FINAL PROJECT REPORT

Project Title: Evaluation of environmental data used for IPM models

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Percentage time per crop: Apple: 45% Pear: 25% Cherry: 25% Stone Fruit: 10%

Other funding sources: None

Total Project Funding: $154,178

Budget History:

Item	Year 1: 2010	Year 2: 2011	Year 3: 2012
Salaries[1]	24,622	28,833	26,000
Benefits [2]	7,810	12,948	10,833
Wages	0	0	5160
Benefits	0	0	882
Equipment [3]	21,000	0	0
Supplies	3,000	3,150	3,500
Travel [4]	2,000	2,100	2,400
Plot Fees	–	–	–
Miscellaneous	–	–	–
Total	58,432	47,031	48,715

Footnotes:
[1]4 months Ute Chambers (Y1-Y3), 2 Months T. Melton Y1, 3 Months Y2-3
[2]Ute Chambers 32%, T Melton 30.9%
[3]Weather stations and sensor costs
[4] within-state travels

Objectives:
1. Evaluate the validity of virtual weather stations using a combination of regional and site-specific (in-orchard) weather monitoring systems and NOAA site-specific forecasts.
2. Evaluate the differences between AWN and within-orchard conditions on model accuracy.
3. Compare the effect of high and low-density plantings as well as overhead cooling on environmental monitoring and how horticultural and operational changes affect model accuracy.

Significant Findings:
- Virtual weather stations work well on the insect models, with average error rates below that needed for pest management purposes when a calibration data set is available.
- Error rates of the corrected data did not increase over the course of the season in either the AWN or Wilbur-Ellis station data, while uncorrected data did.
- Data from AWN stations directly adjacent to orchards predicts insect events will occur later than orchard data before June and late during June-August. These differences can exceed the three-day threshold.
- Wind speed within an orchard is reduced to favorable conditions for CM adult flight compared to measurements taken outside the orchard.
- Both AWN and the NDFD forecasts are better at predicting orchard environmental conditions in high-density orchards than low-density orchards.
- Overhead cooling as used in our study reduces daily maximum temperatures, but had no significant effect on model predictions or on CM longevity.

Results and Discussion:

***Objective 1* –** We have completed analysis of the 2009-2012 NOAA (National Oceanic Atmospheric Administration) site-specific weather forecasts known as the National Digital Forecast Database (NDFD) for possible use as virtual weather stations. The following results are based on data from 2009-2012 for the AWN locations and from 2010-2012 for the Wilbur-Ellis (WE) stations in Central Washington.

To run the analysis, we match up the NDFD forecasts to the actual data recorded by weather stations at each of the AWN/WE locations. We eliminated AWN locations west of the Cascades, locations where fruit is not grown, and those locations where we did not have a complete record over the 3- (WE station) or 4-year (AWN stations) periods. We also eliminated AWN sites that were placed in the middle of irrigated center pivot locations. This left us with 92 AWN sites and 36 WE sites. We compared model performance at predicting nine different "events" (Table 1) in the life history of seven different models (Apple maggot [AM], codling moth [CM], *Lacanobia* fruit worm [LAC], Obliquebanded leafroller [OBLR], *Pandemis* leafroller [PLR], Peach twig borer [PTB], and Western Cherry Fruit Fly [WCFF]).

We ran two separate analyses:
1. We evaluated the relationship between DD calculated from AWN and NDFD data and whether the relationship was stable between the different years. Because we were dealing with very large numbers of stations, models, and years (e.g., 92 x 7 x 4 = 2576 separate regressions for AWN data alone), we knew that statistical differences could be declared in129 of the regressions, even when no statistically significant differences were found at the 95% level. Thus, rather than focusing on strict statistical differences, we graphed the regressions for each year, model and location and looked for a trend in regressions changing (e.g., the slope increasing or decreasing each year).

Table 1. Insect models and events tested to compare model accuracy using the current day NDFD forecasts and real data from WSU-AWN and Wilbur-Ellis Stations in Central Washington.

Model	Events tested
Apple Maggot (AM)	Adult Emergence: 1, 10, 20, 30, 40, 50, 60, 80, and 90%
Codling Moth (CM)	1st moth; 10, 25, 50, 75% egg hatch in 1st generation; 10, 25, 50, and 75% in second
Lacanobia (LAC)	Egg hatch: 1, 10, 25, 50, 75% in 1st generation; 10, 25, 50, and 75% in second
Obliquebanded Leafroller (OBLR)	Larvae in 4th instar: 20, 40, 60, 80, 90% in first generation; 20, 40, 60, and 80% in second
Pandemis Leafroller (PLR)	Larvae in 4th instar: 20, 40, 60, 80, 90% in first generation; 20, 40, 60, and 80% in second
Peach Twig Borer (PTB)	Egg hatch: 1,10, 25 50, 75% in first generation; 10, 25, 50, and 75% in second
Western Cherry Fruit Fly (WCFF)	Adult Emergence: 1, 10, 20, 30, 40, 50, 60, 80, and 90%

2. We ran the models for each year, location, and event using the real weather stations, the raw NDFD temperatures, and a corrected NDFD value based on the regression between the weather station max and minimum temperatures and those from NDFD. The correction was calculated based solely on 2009 data, then applied to 2010-2012 NDFD data for AWN stations and for the Wilbur-Ellis (WE) stations we used 2010 as the calibration year (we did not have 2009 data from WE). We summarized the error in model predictions between the weather stations (AWN or WE), and the raw and corrected NDFD data by model, event, and station. For purposes of management, we considered an error of 3 days to have no effect on control, thus everything was evaluated relative to the ability to achieve an error ≤ 3 days. It is important to realize that in the evaluation of the data even a miss by even one degree-day (DD) can lead to a full days error for that model, location, or event. The phenomenon of small DD differences causing large errors is more common during cool weather periods, for example in spring. Thus, the average error we report is very conservative.

Results:

Comparison of NDFD and station data. Over the four years comparison of NDFD with the AWN stations, we found for roughly 5% of the stations that the error using the NDFD forecasts without any corrections made the data unusable for IPM purposes. This was often found in areas with large elevation changes or diverse topography (narrow river valleys), but not always. In one case (Ellisforde station), switching to an adjacent grid made the errors virtually disappear, so we may be able to switch grids when there is a problematical grid. With our recently acquired ability to access the historical NDFD forecasts throughout the continental US, we can examine this approach using some of the AWN data in the future.

The overall error rate for the raw NOAA data (4.3 days) dropped ≈47% when using the data corrections to 2.3 days (Fig. 1). Error rates over the course of the season were relatively constant using the data correction, while they rose on average about 1 day in the raw NOAA data (Fig. 2A). The western cherry fruit fly and *Lacanobia* models had the lowest overall error rates (1.6 and 1.7 d, respectively), but all models had an overall error rate lower than 3 days (Fig. 1A).

For the WE stations, the overall error rate of the raw NOAA data was reduced ≈44%, from 5.2 to 2.9 days using the data corrections (Fig. 1B). As seen in the AWN-NOAA data pairing, the corrected data for the WE stations did not show significant changes in the error rate over the season (Fig. 2B). The models all performed approximately the same, with the AM, *Lacanobia*, PLR, WCFF having a

Fig. 2. Mean Absolute Deviation of the error rate for seven different insect models across all stations, events and years. Dashed lines are 3 day standard. A. AWN stations. B. Wilbur-Ellis Stations.

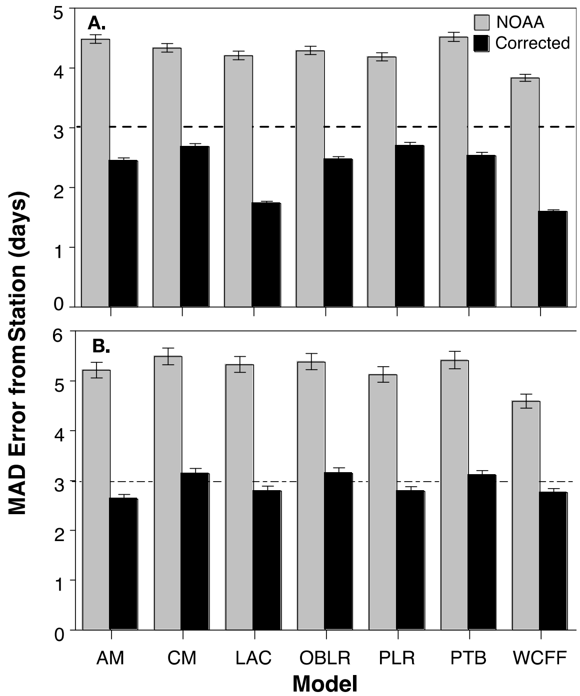
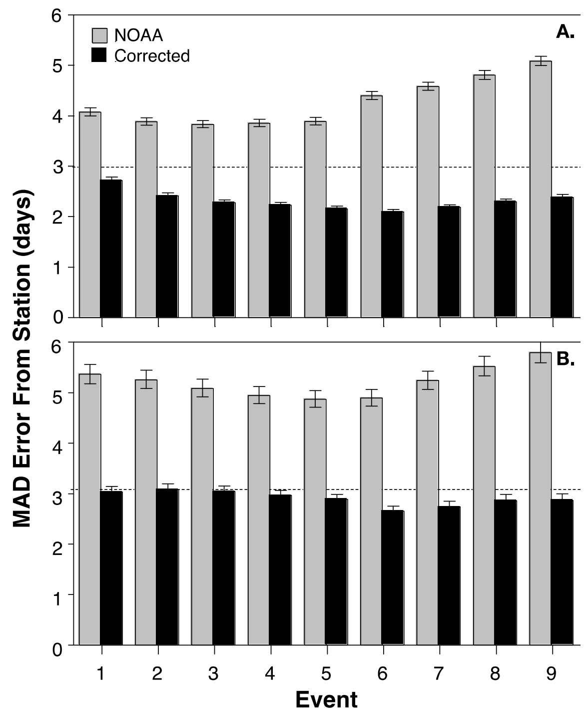


Fig. 2. Mean Absolute Deviation of the error rate for the 9 events over all models, stations and years. Dashed lines are 3 day standard. A. AWN Stations. B. Wilbur-Ellis Stations.



mean corrected error <3 days and the CM, PTB, and OBLR models being just slightly over 3 day error at 3.1, 3.1, and 3.2 days average.

For our analysis, the physical weather stations were used as the standard as if no error in their measurements occurred. The NOAA data or the corrected data were then evaluated based on when predictions occurred using the three different weather readings for each model. However, physical weather stations have an inherent error /failure rate, so it is extremely likely that in some cases the errors were not with the virtual weather station, but with the physical ones. With both the AWN and the Wilbur-Ellis data, such errors were obvious in the temperature data and we needed to implement multiple filters to insure errors from station/sensor failures were minimized. For stations where we found discrepancies between the physical station and the NOAA forecasts that varied significantly by years, we expect that the stations probably are the issue rather than the NDFD forecasts. In addition, errors in the calibration years (2009 AWN, 2010 WE) have a much greater impact on accuracy than errors in subsequent years.

Finally, the error rates we presented are not the minimum error rates possible. This is because at some locations the raw NOAA data performed better than the corrected data. This is relatively easy to see in evaluation of the data particularly when multiple years are available. However, for both the AWN and WE stations, if the raw NOAA error was less than ≈ 2.5 days in the calibration year, in most cases that trend held up for all subsequent years of the study. Thus, we can expect the error rates are lower (albeit not much in most cases) than shown in the graphs or averages reported.

Overall, our work shows that the virtual weather stations are of acceptable error for insect pest management purposes. The data necessary to test the pathology models is all given by the NDFD forecasts, but the greater amount of information required (humidity, rainfall) will certainly complicate validation. While the virtual weather stations work well, they are useful primarily in areas underserved by other weather networks or where weather networks are not well maintained or are experiencing equipment failures. If the weather network is well maintained (including calibration and data checking algorithms) and present in the immediate vicinity, those should have a lower error rate than the virtual weather stations. However, the virtual stations should be strongly considered when the environmental monitoring stations are far from orchards or if the terrain is complex. The NDFD also provides a good check on weather station accuracy and we already use these forecasts to replace AWN data if for some reason a particular station goes off-line or if there are power or Internet failures at the AWN server – we simply update the data once AWN or the station comes back on-line.

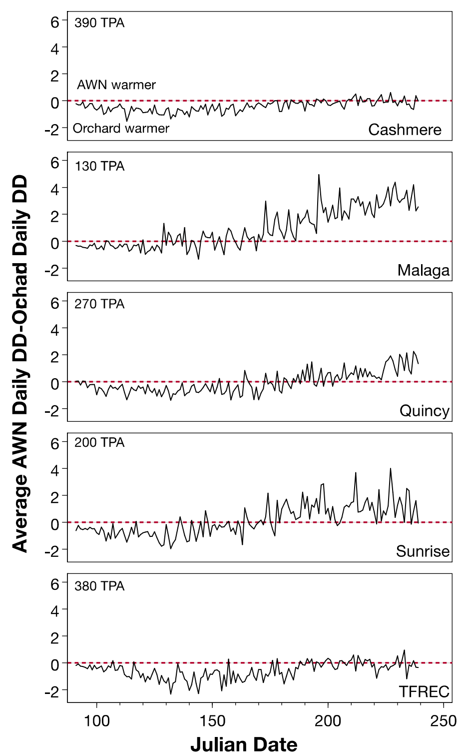
Objective 2. – We have completed three years of microclimate data collection in five orchards immediately adjacent to AWN stations (Table 2). We calculated the daily CM DD using maximum and minimum temperatures from the adjacent AWN station and from a weather station inside the orchard. We then calculated the difference between the two and averaged this over the three-year period at each orchard and plotted the differences versus day of the year to evaluate if there were seasonal differences (biases) in DD accumulations.

Results

Comparison of microclimate between AWN data and orchard interior.

Air temperature: We observed large day-to-day variations and diurnal pattern in the difference of air temperature between the tree canopy and AWN. In all three years, mean air temperature within orchards exceeded air temperature outside of orchards (AWN) in the early part of the season (April-May), and was lower in June-August. This trend results in DD accumulations within the orchard being higher in the early season and lower later in the year. The greatest differences between early and late season were found at the Malaga and Sunrise locations where the tree densities were lowest (130 and 202 trees per acre, respectively) and decreased in the Cashmere and TFREC sites where tree densities were highest (Fig. 3).

Fig. 3. Differences in codling moth DD accumulations calculated using AWN and within orchard weather stations at 5 orchards averaged over a 3-year period. TPA in the upper left corner is trees per acre.



Comparison of model predictions between orchard interior and nearest AWN station. As was found in objective 1, the relationship between AWN and orchard DD is predictable and the slope remained fairly constant from year to year between 2010 and 2012. Looking at model predictions, the average absolute model prediction differences were lowest in 2012 (2.0 ± 1.4 d (mean ± standard deviation) compared to 2010 (2.5 ± 2.0 d) and 2011 (3.0 ± 1.9 d) (Fig. 4). The long and cool spring in 2011 likely caused the larger errors compared to the other two years.

Other microclimate Information:

Bark temperature differed from air temperature regardless of whether the temperatures were measured within or outside the orchard. During February through April, bark temperature was markedly higher than AWN air temperature (by 3.5 ± 5.3°F). We recorded temperature differences of up to 46.9°F at Sunrise in February 2012. On the other hand, during June through August, the average bark temperature was lower than air temperature (by -2.6 ± 5.3°F). This pattern in bark temperature is caused by the leaf expansion and the resulting increased

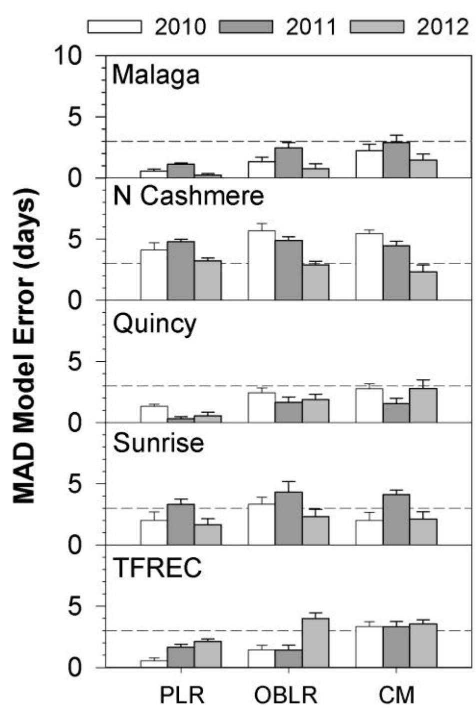
Table 2. Tree density, irrigation placement, and distance and elevation differences to the nearest AWN station for all study sites in objectives 2 and 3.

Orchard	# Trees per acre (HD/LD)	Irrigation	Nearest AWN station	Distance to AWN station (ft)	Elevation difference to AWN station (ft)
Objective 2 (Comparison AWN & orchard interior)					
Malaga	129	overhead	Malaga	395	13
Cashmere	389	under-tree	N Cashmere	165	0
Quincy	519	under-tree	Quincy	250	0
Sunrise	202	overhead	WSU Sunrise	1430	0
TFREC	379	under-tree	WSU TFREC	130	0
Objective 3 (Comparison high- versus low-density)					
Columbia View	2420 / 134	under-tree	Orondo	610 / 670	3 / 15
Orondo	605 / 109	under-tree	Brays Landing	14,760	395
Quincy	519 / 269	under-tree	Quincy	250	0
Sunrise	1452 / 202	under-tree (HD) overhead (LD)	WSU Sunrise	1430	0

interception of solar radiation. Elevated bark temperatures can affect insects that live or overwinter under bark such as codling moth and accelerate emergence in spring. We will continue to evaluate bark temperature to see if we can significantly improve our estimates of emergence of various insects that overwinter under bark.

Objective 3. Environmental data was recorded in four orchard pairs with adjacent high- and low-density apple blocks in 2011 and 2012. Using daily maximum and minimum temperatures we calculated and compared DD accumulations for key insect events between high- and low-density orchards. We also included model predictions based on data from the nearest AWN station (Table 2) to see how AWN data compared to high- and low-density orchard conditions.

Fig. 4. Mean Absolute Deviation of the error rate between orchard and AWN data for three models over all events. Dashed lines are 3 day standard.



Overhead cooling was set up in our high-density apple block at Sunrise along with two sets of data loggers to record microclimatic differences related to the cooling. In the west end of the same block, another pair of data loggers was set up to measure conditions without overhead irrigation. In 2011, cooling intervals were set to 15 min on/ 15 min off between 12 and 5 p.m., while in 2012, cooling intervals were changed to 15 min on/ 10 min off between 12 and 6 p.m. For a period of five days in 2012 (August 17-21), we also tested continuous cooling during the same hours in the afternoon. Overhead cooling was used on 35 days between July 29 and September 13, 2011 and on 39 days between July 6 and August 21, 2012, when daily maximum temperatures were predicted to be above 86°F and the sunburn browning model estimated medium or high risk for sunburn to occur. In the non-cooled section, kaolin was sprayed for sunburn protection on July 14, 2011 and July 3, 2012. To determine the effect on model predictions we calculated DD using the sine-wave method based on daily max/min temperature as well as the 15-min method based on 15-min temperature values. The latter method gives a more accurate picture of possible differences in DD because daily maximum temperatures in cooled plots often occurred after the cooling was turned off (6 p.m.) on very hot days.

Results

Effect of orchard density on environmental parameters. Similarly to Objective 2, the differences in environmental parameters between HD and LD orchards showed large day-to-day variations as well as seasonal and diurnal patterns. However, also as seen in Objective 2, the general trend is that the differences between within orchard and AWN temperatures late in the season are greatest in the low-density orchards and less in the high-density orchards for each pair (Fig. 5). Thus, extra-orchard stations like AWN and virtual weather stations powered by the NDFD are better at estimating heat accumulations within high-density orchards than in older low-density orchards.

Comparison of model predictions in high- and low-density plantings. In both years, the overall mean absolute deviation in model predictions between adjacent high- and low-density orchards was below the three-day threshold for most sites and models. However, as would be expected given the trends shown in Figs. 3 and 5, errors accumulate over the course of the season so that when using extra-orchard data, early season errors make events appear late, while errors later in the season make events seem to occur earlier (Fig. 6). These seasonal increases of model errors were more pronounced in 2011 than in 2012, because the cooler temperatures in 2011 tend to exaggerate error rates.

Bark temperature differed between HD and LD blocks during the day due to differences in penetration of solar radiation. Overall, daytime bark temperature was higher in HD blocks than in LD blocks from April through October, but lower than in LD block during the remaining months. The average difference was -2.7 ± 6.7°F during February and March and 6.8 ± 8.7°F during May-August. This difference increased with canopy development and the canopy provided more shade in the LD blocks. At night, bark temperature in HD trees was similar to or slightly lower than that in LD trees (difference: -0.1 ± 5.5°F).

Fig. 5. Differences between AWN and within orchard daily CM DD accumulations in paired high and low density orchards at four different locations over a three-year period.

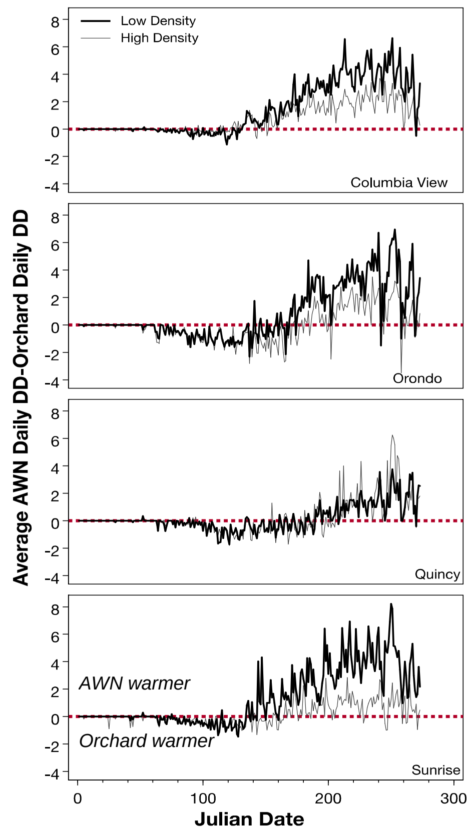
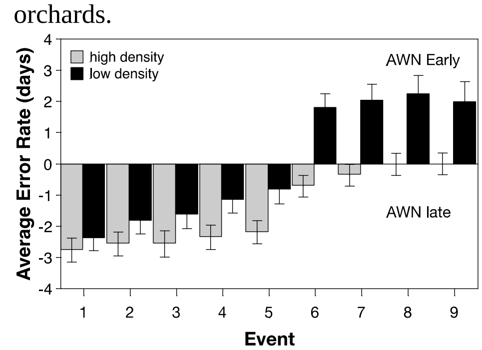
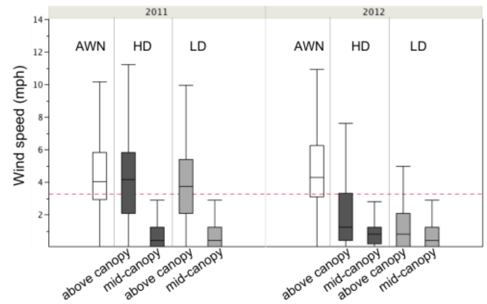


Fig. 6. Difference between when within-orchard and adjacent AWN stations predict CM events at five paired high-low density orchards.



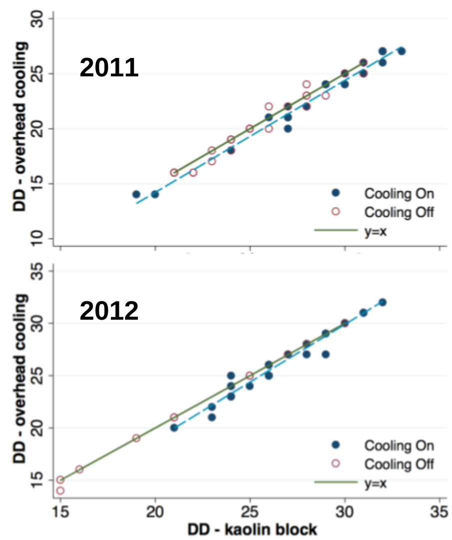
Wind speed within an orchard is dramatically reduced compared to the wind speed outside an orchard (measured by AWN) or above the orchard canopy (Fig. 7). This can have an effect on the flight activity of insects. Our previous research shows that codling moth cannot fly at wind speeds > 3.3 mph. Average wind speed above the canopy or outside the orchard was above 3.3 mph during the flight period (sunset + 3 hours, 7-11pm) from May through August 2011. However, wind speed between the trees was nearly always below 3.3 mph (Fig. 7). This means that CM adults are still capable of dispersing within orchards even though above the canopy wind speeds are unsuitable for directed flight. Models that include wind speed as a measure to predict the likelihood of CM flight and oviposition will need to take these differences in wind speed between orchard interior and the outside into consideration.

Fig. 7. Wind speed (in mph) between 7 p.m. and 11 p.m. at 4 pairs of low- and high-density orchards and at the adjacent AWN station. Dashed line is the upper speed threshold of CM.



Effect of overhead cooling on temperature and model predictions. Overhead cooling in our high-density plot slightly lowered the DD accumulations compared to the kaolin block (Fig. 8), but caused no significant effect on model predictions (< 1 day): CM longevity was also unaffected in both years. Using the 15-min method for DD accumulation, the total difference between overhead cooling and kaolin treatment for CM was 25 DD and 34 DD (on August 26, 2011 and 2012, respectively), and for OBLR 22 and 27 DD (on August 26, 2011 and 2012, respectively).

Fig. 8. Relationship between codling moth DD in overhead-cooled vs. kaolin-treated high-density block.



During the interval cooling period in 2011 and 2012, temperatures were 3.1 ± 1.0 °F and 4.3 ± 1.5 °F lower than in the kaolin block, respectively. Constant cooling, on the other hand, lowered the air temperature by an average of 5.4 ± 1.6 °F. As canopy air temperature drops due to overhead cooling it still follows the curve of the temperature in the kaolin-treated block. This means that fewer heat units are accumulated during that cooling period until the temperature in the cooled block also reaches the upper threshold for models with horizontal cut-off (CM-88°F, OBLR-86°F), at which point heat-units are constant and identical for the overhead cooling and kaolin treatments. Kaolin by itself did not significantly alter canopy air temperature and DD, when comparing the kaolin-treated block and the block without kaolin when overhead cooling was not used.

Even though overhead cooling does not seem to affect codling moth phenology, it might change microclimatic conditions enough to impact disease or rust mite development. Both are positively influenced by relative humidity. However, in our small plots during the cooling hours the relative humidity was very similar in the kaolin and overhead-irrigated block (33% versus 36%, respectively). We noticed that the misted air often drifted with the wind from the overhead-cooling block towards the kaolin block, which were only 15 rows west of the cooled rows. This may seem like it would imply that cooling could be reduced by cooling only every few rows, however, the effect on air temperature is not the key concern in sunburn protection, instead Larry Schrader has indicated that hydro-cooling of the fruit by contact with the water is thought to be the most important factor reducing sunburn.

Executive Summary.

The project has several important outcomes. First, NOAA's National Digital Forecast Database (NDFD) can be used for insect pest management purposes, if there are some calibration data available. We have also recently learned to access the stored historical data (NDFD has been on-line since 2004), so that we can use any historical data that a grower/IPM consultant has previously collected to calibrate a particular virtual station. This possibility still requires someone to run the calibration curve, but it should be possible to automate the process of collecting the data and calibrating the station using a web-based interface. Secondly, our new access to historic NDFD forecasts also means that we should be able to use the NDFD data to implement long range forecasts that provide reasonable predictions (for IPM) out to 35 days from the current time. Both of these projects (virtual weather stations and long-range forecasts) are in a new proposal being submitted and should dramatically leverage the flexibility and usefulness of WSU-DAS.

The third major outcome is showing that differences between extra-orchard stations (such as AWN) and within orchard weather stations causes seasonal biases in model accuracy. Extra-orchard stations tend to underestimate temperatures early in the season and overestimate temperatures late in the season. The differences in outside and inside orchard stations are generally not enough to break the 3-day error barrier, but need to be considered, especially if the outside station is distant from the orchard in question. The current trend to high-density orchards favors accuracy compared to older, low-density orchards regardless of whether the stations are virtual weather stations or fixed stations like AWN. Clearly, calibration of AWN stations should be considered if stations are distant from the target orchard, and the procedures would be similar to calibration of the NDFD forecasts we performed. A very important future study should focus on how far from a station environmental conditions are reasonable predictors of orchard conditions. Obviously, a fixed distance will not be the result, but instead would be related to topographic diversity and local microclimatic variations. However, a combination of historical information from AWN, NDFD, and other sources could be combined with techniques similar to those used in this report to give at least a ballpark figure.

The use of overhead cooling to reduce sunburn does not appear to significantly affect model predictions. However, the higher humidity during what is normally a very dry part of the season may facilitate buildup of rust mites or diseases.

Wind speed measured within the orchard cannot be easily predicted using standard meteorological measurements and standard measurements cannot be used to evaluate effects on insect phenology and reproduction. Borders are the areas where a high proportion of the pests are found, but measurements above the canopy are of limited use in evaluating population dynamics. Even though our data were not taken to evaluate how quickly wind speed drops off moving into a block, it is likely that fruiting wall orchards will have a quicker drop-off with distance from the border, except in the case where the wind blows right down the rows.

The relationship between the bark temperature, solar radiation, and insect emergence in the spring also needs further study. Evaluation of European studies of solar radiation and bark temperatures show trends unlike anything we see in our data. In addition, even if we find the exact relationship, it still does not guarantee predictions based on bark temperature will be better than those based on air temperatures.