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ARTICLE

# Evaluation of selected cider apple (*Malus domestica* Borkh.) cultivars grown in Ontario. I. Horticultural attributes[1]

Derek J. Plotkowski and John A. Cline

**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, Bulmer's 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.

*Key words:* apple juice, cider, hard cider, cider cultivar, cider apple.

**Résumé :** Les auteurs ont sélectionné 28 cultivars de pomme pour la production de cidre, en Ontario. Ensuite, ils ont effectué une expérience afin d'en évaluer le potentiel horticole dans la province. Après la plantation, au printemps de 2015, les pommiers ont été évalués annuellement pour la survie, la hauteur et l'étalement, la croissance du tronc, la date de floraison, l'abondance de fleurs, le nombre de fruits, la chute prématurée, le rendement fruitier, le poids et la fermeté du fruit, la facilité d'extraction du jus et la date de la récolte. Ces paramètres horticoles ont suffi pour qu'on différencie les cultivars. D'autres analyses exploratoires ont révélé l'existence d'un lien entre les paramètres horticoles et l'origine du cultivar, les variétés à cidre britanniques fleurissant les dernières, celles d'Amérique produisant le plus de jus et les françaises connaissant la chute prématurée la plus abondante. Parmi les cultivars prometteurs examinés dans le cadre de cette étude et sur lesquels on pourrait poursuivre des recherches en Ontario, mentionnons Binet Rouge, Bramley's Seedling, Breakwell, Bulmer's 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 et Stoke Red. [Traduit par la Rédaction]

*Mots-clés :* jus de pomme, moût, cidre, pomme à moût, pomme à cidre.

## Introduction

There has been little research and development into cultivating cider apples for fermentation in North America. In Canada, the definition of cider is the product of the alcoholic fermentation of apple juice, which allows for additions such as 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). Ontario cider, and especially craft cider, has been growing as a beverage

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category over the past decade (MNP LLP 2016). In Ontario, cider producers have historically used culinary and dessert apples instead of cider apples to produce alcoholic ciders (Wilson et al. 2003). Meanwhile, a 2018 report found that in Québec, table apples such as McIntosh, Spartan, Empire, and Cortland are most often used for cider to add economic value to lower-quality fruits (Provost 2018).

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. Cider apples are often characterized by juice attributes like high polyphenol and acid concentrations that may not be appealing in fresh market fruit (Merwin et al. 2008). Visual aspects of the fruit are less important (Provost 2018) because the cider maker is concerned about the pressed juice rather than fruit aesthetics. These variations have greatly influenced how varietal selection has occurred in the past. Decades ago, cider trees were often grown on large roots (standard rootstocks or own-rooted) and many fruit would fall to the ground when ripe. This practice is not generally compatible with modern North American harvesting and juicing practices. Many contemporary cider orchards are 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 cider apple cultivars and their climatic adaptations, there are other considerations about growing cider apples in Ontario. Is the season long enough? Do they bloom too early, which predisposes the flowers to frost? Do they mature adequately in an Ontario climate? Are they susceptible to fireblight (*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 to understand before investing time and money into establishing cider orchards.

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. While this study will focus on the horticultural characteristics of cider apple trees and fruit, excluding the consumption of the fruit, a concurrent companion study evaluating the juice attributes of these cultivars was conducted (Plotkowski and Cline 2021). Understanding how the fruit grows, how the tree develops, and how the tree experiences dieback is important for understanding how the tree performs separately from its juice quality. For example, a tree that produces only a few apples each year, even with perfect juice, is not useful to a grower.

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

When evaluating the harvest potential of a tree, parameters often assessed include the total number and weight of fruit, number of fruit harvested, number of pre-harvest fruit that have dropped, weight of harvested fruit, weight of dropped fruit, number of fruit thinned, and percentage of fruit set based on total number of floral clusters (Beach et al. 1903; Bultitude 1983; Khanizadeh and Cousineau 1998; Morgan and Richards 2003; Hanson 2005; Merwin et al. 2008; NSW Department of Primary Industries 2008; Institut Français des Productions Cidricoles 2009; Rothwell 2012; Copas 2013; Jolicoeur 2013; Pôle Fruitier de Bretagne 2013; Shelton 2015; Simmens 2015; Ashridge Trees Ltd. 2020; Grandpa's Orchard 2020; Summerland Varieties Corp. 2020).

The period in which apple trees bloom plays an important role in determining which cultivars are planted together and whether a cultivar is suitable for a particular climate zone. Apples generally are not self-fertile and thus require another variety of apple nearby to act as a pollinizer (Dennis 2003). Another reason bloom date and length are important is that they influence the effect of environmental stressors on fruit set. An early blooming tree has an increased risk of its flowers being damaged by frost (Ballard 1981). Additionally, lower temperatures associated with early bloom dates may inhibit pollinators (Dennis 2003). A late bloom or protracted bloom period may increase the risk of infection with fireblight or other diseases (Grove et al. 2003). 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).

Precocity refers to the length of time after planting it takes a tree to bear fruit. In the cider industry, this is especially important because of the extra time needed to put cider to market compared with fresh fruit (Barden and Neilsen 2003). 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 as well as a faster return on investment compared with standard or semi-dwarf trees (Barden and Neilsen 2003). 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 between-row space. The height and breadth of the tree has long been linked with the trunk cross-sectional area (TCSA; calculated by the measured circumference or diameter of the tree) and total fruit-bearing surface of the tree (Barden and Neilsen 2003).

All apple cultivars tend towards biennial bearing, with some having a greater disposition than others.

Interventions taken to mitigate extreme biennial bearing include fruit thinning and growth regulator sprays before bud set in the summer. Not all cultivars are receptive to this amelioration, however. 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).

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 fruit borne by the tree can be classified as either pre-harvest dropped fruit or harvested fruit. In Canada, dropped fruit are usually discarded or sold for juice. Additionally, a cumulative yield over every year of a tree's life can be calculated as 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 TCSA.

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 with 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 benefiting fruit quality (Peck et al. 2016).

The selection of a harvest date depends on several factors. These include the weather, labour availability, fruit ripeness and intended purpose, and available storage capacity. Ripeness in the field is usually monitored using the starch–iodine test (Blanpied and Silsby 1992) in conjunction with a generalized rating chart and internal ethylene production. Cider producers prefer 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.

Fruit from the apple tree falls at various times throughout the season. After fertilization, the first time-point is known as June drop, which is when fruitlets abscise after fruit set, either naturally or in response to chemical thinners (Dennis 2003). From then until harvest, additional fruit may drop as a result of wind, natural or accidental physical forces, or disease. Preharvest drop varies widely by cultivar and can be mitigated by the use of chemical sprays (Dennis 2003). Some trees will drop mature fruit as soon as it ripens, while other trees will retain their fruit long past maturity.

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 summarized consisted of the phenological stages of the different cultivars, including the full bloom dates in particular; the yield attributes, including the number and weight of fruit on the trees; and the vigour of each cultivar as indicated by tree height, width, and mortality.

The goal of evaluating the horticultural attributes of these apple cultivars was not only to provide practical recommendations for choosing cultivars 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 cultivar's performance in cider production: tree mortality, early and protracted bloom, harvest issues, biennial bearing potential, and processing issues.

These data were subject to exploratory analyses to examine relationships that existed among the horticultural attributes. Given the varying traits selected by growers in each region to adapt to local climates and horticultural practices, it was hypothesized that differences in horticultural attributes would exist among cultivars with different geographic origins.

## Materials and Methods

### Plant materials

The 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, ON. The cultivars were Ashmead's Kernel, Breakwell, Brown's Apple, Bulmer's 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 paid to cultivars with 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 bud wood was available outside of Canada at the time of propagation, which limited the selection of desired cultivars.

In the spring of 2015, the trees were planted at the Simcoe Research Station (Simcoe, ON). They received regular treatment and care as well as integrated pest management for disease and pests according to the local recommendations of the Ontario Ministry of Agriculture, Food, and Rural Affais (OMAFRA 2016). The trees were planted in a randomized complete block, with four blocks of five 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

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

**Note:** Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values and earliest dates, which scales up to blue for the highest values and latest dates.

[a]Value calculated by multiplying the cultivar's juice extraction efficiency by the planting density and the cultivar's harvested weight (Table 5).

block acting as guard trees. Trees were spaced 1 m within and 4.5 m between rows (1667 trees·ha$^{-1}$). Trees were 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.

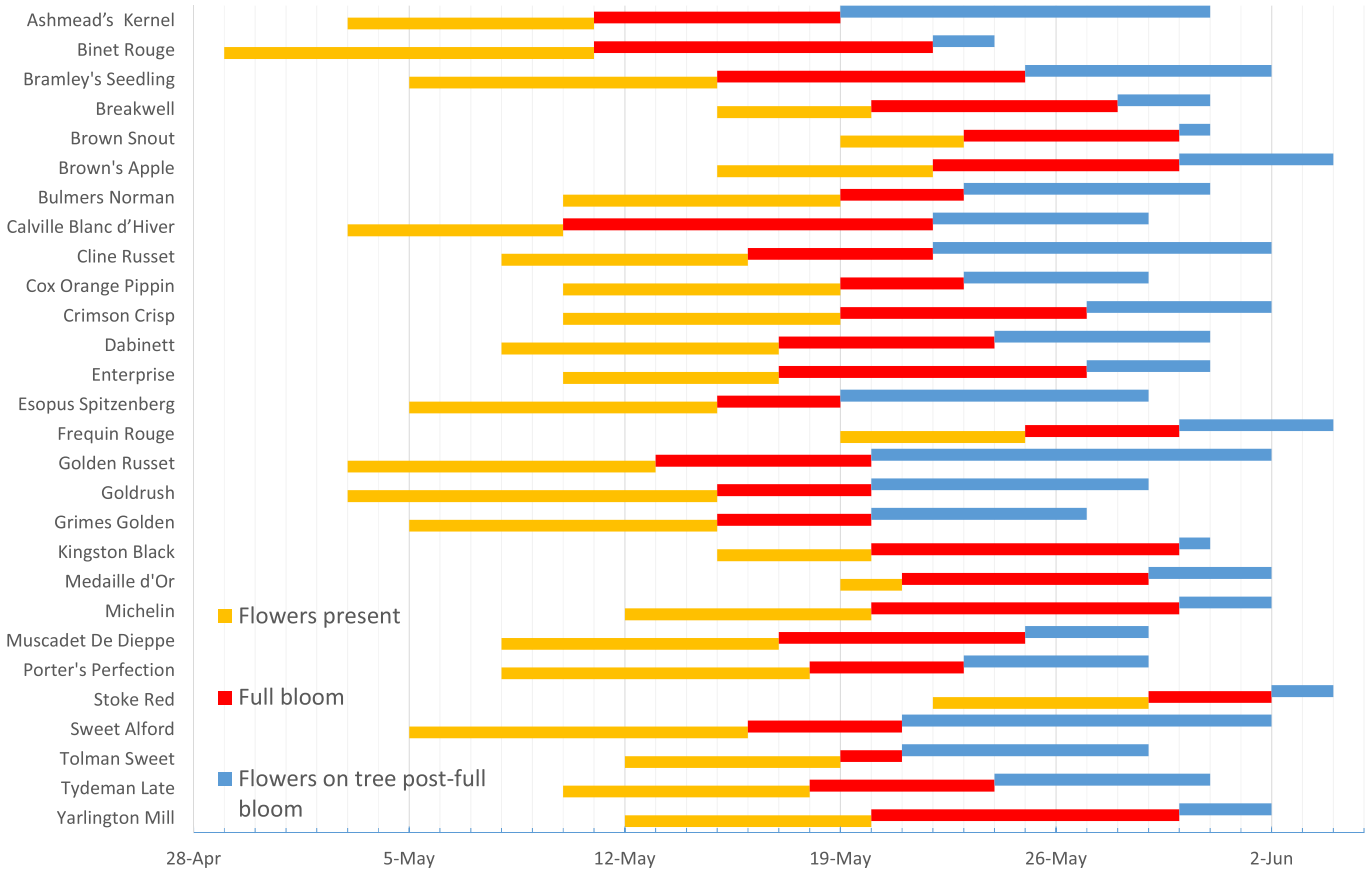
The orchard soil consisted of a Brady sandy loam (Brunisolic Grey Brown Luvisol) (Presant and Acton 1984) with imperfect drainage and soil textures consisting of mainly lacustrine sand and sandy loam over glaciolacustrine clays at depths >1.5 m (Hohner and Presant 1989).

Based on climate normal, the climate of the orchard location is characterized by the following: the average growing degree days from 1 Jan. to 31 Oct. (base 5 °C) is 2222 d (Farmwest 2021). Average daily maximum temperatures in August are 25.8 °C, while the average minimum temperatures in January are −9.1 °C. Average precipitation from 1 May to 31 Oct. is 546 mm, and this is distributed fairly uniformly across these months. On average, there are 137 frost free days (Environment Canada 2021).

### Horticultural measurements

Each autumn, tree size was measured by recording tree width, height, and TCSA 30 cm above the ground using digital calipers (Model 058-6800-4, Mastercraft Canada, Toronto, ON, Canada) or tape measures. Tree mortality was recorded every spring and fall from 2016 to 2018.

**Fig. 1.** Gantt 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).




In the spring of both 2017 and 2018, phenology was rated three to four times per week from late April to the end of flowering in June. The rating system used herein was developed at Washington State University, and covers the progression from the silver tip stage immediately after dormancy to petal fall (Ballard 1981). Flower clusters were counted on each tree at full bloom in May of 2017 and 2018, and fruit were hand-thinned to 10 cm between fruit and single fruit per cluster after June drop each year.

### Yield measurements

In the fall of 2017 and 2018, fruit were 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 2 wk before their projected harvest date based on data from other sites, although in some instances fruit were harvested ahead of the projected schedule. The five selected fruit were weighed and photographed whole. They were then halved transversely and seeded. Half of each apple was photographed, as were its seeds. Notes were taken on seed and fruit colour. Half of each apple was assessed using the starch–iodine method (Blanpied and Silsby 1992) and photographed. For each cultivar, fruit on the data trees, which are 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 and Silsby 1992). At harvest, all pre-harvest drop fruit 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, USA). These counts and weights were recorded for each individual data tree.

A pool of 15 apples, comprised of five random apples sampled from the harvested fruit of each of the three data trees, were weighed on an analytical scale (LC 3200D, Sartorius, Bohemia, NY, USA). Thereafter, the fruit pool was ground with a fruit juicer (Model 8006, Omega, Harrisburg, PA, USA), wrapped in cheesecloth (Grade No. 50, Fisher Scientific, Whitby, ON, Canada), and pressed on a custom-made stainless steel rack and cloth set used in conjunction with a PowerFist hydraulic press (Princess Auto, Hamilton, ON, Canada). The juice was collected in a graduated cylinder and the volume from each pressing was measured. Juice volume

**Table 2.** Growth attributes of 28 apple cultivars grown on M.9 rootstock for cider production (University of Guelph, Simcoe, Ontario, 2018).

| Cultivar | Tree survival as of fall 2018 (%) | TCSA (2018) | | Tree height (2018) (m) | | Tree width (2018) (m) | | Flower clusters (2017) (no.·tree$^{-1}$) | | Flower clusters (2018) (no.·tree$^{-1}$) | | Fruit set (2017) (no.·tree$^{-1}$) | | Fruit set (2018) (no.·tree$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ashmead's Kernel | 95 | 13.4 | def | 3.4 | abc | 1.4 | g–j | 69 | e–i | 104 | bc | 5.6 | c | 8 | b |
| Binet Rouge | 100 | 19.4 | ab | 3.5 | a | 1.7 | ab | 155 | ab | 39 | f–j | 10.4 | c | 22 | b |
| Bramley's Seedling | 100 | 21.1 | a | 3.2 | b–g | 1.7 | a–d | 92 | c–h | 28 | g–j | 7.2 | c | 23 | b |
| Breakwell | 100 | 17.3 | bc | 2.8 | ij | 1.2 | jk | 87 | d–h | 29 | g–j | 7.7 | c | 44 | ab |
| Brown Snout | 100 | 8.1 | ij | 2.8 | ij | 0.9 | l | 48 | ghi | 27 | g–j | 11.3 | c | 29 | b |
| Brown's Apple | 100 | 12.6 | d–g | 2.9 | ghi | 1.5 | e–i | 68 | e–i | 34 | g–j | 10.4 | c | 21 | b |
| Bulmer's Norman | 100 | 14.0 | de | 3.0 | e–i | 1.4 | g–j | 146 | a–d | 11 | j | 7.1 | c | 19 | b |
| Calville Blanc d'Hiver | 100 | 21.2 | a | 3.3 | a–f | 1.6 | b–h | 142 | a–d | 147 | a | 4.3 | c | 8 | b |
| Cline Russet | 95 | 8.2 | ij | 3.0 | d–i | 1.4 | g–j | 58 | f–i | 36 | f–j | 7.7 | c | 16 | b |
| Cox Orange Pippin | 100 | 9.9 | f–i | 3.0 | e–i | 1.5 | c–i | 91 | c–h | 112 | abc | 5.8 | c | 13 | b |
| Crimson Crisp® | 100 | 6.9 | j | 3.0 | e–i | 1.4 | g–j | 65 | e–i | 139 | ab | 8.1 | c | 9 | b |
| Dabinett | 90 | 9.6 | g–j | 3.0 | e–i | 1.5 | c–i | 47 | ghi | 90 | cde | 9.1 | c | 15 | b |
| Enterprise | 100 | 11.9 | d–h | 3.0 | f–i | 1.7 | a–f | 50 | ghi | 70 | c–g | 8.8 | c | 15 | b |
| Esopus Spitzenberg | 100 | 11.6 | e–h | 3.2 | b–g | 1.7 | a–e | 46 | ghi | 36 | f–j | 8.0 | c | 19 | b |
| Frequin Rouge | 100 | 11.1 | f–i | 2.5 | k | 1.3 | hij | 71 | e–i | 57 | d–h | 11.4 | c | 44 | ab |
| Golden Russet | 100 | 12.4 | d–g | 3.4 | ab | 1.5 | e–i | 123 | a–e | 49 | e–i | 6.5 | c | 21 | b |
| GoldRush | 100 | 8.4 | ij | 3.2 | a–f | 1.2 | jk | 125 | a–e | 49 | e–i | 9.6 | c | 17 | b |
| Grimes Golden | 100 | 9.1 | hij | 3.1 | b–h | 1.5 | f–i | 115 | a–f | 95 | cd | 8.1 | c | 18 | b |
| Kingston Black | 100 | 11.1 | f–i | 2.5 | jk | 1.1 | kl | 55 | f–i | 13 | ij | 8.0 | c | 22 | b |
| Medaille d'Or | 95 | 11.2 | f–i | 3.0 | d–i | 1.5 | f–i | 163 | a | 14 | ij | 8.7 | c | 12 | b |
| Michelin | 95 | 12.4 | d–g | 3.3 | a–d | 1.4 | g–j | 97 | b–h | 26 | g–j | 12.8 | bc | 40 | ab |
| Muscadet De Dieppe | 100 | 14.5 | cde | 2.8 | hi | 1.3 | ijk | 51 | ghi | 20 | hij | 14.9 | bc | 16 | b |
| Porter's Perfection | 100 | 20.0 | ab | 3.3 | a–e | 1.6 | a–g | 162 | a | 31 | g–j | 7.9 | c | 48 | ab |
| Stoke Red | 100 | 12.5 | d–g | 3.1 | d–h | 1.5 | d–i | 105 | a–g | 29 | g–j | 9.7 | c | 100 | a |
| Sweet Alford | 100 | 11.8 | d–h | 3.0 | d–i | 1.7 | a–f | 53 | ghi | 77 | c–f | 9.5 | c | 22 | b |
| Tolman Sweet | 100 | 11.1 | f–i | 3.2 | a–g | 1.7 | abc | 36 | hi | 50 | e–i | 11.7 | c | 22 | b |
| Tydeman Late | 90 | 14.8 | cd | 3.2 | a–f | 1.8 | a | 16 | i | 85 | cde | 29.0 | a | 27 | b |
| Yarlington Mill | 100 | 12.4 | d–g | 3.1 | c–h | 1.5 | b–h | 36 | hi | 16 | hij | 24.7 | ab | 49 | ab |
| *P* value | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | |

**Note:** Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values, which scales up to blue for the highest values. Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. TCSA, trunk cross-sectional area.

was divided by the weight of the apples to calculate 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.

### Experimental design and statistical analyses

Explanatory statistics were analyzed using a generalized linear mixed model (the GLIMMIX procedure) in SAS version 9.4 (The SAS Institute Inc., Cary, NC, USA). Significance was evaluated at a $P$ value of 0.05 and residuals were analyzed for normality and outliers, with outliers being excluded from the dataset. Post-hoc means separation was analyzed using the Tukey–Kramer grouping for least square means ($\alpha = 0.05$).

To understand the relationships among variables, exploratory multivariate statistical analyses, including principal component analysis, cluster analysis, and discriminant analysis (the PRINCOMP, FASTCLUS, and DISCRIM procedures, respectively) were performed in SAS version 9.4 (The SAS Institute Inc., Cary, NC, USA). These procedures group variables using, 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 $\chi^2$ test.

## Results

### Bloom data

In 2017, the first blossoms opened on 29 Apr. 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, on 10 May, indicated by a rating of 8 on the Washington State University apple phenology chart (Ballard 1981), whereas Stoke Red was the last to reach full bloom, on 29 May (Table 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

**Table 3.** 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 fruit weight (g) | | Juice extraction efficiency (mL juice·g$^{-1}$ fruit) | | Estimated orchard juice production at 1667 trees·ha$^{-1}$ (L juice·ha$^{-1}$)[a] | Days to harvest | | Full bloom date | Harvest date |
|---|---|---|---|---|---|---|---|---|---|
| Ashmead's Kernel | 167 | b–e | 0.60 | ab | 2120 | 134 | kl | 16 May | 27 Sept. |
| Binet Rouge | 70 | j | 0.45 | ef | 1170 | 109 | q | 18 May | 4 Sept. |
| Bramley's Seedling | 267 | a | 0.64 | ab | 6810 | 121 | n | 19 May | 17 Sept. |
| Breakwell | 138 | d–g | 0.65 | ab | 3110 | 113 | op | 21 May | 11 Sept. |
| Brown Snout | 93 | hij | 0.59 | ab | 1060 | 145 | f | 23 May | 15 Oct. |
| Brown's Apple | 152 | c–f | 0.66 | ab | 4170 | 92 | t | 22 May | 22 Aug. |
| Bulmer's Norman | 110 | ghi | 0.61 | ab | 510 | 97 | s | 22 May | 27 Aug. |
| Calville Blanc d'Hiver | 262 | A | 0.65 | ab | 14840 | 158 | b | 17 May | 22 Oct. |
| Cline Russet | 134 | d–g | 0.64 | ab | 3510 | 142 | gh | 20 May | 9 Oct. |
| Cox Orange Pippin | 158 | b–f | 0.62 | ab | 10040 | 121 | n | 19 May | 17 Sept. |
| Crimson Crisp® | 165 | b–e | 0.68 | a | 10300 | 138 | ij | 19 May | 4 Oct. |
| Dabinett | 192 | b | 0.61 | ab | 9860 | 131 | l | 19 May | 27 Sept. |
| Enterprise | 246 | a | 0.65 | ab | 13460 | 172 | a | 18 May | 6 Nov. |
| Esopus Spitzenberg | 178 | bc | 0.58 | abc | 4850 | 154 | c | 17 May | 18 Oct. |
| Frequin Rouge | 68 | j | 0.48 | de | 870 | 148 | e | 23 May | 18 Oct. |
| Golden Russet | 183 | bc | 0.61 | ab | 6470 | 161 | b | 17 May | 25 Oct. |
| GoldRush | 172 | bcd | 0.66 | ab | 6630 | 173 | a | 17 May | 6 Nov. |
| Grimes Golden | 139 | d–g | 0.66 | ab | 1390 | 149 | de | 19 May | 15 Oct. |
| Kingston Black | 102 | g–j | 0.49 | cde | 630 | 112 | p | 22 May | 11 Sept. |
| Medaille d'Or | 90 | hij | 0.60 | ab | 620 | 128 | m | 22 May | 27 Sept. |
| Michelin | 96 | hij | 0.39 | ef | 990 | 115 | o | 19 May | 11 Sept. |
| Muscadet De Dieppe | 130 | e–h | 0.36 | f | 570 | 114 | op | 20 May | 11 Sept. |
| Porter's Perfection | 81 | ij | 0.60 | ab | 1780 | 141 | hi | 21 May | 9 Oct. |
| Stoke Red | 76 | j | 0.61 | ab | 1660 | 102 | r | 25 May | 4 Sept. |
| Sweet Alford | 190 | bc | 0.59 | abc | 9370 | 144 | fg | 18 May | 9 Oct. |
| Tolman Sweet | 156 | b–f | 0.56 | bcd | 1690 | 136 | jk | 21 May | 4 Oct. |
| Tydeman Late | 164 | b–e | 0.60 | ab | 10550 | 152 | cd | 19 May | 18 Oct. |
| Yarlington Mill | 121 | fgh | 0.39 | ef | 830 | 139 | ij | 23 May | 9 Oct. |
| *P* value | <0.0001 | | <0.0001 | | | <0.0001 | | <0.0001 | <0.0001 |

**Note:** Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values and earliest dates, which scales up to blue for the highest values and latest dates.

[a]Value calculated by multiplying the cultivar's juice extraction efficiency by the planting density and the cultivar's harvested weight (Table 5).

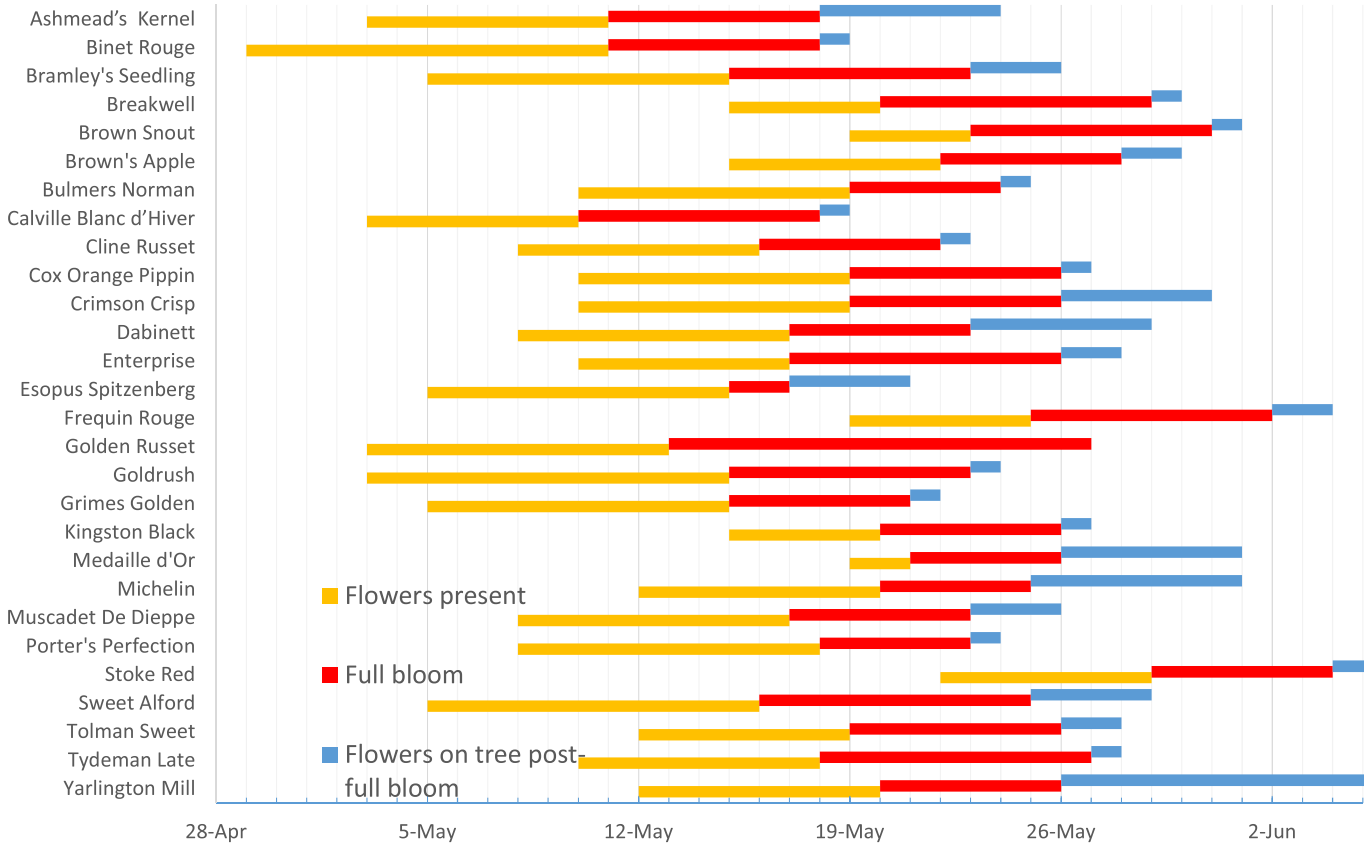
Stoke Red, which dropped their final petals on 3 June. Golden Russet had the longest overall bloom period, whereas Fréquin Rouge had the shortest (Fig. 1). Number of flower clusters ranged from an average of 16 clusters on Tydeman Late to 163 clusters on Medaille d'Or (Table 2).

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, on 16 May, whereas Stoke Red was the last to reach full bloom, on 25 May (Table 3). 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 (Fig. 2). Number of flower clusters ranged from 11 clusters on Bulmer's Norman to 147 clusters on Calville Blanc d'Hiver (Table 2).

### Harvest data

Of the cultivars evaluated, only three produced more than one fruit per tree in the second year of production: Muscadet de Dieppe, Binet Rouge, and Grimes Golden

**Fig. 2.** Gantt 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).




(Table 4). Every cultivar produced a harvestable quantity of greater than one fruit per tree by 2017, the third year of production (Table 5). In 2016, the yield on every cultivar was relatively small, due to tree immaturity (Table 4). In 2017, the total fruit weight per tree ranged from 2.1 kg for Tydeman Late and Brown Snout to 10.7 kg for Bramley's Seedling (Table 5). In 2018, the total fruit weight per tree ranged from 0.7 kg for Medaille d'Or to 14.3 kg for Calville Blanc d'Hiver (Table 6).

As shown in Table 5, in 2017, the harvested fruit weight ranged from to 0.8 kg·tree$^{-1}$ for Tolman Sweet to 8.1 kg·tree$^{-1}$ for Bramley's Seedling and the harvested fruit number ranged from 6 fruit·tree$^{-1}$ for Tolman Sweet to 67 fruit·tree$^{-1}$ for GoldRush. The pre-harvest dropped fruit weight ranged from 0 kg·tree$^{-1}$ for Esopus Spitzenberg and Tydeman Late to 3.7 kg·tree$^{-1}$ for Yarlington Mill. The pre-harvest dropped fruit number ranged from 0 fruit·tree$^{-1}$ for Tydeman Late to 51 fruit·tree$^{-1}$ for Michelin. The percentage of pre-harvest dropped fruit ranged from 1% for GoldRush to 79% for Michelin.

As shown in Table 6, in 2018, the harvested fruit weight ranged from 0.5 kg for Bulmer's Norman to 13.7 kg for Calville Blanc d'Hiver. The harvested fruit number ranged from 5 fruit·tree$^{-1}$ for Bulmer's Norman to 73 fruit·tree$^{-1}$ for Tydeman Late. The pre-harvest dropped fruit weight ranged from 0 kg·tree$^{-1}$ for Medaille d'Or to 8.6 kg·tree$^{-1}$ for Grimes Golden. The pre-harvest dropped fruit number ranged from 1 fruit·tree$^{-1}$ for Medaille d'Or to 61 fruit·tree$^{-1}$ for Grimes Golden. Finally, the percentage of pre-harvest dropped fruit ranged from 5% for Crimson Crisp® to 88% of total fruit per tree for Grimes Golden.

In 2017, the first cultivar 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 with the shortest number of days between full bloom and harvest was Brown's Apple, at 99 d, whereas the longest was GoldRush, at 164 d (Table 1). In 2018, the first cultivar 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 with the shortest number of days between full bloom and harvest was Brown's Apple at 92 d, whereas the longest was GoldRush at 173 d (Table 3).

In 2017, the crop load ranged from 2.0 fruit per cm$^2$ TCSA on Tydeman Late to 14.4 fruit per cm$^2$ TCSA on GoldRush (Table 5). In 2018, the crop load ranged from

**Table 4.** 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$^{-1}$) | | Total fruit harvested (no.·tree$^{-1}$) | | Pre-harvest dropped fruit weight (kg·tree$^{-1}$) | | Pre-harvest dropped fruit (no.·tree$^{-1}$) | | Percentage of total fruit dropped | | Flower clusters (no.·tree$^{-1}$) | | Crop load (no. fruit per cm$^2$ TCSA) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ashmead's Kernel | 0.0 | b | 0.0 | b | 0.0 | b | 0.0 | b | 0.0 | b | 0.0 | c | 1.2 | a–d | 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 |
| Bulmer's 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 | a–d | 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 | a–d | 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 | a–e | 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 | a–d | 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 | a–e | 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 | a–d | 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 | a–d | 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 | a–d | 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 | a–d | 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 | a–e | 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 | b–e | 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 | a–d | 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 | a–d | 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 | a–d | 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 | a–d | 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 | |

**Note:** Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values, which scales up to blue for the highest values. Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. TCSA, trunk cross-sectional area.

0.5 fruit per cm$^2$ TCSA on Bulmer's Norman to 9.4 fruit per cm$^{-2}$ TCSA on Crimson Crisp (Table 6). In 2017, the average fruit weight of the sampled apples ranged from 80 g for a Porter's Perfection apple to 364 g for a Bramley's Seedling apple (Table 1). In 2018, this ranged from 70 g for a Binet Rouge apple to 267 g for a Bramley's Seedling apple (Table 3).

### Growth data

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

From planting in 2015 to the 2018 harvest, the cumulative fruit count for the cultivars ranged from 40 fruit per tree for Kingston Black to 114 fruit per tree for Grimes Golden. The cumulative fruit weight for the cultivars ranged from 3.8 kg per tree for Kingston Black to 20.2 kg per tree for Calville Blanc d'Hiver (Table 6). During the same time period, the survival rate at the Simcoe site ranged from 95% to 100%, with no significant difference among cultivars (Table 2).

### Juice production data

In 2017, the juicing efficiency ranged from 48 mL juice per 100 g fruit for Muscadet de Dieppe to 72 mL juice per 100 g fruit for GoldRush (Table 1). In 2018, the juicing efficiency ranged from 36 mL juice per 100 g fruit for Muscadet de Dieppe to 68 mL juice per 100 g fruit for Crimson Crisp® (Table 3).

In 2017, the estimated juice yield ranged from 780 L juice·ha$^{-1}$ for Tolman Sweet to 11 700 L juice·ha$^{-1}$ for GoldRush (Table 1). In 2018, the estimated juice yield ranged from 510 L juice·ha$^{-1}$ for Bulmer's Norman to 14 840 L juice·ha$^{-1}$ for Calville Blanc d'Hiver (Table 3).

### Multivariate analyses

The principal component analysis indicated that 77% of the horticultural variance among the cultivars could be attributed to four clusters. The first cluster explained

**Table 5.** 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$^{-1}$) | | Total fruit harvested (no.·tree$^{-1}$) | | Pre-harvest dropped fruit weight (kg·tree$^{-1}$) | | Pre-harvest dropped fruit (no.·tree$^{-1}$) | | Percentage of total fruit dropped | | Cumulative fruit count (2016–2017) (no.·tree$^{-1}$) | | Cumulative fruit weight (2016–2017) (kg·tree$^{-1}$) | | Crop load (2017) (no. fruit per cm$^2$ TCSA) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ashmead's Kernel | 3.8 | c–f | 24 | fgh | 2.2 | d–h | 13 | hij | 1.6 | c–h | 11 | d–h | 46 | def | 24 | fgh | 3.8 | c–h | 3.1 | g–j |
| Binet Rouge | 3.9 | c–f | 77 | a | 3.1 | c–h | 58 | ab | 0.9 | f–j | 19 | bcd | 25 | g–j | 77 | a | 4.0 | c–h | 7.9 | bcd |
| Bramley's Seedling | 10.7 | a | 32 | d–h | 8.1 | a | 24 | g–j | 2.6 | abc | 9 | d–h | 27 | g–j | 33 | d–h | 11.0 | a | 2.9 | hij |
| Breakwell | 4.5 | b–f | 32 | d–h | 3.8 | b–f | 26 | e–i | 0.8 | f–j | 6 | e–h | 19 | i–l | 32 | d–h | 4.5 | b–h | 3.7 | f–j |
| Brown Snout | 2.1 | f | 24 | fgh | 1.5 | fgh | 18 | g–j | 0.6 | hij | 7 | e–h | 23 | h–k | 28 | e–h | 2.4 | gh | 5.5 | c–j |
| Brown's Apple | 3.6 | c–f | 33 | d–h | 1.9 | e–h | 16 | g–j | 1.7 | c–g | 17 | c–g | 51 | cde | 33 | d–h | 3.6 | c–h | 5.3 | c–j |
| Bulmer's Norman | 6.4 | b | 51 | bcd | 5.4 | b | 43 | bcd | 1.0 | f–j | 9 | d–h | 16 | jkl | 52 | bcd | 6.4 | b | 7.6 | b–e |
| Calville Blanc d'Hiver | 5.8 | bcd | 29 | e–h | 5.6 | b | 28 | d–i | 0.1 | ij | 1 | h | 3 | l | 29 | e–h | 5.8 | b–e | 2.5 | ij |
| Cline Russet | 3.5 | c–f | 25 | fgh | 3.0 | c–h | 22 | g–j | 0.5 | hij | 4 | gh | 14 | jkl | 25 | fgh | 3.5 | c–h | 6.1 | c–h |
| Cox Orange Pippin | 4.5 | b–f | 28 | e–h | 4.0 | b-e | 25 | f–i | 0.5 | hij | 4 | gh | 13 | jkl | 28 | e–h | 4.5 | b–h | 4.5 | d–j |
| Crimson Crisp® | 3.2 | def | 19 | gh | 2.2 | d–h | 13 | hij | 1.0 | f–j | 6 | fgh | 34 | e–i | 19 | gh | 3.2 | e–h | 3.8 | f–j |
| Dabinett | 4.7 | b–f | 28 | e–h | 4.0 | b–e | 26 | e–i | 0.6 | g–j | 4 | gh | 13 | jkl | 28 | e–h | 4.7 | b–h | 5.0 | c–j |
| Enterprise | 5.1 | b–e | 23 | fgh | 5.0 | bc | 22 | g–j | 0.1 | ij | 1 | h | 5 | kl | 23 | fgh | 5.1 | b–g | 3.2 | hij |
| Esopus Spitzenberg | 2.8 | ef | 20 | gh | 2.7 | c–h | 20 | g–j | 0.0 | j | 1 | h | 3 | l | 20 | gh | 2.8 | fgh | 3.1 | hij |
| Frequin Rouge | 2.8 | ef | 33 | d–h | 1.6 | fgh | 18 | g–j | 1.2 | e–i | 15 | d–g | 49 | cde | 33 | d–h | 2.8 | fgh | 5.2 | c–j |
| Golden Russet | 5.3 | b–e | 38 | d–h | 4.3 | bcd | 30 | c–h | 1.0 | f–j | 8 | e–h | 19 | i–l | 38 | d–h | 5.5 | b–f | 5.9 | c–i |
| 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 | c–f | 4.1 | b–e | 29 | d–i | 2.2 | cde | 15 | d–g | 33 | e–i | 44 | c–f | 6.2 | bc | 7.2 | c–f |
| Kingston Black | 2.7 | ef | 28 | fgh | 1.2 | gh | 11 | ij | 1.6 | c–h | 16 | def | 58 | bcd | 28 | fgh | 2.8 | fgh | 5.1 | c–j |
| Medaille d'Or | 6.1 | bc | 65 | abc | 4.5 | bcd | 48 | bc | 1.6 | c–h | 17 | def | 29 | f–j | 65 | abc | 6.1 | bcd | 11.1 | ab |
| Michelin | 4.5 | b–f | 64 | abc | 1.0 | h | 14 | g–j | 3.5 | ab | 51 | a | 79 | a | 68 | ab | 4.9 | b–h | 8.7 | bc |
| Muscadet De Dieppe | 3.7 | c-f | 40 | d–g | 2.3 | d–h | 24 | g–j | 1.4 | d–h | 15 | d–g | 43 | d–g | 40 | d–g | 3.7 | c–h | 5.4 | c–j |
| Porter's Perfection | 4.9 | b-e | 75 | a | 3.0 | c–h | 46 | bcd | 1.8 | c–f | 29 | bcd | 38 | d–h | 75 | a | 4.9 | b–h | 8.0 | bc |
| Stoke Red | 4.1 | b-f | 51 | b–e | 2.7 | c–h | 32 | c–g | 1.5 | d–h | 19 | bcd | 40 | d–h | 51 | b–e | 4.1 | b–h | 8.5 | bc |
| Sweet Alford | 4.9 | b-e | 31 | e–h | 3.5 | b–g | 23 | g–j | 1.4 | d–h | 8 | d–h | 27 | g–j | 31 | e–h | 4.9 | b–h | 4.4 | e–j |
| Tolman Sweet | 3.3 | def | 23 | fgh | 0.8 | h | 6 | j | 2.5 | bcd | 18 | cde | 75 | ab | 24 | fgh | 3.4 | d–h | 3.7 | g–j |
| Tydeman Late | 2.1 | f | 16 | h | 2.1 | d–h | 15 | g–j | 0.0 | j | 0 | h | 3 | l | 16 | h | 2.1 | h | 2.0 | j |
| Yarlington Mill | 5.6 | bcd | 43 | c–f | 1.9 | e–h | 15 | g–j | 3.7 | a | 28 | bc | 66 | abc | 44 | c–f | 5.8 | b–e | 6.5 | c–g |
| *P* value | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | | <0.0001 | |

**Note:** Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values, which scales up to blue for the highest values. TCSA, trunk cross-sectional area.

32% of the variance and was mostly influenced by the total fruit weight and the total fruit number. The second cluster explained 24% of the variance and was mostly influenced by tree TCSA and height. The third cluster explained 11% of the variance and mostly influenced by 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 using 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 $\chi^2$ test at 95% confidence indicated a goodness of fit for both origin and cultivar (Table 7).

## Discussion

### Evaluation criteria

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 (unpublished data). 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,

**Table 6.** 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$^{-1}$) | | Total fruit harvested (no.·tree$^{-1}$) | | Pre-harvest dropped fruit weight (kg·tree$^{-1}$) | | Pre-harvest dropped fruit (no.·tree$^{-1}$) | | Percentage of total fruit dropped | | Cumulative fruit count (no.·tree$^{-1}$) | | Cumulative fruit weight (2016–2018) (kg·tree$^{-1}$) | | Crop load (no. fruit per cm$^2$ TCSA) | | Bienniality index (2016–2018)[a] | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ashmead's Kernel | 6.0 | e–i | 39 | b–h | 2.1 | f–i | 12 | fg | 3.9 | b | 27 | bc | 69 | abc | 63.3 | d–g | 9.9 | e–i | 2.9 | d–i | 0.25 | d |
| Binet Rouge | 1.7 | hij | 28 | d–h | 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 | c–g | 27 | d–h | 6.4 | c–f | 25 | fg | 0.3 | de | 2 | d | 12 | gh | 60.1 | efg | 17.7 | abc | 1.3 | ghi | 0.42 | bcd |
| Breakwell | 3.2 | f–j | 26 | d–h | 2.9 | f–i | 21 | fg | 0.4 | de | 4 | d | 27 | e–h | 57.3 | fg | 7.4 | g–j | 1.6 | f–i | 0.31 | cd |
| Brown Snout | 2.1 | g–j | 26 | d–h | 1.1 | hi | 13 | fg | 1.0 | de | 13 | cd | 53 | c–e | 54.6 | fg | 4.5 | j | 3.5 | c–i | 0.42 | bcd |
| Brown's Apple | 4.4 | f–j | 32 | c–h | 3.8 | f–i | 26 | fg | 0.6 | de | 6 | d | 15 | gh | 64.8 | d–g | 8.0 | f–j | 2.6 | d–i | 0.37 | bcd |
| Bulmer's 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 | a–e | 13.7 | a | 53 | abc | 0.6 | de | 3 | d | 6 | h | 86.2 | a–f | 20.2 | a | 2.9 | d–i | 0.32 | cd |
| Cline Russet | 3.6 | f–j | 28 | d–h | 3.3 | f–i | 25 | fg | 0.3 | de | 3 | d | 21 | fgh | 53.5 | fg | 7.2 | hij | 3.7 | c–i | 0.33 | cd |
| Cox Orange Pippin | 10.2 | a–e | 70 | ab | 9.7 | a–d | 66 | ab | 0.5 | de | 4 | d | 6 | h | 98.3 | a–e | 14.7 | b–e | 7.2 | abc | 0.46 | bcd |
| Crimson Crisp® | 9.5 | a–e | 61 | a–d | 9.1 | b–e | 58 | abc | 0.3 | de | 3 | d | 5 | h | 79.3 | a–f | 12.7 | c–g | 9.4 | a | 0.56 | a-d |
| Dabinett | 10.2 | a–e | 62 | a–d | 9.7 | a–d | 57 | abc | 0.5 | de | 4 | d | 7 | h | 90.0 | a–f | 14.8 | b–e | 6.2 | a–d | 0.35 | cd |
| Enterprise | 12.9 | ab | 56 | a–e | 12.4 | ab | 53 | abc | 0.5 | de | 2 | d | 5 | h | 78.5 | a–f | 18.0 | ab | 4.6 | b–h | 0.44 | bcd |
| Esopus Spitzenberg | 5.9 | e–i | 38 | b–h | 5.0 | e–h | 29 | fgc | 0.9 | de | 8 | d | 21 | fgh | 57.8 | fg | 8.7 | f–j | 3.7 | c–i | 0.33 | cd |
| Frequin Rouge | 3.6 | f–j | 53 | a–f | 1.1 | hi | 16 | fg | 2.5 | c | 37 | b | 74 | ab | 85.1 | a–f | 6.4 | ij | 5.2 | b–f | 0.70 | abc |
| Golden Russet | 7.0 | c–f | 42 | a–h | 6.4 | c–f | 37 | fbc | 0.6 | de | 5 | d | 13 | gh | 80.8 | a–f | 12.5 | d–h | 3.5 | c–i | 0.25 | d |
| GoldRush | 6.4 | c–h | 40 | a–h | 6.1 | d–g | 38 | fbc | 0.3 | de | 2 | d | 8 | h | 111.0 | ab | 16.9 | a–d | 5.6 | a–e | 0.35 | cd |
| Grimes Golden | 9.9 | a–e | 71 | ab | 1.3 | hi | 10 | fg | 8.6 | a | 61 | a | 88 | a | 114.4 | a | 16.1 | a–d | 8.1 | abc | 0.26 | d |
| Kingston Black | 1.2 | ij | 12 | gh | 0.8 | hi | 8 | fg | 0.4 | de | 4 | d | 35 | e–g | 38.8 | g | 3.8 | j | 1.3 | ghi | 0.53 | a–d |
| Medaille d'Or | 0.7 | j | 7 | h | 0.6 | hi | 6 | g | 0.0 | e | 1 | d | 11 | gh | 71.3 | c–g | 6.7 | ij | 0.8 | hi | 0.92 | a |
| Michelin | 2.7 | f–j | 31 | c–h | 1.5 | hi | 18 | fg | 1.2 | cde | 14 | cd | 45 | c–f | 99.7 | a–d | 7.6 | f–j | 2.5 | d–i | 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 | g–j | 30 | c-h | 1.8 | ghi | 24 | fg | 0.4 | de | 6 | d | 23 | fgh | 105.3 | abc | 7.0 | ij | 1.6 | f–i | 0.49 | bcd |
| Stoke Red | 1.7 | hij | 25 | abc | 1.6 | hi | 23 | fg | 0.1 | e | 2 | d | 21 | fgh | 75.5 | b–g | 5.8 | ij | 2.1 | e–i | 0.61 | a–d |
| Sweet Alford | 11.1 | abc | 67 | d–h | 9.6 | a–d | 58 | abc | 1.5 | cd | 9 | d | 16 | gh | 97.8 | a–e | 16.0 | a–d | 5.7 | a–e | 0.47 | bcd |
| Tolman Sweet | 6.3 | d–h | 45 | a–g | 1.8 | ghi | 12 | fg | 4.5 | b | 33 | b | 75 | ab | 69.2 | c–g | 9.7 | e–i | 4.4 | b–h | 0.33 | cd |
| Tydeman Late | 11.0 | a–d | 77 | a | 10.6 | abc | 73 | a | 0.4 | de | 4 | d | 6 | h | 92.9 | a–f | 13.1 | b–f | 4.8 | b–g | 0.76 | ab |
| Yarlington Mill | 2.6 | f–j | 22 | e–h | 1.3 | hi | 11 | fg | 1.3 | cde | 11 | cd | 56 | bcd | 66.2 | d–g | 8.4 | f–j | 1.7 | f–i | 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 | |

**Note:** Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means. Colour scale is used to indicate value as a visual aid for quick reference. Red is used for the lowest values, which scales up to blue for the highest values. TCSA, trunk cross-sectional area.

[a]Alternate bearing index ($i$) = |(year 1 yield − year 2 yield)|/(year 1 yield + year 2 yield).

Crimson Crisp®, Fréquin Rouge, GoldRush, Kingston Black, and Medaille d'Or (Table 2). 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 (Rothwell 2012; Copas 2013; Jolicoeur 2013; Pôle Fruitier de Bretagne 2013; Shelton 2015; Simmens 2015; Ashridge Trees Ltd. 2020; Grandpa's Orchard 2020) (Table 2).

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 frost-free date has been reported to occur between 3 May (OMAFRA 2020) and 15 May (Brown and 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 3 May. 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 suggested by historical data 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 suggested by historical data include Bramley's Seedling, Brown's Apple, Grimes Golden, Porter's Perfection, and Yarlington Mill (Bultitude 1983; Khanizadeh and Cousineau 1998; Hanson 2005; NSW Department of Primary Industries 2008; Burford 2013; Copas 2013; Simmens 2015; Miles et al. 2017; Ashridge Trees Ltd. 2020) (Tables 1 and 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 cider making. These cultivars include Michelin, Grimes Golden, Ashmead's Kernel, Breakwell, Brown Snout, Esopus Spitzenberg, Fréquin Rouge, Kingston Black, Muscadet de Dieppe, Porter's Perfection, Tolman Sweet, Sweet Alford, and Yarlington

**Table 7.** 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[a] | 9 | 54 | 129 |
| | 51[b] | 7 | 42 | 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 | |

[a]Number of observations classified onto origin.
[b]Percent classified into origin.

Mill. Two cultivars, Brown's Apple and Tydeman Late, produced fruit that rotted and cracked while on the tree, making sorting necessary at harvest. As demonstrated by the low yields in 2016 and the harvestable yields for all cultivars in 2017, the most precocious cultivars were those with high yields in 2017 like Bramley's Seedling and GoldRush (Table 5). While a bienniality index is best calculated in a mature orchard, here it was calculated from the current data 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 two 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 Bulmer's 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 2 years: Bulmer's Norman, Medaille d'Or, Stoke Red, Fréquin Rouge, and Tydeman Late. Each of these cultivars has historically exhibited biennial bearing. Cultivars that produced lower total yields in the first 3 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; The Ontario Department of Agriculture 1914; Khanizadeh and Cousineau 1998; Institut Français des Productions Cidricoles 2009; Moulton et al. 2010; Rothwell 2012; Jolicoeur 2013; Pôle Fruitier de Bretagne 2013; Heekin 2014; Simmens 2015; Cummins 2020; Grandpa's Orchard 2020) (Tables 5 and 6).

Once harvested, cider apples must be processed to procure juice. It is difficult to extract juice from several cultivars, and many others 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 low efficiency could be overcome by grinding the pulp more finely, letting the apples "sweat" in storage, or mixing the apples with other cultivars to aid processing. 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 Muscadet de Dieppe, Fréquin Rouge, and Michelin, but are consistent with reported low juice yields for Binet Rouge, Brown Snout, and Yarlington Mill (Mohr 1988; Rothwell 2012; Copas 2013; Jolicoeur 2013; Pôle Fruitier de Bretagne 2013) (Tables 1 and 2). When grown in Ontario, many cultivars were harvested in a different part of the season than suggested by historical data from other parts of the world. These include Ashmead's Kernel, Binet Rouge, Brown's Apple, Dabinett, Kingston Black, Michelin, Stoke Red, and Sweet Alford, which were harvested earlier than historical reports. In contrast, the only cultivar that was harvested later than historical reports was Calville Blanc d'Hiver (Bultitude 1983; Khanizadeh and Cousineau 1998; Morgan and Richards 2003; Hanson 2005; Merwin et al. 2008; NSW Department of Primary Industries 2008; Institut Français des Productions Cidricoles 2009; Rothwell 2012; Copas 2013; Jolicoeur 2013; Pôle Fruitier de Bretagne 2013; Shelton 2015; Simmens 2015; Ashridge Trees Ltd. 2020; Grandpa's Orchard 2020; Summerland Varieties Corp. 2020) (Tables 1 and 2).

**Table 8.** 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 | Harvest difficulties[a] | Biennial bearing potential | Low juice yield | Overall recommendation |
|---|---|---|---|---|---|---|
| | | | Overall recommended | | | |
| Binet Rouge | Lower | Yes | No | Lower | Yes | Yes |
| Bramley's Seedling | Lower | No | No | Lower | No | Yes |
| Breakwell | Lower | No | Yes | Lower | No | Yes |
| Bulmer's 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 |
| Golden Russet | Lower | Yes | No | Lower | No | Yes |
| GoldRush | Lower | Yes | No | Lower | No | Yes |
| Medaille d'Or | Lower | No | No | Higher | No | Yes |
| Porter's Perfection | Lower | No | Yes | Lower | No | Yes |
| Stoke Red | Lower | No | No | Higher | No | Yes |
| | | | Overall not recommended | | | |
| Ashmead's Kernel | Lower | Yes | Yes | Lower | Yes | No |
| Brown Snout | Lower | No | Yes | Lower | Yes | No |
| Brown's Apple | Lower | No | Yes | Lower | No | No |
| Frequin Rouge | Lower | No | Yes | Higher | Yes | No |
| Grimes Golden | Lower | No | Yes | Lower | No | No |
| Kingston Black | Lower | No | Yes | Lower | Yes | No |
| Michelin | Higher | No | Yes | Lower | Yes | No |
| Muscadet De Dieppe | Lower | No | Yes | Lower | Yes | No |
| 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 |

[a]For most cultivars harvest difficulties consisted of pre-harvest fruit drop and the need for multiple picks, but for Brown's Apple and Tydeman Late the major problem was fruit rotting on trees.

**Screening results**

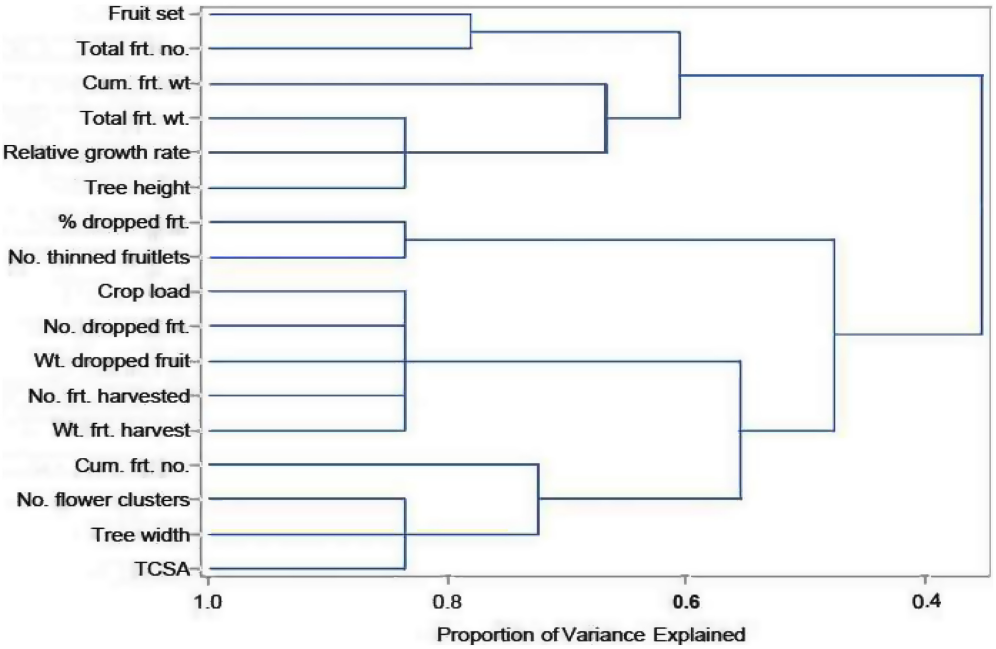
The cultivars were initially screened by removing those that were previously identified as having high tree mortality, early bloom, harvest issues, high biennial bearing potential, or processing issues. Once all of the criteria were applied, few cultivars emerged as suitable candidates. These were Bramley's 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 (Plotkowski and Cline 2021). Many producers who wish to grow cider apples may be willing to put in the effort to grow the cultivars that were screened out, and future horticultural research may overcome the difficulties in growing them, therefore we can expand the overall recommendation list to include cultivars that may be challenging to grow from a horticultural perspective.

It is recommended that the cultivars that 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, Bulmer's 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 8). Other cultivars in this trial may be successful grown under different conditions, though the data here suggest that their cultivation in Ontario would be difficult. Other potential issues that were beyond the scope of this study include the effects of pests and diseases such as fireblight.

**Associations among variables**

Cluster analysis showed that the horticultural attribute dataset contained several associations (Fig. 3),

**Fig. 3.** The association among horticultural attributes measured in 28 apple cultivars grown on M.9 rootstock in 2018 for cider production [fruit set is the percentage of floral clusters that produced fruit in spring 2018; Total fruit no. per tree is the sum of the number of fruit harvested and fruit dropped in fall 2018; Cum. frt. wt. is the sum of the weight of all fruit produced by the tree since planting; Total frt. wt. is the sum of the weight of fruit harvested and fruit dropped in fall 2018; Relative growth rate is the difference in trunk cross-sectional area (TCSA) between fall 2017 and fall 2018; Tree height is the height of the tree measured in fall 2018; % frt. drop is the percentage of the total fruit produced by the tree that fell before harvest in fall 2018; Thinned fruitlets is the number of set fruitlets removed from the tree in spring 2018; Crop load is the number of fruit produced in fall 2018 divided by the TCSA measured in fall 2018; No. dropped fruit. is the number of fruit that fell off the tree before harvest in fall 2018; Wt. dropped frt. is the weight of fruit that fell off the tree before harvest in fall 2018; No. frt. harvested is the number of fruit harvested from the tree in fall 2018; No. frt. harvested is the weight of fruit harvested from the tree in fall 2018; Cum frt. no. is the sum of the number of all fruit produced by the tree since planting; No. flower clusters is the number of floral clusters counted on the tree in spring 2018; Tree width is the average horizontal span of the tree within and between rows in fall 2018; TCSA is the trunk cross-sectional area of the tree calculated from measuring the circumference of the tree at 30 cm above the ground in fall 2018] (University of Guelph, Simcoe, Ontario, 2018).



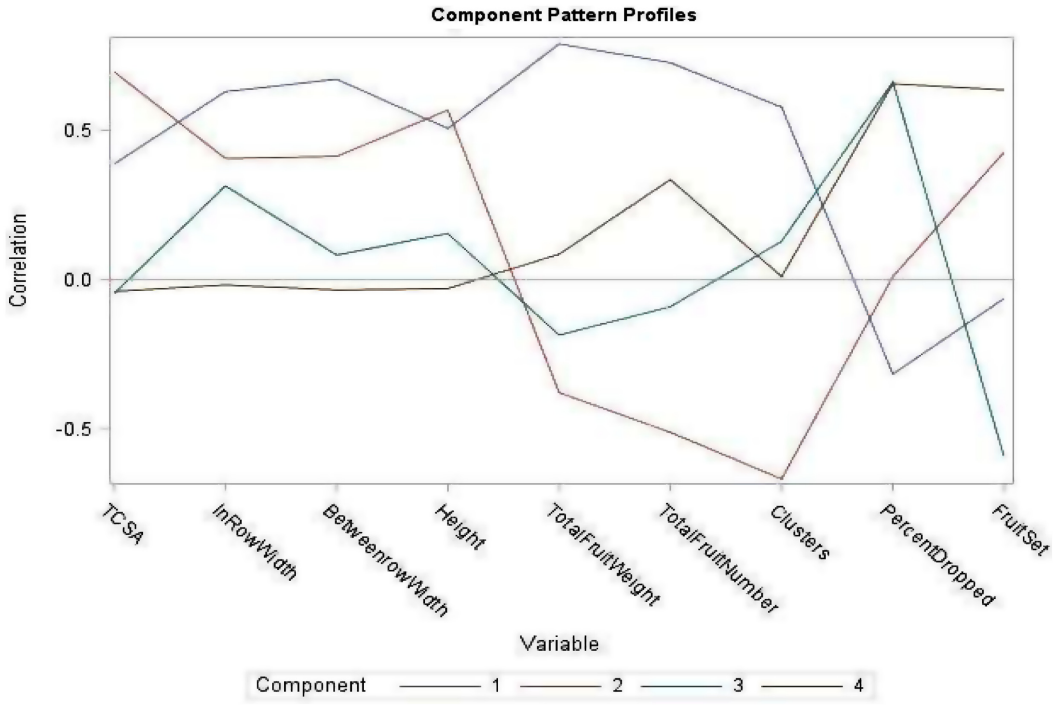

including that of tree height with fruit weight, as well as the number of floral clusters with tree width and TCSA.

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 four dimensions (Fig. 4). The four components, chosen based on the Jolliffe Test, were: component 1: in-row width, between-row width, total fruit weight, total fruit number, and floral clusters; component 2: TCSA, height; component 3: pre-harvest drop percentage, and, component 4: pre-harvest drop percentage and fruit set.

Component pattern charts of the principal components indicate natural groups of associated variables (Fig. 5) using the dimensions detailed in Fig. 4. 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 7). 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 with British and French cultivars. A discriminant analysis of cultivar based on horticultural data indicated that most cultivars are not easily distinguishable when simply examining horticultural attributes, with 51% of data points being misclassified as a different cultivar. Taking these differences into account when planning on orchard may help facilitate orchard design, especially in mixed-cultivar plantings where it may be best to group cultivars

**Fig. 4.** The correlation between horticultural characteristics and the principal components of the horticultural attribute data set (TCSA is the trunk cross-sectional area of the tree calculated from measuring the circumference of the tree at 30 cm above the ground in fall 2018; InRowWidth is the horizontal span of the tree within a row in fall 2018; BetweenRowWidth is the horizontal span of the tree stretching out into the between-row space in fall 2018; Height is the height of the tree measured in fall 2018; TotalFruitWeight is the sum of the weight of fruit harvested and fruit dropped in fall 2018; TotalFruitNumber is the sum of the number of fruit harvested and fruit dropped in fall 2018; Clusters is the number of floral clusters counted on the tree in spring 2018; PercentDropped is the percentage of the total fruit produced by the tree that fell before harvest in fall 2018; FruitSet is the percentage of floral clusters that produced fruit in spring 2018) (University of Guelph, Simcoe, Ontario, 2018).




with similar horticultural properties that require distinct cultivation and harvesting practices.

**Associations based on place of origin**

The 28 cultivars were selected 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 cultivars 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 percentage of pre-harvest drop (Table 9). These associations may reflect the environments in which the cultivars are traditionally grown as well as their method of collection.

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.

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 (Plotkowski and Cline 2021) 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, Bulmer's 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.

**Fig. 5.** The relationship between horticultural characteristics and the principal components of the horticultural attribute data set (University of Guelph, Simcoe, Ontario, 2018).

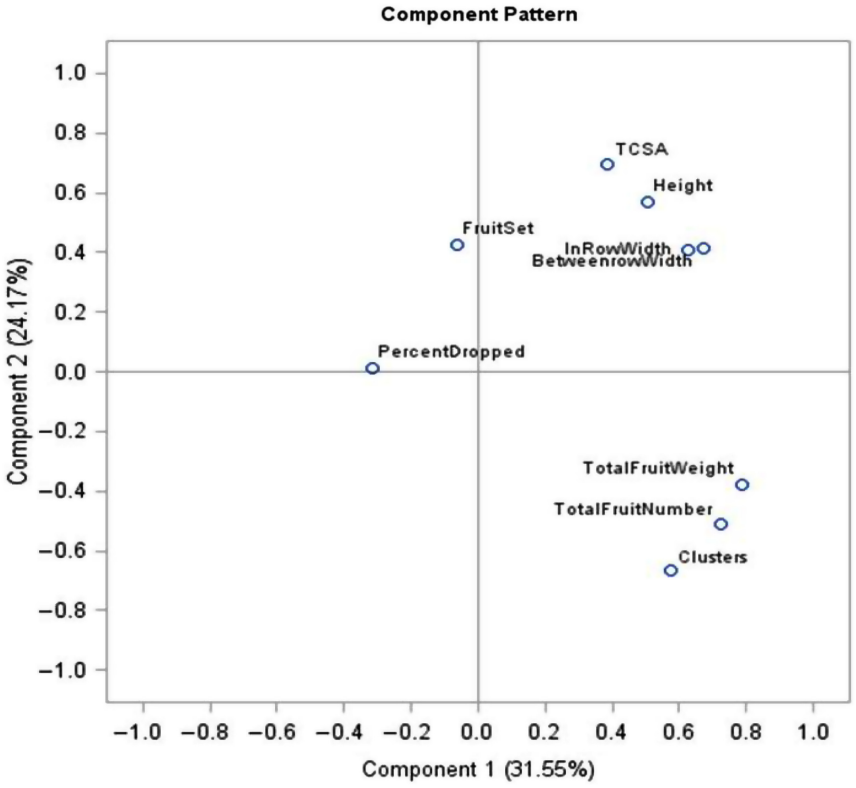



**Table 9.** Variation in horticultural attributes of 28 apple cultivars grown on M.9 rootstock for cider production harvested in 2018 based on cultivar origin (University of Guelph, Simcoe, Ontario, 2018).

| Cultivar origin | Full bloom date | Harvest date | Days to harvest | Juice extraction efficiency (mL juice·g fruit$^{-1}$) | Average selected fruit weight (g) | Pre-harvest drop percentage |
|---|---|---|---|---|---|---|
| France | 19 May | 12b Sept. | 115b | 0.53c | 115b | 38.5a |
| North America | 18 May | 30a Sept. | 134a | 0.64a | 164a | 23.3b |
| United Kingdom | 21 May | 9b Sept. | 110b | 0.60b | 145a | 30.5ab |
| *P* value | | | <0.0001 | <0.0001 | <0.0001 | 0.01 |

**Note:** Values within columns not followed by common letters differ at the 5% level of significance, by Tukey's test of least square means.

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## Author Contributions

DP wrote the original draft of the manuscript. DP carried out the investigations (experiments and data analyses). DP and JC were involved in the initial concept development. Both authors reviewed, edited and approved the final manuscript. DP and JC were involved in developing the methodology. DP and JC secured the funding for this research.

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