Timing of egg hatch by early-season codling moth (Lepidoptera: Tortricidae) predicted by moth catch in pear ester- and codlemone-baited traps

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Abstract—The use of the timing of moth catch in traps to predict the start of egg hatch by first-generation codling moth, *Cydia pomonella* (L.), in apple, *Malus domestica* Borkh. (Rosaceae), was evaluated with ethyl (*E*,*Z*)-2,4-decadienoate (pear ester) and (*E*,*E*)-8,10-dodecadien-1-ol (codlemone) lures. Two sets of paired traps baited with either lure were placed in each of seven orchards and checked daily during the spring flight in 2000 and 2001. Rearing of field-collected eggs and sampling of fruit for injury were used to estimate the date of first egg hatch. Moth catch in traps baited with codlemone and pear ester occurred approximately 144 and 105 degree-days prior to the start of egg hatch, respectively. The effectiveness of using the timing of sustained moth catch in traps baited with these lures as a biological reference point (Biofix) to predict the start of egg hatch when traps were checked every 3–4 d was evaluated in 11 orchards from 2000 to 2002. The calendar date for the start of sustained moth catch in traps baited with either lure varied widely among orchards and years. Significant differences in mean cumulative degree-days from first sustained moth catch until egg hatch were found among male moth catch in codlemone-baited traps and total and female moth catch in pear ester-baited traps. Adjusting the Biofix based on daily temperature thresholds significantly changed the cumulative degree-days required until egg hatch only for female moth catch. No significant differences were found in the accuracy of predicting the date of egg hatch using either the codlemone or pear ester lure or by adjusting the Biofix date using daily temperature thresholds. The cumulative degree-day totals required from Biofix until egg hatch had the lowest variability when the Biofix was (*i*) based on the sustained catch of female moths in a pear ester-baited trap and (*ii*) adjusted with a temperature threshold for moth activity.

Résumé—Nous avons évalué l'utilisation de la phénologie des captures de papillons dans les pièges pour prédire le début de l'éclosion des oeufs chez les carpocapses de la pomme, *Cydia pomonella* (L.), de première génération sur le pommier, *Malus domestica* Borkh. (Rosaceae), à l'aide d'appâts d'éthyl(2*E*,4*Z*)-2-4-décadiènoate (ester de poire) et de (*E*,*E*)-8,10-dodécadièn-1-ol (codlemone). Nous avons placé deux séries de pièges appariés munis de l'un ou de l'autre appât dans sept vergers et les avons relevés tous les jours durant la période de vol du printemps en 2000 et 2001. L'incubation d'oeufs récoltés sur le terrain et l'inventaire des blessures sur les fruits ont servi à déterminer la date de la première éclosion. Les captures des papillons dans les pièges appâtés de codlemone et d'ester de poire commencent respectivement environ 144 et 105 degrés-jours avant le début de l'éclosion des oeufs. Nous avons ensuite vérifié dans 11 vergers de 2000 à 2002 l'efficacité de l'utilisation de la période de captures soutenues des papillons dans les pièges munis de ces appâts et relevés tous les 3-4 j comme point de référence biologique (Biofix) pour prédire le début de l'éclosion des oeufs. La date au calendrier du début des captures soutenues de papillons dans les pièges munis de ces appâts varie considérablement d'un verger à un autre et d'une année à l'autre. Il existe des différences significatives dans le nombre moyen cumulé de degrés-jours entre le début de la capture soutenue de papillons et l'éclosion des oeufs dans le cas des captures de mâles dans les pièges appâtés de codlemone et les cas des captures totales et des captures de femelles dans les pièges appâtés d'ester de poire. L'ajustement des

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Biofix d'après les seuils quotidiens de température change significativement le nombre de degrés-jours requis pour l'éclosion des oeufs seulement dans le cas des captures des papillons femelles. Il n'existe pas de différence significative dans la précision de la prédiction de la date de l'éclosion des oeufs par l'utilisation des appâts de codlemone ou d'ester de poire ou par l'ajustement de la date Biofix à l'aide des seuils de température. La variabilité la plus faible parmi les types de Biofix se retrouve dans le nombre cumulatif total de degrés-jours requis jusqu'à l'éclosion des oeufs par un Biofix (ajusté à un seuil de température relié à l'activité des papillons) déterminé d'après les captures des femelles dans un piège appâté d'ester de poire.

[Traduit par la Rédaction]

Introduction

Traps baited with (*E*,*E*)-8,10-dodecadien-1-ol (codlemone) have been used extensively to monitor the phenology of codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae) (Riedl *et al*. 1986). Predictive phenology models based on the timing of capture of male moths in these traps and temperature-dependent physiological development have been formulated (Riedl *et al*. 1976) and widely implemented to time insecticide applications (Croft and Knight 1983). The accuracy of these models has been improved by using the start of sustained male moth catch as a biological reference point or "Biofix" (Riedl *et al*. 1976). The cumulative degree-day total from Biofix to egg hatch for codling moth includes the occurrence of a male protandry (Howell 1991), a female preoviposition period (Glenn 1922), and the physiological development of the egg stage (Richardson *et al*. 1982).

Effective use of these predictive models is dependent on the establishment of an accurate Biofix. Riedl *et al*. (1976) originally defined a Biofix as "the first male moth or moths in the pheromone trap with no significant interruption in catches thereafter". Both the frequency of trap checking and the population density of codling moth within an orchard can strongly influence the selection of the Biofix. Typically, a Biofix is established for a distinctive growing region when a multitude of traps catch one or more moths on the same night (Beers *et al*. 1993).

The accuracy of phenology models for codling moth has purportedly been improved by adjusting the Biofix based on the occurrence of suitable dusk temperatures for moth sexual activity (>15.6 °C) (Pickel *et al*. 1986; Blago 1992). Maximum daily temperatures (>21.1 °C) have also been shown to be useful predictors of male flight (Pitcairn *et al*. 1990). In some cases, the Biofix has to be reestablished when moth catch is limited to "one night followed by 7–10 d of cold weather" (Beers *et al*. 1993). Knight and Weiss (1996) documented a 25-d delay in female codling moth mating following male moth catch in codlemone-baited traps due to low spring temperatures and the occurrence of high wind speeds during several warm dusk periods.

The use of a Biofix based on male moth catch in codlemone-baited traps has been less successful for characterizing the phenology of codling moth later in the growing season due to yearly variation in diapause induction and a decline in the efficiency of codlemone-baited traps (Riedl *et al*. 1976). The initial insecticide application is timed from a Biofix, and subsequent sprays are most commonly applied at regular calendar intervals based on the residual control provided by the insecticide (Beers *et al*. 1993).

Alternatives to the use of codlemone-baited traps have been developed to improve the prediction of codling moth egg hatch; these include direct sampling of eggs (Zoller 2001) and monitoring of female moths with a variety of nonselective traps (Weissling and Knight 1994). These methods have not been widely adopted owing to their expense and the need for specialized equipment or training. However, the recent development of a synthetic lure baited with (*E*,*Z*)-2,4-decadieonoate (pear ester) allows growers to more easily monitor female codling moth during the growing season with standard sticky traps (Light *et al*. 2001). Studies have been conducted with a pear ester lure to evaluate the influence of trap size, trap placement in the canopy, and lure loading on the attractiveness of baited traps for both sexes of codling moth (Knight and Light 2005*a*, 2005*b*). Development of a standardized protocol for the use of pear ester may lead to an alternative monitoring program for codling moth that can track female moth emergence and activity. Here, we report studies that evaluate the use of pear ester-baited traps as a tool to predict the start of egg hatch of the first summer generation of codling moth. The accuracy of this approach was compared with that of the standard male moth-based Biofix developed with codlemone-baited traps.

Materials and methods

Study sites

Studies were conducted in four unsprayed apple (*Malus domestica* Borkh.; Rosaceae) orchards situated in the Yakima Valley, Washington (46°30′N, 120°50′W), near Zillah, East Moxee, Moxee, and Parker. Orchards were monitored from April to June during the 2000–2002 growing seasons except for East Moxee, which was not included in the study during 2002. All orchards had high population densities of codling moth, with levels of fruit injury >30% at harvest. Orchards were mixed plantings of *M. domestica* 'Delicious' and 'Golden Delicious' except for the orchard near East Moxee, which was planted with *M. domestica* 'Fuji'. Orchards were planted at densities of 550–650 trees per ha and trees were 4.0–4.5 m tall except for the orchard near East Moxee, which was a high-density planting (1500 trees per ha) with a canopy height of 3.0 m. Standard mowing, weed control, and irrigation practices were used, but orchards were not treated with any insecticides during the time that they were monitored for codling moth each year.

Air temperatures within orchards were monitored every 5 min with digital recorders (Avatel, Fort Bragg, California), and daily maximum, minimum, and civil twilight temperatures were recorded. Degree-days were calculated from the minimum and maximum daily temperatures with the modified sine wave method (Allen 1976) using a lower developmental threshold of 10 °C and an upper horizontal temperature cutoff of 31.1 °C for codling moth.

Foliage and fruit were sampled in each orchard 2–3 times per week during May and early June. Twenty shoots with fruit clusters were inspected in the laboratory for codling moth eggs and 200 fruits were inspected in the field for injury on each date. Leaves with eggs were placed in water vials, maintained at 25 °C and 50% RH, and checked daily until eggs hatched. Cumulative degree-days under laboratory conditions (15 degree-days per day) were used to estimate the date of egg hatch in the field.

Establishing a Biofix

In each orchard, two pairs of delta-shaped traps were spaced 100 m apart and >10 m from the edge of the orchard. Within each pair, one trap was baited with a 3.0-mg codlemone lure (Pherocon® CM-L2™, Trécé Inc., Adair, Oklahoma) and the other with a 3.0-mg pear ester lure (Pherocon® CM-DA™, Trécé Inc.). Traps were attached to PVC poles and hung in the upper third of the canopy. Traps were checked daily until mid-May during 2000 and 2001, except in East Moxee in 2001; after mid-May, traps were checked every 3–4 d. Traps in the East Moxee orchard in 2001 and all orchards in 2002 were checked every 3–4 d (Monday and Thursday in 2001 and Tuesday and Friday in 2002). All moths were sexed and females were dissected to determine their mating status.

A separate Biofix was established in each orchard using the start of sustained catch of male codling moths in a codlemone-baited trap or total moths or only female moths in a pear ester-baited trap. The start of sustained moth catch detected with either lure was narrowly defined in our study. First, the mean moth catch of the two traps within each orchard baited with the same lure had to be >1 moth per trap during the period between trap checks. Second, if mean moth catch was <1 moth per trap in the subsequent period between trap checks, then the Biofix was reinitialized to the next period when mean moth catch was >1 moth per trap.

Daily maximum and dusk temperatures within the selected 3- to 4-d period were used to adjust the Biofix. An adjusted Biofix was established as the first day within the 3- to 4-d period when maximum or dusk temperatures exceeded 22.2 or 15.6 °C, respectively. Temperatures had to exceed these thresholds on at least 2 consecutive days within the 3- to 4-d period to trigger an adjusted Biofix. If temperatures during the selected period did not exceed these thresholds, then the first day after the trap check date when either temperature threshold was exceeded for 2 consecutive days was selected as the adjusted Biofix date.

Predicting egg hatch

Traps checked daily

Mean moth catches in traps baited with pear ester (total and female moths) or codlemone (male moths) in orchards sampled daily in 2000 and 2001 (n = 7) were used to "backtrack" from the date of first egg hatch to the expected dates of oviposition and male emergence, respectively. The selected backtracked dates were 86 and 139 degree-days prior to egg hatch for the pear ester and codlemone lures, respectively. The former value was based on the mean degree-day total required for codling moth egg development (Richardson *et al*. 1982). The latter value is widely used to time insecticide sprays based on a male moth Biofix in codlemone-baited traps and coincides with 3% egg hatch (Beers and Brunner 1992). Moth catch data for each of 5 days before and after these "backtracked" dates were summarized.

Traps checked every 3–4 d

Cumulative degree-day totals from the start of sustained catch of male moths in codlemone-baited traps and total and female moths in pear ester-baited traps until egg hatch were calculated when traps were checked every 3–4 d (n = 11). Cumulative degree-day totals were also calculated from the start of sustained moth catch (adjusted Biofix) until egg hatch based on the occurrence of the first day within the 3- to 4-d period when moths were caught and either the maximum temperature was >22.2 °C or the dusk temperature was >15.6 °C. Moth catches from the seven orchards that were checked daily in 2000–2001 were summarized over the same 3- to 4-d intervals as the other orchards included in these analyses.

Statistical analysis

Kruskal–Wallis tests were used to compare cumulative degree-day totals until egg hatch calculated using the dates on which sustained male moth catch in codlemone-baited traps and total and female moth catch in pear ester-baited traps began and dates adjusted on the basis of temperature thresholds (Analytical Software 2003). Differences among years in the cumulative degree-day totals until egg hatch for each of these Biofix types were also evaluated with Kruskal–Wallis tests. The coefficient of variation (CV) was calculated for the cumulative degree-day totals for each Biofix type. A two-way analysis of variance (ANOVA) was used to test for differences in the accuracy of predicting the date of egg hatch using each Biofix type (Analytical Software 2003). The main factors in the model were lure type/moth sex and the inclusion or exclusion of a temperature threshold. The dependent variable was the number of days between the observed and predicted start of egg hatch following Biofix. Data were log(x + 1) transformed prior to the ANOVA. Predicted egg hatch was based on the accumulation of 139 and 105 degree-days after Biofix was established for the codlemone- and pear ester-baited traps, respectively. The latter degree-day total was selected based on experimental data collected during this study from the seven orchards where traps were checked daily. Means were separated with Fisher's least significant difference test, with all significant tests using an experimental error rate of α = 0.05.

Results

Establishing a Biofix

Dates for the start of moth flight and the occurrence of egg hatch varied among orchards and among years within this study (Table 1). For example, first moth catch in codlemone-baited traps varied by up to 18 d within a year (2000) and by 27 d across all 3 years. Similarly, the dates of first moth catch and first female moth catch in pear ester-baited traps also varied widely, by 21 d in 2000 and up to 33 d across all 3 years (Table 1). First moth catch in a codlemone-baited trap was similar to that in a pear ester-baited trap in some orchards (Moxee in 2001) but the two dates varied widely at other sites (*e.g.*, 21 d at East Moxee in 2000).

The start of sustained moth catch coincided with first moth catch for both lures in some orchards but occurred as much as 2 weeks later in other sites (Table 1). The start of sustained moth catch in pear ester-baited traps was similar to that in codlemone-baited traps in two sites but occurred 3–18 d later in the other orchards. The start of sustained female moth catch was similar to the start of sustained total moth catch in pear ester-baited traps in most sites but was delayed by 7–14 d in three orchards (Table 1).

The mating status of female moths captured in pear ester-baited traps was not used in establishing Biofix dates. During this study, >80% of trapped female moths were mated, and only once was a virgin female caught before a mated

Table 1. Summary of calendar dates for first catch and first sustained catch of codling moth (*Cydia pomonella*) in codlemone- and pear ester-baited traps and the occurrence of first egg hatch.

	Date of first moth catch			Date of first sustained moth catch*			
	Codlemone	Pear ester		Codlemone	Pear ester		
Orchard, year	Male moth	Any moth	Female moth	Male moth	Any moth	Female moth	Date of first egg hatch†
Parker, 2000	13 April	24 April	24 April	17 April	24 April	24 April	17 May
Zillah, 2000	20 April	1 May	1 May	20 April	1 May	4 May	26 May
Moxee, 2000	1 May	1 May	8 May	1 May	1 May	15 May	31 May
E. Moxee, 2000	24 April	15 May	15 May	27 April	15 May	15 May	27 May
Parker, 2001	16 April	26 April	30 April	23 April	26 April	3 May	21 May
Zillah, 2001	26 April	26 April	26 April	26 April	26 April	3 May	23 May
Moxee, 2001	3 May	3 May	10 May	3 May	10 May	10 May	25 May
E. Moxee, 2001	10 May	14 May	14 May	10 May	14 May	14 May	25 May
Parker, 2002	23 April	2 May	2 May	26 April	2 May	2 May	26 May
Zillah, 2002	2 May	6 May	13 May	13 May	13 May	13 May	2 June
Moxee, 2002	2 May	6 May	27 May	13 May	20 May	27 May	11 June

*Sustained moth catch for each of the three types of moth catches (male, any, and female) was defined as the first occurrence of moth catch in a trap during a selected time period when mean moth catch was >1 moth per trap and similar or higher moth catches occurred during the following period. If <1 moth was caught per trap in the subsequent time period, then the sustained moth catch was reinitiated in the next period that >1 moth per trap was caught.

†The date of first egg hatch was determined by three methods: rearing of field-collected eggs in the laboratory at 25 °C, sampling of hatched eggs in the field, and sampling of injured fruits in the field.

female (1 d earlier in the Zillah orchard in 2000). The timing of first capture of virgin female codling moths was variable and occurred from 0 to 30 d after the first capture of mated female moths.

Adjusting the Biofix based on the occurrence of suitable temperatures for moth sexual activity within the 3- to 4 -d trap-checking period was relatively straightforward in most orchards. In nearly all cases, the maximum temperatures were >22.2 °C on at least 2 consecutive days during the period when sustained moth catch occurred. However, the dusk temperatures during these periods were often <15.6 °C and would not have been sufficient to establish an adjusted Biofix. The mean (±SE) difference between the daily maximum and dusk temperatures was 5.5 ± 0.6 °C and 6.7 ± 0.7 °C at the start of sustained male and female moth catch in the codlemone- and pear ester-baited traps, respectively. However, in two cases temperatures exceeding the dusk threshold but not the maximum temperature threshold were used to select the adjusted Biofix date. In only one case did the start of sustained moth catch (female moths in a pear ester-baited trap) occur without either the maximum or dusk temperatures exceeding their thresholds for 2 consecutive days (Zillah 2000). Despite the start of a sustained catch of codling moth in the pear ester-baited traps on 4 May in this orchard, the adjusted Biofix was set as 5 May, when the dusk temperature was >15.6 °C.

Predicting egg hatch

Traps checked daily

Data collected from traps placed in seven orchards and monitored daily provided a useful assessment of the expected cumulative degree-day totals from first moth catch to egg hatch using either codlemone or pear ester lures (Fig. 1). The first date of sustained moth catch in codlemone-baited traps occurred 2 days before the expected date when 139 degree-days were "backtracked" from the date of first egg hatch (Fig. 1A). The mean (±SE) daily degree-day accumulation during this period was 2.6 ± 0.2. Thus, egg hatch was estimated to occur approximately 144 degree-days after the start of male moth catch in codlemone-baited traps. Total and female moth catch in pear ester-baited traps increased sharply 3 days before the expected date (86 degree-days before observed egg hatch) (Fig. 1B). The mean (±SE) daily degree-day accumulation during this period was 6.3 ± 0.6. Thus, egg hatch was estimated to occur approximately 105 degree-days after the start of moth catch in pear ester-baited traps.

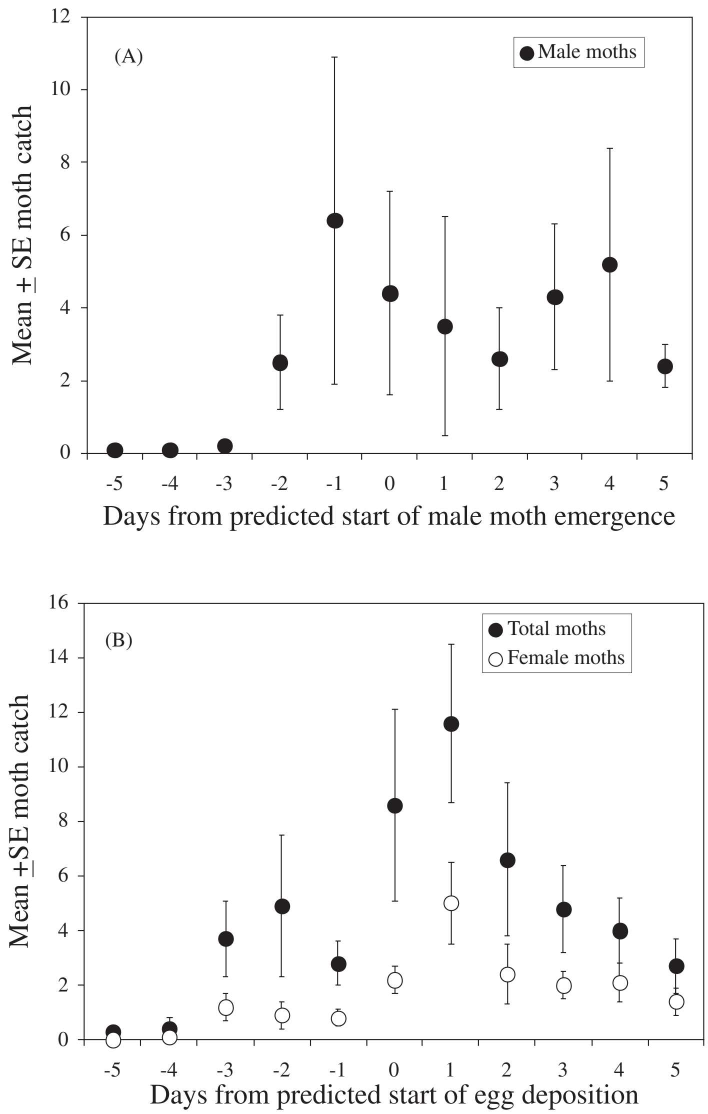
Traps checked every 3–4 d

The mean cumulative degree-day totals from Biofix until egg hatch did not differ among years for either codlemone- or pear ester-baited traps (Table 2). Cumulative degree-day totals from Biofix until egg hatch were significantly higher for male moths caught in a codlemone-baited trap than for female moths caught in a pear ester-baited trap. The cumulative degree-day totals for any moth caught in a pear ester-baited trap were not significantly different from those for males caught in a codlemone-baited trap or only females caught in a pear ester-baited trap (Table 2). However, the CV associated with these cumulative degree-day totals was nearly 50% higher with a Biofix based on any moth caught in a pear ester-baited trap than with the other two Biofix types (Fig. 2A).

Cumulative degree-day totals until the start of egg hatch calculated using an adjusted Biofix based on a temperature threshold were not significantly different from the totals calculated using unadjusted Biofixes, except for the start of sustained female moth catch in a pear ester-baited trap (Table 2). No significant differences in the cumulative degree-day totals occurred among years using the adjusted Biofix with either lure (Table 2). Cumulative degree-day totals from the adjusted Biofix until observed egg hatch were significantly higher for male moths caught in a codlemone-baited trap than for either total or female moths caught in a pear ester-baited trap. There was no difference in degree-days accumulated after the adjusted Biofix until egg hatch between total and female moths caught in a pear ester-baited trap. The CVs associated with each adjusted Biofix were lower than those associated with the respective unadjusted Biofixes (Fig. 2A). The lowest CV among the six Biofix types was associated with the adjusted Biofix for the sustained catch of female moths in a pear ester-baited trap (Fig. 2A).

The mean difference between predicted and observed egg hatch for the six different Biofix types ranged from 1 to 3 d (Fig. 2B). No significant differences in the accuracy of predicting the date of egg hatch (*i.e.*, difference between predicted and observed hatching dates) were found using Biofixes based on male moths

Fig. 1. Mean (±SE) numbers of male codling moths (*Cydia pomonella*) caught in a codlemone-baited trap (A) and total and female moths caught in a pear ester-baited trap (B) before and after the predicted dates for the start of male emergence (139 degree-days prior to egg hatch) (A) and the start of female oviposition (86 degree-days prior to egg hatch) (B) in seven apple orchards.



caught in a codlemone-baited trap or total or female moths caught in a pear ester-baited trap ($F_{2,60}$ = 2.69, P = 0.08). Similarly, the use of an adjusted Biofix was not significantly better for predicting egg hatch than the use of a standard Biofix ($F_{1,60}$ = 3.40, P = 0.07). The interaction of lure type/moth sex and the inclusion or exclusion of a temperature threshold in establishing a Biofix was not significant in this ANOVA ($F_{2,60}$ = 0.32, P = 0.81).

Discussion

Male moth catches in codlemone-baited traps have been instrumental in establishing a biological reference point that can minimize the error in predicting the phenology of codling moth (Riedl *et al.* 1976). In our study, moth catches in either codlemone- or pear ester-baited traps provided similar, and relatively good, prediction of the start of egg hatch

Table 2. Cumulative degree-day totals (mean ± SE) from Biofix and temperature-adjusted Biofix based on moth catch in codlemone- and pear ester-baited traps until detection of egg hatch for codling moth in 11 apple orchards during 2000–2002.

	Biofix			Temperature-adjusted Biofix		
	Codlemone	Pear ester		Codlemone	Pear ester	
Year (no. of orchards)	Male moth	Any moth	Female moth	Male moth	Any moth	Female moth
2000 (4)*	148.5±5.2	113.3±14.3	99.0±7.1	154.3±7.3	113.6±11.4	105.6±4.5
2001 (4)*	130.0±6.7	116.6±11.8	101.2±3.6	141.2±6.2	108.6±5.8	104.8±3.5
2002 (3)*	145.4±10.3	117.0±1.7	87.8±4.0	147.8±7.3	120.1±7.4	104.3±2.2
2000–2002 (11)[†]	140.8±4.6*a*	115.5±6.2*ab*	96.8±3.3*bB*	147.8±4.0*a*	113.5±4.8*b*	105.0±2.0*bA*

*No significant differences in cumulative degree-day totals were found among years for any of the six Biofix types; $H_{2,8}$ statistics < 2.55, P values > 0.05, Kruskal–Wallis tests.

[†]Means followed by different lowercase letters are significantly different within the Biofix ($H_{2,30}$ = 2.44, P < 0.0001) and temperature-adjusted Biofix ($H_{2,30}$ = 25.2, P < 0.0001) columns separately; Kruskal–Wallis tests. For the female moth Biofix, means followed by different uppercase letters are significantly different; $H_{1,20}$ = 4.22, P < 0.05, Kruskal–Wallis test.

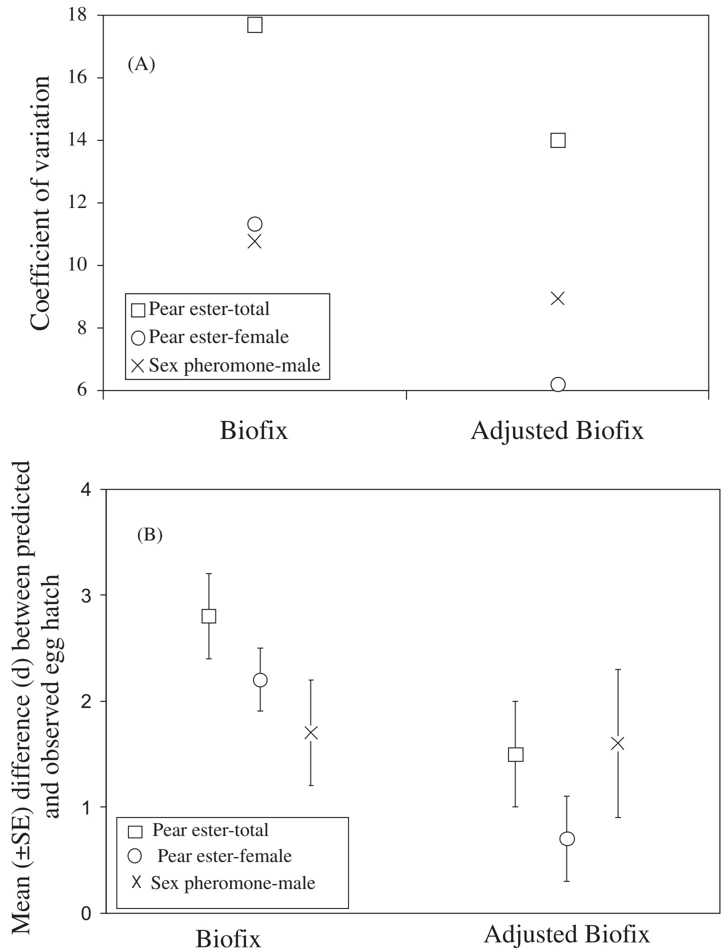
(<3 d difference from observed egg hatch). Interestingly, the temperature-adjusted female-based Biofix provided the most precise (lowest CV) estimate for the cumulative degree-day totals required until the start of egg hatch. This reduced variability was likely effected by the shorter period from first sustained female moth catch to egg hatch (17.8 d) compared with that for male moth catch in codlemone-baited traps (27.0 d) (Table 1). Also, since female moth flight occurred later than male moth flight and the occurrence of cool temperatures was somewhat less frequent later in the growing season, it is likely that the weather had a less variable impact on female moth sexual behaviors influencing oviposition.

The cumulative degree-days required from the start of sustained catch of males in codlemone-baited traps until egg hatch (139) has been empirically derived for codling moth (Beers and Brunner 1992) and is greater than the degree-days required for completion of egg development (86) (Richardson *et al*. 1982). This difference is due to the earlier emergence of males and the occurrence of a female preoviposition period (Riedl *et al*. 1976). Variability in the timing of male protandry and female oviposition among populations in different orchards and among years can contribute to errors in predicting egg hatch (Knight and Weiss 1996). For example, male codling moths have been caught in pear ester-baited traps from 0 to 3 weeks earlier than females (Table 1; Knight and Light 2005*a*). Similarly, the preoviposition period for codling moth is influenced by the occurrence of low field temperatures and can vary from 2 to 17 d (Shelford 1927; Hagley 1973). Our data collected over three growing seasons showed that the best predictor of egg hatch using the female moth-based Biofix was the accumulation of 105 degree-days, or 19 degree-days more than the total required for egg hatch (Richardson *et al*. 1982). During this part of the growing season, 19 degree-days was equivalent to approximately 3 calendar days. Further validation of this approach should be undertaken in other geographical areas and over additional seasons to more firmly establish this value.

Another source of error associated with predicting egg hatch based on moth catch is establishing the start of "sustained catch", which can be influenced by moth density and the frequency of trap checking. The importance of using an explicit definition of "sustained catch" was emphasized in our study by the large difference we observed in some orchards between the dates of first moth catch and first sustained moth catch (1–2 weeks). Meeting the criteria for "sustained catch" was straightforward in our experimental orchards, perhaps because of the high population densities of codling moth. The level of accuracy we obtained in predicting the start of egg hatch with this approach (<3 d difference from observed egg hatch) suggests that checking traps more frequently than every 3–4 d may not be required.

Establishing a Biofix in commercial orchards with low population densities of codling moth is difficult and even more problematic with a female moth-based Biofix. Codling moth populations at low densities (*i.e.*, <10 moths per trap per season and <0.5% fruit injury) in

Fig. 2. Coefficient of variation associated with the cumulative degree-days from each Biofix type to the date of first egg hatch (A) and the mean difference (bars indicate ±SE) between the observed and expected dates of first egg hatch (B) based on three Biofix types with and without the use of a temperature-based threshold (adjusted Biofix) in 11 apple orchards.



commercial orchards in the Pacific Northwest are generally managed with a combination of insecticide sprays and sex pheromone (Knight 1995). Therefore, we determined that the start of sustained catch of female moths in pear ester-baited traps could not have been established in 86 of the 204 commercial apple plots monitored during 2000–2002 owing to low moth catches (Knight and Light 2005*c*). Fortunately, a number of operational factors that can increase the capture of female codling moth in these traps, such as trap size, lure loading, and trap placement within the canopy, have since been identified (Knight and Light 2005*a*). The use of a standardized monitoring protocol using pear ester-baited traps placed in several orchards within a region with high population densities of codling moth will likely improve the effectiveness of this approach.

The influence of temperature on codling moth adult sexual activities has been included in some models to improve the prediction of egg hatch (Pickel *et al*. 1986; Blago 1992). This approach can also be used to establish a Biofix when traps are checked less frequently. Temperature thresholds of 12 °C have been recorded for male codling moth flight under field conditions using timing traps (Batiste *et al*. 1973). However, temperatures >15 °C are required for female mating and oviposition (Putnam 1963), and at dusk these temperatures have corresponded to consistent male moth catches in codlemone-baited traps (Pitcairn *et al*. 1990). Temperature can also shift the timing of codling moth adult crepuscular activity so that it occurs earlier (lower temperatures) or later (higher temperatures) (Batiste *et al*. 1973). In our study we found that the combined use of daily temperature thresholds for both the afternoon (maximum temperature) and dusk was more effective in establishing a Biofix than the use of either threshold alone, but their combined use only marginally improved the prediction of the start of codling moth egg hatch ($P < 0.10$). Nevertheless, careful consideration of the influence of temperature on the sexual activity of codling moth can provide useful insight into the timing of peak periods of mating and oviposition (Knight 2004).

Current phenology models for codling moth use a fixed density distribution of egg hatch as a function of cumulative degree-days following Biofix (Beers and Brunner 1992). However, the natural fluctuations in daily temperatures above and below thresholds for codling moth sexual activity can create significant nonlinear changes in the rate of mating success and fecundity of females as a function of degree-day accumulations (Knight 2004). Furthermore, the seasonal phenology of codling moth in some regions appears to have shifted from historical patterns (Walston and Riedl 2005). Tracking the seasonal activity of female codling moths with pear ester-baited traps could become an important tool with which to redefine the seasonal phenology of codling moth and help optimize management programs targeting both eggs and larvae.

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References

Allen, J.C. 1976. A modified sine wave method for calculating degree days. Environmental Entomology, **5**: 388–396.

Analytical Software. 2003. User's manual: Statistix8. Analytical Software, Tallahassee, Florida.

Batiste, W.C., Olson, W.H., and Berlowitz, A. 1973. Codling moth: influence of temperature and daylight intensity on the periodicity of daily flight in the field. Journal of Economic Entomology, **66**: 883–892.

Beers, E.H., and Brunner, J.F. 1992. Implementation of the codling moth phenology model on apples in Washington State, USA. Acta Phytopathologica et Entomologica Hungarica, **27**: 97–102.

Beers, E.H., Brunner, J.F., Willett, M.J., and Warner, G.M. 1993. Orchard pest management: a resource book for the Pacific Northwest. Good Fruit Grower, Yakima, Washington.

Blago, N. 1992. "BUGOFF 2 G" the adaptation of a Californian model for the codling moth to the Central European conditions. Acta Phytopathologica et Entomologica Hungarica, **27**: 119–125.

Croft, B.A., and Knight, A.L. 1983. Evaluation of the PETE phenology modeling system for integrated pest management of deciduous tree fruit species. Bulletin of the Entomological Society of America, **29**: 37–42.

Croft, B.A., and Riedl, H.W. 1991. Chemical control and resistance to pesticides of the codling moth. *In* Tortricoid pests. *Edited by* L.P.S. van der Geest and H.H. Evenhuis. Elsevier, Amsterdam. pp. 371–387.

Glenn, P.A. 1922. Relation of temperature to development of codling moth. Journal of Economic Entomology, **15**: 193–198.

Hagley, E.A.C. 1973. Timing sprays for codling moth (Lepidoptera: Olethreutidae) control on apple. The Canadian Entomologist, **105**: 1085–1089.

Howell, J.F. 1991. Reproductive biology. *In* Tortricoid pests. *Edited by* L.P.S. van der Geest and H.H. Evenhuis. Elsevier, Amsterdam. pp. 157–174.

Knight, A. 1995. The impact of codling moth (Lepidoptera: Tortricidae) mating disruption on apple pest management in Yakima Valley, Washington. Journal of the Entomological Society of British Columbia, **92**: 29–38.

Knight, A., and Weiss, M. 1996. Improving the codling moth Biofix-based spray timing model. Proceedings of the Washington State Horticultural Association, **92**: 209–210.

Knight, A.L. 2004. Development and testing of a new female-based phenology model for codling moth. *In* Proceedings of the 78th Western Orchard Pest and Disease Management Conference, Portland, Oregon, 14–16 January 2004. *Edited by* J. Dunley. Washington State University, Wenatchee, Washington. p. 15.

Knight, A.L., and Light, D.M. 2005*a*. Factors affecting the differential capture of male and female codling moth (Lepidoptera: Tortricidae) in traps baited with ethyl (*E*, *Z*)-2,4-decadienoate. Environmental Entomology, **34**: 1161–1169.

Knight, A.L., and Light, D.M. 2005*b*. Dose-response of codling moth (Lepidoptera: Tortricidae) to ethyl (*E*, *Z*)-2,4-decadienoate in apple orchards treated with sex pheromone dispensers. Environmental Entomology, **34**: 604–609.

Knight, A.L., and Light, D.M. 2005*c*. Seasonal flight patterns of codling moth (Lepidoptera: Tortricidae) monitored with pear ester and codlemone-baited traps in sex pheromone-treated apple orchards. Environmental Entomology, **34**: 1028–1035.

Light, D.M., Knight, A.L., Henrick, C.A., Rajapaska, D., Lingren, B., Dickens, J.C., Reynolds, K.M., Buttery, R.G., Merrill, G., Roitman, J., and Campbell, B.C. 2001. A pear-derived kairomone with pheromonal potency that attracts male and female codling moth, *Cydia pomonella* (L.). Naturwissenschaften, **88**: 333–338.

Pickel, C.P., Bethell, R.S., and Coates, W.W. 1986. Codling moth management using degree days. Publication 4, University of California Statewide IPM Project, Berkeley, California.

Pitcairn, M.J., Zalom, F.G., and Bentley, W.J. 1990. Weather factors influencing capture of *Cydia pomonella* (Lepidoptera: Tortricidae) in pheromone traps during overwintering flight in California. Environmental Entomology, **19**: 1253–1258.

Putnam, W.L. 1963. The codling moth, *Carpocapsa pomonella* (L.) (Lepidoptera: Tortricidae): a review with special reference to Ontario. Proceedings of the Entomological Society of Ontario, **93**: 22–60.

Richardson, J.C., Jorgensen, C.D., and Croft, B.A. 1982. Embryogenesis of the codling moth, *Laspeyresia pomonella*: use in validating phenology models. Annals of the Entomological Society of America, **75**: 201–209.

Riedl, H., Croft, B.A., and Howitt, A.J. 1976. Forecasting codling moth phenology based on pheromone trap catches and physiological time models. The Canadian Entomologist, **108**: 449–460.

Riedl, H., Howell, J.F., McNally, P.J., and Westigard, P.H. 1986. Codling moth management: use and standardization of pheromone trapping systems. Bulletin 1918, University of California Division of Agriculture and Natural Resources, Oakland, California.

Shelford, V.E. 1927. An experimental investigation of the relations of the codling moth to weather and climate. Illinois Natural History Survey Bulletin, **16**(5): 311–440.

Weissling, T.J., and Knight, A.L. 1994. Passive trap for monitoring codling moth (Lepidoptera: Tortricidae) flight activity. Journal of Economic Entomology, **87**: 103–107.

Walston, A., and Riedl, H. 2005. Codling moth control in Oregon's Hood River Valley: is it resistance, poor timing, or less effective control programs. *In* Proceedings of the 79th Western Orchard Pest and Disease Management Conference, Portland, Oregon, 5–7 January 2005. *Edited by* J. Dunley. Washington State University, Wenatchee, Washington. p. 11.

Zoller, B.G. 2001. Oviposition preference of codling moth between cut and uncut fruit of Bartlett, Bosc, and Beurre Hardy cultivars in the Sacramento Valley. *In* Proceedings of the 75th Western Orchard Pest and Disease Management Conference, Portland, Oregon, 10–12 January 2002. *Edited by* J. Dunley. Washington State University, Wenatchee, Washington. pp. 5–6.