8-2016

The phenology and compatibility of Hazelnut (Corylus avellana) cultivars in Tennessee

Ben Nigel Heard
University of Tennessee at Chattanooga, nigelheard@yahoo.com

The Phenology and Compatibility of Hazelnut (*Corylus avellana*) cultivars in Tennessee

Ben Nigel Heard

Departmental Honors Thesis

The University of Tennessee at Chattanooga

Department of Biology, Geology, and Environmental Sciences

Project Director: J. Hill Craddock

Examination Date: August 10, 2016

Members of Examination Committee

Dr. Ethan Carver

Dr. Clifton Cleaveland

Dr. Stephen Kuhn

Signatures:

____
Project Director

____
Departmental Examiner

____
Departmental Examiner

____
Liaison, Departmental Honors Committee

____
Chair, Departmental Honors Committee

Abstract

The Phenology and Compatibility of Hazelnut (*Corylus avellana*) cultivars in Tennessee

The European hazelnut (*Corylus avellana* L.), is an important temperate zone nut tree species for which there is an expanding demand worldwide. Historically, the Eastern filbert blight disease (EFB), caused by the ascomycete fungus *Anisogramma anomala*, has prevented commercial hazelnut growing in Tennessee. As part of a UTC hazelnut cultivar trial, EFB resistant hazelnut cultivars and numbered selections from Oregon State University and Burnt Ridge Nursery were planted in 2003 at Smith Farm in Ooltewah, TN. Hazelnut trees are wind-pollinated, dichogamous, and self-incompatible, which means they are not self-fertile, their male and female blossoms may open at different times, and they must be cross pollinated. The low seed set observed in the UTC trial may result from the local weather patterns and/or from a lack of adequate pollinizers. I hypothesized that the pollen release and the pistil emergence (female flower receptivity) are not occurring at the same time and therefore sufficient pollination is not occurring amongst the cultivars in the trial. I also hypothesized that the pollinizers may not have the correct *S*-alleles (genetic loci that regulate compatibility) for successful cross pollination. I collected phenological data from thirteen cultivars in the orchard every week during the normal pollination months of January, February, and March 2016. Furthermore, I constructed a table of *S*-alleles for all varieties in the orchard and compiled records for the weather for the orchard for the months of my study. The results of my one season of observation do not support the hypotheses but do provide important baselines for further investigation.

Table of Contents

List of Figures

List of Tables

Introduction

The European hazelnut (*Corylus avellana* L.), is an important temperate zone nut producing tree species for which there is an expanding demand for commercial use worldwide (Ghanbari, Me, Talaie, & Vezvaie, 2004). Turkey and Italy are the world's largest producers of hazelnuts followed by the United States of America, Georgia, and Azerbaijan. (Food and Agriculture Organization of the United Nations, 2014). Hazelnuts are monoecious (has both male and female flowers on the same plant), dichogamous (stamens and pistils mature at different times), wind pollinated, and are normally not capable of self-fertilization. Phenology is the "study of periodic biological events in the plant and animal world that are influenced by the environment, especially temperature changes driven by weather and climate" (Črepinšek, Štampar, Kajfež-Bogataj, & Solar, 2012). Understanding the phenology of the hazelnut tree is essential to managing the crop and getting the best results. The phenology of the European hazelnut differs from most other monoecious trees because they bloom in midwinter. Since most of the trees are protandrous, meaning that the male stamen, or catkin, matures before the female pistil, the timing is key to the pollination process. Cross-pollination must occur in order for a good nut set in the hazelnuts. Pistillate anthesis, the flowering period of the plant during which the female flower parts are receptive to pollen, is temperature dependent and occurs during the winter months of December, January, and February (Olsen, Mehlenbacher, and Azarenko, 2000). If not pollinated, stigmas (the part of the pistil that receives the pollen) can remain receptive for 3 months (Thompson, 1979). Normally, the peak for hazelnut pollination in Oregon is in January. There are no known of reports in the literature for hazelnut pollination timing in Tennessee.

Two of the many factors that can determine nut set in hazelnut are: 1) Pollen-pistil compatibility must be present in the cultivars and 2) Climate and weather can accelerate pollen release before the pistil is exserted or delay the pistil from exserting.

Pollen-stigma incompatibility is important when considering pollinizers in orchard plantings (Ghanbari, Me, Talaie, &Vezvaie, 2004). Self-incompatibility is controlled by a gene locus (the *S* locus) with multiple alleles. There are two main types of self-incompatibility in flowering plants: gametophytic and sporophytic. Gametophytic self-incompatibility is when the haploid *S* genotype in the pollen is expressed and the pistil that contains the same *S*-allele causes the pollen tube growth to be stunted (Hampson, Azarenko, & Soeldner, 1993). Sexual compatibility in hazelnut is controlled by sporophytic self-incompatibility, in which the pollen's *S* expression is controlled by the diploid parental genotype (Hampson et al., 1993). The *S*-alleles, or self-sterility genes, are codominant in the pistil and can be either dominant or codominant in the pollen (Mehlenbacher, 1997). This means that if an allele in the pollen is the same as the allele in the pistil, the cross is incompatible. For example, if a female flower with the S_1S_2 alleles is pollinated by another hazelnut tree whose pollen expresses the S_2 allele, the two trees are incompatible. However, if the S_1S_2 female flower crosses with S_3 pollen, it is compatible. Studies by Dr. Mehlenbacher and others at Oregon State University have revealed some 33 different alleles at the *S* locus in *Corylus avellana L.* in (Mehlenbacher, 1997, 2014). *S*-alleles can be used to determine compatibility amongst cultivars. In hazelnut, *S*-alleles have a dominance hierarchy, which means some alleles are more dominant than others, as shown in Figure 1.

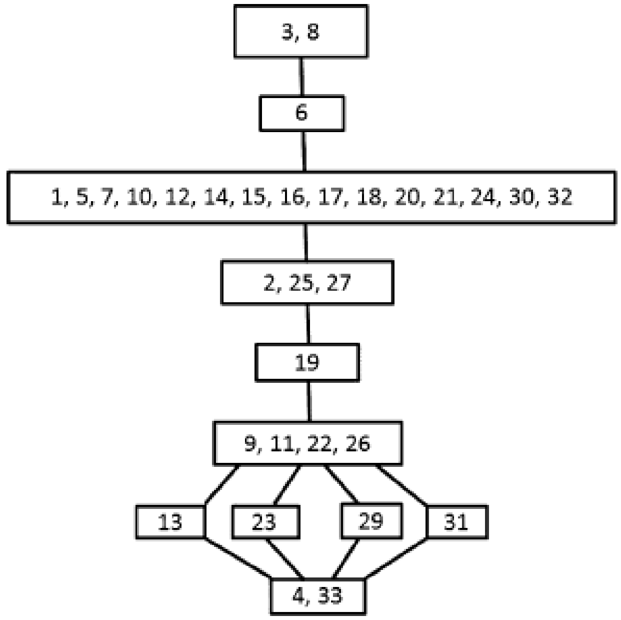

Figure 1. Dominance hierarchy of *S*-alleles in hazelnut pollen. Alleles are dominant to alleles *below* them, and codominant with those at the same level. (Mehlenbacher, 1997, 2014).

In addition to *S*-allele incompatibility, the weather has a part to play with the dispersion of pollen and the exserting and receptivity of the pistillate flowers. The timing of the phases of hazelnut phenology strictly depends on the current temperature and previous year's temperature (Wielgolaski, 1999). The production of hazelnuts is ideally limited to places with milder to warm summers, since hazelnut trees have poor heat tolerance; they are also limited to cooler winters, although many can tolerate extremely low temperatures, some as low as -15 °C (Črepinšek et al., 2012). Warmer air temperatures cause plant development to start earlier in the phenological cycle (Menzel et al., 2006). When temperatures are colder, the possibility of injury to the catkins is greater than to the female pistils (Molnar, Goffreda, & Funk, 2004). The hazelnut's dates of flowering and leafing are dependent on chilling and heat requirements. According to Capik and Molnar, (2014), "Male (catkins, staminate) and female (pistillate) flowers have different chilling requirements to break dormancy, with catkins typically having lower chilling requirements than the female flowers." Hazelnuts typically require a very short period of heat requirement and can vary amongst different cultivars (Mehlenbacher 1991). Other variants such as wind speed and precipitation can also factor into pollination timing. The weather can surely alter flowering time of different genotypes of hazelnut, so different pollinizers need to be present to complement with the others.

Along with compatibility and weather, the density of pollinizers determines pollination efficiency. It is recommended around the world that pollinizer density range from 3% to 30%, and in Oregon, it is standard at 10% (Olsen et al, 2000). Recently, Oregon has recommended placing at least three different pollinizers that release pollen at different times during the ideal stage of pistil flower emergence so that pollination may occur in the orchard consistently (Olsen et al, 2000). Many experts suggest that hazelnut trees should be within 50 to 70 feet between them and their pollinizers.

Table 1. List of hazelnut cultivars at Smith Farm in Ooltewah, TN.

Cultivars				
OSU 553.09	OSU 659.044*	Clark	Delta	Epsilon
Gamma	Hall's Giant	Lewis	Tonda di Giffoni	
VR43-1	Willamette	Yamhill	Zeta	Filazel*
Trazel*	Beaked Hazel*	Bush Hazel*		
Turkish Tree Hazel*				
*Corylus Americana**				

***Denotes cultivar not used in the research.**

Hazelnut trees were planted at the Smith Farm experimental orchard, in Ooltewah, TN, beginning in 2003. Plants of thirteen cultivars and selections were obtained from Oregon State University (OSU) in Corvallis, Oregon and Burnt Ridge Nursery in Onalaska, Washington. An additional 6 cultivars were added to the plantings in 2007. Table 1 contains a list of all cultivars currently at the farm.

Originally, the hazelnut trees were planted to test resistance to Eastern Filbert Blight (EFB) in cultivars and EFB-resistant selections developed at OSU. The planting also included EFB-susceptible cultivars as controls. Overall, the trees planted were expected to range from fully susceptible to highly resistant. Eastern Filbert Blight, a major limiting factor to hazelnut production in the eastern US, is a parasitic fungal disease caused by the ascomycete fungus *Anisogramma anomala* that is indigenous to Northeast America, and which infects most species of *Corylus* (Plant Disease Diagnostic Clinic, 2015). The fungus normally infects the American hazelnut, *Corylus americana*, causing small cankers to form on the branches of the tree, but when introduced to the European Hazelnut, *Corylus avellana*, the fungus causes giant cankers and necrotic lesions, which eventually kill the tree (Plant Disease Diagnostic Clinic, 2015). Western Washington and the Willamette Valley of Oregon, which includes Corvallis, was far outside of the native range of *A. anomala*, so the production of EFB-susceptible European cultivars planted in the 1885 thrived there for many years in relative isolation. (Thompson, Lagerstedt, and Mehlenbacher, 1996; Hummer, 2000). The introduction of Eastern Filbert Blight in western Washington in October 1970, which moved down into the Willamette Valley, has led to the development of EFB resistance cultivars there. (Davison and Davidson, 1973; Mehlenbacher, 1994). Some of these EFB cultivars were worthy of trials in New Jersey (Molnar, Godreda, & Funk, 2004) and Tennessee.

Although showing much promise in the Tennessee trial, the cultivars have been plagued by poor fruit set and poor nut quality in some years.

The aim of this research was to evaluate pollen shed and pistillate flower emergence, and cultivar pollinizer compatibility, in hazelnut cultivars and selections at Smith Farm in Ooltewah, TN for 3 months in order to better understand their response to the weather of the Southeastern region of the United States and to provide data on the phenology of the hazelnuts in the region. The data will help determine whether Tennessee is an adequate place to grow hazelnuts in an effort to one day commercialize hazelnut production.

Materials and Methods

For the present study, a total of 12 different cultivars and OSU selections were observed for 3 months, from January 1th, 2016 to April 1st, 2016 to determine the date of release of pollen and pistil emergence. All of the trees are grown on their own roots; they were propagated (cloned) by stool-bed layering. Most of the clones in this study have 2 or more trees representing them. The trees were planted at a 5 x 10 meter spacing (approximately 15 x 30 feet apart) in 16 rows of ten trees each. Seven of the 16 rows were planted in a completely randomized design (rows A-G); seven rows (H-N) were planted as two “commercial production blocks” consisting of two rows each of the cultivars ‘Lewis’(rows I and J) and ‘Clark’(rows L and M), flanked by rows of six different pollinizer varieties (rows H, K, and N). Not included in the present study are one row (row O) of miscellaneous hybrids and two trees of *Corylus colurna*, and a partial row (row P) of *Corylus americana*. The cultivars that were studied are listed in Table 2 with their source, planting date, and incompatibility alleles. The identification of most of the *S* alleles in the 13 cultivars come from the incompatibility research done by Dr. Shawn Mehlenbacher, at OSU (Olsen et al., 2000). The *S* incompatibility alleles for the cultivars are Clark ($\underline{S_3S_8}$), Hall's Giant ($\underline{S_5S_{15}}$), Lewis ($\underline{S_3S_8}$), Tonda di Giffoni ($\underline{S_2}S_{23}$), VR4-31 (S_1, $\underline{S_3}$), Willamette ($S_1\underline{S_3}$) (Olsen et al., 2000); Gamma ($S_2\underline{S_{10}}$), Delta ($\underline{S_1S_{15}}$), Epsilon ($\underline{S_1}S_4$), Zeta ($\underline{S_1S_1}$) (Mehlenbacher and Smith, 2004); OSU 553.09 ($\underline{S_8}S_{26}$), and Yamhill ($\underline{S_8}S_{26}$) (Mehlenbacher, 2009).

Table 2. Hazelnut cultivars used for tree phenology at Smith Farm in Ooltewah, TN during January 2016 to April 2016.

Cultivar	Source	Date Planted	Incompatibility *S*-alleles[1]
OSU 553.09	OSU	25-Apr-03	$\underline{S_8}$, S_{26}
Clark	Burnt Ridge	14-May-03	$\underline{S_3}$, $\underline{S_8}$
Delta*	Burnt Ridge	14-May-03	$\underline{S_1}$, $\underline{S_{15}}$
Epsilon*	Burnt Ridge	14-May-03	$\underline{S_1}$, S_4
Gamma*	OSU	14-May-03	S_2, $\underline{S_{10}}$
Hall's Giant*	Burnt Ridge	14-May-03	$\underline{S_5}$, $\underline{S_{15}}$
Lewis	Burnt Ridge	14-May-03	$\underline{S_3}$, $\underline{S_8}$
Tonda di Giffoni*	Burnt Ridge	14-May-03	$\underline{S_2}$, S_{23}
VR43-1	Burnt Ridge	14-May-03	S_1, $\underline{S_3}$
Willamette	Burnt Ridge	25-Apr-03	S_1, $\underline{S_3}$
Yamhill	OSU	14-May-03	$\underline{S_8}$, S_{26}
Zeta*	OSU	14-May-03	$\underline{S_1}$, $\underline{S_1}$

[1]Dominant alleles in pollen for each cultivar are underlined.
***Pollinizer varieties included in 'Clark and 'Lewis' production blocks**

During the winter and early spring months of January, February, and March of 2016, the catkins and pistils of the hazelnut cultivars were observed once a week. Both the catkins (Figure 2) and the pistils (Figure 3) were rated on a one to three scale according to their stage in development.

CATKINS. Catkin stage times are not absolute, therefore the stages begin when 60% of the catkins exhibited the characteristics of the stage for each tree. The stage times were determined by observing 50 catkins randomly on each tree for each cultivar. Stage 1 (Figure 2A) for the catkins occurs when the catkin begins to elongate and stretch. Since each cultivar's stamen grows at different rates, the beginning of this stage starts when the catkins are flaccid. Pollen release at this stage is minimal to none. Stage 2 (Figure 2B) occurs when the catkin is intermediately elongated and the individual stamens are beginning to pull apart from one another. There is partially pollen release during this time. Catkins begin Stage 3 (Figure 2C) when they are fully elongated, all the individual stamens are pulled apart, and pollen shed is at its peak. The stage ends once the catkin has shed mostly all of its pollen.

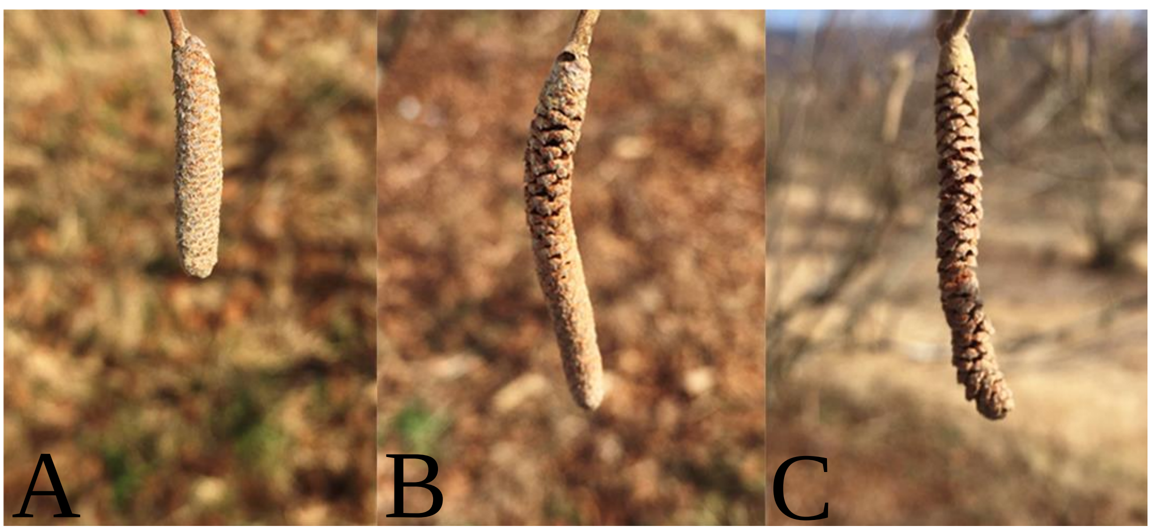

Figure 2. Hazelnut Staminate (Catkin) development. From left to right: Stage 1 (A) (catkin elongating), Stage 2 (B) (intermediate elongation, partially pollen release), and Stage 3 (C) (fully elongated, pollen release peak). Pictures taken at Smith Farm in Ooltewah, TN.

PISTILS. The pistillate flower development begins a little bit later than staminate catkins for most cultivars. Just as in catkin development, pistil stage times are not absolute because all the flowers may not progress at the same rate on the tree. This being said, the stages begin when over 60% of the flowers exhibited that certain stage. Stage 1 (Figure 3A) begins when the floral buds are slightly open but the pistil flowers are not seen emerging. In the beginning of Stage 2, the styles can be seen exserting from the buds indicated by a red cluster (Figure 3B). The pistillate flowers are not fully separated at this point but can begin to be pollinated. Stage 3 (Figure 3C) occurs when the pistillate flowers have fully exserted and separated. However, the end of this stage, as stated previously, may last as long as 3 months if the stigma is not fertilized. For purpose of this research, the stage ends when the styles fall off the buds.

Figure 3. Hazelnut Pistillate (Pistil) development. From left to right: Stage 1 (A) (pistillate flower not exserted), Stage 2 (B) (partially exserted), and Stage 3 (C) (pistils fully exserted). Pictures taken at Smith Farm in Ooltewah, TN.

WEATHER. Since the phenology of the hazelnut depends so much on the weather and climate, temperature data was taken from the location of the Smith Farm in Ooltewah, TN from the Apple weather application on an iPhone. Precipitation was also collected during the study. The data collected was validated by data obtained from

Accuweather and US Climate Data (Accuweather & US Climate Data). The information was then used to determine to correlation between weather and the phenology of the hazelnut cultivars.

Results

COMPATABILITY. The compatibility of the twelve cultivars were compared with one another. OSU 553.09 and Yamhill cultivars ($\underline{S_8}S_{26}$) both can pollinate and be pollinized by Delta, Epsilon, Gamma, Hall's Giant, Tonda di Giffoni, VR4-31, Willamette, and Zeta. The Clark and Lewis cultivars ($\underline{S_3}\underline{S_8}$) both can pollinate and be pollinized by Delta, Epsilon, Gamma, Hall's Giant, Tonda di Giffoni, and Zeta. The Delta cultivar ($\underline{S_1}\underline{S_{15}}$) can pollinate OSU 553.09, Clark, Gamma, Lewis, Tonda di Giffoni, and Yamhill. However, Delta can be pollinized by OSU 553.09, Clark, Gamma, Lewis, Tonda di Giffoni, VR43-1, Willamette, and Yamhill. The Epsilon cultivar ($\underline{S_1}S_4$) can pollinate OSU 553.09, Clark, Gamma, Hall's Giant, Lewis, Tonda di Giffoni, and Yamhill. However, Epsilon can be pollinized by OSU 553.09, Clark, Gamma, Hall's Giant, Lewis, Tonda di Giffoni, VR43-1, Willamette, and Yamhill. The Gamma cultivar ($S_2\underline{S_{10}}$) can pollinate OSU 553.09, Clark, Delta, Epsilon, Hall's Giant, Lewis, Tonda di Giffoni, VR43-1, Willamette, Yamhill, and Zeta. However, Gamma can be pollinized by every cultivar except Tonda di Giffoni. The Hall's Giant cultivar ($\underline{S_5}\underline{S_{15}}$) can pollinate and be pollinized by OSU 553.09, Clark, Epsilon, Gamma, Lewis, Tonda di Giffoni, VR4-31, Willamette, Yamhill, and Zeta. The Tonda di Giffoni cultivar ($\underline{S_2}S_{23}$) can pollinate OSU 553.09, Clark, Delta, Epsilon, Hall's Giant, Lewis, VR4-31, Willamette, Yamhill, and Zeta. Tonda di Giffoni can be pollinized by OSU 553.09, Clark, Delta, Epsilon, Gamma, Hall's Giant, Lewis, VR4-31, Willamette, Yamhill, and Zeta. The

VR4-31 and Willamette cultivars ($S_1\underline{S_3}$) can pollinate OSU 553.09, Delta, Epsilon, Gamma, Hall's Giant, Tonda di Giffoni, Yamhill, and Zeta. However, they can only be pollinized by OSU 553.09, Gamma, Hall's Giant, Tonda di Giffoni, and Yamhill. The Zeta cultivar (S_1S_1) can pollinate OSU 553.09, Clark, Gamma, Hall's Giant, Lewis, Tonda di Giffoni, and Yamhill. However, Zeta can be pollinized by OSU 553.09, Clark, Gamma, Hall's Giant, Lewis, Tonda di Giffoni, VR43-1, Willamette, and Yamhill. Table 3 shows the compatibility of the selected cultivars.

Table 3. Compatibility of selected cultivars at Smith Farm in Ooltewah, TN.

	Cultivars											
	OSU 553.09 ($\underline{S_8}S_{26}$)	**Clark ($\underline{S_3S_8}$)**	**Delta ($\underline{S_1S_{15}}$)**	**Epsilon ($\underline{S_1}S_4$)**	**Gamma ($S_2\underline{S_{10}}$)**	**Hall's Giant ($\underline{S_5S_{15}}$)**	**Lewis ($\underline{S_3S_8}$)**	**Tonda di Giffoni ($\underline{S_2}S_{23}$)**	**VR43-1 ($S_1\underline{S_3}$)**	**Willamette ($S_1\underline{S_3}$)**	**Yamhill ($\underline{S_8}S_{26}$)**	**Zeta ($\underline{S_1S_1}$)**
OSU 553.09 ($\underline{S_8}S_{26}$)	X	I	C	C	C	C	I	C	C	C	I	C
Clark ($\underline{S_3S_8}$)	I	X	C	C	C	C	I	C	I	I	I	C
Delta ($\underline{S_1S_{15}}$)	C	C	X	I	C	I	C	C	0	0	C	I
Epsilon ($\underline{S_1}S_4$)	C	C	I	X	C	C	C	C	0	0	C	I
Gamma ($S_2\underline{S_{10}}$)	C	C	C	C	X	C	C	0	C	C	C	C
Hall's Giant ($\underline{S_5S_{15}}$)	C	C	I	C	C	X	C	C	C	C	C	C
Lewis ($\underline{S_3S_8}$)	I	I	C	C	C	C	X	C	I	I	I	C
Tonda di Giffoni ($\underline{S_2}S_{23}$)	C	C	C	C	0	C	C	X	C	C	C	C
VR43-1 ($S_1\underline{S_3}$)	C	I	0	0	C	C	I	C	X	I	C	0
Willamette ($S_1\underline{S_3}$)	C	I	0	0	C	C	I	C	I	X	C	0
Yamhill ($\underline{S_8}S_{26}$)	I	I	C	C	C	C	I	C	C	C	X	C
Zeta ($\underline{S_1S_1}$)	C	C	I	I	C	C	C	C	0	0	C	X

C = indicates that the cross is compatible   I = indicates an incompatible cross   0 = indicates the cross is compatible in only one direction

WEATHER. Daily climate data was taken from Smith Farm and recorded in Figure 4. The average high temperature for January was 8.8 °C and the average low temperature was -1.4 °C; the maximum and minimum temperatures were 20 °C and -8.8 °C respectively. In February, the average high was 12.8 °C and the average low was 2.4 °C: the maximum was 24.4 °C and the minimum was -5.5 °C. March's average high and low temperatures were 20.2 °C and 7.3 °C respectively. The maximum temperature for the month was 29.4 °C and the minimum temperature was -0.5 °C. An incremental rise in temperatures occurred over the three months, which was expected. However, from Figure 4 it can be seen there are three major peaks in temperature during January to March. The most significant peak occurred from January 27th to February 5th. The other peaks occurred from February 17th to March 1st and from March 6th – March 17th. Pistil emergence depends heavily on peaks in temperature.

Precipitation during the study fluctuated in accordance with normal levels. The total amounts of precipitation during the study in the months of January, February, and March were 98.3 mm, 186.9 mm, and 70.6 mm, respectively. Snowfall occurred on January 22nd and February 9th but the amount was insignificant: 5.1 mm and 7.9 mm, respectively. In Figure 4, four peaks of over 30 mm of precipitation can be seen with the highest peak being February 1st to February 4th. The highest peak coincidentally occurred during and after the most significant peak in temperature. Therefore, one might believe that these peaks in temperature and precipitation might have caused pistil emergence to begin and develop in the cultivars.

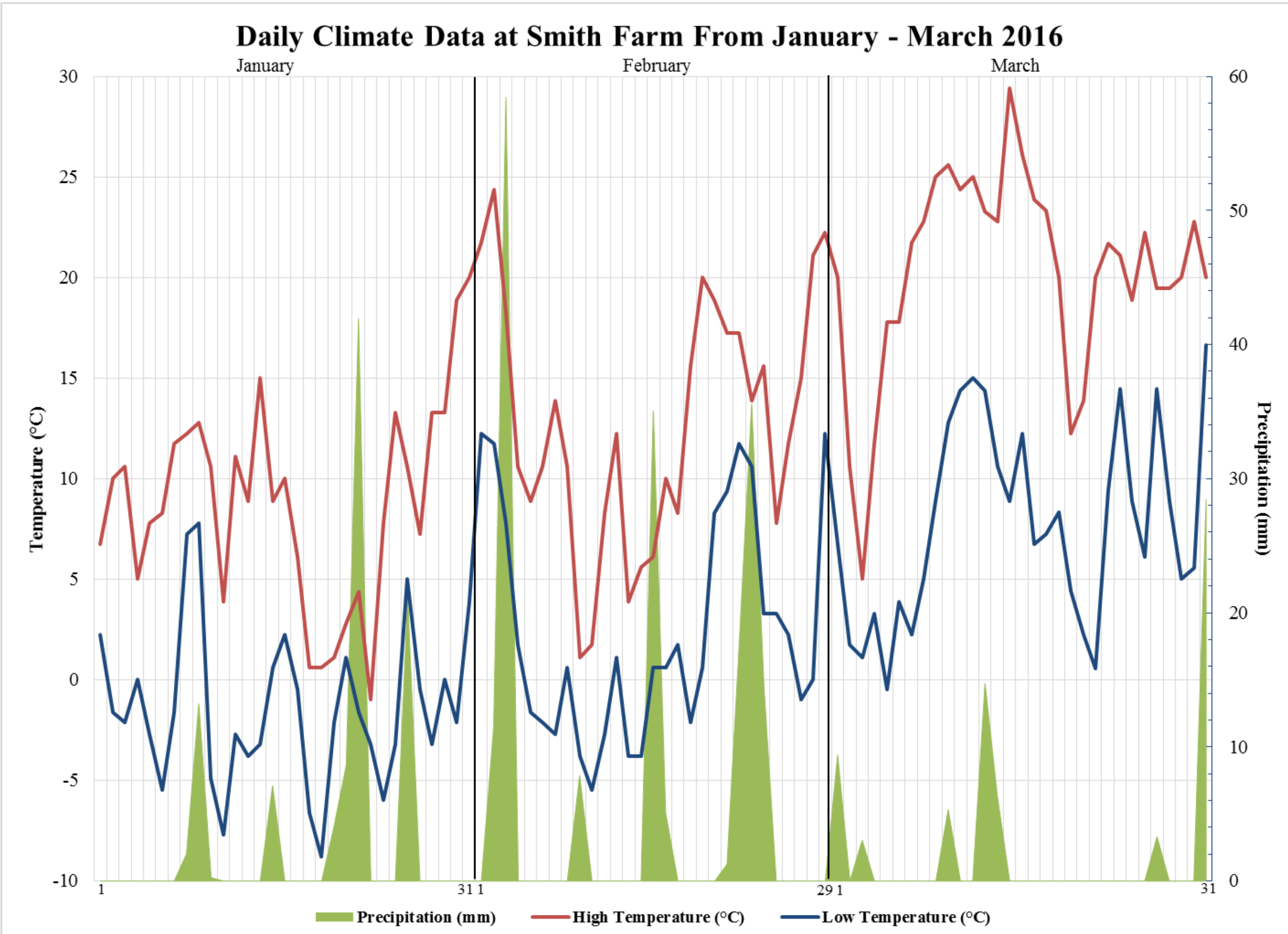

Figure 4: Graphical summary of the daily climate data at Smith Farm in Ooltewah, TN during the months of January, February, and March of 2016. (Data collected by Apple weather application. Data verified by Accuweather and US Climate Data.)

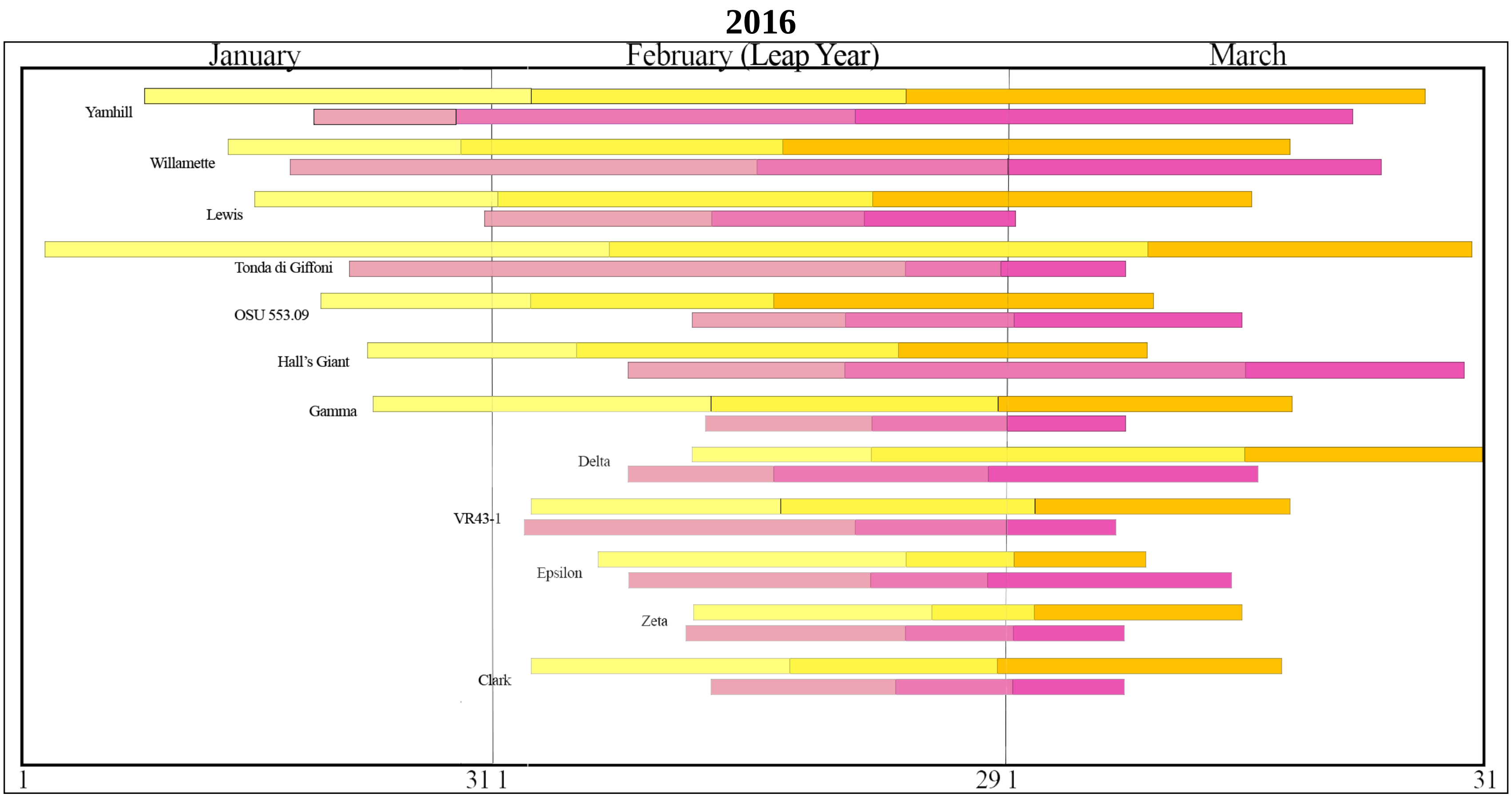

Figure 5. Graphical summary of hazelnut staminate (catkin) and pistillate (pistil) development in 13 cultivars from January 2016 to March 2016. The yellowish colored bars represent hazelnut catkin development. The colors correlate to the stages listed in the text (cream yellow is Stage 1, yellow is Stage 2, and yellow-orange is Stage 3). The pinkish colored bars represent hazelnut pistil development. The light pink is Stage 1, the pink is Stage 2, and magenta is Stage 3. The cultivars name is located between the catkin and pistil bars to which it correlates.

CATKIN DEVELOPMENT. In accordance with the beginning of Stage 1, the cultivars were placed in 3 groups: early group, mid group, and late group. The early group was comprised of the cultivars Tonda di Giffoni, Yamhill, Willamette, Lewis, OSU 553.09, Hall's Giant, and Gamma. These cultivars began catkin elongation during January, the earliest being Tonda di Giffoni. Tonda di Giffoni began Stage 1 on January 2 and ended Stage 3 on March 30. The dates made this particular cultivar have the longest catkin development period out of the entire orchard. The last cultivar to begin elongation in this group was Gamma on January 24. The mid group of the cultivars were Clark, VR4-31, and Epsilon and started Stage 1 in early February. The mid group on average stopped pollen release around mid-March. Delta and Zeta were a part of the late group which did not reach Stage 1 until mid-February. Although Zeta ended Stage 3 on March 13, Delta did not cease pollen release until March 31 making it the last cultivar to release mostly all of its pollen. The dates of each staminate development stage of each select cultivar can be seen in Table 4. Figure 5 shows the graphical summary of the both the hazelnut staminate and pistillate development.

Table 4. **Summary of catkin development in cultivars from Smith Farm in Ooltewah, TN in 2016.**

Cultivar	**Stage 1**	**Stage 2**	**Stage 3**	**Pollen Release End**	**Total Duration**
OSU 553.09	Jan 20	Feb 3	Feb 17	Mar 10	40 days
Clark	Feb 3	Feb 19	Feb 28	Mar 17	51 days
Delta	Feb 10	Feb 21	Mar 14	Mar 31	50 days
Epsilon	Feb 5	Feb 23	Mar 1	Mar 10	34 days
Gamma	Jan 24	Feb 13	Feb 28	Mar 19	55 days
Hall's Giant	Jan 23	Feb 9	Feb 22	Mar 11	48 days
Lewis	Jan 15	Feb 1	Feb 21	Mar 15	60 days
Tonda di Giffoni	Jan 2	Feb 6	Mar 9	Mar 30	88 days
VR4-31	Feb 2	Feb 18	Mar 3	Mar 18	45 days
Willamette	Jan 12	Jan 28	Feb 18	Mar 18	66 days
Yamhill	Jan 5	Feb 2	Feb 23	Mar 26	81 days
Zeta	Feb 10	Feb 25	Mar 3	Mar 13	32 days

PISTIL DEVELOPMENT. Just as it was in staminate development, the cultivars were separated into early, mid, and late groups. The early group included Yamhill, Willamette, Tonda di Giffoni, and Lewis. Pistil development started primarily in mid to late January. Willamette exhibited the earliest time for Stage 1 in which it began on January 17th. Starting on the 30th of the month, Lewis was the last cultivar in this group to begin development, which was 9 days after the second to last cultivar in the group, Tonda di Giffoni. VR4-31, Delta, Epsilon, and Hall's Giant make up the mid-group of pistil development. Three of the four cultivars in this group began pistil development on February 7th. The outlier was VR4-31, beginning on February 1st; this made VR4-31 one of the cultivars in which pistil development started slightly before catkin development. The remaining group of cultivars were OSU 553.09, Gamma, Zeta, and Clark. These cultivars began pistil development around the middle of February and ended in early to mid-March. The full pistillate development dates of each selected cultivar can be seen in Table 5. Figure 5 shows the graphical summary of the both the hazelnut staminate and pistillate development.

Table 5. Summary of pistil development in cultivars from Smith Farm in Ooltewah, TN.

Cultivar	Stage 1	Stage 2	Stage 3	Pistil Exserting End	Total Duration
OSU 553.09	Feb 10	Feb 19	Mar 1	Mar 13	32 days
Clark	Feb 13	Feb 22	Mar 1	Mar 7	23 days
Delta	Feb 7	Feb 17	Feb 27	Mar 16	38 days
Epsilon	Feb 7	Feb 21	Feb 27	Mar 12	34 days
Gamma	Feb 12	Feb 21	Feb 29	Mar 8	25 days
Hall's Giant	Feb 7	Feb 19	Mar 14	Mar 29	51 days
Lewis	Jan 30	Feb 12	Feb 20	Mar 1	31 days
Tonda di Giffoni	Jan 21	Feb 23	Feb 28	Mar 8	47 days
VR4-31	Feb 1	Feb 20	Feb 29	Mar 6	31 days
Willamette	Jan 17	Feb 16	Mar 1	Mar 24	67 days
Yamhill	Jan 19	Jan 29	Feb 20	Mar 22	63 days
Zeta	Feb 9	Feb 23	Mar 1	Mar 7	27 days

Discussions

COMPATIBILITY AND DEVELOPMENT. According to Table 3, compatibility results show that for each cultivar there are at least 6 potential pollinizers. Since all of trees were 5 m (about 15 feet away) from the nearest tree and at maximum within 50 feet from a potential pollinizer, in accordance with pollen density standards at Oregon State University, adequate fertilization should be occurring regularly. However, in order to get the maximum fertilization, peak pollen release (staminate Stage 3) and full pistil emergence (pistillate Stage 3) should coincide with one another. The cultivars OSU 553.09, Clark, Epsilon, Lewis, and Zeta had problems correlating those stages with the

Hall's Giant cultivar. Clark and Lewis ended the Stage 3 of catkin development on March 17th and March 15th respectively which was a few days after the full pistil emergence of Hall's Giant on March 14th. This barely allowed the two stages to coincide and could be seen as insignificant. The catkin Stage 3 ended on March 10th for OSU 553.09 and Epsilon, and on March 13th for Zeta, days before Hall's Giant's full pistil emergence, meaning that there was no overlapping of the stages. Hall's Giant's pistil Stage 3 occurred so late that the peak pollen release for most of its compatible pollinizers did not adequately coincide with its full pistil receptivity. Tonda di Giffoni's pollen release ended on March 30th making it the longest catkin development in the orchard. However, four of Tonda di Giffoni's compatible cultivars' full pistillate emergence did not occur during the full pollen release stage of the cultivars. The Delta cultivar was the most problematic pollinizer in the orchard. The beginning of peak pollen release for the tree occurred on March 14th. Almost all of the cultivars that it is compatible with could not be pollinized during the full pistil emergence because of how late the ideal pollen release stage occurred.

The Hall's Giant, VR4-31, Willamette, and Yamhill cultivars had no problems with correlation of the two ideal stages. All cultivars that they were compatible with could be pollinated at full pistil emergence with their peak pollen release according to the data. It is important to note that Yamhill's Stage 3 pistil development lasted the largest number of days of any cultivar; the time allowed all compatible cultivars to release the maximum amount of pollen to pollinate the pistil when it was fully exserted. All cultivars could be pollinized by the Gamma cultivar at full pistil emergence while also pollinating Gamma at top pollen release, with the exception of Tonda di Giffoni. With Gamma's catkin Stage 3 beginning on February 28th and ending on March 19th, every cultivar's full pistil emergence stage in the orchard was able to be pollinized at its maximum potential.

It was also seen in the study that several cultivars were not compatible in both directions. For example, VR43-1 and Willamette cultivars were able to pollinize Delta, Epsilon, and Zeta, yet could not be pollinated by those same cultivars. The same is true with the Gamma and Tonda di Giffoni cultivars.

WEATHER. The temperatures of the months of January, February, and March were particularly high in accordance with the average monthly highs and lows. The higher temperatures may have caused the pistils to exsert in the cultivars earlier than normal. The most significant peak in the temperature occurred between January 27th and February 2nd where the high was 24.4 °C and the low was 11.7 °C. The spike in temperature seemingly caused the pistil development of several trees to begin. According to Figure 5, directly after the spike, the cultivars OSU 553.09, Clark, Delta, Epsilon, Gamma, Hall's Giant, VR4-31, and Zeta all began Stage 1 of pistillate development within 11 days. Furthermore, during the second peak in temperature (February 17th to March 1st), 10 of the 13 cultivars began stage 3 of pistillate development, the most significant stage in development, indicating that the rise in the temperature again may have caused full emergence of the flowers.

The amount of precipitation was lower than normal levels in January and March. The normal amounts of precipitation in January and March are 125 mm and 126 mm, respectively. In 2016, January had 26.7 mm less precipitation and March had 55.4 mm less precipitation than normal. Conversely, February exceeded its normal value, going from 123 mm (normal amount) to 186.9 mm. The increase in rainfall may have helped in the development process of the pistillate but may have stunted the pollen release of the staminate. The two peaks of rainfall occurring from January 20th to January 22nd and February 2nd to February 3rd can be seen as helping pistillate development. They both occurred during the most significant peak in temperature which could have caused the initiation of pistil development. However, the peak of rainfall occurring from February 21st to February 24th may have caused the pollen on the stamen to clump together and stick to the catkin not allowing wind dispersion to have any effect. The two precipitation peaks on February 2nd to February 3rd and February 21st to February 24th nearly mirrored the first two peaks of the temperature According to Figure 4 and 5, precipitation, temperature, and catkin and pistil development correlate extremely well.

Conclusions

This study was intended to start the process of recording hazelnut phenology and compatibility at Smith Farm in Ooltewah, TN between 12 cultivars and numbered selections in response to observations of unexpectedly low fruit set by trees in the past in the experimental orchard. It was determined that catkin elongation and pollen release varied from cultivar to cultivar. Though air temperature did not play a major role in the development of the staminate catkins, precipitation surely did through the control of pollen release. However, the awakening from dormancy in the pistils, like previous research suggested, was mainly controlled by the increase of air temperature and precipitation. The results suggest that since air temperature and precipitation drastically increased around the end of January and beginning of February, many of the pistillate flowers began the process of emergence around that point as reflected in comparison of Figures 4 and 5. Also, a second increase in rainfall and air temperature during the end of

February and beginning of March caused pistils to fully exsert in many of the cultivars. The start of full pollen release correlated with the second peaks as well. Precipitation levels were lower than normal levels during the study. Normally, a decrease in precipitation has an effect on the development of the trees, but there is no evidence to say that the precipitation has been low before and will be low after this study. According to the data in Figure 5, most of the cultivars' peak pollen release (Stage 3) occurred during full pistil emergence (Stage 3) which would not cause lack of pollination and low seed set.

Adequate *S*-allele diversity is present in the orchard to satisfy the compatibility requirements for cross pollination of all the cultivars. This means that there were enough compatible cultivars in order to pollinate each tree at the orchard. There were some incompatible combinations, such as Lewis and Clark, because the *S*-alleles matched each other. (It did not affect the pollination process as previously suspected for this orchard at Smith Farm.) In conclusion, although my experimental results do not strongly support my original hypotheses, interpretation of these results should be tempered by the fact that only one phenological cycle was represented in the study.

More phenological data, like the data collected for this thesis, would be necessary to draw any general conclusions. Data in the future could also include nut production, including total mass, kernel mass, good seeds, defective seeds, and blanks. Soil fertility could be measured from soil samples at the orchard to inspect how much elemental nutrients are in the soil. Insect damage from the Brown Marmorated Stink Bug, *Halyomorpha halys*, has appeared in the orchard within the past few years and is known to have disrupted hazelnut production in Oregon. Its impact here should also be included in future data collection efforts. There should be a weather station installed at Smith Farm in order to get more accurate readings for temperature and precipitation along with other meteorological data such as humidity and wind speed.

The southeastern area of Tennessee seems like a viable region to grow hazelnut trees based on the results from 2016. Smith Farm, through the results of further studies, has the potential to expand into commercial production, but limitations such as Eastern Filbert Blight may affect the trees in the future. In summary, I hope this study combined with future studies at Smith Farm, will contribute to the success of commercial hazelnut production in Tennessee and the southeastern United States.

References

AccuWeather. (n.d.). Retrieved April 1, 2016, from http://www.accuweather.com/en/us/chattanooga-tn/37402/weather-forecast/331086

Capik, J. M., and Molnar, T. J. (2014). Flowering Phenology of Eastern Filbert Blight-resistant Hazelnut Accessions in New Jersey. *HortTechnology*, *24*(2), 196-208.

Črepinšek, Z., Štampar, F., Kajfež-Bogataj, L., and Solar, A. (2012). The response of Corylus avellana L. phenology to rising temperature in north-eastern Slovenia. *International Journal of Biometeorology*, *56*(4), 681-694.

Davison, A.D. and R.M. Davidson. 1973. *Apioporthe* and *Monchaetia* canker reported in western Washington. *Plant Disease Reporter, 57,* 522-523.

Food and Agriculture Organization of the United Nations. (2014). Crops Production. Retrieved April 1st, 2016 from http://faostat3.fao.org/browse/Q/QC/E

Ghanbari, A., Me, G., Talaie, A., & Vezvaie, A. (2004). Studies on self-Incompatibility alleles in some progenies of hazelnut (Corylus avellana L.) using fluorescence microscope. *International Journal of Agriculture and Biology*, *6*, 113-115.

Hampson, C. R., Azarenko, A. N., & Soeldner, A. (1993). Pollen-stigma interactions following compatible and incompatible pollinations in hazelnut. *Journal of the American Society for Horticultural Science*, *118*(6), 814-819.

Hummer, K. (2000, August). Historical notes on hazelnuts in Oregon. In *V International Congress on Hazelnut*, *556*, 25-28.

Mehlenbacher, S. A. (1991). Chilling requirements of hazelnut cultivars. *Scientia Horticulturae*, *47*(3), 271-282.

Mehlenbacher, S.A. (1994). Genetic improvement of the hazelnut. *Acta Horticulture*, *351*, 551-557.

Mehlenbacher, S. A. (1997). Revised dominance hierarchy for *S*-alleles in Corylus avellana L. *Theoretical and Applied Genetics*, *94*(3-4), 360-366.

Mehlenbacher, S. A., and Smith, D. C. (2004). Hazelnut Pollenizers 'Gamma', 'Delta', 'Epsilon', and 'Zeta'. *HortScience 39*(6), 1498-1499.

Mehlenbacher, S. A., Smith, D. C., & McCluskey, R. L. (2009). 'Yamhill' hazelnut. *HortScience*, *44*(3), 845-847.

Mehlenbacher, S. A. (2014). Geographic Distribution of Incompatibility Alleles in Cultivars and Selections of European Hazelnut. *Journal of the American Society for Horticultural Science*, *139*(2), 191-212.

Menzel, A., Sparks, T. H., Estrella, N., Koch, E., Aasa, A., Ahas, R., and Chmielewski, F. M. (2006). European phenological response to climate change matches the warming pattern. *Global Change Biology*, *12*(10), 1969-1976.

Molnar, T. J., Goffreda, J. C., and Funk, C. R. (2004). Developing Hazelnuts for the Eastern Unites States. *VI International Congress on Hazelnut, 686,* 609-618.

Olsen, J. L., Mehlenbacher, S. A., and Azarenko, A. N. (2000). Hazelnut pollination. *HortTechnology*, *10*(1), 113-115.

Plant Disease Diagnostic Clinic (2015). Eastern Filbert Blight. *Cornell University College of Agriculture and Life Sciences*. Retrieved February 15, 2016, from http://plantclinic.cornell.edu/factsheets/filbertblight.pdf

US Climate Data (n.d.). Retrieved March 28, 2016, from http://www.usclimatedata.com/climate/chattanooga/tennessee/united-states/ustn0084

Thompson, M.M. (1979). Genetics of incompatibility in Corylus avellana L. *Theoretical Applied Genetics*, *54*(3), 113–116.

Thompson, M.M., H.B. Lagerstedt, and S.A. Mehlenbacher. (1996). Hazelnuts. In: Janick, J. and J.N. Moore (eds.). *Fruit breeding*, *3*, 125-184.

Wielgolaski, F. E. (1999). Starting dates and basic temperatures in phenological observations of plants. *International Journal of Biometeorology*, *42*(3), 158-168.