Is Biofix Necessary for Predicting Codling Moth (Lepidoptera: Tortricidae) Emergence in Washington State Apple Orchards?

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ABSTRACT   The heat-driven phenology model used for initiating codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), management in Washington state was examined to determine the need for using the capture of the first moth as a method of synchronizing the model and phenology of field populations (=biofix). We examined trap catch data taken at 1–2-d intervals from two research orchards; one data set encompassed a 28-yr period and the other data set a 4-yr period. We also examined consultant-collected data taken at 7–10-d intervals from 15 sites ($N = 81$), mostly between 2001 and 2005. At the two research sites, we found the mean biofix occurred at 96 degree-days (DD) (DD Celsius by using 10°C lower threshold and 31.1°C horizontal upper threshold) after 1 January (SD = 14.4; min. = 68, max = 122). After correcting for longer sampling intervals in the consultant data set, the biofix at the nonresearch sites occurred at 97 DD ($N = 50$, SD = 14.4; min. = 74, max = 120), nearly identical to that at the research sites. We also examined the performance of the codling moth model at predicting moth flight and egg hatch using a biofix and by just accumulating heat units from 1 January. The model performance was similar in both generations regardless of whether a biofix was used. The elimination of biofix simplifies management and eliminates mistakes associated with poor trap catch, particularly in low-pressure situations where mating disruption reduces trap efficiency.

KEY WORDS   codling moth, phenology, biofix

The apple integrated pest management (IPM) program in Washington state is planned around control of the codling moth, *Cydia pomonella* (L.). Until the deployment of the heat-driven codling moth model originally developed at Michigan State University (MSU) (East Lansing, MI), timing for codling moth sprays were typically initiated 21 d after full bloom (Beers and Brunner 1992). Although that technique may yield good results in certain years and locations, studies showed that the different thresholds for apple tree development and codling moth development resulted in inconsistent timing of applications (Beers and Brunner 1992).

Initial attempts at predicting codling moth flight began in 1922 with the development of a heat-driven model that summed heat units from early in the season (typically 1 March) (Glenn 1922a,b; Shelford 1930; Headlee 1931). The initial models were handicapped in part by the poor performance of bait traps and the difficulty in using light traps over a broad geographical area. The calculations were also somewhat cumbersome and the environmental monitoring equipment of the time required daily attention. The codling moth model currently used in Washington was developed at MSU (Riedl and Croft 1974, Riedl et al. 1976, Welch et al. 1978), culminating in the Predictive Extension Timing Estimator (PETE) model described by Welch et al. (1978). This model was imported into the state of Washington and implemented by Brunner and Hoyt (1982) and evaluated by Beers and Brunner (1992).

The initial work at MSU examined ways to improve the predictive ability of the codling moth model. Riedl et al. (1976) reported that model accuracy could be improved by using the first moth capture (called a biofix) as a way to synchronize the model to field conditions. In their studies in eight orchards, Riedl et al. (1976) calculated that the observed first egg hatch averaged 6.1 DD (± 8.6 SEM) (numbers converted to degree-day [DD] Celsius from DD Fahrenheit used in that study) late when simply accumulating heat units from 1 March compared with 24.6 DD (±2.6 SEM) early when using a biofix. They felt that although the average overall was better using 1 March biofix, the roughly three-fold increase in variability was problematic. When their data are reanalyzed, use of the mean absolute deviation clarifies interpretation of accuracy because use of the average deviation can result in large differences (i.e., one early one late) canceling each other out and making it seem as if the models were working better or worse than they really were.

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Using the mean absolute deviation, the accumulation from 1 January resulted in an error of 21 DD (SEM 8.6) or 1.8 d (SEM 0.8), whereas the first moth biofix numbers resulted in an error of 6 DD (SEM 2.6) or 0.5 d (SEM 0.3). Although the differences between the two methods can potentially be significant in certain research settings, the increased precision comes at a cost related to the extra problems associated with setting a biofix.

From a purely academic perspective, use of a biofix seems to be a biologically sensible way to improve model accuracy. However, from the standpoint of implementing a codling moth DD model across a large area, use of a biofix becomes a significant source of confusion and error. First, in commercial orchards, moth populations are typically low enough that detection of the initial moth flight is difficult, particularly when trap density is low. This problem is exacerbated by use of mating disruption, which reduces the efficiency of the pheromone traps significantly. In extreme cases, biofix may be set only after a significant fraction of the population has emerged, resulting in management recommendation timings that occur too late to prevent damage. Second, consultants in the industry rarely check traps more than once a week during the critical period around biofix. This automatically means that the average error in setting biofix would be 3.5 d, much greater than the gain in accuracy noted by Riedl et al. (1976).

Finally, there is much confusion in the industry over what "biofix" actually represents. Some have recommended that biofix is not the first moth, but the "first consistent" moth catch (Knight and Light 2005). Additional problems with setting biofix occur when trap catch begins and then a cold period (or windy or rainy period) starts; some have recommended changing the biofix to when trap catch begins again after the cold period. This tactic is severely flawed because although moth flight is temperature-dependent between ≈12 and 25°C (Riedl et al. 1979, Song and Riedl 1985), codling moth development is well established to occur above 10°C (Glenn 1922b, Rock and Shaffer 1983, Pitcairn et al. 1991, Howell and Neven 2000). The discovery of a larval aggregation pheromone in codling moth (Duthie et al. 2003) also suggests that males remain close to female pupae and mate with them shortly after emergence. Thus, even though moths are not caught in traps, mating could still be occurring, and the population is still developing. In these situations, resetting the model may severely compromise its accuracy depending on the temperature profile during the period where flight is inhibited and the degree to which the population is aggregated in the previous year.

This study investigates the importance of biofix in Washington apple (*Malus* spp.) orchards for the accuracy of prediction of adult flight and egg hatch, two key parts of our integrated pest management (IPM) program. We use a combination of historical weather data and trap data obtained from consultants at different locations throughout Washington apple growing areas, and an intensively collected data specifically

Table 1. Locations of orchards used for comparison of biofix for WSU and non-WSU sites

Location	County	Yr
Non-WSU sites		
Basin City	Franklin	2003–2005
Brewster	Okanogan	2005–2006
Chinook	Grant	2003–2005
East Wenatchee	Douglas	2001–2005
East Wenatchee 2	Douglas	2002, 2005, 2006
Kennewick	Benton	2001–2005
Mattawa	Grant	1998, 1999, 2001–2005
Orondo	Douglas	2001–2006
Orondo 2	Douglas	1994, 1998, 2002–2005
Oroville	Okanogan	2001–2005
Othello	Adams	2001–2005
Pogue Flat	Okanogan	1999–2005
Prosser	Benton	2001–2005
Quincy	Grant	2001–2006
Royal City	Grant	2001–2005
WSU sites		
Columbia View	Douglas	2001, 2002, 2006–2007
Tree Fruit Research and Extension Center	Chelan	1979–1997, 1999–2007

geared to examining model accuracy of the PETE codling moth model.

Materials and Methods

WSU Data Set. Biofix consistency (first moth catch) was assessed by examining historic records of biofix collected at the WSU-Tree Fruit Research Center (WSU-TFREC) in Wenatchee, WA, from 1979 to 2007. Because of the experimental nature of the WSU orchards, populations there can be considered to be significantly higher than in a commercial apple orchard. Pheromone traps (2–4 per location) were checked every 1–2 d during the critical period of biofix. We also had 4-year's worth of data from 2001, 2002, 2006, and 2007 from the WSU-Columbia View orchard (WSU-CV), near Orondo, WA. These data were paired with weather data taken at the two locations. Degree-day accumulations were started on 1 January and calculated using a single-sine method (Baskerville and Emin 1969), with lower threshold of 10°C and a horizontal upper threshold of 31.1°C (Brunner and Hoyt 1982).

Non-WSU Data Set. Pheromone trap catch data from 15 different locations was collected from IPM managers over the period of 1994–2006 (Table 1) for the period around biofix. These data were then paired with weather data from the corresponding WSU-AgWeather Net stations that the consultants indicated was representative of each orchard location or from their on-site data loggers.

Effect of Biofix on Model Accuracy. To determine model accuracy, during the period of 2001–2007 at WSU-TFREC and 2001–2002 and 2006–2007 at WSU-CV, we collected trap catch data throughout the season at 2–3-d intervals. In addition to pheromone trap catches, we also collected data on fruit damage, which closely tracks egg hatch (Geier 1963) at WSU-TFREC during the seasons of 2001–2004 and 2006–2007, and at the WSU-CV orchards during 2006–2007 yr only.

During the first generation of codling moth in the 2001–2002 seasons we flagged 10 branches, each containing ten fruiting clusters and followed them throughout the generation. This design was replicated in three blocks. After adult flight was detected, the flagged branches were intensively sampled every 1–2 d for fruit damage; larval entry holes were circled with a permanent marker to avoid resampling the same damage. New entries were characterized by a small, shallow entry hole accompanied by fresh frass. The total number of new entries on each tree on each sample date was recorded. Older entries that were not discovered earlier were marked, but not recorded as new injuries. During the second generation, the same methods were followed, but we sampled 100 fruit clusters from each of three blocks.

From 2003 to 2007 (minus 2005 when no data were taken), fruit injury evaluations were initiated before the predicted onset of egg hatch ($\approx$205 DD from 1 January). Four trees were randomly selected at the beginning of the season and flagged for repeated sampling. All the fruit on those trees were inspected at regular intervals for new larval entries. Evaluations were repeated three times per week until harvest (early September). Generally, the crop load ranged from $\approx$50–100 fruit per tree. The sample unit was repeated at two locations for each WSU orchard.

Analysis. We first analyzed the WSU biofix data set to determine the mean $\pm$ SD of the time of biofix and calculated the 99% confidence intervals (CI) around the mean. We considered that any biofix found in the non-WSU data set that was outside the confidence limits was likely caused by three factors: 1) the longer trap checking intervals at non-WSU sites, 2) low population levels/mating disruption that reduced the ability to detect the first moths, or 3) poor weather data. To correct for the longer trap checking intervals used by consultants, we estimated biofix as the average DD accumulation between the last time a trap was checked and the first time a moth was recorded. This correction was only applied to non-WSU sites after 25% emergence (84 DD) had been reached in the WSU data set. For factor 2, all orchards where fewer than 15 moths were caught in the first flight were eliminated from analysis. For factor 3, these sites were typically ones with wildly divergent DD accumulations of first flight and where weather stations were >16 km away, or where weather stations generally seemed to be unrepresentative in terms of slope and aspect compared with the monitored orchard.

We used two methods of comparing the WSU and non-WSU biofix data sets. First, we used notched box plots to detect differences between the two data sets. Briefly, box plots show variability by constructing a box whose lower and upper edges indicate the DD accumulations for 25 and 75% of the data and the line in the middle is the median emergence time. The whiskers extend to extreme values. The notches on the box represent 95% CI about the median and if the notches do not overlap, it indicates significant differences between the populations (Chambers et al.
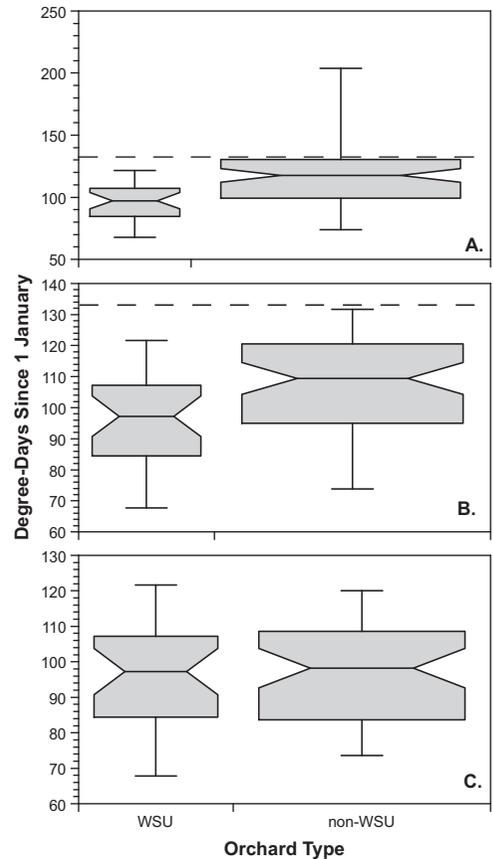

Fig. 1.   Notched box plots comparing WSU and non-WSU sites. (A) Raw data. (B) Corrected for poor weather data. (C) Corrected for sampling interval. Dotted lines in A and B indicate the upper 99% CI for the WSU data.

1983). The second analysis used empirical quantile-quantile (q-q) plots (Chambers et al. 1983) to compare the distributions of DD accumulations at biofix. Quantile-quantile plots were used because they are simple to calculate and allow quick and visually powerful comparisons between distributions. The plots were developed by sorting the DD accumulations at biofix from smallest to largest and then determining the percentiles of the distribution for the WSU and non-WSU data sets separately. The percentiles of the two distributions were then plotted so that the equivalent percentiles (e.g., the first percentile of the data from each distribution, second, etc.) are plotted as a scatter plot. If the two distributions are identical, all the points will lie on a line where $y = x$. If the points are on a straight line, but with a slope different than 1, then the distributions are not identical (they are similar in shape, but differ by a constant) (Chambers et al. 1983). The shape may also be different between distributions, suggesting nonlinear relationships in percentiles where the distribution shape deviates from $y = x$.

For the analysis of model accuracy, we used indifference band validation (Welch et al. 1981). Indiffer-
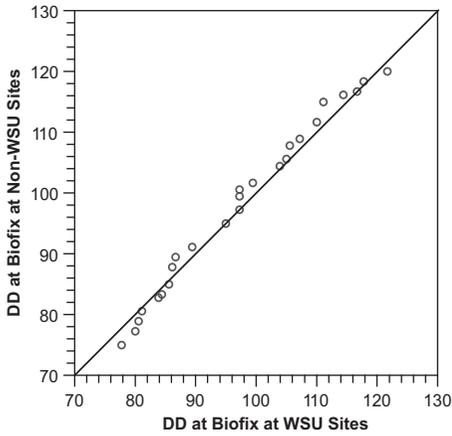
Fig. 2. Quantile-quantile plots of biofix occurrence at WSU and non-WSU sites. Solid line is $y = x$, which denotes no significant differences in distributions.

ence band validation simply plots the Julian day an event (e.g., x percentage of cumulative egg hatch or adults caught per generation) was observed in the field against the Julian day it was predicted to occur by the model. The indifference bands are then superimposed on the data, and the total error rate calculated as the percentage of data points falling outside the indifference bands. For evaluating the codling moth model, we used indifference bands of ±7 d and ran the evaluation twice— once using the observed biofix and once assuming biofix occurred at the average DD accumulation since 1 January (i.e., "no biofix"). To compare the accuracy of the biofix versus no-biofix indifference bands, we used Fisher exact test (SAS Institute 2007) on the relative frequency of failure between the two biofix types for each generation separately and combined.

Results

Biofix Comparisons. The mean biofix at the WSU sites occurred at 96 DD ($N = 34$, SD = 14.4; min. = 68, max = 122 DD) from 1 January. 1 January was chosen as the start of accumulation because it occurs before DD would accumulate in Washington and would facilitate comparisons between different fruit-producing regions if the concept worked in Washington. At the non-WSU sites, with no corrections, the average biofix occurred at 119 DD ($N = 81$, SD = 26.1; min. = 74, max = 205 DD) (Fig. 1A). We corrected the data in two steps: 1) we eliminated sites outside the 99% upper CI (131 DD) (Fig. 1B) and 2) corrected for the sampling intervals which averaged 7.2 DD for the WSU sites, and 22.2 DD for the non-WSU sites (Fig. 1C). We eliminated sites outside the 99% upper CI because we considered them to have either weather data that were not representative of the orchard or population levels that were so low that they were unlikely to be catching the first moth. When those corrections were made, the biofix at the non–WSU sites occurred at 97 DD ($N = 50$, SD = 14.4; min. = 74, max = 120) or virtually identical to the WSU sites (Fig. 1B). The q-q plots confirmed that the two distributions were virtually identical with no differences in shape or location occurring (Fig. 2).

Adult Model Accuracy. Adult model failure rates in the first generation using the biofix and no biofix models were 14.9 and 15.4% ($P = 0.92$) and 6.6% for both models ($P = 1.0$) in the second flight (Figs. 3 and 4). The comparison of accuracy between biofix and no-biofix models for both generations resulted in no significant difference in overall failure rates (11.5 and 11.8%, $P = 0.92$, respectively).

Egg Hatch Accuracy. Egg hatch accuracy is the key component to determining applications of ovicides and larvicides for control of codling moth. Our data showed that model failure rate for egg hatch was not
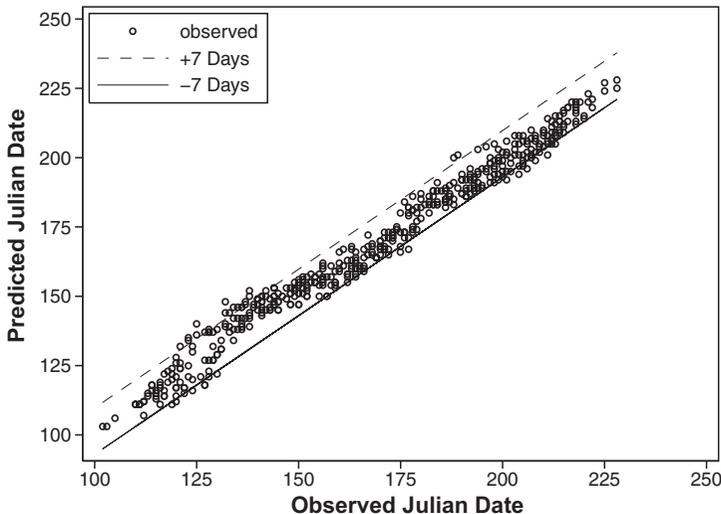

Fig. 3. Indifference band validation of adult flight from the WSU sites using a biofix of first moth.
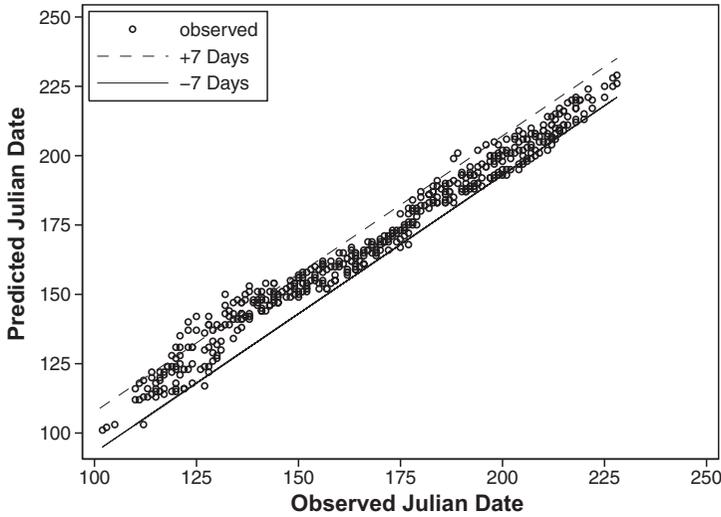
Fig. 4. Indifference band validation of adult flight from the WSU sites using temperature accumulations since 1 January.

significantly different in the first generation for the biofix and no-biofix models (13.9 and 9.8% $P = 0.43$, respectively) (Figs. 5 and 6). In the second generation, there were also no differences between the biofix and no-biofix models (0 and 1.8%, $P = 0.25$, respectively). Comparisons of accuracy for both generations by using the biofix versus no-biofix were also not significantly different (7.2 and 5.9%, $P = 0.36$, respectively).

Discussion

Biofix on a DD scale at both WSU and non-WSU locations were not significantly different when corrections for sampling intervals and poor weather data were applied. There were no apparent differences resulting from different collections when analyzed by county, elevation, or latitude, despite the data collections varying by 2.15° latitude and from 120 to 550 m in elevation. In preliminary studies, we have found that average time (on a DD scale) of first moth from a variety of different locations throughout North America varies from 90 to 270 DD and seems to be a smoothly decreasing function predictable by latitude and altitude, which asymptotically approaches the 96 DD value found in Washington (V.P.J., unpublished). That data suggest that latitudes above 46° would be able to use the same no-biofix model, with few modifications after validation. However, locations below 46° latitude would need to adjust the DD accumulations that trigger the start of the model and further validation to ensure model predictions are useful. Re-
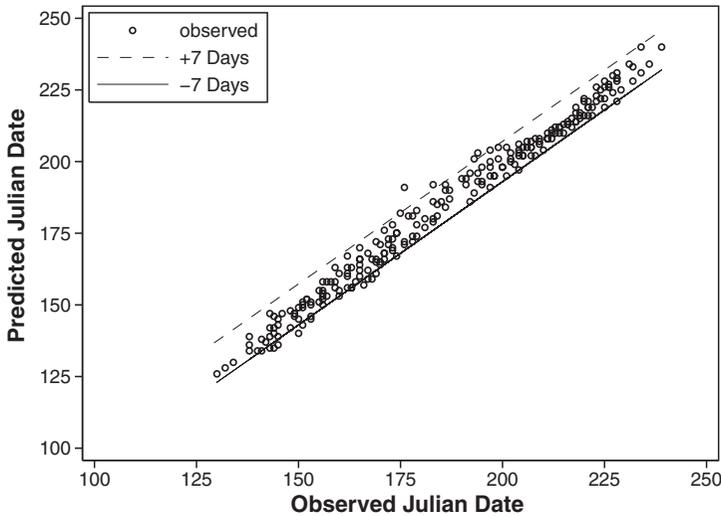

Fig. 5. Indifference band validation of egg hatch from the WSU sites using a biofix of first moth.
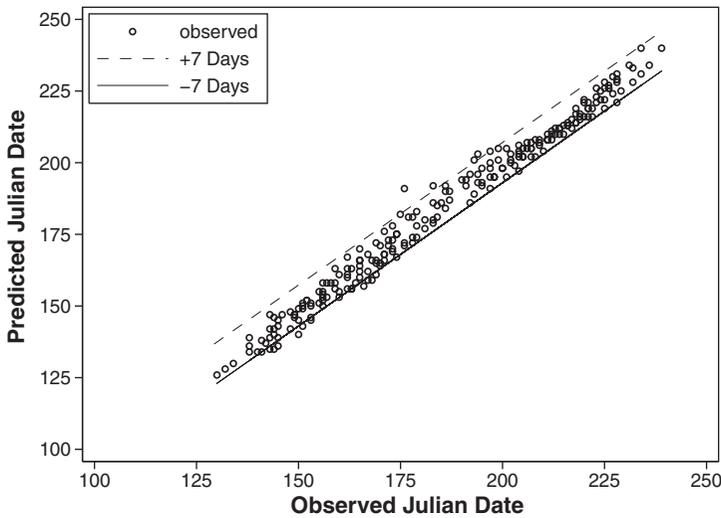
Fig. 6. Indifference band validation of egg hatch from the WSU sites using temperature accumulations since 1 January.

gardless, we need to have a more complete data set of biofix timings for better understanding of how biofix varies over latitudes and altitude and how that affects the usefulness of the codling moth PETE model in those areas.

In terms of model predictions in Washington state, the use of biofix resulted in no significant improvement for either adult flight or egg hatch in our data set. This means that it is reasonable to use the no-biofix approach when using the codling moth PETE model in Washington State. The resulting model is much easier to use and eliminates a key point of confusion among IPM consultants. Although biofix might still be useful in some research studies, the gain in accuracy observed by Riedl et al. (1976) would be swamped out by the weekly trap catch intervals IPM consultants in Washington typically use.

Examination of the indifference band plots showed the primary cause of model failure in both cases (biofix or no bofix) was predictions being late between 150 and 350 DD, suggesting that the first generation adult flight model needs further evaluation. However, the prediction of egg hatch by the model was extremely accurate, and it will likely require no further adjustment, at least under typical Washington conditions. As the egg hatch model is of primary importance in determining spray timing, the adult first flight curve can be modified as more data becomes available.

Acknowledgments

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