is	1061.93
CAIC (smaller is better)	1090.93
HQIC (smaller is better)	1000.47
Pearson Chi-Square	394.05
Pearson Chi-Square / DF	1.54

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016. 86

2016 total fruit harvested weight

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	5.12	<.0001

Fit Statistics	
-2 Res Log Likelihood	901.12
AIC (smaller is	959.12
AICC (smaller is	966.82
BIC (smaller is	1061.93
CAIC (smaller is better)	1090.93
HQIC (smaller is better)	1000.47
Pearson Chi-Square	394.05
Pearson Chi-Square / DF	1.54

2016 total fruit harvested number

Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	6.29	<.0001

Fit Statistics	
-2 Res Log Likelihood	713.04
AIC (smaller is	771.04
AICC (smaller is	778.73
BIC (smaller is	873.85
CAIC (smaller is better)	902.85
HQIC (smaller is better)	812.39
Pearson Chi-Square	189.01
Pearson Chi-Square / DF	0.74

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016. 86

2016 dropped fruit number

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	3.67	<.0001

Fit Statistics

-2 Res Log Likelihood	613.53
AIC (smaller is	671.53
AICC (smaller is	679.23
BIC (smaller is	774.34
CAIC (smaller is better)	803.34
HQIC (smaller is better)	712.88
Pearson Chi-Square	128.13
Pearson Chi-Square / DF	0.5

2016 dropped fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	256	2.29	0.0005

Fit Statistics

-2 Res Log Likelihood	-385.28
AIC (smaller is	-327.28
AICC (smaller is	-319.58
BIC (smaller is	-224.47
CAIC (smaller is better)	-195.47
HQIC (smaller is better)	-285.93
Pearson Chi-Square	2.59
Pearson Chi-Square / DF	0.01

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016. 86

2016 percentage of total fruit dropped

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	257	4.7	<.0001

Fit Statistics	
-2 Res Log Likelihood	52.75
AIC (smaller is	110.75
AICC (smaller is	118.42
BIC (smaller is	213.68
CAIC (smaller is better)	242.68
HQIC (smaller is better)	152.14
Pearson Chi-Square	14.38
Pearson Chi-Square / DF	0.06

2016 flower clusters

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	258	8.65	<.0001

Fit Statistics	
-2 Res Log Likelihood	1594.19
AIC (smaller is	1652.19
AICC (smaller is	1659.82
BIC (smaller is	1755.23
CAIC (smaller is better)	1784.23
HQIC (smaller is better)	1693.62
Pearson Chi-Square	5677.87
Pearson Chi-Square / DF	22.01

Table 3.6. Yield attributes in 2016 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2016. 86

2016 crop load

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	258	8.65	<.0001

Fit Statistics

-2 Res Log Likelihood	1594.19
AIC (smaller is	1652.19
AICC (smaller is	1659.82
BIC (smaller is	1755.23
CAIC (smaller is better)	1784.23
HQIC (smaller is better)	1693.62
Pearson Chi-Square	5677.87
Pearson Chi-Square / DF	22.01

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87

2017 total fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	16.13	<.0001

Fit Statistics

-2 Res Log Likelihood	1312.61
AIC (smaller is	1370.61
AICC (smaller is	1376.71
BIC (smaller is	1479.43
CAIC (smaller is better)	1508.43
HQIC (smaller is better)	1414.09
Pearson Chi-Square	953.37
Pearson Chi-Square / DF	3.03

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.92361	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.09105	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.71339	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	4.52498	**Pr > A-Sq**	<0.0050

2017 total fruit number

na

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87

2017 total fruit harvested weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	22.05	<.0001

Fit Statistics

-2 Res Log Likelihood	1234.18
AIC (smaller is	1292.18
AICC (smaller is	1298.28
BIC (smaller is	1401
CAIC (smaller is better)	1430
HQIC (smaller is better)	1335.66
Pearson Chi-Square	743.24
Pearson Chi-Square / DF	2.36

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.89026	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.09845	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	1.06857	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	7.0201	**Pr > A-Sq**	<0.0050

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87

2017 total fruit harvested number

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	18.22	<.0001

Fit Statistics

-2 Res Log Likelihood	2527.47
AIC (smaller is	2585.47
AICC (smaller is	2591.57
BIC (smaller is	2694.29
CAIC (smaller is better)	2723.29
HQIC (smaller is better)	2628.94
Pearson Chi-Square	45102.61
Pearson Chi-Square / DF	143.18

2017 dropped fruit number

na

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87*2017 dropped fruit weight*

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	20.1	<.0001

Fit Statistics

-2 Res Log Likelihood	779.86
AIC (smaller is	837.86
AICC (smaller is	843.96
BIC (smaller is	946.68
CAIC (smaller is better)	975.68
HQIC (smaller is better)	881.34
Pearson Chi-Square	175.69
Pearson Chi-Square / DF	0.56

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.87966	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.14367	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.60413	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	10.5348	Pr > A-Sq	<0.0050

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87

2017 percentage of total fruit dropped

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	311	38.6	<.0001

Fit Statistics

-2 Res Log Likelihood	2498.19
AIC (smaller is	2556.19
AICC (smaller is	2562.38
BIC (smaller is	2664.64
CAIC (smaller is better)	2693.64
HQIC (smaller is better)	2599.54
Pearson Chi-Square	44862.62
Pearson Chi-Square / DF	144.25

2017 cumulative fruit count

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	17.36	<.0001

Fit Statistics

-2 Res Log Likelihood	2666.73
AIC (smaller is	2724.73
AICC (smaller is	2730.83
BIC (smaller is	2833.55
CAIC (smaller is better)	2862.55
HQIC (smaller is better)	2768.21
Pearson Chi-Square	70178.38
Pearson Chi-Square / DF	222.79

Table 3.7. Yield attributes in 2017 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2017. 87

2017 cumulative fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	315	16.47	<.0001

Fit Statistics

-2 Res Log Likelihood	1326.87
AIC (smaller is	1384.87
AICC (smaller is	1390.97
BIC (smaller is	1493.69
CAIC (smaller is better)	1522.69
HQIC (smaller is better)	1428.35
Pearson Chi-Square	997.52
Pearson Chi-Square / DF	3.17

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 total fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	313	20.56	<.0001

Fit Statistics

-2 Res Log Likelihood	1671.69
AIC (smaller is	1729.69
AICC (smaller is	1735.84
BIC (smaller is	1838.33
CAIC (smaller is better)	1867.33
HQIC (smaller is better)	1773.11
Pearson Chi-Square	3061.53
Pearson Chi-Square / DF	9.78

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.89969	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.13379	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.56532	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	9.82962	Pr > A-Sq	<0.0050

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 total fruit number

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	313	8.35	<.0001

Fit Statistics

-2 Res Log Likelihood	2962.31
AIC (smaller is	3020.31
AICC (smaller is	3026.45
BIC (smaller is	3128.95
CAIC (smaller is better)	3157.95
HQIC (smaller is better)	3063.72
Pearson Chi-Square	189099.3
Pearson Chi-Square / DF	604.15

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 total fruit harvested weight

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	314	24.89	<.0001

Fit Statistics	
-2 Res Log Likelihood	1618.90
AIC (smaller is	1676.9
AICC (smaller is	1683.03
BIC (smaller is	1785.63
CAIC (smaller is better)	1814.63
HQIC (smaller is better)	1720.35
Pearson Chi-Square	2553.32
Pearson Chi-Square / DF	8.13

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.82044	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.18807	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	3.83937	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	21.645	**Pr > A-Sq**	<0.0050

2018 total fruit harvested number

na

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 dropped fruit number

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	313	21.42	<.0001

Fit Statistics

-2 Res Log Likelihood	2411.37
AIC (smaller is	2469.37
AICC (smaller is	2475.52
BIC (smaller is	2578.01
CAIC (smaller is better)	2607.01
HQIC (smaller is better)	2512.79
Pearson Chi-Square	32529.92
Pearson Chi-Square / DF	103.93

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 dropped fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	314	51.64	<.0001

Fit Statistics

-2 Res Log Likelihood	875.51
AIC (smaller is	933.51
AICC (smaller	939.64
BIC (smaller is	1042.25
CAIC (smaller is better)	1071.25
HQIC (smaller is better)	976.96
Pearson Chi-Square	239.29
Pearson Chi-Square / DF	0.76

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.5865	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.2814	Pr > D	<0.0100
Cramer-von Mises	W-Sq	9.8157	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	50.62	Pr > A-Sq	<0.0050

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 percentage of total fruit dropped

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	300	28.43	<.0001

Fit Statistics	
-2 Res Log Likelihood	2597.07
AIC (smaller is	2655.07
AICC (smaller is	2661.51
BIC (smaller is	2762.48
CAIC (smaller is better)	2791.48
HQIC (smaller is better)	2698.05
Pearson Chi-Square	80403.57
Pearson Chi-Square / DF	268.01

2018 cumulative fruit count

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	313	7.85	<.0001

Fit Statistics	
-2 Res Log Likelihood	2972.66
AIC (smaller is	3030.66
AICC (smaller is	3036.8
BIC (smaller is	3139.3
CAIC (smaller is better)	3168.3
HQIC (smaller is better)	3074.07
Pearson Chi-Square	195457.3
Pearson Chi-Square / DF	624.46

Table 3.8. Yield attributes in 2018 of 28 apple cultivars grown on M.9 rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 88

2018 cumulative fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	314	23.05	<.0001

Fit Statistics

-2 Res Log Likelihood	1733.04
AIC (smaller is	1791.04
AICC (smaller is	1797.17
BIC (smaller is	1899.78
CAIC (smaller is better)	1928.78
HQIC (smaller is better)	1834.49
Pearson Chi-Square	3672.53
Pearson Chi-Square / DF	11.7

Table 3.9. Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 89

Full bloom date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	12.59	<.0001

Fit Statistics

-2 Res Log Likelihood	1291.84
AIC (smaller is	1293.84
AICC (smaller is	1293.86
BIC (smaller is	1294.78
CAIC (smaller is better)	1295.78
HQIC (smaller is better)	1294
Generalized Chi-Square	3119.29
Gener. Chi-Square / DF	13.22

Harvest date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	48.3	<.0001

Fit Statistics

-2 Res Log Likelihood	1949.31
AIC (smaller is	1953.31
AICC (smaller is	1953.36
BIC (smaller is	1955.19
CAIC (smaller is better)	1957.19
HQIC (smaller is better)	1953.63
Generalized Chi-Square	46530.01
Gener. Chi-Square / DF	197.16

Table 3.9. Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 89

Days to harvest

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	53.38	<.0001

Fit Statistics

-2 Res Log Likelihood	1976.99
AIC (smaller is	1980.99
AICC (smaller is	1981.04
BIC (smaller is	1982.88
CAIC (smaller is better)	1984.88
HQIC (smaller is better)	1981.31
Generalized Chi-Square	52382.21
Gener. Chi-Square / DF	221.96

Juice extraction efficiency

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	217	31.91	<.0001

Fit Statistics

-2 Res Log Likelihood	-550.08
AIC (smaller is	-548.08
AICC (smaller is	-548.06
BIC (smaller is	-547.13
CAIC (smaller is better)	-546.13
HQIC (smaller is better)	-547.92
Generalized Chi-Square	1.25
Gener. Chi-Square / DF	0.01

Table 3.9. Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 89

Average selected fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	11.02	<.0001

Fit Statistics

-2 Res Log Likelihood	2565.48
AIC (smaller is	2567.48
AICC (smaller is	2567.5
BIC (smaller is	2568.43
CAIC (smaller is better)	2569.43
HQIC (smaller is better)	2567.64
Generalized Chi-Square	688414.7
Gener. Chi-Square / DF	2917.01

Table 3.9. Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 89

Pre-harvest drop percentage

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	215	5.42	0.0051
PressDate	1	13	130.99	<.0001
Treatment*PressDate	2	13	22.8	<.0001

Fit Statistics

-2 Res Log	2090.74
AIC (smaller is	2092.74
AICC (smaller is better)	2092.76
BIC (smaller is better)	2093.83
CAIC (smaller is better)	2094.83
HQIC (smaller is better)	2093
Generalized Chi-Square	130253.7
Gener. Chi-Square / DF	576.34

Figure 3.3 The association among horticultural attributes measured in 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 91

Cluster Summary for 8 Clusters					
Cluster	Members	Cluster Variation	Variation Explained	Proportion Explained	Second Eigenvalue
1	5	5	3.82923	0.7658	0.5223
2	3	3	2.4281	0.8094	0.4818
3	2	2	1.67633	0.8382	0.3237
4	3	3	2.26553	0.7552	0.6436
5	1	1	1	1	
6	1	1	1	1	
7	1	1	1	1	
8	1	1	1	1	

8 Clusters		R-squared with		1-R**2
Cluster	Variable	Own Cluster	Next Closest	Ratio
Cluster 1	F18HarvestWeight	0.9616	0.5303	0.0818
	F18HarvestNumber	0.7995	0.269	0.2742
	F18DropWeight	0.72	0.4925	0.5518
	F18DropNumber	0.5758	0.1759	0.5147
	F18CropLoad	0.7723	0.4182	0.3913
Cluster 2	F18PlantHeight	0.906	0.1605	0.112
	F18RelativeGrowth	0.8732	0.2356	0.166
	F18TotalFruitWeight	0.649	0.189	0.4329
Cluster 3	S18ThinnedFruitlets	0.8382	0.1864	0.1989
	F18PercentDropped	0.8382	0.1424	0.1887
Cluster 4	F18TCSA	0.498	0.0608	0.5345
	F18Width	0.8802	0.6604	0.3528
	S18Clusters	0.8873	0.4212	0.1946
Cluster 5	S18FruitSet	1	0.0334	0
Cluster 6	CumulativeWeight2018	1	0.4909	0
Cluster 7	CumulativeNumber2018	1	0.4909	0
Cluster 8	F18TotalFruitNumber	1	0.1113	0

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 124

TA

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	199.49	<.0001

Fit Statistics

-2 Res Log Likelihood	655.89
AIC (smaller is	713.89
AICC (smaller is	740.25
BIC (smaller is	788.25
CAIC (smaller is better)	817.25
HQIC (smaller is better)	743.95
Pearson Chi-Square	3413.96
Pearson Chi-	35.56

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.93792	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.132	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.28813	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	2.2201	Pr > A-Sq	<0.0050

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 124

Soluble solids

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	64.05	<.0001

Fit Statistics

-2 Res Log Likelihood	189.22
AIC (smaller is	247.22
AICC (smaller is	273.58
BIC (smaller is	321.59
CAIC (smaller is better)	350.59
HQIC (smaller is better)	277.28
Pearson Chi-Square	26.43
Pearson Chi-	0.28

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.99041	Pr < W	0.5468
Kolmogorov-Smirnov	D	0.04917	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.03253	Pr > W-Sq	>0.2500
Anderson-Darling	A-Sq	0.26653	Pr > A-Sq	>0.2500

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 124

pH

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	499.65	<.0001

Fit Statistics

-2 Res Log Likelihood	-278.29
AIC (smaller is	-220.29
AICC (smaller is	-193.92
BIC (smaller is	-145.92
CAIC (smaller is better)	-116.92
HQIC (smaller is better)	-190.23
Pearson Chi-Square	0.2
Pearson Chi-	0

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	**W**	0.89324	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.22813	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	1.09109	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	5.51531	**Pr > A-Sq**	<0.0050

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 124

Formol

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	18.63	<.0001

Fit Statistics

-2 Res Log Likelihood	867.01
AIC (smaller is	925.01
AICC (smaller is	951.38
BIC (smaller is	999.38
CAIC (smaller is better)	1028.38
HQIC (smaller is better)	955.07
Pearson Chi-Square	30787.19
Pearson Chi-	320.7

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.95664	Pr < W	0.0005
Kolmogorov-Smirnov	D	0.1007	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.28613	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.64547	Pr > A-Sq	<0.0050

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. **124**

Polyphenols

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	29.23	<.0001

Fit Statistics

-2 Res Log Likelihood	1195.18
AIC (smaller is	1253.18
AICC (smaller is	1279.55
BIC (smaller is	1327.55
CAIC (smaller is better)	1356.55
HQIC (smaller is better)	1283.24
Pearson Chi-Square	939690.1
Pearson Chi-	9788.44

Table 4.1. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2017. University of Guelph, Simcoe, Ontario, 2017. 124

Ascorbic acid interference

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	96	29.24	<.0001

Fit Statistics

-2 Res Log Likelihood	888.33
AIC (smaller is	946.33
AICC (smaller is	972.7
BIC (smaller is	1020.7
CAIC (smaller is better)	1049.7
HQIC (smaller is better)	976.39
Pearson Chi-Square	38444.02
Pearson Chi-	400.46

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.8015	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.18812	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.25014	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	7.4498	Pr > A-Sq	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

TA

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	87	130.46	<.0001

Fit Statistics	
-2 Res Log Likelihood	643.89
AIC (smaller is	701.89
AICC (smaller is	732.41
BIC (smaller is	773.4
CAIC (smaller is better)	802.4
HQIC (smaller is better)	730.68
Pearson Chi-Square	5314.46
Pearson Chi-	61.09

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.94445	**Pr < W**	0.0001
Kolmogorov-Smirnov	**D**	0.09094	**Pr > D**	0.02
Cramer-von Mises	**W-Sq**	0.20261	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	1.6796	**Pr > A-Sq**	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

Soluble solids

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	87	16.58	<.0001

Fit Statistics

-2 Res Log Likelihood	251.41
AIC (smaller is	309.41
AICC (smaller is	339.94
BIC (smaller is	380.92
CAIC (smaller is better)	409.92
HQIC (smaller is better)	338.21
Pearson Chi-Square	58.38
Pearson Chi-	0.67

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.93815	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.13483	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.45736	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	2.51316	Pr > A-Sq	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

pH

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	87	278.08	<.0001

Fit Statistics

-2 Res Log Likelihood	-198.25
AIC (smaller is	-140.25
AICC (smaller is	-109.72
BIC (smaller is	-68.74
CAIC (smaller is better)	-39.74
HQIC (smaller is better)	-111.45
Pearson Chi-Square	0.33
Pearson Chi-	0

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.94011	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.15912	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.59368	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	2.99432	Pr > A-Sq	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

Formol

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	87	10.63	<.0001

Fit Statistics

-2 Res Log Likelihood	849.84
AIC (smaller is	907.84
AICC (smaller is	938.37
BIC (smaller is	979.35
CAIC (smaller is better)	1008.35
HQIC (smaller is better)	936.64
Pearson Chi-Square	56699.29
Pearson Chi-	651.72

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.93694	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.12293	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.3391	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.99037	Pr > A-Sq	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

Polyphenols

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Cultivar	27	86	30.87	<.0001

Fit Statistics

-2 Res Log Likelihood	1073.62
AIC (smaller is	1131.62
AICC (smaller is	1162.69
BIC (smaller is	1202.8
CAIC (smaller is better)	1231.8
HQIC (smaller is better)	1160.27
Pearson Chi-Square	845527.8
Pearson Chi-	9831.72

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.89024	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.16713	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.77491	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	4.64992	Pr > A-Sq	<0.0050

Table 4.2. Juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 125

Firmness

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Cultivar	27	85	26.14	<.0001

Fit Statistics	
-2 Res Log Likelihood	176.49
AIC (smaller is	234.49
AICC (smaller is	266.13
BIC (smaller is	305.33
CAIC (smaller is better)	334.33
HQIC (smaller is better)	262.98
Pearson Chi-Square	25.23
Pearson Chi-	0.3

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.96336	**Pr < W**	0.0035
Kolmogorov-Smirnov	**D**	0.07971	**Pr > D**	0.0777
Cramer-von Mises	**W-Sq**	0.08494	**Pr > W-Sq**	0.1835
Anderson-Darling	**A-Sq**	0.80877	**Pr > A-Sq**	0.0371

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

Soluble solids

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	0.24	0.7879

Fit Statistics

-2 Res Log Likelihood	970.00
AIC (smaller is	974
AICC (smaller is	974.06
BIC (smaller is	975.89
CAIC (smaller is better)	977.89
HQIC (smaller is better)	974.32
Generalized Chi-Square	731.28
Gener. Chi-Square / DF	3.1

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

TA

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	7.63	0.0006

Fit Statistics

-2 Res Log Likelihood	2439.84
AIC (smaller is	2441.84
AICC (smaller is	2441.86
BIC (smaller is	2442.79
CAIC (smaller is better)	2443.79
HQIC (smaller is better)	2442
Generalized Chi-Square	404247.5
Gener. Chi-Square / DF	1712.91

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

pH

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Origin	2	218	9.63	<.0001

Fit Statistics	
-2 Res Log Likelihood	332.53
AIC (smaller is	334.53
AICC (smaller is	334.54
BIC (smaller is	335.47
CAIC (smaller is better)	336.47
HQIC (smaller is better)	334.69
Generalized Chi-Square	53.54
Gener. Chi-Square / DF	0.23

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

Formol

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	218	2.05	0.1308

Fit Statistics

-2 Res Log Likelihood	2483.86
AIC (smaller is	2485.86
AICC (smaller is	2485.88
BIC (smaller is	2486.81
CAIC (smaller is better)	2487.81
HQIC (smaller is better)	2486.02
Generalized Chi-Square	487140.2
Gener. Chi-Square / DF	2064.15

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

Polyphenols

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	217	44.38	<.0001

Fit Statistics

-2 Res Log Likelihood	3233.58
AIC (smaller is	3237.58
AICC (smaller is	3237.63
BIC (smaller is	3239.47
CAIC (smaller is better)	3241.47
HQIC (smaller is better)	3237.9
Generalized Chi-Square	11510877
Gener. Chi-Square / DF	48982.46

Table 4.8. Variation in juice attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin. University of Guelph, Simcoe, Ontario, 2018. 131

Firmness

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Origin	2	103	10.78	<.0001

Fit Statistics

-2 Res Log Likelihood	386.48
AIC (smaller is	388.48
AICC (smaller is	388.52
BIC (smaller is	389.43
CAIC (smaller is better)	390.43
HQIC (smaller is better)	388.64
Generalized Chi-Square	196.2
Gener. Chi-Square / DF	1.78

Figure 4.1The association among juice attributes of fruits measured in 28 apple cultivars grown on M.9. rootstock for cider production. University of Guelph, Simcoe, Ontario, 2018. 130

Cluster Summary for 5 Clusters

Cluster	Members	Cluster Variation	Variation Explained	Proportion Explained	Second Eigenvalue
1	2	2	1.88247	0.9412	0.1175
2	2	2	1.33976	0.6699	0.6602
3	1	1	1	1	
4	2	2	1.51797	0.759	0.482
5	1	1	1	1	

Total variation explained = 6.740197 Proportion = 0.8425

5 Clusters		R-squared with		1-R**2
Cluster	Variable	Own Cluster	Next Closest	Ratio
Cluster 1	TA	0.9412	0.2164	0.075
	pH	0.9412	0.2702	0.0805
Cluster 2	DaysToHarvest	0.6699	0.1687	0.3971
	Brix	0.6699	0.1073	0.3698
Cluster 3	Formol	1	0.058	0
Cluster 4	WeightAvg	0.759	0.11	0.2708
	JuiceEff	0.759	0.3057	0.3471
Cluster 5	Polyphenols	1	0.1024	0

No cluster meets the criterion for splitting.

Table 5.1. Primary amino nitrogen concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 164

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	15.03	0.001
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	252.65
AIC (smaller is better)	227.34
AICC (smaller is better)	228.34
BIC (smaller is better)	226.92
CAIC (smaller is better)	228.92
HQIC (smaller is better)	225.67
Generalized Chi-Square	1224226
Gener. Chi-Square / DF	81615.1

Table 5.1. Primary amino nitrogen concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 164

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	33.8	<.0001
HarvestDate	5	90	132.69	<.0001
HarvestDat*Treatment	10	90	2.56	0.009

Fit Statistics

-2 Res Log Likelihood	804.68
AIC (smaller is	842.68
AICC (smaller is	853.53
BIC (smaller is	890.17
CAIC (smaller is better)	909.17
HQIC (smaller is better)	861.83
Pearson Chi-Square	28133.87
Pearson Chi-	312.6

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.8543	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.18137	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.0642	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	5.98452	Pr > A-Sq	<0.0050

Table 5.1. Primary amino nitrogen concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 164

2018 spray number x sampling date

Fit Statistics				
-2 Res Log Likelihood	Formol			
AIC (smaller is better)	226.12			
AICC (smaller is better)	226.58			
BIC (smaller is better)	227.9			
CAIC (smaller is better)	229.9			
HQIC (smaller is better)	226.36			
Generalized Chi-Square	1712.16			
Gener. Chi-Square / DF	59.04			
Covariance Parameter Estimates				
Cov Parm	Estimate	Standard Error		
Block	33.1314	25.3962		
Residual	59.0401	21.9533		
Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	11.12	0.0013
PressDate	1	14	2.87	0.1124
Treatment*PressDate	2	14	3.34	0.0654

Table 5.2. Aspartic acid concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 166

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	15.03	0.001
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log Likelihood	252.65
AIC (smaller is better)	227.34
AICC (smaller is better)	228.34
BIC (smaller is better)	226.92
CAIC (smaller is better)	228.92
HQIC (smaller is better)	225.67
Generalized Chi-Square	1224226
Gener. Chi-Square / DF	81615.1

Table 5.2. Aspartic acid concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 166

2017 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	90	13.17	<.0001
HarvestDate	5	90	178.25	<.0001
HarvestDat*Treatment	10	90	4.07	0.0001

Fit Statistics	
-2 Res Log Likelihood	1269.35
AIC (smaller is	1307.35
AICC (smaller is	1318.21
BIC (smaller is	1354.85
CAIC (smaller is better)	1373.85
HQIC (smaller is better)	1326.51
Pearson Chi-Square	4915101
Pearson Chi-	54612.24

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.80563	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.27645	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	1.83739	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	9.48808	**Pr > A-Sq**	<0.0050

Table 5.2. Aspartic acid concentrations in 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 166

2018 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	14	3.71	0.0508
PressDate	1	14	0.84	0.376
Treatment*PressDate	2	14	2.41	0.1264
Fit Statistics				
-2 Res Log Likelihood				
403.45	AIC (smaller is better)			
AICC (smaller is better)	407.45			
BIC (smaller is better)	407.91			
CAIC (smaller is better)	409.23			
HQIC (smaller is better)	411.23			
Generalized Chi-Square	407.69			
Gener. Chi-Square / DF	854562.1			
443.78	29467.66			

Table 5.3 . Asparagine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 167

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	13.38	0.0015
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	163.77
AIC (smaller is better)	256.65
AICC (smaller is better)	257.65
BIC (smaller is better)	256.23
CAIC (smaller is better)	258.23
HQIC (smaller is better)	254.98
Generalized Chi-Square	1.2E+07
Gener. Chi-Square / DF	781134

Table 5.3 . Asparagine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 167

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	33.87	<.0001
HarvestDate	5	90	208.78	<.0001
HarvestDat*Treatment	10	90	2.42	0.0134

Fit Statistics

-2 Res Log Likelihood	1532.91
AIC (smaller is	1570.91
AICC (smaller is	1581.77
BIC (smaller is	1618.41
CAIC (smaller is better)	1637.41
HQIC (smaller is better)	1590.07
Pearson Chi-Square	91905140
Pearson Chi-	1021168

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.85104	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.19432	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.0839	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	6.07248	Pr > A-Sq	<0.0050

Table 5.3 . Asparagine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 167

2018 spray number x sampling date

Fit Statistics				
-2 Res Log Likelihood	263.25			
AIC (smaller is better)	447.78			
AICC (smaller is better)	448.25			
BIC (smaller is better)	449.56			
CAIC (smaller is better)	451.56			
HQIC (smaller is better)	448.03			
Generalized Chi-Square	3766435			
Gener. Chi-Square / DF	129877.1			
Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	18.81	0.0001
PressDate	1	14	2.66	0.125
Treatment*PressDate	2	14	3.4	0.0626

Table 5.4. Serine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 168

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	3.01	0.095
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	154.72
AIC (smaller is better)	167.77
AICC (smaller is better)	168.77
BIC (smaller is better)	167.36
CAIC (smaller is better)	169.36
HQIC (smaller is better)	166.11
Generalized Chi-Square	30272.9
Gener. Chi-Square / DF	2018.2

Table 5.4. Serine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 168

2017 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	90	17.91	<.0001
HarvestDate	5	90	58.01	<.0001
HarvestDat*Treatment	10	90	1.73	0.0859

Fit Statistics	
-2 Res Log Likelihood	957.62
AIC (smaller is	995.62
AICC (smaller is	1006.48
BIC (smaller is	1043.12
CAIC (smaller is better)	1062.12
HQIC (smaller is better)	1014.77
Pearson Chi-Square	153911.7
Pearson Chi-	1710.13

Table 5.4. Serine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 168

2018 spray number x sampling date

Fit Statistics				
-2 Res Log Likelihood	Covariance Parameter Estimates			
AIC (smaller is better)	267.25			
AICC (smaller is better)	267.72			
BIC (smaller is better)	269.04			
CAIC (smaller is better)	271.04			
HQIC (smaller is better)	267.5			
Generalized Chi-Square	9024.86			
Gener. Chi-Square / DF	311.2			
Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	14	13.61	0.0005
PressDate	1	14	43.64	251.30
Treatment*PressDate	2	14	2.63	0.1074

Table 5.5. Glutamine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 169

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	4.39	0.0429
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	LS-
AIC (smaller is better)	156.72
AICC (smaller is better)	157.03
BIC (smaller is better)	156.51
CAIC (smaller is better)	157.51
HQIC (smaller is better)	155.89
Generalized Chi-Square	18520.4
Gener. Chi-Square / DF	1234.7

Table 5.5. Glutamine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 169

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	15.19	<.0001
HarvestDate	5	90	139.5	<.0001
HarvestDat*Treatment	10	90	4.7	<.0001

Fit Statistics

-2 Res Log Likelihood	985.30
AIC (smaller is	1023.3
AICC (smaller is	1034.16
BIC (smaller is	1070.8
CAIC (smaller is better)	1089.8
HQIC (smaller is better)	1042.46
Pearson Chi-Square	209336.5
Pearson Chi-	2325.96

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.93423	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.12005	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.39625	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	2.37364	Pr > A-Sq	<0.0050

Table 5.5. Glutamine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 169

2018 spray number x sampling date

Fit Statistics				
-2 Res Log Likelihood	209.26			
AIC (smaller is better)	255.3			
AICC (smaller is better)	255.77			
BIC (smaller is better)	257.08			
CAIC (smaller is better)	259.08			
HQIC (smaller is better)	255.55			
Generalized Chi-Square	5563.53			
Gener. Chi-Square / DF	191.85			
Type III Tests of Fixed Effects				
Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	7.98	0.0049
PressDate	1	14	406.23	<.0001
Treatment*PressDate	2	14	1.26	0.315

Table 5.6. Alanine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 170

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	6.29	0.017
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	115.05
AIC (smaller is better)	154.45
AICC (smaller is better)	155.45
BIC (smaller is better)	154.03
CAIC (smaller is better)	156.03
HQIC (smaller is better)	152.78
Generalized Chi-Square	9270.27
Gener. Chi-Square / DF	618.02

Table 5.6. Alanine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 170

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	8.36	0.0005
HarvestDate	5	90	98.95	<.0001
HarvestDat*Treatment	10	90	2.11	0.0314

Fit Statistics

-2 Res Log Likelihood	829.88
AIC (smaller is	867.88
AICC (smaller is	878.74
BIC (smaller is	915.38
CAIC (smaller is better)	934.38
HQIC (smaller is better)	887.03
Pearson Chi-Square	37227.22
Pearson Chi-	413.64

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.8104	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.20995	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.5074	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	8.17274	Pr > A-Sq	<0.0050

Table 5.6. Alanine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 170

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	250.27	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	213.26	Treatment	2	14	3.3	0.0669
AICC (smaller is better)	213.72	PressDate	1	14	15.81	0.0014
BIC (smaller is better)	215.04	Treatment* PressDate	2	14	0.66	0.5332
CAIC (smaller is better)	217.04					
HQIC (smaller is better)	213.5					
Generalized Chi-Square	1453.9					
Gener. Chi-Square / DF	50.13					

Table 5.7. Valine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 171

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	2.56	0.1268
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	107.44
AIC (smaller is better)	119.05
AICC (smaller is better)	120.05
BIC (smaller is better)	118.63
CAIC (smaller is better)	120.63
HQIC (smaller is better)	117.38
Generalized Chi-Square	1207.6
Gener. Chi-Square / DF	80.51

Table 5.7. Valine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 171

2017 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	90	2.88	0.0613
HarvestDate	5	90	92.77	<.0001
HarvestDat*Treatment	10	90	1.04	0.4175

Fit Statistics	
-2 Res Log Likelihood	614.00
AIC (smaller is	652
AICC (smaller is	662.85
BIC (smaller is	699.49
CAIC (smaller is better)	718.49
HQIC (smaller is better)	671.15
Pearson Chi-Square	3381.48
Pearson Chi-	37.57

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.95223	**Pr < W**	0.0007
Kolmogorov-Smirnov	**D**	0.12012	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.1203	**Pr > W-Sq**	0.0617
Anderson-Darling	**A-Sq**	1.27163	**Pr > A-Sq**	<0.0050

Table 5.7. Valine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 171

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	.	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	179.14	Treatment	2	14	13.21	0.0006
AICC (smaller is better)	179.29	PressDate	1	14	14.64	0.0019
BIC (smaller is better)	180.04	Treatment* PressDate	2	14	1.52	0.2532
CAIC (smaller is better)	181.04					
HQIC (smaller is better)	179.27					
Generalized Chi-Square	530.3					
Gener. Chi-Square / DF	18.29					

Table 5.8. Methionine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 172

2016 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	10	8.45	0.0071
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics	
-2 Res Log	111.91
AIC (smaller is better)	111.44
AICC (smaller is better)	112.44
BIC (smaller is better)	111.03
CAIC (smaller is better)	113.03
HQIC (smaller is better)	109.78
Generalized Chi-Square	693.23
Gener. Chi-Square / DF	46.22

Table 5.8. Methionine concentrations in mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 172

2017 spray number x sampling date

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	2.08	0.1304
HarvestDate	5	90	106.91	<.0001
HarvestDat*Treatment	10	90	2.95	0.003

Fit Statistics

-2 Res Log Likelihood	699.59
AIC (smaller is	737.59
AICC (smaller is	748.44
BIC (smaller is	785.08
CAIC (smaller is better)	804.08
HQIC (smaller is better)	756.74
Pearson Chi-Square	8752.3
Pearson Chi-	97.25

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.94566	Pr < W	0.0002
Kolmogorov-Smirnov	D	0.13163	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.20013	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.71571	Pr > A-Sq	<0.0050

Table 5.8. Methionine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 172

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	The SAS System	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	216.35	Treatment	2	14	1.22	0.3244
AICC (smaller is better)	216.82	PressDate	1	14	33.17	<.0001
BIC (smaller is better)	218.14	Treatment* PressDate	2	14	0.8	0.4687
CAIC (smaller is better)	220.14					
HQIC (smaller is better)	216.6					
Generalized Chi-Square	1419.28					
Gener. Chi-Square / DF	48.94					

Table 5.9. Glutamic acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 173

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	6.14	0.0182
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	122.93
AIC (smaller is better)	115.91
AICC (smaller is better)	116.91
BIC (smaller is better)	115.49
CAIC (smaller is better)	117.49
HQIC (smaller is better)	114.24
Generalized Chi-Square	960.3
Gener. Chi-Square / DF	64.02

Table 5.9. Glutamic acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 173

2017 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	90	5.23	0.0071
HarvestDate	5	90	163.4	<.0001
HarvestDat*Treatment	10	90	3.58	0.0005

Fit Statistics	
-2 Res Log Likelihood	1022.34
AIC (smaller is	1060.34
AICC (smaller is	1071.2
BIC (smaller is	1107.84
CAIC (smaller is better)	1126.84
HQIC (smaller is better)	1079.49
Pearson Chi-Square	315913
Pearson Chi-	3510.14

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.93461	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.16439	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.44474	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	2.5859	**Pr > A-Sq**	<0.0050

Table 5.9. Glutamic acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 173

2018 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatme	2	14	1.48	0.2622
PressD	1	14	23.32	0.0003
Treatme	2	14	3.6	0.0546

Table 5.10. Histidine concentrations in mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 174

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	0.34	0.7128
HarvestDate	5	90	680.11	<.0001
HarvestDat*Treatment	10	90	0.36	0.9596

Fit Statistics

-2 Res Log Likelihood	607.39
AIC (smaller is	645.39
AICC (smaller is	656.24
BIC (smaller is	692.88
CAIC (smaller is better)	711.88
HQIC (smaller is better)	664.54
Pearson Chi-Square	3142.04
Pearson Chi-	34.91

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.48192	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.49688	Pr > D	<0.0100
Cramer-von Mises	W-Sq	5.81119	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	28.6166	Pr > A-Sq	<0.0050

Table 5.11. Arginine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-` solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 175

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	0.37	0.6934
HarvestDate	5	90	206.55	<.0001
HarvestDat*Treatment	10	90	0.37	0.957

Fit Statistics

-2 Res Log Likelihood	614.28
AIC (smaller is	652.28
AICC (smaller is	663.14
BIC (smaller is	699.78
CAIC (smaller is better)	718.78
HQIC (smaller is better)	671.43
Pearson Chi-Square	3392.23
Pearson Chi-	37.69

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.45553	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.50757	Pr > D	<0.0100
Cramer-von Mises	W-Sq	6.14632	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	30.1534	Pr > A-Sq	<0.0050

Table 5.12. Glycine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 176

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	11.75	0.0024
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	86.43
AIC (smaller is better)	126.93
AICC (smaller is better)	127.93
BIC (smaller is better)	126.52
CAIC (smaller is better)	128.52
HQIC (smaller is better)	125.27
Generalized Chi-Square	2049.46
Gener. Chi-Square / DF	136.63

Table 5.12. Glycine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 176

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	14.12	<.0001
HarvestDate	5	90	17.76	<.0001
HarvestDat*Treatment	10	90	1.71	0.0909

Fit Statistics

-2 Res Log Likelihood	734.46
AIC (smaller is	772.46
AICC (smaller is	783.31
BIC (smaller is	819.95
CAIC (smaller is better)	838.95
HQIC (smaller is better)	791.61
Pearson Chi-Square	12894.1
Pearson Chi-	143.27

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.97115	Pr < W	0.0189
Kolmogorov-Smirnov	D	0.09444	Pr > D	0.0188
Cramer-von Mises	W-Sq	0.20084	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	1.10404	Pr > A-Sq	0.0069

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	157.63	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	254.27	Treatment	2	14	0.7	0.5145
AICC (smaller is better)	254.73	PressDate	1	14	7.87	0.014
BIC (smaller is better)	256.05	Treatment* PressDate	2	14	0.48	0.6282
CAIC (smaller is better)	258.05					
HQIC (smaller is better)	254.51					
Generalized Chi-Square	6276.76					
Gener. Chi-Square / DF	216.44					

Table 5.13. Cysteine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1

solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 177

2016 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	10	11.52	0.0025
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics	
-2 Res Log	154.09
AIC (smaller is better)	90.43
AICC (smaller is better)	91.43
BIC (smaller is better)	90.01
CAIC (smaller is better)	92.01
HQIC (smaller is better)	88.76
Generalized Chi-Square	125.87
Gener. Chi-Square / DF	8.39

Table 5.13. Cysteine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 177

2017 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	90	5.52	0.0055
HarvestDate	5	90	22.67	<.0001
HarvestDat*Treatment	10	90	0.64	0.7734

Fit Statistics	
-2 Res Log Likelihood	608.20
AIC (smaller is	646.2
AICC (smaller is	657.06
BIC (smaller is	693.7
CAIC (smaller is better)	712.7
HQIC (smaller is better)	665.36
Pearson Chi-Square	3170.75
Pearson Chi-	35.23

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.92707	**Pr < W**	<0.0001
Kolmogorov-Smirnov	**D**	0.12851	**Pr > D**	<0.0100
Cramer-von Mises	**W-Sq**	0.36396	**Pr > W-Sq**	<0.0050
Anderson-Darling	**A-Sq**	2.02253	**Pr > A-Sq**	<0.0050

Table 5.13. Cysteine concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 177

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	Treatment Least Squares Means	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	116.81	Treatment	2	14	10.61	0.0016
AICC (smaller is better)	117.27	PressDate	1	14	24.9	0.0002
BIC (smaller is better)	118.59	Treatment*PressDate	2	14	2.14	0.155
CAIC (smaller is better)	120.59					
HQIC (smaller is better)	117.05					
Generalized Chi-Square	47.85					
Gener. Chi-Square / DF	1.65					

Table 5.14. Gamma-aminobutyric acid (GABA) concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 178

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	1.77	0.2192
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	
AIC (smaller is better)	158.09
AICC (smaller is better)	159.09
BIC (smaller is better)	157.67
CAIC (smaller is better)	159.67
HQIC (smaller is better)	156.42
Generalized Chi-Square	9920.82
Gener. Chi-Square / DF	661.39

Table 5.14. Gamma-aminobutyric acid (GABA) concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 178

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	5.72	0.0046
HarvestDate	5	90	18.87	<.0001
HarvestDat*Treatment	10	90	1.14	0.3402

Fit Statistics

-2 Res Log Likelihood	717.14
AIC (smaller is	755.14
AICC (smaller is	765.99
BIC (smaller is	802.63
CAIC (smaller is better)	821.63
HQIC (smaller is better)	774.29
Pearson Chi-Square	10636.8
Pearson Chi-	118.19

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.82774	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.24114	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.27627	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	8.13712	Pr > A-Sq	<0.0050

Table 5.14. Gamma-aminobutyric acid (GABA) concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.   178

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	112.81	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	161.63	Treatment	2	14	3.09	0.0773
AICC (smaller is better)	162.09	PressDate	1	14	94.21	<.0001
BIC (smaller is better)	163.41	Treatment* PressDate	2	14	0.25	0.7827
CAIC (smaller is better)	165.41					
HQIC (smaller is better)	161.87					
Generalized Chi-Square	195.63					
Gener. Chi-Square / DF	6.75					

Table 5.15. Yeast assimilable nitrogen (YAN) in juice of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.   179

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	40	73.2	<.0001
HarvestDate	2	40	0.63	0.5374
Treatment*HarvestDat	4	40	1.22	0.3171

Fit Statistics

-2 Res Log	Covariance Parameter Estimates
AIC (smaller is better)	402.45
AICC (smaller is better)	402.74
BIC (smaller is better)	402.04
CAIC (smaller is better)	404.04
HQIC (smaller is better)	400.79
Generalized Chi-Square	11287.24
Gener. Chi-Square / DF	250.83

Table 5.15. Yeast assimilable nitrogen (YAN) in juice of mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 179

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	77	83.84	<.0001
HarvestDate	5	77	360.8	<.0001
HarvestDat*Treatment	10	77	2.05	0.0395

Fit Statistics

-2 Res Log	698.48
AIC (smaller is better)	702.48
AICC (smaller is better)	702.64
BIC (smaller is better)	702.07
CAIC (smaller is better)	704.07
HQIC (smaller is better)	700.82
Generalized Chi-Square	15148.36
Gener. Chi-Square / DF	184.74

Table 5.15. Yeast assimilable nitrogen (YAN) in juice of mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 179

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	D	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	248.87	Treatment	2	14	12.74	0.0007
AICC (smaller is better)	249.33	PressDate	1	14	57.6	<.0001
BIC (smaller is better)	250.65	Treatment* PressDate	2	14	2.75	0.098
CAIC (smaller is better)	252.65					
HQIC (smaller is better)	249.11					
Generalized Chi-Square	4195.71					
Gener. Chi-Square / DF	144.68					

Table 5.16. Sum of assimilable amino acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 180

2016 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	10	20.04	0.0003
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics

-2 Res Log	256.39
AIC (smaller is better)	258.39
AICC (smaller is better)	258.69
BIC (smaller is better)	258.18
CAIC (smaller is better)	259.18
HQIC (smaller is better)	257.55
Generalized Chi-Square	16260346
Gener. Chi-Square / DF	1084023

Table 5.16. Sum of assimilable amino acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 180

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	90	33.8	<.0001
HarvestDate	5	90	132.69	<.0001
HarvestDat*Treatment	10	90	2.56	0.009

Fit Statistics

-2 Res Log Likelihood	1572.95
AIC (smaller is	1610.95
AICC (smaller is	1621.81
BIC (smaller is	1658.45
CAIC (smaller is better)	1677.45
HQIC (smaller is better)	1630.11
Pearson Chi-Square	1.43E+08
Pearson Chi-	1593365

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.8543	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.18137	Pr > D	<0.0100
Cramer-von Mises	W-Sq	1.0642	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	5.98452	Pr > A-Sq	<0.0050

Table 5.16. Sum of assimilable amino acid concentrations in mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018.   180

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	Differences of Treatment Least Squares Means	**Effect**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
AIC (smaller is better)	473.67	**Treatment**	2	14	11.12	0.0013
AICC (smaller is better)	474.13	**PressDate**	1	14	2.87	0.1124
BIC (smaller is better)	475.45	**Treatment*PressDate**	2	14	3.34	0.0654
CAIC (smaller is better)	477.45					
HQIC (smaller is better)	473.92					
Generalized Chi-Square	8727077					
Gener. Chi-Square / DF	300933.7					

Table 5.17. Estimated residual (non-amino) yeast assimilable nitrogen (YAN) in juice of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 181

2016 spray number x sampling date

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	10	1.55	0.259
HarvestDate	0	.	.	.
Treatment*HarvestDat	0	.	.	.

Fit Statistics	
-2 Res Log	130.05
AIC (smaller is better)	132.05
AICC (smaller is better)	132.35
BIC (smaller is better)	131.84
CAIC (smaller is better)	132.84
HQIC (smaller is better)	131.21
Generalized Chi-Square	3574.28
Gener. Chi-Square / DF	238.29

Table 5.17. Estimated residual (non-amino) yeast assimilable nitrogen (YAN) in juice of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 181

2017 spray number x sampling date

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	77	1.94	0.151
HarvestDate	5	77	16.26	<.0001
HarvestDat*Treatment	10	77	1.55	0.1376

Fit Statistics

-2 Res Log	719.22
AIC (smaller is better)	723.22
AICC (smaller is better)	723.38
BIC (smaller is better)	722.81
CAIC (smaller is better)	724.81
HQIC (smaller is better)	721.56
Generalized Chi-Square	21022.86
Gener. Chi-Square / DF	256.38

Table 5.17. Estimated residual (non-amino) yeast assimilable nitrogen (YAN) in juice of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2016, 2017, and 2018. University of Guelph, Simcoe, Ontario, 2018. 181

2018 spray number x sampling date

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	TA	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	222.82	Treatment	2	14	7.66	0.0056
AICC (smaller is better)	222.96	PressDate	1	14	75.15	<.0001
BIC (smaller is better)	223.71	Treatment* PressDate	2	14	0.67	0.5286
CAIC (smaller is better)	224.71					
HQIC (smaller is better)	222.94					
Generalized Chi-Square	2390.77					
Gener. Chi-Square / DF	82.44					

Table 5.18. Juice attributes of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

TA

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	11.4	0.0012
PressDate	1	14	204.89	<.0001
Treatment*PressDate	2	14	5.19	0.0206

Fit Statistics

-2 Res Log	164.25
AIC (smaller is	168.25
AICC (smaller is better)	168.72
BIC (smaller is better)	170.04
CAIC (smaller is better)	172.04
HQIC (smaller is better)	168.5
Generalized Chi-Square	146.38
Gener. Chi-Square / DF	5.05

Table 5.18. Juice attributes of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

Soluble solids

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	0.7	0.5135
PressDate	1	14	9.58	0.0079
Treatment*PressDate	2	14	0.49	0.6241

Fit Statistics

-2 Res Log	28.77
AIC (smaller is	32.77
AICC (smaller is better)	33.23
BIC (smaller is better)	34.55
CAIC (smaller is better)	36.55
HQIC (smaller is better)	33.01
Generalized Chi-Square	1.24
Gener. Chi-Square / DF	0.04

Table 5.18. Juice attributes of mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

Polyphenols

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Treatment	2	14	1.2	0.3299
PressDate	1	14	26.44	0.0001
Treatment*PressDate	2	14	2.25	0.1418

Fit Statistics	
-2 Res Log	403.45
AIC (smaller is	297.41
AICC (smaller is better)	297.87
BIC (smaller is better)	299.19
CAIC (smaller is better)	301.19
HQIC (smaller is better)	297.66
Generalized Chi-Square	21807.4
Gener. Chi-Square / DF	751.98

Table 5.18. Juice attributes of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

Ascorbic acid interference

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	0.16	0.8531
PressDate	1	14	1236.57	<.0001
Treatment*PressDate	2	14	0.96	0.4068

Fit Statistics

-2 Res Log	293.41
AIC (smaller is	290.19
AICC (smaller is better)	290.65
BIC (smaller is better)	291.97
CAIC (smaller is better)	293.97
HQIC (smaller is better)	290.43
Generalized Chi-Square	19593.76
Gener. Chi-Square / DF	675.65

Table 5.18. Juice attributes of mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

pH

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	3	0.0825
PressDate	1	14	329.51	<.0001
Treatment*PressDate	2	14	3.91	0.0449

Fit Statistics

-2 Res Log	-109.71
AIC (smaller is	-105.71
AICC (smaller is better)	-105.25
BIC (smaller is better)	-103.93
CAIC (smaller is better)	-101.93
HQIC (smaller is better)	-105.47
Generalized Chi-Square	0.02
Gener. Chi-Square / DF	0

Table 5.18. Juice attributes of mature 'Crimson Crisp®' apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

Fruit weight

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	14	5.66	0.0158
PressDate	1	14	5.34	0.0366
Treatment*PressDate	2	14	0.11	0.8971

Fit Statistics

-2 Res Log	E
AIC (smaller is	232.63
AICC (smaller is better)	233.09
BIC (smaller is better)	234.41
CAIC (smaller is better)	236.41
HQIC (smaller is better)	232.87
Generalized Chi-Square	2138.06
Gener. Chi-Square / DF	73.73

Table 5.18. Juice attributes of mature ‘Crimson Crisp®’ apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018. 182

Juicing efficiency

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Treatment	2	13	0.57	0.5777
PressDate	1	13	130.99	<.0001
Treatment*PressDate	2	13	22.8	<.0001

Fit Statistics

-2 Res Log	286.19
AIC (smaller is	-147.26
AICC (smaller is better)	-147.11
BIC (smaller is better)	-146.37
CAIC (smaller is better)	-145.37
HQIC (smaller is better)	-147.14
Generalized Chi-Square	0.01
Gener. Chi-Square / DF	0

Table 5.19. Relative concentrations of amino acids in juice of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Proportion of Asp

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	-145.34	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	-141.34	Year	2	40	44.85	<.0001
AICC (smaller is better)	-141.06	Spray	2	40	21.91	<.0001
BIC (smaller is better)	-141.76	Year*Spra	4	40	2.35	0.0706
CAIC (smaller is better)	-139.76					
HQIC (smaller is better)	-143.01					
Generalized Chi-Square	0.06					
Gener. Chi-Square / DF	0					

Proportion of Asn

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood		Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	-130.87	Year	2	40	59.04	<.0001
AICC (smaller is better)	-130.58	Spray	2	40	31.21	<.0001
BIC (smaller is better)	-131.28	Year*Spray	4	40	1.74	0.1596
CAIC (smaller is better)	-129.28					
HQIC (smaller is better)	-132.54					
Generalized Chi-Square	0.08					
Gener. Chi-Square / DF	0					

Table 5.19. Relative concentrations of amino acids in juice of mature Crimson Crisp® apple fruit treated with 5.1 g N L-1 solution foliar urea sprays harvested in 2018. University of Guelph, Simcoe, Ontario, 2018.

Proportion of other amino acids

Fit Statistics		Type III Tests of Fixed Effects				
-2 Res Log Likelihood	-278.59	Effect	Num DF	Den DF	F Value	Pr > F
AIC (smaller is better)	-276.59	Year	2	40	79.04	<.0001
AICC (smaller is better)	-276.5	Spray	2	40	50.28	<.0001
BIC (smaller is better)	-276.8	Year*Spray	4	40	2.95	0.0318
CAIC (smaller is better)	-275.8					
HQIC (smaller is better)	-277.43					
Generalized Chi-Square	0					
Gener. Chi-Square / DF	0					

Table 6.1. Kinetics of the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast and varying concentrations of sugar and YAN. University of Guelph, Guelph, Ontario, 2019. 208

Max fermentation rate sugar x YAN

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Brix	4	49	6.42	0.0003
YAN	4	49	290.62	<.0001
Brix*YAN	16	49	2.77	0.0032

Tests for Normality

Test	Statistic		p Value	
Shapiro-	W	0.95519	Pr < W	0.0097
Kolmog	D	0.08692	Pr > D	>0.1500
Cramer-von Mises	W-Sq	0.11999	Pr > W-Sq	0.0618
Anderson-Darling	A-Sq	0.90691	Pr > A-Sq	0.021

Time to max rate sugar x YAN

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Brix	4	49	8.21	<.0001
YAN	4	49	12.48	<.0001
Brix*YAN	16	49	2.65	0.0045

Tests for Normality

Test	Statistic		p Value	
Shapiro-	W	0.973	Pr < W	0.1091
Kolmog	D	0.10726	Pr > D	0.0319
Cramer-von Mises	W-Sq	0.11204	Pr > W-Sq	0.08
Anderson-Darling	A-Sq	0.71869	Pr > A-Sq	0.0607

Table 6.1. Kinetics of the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast and varying concentrations of sugar and YAN. University of Guelph, Guelph, Ontario, 2019. 208

Time to completion sugar x YAN

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Brix	4	49	105.13	<.0001
YAN	4	49	57.85	<.0001
Brix*YAN	16	49	13.51	<.0001

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.74466	Pr < W	<0.0001
Kolmogorov-Smirnov	D	0.27109	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.96506	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	5.75172	Pr > A-Sq	<0.0050

Table 6.2. Kinetics of the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast and varying concentrations of sugar and proportions of YAN to sugar. University of Guelph, Guelph, Ontario, 2019. 208

Max fermentation rate sugar x YAN

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Brix	4	29	139.22	<.0001
Proportion	2	29	4.86	0.0151
Brix*Proportion	8	29	7.45	<.0001

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.95379	**Pr < W**	0.0707
Kolmogorov-Smirnov	**D**	0.13891	**Pr > D**	0.0279
Cramer-von Mises	**W-Sq**	0.13735	**Pr > W-Sq**	0.0354
Anderson-Darling	**A-Sq**	0.7987	**Pr > A-Sq**	0.0374

Time to max rate sugar x YAN

Type III Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Brix	4	29	14.98	<.0001
Proportion	2	29	9.72	0.0006
Brix*Proportion	8	29	6.91	<.0001

Tests for Normality				
Test	**Statistic**		**p Value**	
Shapiro-Wilk	**W**	0.96742	**Pr < W**	0.2329
Kolmogorov-Smirnov	**D**	0.08277	**Pr > D**	>0.1500
Cramer-von Mises	**W-Sq**	0.06101	**Pr > W-Sq**	>0.2500
Anderson-Darling	**A-Sq**	0.41544	**Pr > A-Sq**	>0.2500

Table 6.2. Kinetics of the fermentation of 2017 'GoldRush' apple juice with Davis522 yeast and varying concentrations of sugar and proportions of YAN to sugar. University of Guelph, Guelph, Ontario, 2019. 208

Time to completion sugar x YAN

Type III Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Brix	4	29	14.11	<.0001
Proportion	2	29	5.42	0.01
Brix*Proportion	8	29	11.21	<.0001

Tests for Normality

Test	Statistic		p Value	
Shapiro-Wilk	W	0.87316	Pr < W	0.0002
Kolmogorov-Smirnov	D	0.19019	Pr > D	<0.0100
Cramer-von Mises	W-Sq	0.36558	Pr > W-Sq	<0.0050
Anderson-Darling	A-Sq	2.22301	Pr > A-Sq	<0.0050

Figure 6.1 Regression line for proportion of YAN to sugar and the maximum fermentation rate in January 2019. 209

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	0.000939	0.000939	340.72	<.0001
Error	73	0.0002012	2.76E-06		
Corrected Total	74	0.00114			

Root MSE	0.00166	**R-Square**	0.8236
Dependent Mean	0.02209	**Adj R-Sq**	0.8211
Coeff Var	7.51567		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	0.01115	0.0006227	17.91	<.0001
Proportion	**1**	0.00141	7.627E-05	18.46	<.0001

Figure 6.2 Regression line for proportion of YAN to sugar and the time to maximum fermentation rate in January 2019. 210

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	3641.5073	3641.5073	54.47	<.0001
Error	73	4879.8814	66.84769		
Corrected Total	74	8521.3886			

Root MSE	8.17604	**R-Square**	0.4273
Dependent Mean	126.9297	**Adj R-Sq**	0.4195
Coeff Var	6.44139		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	148.46577	3.06682	48.41	<.0001
Proportion	**1**	-2.77232	0.37562	-7.38	<.0001

Figure 6.3 Regression line for proportion of YAN to sugar and the time to complete fermentation in January 2019. 211

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	301563	301563	73.37	<.0001
Error	73	300048	4110.2465		
Corrected Total	74	601611			

Root MSE	64.1112	**R-Square**	0.5013
Dependent Mean	663.2153	**Adj R-Sq**	0.4944
Coeff Var	9.66673		

Parameter Estimates

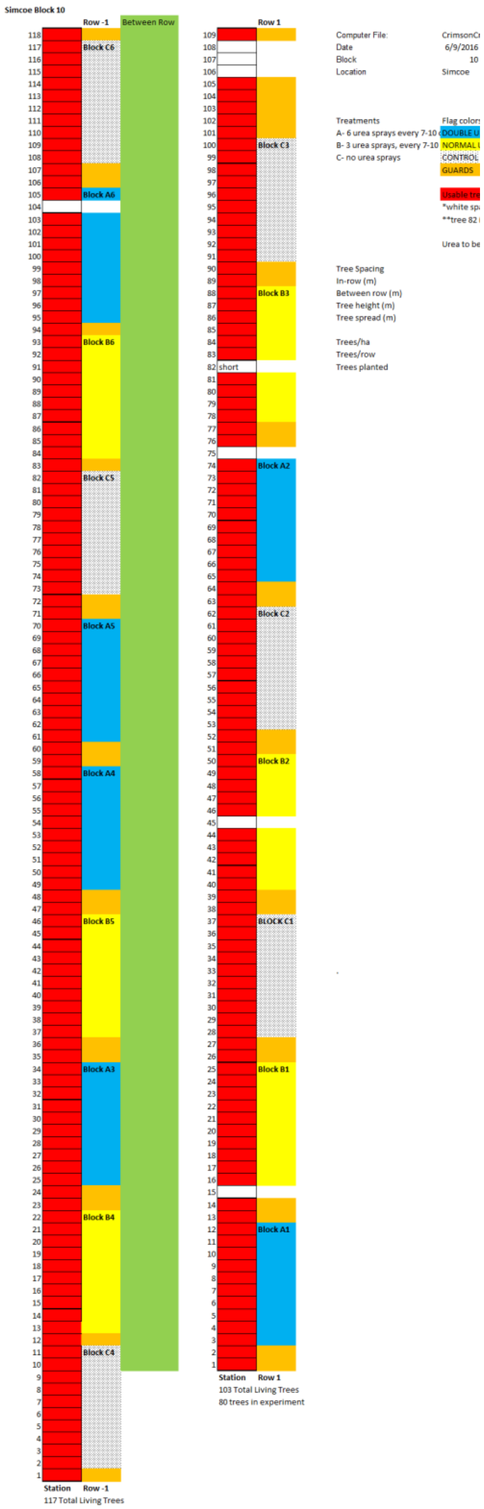
Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	**1**	859.19675	24.048	35.73	<.0001
Proportion	**1**	-25.22851	2.94534	-8.57	<.0001

Appendix 2 Site Plans

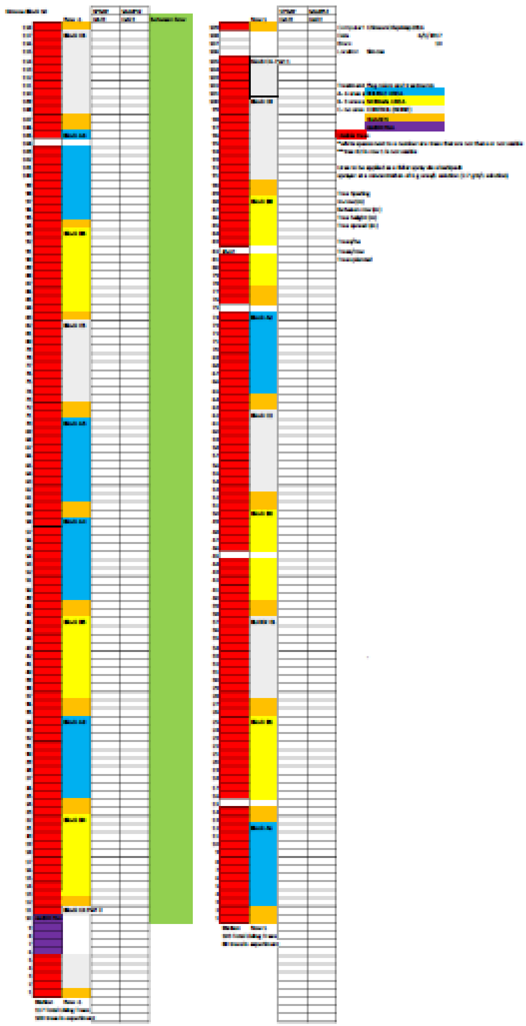
Site Maps

Changes in amino acid composition in apple (*Malus domestica* Borkh*.)* juice from fruit set to harvest, after cold-storage, and in response to summer foliar urea applications

2016 Map:


Simcoe Block 10
Row -1
Between Row
Row 1
Block C6
Block A6
Block B6
Block C5
Block A5
Block A4
Block B5
Block A3
Block B4
Block C4
Block C3
Block B3
short
Block A2
Block C2
Block B2
BLOCK C1
Block B1
Block A1
Station
103 Total Living Trees
80 trees in experiment
117 Total Living Trees
100 trees in experiment
Computer File:
Date
6/9/2016
Block
10
Location
Simcoe
Treatments
A- 6 urea sprays every 7-10
B- 3 urea sprays, every 7-10
C- no urea sprays
GUARDS
Tree Spacing
In-row (m)
Between row (m)
Tree height (m)
Tree spread (m)
Trees/ha
Trees/row
Trees planted

2017 and 2018 Map:



Horticultural and Juice Attribute Experiments

Simcoe Site

2015 Cider Apple Cultivar Experiment

	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8
77	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	X	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	X
76	CBH-1	KB-2	SR-2	X	BA-3	BSe-4	E-4	X
75	CBH-1	KB-2	SR-2	X	BA-3	BSe-4	E-4	X
74	CBH-1	KB-2	SR-2	X	BA-3	BSe-4	E-4	X
73	CBH-1	KB-2	SR-2	X	BA-3	BSe-4	E-4	X
72	CBH-1	KB-2	SR-2	X	BA-3	BSe-4	E-4	X
71	E-1	M-1	COP-2	X	GR-3	TB-3	dead	X
70	E-1	M-1	COP-2	X	GR-3	TB-3	MO-4	X
69	E-1	M-1	COP-2	X	GR-3	TB-3	MO-4	X
68	E-1	M-1	COP-2	X	GR-3	TB-3	MO-4	X
67	E-1	M-1	COP-2	Guard -	GR-3	TB-3	MO-4	Guard -
66	ES-1	SR-1	BN-2	BSn-2	BSn-3	YM-3	TL-4	G-4
65	ES-1	SR-1	BN-2	BSn-2	BSn-3	YM-3	TL-4	G-4
64	ES-1	SR-1	BN-2	BSn-2	BSn-3	YM-3	TL-4	G-4
63	ES-1	SR-1	BN-2	BSn-2	BSn-3	YM-3	TL-4	G-4
62	ES-1	SR-1	BN-2	BSn-2	BSn-3	YM-3	TL-4	G-4
61	MD-1	FR-1	MO-2	SA-2	TL-3	TS-3	GG-4	BSn-4
60	MD-1	FR-1	MO-2	SA-2	TL-3	TS-3	GG-4	BSn-4
59	MD-1	FR-1	MO-2	SA-2	TL-3	TS-3	GG-4	BSn-4
58	MD-1	FR-1	MO-2	SA-2	TL-3	TS-3	GG-4	BSn-4
57	MD-1	FR-1	MO-2	SA-2	TL-3	TS-3	GG-4	BSn-4
56	CR-1	BSn-1	BSe-2	G-2	BN-3	MD-3	D-4	TS-4
55	CR-1	BSn-1	BSe-2	G-2	BN-3	MD-3	dead	TS-4
54	dead	BSn-1	BSe-2	G-2	BN-3	MD-3	D-4	TS-4
53	CR-1	BSn-1	BSe-2	G-2	BN-3	MD-3	D-4	TS-4
52	CR-1	BSn-1	BSe-2	G-2	BN-3	MD-3	D-4	TS-4
51	AK-1	TB-1	M-2	TL-2	MO-3	SA-3	AK-4	ES-4
50	AK-1	TB-1	M-2	TL-2	MO-3	SA-3	AK-4	ES-4
49	AK-1	TB-1	M-2	TL-2	MO-3	SA-3	AK-4	ES-4
48	AK-1	TB-1	M-2	TL-2	MO-3	SA-3	AK-4	ES-4
47	AK-1	TB-1	M-2	TL-2	MO-3	SA-3	AK-4	ES-4
46	BSe-1	PP-1	TB-2	CC-2	AK-3	dead	GR-4	B-4
45	BSe-1	PP-1	TB-2	CC-2	AK-3	BSe-3	GR-4	B-4
44	BSe-1	PP-1	TB-2	CC-2	AK-3	BSe-3	GR-4	B-4
43	BSe-1	PP-1	TB-2	CC-2	AK-3	BSe-3	GR-4	B-4
42	BSe-1	PP-1	TB-2	CC-2	dead	BSe-3	GR-4	B-4
41	D-1	COP-1	FR-2	TS-2	GG-3	ES-3	CBH-4	KB-4
40	D-1	COP-1	FR-2	TS-2	GG-3	ES-3	CBH-4	KB-4
39	D-1	COP-1	FR-2	TS-2	GG-3	ES-3	CBH-4	KB-4
38	D-1	COP-1	FR-2	TS-2	GG-3	ES-3	CBH-4	KB-4
37	D-1	COP-1	FR-2	TS-2	GG-3	ES-3	CBH-4	KB-4
36	G-1	BA-1	B-2	D-2	dead	CBH-3	CC-4	CR-4
35	G-1	BA-1	B-2	D-2	CC-3	CBH-3	CC-4	CR-4
34	G-1	BA-1	B-2	D-2	CC-3	CBH-3	CC-4	CR-4
33	G-1	BA-1	B-2	D-2	CC-3	CBH-3	CC-4	CR-4
32	G-1	BA-1	B-2	D-2	CC-3	CBH-3	CC-4	CR-4
31	KB-1	TS-1	MD-2	ES-2	CR-3	KB-3	SR-4	COP-4
30	KB-1	TS-1	MD-2	ES-2	CR-3	KB-3	SR-4	COP-4
29	KB-1	TS-1	MD-2	ES-2	CR-3	KB-3	SR-4	COP-4
28	KB-1	TS-1	MD-2	ES-2	CR-3	KB-3	SR-4	COP-4
27	KB-1	TS-1	MD-2	ES-2	CR-3	KB-3	SR-4	COP-4
26	GR-1	SA-1	GG-2	CR-2	SR-3	M-3	BN-4	M-4
25	GR-1	SA-1	GG-2	CR-2	SR-3	M-3	BN-4	M-4
24	GR-1	SA-1	GG-2	CR-2	SR-3	M-3	BN-4	M-4
23	GR-1	SA-1	GG-2	CR-2	SR-3	dead	BN-4	M-4
22	GR-1	SA-1	GG-2	CR-2	SR-3	M-3	BN-4	M-4
21	BR-1	BN-1	GR-2	YM-2	PP-3	BR-3	BR-4	FR-4
20	BR-1	BN-1	GR-2	YM-2	PP-3	BR-3	BR-4	FR-4
19	BR-1	BN-1	GR-2	YM-2	PP-3	BR-3	BR-4	FR-4
18	BR-1	BN-1	GR-2	YM-2	PP-3	BR-3	BR-4	FR-4
17	BR-1	BN-1	GR-2	YM-2	PP-3	BR-3	BR-4	FR-4
16	MO-1	TL-1	CBH-2	AK-2	dead	G-3	MD-4	SA-4
15	MO-1	TL-1	CBH-2	AK-2	D-3	G-3	MD-4	SA-4
14	MO-1	dead	CBH-2	AK-2	D-3	G-3	MD-4	SA-4
13	MO-1	TL-1	CBH-2	AK-2	D-3	G-3	MD-4	SA-4
12	MO-1	dead	CBH-2	AK-2	D-3	G-3	MD-4	SA-4
11	GG-1	B-1	BR-2	BA-2	E-3	FR-3	BA-4	TB-4
10	GG-1	B-1	BR-2	BA-2	E-3	FR-3	BA-4	TB-4
9	GG-1	B-1	BR-2	BA-2	E-3	FR-3	BA-4	TB-4
8	GG-1	B-1	BR-2	BA-2	E-3	FR-3	BA-4	TB-4
7	GG-1	B-1	BR-2	BA-2	E-3	FR-3	BA-4	TB-4
6	YM-1	CC-1	dead	PP-2	B-3	COP-3	PP-4	YM-4
5	YM-1	CC-1	E-2	PP-2	B-3	COP-3	PP-4	YM-4
4	YM-1	CC-1	E-2	PP-2	dead	COP-3	PP-4	YM-4
3	YM-1	CC-1	E-2	PP-2	B-3	COP-3	PP-4	YM-4
2	YM-1	CC-1	E-2	PP-2	B-3	COP-3	PP-4	YM-4
1	dead	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9	Guard - Buckeye Gala B9
	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8
	4 m between rows	4 m between rows	4 m between rows	4 m between rows	4 m between rows	4 m between rows	4 m between rows	4 m between rows

Planting Date:	04/28/2015	
Computer File:	**2015 Cider Apple Cultivar Experiment**	
Date	2/8/2020 23:02	
Location	Block 14	University of Guelph, Sim
Map	http://goo.gl/maps/Yfni5	
Total Area	0.912912	ha
	0.37	acres
Row Lenth	115.5	meters
Date Trees planted		
Irrigation	2 L/hr Emitters	
Rootstock	M.9	

	Code	Cultivar
1	AK	Ashmead's Kernal
2	BR	Binet Rouge
3	BSe	Bramley's Seedling
4	B	Breakwell
5	BSn	Brown Snout
6	BA	Brown's Apple
7	BN	Bulmers Norman
8	CBH	Calville Blanc d'Hiver
9	CR	Cline Russet
10	COP	Cox Orange Pippin
11	CC	Crimson Crisp
12	D	Dabinett
13	E	Enterprise
14	ES	Esopus Spitzenberg
15	FR	Frequin Rouge
16	GR	Golden Russet
17	G	Goldrush
18	GG	Grimes Golden
19	KB	Kingston Black
20	MO	Medaille d'Or
21	M	Michelin
22	MD	Muscadet De Dieppe
23	PP	Porter's Perfection
24	SR	Stoke's Red
25	SA	Sweet Alford
26	TS	Tolman Sweet
27	TB	Tremlett' s Bitter
28	TL	Tydeman Late
29	YM	Yarlington Mill

Experimental Design (for each experiment)	
Reps	4
Trees/Rep	5
Cultivars	29
Total Trees	580
Tree/Row	77
Rows	8

Tree SpacinG	Feet	Meters
In-row (ft/m)	4.92	1.50
Between-row (ft/m)	13.12	4.00
Trees/ha	1667	
Trees/acre	675	
System	Vertical Axe	
Total Area	0.37	acres
Land Area		
Width	32	m
Length	116	m

N

Twin Pines Site

2015 Cider Apple Cultivar Experiment - Twin Pines

	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8	Row 9	Row 10
60	ES	dead	B	missing	FR	G	AK	M	SR	BR
59	ES	TL	B	BSn	dead	G	AK	dead	SR	BR
58	ES	TL	B	BSn	FR	G	AK	M	SR	BR
57	ES	TL	B	BSn	FR	G	AK	dead	SR	BR
56	ES	dead	B	BSn	FR	G	AK	M	dead	BR
55	ES	dead	B	BSn	dead	G	AK	dead	SR	dead
54	ES	TL	B	BSn	FR	G	AK	dead	SR	dead
53	dead	TL	dead	dead	FR	G	AK	M	SR	dead
52	ES	TL	B	BSn	FR	G	dead	dead	SR	BR
51	ES	TL	B	BSn	dead	G	AK	dead	SR	dead
50	ES	TL	B	BSn	FR	G	AK	dead	SR	BR
49	ES	TL	dead	BSn	dead	G	dead	dead	SR	BR
48	ES	TL	B	BSn	FR	G	AK	dead	SR	BR
47	ES	TL	B	dead	FR	G	AK	M	SR	BR
46	ES	TL	B	BSn	FR	G	AK	dead	SR	BR
45	ES	TL	B	BSn	FR	G	dead	M	SR	BR
44	ES	TL	B	BSn	FR	G	dead	M	SR	BR
43	ES	TL	B	dead	missing	G	AK	M	SR	BR
42	ES	TL	B	dead	missing	G	AK	M	dead	BR
41	ES	TL	B	dead	missing	G	AK	M	dead	BR
40		D	missing	SA	Bse	TS	TB	KB	MD	dead
39		D	missing	SA	dead	TS	TB	dead	MD	BA
38		D	missing	SA	Bse	dead	TB	KB	MD	BA
37		dead	missing	SA	Bse	dead	TB	KB	MD	dead
36		dead	missing	SA	Bse	TS	TB	KB	MD	BA
35		D	missing	SA	Bse	dead	dead	KB	MD	BA
34		D	missing	SA	Bse	TS	TB	KB	MD	BA
33		D	missing	SA	Bse	dead	TB	KB	dead	BA
32		D	GR	SA	Bse	TS	TB	KB	MD	BA
31		D	GR	SA	Bse	TS	TB	dead	MD	BA
30	No Trees Planted	D	GR	SA	Bse	dead	TB	KB	MD	BA
29		D	GR	SA	Bse	dead	TB	KB	MD	dead
28		D	GR	SA	Bse	dead	TB	KB	MD	dead
27		dead	GR	SA	Bse	dead	TB	KB	MD	dead
26		dead	GR	SA	Bse	dead	TB	KB	MD	BA
25		D	GR	dead	Bse	TS	TB	KB	MD	dead
24		dead	GR	dead	dead	TS	TB	KB	MD	BA
23		D	GR	SA	Bse	dead	dead	dead	MD	dead
22		D	GR	SA	dead	dead	TB	dead	MD	dead
21		dead	GR	SA	dead	dead	dead	KB	MD	dead
20	GG	dead	CR	dead	COP	PP	dead	BN	CBH	dead
19	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
18	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
17	GG	dead	CR	CC	dead	PP	YM	BN	CBH	MO
16	GG	E	CR	dead	COP	dead	YM	BN	CBH	MO
15	GG	dead	CR	CC	COP	PP	YM	BN	dead	MO
14	GG	E	CR	dead	COP	dead	YM	BN	CBH	dead
13	GG	E	CR	CC	COP	PP	YM	BN	CBH	dead
12	GG	missing	CR	CC	COP	PP	YM	BN	CBH	MO
11	GG	E	CR	CC	COP	dead	YM	BN	CBH	dead
10	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
9	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
8	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
7	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
6	GG	E	CR	CC	COP	PP	YM	BN	CBH	dead
5	GG	dead	CR	CC	COP	PP	YM	BN	CBH	MO
4	GG	E	CR	CC	COP	PP	YM	BN	CBH	dead
3	GG	dead	CR	CC	dead	PP	YM	BN	CBH	dead
2	GG	E	CR	CC	COP	PP	YM	BN	CBH	MO
1	GG	dead	CR	CC	COP	dead	YM	BN	CBH	MO
	Row 1	Row 2	Row 3	Row 4	Row 5	Row 6	Row 7	Row 8	Row 9	Row 10

Planting Date:			
Computer File:	**2015 Cider Apple Cultivar Experiment - T**		
Date	2/8/2020 23:02		
Location	Mark and Mike Vansteenkiste		
Address	8169 Kennedy Line, Thedford		
Map	https://www.google.ca/maps/place/Twin+Pine		
Total Area	0.69	ha	0.28
Row Length	240	feet	
Irrigation	**Drip**		

	Code	Cultivar
1	AK	Ashmead's Kernel
2	BR	Binet Rouge
3	BSe	Bramley's Seedling
4	B	Breakwell
5	BSn	Brown Snout
6	BA	Brown's Apple
7	BN	Bulmers Norman
8	CBH	Calville Blanc d'Hiver
9	CR	Cline Russet
10	COP	Cox Orange Pippin
11	CC	Crimson Crisp
12	D	Dabinett
13	E	Enterprise
14	ES	Esopus Spitzenberg
15	FR	Frequin Rouge
16	GR	Golden Russet
17	G	Goldrush
18	GG	Grimes Golden
19	KB	Kingston Black
20	MO	Medaille d'Or
21	M	Michelin
22	MD	Muscadet de Dieppe
23	PP	Porter's Perfection
24	SR	Stoke's Red
25	SA	Sweet Alford
26	TS	Tolman Sweet
27	TB	Tremlett' s Bitter
28	TL	Tydeman Late
29	YM	Yarlington Mill

Experimental Design (for each experiment)	
Reps	1
Trees/Rep	20
Cultivars	29
Total Trees	580
Tree/Row	60
Rows	10

N

Tree SpacinG	Feet	Meters
In-row (ft/m)	4.00	1.22
Between-row (ft/m)	12.50	3.81
Trees/ha	2153	
Trees/acre	872	
System		
Total Area	0.28	acres
Land Area		
Width	38	m
Length	73	m

Spirit Tree Site

2016 Cider Apple Cultivar Experiment - Spirit Tree

	Row 1	Row 2	Row 3	Row 4
95			TS	
94	TB		TS	
93	TB		TS	
92	TB	TS	TS	
91	TB	TS	TS	
90	TB	TS	TS	
89	TB	TS	TS	
88	TB	TS	TS	
87	TB	KB	TS	
86	TB	KB	TS	
85	TB	KB	TS	
84	TB	KB	TS	
83	TB	KB	TS	
82	TB	KB	TS	
81	TB	KB	TS	
80	TB	KB	BSn	
79	TB	KB	BSn	
78	dead	KB	BSn	
77	TB	KB	BSn	
76	TB	KB	BSn	
75	TB	KB	BSn	
74	COP	KB	BSn	
73	COP	KB	BSn	
72	COP	KB	BSn	
71	dead	KB	BSn	
70	dead	KB	BSn	
69	COP	KB	BSn	
68	COP	KB	BSn	
67	COP	GR	BSn	
66	COP	GR	BSn	
65	COP	GR	dead	
64	COP	GR	BSn	
63	COP	GR	BSn	
62	COP	GR	BSn	
61	COP	GR	BSn	
60	COP	dead	BSe	
59	COP	GR	BSe	
58	COP	GR	BSe	
57	COP	GR	BSe	
56	COP	GR	BSe	
55	COP	dead	BSe	
54	dead	GR	BSe	
53	FR	GR	BSe	
52	FR	GR	BSe	
51	dead	GR	BSe	
50	dead	GR	BSe	
49	FR	GR	BSe	
48	FR	GR	BSe	
47	FR	dead	BSe	
46	FR	M	BSe	
45	FR	dead	BSe	
44	FR	M	BSe	
43	FR	M	BSe	
42	FR	M	BSe	
41	FR	dead	BSe	
40	FR	M	RR	
39	FR	M	RR	
38	FR	M	dead	
37	FR	dead	RR	
36	FR	M	RR	
35	FR	M	dead	
34	F	M	RR	
33	F	dead	RR	
32	F	dead	dead	
31	F	M	RR	
30	F	M	RR	
29	F	M	dead	
28	F	M	RR	
27	F	BW	RR	
26	F	BW	RR	
25	F	BW	RR	
24	F	BW	RR	
23	F	BW	RR	
22	F	BW	RR	
21	F	BW	RR	
20	F	BW	CJ	
19	F	dead	CJ	
18	F	BW	CJ	
17	F	dead	CJ	
16	F	BW	CJ	
15	F	BW	CJ	
14	ES	BW	CJ	
13	ES	BW	dead	dead
12	ES	BW	CJ	D
11	ES	BW	CJ	dead
10	dead	BW	CJ	D
9	ES	BW	CJ	D
8	dead	BW	dead	D
7	ES	ES	CJ	D
6	ES	ES	CJ	D
5	ES	ES	CJ	D
4	ES	ES	CJ	D
3	ES	ES	CJ	dead
2	ES	ES	dead	D
1	ES	ES	CJ	dead
	Row 1	Row 2	Row 3	Row 4

Boston Mills Rd

Planting Date:	Spring 2016		
Computer File:	**2016 Cider Apple Cultivar Experiment - S**		
Date	2/8/2020 23:02		
Location	Thomas Wilson		
Address	1137 Boston Mills Rd, Terra Cotta		
Map	https://www.google.ca/maps/place/Spirit+Tree		
Total Area	0.40	ha	0.16
Row Length	380	feet	
Irrigation			

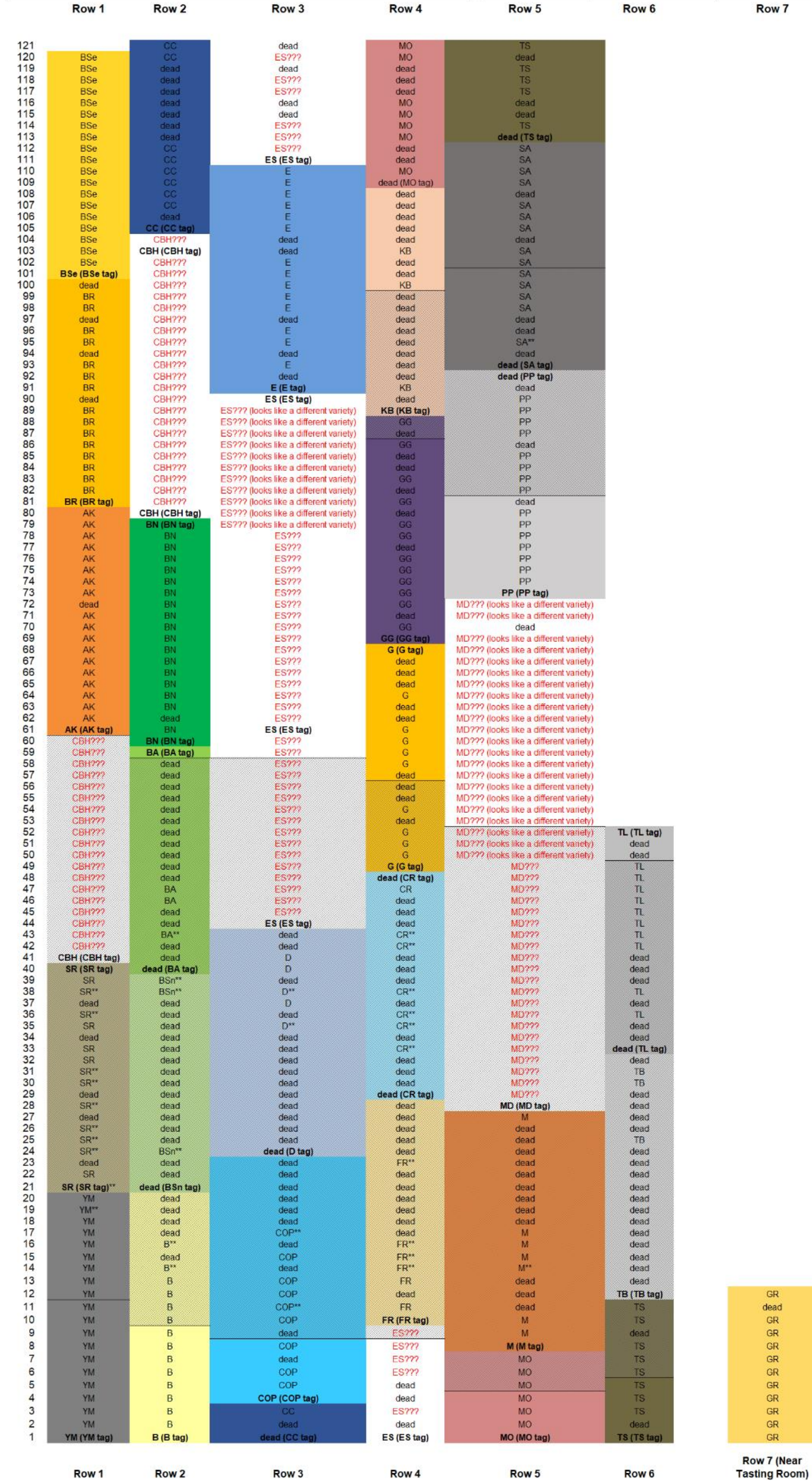
	Code	Cultivar
1	BSe	Bramley's Seedling
2	BSn	Brown Snout
3	BW	Baldwin
4	CJ	Chisel Jersey
5	COP	Cox Orange Pippin
6	D	Dabinett
7	ES	Esopus Spitzenberg
8	F	Foxwhelp
9	FR	Frequin Rouge
10	GR	Golden Russet
11	KB	Kingston Black
12	M	Michelin
13	RR	Roxbury Russet
15	TB	Tremlett' s Bitter
14	TS	Tolman Sweet
	⟶	post

Experimental Design (for each experiment)	
Reps	1
Trees/Rep	20
Cultivars	15
Total Trees	294
Tree/Row	95
Rows	4

Tree SpacinG	Feet	Meters
In-row (ft/m)	4.00	1.00
Between-row (ft/m)	12.50	4.25
Trees/ha	2353	
Trees/acre	953	
System	Central leader	
Total Area	0.16	acres
Land Area		
Width	17	m
Length	95	m

County Cider Site

2015 Cider Apple Cultivar Experiment - County Cider



Planting Date:	Spring 2015		
Computer File:	**2015 Cider Apple Cultivar Experiment - (**		
Date	2/8/2020 23:02		
Location	Grant Howes		
Address	657 Bongards Crossroad, Waupoos		
Map	https://www.google.ca/maps/place/County+Ci		
Total Area	0.89	ha	0.36
Row Length	526	feet	
Irrigation	N/A		

	Code	Cultivar
1	AK	Ashmead's Kernel
2	BR	Binet Rouge
3	BSe	Bramley's Seedling
4	B	Breakwell
5	BSn	Brown Snout
6	BA	Brown's Apple
7	BN	Bulmers Norman
8	CBH	Calville Blanc d'Hiver
9	CR	Cline Russet
10	COP	Cox Orange Pippin
11	CC	Crimson Crisp
12	D	Dabinett
13	E	Enterprise
14	ES	Esopus Spitzenberg
15	FR	Frequin Rouge
16	GR	Golden Russet
17	G	Goldrush
18	GG	Grimes Golden
19	KB	Kingston Black
20	MO	Medaille d'Or
21	M	Michelin
22	MD	Muscadet de Dieppe
23	PP	Porter's Perfection
24	SR	Stoke's Red
25	SA	Sweet Alford
26	TS	Tolman Sweet
27	TB	Tremlett' s Bitter
28	TL	Tydeman Late
29	YM	Yarlington Mill
	**	scion rooted trees
		flood zone

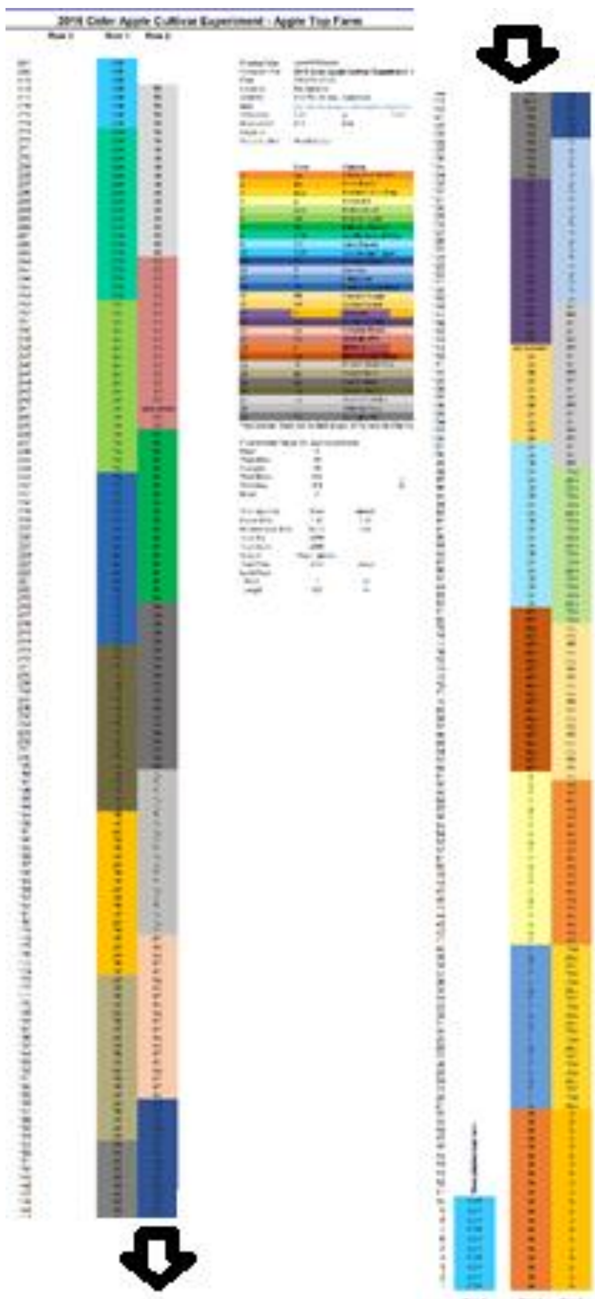
Experimental Design (for each experiment)

Reps	1
Trees/Rep	20
Cultivars	29
Total Trees	580
Tree/Row	121
Rows	6

N

Tree Spacing	Feet	Meters
In-row (ft/m)	4.35	1.33
Between-row (ft/m)	12.22	3.73
Trees/ha	2026	
Trees/acre	820	
System	Slender spindle	
Total Area	0.36	acres
Land Area		
Width	22	m
Length	160	m

Apple Top Farms Site



APPENDIX 3 OFF-SITE DATA

The results of the growth measurement analyses for each cultivar from 2015-2018 at the Simcoe Research Station were already summarized. While the results from the off-site locations could not be statistically compared with the results from the Simcoe site, they are useful for looking at general trends.

At the Thedford site there was a fire blight outbreak in 2017 that led to the growers withholding nitrogen fertilization to control growth and limit its effects. There was a low survival rate in several cultivars, including ‘Enterprise’ (35%), ‘Michelin’ (45%), ‘Tolman Sweet’ (45%), and ‘Brown’s Apple’ (50%) (Table 3.9). TCSA and winter dieback shoots are also reported. At the Clarksburg site, which was organically managed, all the cultivars had a high survival rate and little winter dieback (Table 3.10). Part of the orchard at Picton was planted in a flood zone, which resulted in dead trees. This should not be considered to be a problem with the affected cultivars (Table 3.11). The Caledon site, was planted in 2016 and had some additional cultivars, including Baldwin, Chisel Jersey, Foxwhelp, and Roxbury Russet (Table 3.12).

Table A4.1. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. Thedford, Ontario, 2018.

Cultivar	Survival rate fall 2018	Spring 2015 TCSA (cm^2) [z]	Fall 2015 TCSA (cm^2)	2015 relative growth (cm^2)	Fall 2016 TCSA (cm^2)	2016 relative growth (cm^2)	Fall 2017 TCSA (cm^2)	2017 relative growth (cm^2)	Fall 2018 TCSA (cm^2)	2018 relative growth (cm^2)	2016 dieback shoot number (dieback shoots $tree^{-1}$)	2016 dieback shoot length (cm)	2017 dieback shoot number (dieback shoots $tree^{-1}$)	2017 dieback shoot length (cm)	2018 dieback shoot number (dieback shoots $tree^{-1}$)	2018 dieback shoot length (cm)
Ashmead's Kernel	80%	1.0	1.7	0.7	2.0	0.3	4.2	2.1	5.8	1.6	0.6	5.0	0.9	25.2	0.4	6.9
Binet Rouge	75%	1.7	2.3	0.7	2.7	0.4	5.6	2.9	7.7	3.4	2.4	40.9	0.7	2.6	0.1	0.9
Bramley's Seedling	80%	1.4	1.8	0.4	2.2	0.4	4.8	2.7	6.9	2.0	0.8	2.9	0.7	7.7	0.1	0.0
Breakwell	90%	1.3	1.7	0.5	2.1	0.4	4.6	2.4	6.0	1.5	0.3	0.8	0.6	4.6	0.2	0.0
Brown Snout	65%	0.9	1.2	0.3	1.4	0.2	2.9	1.5	4.2	1.2	0.1	0.4	0.6	11.6	0.0	0.0
Brown's Apple	50%	1.3	1.7	0.4	1.8	0.2	3.4	1.6	4.0	1.2	1.1	38.4	0.6	8.7	0.4	6.5
Bulmers Norman	93%	1.4	1.6	0.2	1.7	0.0	2.8	1.2	4.3	1.2	0.1	1.0	0.2	1.2	0.1	0.3
Calville Blanc d'Hiver	95%	1.6	2.0	0.4	2.1	0.1	4.1	2.0	6.5	2.4	1.7	12.6	0.2	0.9	0.0	0.0
Cline Russet	100%	1.0	1.2	0.2	1.3	0.1	2.1	0.8	2.9	0.8	1.4	4.8	0.6	1.5	0.1	1.6
Cox Orange Pippin	90%	1.0	1.5	0.5	1.8	0.3	3.1	1.4	3.9	0.8	4.3	21.0	2.1	11.3	0.9	3.9
Crimson Crisp	75%	0.7	1.0	0.3	1.2	0.2	2.4	1.2	3.5	1.1	1.5	11.2	1.6	8.2	0.4	1.8
Dabinett	65%	1.0	1.3	0.3	1.8	0.5	3.0	1.4	3.6	1.0	3.9	40.3	2.9	29.1	0.8	2.9
Enterprise	35%	1.2	1.9	0.6	2.2	0.3	4.0	1.7	4.2	1.4	3.8	45.0	3.0	22.8	1.0	0.0
Esopus Spitzenberg	95%	1.1	1.9	0.8	2.5	0.6	4.6	2.1	6.0	1.4	2.5	18.5	1.0	3.5	0.2	3.3
Frequin Rouge	82%	0.9	1.5	0.5	1.8	0.4	3.5	1.5	3.9	0.7	0.0	0.0	0.3	1.3	0.5	11.4
Golden Russet	100%	0.8	1.2	0.4	1.6	0.3	3.5	1.9	4.5	1.0	2.9	34.8	2.6	26.3	1.2	15.0
GoldRush	100%	1.2	2.0	0.7	2.4	0.4	4.0	1.6	5.0	1.0	2.1	22.1	0.6	0.6	0.1	1.0
Grimes Golden	100%	1.1	1.5	0.4	1.5	0.0	3.0	1.4	3.8	0.9	1.0	4.4	0.3	1.0	0.0	0.0
Kingston Black	80%	1.4	1.8	0.4	2.4	0.5	3.7	1.3	5.3	1.7	1.2	7.2	0.4	0.0	0.3	6.6
Medaille d'Or	65%	1.3	1.7	0.4	2.0	0.3	3.0	1.1	4.1	1.1	1.9	8.8	0.6	1.3	0.2	3.2
Michelin	45%	1.3	1.9	0.6	2.5	0.4	3.9	1.3	5.7	1.6	0.4	2.3	0.5	29.1	0.0	0.0
Muscadet De Dieppe	95%	1.3	1.9	0.6	2.3	0.3	4.4	2.1	5.3	0.9	0.5	3.4	0.4	0.3	0.2	1.4
Porter's Perfection	80%	1.4	1.9	0.4	2.1	0.3	4.0	1.8	5.5	1.7	0.8	4.3	0.6	3.4	0.6	8.7
Stoke Red	70%	1.2	1.9	0.7	2.6	0.7	4.7	2.1	5.9	1.2	0.6	5.3	0.2	3.5	0.1	0.5
Sweet Alford	90%	1.4	1.8	0.4	2.3	0.4	3.7	1.4	4.4	0.9	1.0	18.1	0.0	0.0	0.2	2.9
Tolman Sweet	45%	1.1	1.8	0.6	2.1	0.3	4.2	1.9	4.4	2.0	1.2	8.5	0.0	0.0	0.0	0.0
Tydeman Late	85%	0.9	1.7	0.7	2.6	0.9	5.3	2.8	7.7	2.8	2.7	16.7	1.2	5.7	0.1	2.1
Yarlington Mill	90%	1.2	1.5	0.3	1.6	0.0	2.3	0.7	3.0	0.9	1.1	6.0	0.3	12.3	0.5	16.5

[z] Trunk cross-sectional area.

Table A4.2. Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production. Clarskburg, Ontario, 2018.

Cultivar	Survival rate fall 2018	Spring 2015 TCSA (cm^2) [z]	Fall 2015 TCSA (cm^2)	2015 relative growth (cm^2)	Fall 2016 TCSA (cm^2)	2016 relative growth (cm^2)	Fall 2017 TCSA (cm^2)	2017 relative growth (cm^2)	Fall 2018 TCSA (cm^2)	2018 relative growth (cm^2)	2016 dieback shoot number (dieback shoots $tree^{-1}$)	2016 dieback shoot length (cm)	2017 dieback shoot number (dieback shoots $tree^{-1}$)	2017 dieback shoot length (cm)	2018 dieback shoot number (dieback shoots $tree^{-1}$)	2018 dieback shoot length (cm)
Ashmead's Kernel	100%	0.8	1.4	0.7	2.1	0.7	3.9	1.7	5.6	1.8	0.0	0.0	0.0	0.0	1.0	3.6
Binet Rouge	100%	1.1	2.3	1.3	3.5	1.2	7.1	3.6	9.2	2.8	0.3	3.5	0.3	0.9	2.0	18.0
Bramley's Seedling	100%	1.1	1.8	0.7	2.4	0.7	4.6	2.2	6.3	1.6	0.0	0.0	0.1	0.1	0.4	1.1
Breakwell	100%	1.2	2.0	0.8	2.5	0.5	4.4	1.9	5.5	1.8	0.0	0.0	0.0	0.2	0.4	7.5
Brown Snout	100%	0.7	1.2	0.6	1.5	0.3	2.9	1.4	3.3	0.4	0.0	0.0	0.1	0.2	0.0	0.0
Brown's Apple	100%	0.5	1.7	1.2	2.5	0.7	4.1	1.6	5.2	1.9	0.0	0.0	0.1	0.1	0.6	9.7
Bulmers Norman	100%	0.9	2.1	1.2	3.0	0.9	5.5	2.5	6.9	1.8	0.1	0.4	0.0	0.0	0.2	0.8
Calville Blanc d'Hiver	100%	1.2	2.4	1.3	3.5	1.0	6.2	2.8	8.2	2.7	0.0	0.0	0.0	0.0	3.5	20.8
Cline Russet	100%	0.7	1.3	0.6	1.7	0.4	3.2	1.5	3.5	1.1	0.4	2.7	0.8	2.0	0.7	8.7
Cox Orange Pippin	100%	0.7	2.0	1.2	2.5	0.5	4.5	2.0	6.7	2.1	0.2	4.1	0.3	5.3	1.1	10.2
Crimson Crisp	100%	0.3	1.1	0.8	1.8	0.7	3.6	1.8	5.1	1.4	0.3	4.3	3.5	0.7	1.6	5.0
Dabinett	100%	0.4	1.1	0.7	1.6	0.5	3.1	1.5	4.6	1.5	0.3	1.6	0.2	1.0	1.3	3.1
Enterprise	95%	1.0	1.9	0.9	3.0	1.2	5.6	2.6	6.1	1.2	0.0	6.2	0.1	0.9	0.4	8.4
Esopus Spitzenberg	100%	0.6	1.8	1.1	2.5	0.7	4.4	2.0	5.5	1.9	0.2	1.8	0.1	2.1	0.4	7.7
Frequin Rouge	100%	0.8	1.7	0.9	2.4	0.7	4.1	1.6	5.6	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Golden Russet	89%	0.6	0.9	0.6	1.5	0.6	2.9	1.4	2.3	0.1	0.5	6.1	0.8	2.8	0.5	8.5
GoldRush	95%	0.9	1.7	0.7	2.1	0.5	4.1	2.0	4.4	0.3	0.2	2.2	0.2	0.6	0.7	3.0
Grimes Golden	100%	0.9	1.8	0.9	2.5	0.7	4.4	1.9	4.5	0.9	0.0	0.0	0.1	0.3	0.7	9.2
Kingston Black	95%	1.2	2.5	1.3	3.6	1.1	6.3	2.8	9.5	3.1	0.1	0.6	0.0	0.0	3.2	21.3
Medaille d'Or	95%	0.9	2.3	1.4	3.4	1.1	4.8	1.4	6.5	1.7	0.2	2.5	0.1	0.4	1.2	4.1
Michelin	100%	1.1	2.4	1.3	3.1	0.7	5.3	2.2	6.4	1.9	0.0	0.0	0.0	0.0	0.4	7.6
Muscadet De Dieppe	100%	1.1	1.9	0.8	2.5	0.6	4.0	1.6	4.5	1.2	0.1	0.2	0.1	0.2	0.3	7.4
Porter's Perfection	100%	1.2	2.3	1.1	3.1	0.8	5.9	2.8	7.5	1.6	0.1	1.6	0.4	4.4	0.4	0.8
Stoke Red	100%	1.0	2.1	1.1	3.3	1.3	5.1	1.7	7.2	2.8	0.2	1.8	0.4	2.5	0.7	10.5
Sweet Alford	100%	1.2	1.9	0.7	2.6	0.7	5.1	2.5	6.9	1.9	0.4	3.8	0.7	5.0	2.5	9.0
Tolman Sweet	100%	0.8	1.9	1.1	2.4	0.6	4.2	1.8	5.0	1.5	0.0	0.0	0.1	0.2	0.5	8.4
Tydeman Late	100%	0.5	1.2	0.7	2.0	0.8	4.6	2.6	7.4	2.8	0.2	12.5	0.1	1.5	1.7	12.0
Yarlington Mill	95%	0.8	1.9	1.0	2.6	0.7	4.0	1.4	5.1	1.9	0.2	2.6	0.4	2.1	0.7	10.9

[z] Trunk cross-sectional area.

Table A4.3. Growth attributes of 25 apple cultivars grown on M.9 rootstock for cider production. Picton, Ontario, 2017.

Cultivar	Survival rate fall 2018	Spring 2015 TCSA (cm^2) [z]	Fall 2015 TCSA (cm^2)	2015 relative growth (cm^2)	Fall 2016 TCSA (cm^2)	2016 relative growth (cm^2)	Fall 2017 TCSA (cm^2)	2017 relative growth (cm^2)	Fall 2018 TCSA (cm^2)	2018 relative growth (cm^2)	2016 dieback shoot number (dieback shoots $tree^{-1}$)	2016 dieback shoot length (cm)	2017 dieback shoot number (dieback shoots $tree^{-1}$)	2017 dieback shoot length (cm)	2018 dieback shoot number (dieback shoots $tree^{-1}$)	2018 dieback shoot length (cm)
Ashmead's Kernel	85%	0.94	1.43	0.47	1.84	0.38	3.11	1.27	6.01	2.85	1.68	11.7	0.89	4.3	1.6	7.1
Binet Rouge	80%	1.40	1.74	0.27	1.92	0.19	2.54	0.57	4.24	2.01	2.18	14.5	2.18	12.1	3.1	0.0
Bramley's Seedling	100%	1.43	1.98	0.56	2.12	0.14	3.71	1.59	6.95	3.24	0.65	3.7	0.20	1.1	0.3	18.8
Breakwell	40%	1.03	1.24	0.21	1.28	0.03	1.59	0.25	3.08	1.30	0.78	4.0	0.13	4.5	0.6	7.3
Brown Snout	0%	0.65	0.98	0.24	0.76	0.28	1.59	0.38	1.03	-0.27	2.06	22.6	0.00	0.0	0.6	1.6
Brown's Apple	5%	1.03	1.33	0.18	0.88	0.17	2.14	0.51	0.34	-0.94	0.50	10.3	0.20	4.5	0.5	3.0
Bulmers Norman	48%	1.13	1.42	0.28	1.55	0.13	2.41	0.86	4.64	2.26	0.63	4.8	0.11	0.2	1.1	2.4
Cline Russet	5%	0.74	0.89	0.15	0.93	0.04	1.30	0.34	2.91	0.83	2.38	21.5	0.63	2.5	1.5	6.8
Cox Orange Pippin	25%	0.92	1.33	0.37	1.56	0.23	2.27	0.68	3.97	1.47	6.18	58.5	1.70	15.1	5.4	23.0
Crimson Crisp	50%	0.60	0.94	0.21	1.00	0.10	1.58	0.50	n/a	n/a	2.08	23.9	2.91	19.8	5.1	17.3
Dabinett	0%	0.91	1.27	0.34	1.48	0.27	2.58	0.93	3.47	1.31	3.57	26.6	2.29	21.9	0.0	0.0
Enterprise	75%	0.96	1.34	0.36	1.57	0.23	3.46	1.80	6.77	3.21	3.44	30.9	3.27	22.6	1.4	11.4
Frequin Rouge	0%	0.64	0.74	0.11	0.70	0.07	1.23	0.41	6.77	3.21	0.71	2.7	0.29	1.8	1.4	0.0
Golden Russet	83%	0.88	1.34	0.46	2.24	0.90	3.19	0.96	5.16	2.49	3.77	41.4	10.93	54.4	5.0	131.8
GoldRush	40%	0.81	1.07	0.24	1.10	0.03	1.77	0.57	3.20	1.31	1.47	11.2	1.33	11.7	2.4	9.7
Grimes Golden	60%	0.93	1.19	0.26	1.31	0.12	2.28	0.97	4.24	1.88	2.00	15.4	1.62	12.0	1.3	31.5
Kingston Black	10%	1.03	1.41	0.23	1.56	0.08	2.64	0.92	2.07	0.16	3.00	30.1	0.80	9.4	3.5	20.5
Medaille d'Or	65%	0.81	1.07	0.26	1.37	0.30	1.95	0.58	3.64	1.64	1.21	7.1	0.14	0.8	0.9	5.1
Michelin	15%	0.97	1.23	0.25	1.39	0.26	1.93	0.35	3.95	1.82	1.53	11.8	0.33	2.5	3.8	23.0
Porter's Perfection	60%	1.38	1.72	0.35	2.09	0.37	2.80	0.71	5.90	2.93	3.24	62.0	1.19	15.3	1.9	14.3
Stoke Red	10%	1.10	1.33	0.22	1.61	0.24	2.21	0.51	3.77	1.48	2.21	17.8	2.13	12.2	10.8	66.8
Sweet Alford	50%	1.02	1.31	0.29	1.46	0.23	3.12	1.63	5.82	2.49	2.31	51.7	1.17	18.8	0.1	4.8
Tolman Sweet	55%	0.92	1.10	0.17	1.28	0.16	1.65	0.37	3.50	1.71	0.60	8.3	0.21	1.1	0.4	1.2
Tydeman Late	50%	0.64	0.92	0.24	1.01	0.08	1.59	0.57	4.31	2.40	5.62	54.7	2.00	17.1	1.3	4.7
Yarlington Mill	80%	1.10	1.45	0.37	1.51	0.07	2.02	0.50	2.95	0.87	0.35	5.0	0.45	3.3	1.9	14.0

[z] Trunk cross-sectional area.

Table A4.4. Growth attributes of 15 apple cultivars grown on M.9 rootstock for cider production. Caledon, Ontario, 2017.

Cultivar	Survival rate fall 2018	Spring 2016 TCSA (cm^2) [z]	Fall 2016 TCSA (cm^2)	2016 relative growth (cm^2)	Fall 2017 TCSA (cm^2)	2017 relative growth (cm^2)	Fall 2018 TCSA (cm^2)	2018 relative growth (cm^2)	2017 dieback shoot number (dieback shoots $tree^{-1}$)	2017 dieback shoot length (cm)	2018 dieback shoot number (dieback shoots $tree^{-1}$)	2018 dieback shoot length (cm)
Baldwin	80%	0.86	1.03	0.17	1.60	0.57	2.82	1.2	0.8	2.9	1.8	5.9
Bramley's Seedling	100%	1.01	1.07	0.06	1.52	0.45	2.78	1.3	0.2	0.8	1.0	2.4
Brown Snout	95%	0.99	1.11	0.12	1.39	0.28	2.17	0.8	0.7	1.7	1.4	3.2
Bulmer's Norman	90%	0.96	1.04	0.08	1.56	0.52	2.42	0.8	0.1	0.2	0.8	2.5
Chisel Jersey	85%	0.62	0.74	0.12	0.98	0.24	2.02	1.0	0.5	1.4	1.2	2.7
Cox's Orange Pippin	80%	0.56	0.63	0.07	0.98	0.35	1.65	0.7	0.0	0.0	0.8	3.1
Dabinett	69%	0.55	0.58	0.03	0.91	0.33	1.83	0.9	0.0	0.0	0.8	1.8
Esopus Spitzenberg	90%	0.75	0.90	0.15	1.26	0.36	1.87	0.6	0.6	1.2	0.7	2.1
Foxwhelp	100%	0.75	0.80	0.05	1.08	0.28	1.74	1.0	0.1	0.6	0.7	0.8
Frequin Rouge	85%	0.70	0.77	0.07	1.18	0.41	1.73	0.6	0.1	0.2	0.7	1.7
Golden Russet	85%	0.62	0.74	0.12	1.09	0.36	2.00	0.9	1.0	2.8	1.2	2.7
Kingston Black	100%	0.75	0.90	0.15	1.48	0.58	2.28	0.8	0.2	0.4	1.3	3.2
Michelin	70%	0.73	0.83	0.11	1.29	0.45	2.37	1.1	0.5	0.9	1.4	3.0
Roxbury Russet	75%	0.74	0.80	0.06	0.93	0.14	1.51	0.6	0.7	1.8	0.8	3.3
Tolman Sweet	95%	0.54	0.68	0.14	1.02	0.34	1.84	0.8	0.9	1.7	1.1	2.4

[z] Trunk cross-sectional area.

APPENDIX 4 CULTIVAR INFORMATION SHEETS

Cultivar Sheets

These sheets may be published as a sort of extension document for Ontario growers. They contain horticultural and juice data for each cultivar studied as well as the following pictures:

Fruit on tree

Flowers in bloom

Full tree

Five fruit on grid

5 fruit halved fresh

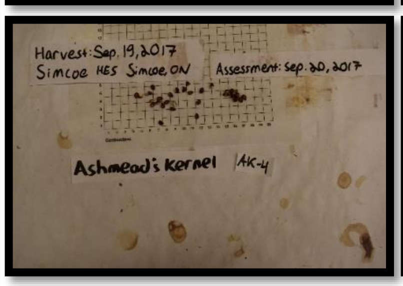
5 fruit halved and treated for starch-iodine analysis

Seeds of five fruits

Ashmead’s Kernel

Origin: English

Summary: ‘Ashmead’s Kernel’ is a good sharp for cultivation in Ontario. It has a high survival rate, but blooms before frost-safe dates. The fruit drops as it ripens, making its harvest a multi-pick. Its high sugar and nitrogen concentrations make it suitable for blending to increase alcohol and nutrition, but it has a low juicing efficiency. It is still recommended.



Juice Characteristics for Ashmead's Kernel

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	18.3	16.1
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	95	108
Juice pH	3.45	3.31
Juice formol number (mg YAN L^{-1} juice)	148	169
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	366	372
Juice Classification	Sharp	Sharp

Yield Characteristics for Ashmead's Kernel

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	188	167
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.57	0.60
Estimated juice yield per tree (L juice tree^{-1})	-	1.3	1.3
Estimated juice yield per acre (L juice 675 trees^{-1})		850	859
Total harvested fruit weight (kg tree^{-1})	0.03	2.23	2.1
Total fruit harvested (no. tree^{-1})	0.1	13	12
Dropped fruit weight (kg tree^{-1})	0.00	1.56	3.9
Dropped fruit (no. tree^{-1})	0.0	11	27
Total fruit weight (kg tree^{-1})	0.03	3.78	6.0
Total fruit (no.)	0.1	24	39
Flower clusters (no. tree^{-1})	0.7	69	104
Crop Load (no fruit cm^{-2} TCSA)	0.0	3.1	2.9

Growth Characteristics for Ashmead's Kernel

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	11-May	-	-	16-May	-	-
Harvest Date	26-Sep	-	-	27-Sep	-	-
Days to harvest	138	-	-	134	-	-
Survival rate from spring 2015 planting	95%	90%	100%	95%	83%	100%
TCSA (cm^2)	7.7	4.2	3.9	13.4	5.8	5.6
Height (m)	3.03	-	-	3.4	-	-
Width (m)	1.33	-	-	1.4	-	-

Binet Rouge

Origin: French

Summary: ‘Binet Rouge’ is suitable for cultivation in Ontario. It has a high survival rate, though its early bloom time puts it at risk for frost damage. Its high pH means that it needs to be blended with other juices to make a safe fermentation environment. It has a low juicing efficiency.

Juice Characteristics for Binet Rouge

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	15.1	13.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	37	43
Juice pH	4.44	4.41
Juice formol number (mg YAN L^{-1} juice)	104	185.1
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	915	880
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Binet Rouge

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	81	70
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.53	0.45
Estimated juice yield per tree (L juice tree^{-1})	-	1.6	0.7
Estimated juice yield per acre (L juice 675 trees^{-1})		1083	473
Total harvested fruit weight (kg tree^{-1})	0.03	3.06	1.5
Total fruit harvested (no. tree^{-1})	0.3	58	21
Dropped fruit weight (kg tree^{-1})	0.06	0.87	0.1
Dropped fruit (no. tree^{-1})	0.7	19	3
Total fruit weight (kg tree^{-1})	0.07	3.92	1.7
Total fruit (no.)	1.0	77	28
Flower clusters (no. tree^{-1})	2.6	155	39
Crop Load (no fruit cm^{-2} TCSA)	0.1	7.9	1.5

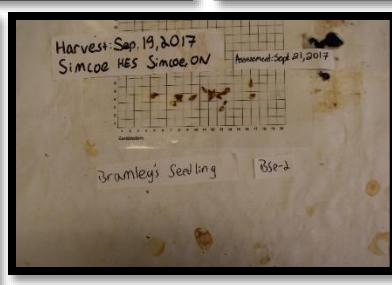
Growth Characteristics for Binet Rouge

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	11-May	-	-	18-May	-	-
Harvest Date	16-Sep	-	-	4-Sep	-	-
Days to harvest	127.5	-	-	109	-	-
Survival rate from spring 2015 planting	100%	80%	100%	100%	75%	100%
TCSA (cm^2)	9.9	5.6	7.1	19.4	7.7	9.2
Height (m)	3.1	-	-	3.5	-	-
Width (m)	1.7	-	-	1.7	-	-

Bramley’s Seedling

Origin: English

Summary: ‘Bramley’s Seedling’ is a good sharp for cultivation in Ontario. It has a high yield and large fruit. It has good survivability and blooms within frost-safe dates. It is also an exceptional baking apple.



Juice Characteristics for Bramley's Seedling

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	12.7	11.9
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	145	191
Juice pH	3.00	2.70
Juice formol number (mg YAN L^{-1} juice)	73	133
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	337	373
Juice Classification	Sharp	Sharp

Yield Characteristics for Bramley's Seedling

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	364	267
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.69	0.64
Estimated juice yield per tree (L juice $tree^{-1}$)	-	5.5	4.1
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		3739	2758
Total harvested fruit weight (kg $tree^{-1}$)	0.13	8.09	6.4
Total fruit harvested (no. $tree^{-1}$)	0.4	24	26
Dropped fruit weight (kg $tree^{-1}$)	0.06	2.63	0.3
Dropped fruit (no. $tree^{-1}$)	0.2	9	2
Total fruit weight (kg $tree^{-1}$)	0.18	10.72	6.7
Total fruit (no.)	0.5	32	27
Flower clusters (no. $tree^{-1}$)	1.1	92	28
Crop Load (no fruit cm^{-2} TCSA)	0.1	2.9	1.3

Growth Characteristics for Bramley's Seedling

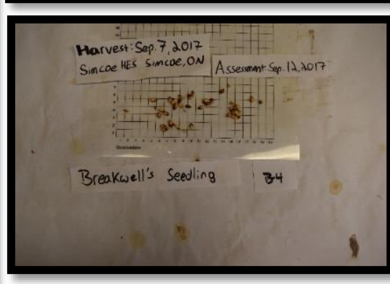
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	15-May	-	-	19-May	-	-
Harvest Date	25-Sep	-	-	17-Sep	-	-
Days to harvest	132.75	-	-	121	-	-
spring 2015	95%	80%	100%	95%	75%	100%
TCSA (cm^2)	11.1	4.84	4.62	21.1	6.9	6.3
Height (m)	2.96	-	-	3.2	-	-
Width (m)	1.68	-	-	1.7	-	-

Breakwell's Seedling

Synonyms: Breakwell

Origin: English

Summary: 'Breakwell's Seedling' has a high yield and acidity, but it is a multipack variety that ripens over a long period. This makes it less suitable for cultivation in Ontario.



Juice Characteristics for Breakwell's Seedling

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	11.4	12.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	158	190
Juice pH	3.08	2.88
Juice formol number (mg YAN L^{-1} juice)	69	103
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	446	436
Juice Classification	Sharp	Sharp

Yield Characteristics for Breakwell's Seedling

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	151	138
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.65	0.65
Estimated juice yield per tree (L juice $tree^{-1}$)	-	2.4	1.9
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1636	1258
Total harvested fruit weight (kg $tree^{-1}$)	0.00	3.8	2.9
Total fruit harvested (no. $tree^{-1}$)	0.0	26	5
Dropped fruit weight (kg $tree^{-1}$)	0.03	0.8	0.4
Dropped fruit (no. $tree^{-1}$)	0.2	6	4
Total fruit weight (kg $tree^{-1}$)	0.03	4.5	3.2
Total fruit (no.)	0.2	32	26
Flower clusters (no. $tree^{-1}$)	0.2	87	29
Crop Load (no fruit cm^{-2} TCSA)	0.0	3.7	1.6

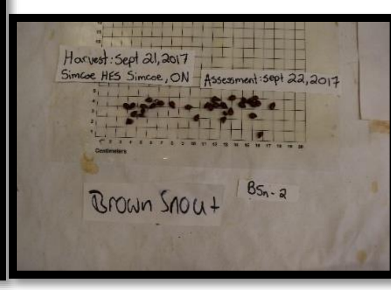
Growth Characteristics for Breakwell's Seedling

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	20-May	-	-	21-May	-	-
Harvest Date	8-Sep	-	-	11-Sep	-	-
Days to harvest	111	-	-	113	-	-
Survival rate from spring 2015 planting	95%	90%	100%	95%	90%	100%
TCSA (cm^2)	8.9	4.56	4.38	17.3	6.0	5.5
Height (m)	2.41	-	-	2.8	-	-
Width (m)	0.98	-	-	1.2	-	-

Brown Snout

Origin: English

Summary: Brown Snout produces a balanced juice in Ontario, though it has a low survival rate at some sites. Many fruits rotted on the tree before harvest and it was a multipack variety. The fruits had a low juicing efficiency and ultimately is not well suited to Ontario.



Juice Characteristics for Brown Snout

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	16.4	17.6
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	58	77
Juice pH	4.09	4.01
Juice formol number (mg YAN L^{-1} juice)	170	158
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	479	577
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Brown Snout

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	85	93
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.61	0.59
Estimated juice yield per tree (L juice tree^{-1})	-	0.9	0.6
Estimated juice yield per acre (L juice 675 trees^{-1})		613	430
Total harvested fruit weight (kg tree^{-1})	0.2	1.5	1.1
Total fruit harvested (no. tree^{-1})	2.2	18	25
Dropped fruit weight (kg tree^{-1})	0.1	0.6	1.0
Dropped fruit (no. tree^{-1})	1.0	7	13
Total fruit weight (kg tree^{-1})	0.3	2.1	2.1
Total fruit (no.)	3.2	24	26
Flower clusters (no. tree^{-1})	5.1	48	27
Crop Load (no fruit cm^{-2} TCSA)	1.2	5.5	3.5

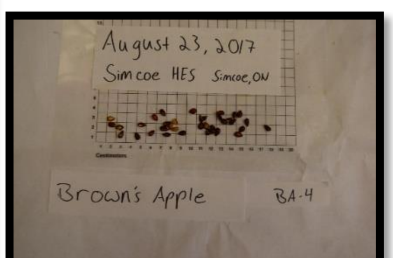
Growth Characteristics for Brown Snout

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	23-May	-	-	23-May	-	-
Harvest Date	5-Oct	-	-	15-Oct	-	-
Days to harvest	135	-	-	145	-	-
Survival rate from spring 2015 planting	100%	74%	100%	100%	40%	100%
TCSA (cm^2)	5.5	2.9	2.9	8.1	4.2	3.3
Height (m)	2.5	-	-	2.8	-	-
Width (m)	0.8	-	-	0.9	-	-

Brown’s Apple

Origin: English

Summary: ‘Brown’s Apple’ ripens early and flowers late, which would normally make it a good short-season apple in Ontario, however the apples rot on the tree and are prone to dropping. In other regions this apple ripens later in the season. It is not well-suited to Ontario.



Juice Characteristics for Brown's Apple

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	10.6	11.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	101	114
Juice pH	3.33	3.39
Juice formol number (mg YAN L^{-1} juice)	116	154
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	770	799
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Brown's Apple

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	123	152
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.62	0.66
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.1	2.5
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		774	1690
Total harvested fruit weight (kg $tree^{-1}$)	0.00	1.9	3.8
Total fruit harvested (no. $tree^{-1}$)	0.0	16	25
Dropped fruit weight (kg $tree^{-1}$)	0.02	1.7	0.6
Dropped fruit (no. $tree^{-1}$)	0.2	17	6
Total fruit weight (kg $tree^{-1}$)	0.02	3.6	4.4
Total fruit (no.)	0.2	33	32
Flower clusters (no. $tree^{-1}$)	1.4	68	34
Crop Load (no fruit cm^{-2} TCSA)	0.1	5.3	2.6

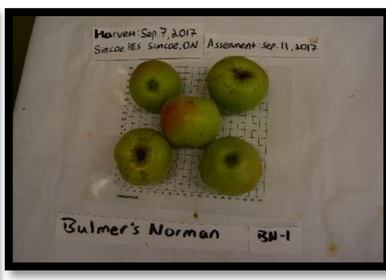
Growth Characteristics for Brown's Apple

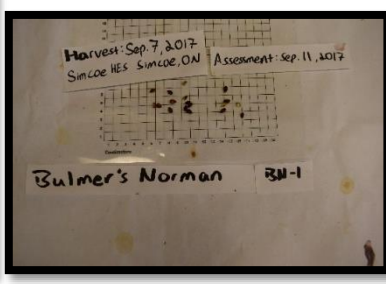
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	22-May	-	-	22-May	-	-
Harvest Date	29-Aug	-	-	22-Aug	-	-
Days to harvest	99	-	-	92	-	-
Survival rate from spring 2015 planting	100%	50%	100%	100%	33%	100%
TCSA (cm^2)	6.2	3.38	4.06	12.6	4.0	5.2
Height (m)	2.5	-	-	2.9	-	-
Width (m)	1.3	-	-	1.5	-	-

Bulmers Norman

Origin: English

Summary: 'Bulmers Norman' ripens early and flowers late, making it a good short-season apple in Ontario. Although it is highly biennial, it produces a high-polyphenol juice. It is a suitable cultivar for growth in Ontario.





Juice Characteristics for Bulmer's Norman

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	12.0	13.3
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	37	63
Juice pH	4.07	4.15
Juice formol number (mg YAN L^{-1} juice)	157	256
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	830	923
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Bulmer's Norman

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	106	110
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.69	0.61
Estimated juice yield per tree (L juice $tree^{-1}$)	-	3.7	0.3
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		2500	207
Total harvested fruit weight (kg $tree^{-1}$)	0.01	5.4	0.5
Total fruit harvested (no. $tree^{-1}$)	0.1	43	13
Dropped fruit weight (kg $tree^{-1}$)	0.05	1.1	0.3
Dropped fruit (no. $tree^{-1}$)	0.5	9	3
Total fruit weight (kg $tree^{-1}$)	0.05	6.5	0.8
Total fruit (no.)	0.5	52	8
Flower clusters (no. $tree^{-1}$)	3.5	146	11
Crop Load (no fruit cm^{-2} TCSA)	0.1	7.6	0.5

Growth Characteristics for Bulmer's Norman

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	19-May	-	-	22-May	-	-
Harvest Date	7-Sep	-	-	27-Aug	-	-
Days to harvest	111	-	-	97	-	-
Survival rate from spring 2015 planting	100%	100%	100%	100%	93%	100%
TCSA (cm^2)	6.8	2.8	5.5	14.0	4.3	6.9
Height (m)	2.7	-	-	3.0	-	-
Width (m)	1.3	-	-	1.4	-	-

Calville Blanc d’Hiver

Synonyms: Calville Blanc, Winter White Calville

Origin: French

Summary: ‘Calville Blanc d’Hiver’ flowers early but produces regularly and abundantly. Its apples are large and high in acid. It is a good option for growth in Ontario and is also an exceptional baking apple.

Juice Characteristics for Calville Blanc d'Hiver		
Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.1	12.9
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	132	125
Juice pH	3.19	3.21
Juice formol number (mg YAN L^{-1} juice)	97	104
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	317	258
Juice Classification	Sharp	Sharp

Yield Characteristics for Calville Blanc d'Hiver			
Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	204	262
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.65	0.65
Estimated juice yield per tree (L juice $tree^{-1}$)	-	3.7	8.9
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		2466	6008
Total harvested fruit weight (kg $tree^{-1}$)	0.07	5.6	13.7
Total fruit harvested (no. $tree^{-1}$)	0.4	28	53
Dropped fruit weight (kg $tree^{-1}$)	0.00	0.1	0.6
Dropped fruit (no. $tree^{-1}$)	0.0	1	3
Total fruit weight (kg $tree^{-1}$)	0.07	5.8	14.3
Total fruit (no.)	0.4	29	57
Flower clusters (no. $tree^{-1}$)	13.9	142	147
Crop Load (no fruit cm^{-2} TCSA)	0.1	2.5	2.9

Growth Characteristics for Calville Blanc d'Hiver						
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	10-May	-	-	17-May	-	-
Harvest Date	13-Oct	-	-	22-Oct	-	-
Days to harvest	156	-	-	158	-	-
Survival rate from spring 2015 planting	100%	95%	100%	100%	95%	100%
TCSA (cm^2)	12.2	4.1	6.2	21.2	6.5	8.2
Height (m)	3.0	-	-	3.3	-	-
Width (m)	1.5	-	-	1.6	-	-

Cline Russet

Origin: Canadian

Summary: ‘Cline Russet’ shows promise as a regular producer in Canada. It produces a sweet juice. It has no major cultivation issues.

Juice Characteristics for Cline Russet

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.5	14.0
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	60	86
Juice pH	3.74	3.53
Juice formol number (mg YAN L^{-1} juice)	82	123
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	230	188
Juice Classification	Sweet	Sweet

Yield Characteristics for Cline Russet

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	149	134
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.68	0.64
Estimated juice yield per tree (L juice tree^{-1})	-	2.0	2.1
Estimated juice yield per acre (L juice 675 trees^{-1})	-	1377	1421
Total harvested fruit weight (kg tree^{-1})	0.00	3.0	3.3
Total fruit harvested (no. tree^{-1})	0.0	22	58
Dropped fruit weight (kg tree^{-1})	0.00	0.5	0.3
Dropped fruit (no. tree^{-1})	0.0	4	3
Total fruit weight (kg tree^{-1})	0.00	3.6	3.6
Total fruit (no.)	0.0	25	28
Flower clusters (no. tree^{-1})	3.1	58	36
Crop Load (no fruit cm^{-2} TCSA)	0.0	6.1	3.7

Growth Characteristics for Cline Russet

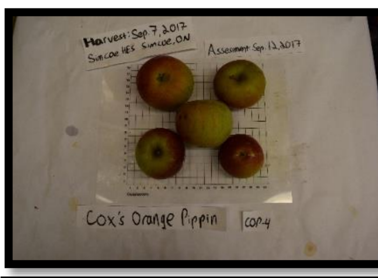
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	16-May	-	-	20-May	-	-
Harvest Date	13-Oct	-	-	9-Oct	-	-
Days to harvest	150	-	-	142	-	-
Survival rate from spring 2015 planting	95%	95%	100%	95%	95%	100%
TCSA (cm^2)	4.7	4.1	6.2	8.2	2.9	3.5
Height (m)	2.8	-	-	3.0	-	-
Width (m)	1.2	-	-	1.4	-	-

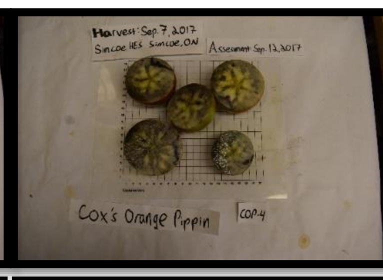
Cox Orange Pippin

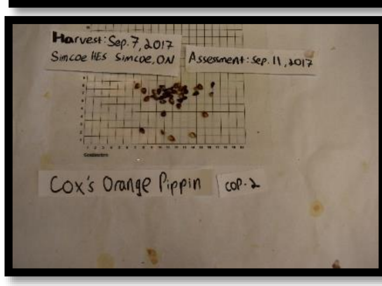
Synonyms: Cox

Origin: English

Summary: 'Cox Orange Pippin' is a regular producer, but it has a low juicing efficiency. It can be grown well enough in Ontario, but there are better options.







Juice Characteristics for Cox's Orange Pippin

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	15.7	12.3
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	82	110
Juice pH	3.49	3.08
Juice formol number (mg YAN L^{-1} juice)	146	167
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	256	230
Juice Classification	Sweet	Sweet

Yield Characteristics for Cox's Orange Pippin

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	181	158
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.53	0.62
Estimated juice yield per tree (L juice $tree^{-1}$)	-	2.1	6.0
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1439	4066
Total harvested fruit weight (kg $tree^{-1}$)	0.0	4.0	9.7
Total fruit harvested (no. $tree^{-1}$)	0.0	25	66
Dropped fruit weight (kg $tree^{-1}$)	0.0	0.5	0.5
Dropped fruit (no. $tree^{-1}$)	0.0	4	4
Total fruit weight (kg $tree^{-1}$)	0.0	4.5	10.2
Total fruit (no.)	0.0	28	70
Flower clusters (no. $tree^{-1}$)	0.0	91	112
Crop Load (no fruit cm^{-2} TCSA)	0.0	4.5	7.2

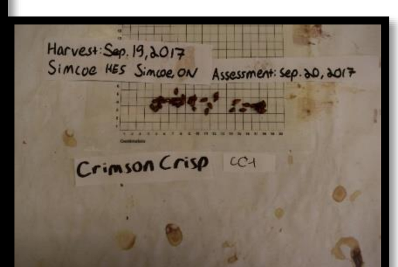
Growth Characteristics for Cox's Orange Pippin

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	19-May	-	-	19-May	-	-
Harvest Date	3-Oct	-	-	17-Sep	-	-
Days to harvest	137	-	-	121	-	-
Survival rate from spring 2015 planting	100%	90%	100%	100%	85%	100%
TCSA (cm^2)	6.5	3.1	4.5	9.9	3.9	6.7
Height (m)	2.8	-	-	3.0	-	-
Width (m)	1.3	-	-	1.5	-	-

Crimson Crisp ®

Origin: American

Summary: Crimson Crisp ® shows promise as a regular producer in Canada. It is a sweet apple with good fermentation potential. It produces a pink juice due to pigment in the skin, though the colour disappears with sulfiting.



Juice Characteristics for Crimson Crisp		
Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	13.7	11.9
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	74	86
Juice pH	3.54	3.40
Juice formol number (mg YAN L^{-1} juice)	104	128
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	271	180
Juice Classification	Sweet	Sweet

Yield Characteristics for Crimson Crisp			
Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	133	165
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.68	0.68
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.5	6.2
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1017	4172
Total harvested fruit weight (kg $tree^{-1}$)	0.0	2.2	9.1
Total fruit harvested (no. $tree^{-1}$)	0.0	13	25
Dropped fruit weight (kg $tree^{-1}$)	0.0	1.0	0.3
Dropped fruit (no. $tree^{-1}$)	0.0	6	3
Total fruit weight (kg $tree^{-1}$)	0.0	3.2	9.5
Total fruit (no.)	0.0	19	61
Flower clusters (no. $tree^{-1}$)	3.2	65	139
Crop Load (no fruit cm^{-2} TCSA)	0.0	3.8	9.4

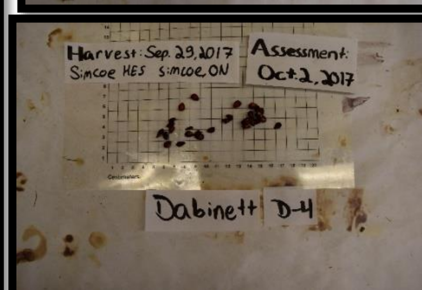
Growth Characteristics for Crimson Crisp						
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	19-May	-	-	19-May	-	-
Harvest Date	3-Oct	-	-	4-Oct	-	-
Days to harvest	137	-	-	138	-	-
Survival rate from spring 2015 planting	95%	85%	100%	95%	75%	100%
TCSA (cm^2)	4.9	2.40	3.63	8.2	3.5	5.1
Height (m)	2.82	-	-	3.0	-	-
Width (m)	1.21	-	-	1.4	-	-

Dabinett

Synonyms: ‘Dabinette’

Origin: English

Summary: ‘Dabinett’ has some survival issues, but it produces good juice. It produces low polyphenol concentrations when compared to when it is grown in other countries. It has a low juicing efficiency, but it is a regular bearer and is suitable for Ontario.



Juice Characteristics for Dabinett

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.9	13.0
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	82	104
Juice pH	3.50	3.19
Juice formol number (mg YAN L^{-1} juice)	145	151
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	256	188
Juice Classification	Sweet	Sharp

Yield Characteristics for Dabinett

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	176	192
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.51	0.61
Estimated juice yield per tree (L juice $tree^{-1}$)	-	2.1	5.9
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1391	3993
Total harvested fruit weight (kg $tree^{-1}$)	0.0	4.0	9.7
Total fruit harvested (no. $tree^{-1}$)	0.0	26	57
Dropped fruit weight (kg $tree^{-1}$)	0.0	0.6	0.5
Dropped fruit (no. $tree^{-1}$)	0.0	4	4
Total fruit weight (kg $tree^{-1}$)	0.0	4.6	10.2
Total fruit (no.)	0.0	30	62
Flower clusters (no. $tree^{-1}$)	0.0	47	90
Crop Load (no fruit cm^{-2} TCSA)	0.0	5.0	6.2

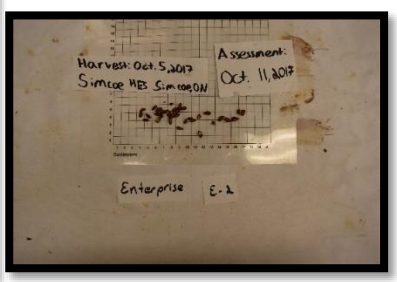
Growth Characteristics for Dabinett

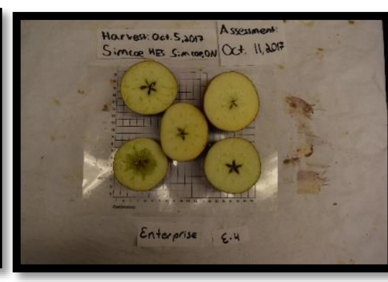
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	17-May	-	-	19-May	-	-
Harvest Date	3-Oct	-	-	27-Sep	-	-
Days to harvest	139	-	-	131	-	-
Survival rate from spring 2015 planting	90%	68%	100%	90%	57%	100%
TCSA (cm^2)	6.1	3.0	3.1	9.6	3.6	4.6
Height (m)	2.7	-	-	3.0	-	-
Width (m)	1.3	-	-	1.5	-	-

Enterprise

Origin: American

Summary: 'Enterprise' has survival issues at some sites, but it regular produces a large crop. It is harvested late in the season and produces a balanced juice.





Juice Characteristics for Enterprise

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.2	13.9
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	102	102
Juice pH	3.41	3.54
Juice formol number (mg YAN L^{-1} juice)	118	139
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	246	225
Juice Classification	Sharp	Sharp

Yield Characteristics for Enterprise

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	225	246
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.65	0.65
Estimated juice yield per tree (L juice $tree^{-1}$)	-	3.2	8.1
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		2187	5449
Total harvested fruit weight (kg $tree^{-1}$)	0.02	5.0	12.4
Total fruit harvested (no. $tree^{-1}$)	0.1	22	53
Dropped fruit weight (kg $tree^{-1}$)	0.0	0.1	0.5
Dropped fruit (no. $tree^{-1}$)	0.0	1	2
Total fruit weight (kg $tree^{-1}$)	0.02	5.1	12.9
Total fruit (no.)	0.1	23	56
Flower clusters (no. $tree^{-1}$)	0.4	50	70
Crop Load (no fruit cm^{-2} TCSA)	0.0	3.2	4.6

Growth Characteristics for Enterprise

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	17-May	-	-	18-May	-	-
Harvest Date	20-Oct	-	-	6-Nov	-	-
Days to harvest	156	-	-	172	-	-
Survival rate from spring 2015 planting	100%	35%	100%	100%	20%	95%
TCSA (cm^2)	6.9	4.0	5.6	11.9	4.2	6.1
Height (m)	2.8	-	-	3.0	-	-
Width (m)	1.7	-	-	1.7	-	-

Esopus Spitzenberg

Synonyms: Spitzenberg

Origin: American

Summary: 'Esopus Spitzenberg' is a regular producer, but it also experiences some dropping issues at harvest. It shows promise for Ontario.

Juice Characteristics for Esopus Spitzenberg

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	15.4	14.9
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	97	116
Juice pH	3.38	3.60
Juice formol number (mg YAN L^{-1} juice)	113	152
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	250	222
Juice Classification	Sharp	Sharp

Growth Characteristics for Esopus Spitzenberg

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	15-May	-	-	17-May	-	-
Harvest Date	5-Oct	-	-	18-Oct	-	-
Days to harvest	143	-	-	154	-	-
Survival rate from spring 2015 planting	100%	95%	100%	100%	95%	100%
TCSA (cm^2)	6.3	4.6	4.4	11.6	6.0	5.5
Height (m)	3.0	-	-	3.2	-	-
Width (m)	1.5	-	-	1.7	-	-

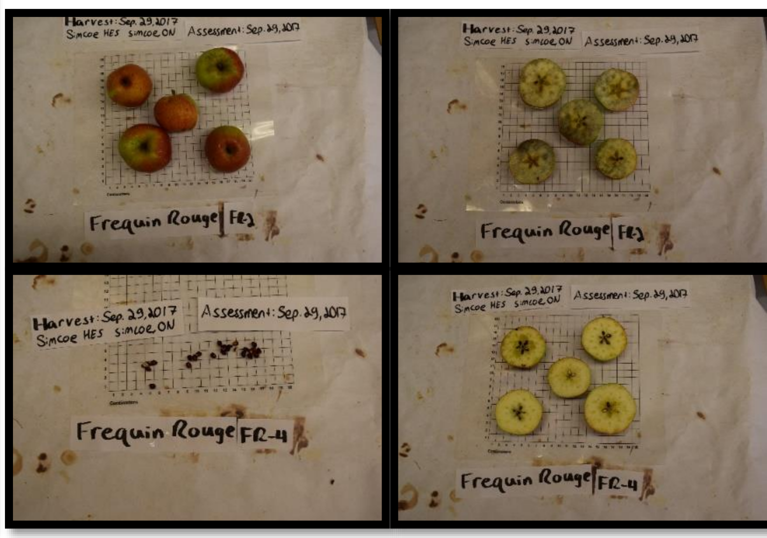
Yield Characteristics for Esopus Spitzenberg

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	151	178
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.62	0.58
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.7	2.9
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1144	1963
Total harvested fruit weight (kg $tree^{-1}$)	0.01	2.7	5.0
Total fruit harvested (no. $tree^{-1}$)	0.1	20	29
Dropped fruit weight (kg $tree^{-1}$)	0.0	0.0	0.9
Dropped fruit (no. $tree^{-1}$)	0.0	1	8
Total fruit weight (kg $tree^{-1}$)	0.01	2.8	5.9
Total fruit (no.)	0.1	20	38
Flower clusters (no. $tree^{-1}$)	0.2	46	36
Crop Load (no fruit cm^{-2} TCSA)	0.0	3.1	3.7

Fréquin Rouge

Origin: French

Summary: ‘Fréquin Rouge’ produces a high-quality juice, though its biennial tendencies, low harvestable yield, and low juicing efficiency make it unsuitable for Ontario.



Juice Characteristics for Frequin Rouge		
Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	16.0	16.4
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	32	53
Juice pH	4.61	4.39
Juice formol number (mg YAN L^{-1} juice)	148	149
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	515	639
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Frequin Rouge			
Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	98	68
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.52	0.48
Estimated juice yield per tree (L juice tree^{-1})	-	0.8	0.5
Estimated juice yield per acre (L juice 675 trees^{-1})		572	351
Total harvested fruit weight (kg tree^{-1})	0.0	1.6	1.1
Total fruit harvested (no. tree^{-1})	0.0	18	16
Dropped fruit weight (kg tree^{-1})	0.0	1.2	2.5
Dropped fruit (no. tree^{-1})	0.0	15	37
Total fruit weight (kg tree^{-1})	0.0	2.8	3.6
Total fruit (no.)	0.0	33	53
Flower clusters (no. tree^{-1})	0.0	71	57
Crop Load (no fruit cm^{-2} TCSA)	0.0	5.2	5.2

Growth Characteristics for Frequin Rouge						
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	24-May	-	-	23-May	-	-
Harvest Date	3-Oct	-	-	18-Oct	-	-
Days to harvest	131.5	-	-	148	-	-
Survival rate from spring 2015 planting	100%	76%	100%	100%	65%	100%
TCSA (cm^2)	6.3	3.5	4.1	11.1	3.9	5.6
Height (m)	2.2	-	-	2.5	-	-
Width (m)	1.1	-	-	1.3	-	-

Golden Russet

Origin: American

Summary: 'Golden Russet' is a solid annual bearer that produces juice with moderate polyphenols and acidity. It has no major cultivation issues and produces high-quality juice.

Juice Characteristics for Golden Russet

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	16.6	16.4
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	85	113
Juice pH	3.47	3.48
Juice formol number (mg YAN L^{-1} juice)	166	207
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	380	315
Juice Classification	Sharp	Sharp

Yield Characteristics for Golden Russet

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	146	183
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.63	0.61
Estimated juice yield per tree (L juice tree^{-1})	-	2.7	3.9
Estimated juice yield per acre (L juice 675 trees^{-1})		1835	2622
Total harvested fruit weight (kg tree^{-1})	0.08	4.3	6.4
Total fruit harvested (no. tree^{-1})	0.6	30	38
Dropped fruit weight (kg tree^{-1})	0.02	1.0	0.6
Dropped fruit (no. tree^{-1})	0.1	8	5
Total fruit weight (kg tree^{-1})	0.09	5.3	7.0
Total fruit (no.)	0.7	38	42
Flower clusters (no. tree^{-1})	2.5	123	49
Crop Load (no fruit cm^{-2} TCSA)	0.2	5.9	3.5

Growth Characteristics for Golden Russet

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	13-May	-	-	17-May	-	-
Harvest Date	6-Oct	-	-	25-Oct	-	-
Days to harvest	145.5	-	-	161	-	-
Survival rate from spring 2015 planting	100%	100%	89%	100%	60%	78%
TCSA (cm^2)	6.4	3.5	2.9	12.4	4.5	5.16
Height (m)	3.1	-	-	3.4	-	-
Width (m)	1.5	-	-	1.5	-	-

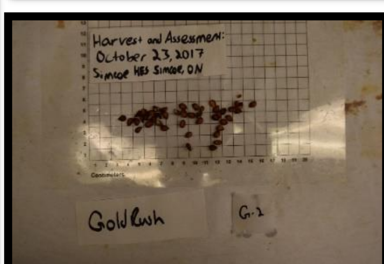
GoldRush

Synonyms: ‘GoldRush’

Origin: American

Summary: ‘GoldRush’ is produces an ample crop annually. It is harvested late in the season and has no major cultivation issues. It produces a high-quality juice for cider.



Juice Characteristics for GoldRush

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	12.9	13.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	89	123
Juice pH	3.28	3.42
Juice formol number (mg YAN L^{-1} juice)	71	145
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	246	189
Juice Classification	Sharp	Sharp

Yield Characteristics for GoldRush

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	156	172
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.71	0.66
Estimated juice yield per tree (L juice tree^{-1})	-	6.9	4.0
Estimated juice yield per acre (L juice 675 trees^{-1})		4669	2686
Total harvested fruit weight (kg tree^{-1})	0.5	9.8	6.1
Total fruit harvested (no. tree^{-1})	3.0	67	10
Dropped fruit weight (kg tree^{-1})	0.01	0.1	0.3
Dropped fruit (no. tree^{-1})	0.1	1	2
Total fruit weight (kg tree^{-1})	0.5	9.9	6.4
Total fruit (no.)	3.0	68	40
Flower clusters (no. tree^{-1})	21	125	49
Crop Load (no fruit cm^{-2} TCSA)	0.8	14.4	5.6

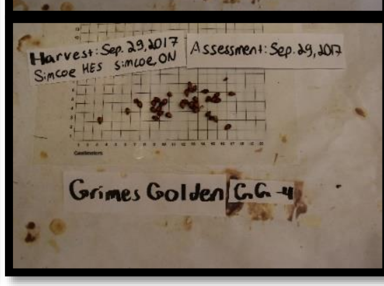
Growth Characteristics for GoldRush

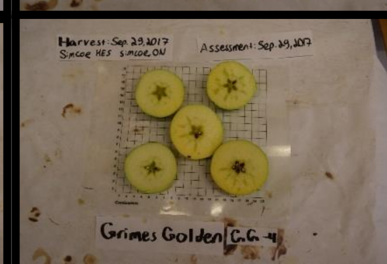
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	15-May	-	-	17-May	-	-
Harvest Date	26-Oct	-	-	6-Nov	-	-
Days to harvest	164	-	-	173	-	-
Survival rate from spring 2015 planting	100%	100%	100%	100%	100%	100%
TCSA (cm^2)	4.8	4.0	4.1	8.4	5.0	4.4
Height (m)	2.9	-	-	3.2	-	-
Width (m)	1.1	-	-	1.2	-	-

Grimes Golden

Origin: American

Summary: 'Grimes Golden' is a high producer, but the apples drop on the ground as soon as they are ripe. It is a multipack variety. This is not suited to typical harvesting systems in Ontario and would make large-scale production in the province difficult.





Juice Characteristics for Grimes Golden

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	13.8	12.4
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	93	91
Juice pH	3.48	3.44
Juice formol number (mg YAN L^{-1} juice)	81	82
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	275	277
Juice Classification	Sharp	Sharp

Yield Characteristics for Grimes Golden

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	153	139
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.64	0.66
Estimated juice yield per tree (L juice $tree^{-1}$)	-	2.6	0.8
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1739	564
Total harvested fruit weight (kg $tree^{-1}$)	0.02	4.1	1.3
Total fruit harvested (no. $tree^{-1}$)	0.1	29	10
Dropped fruit weight (kg $tree^{-1}$)	0.00	2.2	8.6
Dropped fruit (no. $tree^{-1}$)	0.0	15	61
Total fruit weight (kg $tree^{-1}$)	0.02	6.2	9.9
Total fruit (no.)	0.1	44	71
Flower clusters (no. $tree^{-1}$)	4.1	115	95
Crop Load (no fruit cm^{-2} TCSA)	0.0	7.2	8.1

Growth Characteristics for Grimes Golden

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	14-May	-	-	19-May	-	-
Harvest Date	4-Oct	-	-	15-Oct	-	-
Days to harvest	142.75	-	-	149	-	-
Survival rate from spring 2015 planting	100%	100%	100%	100%	100%	100%
TCSA (cm^2)	6.2	3.0	4.4	9.1	3.8	4.5
Height (m)	2.8	-	-	3.1	-	-
Width (m)	1.4	-	-	1.5	-	-

Kingston Black

Origin: English

Summary: 'Kingston Black' produces a high-quality juice but has a very low yield and low juicing efficiency. It is a multipack variety, which makes harvesting difficult. It is not well-suited to cultivation in Ontario.

Juice Characteristics for Kingston Black

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.0	14.1
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	86	112
Juice pH	3.49	3.23
Juice formol number (mg YAN L^{-1} juice)	80	110
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	437	493
Juice Classification	Bittersharp	Bittersharp

Yield Characteristics for Kingston Black

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	114	102
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.55	0.49
Estimated juice yield per tree (L juice $tree^{-1}$)	-	0.6	0.4
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		438	256
Total harvested fruit weight (kg $tree^{-1}$)	0.02	1.2	0.8
Total fruit harvested (no. $tree^{-1}$)	0.2	11	8
Dropped fruit weight (kg $tree^{-1}$)	0.02	1.6	0.4
Dropped fruit (no. $tree^{-1}$)	0.3	16	4
Total fruit weight (kg $tree^{-1}$)	0.04	2.7	1.2
Total fruit (no.)	0.5	28	12
Flower clusters (no. $tree^{-1}$)	1.1	55	13
Crop Load (no fruit cm^{-2} TCSA)	0.1	5.1	1.3

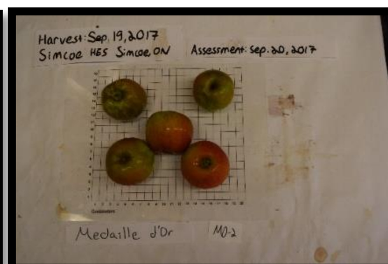
Growth Characteristics for Kingston Black

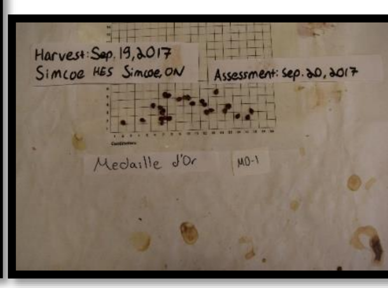
Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	20-May	-	-	22-May	-	-
Harvest Date	16-Sep	-	-	11-Sep	-	-
Days to harvest	119	-	-	112	-	-
Survival rate from spring 2015 planting	100%	80%	100%	100%	66%	95%
TCSA (cm^2)	5.4	3.7	6.3	11.1	4.1	9.5
Height (m)	2.3	-	-	2.5	-	-
Width (m)	1.0	-	-	1.1	-	-

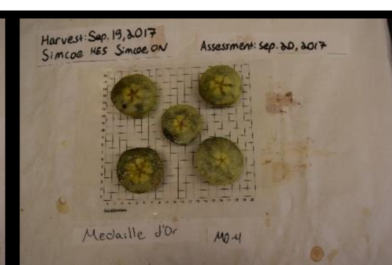
Medaille d'Or

Origin: French

Summary: 'Medaille d'Or' produces abundant sweet juice but is highly biennial. Its juice is high in polyphenols and can be adequately grown in Ontario.







Juice Characteristics for Medaille d'Or

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	15.3	16.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	137	171
Juice pH	3.18	3.03
Juice formol number (mg YAN L^{-1} juice)	60	120
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	557	875
Juice Classification	Bittersharp	Bittersharp

Yield Characteristics for Medaille d'Or

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	95	90
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.67	0.60
Estimated juice yield per tree (L juice $tree^{-1}$)	-	3.0	0.4
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		2008	251
Total harvested fruit weight (kg $tree^{-1}$)	0.0	4.5	0.6
Total fruit harvested (no. $tree^{-1}$)	0.0	48	18
Dropped fruit weight (kg $tree^{-1}$)	0.0	1.6	0.03
Dropped fruit (no. $tree^{-1}$)	0.0	17	1
Total fruit weight (kg $tree^{-1}$)	0.0	6.1	0.7
Total fruit (no.)	0.0	65	7
Flower clusters (no. $tree^{-1}$)	0.1	163	14
Crop Load (no fruit cm^{-2} TCSA)	0.0	11.1	0.8

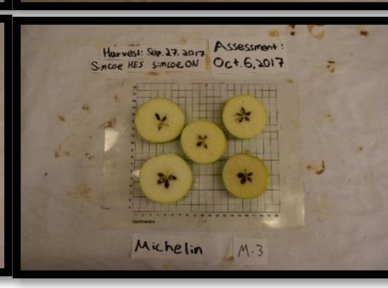
Growth Characteristics for Medaille d'Or

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	21-May	-	-	22-May	-	-
Harvest Date	29-Sep	-	-	27-Sep	-	-
Days to harvest	131	-	-	128	-	-
Survival rate from spring 2015 planting	95%	63%	95%	95%	40%	95%
TCSA (cm^2)	6.0	3.0	4.8	11.2	4.1	6.5
Height (m)	2.8	-	-	3.0	-	-
Width (m)	1.4	-	-	1.5	-	-

Michelin

Origin: French

Summary: ‘Michelin’ produces bittersweet juice, but it has a low juicing efficiency. It has survival issues at some sites. Its biggest problem is that it is a multipack variety that drops its fruit as soon as it ripens. This is not suitable for harvesting practices in Ontario and it cannot be recommended.



Juice Characteristics for Michelin

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	13.0	12.8
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	43	50
Juice pH	4.17	3.95
Juice formol number (mg YAN L^{-1} juice)	145	168
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	564	585
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Michelin

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)z	-	81	96
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.59	0.39
Estimated juice yield per tree (L juice $tree^{-1}$)	-	0.6	0.6
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		400	399
Total harvested fruit weight (kg $tree^{-1}$)	0.01	1.0	1.5
Total fruit harvested (no. $tree^{-1}$)	0.1	14	8
Dropped fruit weight (kg $tree^{-1}$)	0.3	3.5	1.2
Dropped fruit (no. $tree^{-1}$)	3.3	51	14
Total fruit weight (kg $tree^{-1}$)	0.3	4.5	2.7
Total fruit (no.)	3.4	64	31
Flower clusters (no. $tree^{-1}$)	9.5	97	26
Crop Load (no fruit cm^{-2} TCSA)	0.7	8.7	2.5

Growth Characteristics for Michelin

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	20-May	-	-	19-May	-	-
Harvest Date	27-Sep	-	-	11-Sep	-	-
Days to harvest	131	-	-	115	-	-
Survival rate from spring 2015 planting	95%	50%	100%	95%	42%	100%
TCSA (cm^2)	6.8	3.9	5.3	12.4	5.7	6.4
Height (m)	3.0	-	-	3.3	-	-
Width (m)	1.3	-	-	1.4	-	-

Muscadet de Dieppe

Origin: French

Summary: 'Muscadet de Dieppe' produces a bittersweet juice, but it is a multipack variety that drops its fruit when ripe. This is unsuitable for harvesting practices in Ontario. The fruit also has a low juicing efficiency. Ultimately its low yield makes it hard to recommend.

Juice Characteristics for Muscadet de Dieppe

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	12.9	14.0
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	40	46
Juice pH	3.98	4.11
Juice formol number (mg YAN L^{-1} juice)	97	101
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	693	567
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Muscadet de Dieppe

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	105	130
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.49	0.36
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.1	0.3
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		764	231
Total harvested fruit weight (kg $tree^{-1}$)	0.01	2.3	1.0
Total fruit harvested (no. $tree^{-1}$)	0.1	24	6
Dropped fruit weight (kg $tree^{-1}$)	0.02	1.4	0.7
Dropped fruit (no. $tree^{-1}$)	0.2	15	7
Total fruit weight (kg $tree^{-1}$)	0.03	3.7	1.7
Total fruit (no.)	0.3	40	16
Flower clusters (no. $tree^{-1}$)	1.1	51	20
Crop Load (no fruit cm^{-2} TCSA)	0.1	5.4	1.1

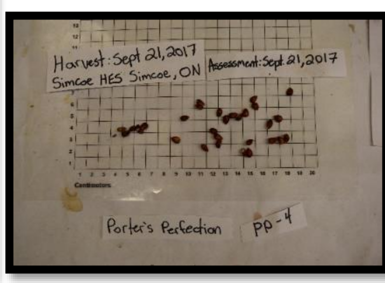
Growth Characteristics for Muscadet de Dieppe

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	17-May	-	-	20-May	-	-
Harvest Date	8-Sep	-	-	11-Sep	-	-
Days to harvest	114	-	-	114	-	-
Survival rate from spring 2015 planting	100%	95%	100%	100%	95%	100%
TCSA (cm^2)	7.4	4.4	4.0	14.5	5.3	4.5
Height (m)	2.6	-	-	2.8	-	-
Width (m)	1.2	-	-	1.3	-	-

Porter’s Perfection

Origin: English

Summary: ‘Porter’s Perfection’ produces a large volume of fruit, which are often fused. Though it tends towards bienniality and fruit dropping, the juice it produces is a high-quality bittersharp.



Juice Characteristics for Porter's Perfection

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.6	14.0
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	121	138
Juice pH	3.30	3.24
Juice formol number (mg YAN L^{-1} juice)	104	138
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	925	865
Juice Classification	Bittersharp	Bittersharp

Yield Characteristics for Porter's Perfection

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)z	-	80	81
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.61	0.60
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.8	1.1
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1246	720
Total harvested fruit weight (kg $tree^{-1}$)	0.02	3.0	1.8
Total fruit harvested (no. $tree^{-1}$)	0.2	46	24
Dropped fruit weight (kg $tree^{-1}$)	0.0	1.8	0.4
Dropped fruit (no. $tree^{-1}$)	0.0	29	6
Total fruit weight (kg $tree^{-1}$)	0.02	4.9	2.1
Total fruit (no.)	0.2	75	30
Flower clusters (no. $tree^{-1}$)	0.6	162	31
Crop Load (no fruit cm^{-2} TCSA)	0.0	8.0	1.6

Growth Characteristics for Porter's Perfection

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	18-May	-	-	21-May	-	-
Harvest Date	5-Oct	-	-	9-Oct	-	-
Days to harvest	140	-	-	141	-	-
Survival rate from spring 2015 planting	100%	80%	100%	100%	68%	100%
TCSA (cm^2)	9.5	4.0	5.9	20.0	5.5	7.5
Height (m)	3.0	-	-	3.3	-	-
Width (m)	1.55	-	-	1.6	-	-

Stoke Red

Synonyms: Stoke’s Red

Origin: English

Summary: ‘Stoke Red’ is suitable for cultivation in Ontario. It has a high survival rate and blooms well within frost-safe dates, though it has a low yield and biennial tendencies.

Juice Characteristics for Stoke Red

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	12.8	13.6
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	101	120
Juice pH	3.42	3.39
Juice formol number (mg YAN L^{-1} juice)	78	148
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	1042	876
Juice Classification	Bittersharp	Bittersharp

Yield Characteristics for Stoke Red

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	93	76
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.64	0.61
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.60	1.00
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		1080	672
Total harvested fruit weight (kg $tree^{-1}$)	0	2.5	1.6
Total fruit harvested (no.)	0	32	58
Dropped fruit weight (kg)	0	1.5	0.1
Dropped fruit (no.)	0	19	2
Total fruit weight (kg)	0	3.9	1.7
Total fruit (no.)	0	51	67
Flower clusters (no.)	0	105	29
Crop Load (no fruit cm^{-2} TCSA)	0.0	8.5	5.7

Growth Characteristics for Stoke Red

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	29-May	-	-	25-May	-	-
Harvest Date	16-Sep	-	-	4-Sep	-	-
Days to harvest	109.5	-	-	102	-	-
Survival rate from spring 2015 planting	100%	80%	100%	100%	70%	100%
TCSA (cm^2)	6.0	4.7	5.1	11.8	5.9	7.2
Height (m)	3.0	-	-	3.1	-	-
Width (m)	1.5	-	-	1.5	-	-

Sweet Alford

Origin: English

Summary: ‘Sweet Alford’ produces abundant sweet juice, though it has a low juicing efficiency. It is suitable for cultivation in Ontario.

Juice Characteristics for Sweet Alford

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	15.7	13.0
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	31	35
Juice pH	4.76	4.57
Juice formol number (mg YAN L^{-1} juice)	82	98
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	208	131
Juice Classification	Sweet	Sweet

Yield Characteristics for Sweet Alford

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	162	190
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.60	0.59
Estimated juice yield per tree (L juice tree^{-1})	-	2.1	5.6
Estimated juice yield per acre (L juice 675 trees^{-1})		1406	3794
Total harvested fruit weight (kg tree^{-1})	0.0	3.5	9.6
Total fruit harvested (no. tree^{-1})	0.0	23	23
Dropped fruit weight (kg tree^{-1})	0.0	1.4	1.5
Dropped fruit (no. tree^{-1})	0.0	8	9
Total fruit weight (kg tree^{-1})	0.0	4.9	11.1
Total fruit (no.)	0.0	32	25
Flower clusters (no. tree^{-1})	0.1	53	77
Crop Load (no fruit cm^{-2} TCSA)	0.0	4.4	5.7

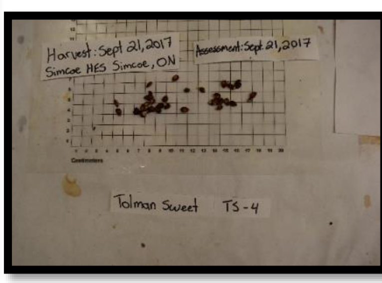
Growth Characteristics for Sweet Alford

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	16-May	-	-	18-May	-	-
Harvest Date	6-Oct	-	-	9-Oct	-	-
Days to harvest	143	-	-	144	-	-
Survival rate from spring 2015 planting	100%	90%	100%	100%	90%	100%
TCSA (cm^2)	7.7	3.7	5.1	11.8	4.4	6.9
Height (m)	2.6	-	-	3.0	-	-
Width (m)	1.4	-	-	1.7	-	-

Tolman Sweet

Origin: English

Summary: ‘Tolman Sweet’ produces abundant sweet juice, but it has survival issues at some sites. The fruit drops from the tree as soon as it ripens, making it unsuitable for typical harvest practices in Ontario. The crop loss makes it hard to recommend.



Juice Characteristics for Tolman Sweet

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.6	13.5
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	34	49
Juice pH	4.45	4.26
Juice formol number (mg YAN L^{-1} juice)	155	134
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	185	228
Juice Classification	Sweet	Sweet

Yield Characteristics for Tolman Sweet

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)z	-	143	156
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.61	0.56
Estimated juice yield per tree (L juice $tree^{-1}$)	-	0.5	1.0
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		314	686
Total harvested fruit weight (kg $tree^{-1}$)	0.1	0.8	1.8
Total fruit harvested (no. $tree^{-1}$)	0.4	6	12
Dropped fruit weight (kg $tree^{-1}$)	0.1	2.5	4.5
Dropped fruit (no. $tree^{-1}$)	0.5	18	33
Total fruit weight (kg $tree^{-1}$)	0.1	3.3	6.3
Total fruit (no.)	0.9	23	45
Flower clusters (no. $tree^{-1}$)	4.5	36	50
Crop Load (no fruit cm^{-2} TCSA)	0.2	3.7	4.4

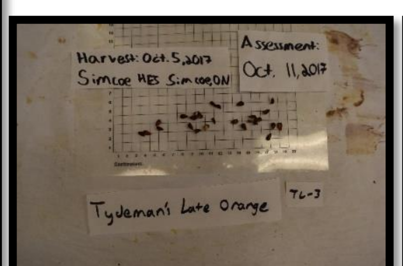
Growth Characteristics for Tolman Sweet

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	19-May	-	-	21-May	-	-
Harvest Date	26-Sep	-	-	4-Oct	-	-
Days to harvest	130	-	-	136	-	-
Survival rate from spring 2015 planting	100%	40%	100%	100%	30%	100%
TCSA (cm^2)	6.5	4.2	4.2	11.1	8.5	5.0
Height (m)	2.9	-	-	3.2	-	-
Width (m)	1.5	-	-	1.7	-	-

Tydeman's Late Orange

Origin: English

Summary: 'Tydeman Late' produces a very sweet juice, though it has a problem with cracking and fruit quality. It has some survival issues at some sites and it is highly biennial. The fruit quality issues at harvest make this variety unsuitable for Ontario.



Juice Characteristics for Tydeman's Late Orange

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	17.1	16.3
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	176	179
Juice pH	3.18	3.12
Juice formol number (mg YAN L^{-1} juice)	206	157
Corrected juice polyphenols (µg gallic acid equivalents mL^{-1} juice)	314	259
Juice Classification	Sharp	Sharp

Yield Characteristics for Tydeman's Late Orange

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	156	164
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.60	0.60
Estimated juice yield per tree (L juice $tree^{-1}$)	-	1.3	6.3
Estimated juice yield per acre (L juice 675 $trees^{-1}$)		850	4272
Total harvested fruit weight (kg $tree^{-1}$)	0.0	2.1	10.6
Total fruit harvested (no. $tree^{-1}$)	0.0	15	73
Dropped fruit weight (kg $tree^{-1}$)	0.0	0.0	0.4
Dropped fruit (no. $tree^{-1}$)	0.0	0	4
Total fruit weight (kg $tree^{-1}$)	0.0	2.1	11.0
Total fruit (no.)	0.0	16	77
Flower clusters (no. $tree^{-1}$)	0.0	16	85
Crop Load (no fruit cm^{-2} TCSA)	0.0	2.0	4.8

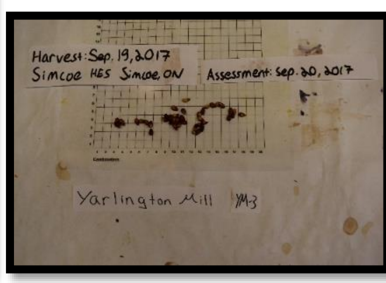
Growth Characteristics for Tydeman's Late Orange

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	18-May	-	-	19-May	-	-
Harvest Date	3-Oct	-	-	18-Oct	-	-
Days to harvest	138	-	-	152	-	-
Survival rate from spring 2015 planting	90%	85%	100%	85%	80%	100%
TCSA (cm^2)	8.9	5.3	4.6	14.8	7.7	7.4
Height (m)	3.1	-	-	3.2	-	-
Width (m)	1.6	-	-	1.8	-	-

Yarlington Mill

Origin: English

Summary: 'Yarlington Mill' produces bittersweet juice, though it tends towards bienniality. It has a low juicing efficiency and drops on the ground as it ripens, but its juice quality is good.



Juice Characteristics for Yarlington Mill

Location and Year	Simcoe, ON 2017	Simcoe, ON 2018
Soluble solids (°Brix)	14.1	16.7
Titratable acidity (as mg malic acid 100 mL^{-1} juice)	40	57
Juice pH	4.30	4.24
Juice formol number (mg YAN L^{-1} juice)	83	132
Corrected juice polyphenols (μg gallic acid equivalents mL^{-1} juice)	737	640
Juice Classification	Bittersweet	Bittersweet

Yield Characteristics for Yarlington Mill

Location and Year	Simcoe, ON 2016	Simcoe, ON 2017	Simcoe, ON 2018
Average selected fruit weight (g)	-	136	121
Juice extraction efficiency (mL juice g^{-1} fruit)	-	0.51	0.39
Estimated juice yield per tree (L juice tree^{-1})	-	1.0	0.5
Estimated juice yield per acre (L juice 675 trees^{-1})		645	335
Total harvested fruit weight (kg tree^{-1})	0.1	1.9	1.3
Total fruit harvested (no. tree^{-1})	0.9	15	11
Dropped fruit weight (kg tree^{-1})	0.1	3.7	1.3
Dropped fruit (no. tree^{-1})	0.4	28	11
Total fruit weight (kg tree^{-1})	0.2	5.6	2.6
Total fruit (no.)	1.2	43	22
Flower clusters (no. tree^{-1})	1.8	36	16
Crop Load (no fruit cm^{-2} TCSA)	0.3	6.5	1.7

Growth Characteristics for Yarlington Mill

Location and Year	Simcoe, ON 2017	Thedford, ON 2017	Clarksburg, ON 2017	Simcoe, ON 2018	Thedford, ON 2018	Clarksburg, ON 2018
Bloom Date	20-May	-	-	23-May	-	-
Harvest Date	25-Sep	-	-	9-Oct	-	-
Days to harvest	128.5	-	-	139	-	-
Survival rate from spring 2015 planting	100%	95%	95%	100%	95%	95%
TCSA (cm^2)	6.7	2.3	4.0	12.4	3.0	5.1
Height (m)	2.9	-	-	3.1	-	-
Width (m)	1.5	-	-	1.5	-	-