Research Article

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Predicting the emergence of the codling moth, *Cydia pomonella* (Lepidoptera: Tortricidae), on a degree-day scale in North America

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Abstract

BACKGROUND: Codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), is a major pest of apple, pear and walnut production in North America. Management programs are based on preventing larval entry into the fruit or nut and are typically timed by heat-driven models that are synchronized to field populations by first capture of overwintering moths in pheromone traps. Unfortunately, trap capture is affected by a range of environmental parameters as well as by the use of mating disruption, which makes detecting first flight difficult, thus complicating implementation of management programs. The present goal was to evaluate data collected from a broad range of locations across North America to see whether average first spring emergence times could be predicted.

RESULTS: Average emergence time on a degree-day scale from 1 January was predictable using latitude and elevation. Sites at elevations of <400 m fit a simple quadratic equation using latitude, but, when higher elevations were included, a multiple regression using elevation was required.

CONCLUSIONS: The present models can be used to simplify management programs for codling moth in areas where heat-driven models that require extensive trapping to synchronize with emergence are currently used.
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Keywords: codling moth; biofix; models; pest management

1 INTRODUCTION

The codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), is the key pest of apples, pears and walnuts in much of the world, and particularly in North American production areas.[1−3] Current management practices for codling moth typically consist of mating disruption in combination with insecticide sprays or insecticide sprays alone.[4−9] Depending upon the insecticide used, sprays are targeted either at the egg stage or at the stage of emerging first-instar larvae and are timed by heat-driven phenology models or by the empirically derived number of degree-days (DDs) past adult emergence. Many modifications of the phenology models have been made over time, with the initial models being developed in the early 1920s.[10] Those models showed great promise, but the combination of poor trapping tools, the computationally extensive methods of calculating heat accumulations and the difficulty of obtaining accurate and timely weather data greatly restricted their use. By the mid-1970s, the development of pheromone monitoring traps, standardized methods of calculating heat accumulations and computers provided the tools necessary to re-investigate the use of heat-driven phenology models to help guide timing of insecticides against the codling moth. The codling moth model currently used in much of North America was developed at Michigan State University (MSU) in a series of papers,[11−13] culminating in the PETE (Predictive Extension Timing Estimator) model.[13]

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A key factor in the PETE model has been the use of a 'biofix' (a biological event such as first moth capture in a pheromone trap) to synchronize the model to field populations.[12] Determining the biofix can be a major source of error in the use of the PETE model for large-scale implementation.[14] The reasons for these errors lie in a number of factors such as low trap density, weekly trap check intervals (instead of daily), low population levels common in commercial orchards and the use of mating disruption.[14] All of these factors make it difficult to pinpoint the time of biofix exactly. In addition, vague notions proliferated in the literature as to the exact definition of biofix (e.g. first moth, first sustained moth capture, first night with more than five moths captured or at least a single moth caught on several consecutive nights) add to the confusion. Because the idea is to synchronize the model to the observed emergence time, the logic of the different definitions of biofix are difficult to fathom, particularly as temperatures may be too low (or it may be too windy) for flight, but still warm enough for development to occur. In these situations, waiting for a consistent flight would not improve model predictions, but instead would likely make them worse.

In Washington State, previous studies showed that average emergence of the first moth occurred at 96 DDs ($^{\circ}$C) after 1 January, and that it did not vary significantly within the state, regardless of elevation or latitude.[14] However, Jones *et al.*[14] also mentioned that preliminary data suggested that biofix was predictable in other areas of North America. If a location-based biofix could be developed, it would allow a significant improvement in the use of the PETE model or other heat-driven models employed in North America that typically require a biofix to initiate model predictions.

In the present paper, the timing of first codling moth emergence is evaluated using a combination of data collected from websites, publications and researchers across the United States.

2 EXPERIMENTAL METHODS

2.1 Data sources
Pheromone trap moth capture data were used exclusively in this study and were collected from a variety of sources in North America (Table 1). Data from emergence cages, bait traps and light trap data were excluded because they can be affected by poor ventilation of emergence cages, age of moths or the phase of the moon respectively. Pheromone traps are relatively consistent and have the advantage of averaging effects of moth emergence across south- and north-facing overwintering sites. For this primary dataset, the moth capture data were paired with temperature data from the closest weather station or from data loggers kept in the orchard. All weather stations were within a 10 km radius of the locations sampled, and in most cases they were immediately adjacent to or inside the orchard. The single sine wave method[15] with a lower threshold of 10 $^{\circ}$C and an upper horizontal cut-off of 31 $^{\circ}$C was used to compute DDs; all DDs mentioned in the paper are DDs Celcius.[16–19] All data were tied to as close a location as possible, although for some data (from Utah and Illinois) the exact locations were estimated as occurring at the closest municipal township where weather data were found. In situations where the actual trap catch data were available over time, it was possible to correct for the sampling interval by taking the average of the DDs from the first sampling period where moth capture occurred and the DDs from the previous date when no moth capture occurred.[14] In some cases, however, no such information was available, and the uncorrected data were used.

A secondary dataset collected from European literature data provided average DD accumulations using the same lower threshold. For most of these data, DD accumulations were calculated using the mean daily temperature and subtracting the 10 $^{\circ}$C threshold. For the entire secondary dataset, the original trap and temperature data were not available for recalculation. Therefore, only statistics that were either reported or that could be calculated from the paper were used. An additional problem with the secondary dataset is that, for some of the sites, the locations were reported only generally (e.g. data taken from 129 orchards near Lake Geneva[20]), so that potential errors in latitude and elevation were possible. Because of the potential errors in this dataset, it was used primarily to evaluate whether large differences in emergence times at latitudes outside those found in the primary dataset occurred.

2.2 Analysis
Because of the diversity of locations being analyzed, it was suspected that emergence would potentially be a function of latitude and elevation. After a brief visual examination of the data, it was decided to classify each site by its elevation (0–199 m, 200–400 m or >400 m), and the average emergence DDs (accumulated since 1 January) for each site versus the latitude at that site were then plotted using different symbols for the three elevation classes. To test formally for relationships, use was made of stepwise polynomial regression[21] and the elevation for each site (not the three elevation classes). The data were fitted using an analytical weighting determined by the number of years that were available at each location to calculate the mean emergence time since 1 January on a cumulative DD basis; $P = 0.05$ was used to eliminate any non-significant factors.

3 RESULTS
The dataset consisted of 366 location-years from 33 different locations (Table 1). Of those, 346 location-years (29 locations) were in the primary dataset and 20 location-years (four locations) were in the secondary set. The average emergence times in the primary dataset varied from 254 DDs (Kern County, CA) to 90 DDs (Cache Co, UT) since 1 January, the latitude varied from 35.21° N (Kern County, CA) to 48.42° N (Okanogan County, WA) and the elevation varied from 11 m (Solano County, CA) to 1450 m (Davis County, UT). The secondary dataset was skewed towards higher latitudes in European locations (46.40–55.67° N, 24–532 m elevation), and all sites showed little variation around 100 DDs (Table 1).

The initial visual examination of the primary dataset suggested that elevations of >400 m (hollow diamonds in Fig. 1) were outliers in what otherwise would have been a simple quadratic fit using latitude as a predictor. Elevations between 200 and 400 m increased slightly the variability around the prediction line, but the stepwise procedure did not require that elevation be added to the model (Fig. 1). Using the 0–400 m data resulted in the prediction equation

$$\text{Mean emergence time (DDs)} = 1923.387 - 73.806 \times latitude$$
$$+ 0.745 \times latitude^2$$

($R^2 = 0.974$; $F = 361.3$; df = 2, 18; $P > 0.001$). Examination of the observed versus predicted emergence times for sites of 0–400 m elevation showed good fit to the model, with no pattern of deviations (Fig. 2) related to crop type, latitude or elevation.

Table 1. First emergence of codling moth at 29 sites, and literature data from four additional locations at high latitudes

Code	State or country	City or county	Latitude (north)	Elevation (m)	Julian date> (mean ± SEM)	Degree-days (mean ± SEM)	N^a	Host	Datasource
1	CA	Kern	35.21	155	84 ± 2.1	254 ± 12.5	8	Walnut	W Bentley
2	CA	Solano	38.23	11	86 ± 6.2	189 ± 10.5	5	Pear	RA Van Steenwyk
3	CA	San Benito	36.85	113	97 ± 4.7	216 ± 15.7	4	Walnut	W Coates
4	CA	San Joaquin	37.70	29	89 ± 4.3	202 ± 11.9	6	Walnut	RA Van Steenwyk
5	IL	Belleville	38.53	169	118 ± 3.7	186 ± 2.8	4	Apple	ipm.illinois.edu/ifvn/
6	IL	Urbana	40.11	225	125 ± 2.5	180 ± 9.4	4	Apple	ipm.illinois.edu/ifvn/
7	IL	Edwardsville	38.99	172	114 ± 1.9	168 ± 17.7	4	Apple	ipm.illinois.edu/ifvn/
8	MI	Allegan	42.59	205	128 ± 1.9	129 ± 4.6[b]	9	Apple	agbioresearch.msu.edu/tnrc/research.html
9	MO	New Franklin	39.02	195	109 ± 2.3	178 ± 15.4	8	Apple	B Barrett
10	NC	Mills River	35.43	687	111 ± 0.8	197 ± 7.8	7	Apple	J Walgenbach
11	NC	Henderson	35.34	656	106 ± 2.2	193 ± 15.4	7	Apple	J Walgenbach
12	NY	Geneva	42.86	165	140 ± 2.2	139 ± 7.9	12	Apple	www.scaffolds.entomology.cornell.edu/
13	NY	Highland	41.69	57	130 ± 2.3	139 ± 10.1	12	Apple	www.scaffolds.entomology.cornell.edu/
14	OH	Columbus	40.01	247	121 ± 1.1	176 ± 3.9	8	Apple	ipm.osu.edu/pageview.asp?id = 18
15	OR	Hood River	45.69	162	126 ± 2.9	111 ± 6.9[b]	9	Pear	www.nass.usda.gov
16	OR	Medford	42.34	426	105 ± 1.3	113 ± 3.8	38	Pear	R Hilton
17	PA	Biglerville	39.93	196	122 ± 2.1	151 ± 6.8	12	Apple	LA Hull
18	UT	Boxelder	41.51	1350	117 ± 3.1	104 ± 3.7[b]	9	Apple	DG Alston
19	UT	Cache	41.73	1387	126 ± 2.2	90 ± 3.5[b]	15	Apple	DG Alston
20	UT	Davis	41.03	1449	120 ± 2.5	108 ± 5.3[b]	8	Apple	DG Alston
21	UT	Utah	40.08	1445	119 ± 1.6	119 ± 3.7[b]	38	Apple	DG Alston
22	VT	Burlington	44.43	68	136 ± 2.1	121 ± 6.3	10	Apple	orchard.uvm.edu/uvmapple
23	VA	Winchester	39.11	292	118 ± 1.5	189 ± 6.7[b]	13	Apple	www.arec.vaes.vt.edu/alson-h-smith/treefruit/entomology/tree-fruit-pest-management/index.html
24	WA	Benton	46.33	118	111 ± 1.2	101 ± 4.7	8	Apple	TJ Smith
25	WA	Chelan	47.44	245	114 ± 1.3	97 ± 2.4	33	Apple	JF Brunner and VP Jones
26	WA	Douglas	47.44	245	118 ± 1.4	96 ± 3.5	18	Apple	TJ Smith
27	WA	Grant	47.22	451	113 ± 1.2	100 ± 2.1	26	Apple	TJ Smith
28	WA	Okanogan	48.42	362	122 ± 2.6	102 ± 3.2	8	Apple	TJ Smith
29	WV	Kearneysville	39.39	171	119 ± 2.4	172 ± 6.2	8	Apple	www.caf.wvu.edu/kearneysville
30	Denmark	Glostrup	55.40	24	–	100[b]	4	Apple	Ravn and Madsen[24]
31	England	East Malling	51.28	162	–	100[b]	5	Apple	Cranham[27]
32	Switzerland	Geneva	46.40	436	–	89 ± 29.5[b]	7	Apple	Charmillot[20]
33	Switzerland	Wadenswil	47.23	422	–	100[b]	4	Apple	Graf et al.[22]

[a] Orchard-years of data.
[b] Data not corrected for sampling interval.

Including data from areas with elevations of over 400 m in the analysis required both latitude and elevation to represent the data accurately. If elevation was ignored, the predicted curve was shifted downwards and described the general shape but poorly fitted the data (adjusted $R^2 = 0.786$). The multiple regression used to describe the data was

$$\text{Mean emergence time (DDs)} = 1755.599 - 66.777$$
$$\times latitude + 0.676 \times latitude^2 - 0.0347 \times elevation \text{ (m)}$$

($F = 151.1$; df = 3, 25; adjusted $R^2 = 0.94$). The plot of the observed versus predicted emergence times on a DD scale fits the overall dataset well (Fig. 3), but, even with the elevation component, if the location was under 400 m, the other regression gave slightly better predictions. As with the other regression, there were no systematic differences related to crop type, latitude or elevation.

4 DISCUSSION AND CONCLUSIONS

The average time of first pheromone trap catch of codling moth on a degree-day scale in the northern hemisphere appears to be predictable with only knowledge of the latitude and elevation of the site. The relationship of latitude and elevation to emergence probably reflects at least partially the decreasing solar radiation at higher latitudes that directly heats the bark or soil where codling moth overwinters. There is significant year-to-year variation about the mean emergence time, and research in Europe suggests that variability in predictions can be reduced if the solar radiation is used.[22,23] Unfortunately, the solar radiation and tree trunk temperature data used for validation by Graf et al.[22,23] were not available for the sites in the present primary dataset.

The lack of any observed deviation related to crop type is somewhat tentative because so few walnut and pear datasets were available. However, it is interesting because the tree and canopy densities are rather marked between crops, but trap capture timing did not appear to reflect crop type except as would be expected
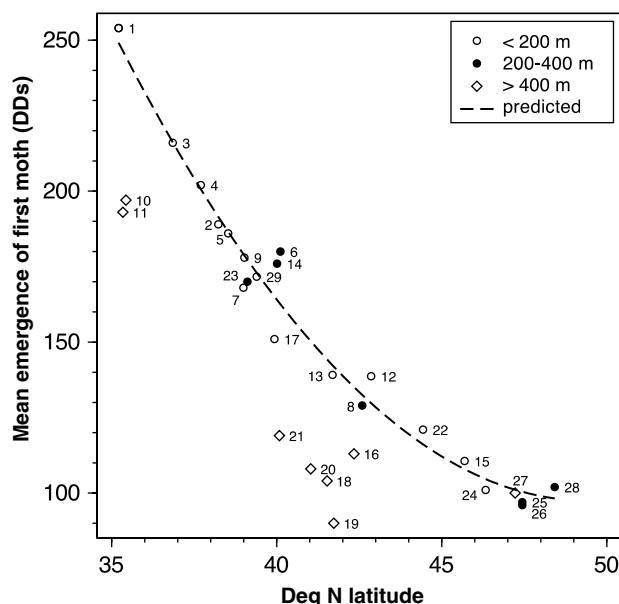
1395

Figure 1. Plot of the mean first emergence time for codling moth (DDs since 1 January) at 29 different locations in North America versus latitude. Dashed line is the quadratic fit for altitudes below 400 m. Numbers correspond to the location codes found in Table 1.
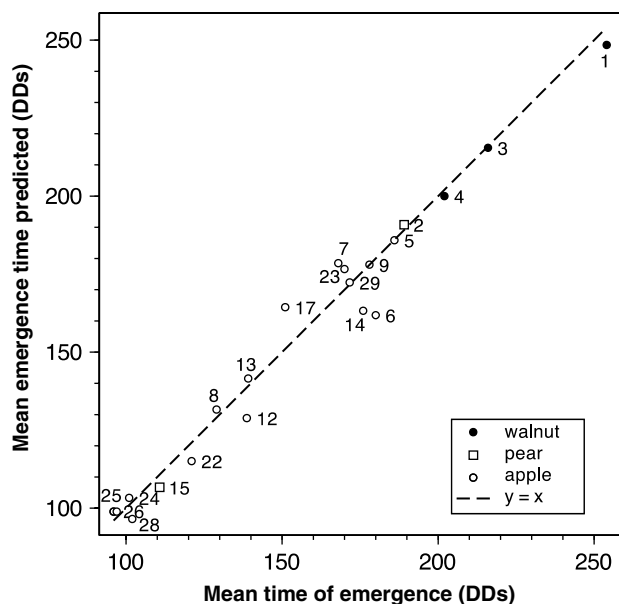

Figure 2. Plot of the predicted and observed mean emergence time for the first moth for altitudes below 400 m. Dashed line indicates *y* = *x*. Numbers correspond to the location codes found in Table 1; open circles are data from apple orchards; open squares are data from pear orchards; filled circles are data from walnut orchards.

Figure 3. Plot of the predicted and observed emergence time for the first moth using the entire primary dataset (all altitudes). Dashed line indicates *y* = *x*. Numbers correspond to the location codes found in Table 1; open circles are data from apple orchards; open squares are data from pear orchards; filled circles are data from walnut orchards.

time, low-density orchards are generally cooler and accumulate fewer DDs (Jones V and Chambers U, unpublished).

The data collected are for locations with more than one generation per year, with the exception of the data from Denmark (55.67° N latitude).[24] Throughout the world there are several cases of codling moth reported with only one generation per year, and these populations may or may not follow the same sort of trend observed in the present dataset. The Danish information suggests that populations at high latitudes may respond similarly to the present larger dataset. However, in New Zealand (≈39° S latitude), where codling moth has only a single generation per year, moth emergence and phenology appear to be quite different, and researchers have suggested that those populations may have a different overwintering state related to relatively mild winter temperatures and fewer chilling degree-days than found in most apple production regions in the northern hemisphere.[25]

The authors would also caution against extrapolating the equations used to predict first pheromone trap catch to latitudes lower than the 35.2° N latitude found in the present primary dataset, particularly at low elevations. Firstly, polynomials can cause artifacts near the ends of the dataset, especially if the data fall outside the range of latitude used to generate the regression. Secondly, these types of site are almost certainly relatively abnormal for apple, pear or walnut production and likely have issues related to diapause induction/termination or insufficient chilling units for codling moth.[25,26] Finally, the authors did not find literature or original data paired with temperature data that would allow them to check how well the model works in the southern hemisphere (i.e. by disregarding north versus south in the regression) where host plants are grown.

At the high latitude end of the present primary dataset, it appears that the average first moth pheromone trap capture levels off at ≈ 100 DDs. The secondary dataset appears to confirm this observation, but the DD totals in three of the four secondary data sources[20,24,27] were calculated by taking the average daily

by latitude and altitude. There is no access to tree density or canopy size in the present dataset, so an analysis of that factor is impossible with the present data. However, even within apple orchards, differences in the density of trees can vary from roughly 120 to several thousand per acre. In Washington State, it has been found across multiple sites and years that seasonal codling moth DD accumulations (using air temperature within the orchard) are virtually identical between adjacent high- and low-density blocks before roughly 9 June (well after codling moth emerges); after that
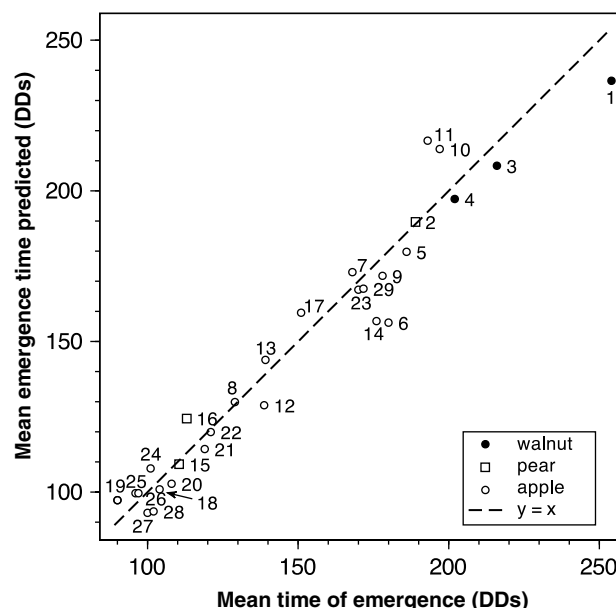
temperature and subtracting the 10 °C threshold. This method is a very simplistic way of calculating degree-days that, in the authors' experience, grossly underestimates heat accumulation in the spring by comparison with the single sine method or using 15 min temperature summations. Thus, it cannot be established with certainty that the values reported at these higher latitudes would not be higher if they had been calculated with the single sine method used here. In the fourth study,[22] 100 DDs is reported as the average first emergence according to heat accumulations from temperature readings taken at 12 min intervals, so at least one of the data points clearly fits the pattern of the North American data.

The practical value of predicting general emergence (first trap catch) time of codling moth is related to management decisions. In Washington State, where all of the apple production areas are above the approximate point on the emergence curve where it levels off at ≈ 100 DDs, model predictions of adult flight and egg hatch based on the average emergence time have been shown to be as accurate as when using 'biofix' associated with moth capture in pheromone traps.[14] This is probably because the daily degree-day accumulations around the start of flight are low, which results in any errors associated with setting biofix being only a small percentage of the total degree-day accumulations needed for different phenological events of interest (e.g. flight, egg hatch, etc.) that occur later in the season. The resulting 'no-biofix' management program is much easier to explain to growers and pest management consultants. It also eliminates issues associated with different definitions of biofix and situations where moth capture starts, but then is suppressed by temperature, rainfall and/or wind.

It is important to distinguish between accurately predicting first trap catch and predicting subsequent key phenological events using the generalized codling moth model. The present data can be used as a starting point, but local validation of the general model needs to be performed.[14] In addition, in locations where insecticide timings are not based on the percentage egg hatch as predicted by the PETE model (or a variation of it), but instead are based on empirically derived DD accumulations after biofix (and dependent on their definition of biofix), further validation will be required.

Given the equations used to generate emergence times to predict the overall emergence pattern, reporting the phenology in areas below 45° N should continue to use the predicted first emergence and to use DD accumulations reset to zero once the average time of emergence is reached to keep the current 'DDs from biofix' scale of cumulative DDs. This allows researchers, consultants and extension people easily to remember key degree-day timings for the phenology and management recommendations throughout a large and topographically diverse area. In Washington, recommendations are based on cumulative DDs since 1 January to reflect the fact that no trends in moth emergence were found that were related to latitude or elevation.[14] While this approach is considerably simpler to explain to growers, consultants and other users of the information in Washington, other areas can convert the Washington scale to the 'DDs from biofix' scale by simply subtracting the average emergence time in Washington (96 DDs) from the phenological event of interest.

Finally, pest management research and outreach in the future will likely be characterized by the availability of fewer resources but greater demands for sustainable and information-intensive ecologically viable management programs. While the conflicts between reduced resources for research and the demand for

greater complexity are a stumbling block, using the meta-analysis approach of having datasets for a particular insect spanning large areas of its range opens the door to understanding its ecological niche and factors driving its population dynamics. In turn, that information provides insights and tools to help optimize management programs over a large area while minimizing the costs.

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