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Source: Canadian Journal of Plant Science, 101(6) : 803-817

Published By: Canadian Science Publishing

URL: https://doi.org/10.1139/cjps-2020-0333

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ARTICLE

# Hazelnut floral phenology in southern Ontario[1]

Toktam Taghavi, Alireza Rahemi, Adam Dale, Dragan Galic, and John Kelly

**Abstract:** Hazelnut (*Corylus avellana* L.) is a monoecious, dichogamous plant species that flowers in winter and early spring. In traditional hazelnut growing regions, hazelnut cultivars generally express protandry where the male flowers bloom before the female flowers. Nut set requires that compatible pollen be shed when the stigmas of the main cultivar are receptive. In this study, the floral phenology and date of leaf budbreak of five selections and 19 hazelnut cultivars from Europe and North America were observed over 4 yr in southern Ontario, and results were compared with cumulative growing degree days (GDD). In the continental climate of southern Ontario, most cultivars showed protogyny. Flowering dates varied over the years with pollination occurring in a period of 2–3 wk in early spring. These cultivars were classified into early, mid, and late blooming types. A GDD model was a better tool than average daily temperatures to predict the flowering dates of catkins and female flowers. Averaged over years, most of the cultivars in this study have a female bloom that is likely too early for the pollen shed by most of the other cultivars. This would likely impact yields in a commercial orchard. However, 'Jefferson', 'Gene', and 'Epsilon' have late females that are receptive when other cultivars are shedding pollen.

*Key words:* filbert, cumulative growing degree days, flowering stages, dichogamy, pollinizer.

**Résumé :** Le noisetier commun (*Corylus avellana* L.) est une espèce monoïque dichogame qui fleurit en hiver et au début du printemps. Dans les régions où on en fait traditionnellement la culture, les variétés expriment habituellement la protandrie, les anthères (organe mâle) fleurissant avant le pistil (organe femelle). Pour qu'il y ait nouaison, le pollen compatible doit être libéré quand les pistils du cultivar principal sont prêts à l'accueillir. Les auteurs ont étudié la phénologie florale et la date du débourrage de cinq obtentions et de 19 cultivars de noisetiers européens et nord-américains dans le sud de l'Ontario pendant quatre ans. Ils ont ensuite comparé leurs résultats au nombre cumulatif de degrés-jours de croissance. Dans le climat continental caractéristique au sud ontarien, la plupart des cultivars sont protérogynes. La date de la floraison varie d'année en année, la pollinisation survenant au cours d'une période de deux à trois semaines, tôt au printemps. Les auteurs ont classé les cultivars en trois groupes : à floraison hâtive, mi-hâtive et tardive. La modélisation du nombre de degrés-jours de croissance s'avère plus utile que la moyenne des températures quotidiennes pour prédire le moment où fleuriront les chatons et les fleurs femelles. Selon les moyennes annuelles, les pistils de la majorité des cultivars examinés fleuriront sans doute trop tôt pour être fécondés par le pollen de nombreux autres cultivars, ce qui réduira le rendement du verger commercial. Néanmoins, les variétés Jefferson, Gene et Epsilon produisent des fleurs femelles suffisamment tardives pour être fertilisées par le pollen d'autres cultivars. [Traduit par la Rédaction]

*Mots-clés :* noisette, nombre cumulatif de degrés-jours, stades de la floraison, dichogamie, pollinisateur.

## Introduction

Hazelnuts are ranked fifth globally in overall tree nut production (FAO Statistics; FAO 2019), and the world demand is increasing steadily due to health benefits and significant demand from food processors and chocolate-making companies (Nera et al. 2020). Almost

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Received 19 December 2020. Accepted 27 August 2021.

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*T. Taghavi served as an Associate Editor at the time of manuscript review and acceptance; peer review and editorial decisions regarding this manuscript were handled by K. Congreves.

[1] This article is part of a Special Issue entitled "Advancements in Canadian horticulture, in celebration of the 100th year of horticulture research at the University of Saskatchewan".

Can. J. Plant Sci. **101:** 803–817 (2021) dx.doi.org/10.1139/cjps-2020-0333

all of the hazelnut production in North America is in the Willamette Valley of Oregon; however, the newly established food processors in Ontario, Canada, have increased the demand for hazelnut encouraging growers to plant hazelnuts in the continental climate of this area.

Hazelnuts are monoecious, wind-pollinated, and self-incompatible. Therefore, nut production is dependent on successful cross-pollination, which involves the pollination of female flowers with genetically compatible pollen. The self-incompatibility of hazelnut is sporophytic, with 33 known S-alleles found at a single locus. Both alleles are expressed in the stigma but dominance and codominance can occur in the pollen (Thompson 1979; Mehlenbacher 1997; Olsen et al. 2000; Mehlenbacher 2014).

After flower bud initiation during the summer, hazelnuts enter dormancy in the fall in response to shortening day length. Vegetative buds, female inflorescences, and catkins require chilling to overcome dormancy. Male and female flowers have different chilling requirements to break dormancy leading to the dichogamy of bloom in hazelnuts. The chilling requirements of catkins (100–860 h) are generally lower than those of female inflorescences (290–1550 h; Mehlenbacher 1991*a*) or vegetative buds. After the chilling requirement has been met, bud development can be modeled and predicted using growing degree days.

Traditionally, hazelnuts are grown in areas close to large bodies of water, including Oregon, where winter temperatures are moderate (Thompson 1979; Mehlenbacher 1991*b*). In this climate, hazelnuts are protandrous (Thompson et al. 1996), while in climates with long, cold winters, such as southern Poland and inland Slovenia, they are protogynous (female flowers mature before catkins) and rarely homogamous (female and male flowers bloom at the same time) (Solar and Stampar 2009; Crepinšek et al. 2012; Piskornik et al. 2001). In moderate climates, hazelnut flower buds open over 2–3 mo from early December through March depending on the genotype, location, and year (Germain 1994; Thompson et al. 1996; Olsen et al. 2000; Piskornik et al. 2001; Solar and Stampar 2009; Crepinšek et al. 2012). In the continental climates of southern Poland and Ontario, Canada, with frigid winters followed by short springs, hazelnuts flower in early spring over 2–3 wk in response to warming temperatures (Solar and Stampar 2009).

The pollen grain of the hazelnut is very small (25–40 μm), and pollination is only anemophilous (wind-pollinated). The female flower is receptive to pollen when the red color of the stigma is visible at the tip of the bud (red dot stage; Olsen 2013). The stigma stays receptive to pollen over 2–3 mo until they receive pollen (Thompson 1979). Shortly after the compatible pollen lands on the stigma, the pollen grains germinate, and the stigma color changes to brown and loses receptivity.

Mehlenbacher (1991*a*) determined chilling temperatures of 0–7 °C were needed to fulfill the chilling requirements of hazelnut buds and to break the true dormancy, while Tiyayon (2008) indicated that a wider temperature range (5–15 °C) breaks the dormancy. Turcu et al. (2001) showed that endodormancy concluded following a period of 3–6 d when daytime temperatures have been below zero in November and December and plants have begun accumulating heat units. In Ontario, the chilling requirements are fulfilled by the end of December (Colombo 1998). After that, post-chill warmth is required for hazelnut flowering, and heat accumulation is measured starting when the chilling requirement had been met (Galan et al. 2005).

Catkins and female flowers have different chilling requirements and respond to temperature differently. Therefore, calendar dates of anthesis are very much temperature-dependent and vary greatly from year to year and among locations; however, heat accumulation units (growing degree days, GDD) are frequently used to predict flowering time and are useful for orchard management decisions. Because temperatures can vary significantly from year to year, the use of GDD has vastly improved the prediction of flowering phenological events compared with other approaches such as time of the year or the number of days (e.g., Gilmore and Rogers 1958; Cross and Zuber 1972; Russelle et al. 1984).

The heat requirement is generally higher for catkins than for female flowers (Barbeau 1972; Kavardzhikov 1980; Mehlenbacher 1991*b*; Turcu et al. 2001; Baldwin 2015). It is calculated as cumulative growing degree days (CGDD) to flowering using an estimated base temperature and a starting date (Crepinšek et al. 2012).

Hazelnuts have a complicated floral biology. There is a lack of synchrony between the anthesis of male and female flowers (dichogamy), incompatibility among pollinizers and main cultivars (Olsen et al. 2000), and a strong interaction between the genotype and the local thermal conditions, which all affect fruit set and yield (Mehlenbacher 1991*b*; Santos and Silva 1994; Turcu et al. 2001). Therefore, phenological data have to be obtained to select an appropriate combinations of cultivars and pollinizers for local conditions (Bastias and Grau 2005).

The objective of this study was to evaluate the phenology of flowers and date of budbreak of 24 hazelnut cultivars and selections over 4 yr in relation to CGDD in the continental climate of southern Ontario.

## Materials and Methods

### Location

A research plot of hazelnuts was planted at the University of Guelph, Simcoe Research Station, Simcoe, Ontario, Canada (latitude 42° 83′ N, longitude 80° 30′ W, elevation 200 m). The land is gently sloped (1%–4%), and the soil type is Fox sand with a low organic matter content (1.2%). Based on the most recent hardiness zone map, Simcoe is located in hardiness zone 6b (1981–2010, NRC 2021). The climate is a humid continental climate

(Fig. 1A–C) with an annual average temperature of 7.8 °C and an absolute minimum of −33.9 °C over 30 yr (1971–2000; ECCC 2018).

### Plant material

Twenty-four hazelnut cultivars and selections were planted between 2008–2010. The origins of the cultivars were Europe ('Barcelona', 'Hall's Giant', and 'Tonda di Giffoni), Oregon ('Lewis', 'Clark', 'Santiam', 'Yamhill', 'Jefferson', 'Epsilon', 'Sacajawea', 'Zeta', 'Delta', 'Gamma', 'Theta', 'Butler', and 'Jemtegaard #5'), New York ('Gene' and 'Slate'), Washington ('Gasaway'), Michigan ('Farris G17') and Ontario, Canada ('Norfolk', 'Chelsea', 'C-409', and 'Alex'). Most of these cultivars are pure *Corylus avellana* L., but the New York and Michigan selections ('Gene', 'Slate', and 'Farris G17') are *C. americana* × *C. avellana* hybrids, and 'Alex' is a hybrid with some *Corylus Colurna* L. in its pedigree. The Ontario selections ('Norfolk', 'Chelsea', and 'C-409') are clonally propagated and arose from open-pollination of interspecific hybrids at Grimo Nut Nursery (Niagara-on-the-Lake, ON, Canada). The trees for the trial were purchased from three nurseries in Canada (Table 1). They were planted in a randomized complete block design with four replicates and three plants per plot with 5 m between rows and 3 m space within the rows. Trees were trained to 2–6 stems. Catkin cold injury was rated for the years 2011–2016, except 2015. A branch with at least 100 catkins on the east side of the middle tree of each plot was selected and labeled. At the end of the pollination season and before catkin drop, the total number of catkins and the number of catkins injured by cold (as indicated by brown color or failure of at least 50% of the catkin to expand) were rated, and catkin survivability calculated. For further details about the research plot, catkin survivability, and yield, refer to Taghavi et al. (2020).

### Assessment of flower phenological stages

During 2011, 2012, 2013, and 2016 catkins and female flowers were observed 2–3 times a week from early February until the end of April. Germain and Sarraquigne (2004) illustrated the phenological stages of male and female inflorescences. They developed ratings that allow comparisons to be made across cultivars and locations. Phenological data of flowers in this experiment were recorded based on the rating system of Germain and Sarraquigne (2004) and Solar and Stampar (2011). The 4 yr average was then calculated (Tables 2 and 3). Finally, individual year average and the 4 yr averages were graphed to visualize the differences among the cultivars and year-to-year variation (Fig. 2A–E).

The catkins' phenological stages were recorded from when the catkin bracts were closely interlinked (Bm) until the catkins fell on the ground (Hm). Based on Germain and Sarraquigne (2004), the catkin phenological stages are: Bm (catkin on average 4 cm long depending on the cultivar, catkin bracts are closely interlinked); Dm (rapid elongation of catkins and separation of bracts); Em (anthers well-differentiated in catkin and yellow coloration appears); Fm1 (anthers yellow and starting to shed pollen, 5% of catkins elongated); Fm2 (peak of pollen shed-full bloom anther dehiscence pollen, 50% of catkins are elongated); Fm3 (end of pollen shed-browning of anthers and pollen very rare); Gm (drying of catkins and not much pollen); and Hm (catkins falling on the ground). The times when the catkins were shedding pollen (stages Em1 to Fm3) are shown in Table 2. Capik and Molnar (2014) used calendar days to classify phenological stages; however, we assigned the cultivars to groups based on CGDD. The CGDD range for cultivars that shed pollen (stage Em) early was 101–122 CGDD, mid-season was 123–144 CGDD, and late was 145–167 CGDD.

Female flower development was recorded from when the red dots first appeared (Ef) until the last flowers were open (Ff3). Germain and Sarraquigne (2004) classified female flowers into the following stages: Af (vegetative budbreak); Ef (red dot of stigmas appears); Ff1 (stigma become receptivity, 5% of flowers have elongated styles); Ff2 (peak stigma receptivity –50% of flowers are open); and Ff3 (end of stigma receptivity, last flowers are receptive). To calculate the effective pollination period (EPP), only phenological stages Ef to Ff3 when stigmas were receptive are shown in Table 2. Based on the CGDD needed for beginning of anthesis, the time of stigma receptivity was classified into three groups, early (42–59 CGDD), mid (69–91 CGDD), and late (92–117 CGDD).

### GDD

The first of January was considered the starting date for accumulation of heat units by hazelnuts in this study because deciduous trees fulfill their chilling requirement by the end of December in Ontario (Colombo 1998). Weather data were collected from a weather station located onsite at the Simcoe Research Station and 700 m away from the research hazelnut plots.

When the buds entered each phenological stage, the calendar dates were recorded and converted to the Julian day based on Capik and Molnar (2014). The numbers were then averaged across each cultivar's replicates to represent the average date each entered that stage. The process was repeated for each year of the study.

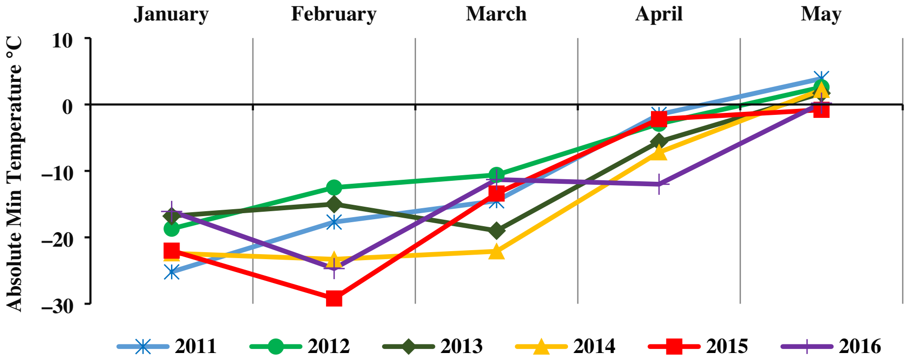
CGDD were calculated according to the following formula by taking the average daily maximum and minimum temperatures above the base temperature of 0 °C

$$\mathrm{CGDD} = \sum_{i=1}^{n} (Ta - Tb)$$

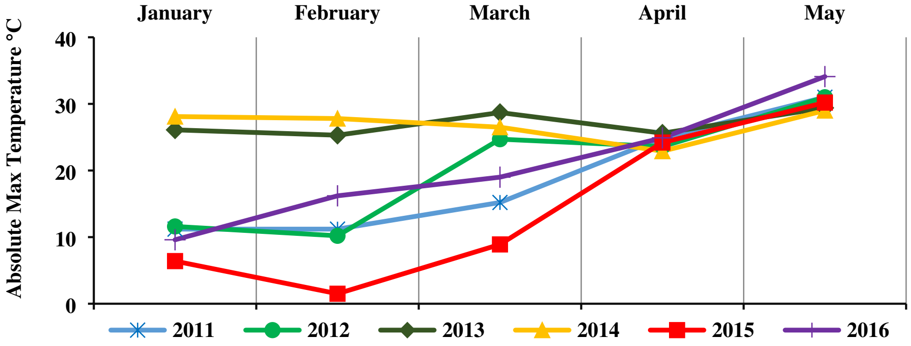
where $n$ is the number of days from the first of January to the date of occurrence of each phenological stage, $Ta$ is the average daily temperature, and $Tb$ is the base temperature (0 °C).

**Fig. 1.** Temperature data collected from the weather station 700 m away from the research plot at the university of Guelph, Simcoe Research Station, Simcoe, Ontario, Canada. (A) Monthly absolute minimum temperatures, (B) monthly absolute maximum temperatures, (C) average monthly temperatures during January, February, March, April, and May of successive years (2011–2016), and (D) cumulative growing degree days (GDD), base 0 °C for 2011–2013, and 2016 from January to May (GDD are used to estimate the growth and development of plants during the growing season).

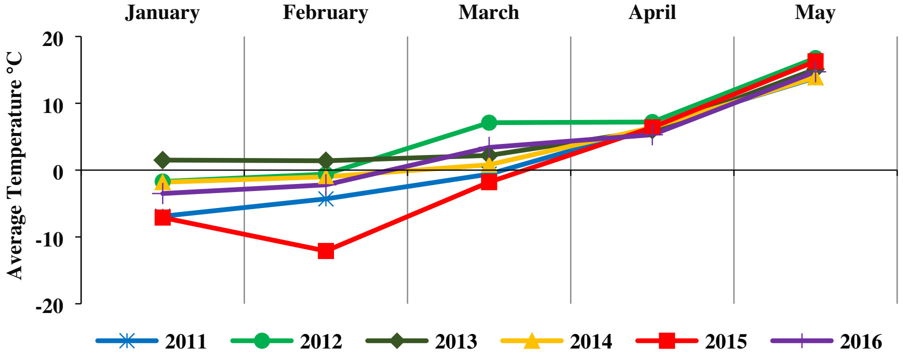
(A) Absolute minimum temperature



(B) Absolute maximum temperature



(C) Average temperature



(D) Cumulative Growing Degree Days - Monthly

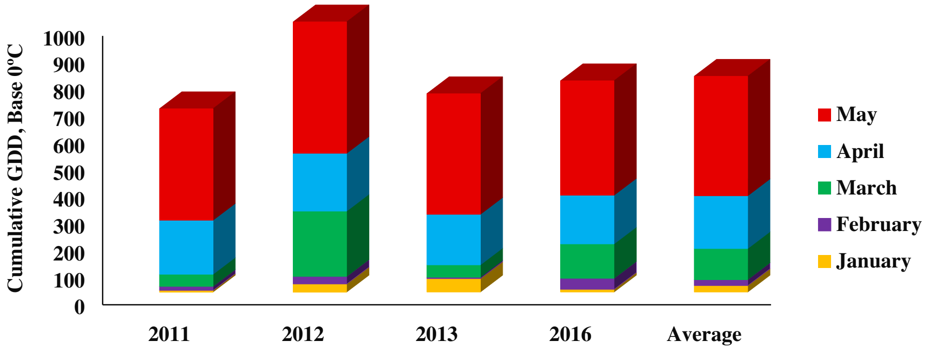


**Table 1.** Hazelnut cultivars planted, their location and (or) country of origin, producing nursery, year planted, and their self-incompatibility alleles.

| Cultivar/Genotype | Location/ Country of Origin Nursery | Year planted | S-alleles* |
|---|---|---|---|
| Barcelona | Spain[a] | 2008 and 2009 | 1 2 |
| Tonda di Giffoni | Italy[b] | 2009 | 2 23 |
| Hall's Giant | Germany/France[b] | 2009 | 5 15 |
| Butler | Oregon, USA[a] | 2008 and 2009 | 2 3 |
| Clark | Oregon, USA[a] | 2008 and 2009 | 3 8 |
| Delta | Oregon, USA[b] | 2009 | 1 15 |
| Epsilon | Oregon, USA[c] | 2010 | 1 4 |
| Jefferson | Oregon, USA[b] | 2009 | 1 3 |
| Jemtegaard #5 | Oregon, USA[a] | 2008 and 2009 | 2 3 |
| Lewis | Oregon, USA[a] | 2008 and 2009 | 3 8 |
| Sacajawea | Oregon, USA[b] | 2009 | 1 22 |
| Santiam | Oregon, USA[b] | 2009 | 3 15 |
| Theta | Oregon, USA[c] | 2010 | 5 15 |
| Yamhill | Oregon, USA[b] | 2009 | 8 26 |
| Zeta | Oregon, USA[c] | 2010 | 1 1 |
| Gamma | Oregon, USA[b] | 2009 | 2 10 |
| Gasaway | Washington, USA[b] | 2008 | 3 26 |
| Farris G17 | Michigan, USA[b] | 2010 | Unknown |
| Gene (Geneva, NY 398)** | New York, USA[b] | 2008 and 2009 | 15 23 |
| Slate (NY 616) | New York, USA[b] | 2009 | 1 23 |
| Norfolk (C-16) | ON, Canada[c] | 2009 | 12 25 |
| Chelsea (C-28) | ON, Canada[c] | 2009 | 1 20 |
| C-409 | ON, Canada[c] | 2009 | 12 25 |
| Alex (Grimo 186M**) | ON, Canada[b] | 2008 and 2009 | Unknown |

**Note:** *If the stigma and the pollen express the same allele, the cross is incompatible. Alleles expressed by the pollen are underlined. The alleles have not yet been identified for 'Farris G17' and 'Alex'. **Former names are in the bracket.

[a] Gamps Nut Nursery, Langley, British Columbia (BC), Canada.

[b] Grimo Nut Nursery, Niagara-on-the-Lake, Ontario (ON), Canada.

[c] Earthgen International Ltd., Wainfleet, Ontario, Canada. ** Former names are in the bracket.

If the mean daily temperature was lower than 0 °C, then GDD = 0. The daily GDD was averaged over the 4 yr of the study.

## Results

### Weather

During the 6 yr (2011–2016) of this trial, the coldest day was −29.2 °C on 16 Feb 2015, and the hottest day was 36.3 °C on 21 July 2011 (Figures 1A and 1B). The coldest temperature killed sensitive hazelnut cultivars. Anecdotal evidence shows that most European and Oregon cultivars are sensitive to temperatures below −28 °C. Temperatures below −28 °C happened only once in Simcoe over the previous 25 yr (16 Feb 2015) and just twice during the last 50 yr (1976 and 2015). During 2014 and 2015, minimum temperatures remained low from January till mid-March (Fig. 1A) and led to yield reduction in both years. Therefore, phenological data were not recorded in 2014 and 2015 because very cold temperatures damaged flowers and reduced nut yield (Taghavi et al. 2020), but were recorded for 4 of the 6 yr of the trial.

In March 2012 (Fig. 1B), the very warm temperatures resulted in early catkin elongation, which made them prone to frost damage in April (data not shown). Consequently, the catkins turned brown, or at least 50% of the catkins failed to expand; however, this did not affect their nut yield (Taghavi et al. 2020). The very low temperatures during Feb. 2015 and higher than normal daily temperatures in Mar. 2012 are reflected in the average daily temperatures (Figure 1C). The average daily temperatures of other years show a similar pattern with a gradual increase from February to April.

Over the 4 yr of data collection, CGDD in January-–March was much more variable than in April–May (Fig. 1D). The monthly CGDD was higher in a warm year (2012) than in other years, with the 2012 March CGDD surpassing the April GCDD of the other four years.

### Assessment of flower bud phenological stages

The phenological stages of male (blue bars), female (pink bars), and vegetative buds (green bars) for individual years (2011–2013 and 2016) and the average of 4 yr are shown in Fig. 2 (A–E). Only phenological stages that

**Table 2.** The average of cumulative growing degree days (CGDD) with base 0 °C in 2011–2014 and 2016 and corresponding Julian days, and suggested classification for the male flowering of the hazelnut cultivars at Simcoe Research Station, ON, Canada.

| | Pollen release | | |
|---|---|---|---|
| Cultivar/Genotype | Julian day | CGDD | Classification* |
| Tonda di Giffoni | 76–93 | 101–174 | early |
| Norfolk | 76–93 | 101–174 | early |
| Butler | 77–94 | 109–178 | early |
| C–409 | 78–92 | 113–171 | early |
| Alex | 78–92 | 113–171 | early |
| Gamma | 78–93 | 113–174 | early |
| Gene | 79–95 | 117–181 | early |
| Jefferson | 79–93 | 117–174 | early |
| Barcelona | 80–95 | 122–181 | early |
| Clark | 80–96 | 122–183 | early |
| Chelsea | 81–94 | 128–178 | mid |
| Epsilon | 81–95 | 128–181 | mid |
| Hall's Giant | 81–95 | 128–181 | mid |
| Lewis | 81–101 | 128–212 | mid |
| Santiam | 82–94 | 133–178 | mid |
| Slate | 83–94 | 138–178 | mid |
| Farris G17 | 83–95 | 138–181 | mid |
| Yamhill | 83–97 | 138–188 | mid |
| Jemtegaard #5 | 84–101 | 141–212 | mid |
| Delta | 85–98 | 145–194 | late |
| Zeta | 86–106 | 147–244 | late |
| Theta | 91–106 | 167–244 | late |
| Average | 81–96 | 127–188 | — |
| Range | 76–106 | 101–244 | — |

**Note:** Phenological stages for catkins are: anthers well-differentiated in catkins, yellow coloration appears (Em) to end of pollen shed, and browning of anthers and pollen very rare (Fm3). *Classification for the first stage of pollen release is early (101–122), mid (123–144), and late (145–167) unit of CGDD.

include pollen shed and stigma receptivity are shown in Table 2 and Fig. 2 (A–E). The time of flowering for male, female, and vegetative budbreak of each cultivar varied from year to year based upon the temperature profile (Fig. 2A–D); however, the CGDD data showed almost the same pattern in each of the 4 yr. For female flowers, the earliest receptivity was on 11 Feb. 2012 and the latest was on 14 Mar. 2011. Nearly all of the cultivars showed protogyny; only 'Alex' in 2011 had catkins shed pollen before females were receptive (Fig. 2A, 2011). Most of the 'Sacajawea' trees died in this trial and did not produce flowers. Also, 'Gasaway' set very few flowers. Therefore, no data are presented for 'Sacajawea' and 'Gasaway'.

### Male flower development (catkin elongation and pollen shed)

Catkin phenological stages from well-differentiated catkins (Em) to the end of pollen shed (Fm3) are shown in Table 2 and Fig. 2 (A–E, blue bars). Based on the commencement of the first stage (Em), we classified the cultivars as early, mid-season, or late flowering (Table 2). Over the 4 yr, CGDD ranged from 101 to 244 among the cultivars. 'Tonda di Giffoni' and 'Norfolk' were the earliest to reach stage Em (bracts differentiation) (Table 2, Figure 2E). Although 'Tonda di Giffoni' was the earliest male flowering (blue bars in Figure 2, average), the trees struggled to survive in Simcoe's cold winters, and in most years there were not many flowers and fruits formed. Other early cultivars were 'Butler', 'C-409', 'Alex', 'Gamma', 'Gene', 'Jefferson', 'Barcelona' and 'Clark'. The Oregon pollinizers 'Delta', 'Zeta' and 'Theta' were late and needed 145 CGDD to reach stage Em (differentiate catkin bracts). The rest of the cultivars ('Chelsea', 'Epsilon', 'Hall's Giant', 'Lewis', 'Santiam', 'Slate', 'Farris G17', 'Yamhill' and 'Jemtegaard #5') shed pollen in mid-season when CGDD had been accumulated and required at least 128 CGDD for catkin development.

### Female flower development

Female phenological stages from red dot appears on stigmas (Ef) to last flowers are open (Ff3) are shown in

**Table 3.** The average of cumulative growing degree days (CGDD) with base 0 °C in 2011–2014 and 2016 and corresponding Julian days, and suggested classification for female flowering of the hazelnut cultivars at Simcoe Research Station, ON, Canada.

| | Stigma receptivity | | |
|---|---|---|---|
| Cultivar/Genotype | Julian day | CGDD | Classification* |
| Tonda di Giffoni | 57–92 | 42–171 | early |
| Lewis | 57–93 | 42–174 | early |
| Slate | 57–93 | 42–174 | early |
| Barcelona | 58–92 | 43–171 | early |
| Yamhill | 60–95 | 46–181 | early |
| Butler | 63–93 | 49–174 | early |
| Santiam | 63–96 | 49–183 | early |
| Delta | 65–97 | 50–188 | early |
| Jemtegaard #5 | 66–94 | 50–178 | early |
| Hall's Giant | 66–96 | 50–183 | early |
| Norfolk | 67–94 | 55–178 | early |
| Gamma | 68–94 | 60–178 | mid |
| Farris G17 | 68–96 | 60–183 | mid |
| Chelsea | 72–95 | 78–181 | mid |
| C-409 | 73–97 | 82–188 | mid |
| Clark | 74–94 | 86–178 | mid |
| Alex | 75–97 | 92–188 | late |
| Zeta | 76–98 | 101–194 | late |
| Gene | 77–98 | 109–194 | late |
| Epsilon | 77–99 | 109–200 | late |
| Jefferson | 79–102 | 117–217 | late |
| Theta | — | — | — |
| Average | 68–96 | 67–184 | — |
| Range | 57–102 | 42–217 | — |

**Note:** Phenological stages for stigmas: red dot appears on stigmas (Ef) to last flowers are open (Ff3). *Classification for the first stage of female receptivity is early (42–59), mid (60–91), and late (92–117) unit of CGDD. Values not presented for 'Theta' because of insufficient data.

Table 3 and Fig. 2 (A-E, pink bars). We classified these cultivars as early, mid-season or late (Table 3). Female receptivity occurred over a broader range of CGDD (42–217) than catkins (101–244, Table 3 and Fig. 2E), and as a result, female flowering (45 d, Julian day 57–102) was earlier and more prolonged than male flowering (30 d, Julian day 76–106). The cultivars with early females were 'Tonda di Giffoni', 'Lewis', 'Slate', 'Barcelona', 'Yamhill', 'Butler', 'Santiam', 'Delta', 'Jemtegaard #5', 'Hall's Giant', and 'Norfolk'. These cultivars with early females may not receive enough pollen since their stigmas are receptive when no pollen is available. The catkins began to shed pollen at 101 CGDD, while this group needs only 42–55 CGDD for the first female flowers to become receptive. The mid-season cultivars 'Gamma', 'Farris G17', 'Chelsea', 'C-409', and 'Clark' need 60 - 86 CGDD to become receptive to pollen. The cultivars with late female flowers are 'Alex', 'Zeta', 'Gene' and 'Epsilon', with the female of 'Jefferson' being the latest of all. They need 92–117 CGDD for stigmas to become receptive.

For successful fruit set and nut production, the pollen shed (stage Fm1 to Fm2) and female receptivity (stage Ff1 to Ff2) of compatible cultivars should overlap (Table 3 and Fig. 2A–E). This phenomenon is called the effective pollination period (EPP). The EPP can be up to 2–3 mo in most growing areas but is only 2–3 wk in southern Ontario. Any frost damage during these 2–3 wk can be detrimental to yield if the number of pollinizers is limited and the catkins are frost-damaged.

Vegetative budbreak, averaged over 4 yr, was earliest in 'Barcelona', 'Butler', and 'Clark' with 178 CGDD, and the latest cultivar was 'Theta' with 223 CGDD. The mid-season group included 'Farris G17', 'Gamma', 'Gasaway', 'Jefferson', and 'Santiam', which needed at least 193 CGDD to break the dormancy.

## Discussion

### Assessment of flower commencement and duration

Flower development and phenology is a function of the cultivars' genetics and the local climate. In the warm climates of New South Wales, Australia, and the central

**Fig. 2.** The red line shows cumulative growing degree days (CGDD) with a base of 0 °C. Graphical summary of the phenological development of the male and female flowers and vegetative buds of 24 hazelnut cultivars at Simcoe, ON, Canada, during 2011, 2012, 2013, and 2016. The gradient of colors corresponds to the stages of growth development. The blue bars represent staminate flower development. The pink bars represent pistillate flower development. The development of vegetative buds is represented by green bars. Anthers well-differentiated in catkins, a yellow coloration appears in Em, and pollen starts to shed in Fm1 to Fm3. Styles are receptive from Ef to Ff2, and flowering is finished with the blackening of stigmas at Ff3. Vegetative buds start with swelling of the bud in Bf to appear three fully expanded leaves in C3. Blanked bar means did not have any catkins or stigmas or lack of data information.

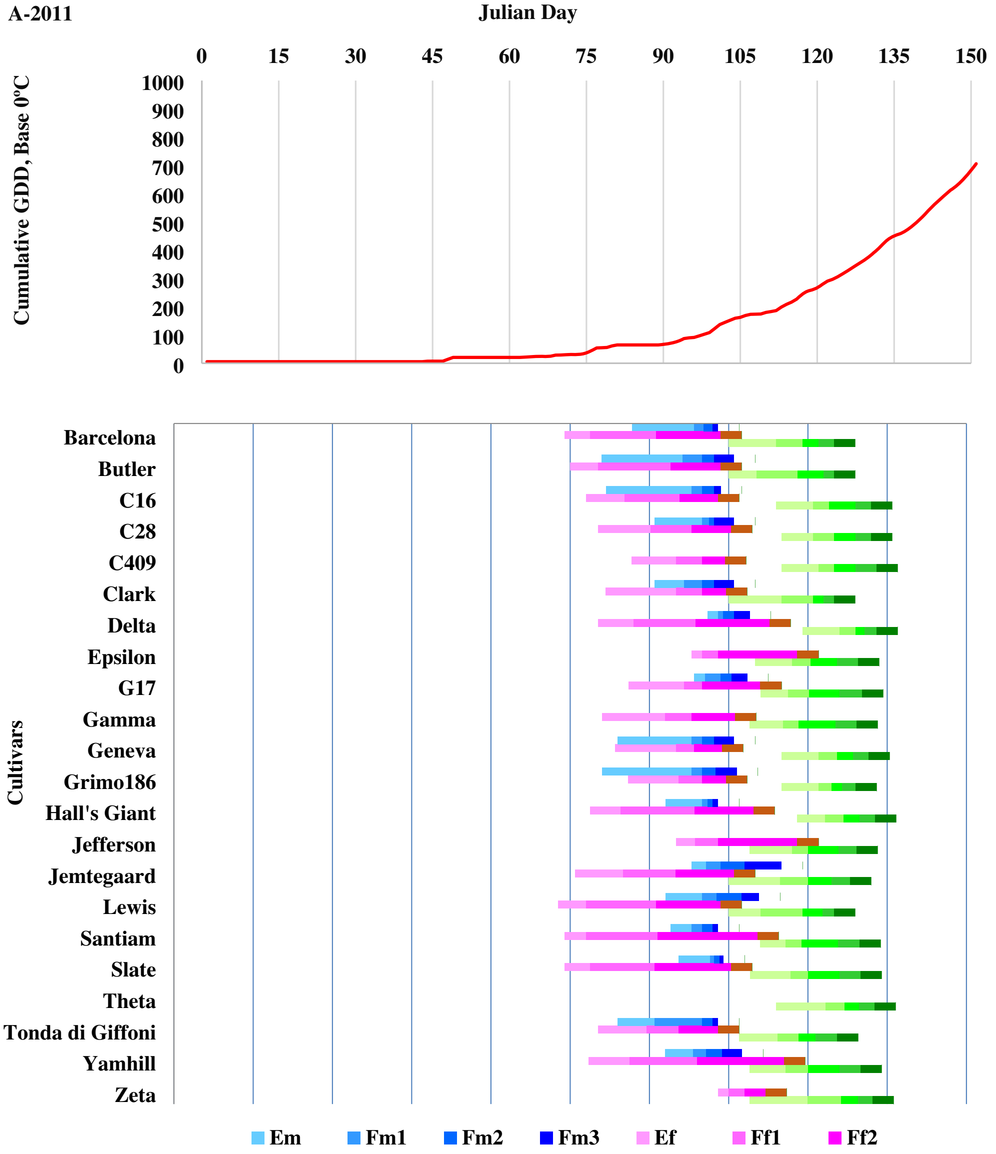


**Fig. 2.** (*continued*)

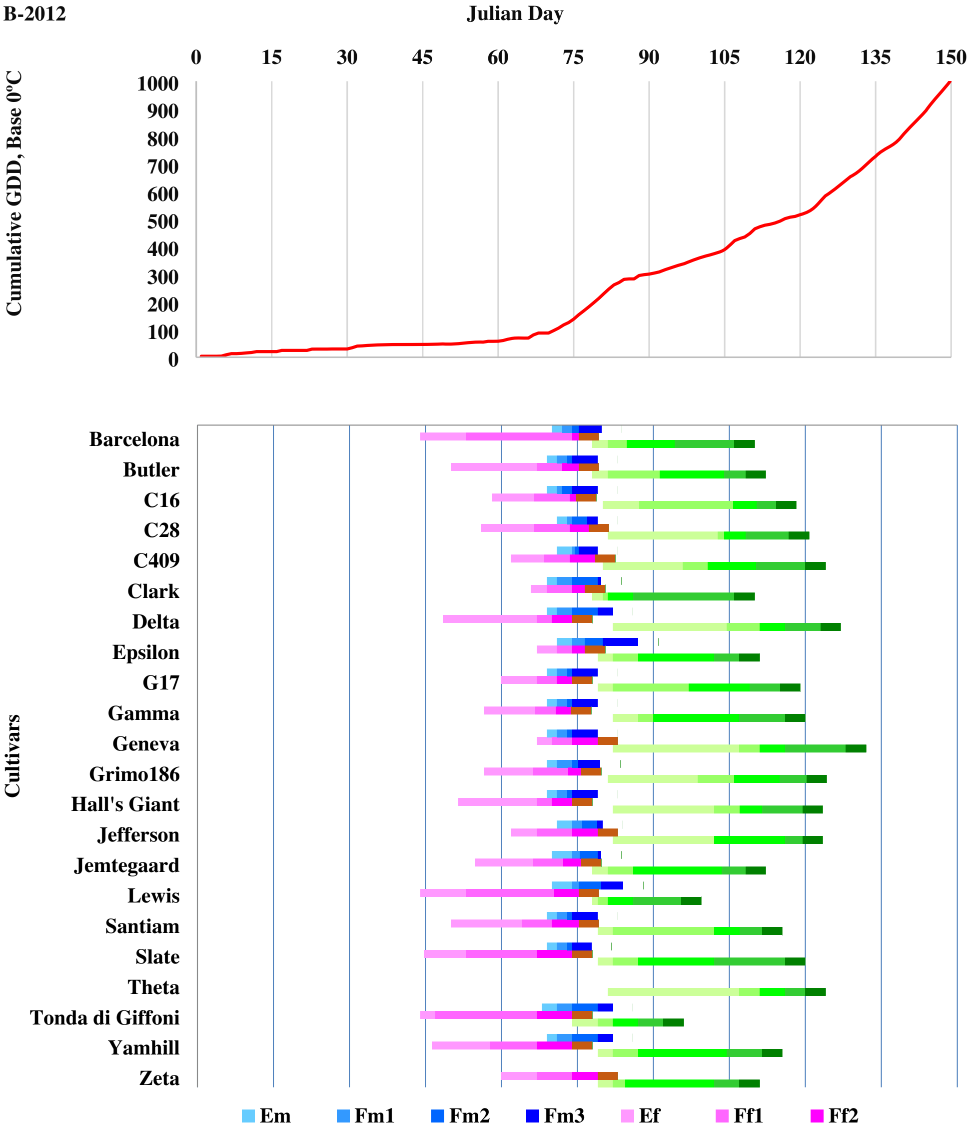


**Fig. 2.** (*continued*)

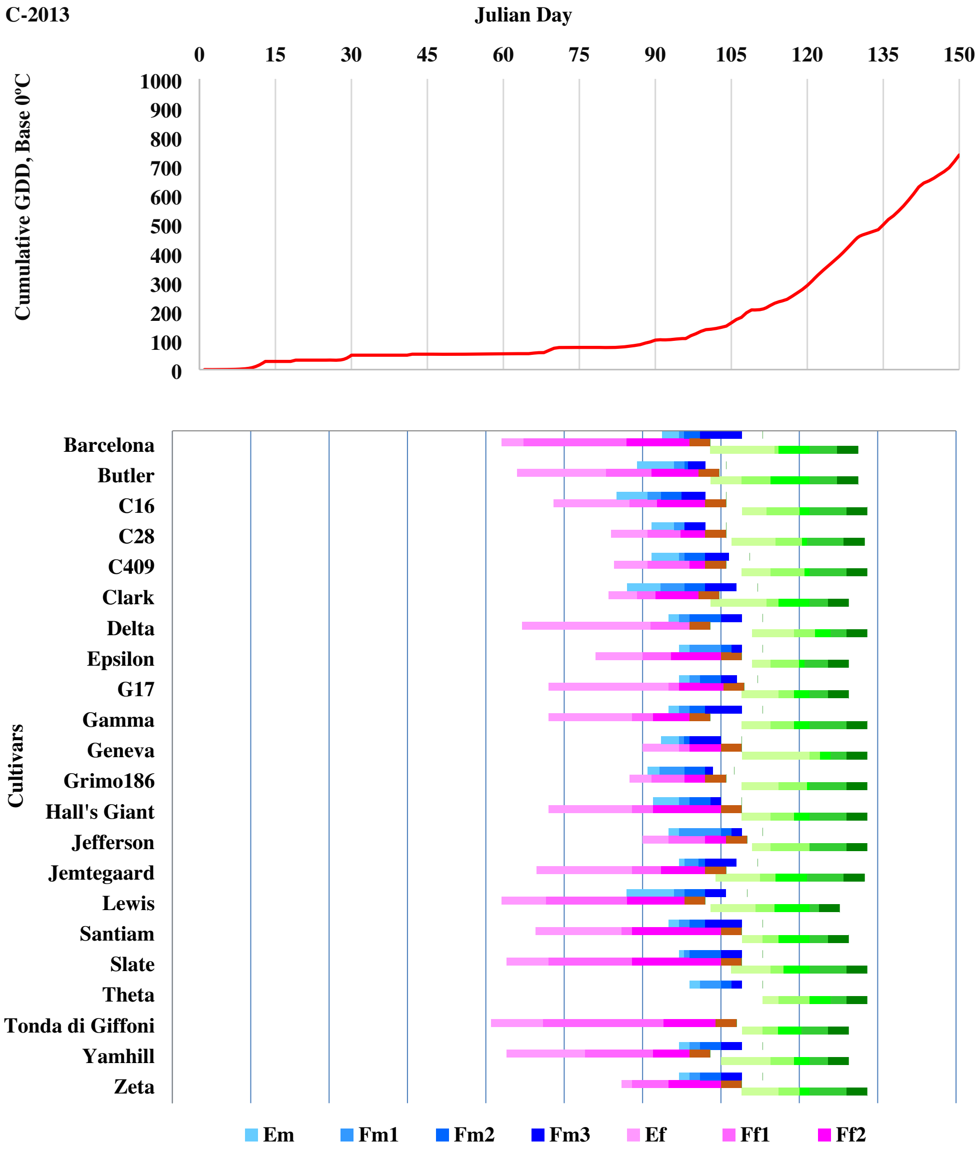


**Fig. 2.** (*continued*)

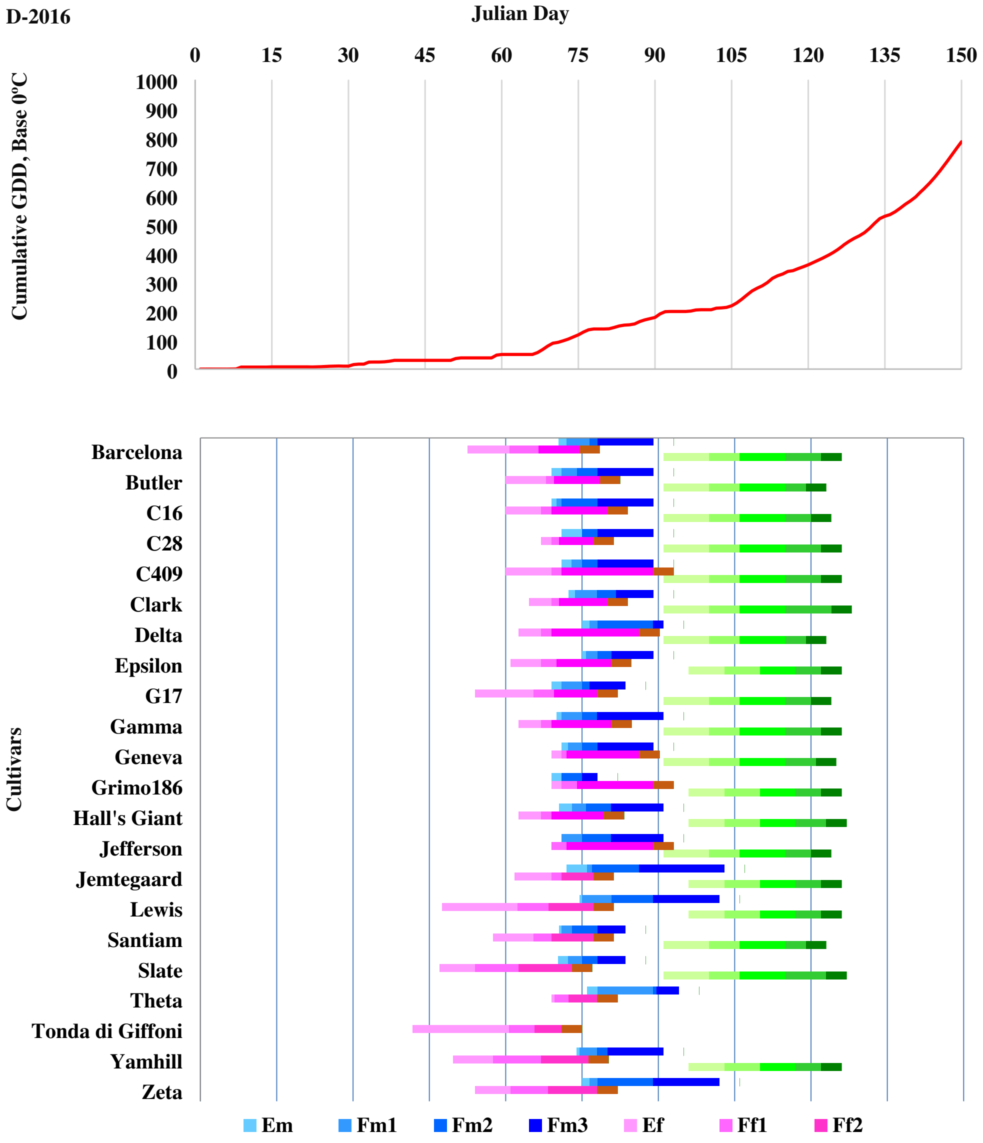
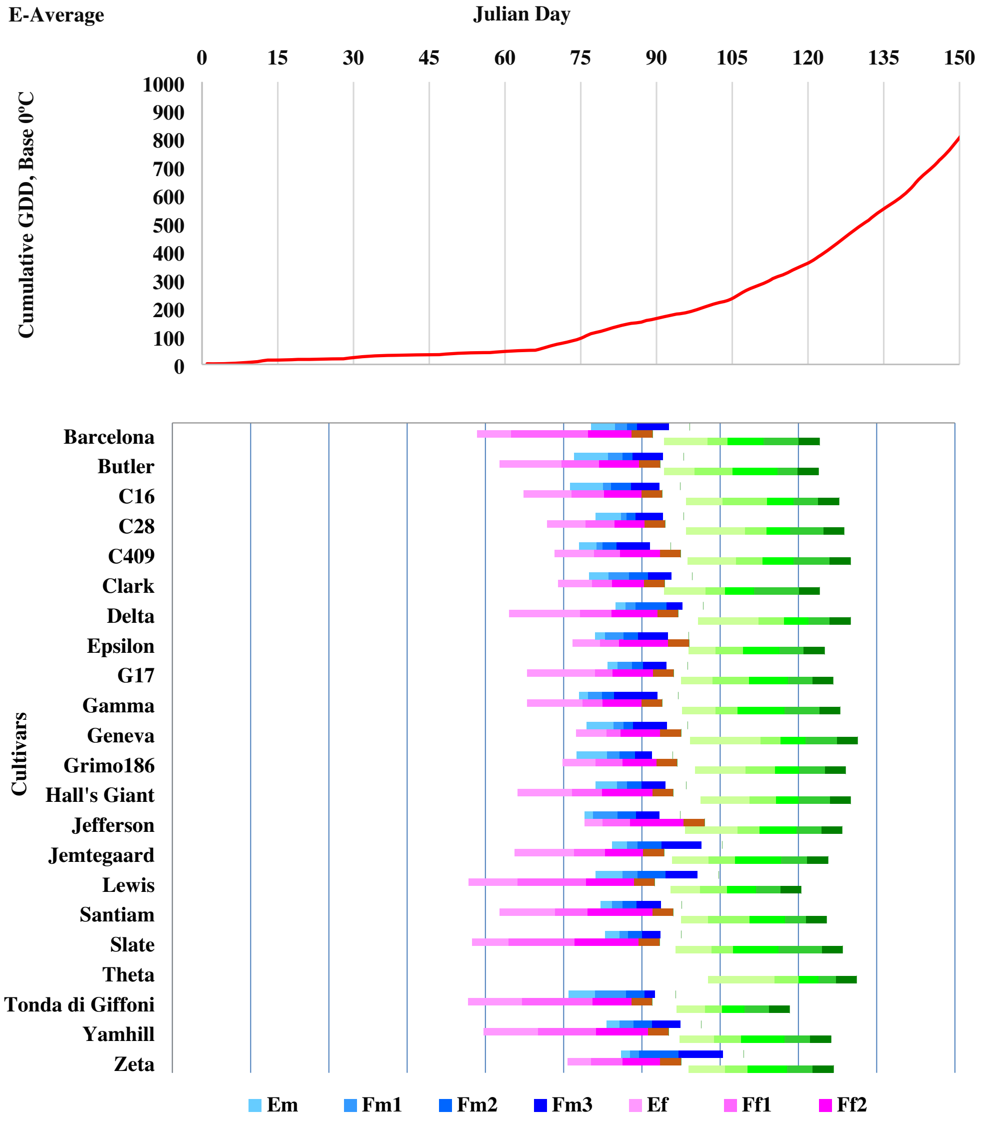


**Fig. 2.** (*concluded*)



valley of Chile (in southern hemisphere), female and male flowering starts mid-April (after a few weeks of cold temperatures) and lasts to the end of May (Baldwin et al. 2001; Bastias and Grau 2005). In areas with mild climates such as the Willamette Valley in Oregon, southwest France, or central Italy, the anthesis of pistillate flowers takes place from the beginning of December until the end of March, depending on the weather. Pollen shed and anthesis of pistillate flowers occur over a period of several weeks to several months, and if pollination is prevented, the stigmas stay receptive for 3 mo.

In the continental climate of southern Poland and inland Slovenia (with a colder fall and winter), the duration of both male and female flowering is shorter. Anthesis begins later towards the end of January or the beginning of February and finishes in the second half of April.

For any given cultivar, the duration of pollen shed and female receptivity varies with winter temperatures, being shorter in locations with low temperatures (Kavardzhikov 1982). Piskornik et al. (2001) reported that temperature affects the duration of flowering. In that study, the mean temperature was 5–10 °C, and the flowering duration was about 22 d. When the mean temperature did not exceed 3 °C, the flowering duration was about 43 d. Therefore, the EPP (when pollen shed and female receptivity overlap) is 2–3 mo in areas with a milder climate such as Oregon (Thompson 1979), but is only 2–3 wk in southern Ontario. The compressed flowering is due to the below-freezing temperatures during winter, which delays the bloom to a short period in early spring, as has been seen in other colder climates (Capik and Molnar 2014; Solar and Stampar 2009).

The date and duration of bloom also varied from year to year, similar to other reports (Capik and Molnar 2014). Our results confirm that the cultivar 'Tonda di Giffoni' was one of the earliest, and 'Jefferson' the latest, for female flowering (Capik and Molnar 2014). While we have not studied the duration of receptivity of unpollinated female flowers in the cold climate of southern Ontario, it appears to be at most 32 d. Thompson (1979) reported that in the Willamette Valley, unpollinated females remain receptive for up to 2 to 3 mo. We found that in southern Ontario, females were receptive for about 2 wk prior to the peak of pollen shed of the cultivars in the trial. Therefore, some of the earliest female blooming plants would be unlikely to receive sufficient pollen. In a few cultivars, however, such as 'Alex', 'Gene', 'Epsilon', and 'Jefferson', females were receptive only a few days before pollen was shed. These cultivars are more likely to be successful in this region. In breeding programs, attention should be given to cultivars with late female blooms for cold climates like southern Ontario to increase the EPP.

### Assessment of flower dichogamy

The degree of dichogamy is strongly influenced by local thermal conditions and varies widely between years (Bastias and Grau 2005). In the warm climates of eastern Spain (Rovira and Tous 2001) and Chile (Bastias and Grau 2005), most cultivars show protandry with catkins shedding pollen before female become receptive. In mild climates like that of the Willamette Valley in Oregon, protandry is more common in a warm season (temperatures > 9 °C) and protogyny more common in a cool season (temperatures < 9 °C) (Mehlenbacher 1991*b*; Olsen et al. 2000).

Genotypes that were clearly protandrous under the conditions in the mild climates of central Italy (Manzo and Tamponi 1982), southern France (Germain 1994), or Oregon (Mehlenbacher 1991*b*) showed protogyny or homogamy in the cool climate of southern Poland, which has considerably more severe winters. Similarly, in other areas with cold winters, such as New Jersey, protogyny and homogamy are common (Turcu et al. 2001; Bastias and Grau 2005; Capik and Molnar 2014). Thus, the degree of homogamy depends on both genotype and environmental conditions. Warm temperature in December–February accelerates catkin elongation (Bergougnoux et al. 1978; Mehlenbacher et al. 1991*a*; Germain 1994; Olsen et al. 2000). Also, catkins and female inflorescences have different post-dormancy heat requirements. Catkins have low chilling and high heat unit requirements, whereas female flowers have high chilling and low heat unit requirements (Mehlenbacher 1991*a*; Baldwin 2015). This is probably the reason why post-dormancy weather conditions strongly influence the time of flowering of both types of inflorescences, causing different dichogamy patterns in different years, even in a single cultivar. This phenomenon is especially pronounced in areas with a cold autumn and frigid winters, such as southern Ontario. In regions with continental climates (i.e., Canada, Poland and Slovenia), endodormancy is usually followed by an ecodormancy period, the length of which varies from year to year (Piskornik et al. 2001; Crepinšek et al. 2012).

Where winter climates are severely cold, post-dormancy warmth seems to become a more significant factor. For areas with long winters, post-chill warmth accumulation in late winter would be protracted and delay flowering (Baldwin 2015). The difference in the post-chill heat requirements of catkins and female inflorescences, presented by Turcu et al. (2001) for 14 cultivars in Romania are low (99–150 GDD for catkins, and 102–147 GDD for female flowers) compared with the chill requirements in Oregon reported by Mehlenbacher (1991*a*) (100–860 h for catkins, and 290–1550 h for female flowers).

Germain and Dimoulas (1979) showed that catkin development ceased once temperatures fell to about 0 °C. Tiyayon (2008) indicated that post-dormancy heat requirements was lower for catkin elongation when chilling hours increased. This author believed the optimum temperature for catkin elongation was 15 °C (Tiyayon 2008) and this explains the protogynous behavior of flowers in the continental climate of southern Ontario.

Catkin survival is a matter of concern in southern Ontario, mainly when pollinizers are limited to one or two cultivars, and frost happens during pollen shed. To overcome this challenge, several compatible pollinizers with different flowering times should be planted. The proper proportion and distribution of cultivars is essential for the efficient transport of pollen from pollinizer cultivars to main cultivars.

The order in which cultivars enter the phenological stages for pollen shed and female receptivity are similar from year to year. However, the calendar dates on which they enter these stages differ each year; the commencement date of each stage is very different from one year to another and tends to follow the average temperature rather than calendar date (Capik and Molnar 2014). Our results show that the CGDD is better than average daily temperature for predicting the flowering dates of both catkins and female flowers. CGDD has less fluctuation and better reflects the changes in phenological stages compared with the average daily temperatures.

## Conclusion

The results provide a benchmark for growers in southern Ontario's cold climate and similar climates for early and late cultivars. Hazelnuts show protogyny in this climate, and for most of the cultivars evaluated, female flowers broke dormancy 2 wk ahead of male flowers. Plants with female flowers requiring a larger CGDD period (e.g., 'Alex', 'Gene', 'Epsilon', and 'Jefferson') may prove better adapted to cold climates like Ontario.

They will be in better synchrony with pollen shed across a wider number of cultivars. Comparison of historical CGDD with our data can better illuminate the flower phenological performance of a cultivar in a similar climate.

The possibility of growing hazelnuts commercially in areas with low winter temperatures depends on the ability of cultivars to extend the flowering time to the onset of more favorable weather conditions. Future hazelnut breeding programs need to consider flower phenology to breed for cold climates and develop late female blooming cultivars to be in better synchrony with pollen shed across a wider number of cultivars.

There is also a need for pollinizers resistant to colder temperatures, as the early female flowers are receptive when there is little or no pollen available due to cold damaged catkins. The other pattern observed in Ontario's continental cold climate is that the EPP is 2–3 wk, while it is 2–3 mo in milder climates. While the female flowering may last longer (about 1–2 mo), the catkins elongate very quickly in response to warmer spring temperatures and shed the pollen in 2–3 wk. Any attempts to prevent frost damage to the catkins may improve nut production in this critical time for pollination.

Two or more pollinizer cultivars with complementary pollen shedding and bloom periods should be planted in alternating rows in the orchard to facilitate the cross-pollination necessary for proper nut formation. Therefore, the two main factors in selecting the pollinizers are the genetic compatibility and the overlap of pollen shed by the pollinizer and female receptivity of the main cultivar. Different pollinizers should be considered, covering the beginning, middle, and end of the stigma receptivity period.

## Acknowledgements

Funding for this project, in part via contributions from the Agricultural Adaptation Council through the Canadian Agricultural Adaptation Program 2014–2019; Growing Forward 2 Program (Agri-Innovation Program) and the Ontario Centres of Excellence, is greatly appreciated. We also gratefully acknowledge the contribution of Ferrero SpA., our technicians, and summer students. This article is a contribution of the Virginia State University (VSU), Agricultural Research Station (Journal Article Series Number 370).

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