FINAL PROJECT REPORT

Project Title: Development and validation of a precision pollination model

PI: Gloria DeGrandi-Hoffman
Organization: USDA-ARS Tucson
Telephone: 520-647-9187
Email: Gloria.Hoffman@ars.usda.gov
Address: Carl Hayden Bee Research Center
Address 2: 2000 East Allen Rd
City/State/Zip: Tucson, AZ 85719

Co-PI (2): Vincent P. Jones
Organization: WSU-TFREC
Telephone: 509-663-8181 x291
Email: vpjones@wsu.edu
Address: Dept. Entomology/TFREC
Address 2: 1100 N. Western Ave
City/State/Zip: Wenatchee, WA 98801

Co-PI (3): Tory Schmidt
Organization: WTFRC
Telephone: 509-665-8271 x4
Email: tory@treefruitresearch.com
Address: 1719 Springwater Ave
City/State/Zip: Wenatchee, WA 98801

Cooperators: Dr. Stefano Musacchi (WSU-TFREC), Karen Lewis (WSU-Extension), Dr. Melba Salazar-Gutierrez (WSU-Prosser), Dr. Lee Kalcsits (WSU-TFREC), Dr. Kirti Rajagopalan (WSU-Pullman).

Total Project Request: Year 1: $95,834 Year 2: $103,359 Year 3: $104,569

Percentage time per crop: Apple: 80 Pear: 0 Cherry:20 Stone Fruit: 0

WTFRC Collaborative Expenses:

Item	2016	2017	2018	**2019**
Salaries	5000	5000	5000	**0**
Benefits	2000	2000	2000	**0**
Wages	8000	12,000	12,000	**0**
Benefits	2400	3600	3600	**0**
RCA Room Rental				
Supplies				
Travel	1800	2000	2000	**0**
Miscellaneous				
Total	19,200	24,600	24,600	**0**

Budget 1

Organization Name: USDA-ARS **Contract Administrator:** Laura Elmore
Telephone: 520-647-9160 **Email address:** Laura.Elmore@ars.usda.gov

Item		2017	2018	**2019**
Salaries		$1000	$1000	**0**
Benefits				
Wages				
Benefits				
Equipment				
Supplies				
Travel		$4,000	$4,000	**0**
Plot Fees				
Miscellaneous				
Total			$5,000	**0**

Footnotes:

Organization: WSU-TFREC **Contract Administrator**: Katy Roberts/Shelli Thompkins
Telephone: 509-335-2885/509-293-8803 **Email:** arcgrants@wsu.edu / shelli.tompkins@wsu.edu

Item	2016	2017	2018	**2019**
Salaries[1]	35,000	45,000	46,800	**0**
Benefits[1]	15,120	11,493	11,953	**0**
Wages[2]	18,800	11,440	11,898	**0**
Benefits[2]	1,214	309	321	**0**
Equipment				
Supplies	3,500	3,500	2,500	**0**
Travel[3]	3,000	1,500	1,560	**0**
Miscellaneous				
Plot Fees				
Total	76,634	73,242	75,032	**0**

Footnotes:
[1] Salaries and benefits are for a half-time grant manager
[2] Wages and benefits are for student temporary employees.

Objectives:

1. Update DeGrandi-Hoffman's original apple bloom phenology model to incorporate newer cultivars and horticultural advances.
2. Examine the effects of netting on honey bee foraging and modify foraging model accordingly.
3. Incorporate information on honey bee foraging and cross-pollination rates into the pollen tube growth model to improve decision making and thinning practices. Also evaluate foraging model on cherry.
4. Evaluate the effects of variability in spring weather conditions, as well as directional shifts toward earlier bloom, on fruit set and best pollination management strategies.

Significant Findings:

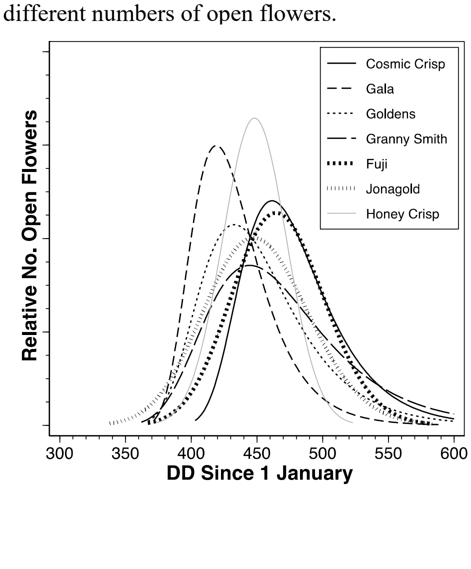
- Timing of full bloom is predictable for seven new cultivars: Cosmic Crisp, Fuji, Gala, Granny Smith, Jonagold, Golden Delicious, and Honey Crisp.
- Netting slows the progression of bloom compared to no nets, reduces the abundance of honeybees foraging, and results in lower and more variable fruit set.
- Honeybee foraging is driven by the number and relative abundance of open flowers on the mix of cultivars open at any time throughout the bloom period.
- Fruit set is completed in a fairly narrow window with 5% fruit set by 350 DD and 95% by 425-450 DD.
- Our fruit set model shows that the latter roughly 24% of flowers only contribute about 5% to the fruit set observed in our studies.
- Evaluation of the effect of climate change scenarios on honeybee foraging showed that temperatures during the bloom period will have a minor effect on foraging rates. However, the shorter daylength and lower intensity of sunlight occurring earlier in the year, when apples will bloom in Washington, will cause up to 20% reduction in foraging efficiency.

Obj. 1. Update DeGrandi-Hoffman's original apple bloom phenology model to incorporate newer cultivars and horticultural advances.

Materials and Methods: The past four years, we collected bloom phenology data at the WSU Sunrise orchard from six different cultivars (Fuji, Gala, Golden, Granny Smith, Jonagold, and Cosmic Crisp, Honeycrisp (2019 only)) and also analyzed data collected in 2016 from Honeycrisp and Gala (Honeycrisp were collected from two locations, Gala from one). Data collection focused only on the bloom period and we counted the number of blooms open at each visit on a given number of branches on a particular number of trees rather than following a smaller number of marked buds. This gives a much larger number of blooms at any point in time and seemed to define the bloom period much better. Analysis was done by examining the fit to five different statistical distributions and choosing the one that gives the best fit to the observed data.

Results: We have analyzed the data for bloom for all cultivars and have well defined the bloom period for each of the cultivars (Fig. 1). The models on DAS will be updated with the newest models based on our data for the last four year. These values have also been used in our fruit set model (objective 3).

Fig. 1. Probability density functions for the different numbers of open flowers.



Objective 2. Examine the effects of netting on honey bee foraging and modify foraging model.

Methods: Two adjacent blocks of Fuji's were used for this study. One block had overhead nets deployed before bloom while the other block was not covered with overhead netting throughout the study. The study utilized the entire 9 acre "no-net" block and ≈10 A of the 24 A block covered with netting. Trees in both blocks were trained on trellises. The net was a white 20% light-reducing netting that extended down over the top wires about 2 ft along the sides, 4 ft down along the front and all the way to down to the ground on the back (west side).

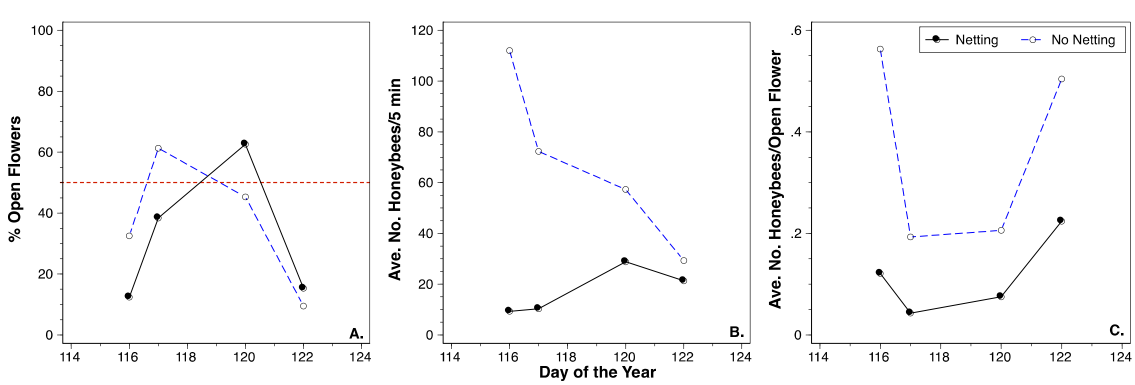
Bloom progression assessment: The blossoms were hand-thinned to about one flower per spur at the start of bloom in each block. In each block, three sections along the trellis were marked and each section contained ≈200 flower buds. The number of flowers observed for bloom progression was 618 and 610 flowers in the net and no-net blocks, respectively. The number of open flowers were recorded each time the flowers were observed, and these data was used to estimate % bloom.

Honeybee abundance: On April 4, four sets of four hives were placed under the nets next to the trees on the west side of the netted block and two sets of four hives were placed along the east edge of the block with no nets. The abundance of honey bees foraging in each block was assessed by slowly walking down a row and counting bees observed on or near apple trees during five-minute intervals. Three to six 5-min observations were made in each block on the days foraging bees were counted. All counts made within a block were averaged on a daily basis.

Fruit set: Transects were set up along the entire length of seven rows in each block and each transect contained five trees that were used for estimating fruit set (n = 35 trees per block). Distances for trees located along each transect were 40, 200, 360, 600 and 760 ft from the side of each block where the bee hives were located. The length of each tree row was ≈ 800 ft and the trees closest to the edges of the blocks were located 40 ft in from the edges.

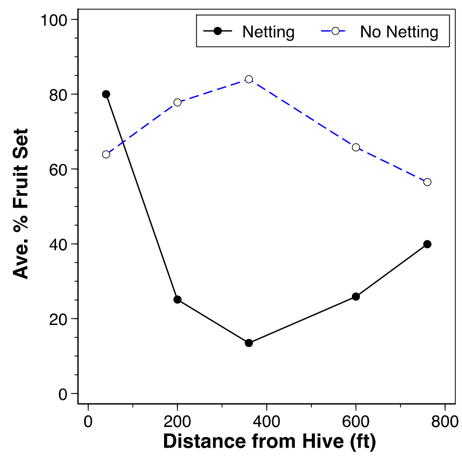
Results: We observed several differences between the net and no-net blocks. First was that bloom progressed earlier in the no-net block compared with bloom under netting (Fig. 2a). Fifty percent bloom occurred on 27 Apr in the no-net block compared with 29 Apr for 50% bloom under nets. We also observed considerably more honeybees foraging in apple trees without nets compared with the amount observed foraging under nets (Fig. 2b). When we standardized the number of bees per open blossom, we saw that the abundance of bees per open blossom was always higher in the block without nets (2c). Fruit set was more uniform (between 60-80%) along transects in the no-net block compared with the uniformity of fruit set observed under nets (15-80%) (Fig. 3). Fruit set in the block covered with nets decreased along the transects from the edges into the interior of the block.

Fig. 2. Effect of netting on flowering and honeybee foraging. A) Progression of flowering. B) Number of honeybees observed in 5 minute samples. C) Average number of honeybees per open flower.



We also saw additional ways that nets impacted pollinators. Bees often fly up and out when leaving an area. In this study, we observed that wild bees, bumble bees and honey bees became trapped in the upper corners where the nets were folded over the top wires. This resulted in exhaustion of the bees and an accumulation of dead and dying bees on the ground under the corner. It appears that having the edge of the net folded down over the top wire prevented some bees from leaving the netted area. One possible solution would be to install the nets so that they are flat. However, bees often were seen flying up and bouncing off the interior net ceiling indicating that nets inhibit upward flight of honey bees. Overall, orchard netting appears to negatively impact honey bee flight during bloom and subsequent fruit set.

Fig.3. Effect of netting on fruit set.



Obj. 3. Incorporate information on honeybee foraging and cross pollination rates into the pollen tube growth model to improve decision making and thinning practices. Evaluate foraging on cherry.

Methods Cultivar Choice and Fruit Set: The evaluation of flowering is discussed in objective 1, but those data were also used to calculate the relative proportion of flowers that were open for the different cultivars throughout the bloom period (Fig. 4.) The proportion of open blossoms for each cultivar includes data from figure 1, and the relative abundance of the different flowers in our plots. That data was paired with the foraging rates (number of bees on each cultivar) that were taken every few hours throughout the foraging periods.

We also did some studies on fruit set involving the four cultivars Fuji, Golden, Granny, and Jonagold; we were not allowed to do any thinning of the Cosmic Crisp in either the location at Sunrise or in

Fig. 4. The proportion of total open flowers each cultivar comprises throughout the bloom period. Based on data from figure 1

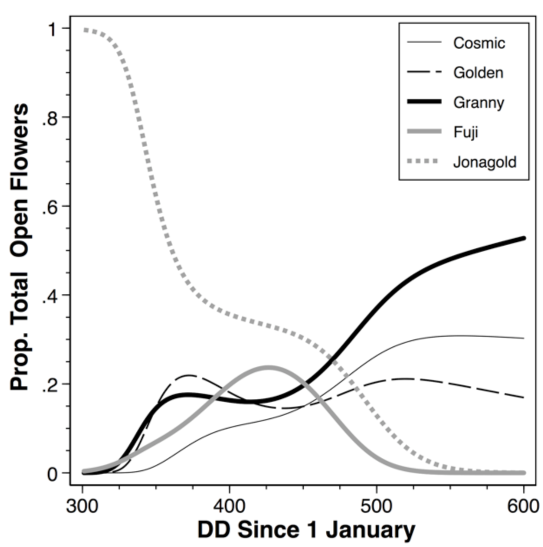
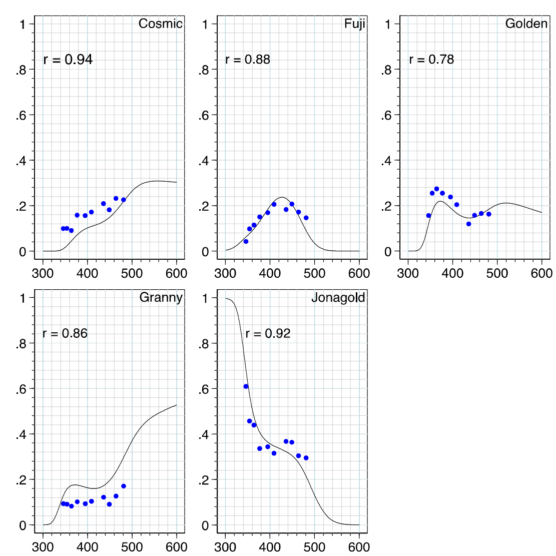


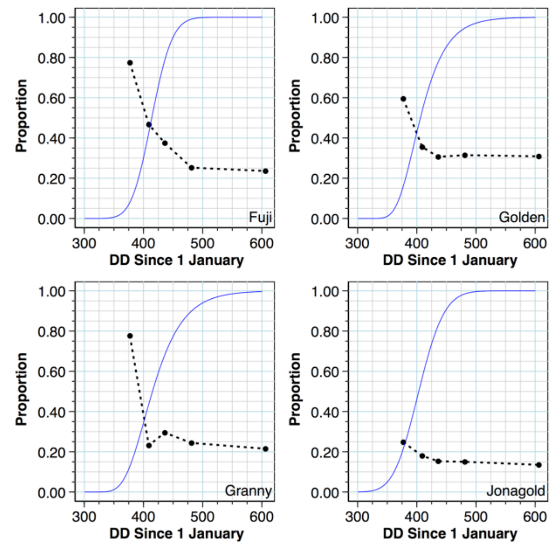
Fig. 5. Correlations between the relative number of open blooms (solid line) and the proportion of honeybees foraging each date on that cultivar.



Quincy, so we have fruit set if no thinning occurred, but nothing else for that cultivar. Hand thinning happened on April 24, 26, 28, and May 1st. These thinning dates corresponded to 337, 416, 459, and 504 DD. The "no thinning" count was done on 24 April, but assumption is that this happened at the end of the flowering period or ≈ 600 DD.

Methods Cherry Flowering Time: The cherry flowering was investigated in 2018. We were able to determine the bloom phenology of Chelan cherries at a single location near Rock Island. The overlap of bloom in apples and cherries made it nearly impossible to sample both and the choice of apples as being more important was based on the larger amount of data that we had and felt that we could finish up this past year. We did not do more cherry work as Dr. Mike Willett indicated at the last technology review that cherry bloom work had been completed at the OSU Hood River Station and not to pursuit this further.

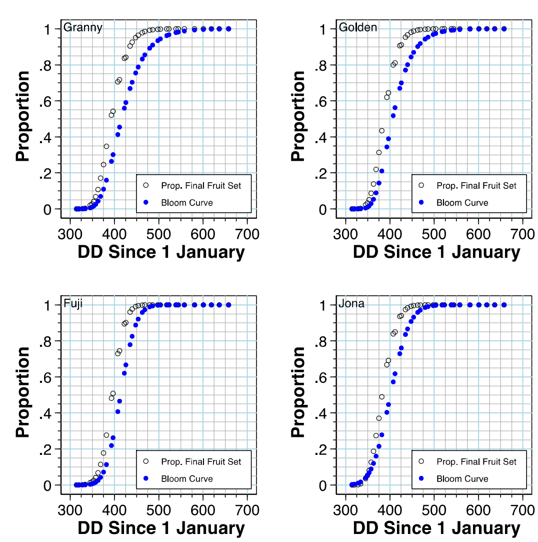
Fig. 6. Bloom curve (solid line) and fruit set when all open flowers were removed at five different times of the season for four different apple cultivars



Results Cultivar Choice by Honeybees: The data showed that the honeybee distribution on the different cultivars was highly correlated to the relative proportion of flowers that were in bloom (Fig. 4). The correlations were very good and support the idea that the honeybees do not actively discriminate among cultivars, instead their distribution is related to the numbers of flowers that are open on a particular cultivar at any given time. While there were some differences where the number of bees (dark dots) were higher than the proportion of flowers open on Cosmic Crisp (Fig. 5) – this is likely due to the Cosmic Crisp block being closest to the large bee yard. Similarly, the Granny area sampled for bees was the location that was farthest from any of the hives, whereas Fuji, Golden, and Jonagold were about the same distance from the hives and track the bloom density curve very well.

Results Fruit Set: The fruit set was highest early in the bloom period for all cultivars, then tended to flatten out by the second time the flowers were thinned (Fig. 6). The exception to this was Fuji whose flowering tends to start and peak later than the other cultivars – that cultivar didn't flatten out until the last hand thinning on 1 May. Jonagold, which starts blooming early and comprises the majority of the cultivars in our blocks showed very little variation in fruit set throughout the season. This is because early on, the majority of the flowers open were other Jonagold flowers, so that the cross-pollination rates for that cultivar were very low initially, and throughout the majority of the flowering period (until about 460 DD).

Fig. 7. Proportion final fruit set (open circles) and proportion bloom completed (solid circles) for each of four cultivars tracked at the Sunrise orchard in 2018.



When the bloom curve (blue dots – cumulative proportion of all flowers open) is plotted on the same axis as the cumulative proportion of all fruit set (Fig. 7), we found the latter 24% of the flowers from Jonagold only contributed about 5% of the total fruit set for that cultivar. Virtually the same percentages were also found for the other 3 cultivars (24.5, 23, and 23% for Granny, Golden, and Fuji's, respectively). You can see in the difference is that the latter flowers really play almost no role in fruit set.

Examination of the model output also showed that the window for setting fruit is fairly narrow; the center 90% of all fruit are set within 75 to 100 DD. For all 4 cultivars fruit set reached around 5% fruit set at 350 DD and 95% fruit set between 425-450 DD.

Obj. 4. Evaluate the effects of variability in spring weather conditions, as well as directional shifts toward earlier bloom on fruit set and best pollination management strategies.

Evaluation of bloom time was presented in last year's progress report and showed that at three representative locations (Richland, Wenatchee, Wapato) median bloom time (median is when half the years evaluated will be above and half below all bloom time values) will be changed by 21 days using the mild scenario (RCP 4.5 -up to 650 ppm CO_2 with stabilization after 2100) and 30 days using the increasingly more likely climate change scenario (RCP 8.5 – 1380 ppm CO_2 and still rising at 2100.

The earlier flowering time poses several possible problems for honeybee pollination. First, bloom starts earlier in the year which means that the day length occurring at those earlier dates will reduce honeybee foraging time (since they only forage during the day). Secondly, the sunlight is less intense early in the season, which also affects foraging rates. Third, the temperatures around the bloom period may be more variable with either higher or lower temperature profiles during the day. The temperature profile is also a key driver of honeybee foraging and could affect foraging either positively or negatively. The fourth potential issue is that Washington tree fruit is not the only crop that is affected by climate change and it is likely that crops like almonds that bloom earlier in the year will also be shifted. At first glance, it might seem the shift in almonds will not be a problem, because we use the same bees that pollinate California almonds. However, population growth in honeybee colonies is driven by day length. Egg laying by queens does not occur until day lengths reach 10-11 hours photoperiod. Thus, we might not have well developed colonies (with large amounts of brood from pollination of almonds) to the extent that we currently enjoy.

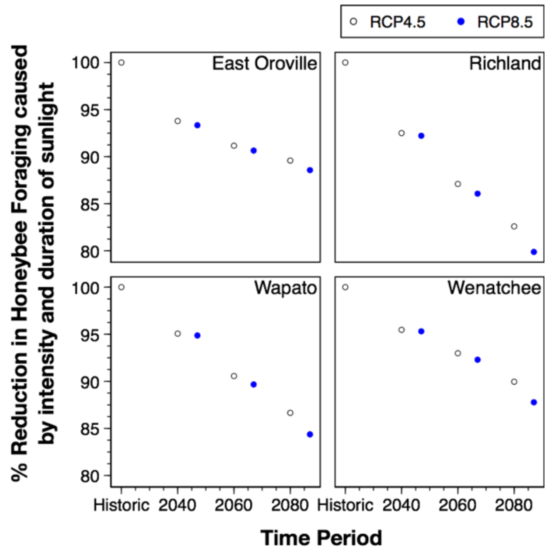
Methods: To test the first two issues, we used data gathered the past two years for bloom timing of Cosmic Crisp (very late blooming) and Jonagold (very early blooming) and examined the period between 5% flowering of Jonagold and 95% flowering of Cosmic Crisp. We used the same climate change scenarios for the same three locations (Richland, Wenatchee, Wapato) as before and added another one (Oroville) to examine how much the temperatures and reduced sunlight might affect honeybee foraging rates across the north-south extent of Washington tree fruit production. As before, we used the periods for historical (1979-2005), 2040 (2025-2055), 2060 (2045-2075), and 2080 (2065-2095) using the two climate change scenarios.

Results: We found that the median temperature profile during the bloom period did not vary more than 1.2°F at any site with either climate change scenario. These relatively small temperature changes during the bloom period resulted in about the same performance in honeybees foraging, with only a slight change (max < 3.4%) in foraging rates related to temperature. Essentially, even though the bloom period occurs much earlier on a calendar date basis, the temperature profiles will not vary enough to effect honeybee foraging.

In contrast to the temperature effects, the median sunlight duration at the earlier dates of bloom vary from ≈1.1-1.6 hours less (RCP8.5) or 1-1.3 hours (RCP4.5) less with the reduction increasing from

Oroville to Richland. These values correspond to a reduction in foraging time of 7.5-10.9% or 6.4-9.5% for the more severe and less severe scenarios, respectively.

Fig. 8. Change in honeybee foraging rate caused by shift in time of bloom which causes foraging to occur under less intense sunlight and shorter days. RCP4.5 is mild climate change scenario, RCP8.5 is the more severe situation.



In addition to reduced foraging times because of the earlier flowering times, the sunlight intensity at any given time is also affected by day of the year and is reduced early in the year compared to the historical foraging time. The differences in sunlight intensity from bloom occurring earlier in the year causes about a 4-10% reduction in foraging rates compared to the historical normal bloom period (this is based on the clear sky radiation, so it doesn't consider any change in cloud cover that is not predictable). Overall, the reduction in foraging caused by changes in both sunlight duration and intensity amounts to roughly 10.4-17.4 and 11.4- 20.1% reduction (RCP4.5 and RCP8.5, respectively) compared to the historical time of bloom. All of these effects are smallest in the more northerly locations and increase going south and as time goes on.

The changes in honeybee foraging related to climate change appear to be primarily a result of the shorter day length and lower intensity of sunlight earlier in the season. The climate change scenarios do not provide any indication of cloudiness, so our study assumes the clear sky radiation value and how that changes over the year. If there are any differences that are systematic (*e.g.,* earlier days are cloudier as the climate changes), then the effects may be greater or lesser than what our study suggests. Regardless, the changes should occur relatively slowly, but the expectation should be that the bees will be less efficient (up to ≈20%) which would require more bees to achieve the same results as we have currently. Another way to view this is from the perspective of "climate analogs", where we look at a location in the future and compare it a current location. In this sense, the flowering time in Oroville will be similar to the Richland location in 2080 under the RCP4.5 and in 2060 under RCP8.5. Similarly, in 2040 Wenatchee will have the same median flowering time as Richland currently does under either climate change scenario.

Executive Summary

Project Title: Development and validation of a precision pollination model

Keywords: apple bloom curves, netting effects on honeybees, climate change effects on pollination, fruit set model

Abstract: Bloom curves for 7 different apple cultivars were developed. Netting during bloom slows bloom, disorients honeybees, and reduces both pollination and fruit set. A fruit set/pollination model shows that the first 95% of fruit set happens within the first 75% flowering. Climate change will reduce honeybee efficiency between 11.4-20.1%.

Summary: We developed bloom curve models to predict when bloom occurs on a degree-day basis for the cultivars Fuji, Gala, Golden Delicious, Granny Smith, Jonagold, Cosmic Crisp and Honeycrisp. These models are useful in timing predictions, but also understanding the overall pollination/fruit set system and in models for fruit set.

We also evaluated the effects of netting being up during the bloom period. We found that the netting slowed the process of bloom, reduced the number of honeybees foraging under netting, and made fruit set much more erratic than in open areas. We also found that if the edge of the netting was dropped down slightly from the top (*e.g.,* a foot), that the honeybees tended to get caught in the area and die of exhaustion because they couldn't return to the hive and couldn't escape.

Evaluation of the honeybee foraging patterns on different showed that they were determined by the relative abundance of the flowers compared to the other cultivars – the more flowers present on a particular cultivar was highly correlated to the number of honeybees foraging there. We also found that a modified version of Dr. DeGrandi-Hoffman's model predicting fruit set tracked well with our field studies where we examined fruit set in manipulated plots (where we thinned or not at different times throughout bloom). Further examination suggests that the first 75% of the bloom period is responsible for 95% of the fruit set and that most of the fruit set occurs in the period of 350-450 DD.

The effect of climate change was evaluated using climate change scenarios and the honeybee foraging model currently on WSU-DAS. This model is a variation of Dr. DeGrandi-Hoffman's foraging model and allows us to evaluate the quality of foraging based on temperature, wind speed, solar radiation, and rainfall. For our simulations, we only incorporated climate change scenarios for temperature and solar radiation, since rainfall and windspeed are not well predicted by the climate change scenarios. We found that bloom should occur between 21-30 days earlier by 2080, but the temperature profile during the bloom period would change only slightly (1.2°F), which would have minimal impact on honeybee foraging. However, the earlier bloom dates would decrease the median daylength between 1.1-1.6 hours (using the most likely scenario) or 7.5-11%. Moreover, the median intensity of sunlight also would be reduced so that overall we expect foraging would be reduced from 11.4-20.1% depending on the location and time frame examined. These effects could be much worse if there is some systematic change in windspeed or rainfall that would occur in the earlier times. Note these effects do not consider how the honeybee colony health and population dynamics would be affected by climate change, which is being examined in another grant (not funded by the commission).