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FORECASTING CODLING MOTH PHENOLOGY BASED ON PHEROMONE TRAP CATCHES AND PHYSIOLOGICAL-TIME MODELS

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Abstract

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The relationship of pheromone trap catch to emergence and oviposition of the codling moth was defined for the two-generation climate of Michigan. Catch anticipated emergence and oviposition during spring flight when the trap displayed greatest efficiency, but lagged behind emergence and closely followed oviposition during the second generation. Trapping efficiency declined towards the end of the first generation and was generally lower during summer flight. Factors which possibly relate to this efficiency loss are discussed. First catch and the catch peaks in both generations were evaluated as reference points for the prediction of phenological events (particularly egg hatch) in both generations. Of four forecasting methods, degree day and developmental unit summations, starting from first catch, for the preoviposition and incubation period were most reliable in predicting the beginning of spring brood egg hatch.

Introduction

Since the identification of the codling moth sex-attractant trans-8, trans-10-dodecadien-1-ol (Roelofs *et al.* 1971), the sex-pheromone trap has been widely accepted as a supplement to or replacement for traditional monitoring methods for spray timing (Batiste *et al.* 1970; Madsen and Vakenti 1972; Mani *et al.* 1972). Madsen and Vakenti (1973) successfully used pheromone trap catches and visual examination of fruit entry to determine the need for spraying. For timing of the first cover spray Batiste *et al.* (1973) placed oviposition cages with unmated moths in the field after the first males had been caught in pheromone traps to monitor egg development and first hatch. Glenn (1922) based predictions of the first appearance of the various life stages over the season on physiological time (degree days). This method, solely based on temperature, gave satisfactory results for spray timing (Headlee 1931). A further refinement was introduced by Shelford (1927), who studied the combined effect of temperature, relative humidity, and precipitation on codling moth development. Shelford's developmental unit (du) method requires a large amount of detailed climatic information and data handling. Thus, it has not been extensively used nor properly evaluated and compared to the more simple degree day (dd) method for prognosis. However, with the use of high speed computers and the development of on-line environmental monitoring capabilities (Haynes *et al.* 1973) the data requirements for such methods could be met on a real-time basis and use of these tools for tracking pest development becomes feasible.

Forecasting methods based entirely on climatic data input without reference to the population tend to lack realism and accuracy. Therefore, we proposed in this field study to characterize in a seasonal pheromone trapping record, biological reference points which show a consistent relationship to certain phenological events which are critical for the timing of control measures, and which are readily identifiable as the season progresses. Our overall objective was, to define the relationship between pheromone trap catch, emergence, and oviposition for the two-generation climate in Michigan as the basis for a workable forecasting system which could be easily incorporated in a pest management program for deciduous fruit.

Materials and Methods

In 1973 seven orchards located in southwestern Michigan in a 50 by 30 sq. mile area were chosen for this study; all but orchard 7 were mature orchards which were either commercially abandoned (Nos. 1, 2, 6, 7) or had not been sprayed with broadspectrum insecticides during 1973 (Nos. 3, 4, 5). Their size ranged from 3 to 20 acres and the major fruit varieties represented were Red Delicious, Northern Spy, Jonathan, MacIntosh, and Ida Red.

Sectar 1^{®1} traps baited with Codlemone^{®2} septa and the bottom ends left open were placed in the orchards at a density of 1 trap per 4 acres (no traps at the borders). Septa were changed every 2 weeks throughout the season, but traps were replaced only once around 15 July except in orchard 7 where traps were renewed biweekly. During the week before first male catch, orchards were visited at least every other day to accurately determine first male moth activity. Later, catch was recorded 3 times per week in orchards 1, 2, and 7 and once per week in the others. Records of spring brood emergence in orchards 1 and 2 were obtained from 6-in.-wide corrugated cardboard bands which had been fastened around the lower portion of 20 tree trunks throughout the blocks during the previous season. Ten days before the anticipated first emergence the bands were taken off the individual trees and fastened around vertical log sections in a cone-shaped screen cage with a gelatin mold on top as the collecting device. The removal of the bands from the cocooning habitat (lower tree trunk) and repositioning in cages to observe emergence might have introduced some bias. However, this possible error was minimized (*a*) by attaching each band in its original cardinal position to the log section and (*b*) by positioning each cage within the canopy next to the trunk. Emerging moths readily flew upwards to the top of the cage where they fell into the ethylene-glycol-filled mold. There the moths were easily counted and sexed. Summer generation emergence in orchard 7 was similarly monitored with corrugated cardboard bands which were renewed every 10 days beginning 25 June.

In orchards 1 to 6 first egg hatch was directly observed by randomly checking 50 fruit clusters on each of 10 trees in early June. In orchard 7 weekly egg counts were taken beginning 5 June until the first half of September. Each week, 50 fruit clusters were checked at random on each of eight trees without removing the cluster. A sampling interval of 1 week seemed adequate since during the summer months, the degree day accumulation averaged 150 (above 50°F) per week in this orchard which is slightly less than the 158 dd for the incubation period (Glenn 1922). This orchard was ca. 20 years old and had 129 trees of which half were fruit-bearing in 1973 with an average of 200 fruit/tree. In 1974 the study was continued in orchard 7 with several modifications in the experimental design. Again, only half of the trees in this orchard bore fruit in 1974 with an average of 600 fruit/tree. One of the two Sectar 1 traps was replaced with a timing pheromone trap (Riedl, unpub. data) which recorded hourly catches throughout the season. During spring flight Pherocon CM-X^{®2} caps were employed (renewed every 4 weeks); however, for the summer flight again Codlemone septa were used (renewed biweekly). Emergence records were obtained as in 1973 with corrugated cardboard bands. On each of 10 trees 25 fruit clusters were tagged and sampled weekly for eggs.

Weather stations were set up in each orchard to record temperature, relative humidity, and precipitation from the middle of April until the end of moth activity. Climatic data for preceding months were taken from the nearest NOAA or agricultural weather station (AAM Ceel VanDenBrink). Degree days (dd) were calculated from the daily minimum and maximum temperatures according to the sinus wave method by Baskerville and Emin (1969). The lower and upper thresholds used for the computations of degree days were 50°F (10°C) and 88°F (31°C). These figures as well as the dd totals

^{1,2}3-M Corporation, St. Paul, Minn., and Zoecon Co., Palo Alto, Calif., respectively.

for the various developmental stages were taken from Glenn (1922). In addition, developmental unit (du) totals were computed for the incubation period from corresponding 2-hourly readings of temperature and relative humidity based on Shelford's method (1927).

For direct comparison, interpretation, and incorporation into a predictive model, cumulative catch, emergence, and oviposition were defined on a degree day scale. Because of the sigmoid distribution and positive skewness of these data, degree days (abscissa) were transformed to log (base 10) and cumulative per cent (ordinate) to probits (probability units). Then a least-square analysis was performed as a curve-fitting routine. Morris and Fulton (1970) suggested and used this log-probit analysis for similar data. The r^2 values ranged from .96 to .99 which indicated good fit of the calculated log-probit lines to these data sets. For some spring catch data a log-probit transformation gave a poorer fit than using either degree days (x) or cumulative per cent without transformation. The line with the highest r^2 was then chosen as the best fit. The 50% emergence and oviposition points for both generations were calculated with this method for orchards 1, 2, and 7 respectively. For the determination of egg hatch it was assumed that the live eggs included in the weekly samples had passed on the average through half of the total incubation period (158 dd). Points of egg hatch were calculated by adding 79 dd to dd totals for oviposition. During the 2 years of study no appreciable overlap between generations was observed and the midpoint between spring and summer generation was determined on the basis of emergence data.

Results and Discussion

RELATIONSHIP OF EMERGENCE AND OVIPOSITION TO PHEROMONE TRAP CATCH

Pheromone catch of male moths frequently has been interpreted in a chronological sense with respect to female activity, oviposition, and egg hatch. Because of the nature of the pheromone trap and its possible interaction and competition with the female population there is some question if the same trap catch interpretation can be applied throughout a given season. Mani *et al.* (1972) pointed out the necessity for a new interpretation of pheromone catches in early season because of observed differences to light trap catches which in their opinion reflected more closely ovipositional activity. Bait traps which were widely used at one time for monitoring purposes were found to indicate moth activity and egg laying sufficiently well to be useful for the timing of control measures (Baker 1942).

In 1973, catch in pheromone traps preceded emergence from cardboard bands in field cages by 50 dd (5 days) in orchard 1 (Fig. 1a) and 82 dd (8 days) in orchard 2 (Fig. 1b). In 1974 this interval was 32 dd (5 days) in orchard 7 (Fig. 2b). Trunk bands are only an indirect method to obtain emergence data, since they represent an artificial cocooning site and sample only a small portion of the actual cocooning habitat which might not indicate the total variation of emergence due to microclimatic effects (Peterson 1928). Pheromone trap catch, on the other hand, represents a collection of male moths which emerged from the various cocooning habitats (tree and soil) and can give therefore a more realistic estimate of the beginning and end point of male emergence and activity within the trap range. The observed interval between first catch and first emergence from trunk bands seems to confirm the sensitivity of the pheromone trap to detect first emergence and flight activity.

Percentage cumulative emergence (males and females combined) and pheromone trap catch are plotted (Figs. 1, 2) on a time-temperature scale (degree days) above developmental zero (50°F). In both generations, spring and summer, catch curves deviated significantly from the less skewed emergence curves. This was not unexpected since pheromone trap catches reflect the active male population and are therefore only

an indirect representation of emergence. Some of the fluctuations of the cumulative catch curve can be attributed to the fact that activity is conditioned by a higher temperature threshold (60°F) than is development (50°F) and can be completely inhibited by climatic conditions (wind, precipitation) which have comparatively little effect on physiological development and emergence.

The patterns of cumulative catch to emergence for the spring and the summer generation were consistent in both years (Figs. 1, 2). Assuming that the pheromone trap mimics successfully the natural pheromone communication from female to male, competition between traps and feral female moths for males could be an important factor which could influence trap catch size and the probability of male-female encounter. The degree of competition, then, is dependent on (a) the ratio between female density (variable) and trap density (constant) per unit area, (b) the sex ratio if different from unity, and (c) the relative attractiveness of the artificial pheromone source. Roelofs *et al.* (1970) have discussed these factors and competition in a mathematical model for male removal with the pheromone trap. Differences in seasonal sex ratios from year to year were observed by MacLellan (1972) in populations from commercial plantings and by Hagley (1973) in populations from abandoned orchards. This phenomenon is apparently related to density. Changes in the sex ratio occur also within a season and Table I gives an example for the trend in the sex ratio from below unity (males predominant) initially to above unity later on (females predominant) during spring

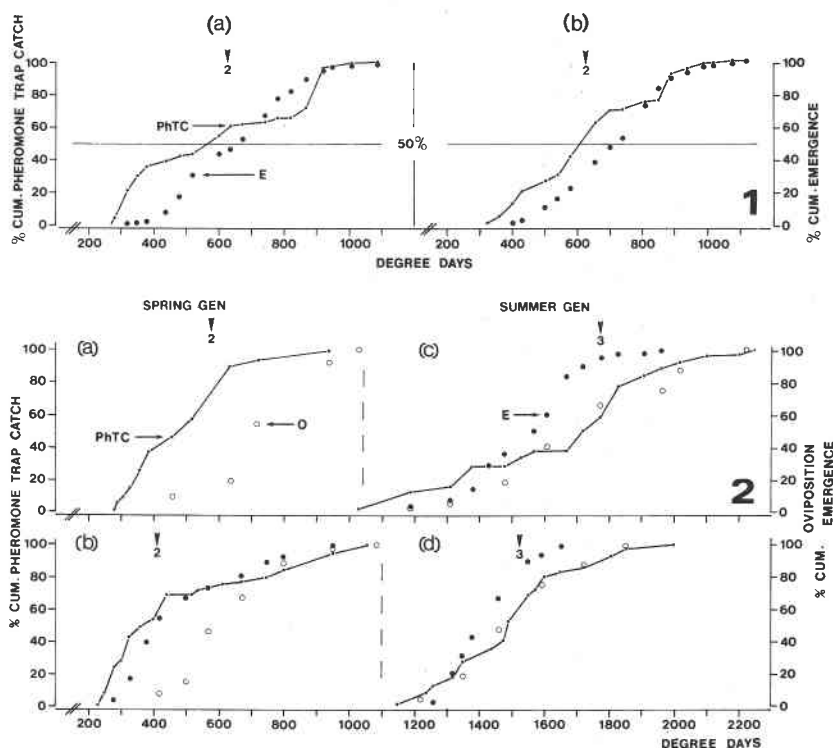


FIG. 1. Relationship of cumulative spring generation emergence (E) to pheromone trap catch (PhTC) during 1973 at (a) Izenbart 1 and (b) Empire 2; arrow indicates biological fixpoint 2.

FIG. 2. Relationship of cumulative emergence (E) and oviposition (O) to pheromone trap catch (PhTC) during spring and summer generation at Nadeau 7 in (a, c) 1973 and (b, d) 1974; arrows indicate biological fixpoints, 2 and 3.

Table I. Sex ratio in codling moth population emerging from cardboard bands during
(a) spring and (b) summer 1973

	Degree days after Jan. 1		No. males	No. females	Sex ratio females/males
	From	To			
(a) Empire 2	400	550	49	33	.67
	550	700	80	89	1.11
	700	850	85	100	1.18
	850	1000	29	42	1.45
	1000	1150	7	8	1.14
(b) Nadeau 7	1200	1400	10	20	2.00
	1400	1600	8	22	2.75
	1600	1800	10	26	2.60
	1800	2000	0	3	>1.00

emergence. Other researchers have found a similar trend in the sex ratio of the emerging overwintering generation (Hall 1929; Hagley 1973) and a tendency towards protandry (Tadic 1963). Such a shift in the sex ratio was not observed for the summer generation with the sex ratio staying above one throughout the emergence period (Table I) which agrees with data given by Tadic (1963) but not with Hagley (1973), who reported an upward shifting sex ratio for the summer generation with a higher number of males initially. The within-season sex ratio changes in the other orchards where emergence was monitored were similar to the data given in Table I.

The initial increase of trap catches at the very beginning of emergence (note steep slope of cumulative catch curve in lower tail: Figs. 1a, b; 2a, b) and a lag of ca. 50–100 dd between the 50% level of cumulative catch and emergence (Figs. 1a, b; 2b) gave evidence for the high trapping efficiency when competition was reduced in early season since population densities were still low and males predominated in the population (Table I).

The average cumulative catch/trap during the spring emergence reached 63 and 68 moths in orchards 1 and 2 respectively while at Nadeau 7 it was considerably less in 1973 and 1974 (30 and 45 moths respectively). These catch totals suggest actual differences in population density between orchards 1 and 2 and orchard 7. The relationship of cumulative catch to emergence was basically similar in both density situations; Fig. 1a and b seemed to indicate, however, a stronger response to the trap beyond the 50% emergence point. This is reflected in Fig. 1a and b as steepening slope in cumulative catch curves which would appear as bimodal curves if data were plotted not as cumulative per cent, but as mean catch per degree day interval. This effect was not apparent at Nadeau 7 with the lower density (Fig. 2) although a slight increase in catches occurred towards the end of spring oviposition (Fig. 3). Further studies are necessary to clarify if the degree of bimodality in the catch curve is density-related or if it is caused by the variable effect of climatic factors on male pheromone response.

Complete records of summer generation emergence were only obtained in orchard 7 since orchards 1 and 2 lost their fruit due to frost and disease. The relationship between cumulative catch and emergence of this generation (Fig. 2c, d) was the reverse from the spring generation pattern (Figs. 1a, b; 2b). While catch was skewed early in spring, it was less skewed for the summer generation. The 50% catch point lagged behind the 50% emergence point by ca. 100 dd giving evidence for an even greater reduction in trapping efficiency during the summer generation when population densities were higher than in spring with a sex ratio favoring females (Table I).

Particularly significant is the relationship of catch to oviposition since the latter is a more direct indicator for the intensity of sexual activity and competition. The egg densities graphed in Fig. 3a and b include all stages (white, red-ring, blackhead) and were adjusted for crop load and fruit drop in each year respectively. The population density at Nadeau 7 was higher in 1974 than in 1973 which is evident from the trap catches and egg density counts (Fig. 3). In 1973, conditions during evenings were, on the whole, favorable for moth flight in June and July. In the middle of August, rainfall on successive evenings plus cooler temperatures could have impaired ovipositional activity. In 1974 evenings were cooler in June, possibly suppressing earlier oviposition (Fig. 3). During spring emergence, ovipositional activity was still low when catch reached the 50% point and lagged behind catch by ca. 200 dd (Fig. 2a, b). The magnitude of pheromone catches during spring flight was almost inversely related to oviposition or the intensity of sexual activity in the population (Fig. 3a, b). Catches peaked (Biofix 2) before egg density began to increase and dropped off sharply once oviposition reached a maximum. Towards the end of first generation oviposition and between generations catches recovered slightly, possibly due to a lessening in competition since the population density and sexual activity were low. Catches followed the increase in egg density in the second generation; however, the peak catches were not taken until after the oviposition peaks (Fig. 2c, d; Fig. 3). Studies with the tufted apple bud moth, *Platynota idaeusalis*, have yielded similar relationships between catch and the number of egg masses deposited (W. M. Bode, Penn State University, pers. comm.). This delay in the summer generation peak catch could be caused again by competition. The intensity of sexual activity and therefore competition with the trap must have been highest shortly before egg densities peaked. Once this point was passed more males responded to the trap stimulus again which created an artificial peak with no equivalent in terms of emergence or oviposition.

Evidence suggests that the trapping efficiency during the summer generation was lower than during the first half of the season. In 1973 a total of 60 male moths were caught in orchard 7 during spring emergence (until 10 July) and another 60 males

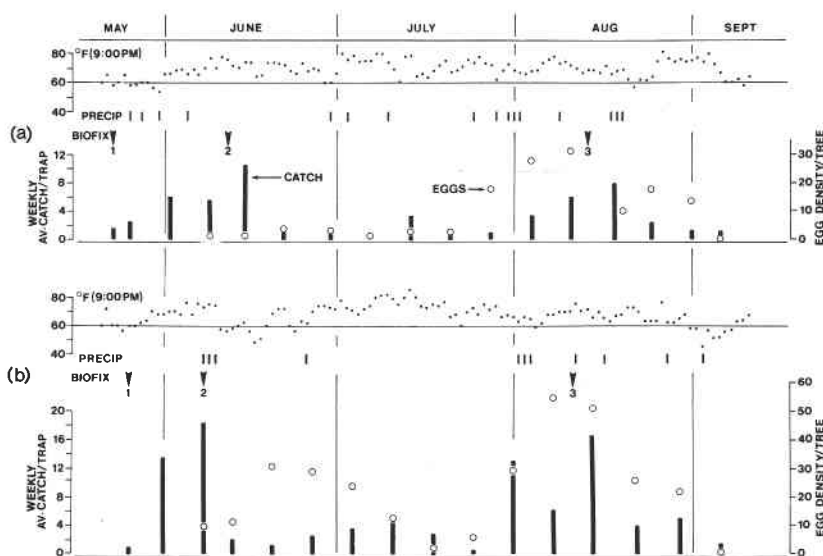


FIG. 3. Evening temperatures, precipitation, weekly pheromone trap catches, and oviposition at Nadeau 7 in (a) 1973 and (b) 1974; arrows indicate biological fixpoints, 1, 2, and 3.

thereafter until 10 Sept. with no net increase in catch. In 1974 99 moths were caught during spring and 90 moths during summer flight. However, the 1974 catches cannot be compared since different pheromone caps were used for the spring and summer. On the other hand, the egg population increased several fold from the first to the second generation in both years. This surge in egg density was obviously not reflected by male catches and can be explained only in part by the lower female fecundity during spring (Hagley 1973). A re-examination of trap catch and infestation data from 21 orchards in 1972 (Riedl and Croft 1974) indicated that on an average, infestation increased 5.5-fold from the first to the second generation while catch only doubled. In the same study it was demonstrated that the relationship between pheromone trap catch and absolute damage changed from a linear form in the first half of the season to an exponential form in the second half. The shift occurred in early August before the trap catches of the summer generation began to peak.

FORECASTING OF PHENOLOGY

The reliability of physiological-time models (dd's or du's) for forecasting without reference to the actual population is naturally variable and inaccuracies increase as predictions are extended over longer time spans. Glenn (1922) and Shelford (1927) suggested the use of biological reference points, such as first or peak pupation, and starting the accumulation of dd's or du's from these points for a more realistic prediction of adult emergence. In the 1973-74 pheromone trap catch records, three readily identifiable points were consistently related to critical phenological events. Biofix 1 was defined as the first male moth or moths in the pheromone trap with no significant interruption in catches thereafter. If several days without catches followed, then the beginning of continuous pheromone trap catches was defined as Biofix 1. In the Michigan fruit belt this event can be expected after 281 dd (± 15 S.E.) degree days have accumulated beyond 1 Jan. Peak catch for both generations (Biofix 2, 3) was defined as the highest combined catch of 4 days (two check periods). The second day was used then as actual reference point. This allowed for a more accurate definition of peak catch than using the highest weekly catch figure. Peak catch during spring (Biofix 2) correlated well with the 50% emergence point in 1973 and occurred 20 dd after (Fig. 1a) and 32 dd before (Fig. 1b) the half point of emergence. Biofix 2 in the 1974 spring flight catch record from orchard 7 was 32 dd early (Fig. 2b) and it is likely that it is unreliable as a reference point because of the inconsistent and diminishing release rate of the CM-X[®] attractant septum (C. M. Olson, Zoecon Co., pers. comm.). This was supported by trap records from a nearby abandoned orchard (2 miles south) with Codlemone[®]-baited traps which showed peak catches for that area several days after the peak catch in orchard 7. On an average, spring flight peak catch occurred 280 dd (± 40 S.E.) after Biofix 1. This figure can be useful to identify Biofix 2 if several peaks appear in the trapping record. This was the case in orchard 1 in 1973 where the highest catch during spring flight was taken following Biofix 1 with two smaller catch peaks thereafter (Fig. 1a; note steepness of slope). Peak catch in the summer generation (Biofix 3) occurred 1486 dd (± 74 S.E.) after first catch, did not anticipate 50% oviposition and was 92 and 32 dd late in 1973 and 74 respectively (Fig. 2c, d); there was better agreement between Biofix 3 and the 50% second generation egg hatch point (Table IV) and it could be possibly used as a direct indicator for that event.

Prediction of Beginning Egg Hatch of Spring Generation

First pheromone trap catch of male moths was used in this study as a biological fixpoint (Biofix 1) and served as the starting point for dd and du projections for egg hatch of the spring generation. The lag time between first male activity, as indicated by

the pheromone trap, and first oviposition is difficult to determine accurately. It is affected by the earlier emergence of males as compared to females (protandry) and the variable duration of the preoviposition period. The duration of the preoviposition period is dependent on environmental conditions for sexual activity and egg laying. Shelford (1927) calculated the preoviposition period as a total of 2 days with temperatures above 60°F (activity threshold) during the evening hours. Glenn (1922) suggested 50 dd above 50°F (developmental threshold) as an approximation for the preoviposition period. These values are only estimations for this period which can vary in Ontario from 2 to 17 days (Hagley 1973). The reliability of four forecasting methods for first egg hatch was judged by the deviation of each prediction from the actually observed first egg hatch in the field (Table II). Although it is unlikely that the 'first' hatching egg was detected, high population intensity because of low fruit set in both years increased the probability of detecting first hatch as compared to a year with normal fruit set.

Predictions by dd without reference to a biological fixpoint and based on the total accumulation since 1 Jan. displayed great variability and ranged from 3 days early to 2 days late; the average prediction was close to the actually observed event in the field but its standard error was ca. twice as large as for the last two methods (Table II). The other three methods used first catch (Biofix 1) as the starting point. A fixed time span of 21 days after first catch has been used by fruit growers in Michigan as a guide for timing the first spray. This empirical method is obviously inflexible since it does not take into account the climatically conditioned variability in the duration of the preoviposition and incubation period. The average prediction with this method for orchard 1 to 7 was 78 dd (or ca. 4 days late) with large standard error. The dd and du method, starting with Biofix 1, underestimated the period between first catch and first egg hatch by 44 and 32 dd or ca. 2–3 days respectively; both predicted first hatch consistently early with small standard error (Table II). Since Shelford's method takes into account the effect of relative humidity in addition to temperature one would expect an improvement in the prediction. However, this improvement was not apparent for the short-term prediction of egg hatch, and the small variation between these two methods was primarily due to the different computation of the preovisposition period. The dd sum which accumulated from Biofix 1 until first egg hatch averaged 253 (Table II). Hagley (1973) calculated dd totals of 259 in 1971 and 244 in 1972 for the same period in Ontario. His figures fall in the same range as our dd sums although he worked with a higher threshold for egg development (52°F).

Table II. Comparison of four forecasting methods for first egg hatch

	No.	Observed ^a 1st egg hatch	Observed ^b				Biofix 1 → hatch (dd)
			dd	Biofix 1 + 21 days	Biofix 1 + dd	Biofix 1 + du	
Izenbart	1	522	+45 (+2)	+ 45 (+2)	-40 (-2)	-41 (-2)	250
Empire	2	577	-24 (-1)	+ 47 (+2)	-55 (-2)	0	263
Hickory	3	622 ^c	-70 (-3)	+139 (+6)	-54 (-2)	-52 (-2)	262
Upjohn	4	634 ^c	-22 (-1)	+186 (+8)	-35 (-2)	-48 (-2)	243
VanDragt	5	520	+46 (+2)	+ 70 (+4)	-20 (-1)	-37 (-2)	228
Schmid	6	474	+43 (+2)	+ 70 (+3)	-38 (-1)	-25 (-1)	246
Nadeau 73	7	556	+28 (+1)	+ 52 (+2)	-57 (-3)	0	265
Nadeau 74	7	508	+42 (+4)	+ 17 (+2)	-55 (-3)	-53 (-3)	263
Av. dev.			+11	+ 78	-44	-32	253
S.E.			±16	± 20	± 5	± 8	±5

^a DD total from Jan. 1.

^b Deviations in DD and days (parentheses) from first egg hatch in the field.

^c Estimated from time of appearance of first damage.

Table III. Forecasting of 50% egg hatch in first and second generation from Biofix 2 and 3 for Nadeau 7 in 1973 and 1974

First generation			
	Observed ^a	Biofix 2 + 208 ^c	Dev. ^b
1973	763	792	+30
1974	683	618	-65

Second generation							
	Observed ^a	Biofix 3 + 208 ^c	Dev. ^b	Biofix 3	Dev. ^b	Biofix 2 + 1208 ^d	Dev. ^b
1973	1761	1982	+221	1774	+13	1792	+31
1974	1570	1731	+161	1523	-47	1618	+48

^a Calculated from log-probit equations for oviposition curves in Fig. 2.

^b Deviation in degree days (predicted minus observed).

^c Degree day total for preoviposition + incubation.

^d Degree day total for preoviposition + incubation + full generation cycle.

Prediction of 50% Egg Hatch in First and Second Generation

In addition to predicting the first hatch of codling moth larvae, control measures might be timed with respect to maximum egg hatch so as to effect the greatest fruit protection against larval entry. To predict the 50% point of first generation egg hatch, degree days were summed for the preoviposition and incubation period (50+158 dd) beyond Biofix 2. In 1973 this prediction was 30 dd late, but was 65 dd early in 1974 (Table III). For the summer generation Biofix 3 seems to have little value as a reference point for dd predictions since the 50% egg hatch point was predicted 221 and 161 dd (Table III) after the actual event in the field. Therefore spring generation peak catches (Biofix 2) were evaluated as reference points for second generation egg hatch. This point was projected after 50+158+1000 dd (preoviposition + incubation + full generation cycle) accumulated beyond Biofix 2. In both years the projection was reasonably close to the actual event (Table III).

Prediction of Average Seasonal Phenology

Combining the individual curves for cumulative pheromone trap catch, emergence and oviposition from orchards 1, 2, and 7 (Figs. 1, 2) one can arrive at the average cumulative curves which can be readily used for prediction purposes (Fig. 4). Spring catch data from Nadeau 7 in 1974 were not included since a different pheromone cap was employed than in the other orchards. These curves are centered to first catch (Biofix 1) and the respective log-probit equations are listed in Table IV; since they are defined

Table IV. Log-probit equations for the average proportion of pheromone trap catch, emergence, and oviposition for the spring and summer generation

	Spring	Summer
Catch	$y^a = -12.993 + 6.665 \log (x + 281)$	$y = -33.157 + 12.30 \log x$
Emergence	$y = -5.739 + 4.358 \log x^b$	$y = -62.536 + 21.924 \log x$
Oviposition	$y = -10.037 + 5.843 \log x$	$y = -40.683 + 14.641 \log x$

^ay expressed in probits; for conversion to per cent use table of probits

^bx degree days after Biofix 1

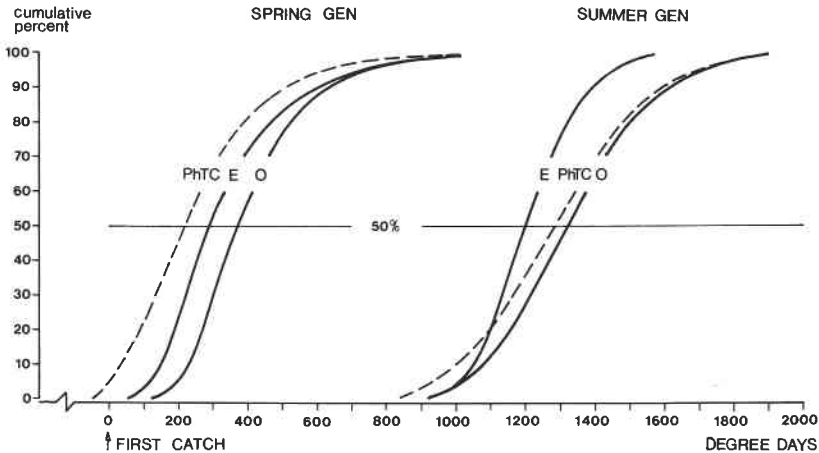


FIG. 4. Average relationships of cumulative emergence (E) and oviposition (O) to pheromone trap catch (PhTC) in both generations.

on a time-temperature scale, they can be used to predict the average proportion of pheromone trap catch taken, moths emerged, or eggs deposited for any dd total after first catch during the spring and summer generation.

The slope of the cumulative emergence curve in the spring generation deviates little from the oviposition curve (Fig. 4). This indicates little bias in the method used to measure spring emergence. However, the significant difference in slope between the emergence and oviposition curves in the summer generation suggests considerable bias. One must conclude therefore that the summer generation emergence curve presented in Fig. 4 does not express well the actual emergence from natural cocooning sites.

In Michigan the duration of second generation emergence and oviposition can vary from year to year depending on the proportion of first generation larvae entering diapause. In a year with a warm spring and summer fewer first generation larvae will enter diapause resulting in an extended second generation. The opposite would be expected for a cold year. Because of this variability the average cumulative curves for the summer generation (Fig. 4) are only of limited value for predictive purposes. The effect of diapause on second generation phenology and methods to predict it more accurately for climatically different years will be the subject of a forthcoming publication.

Summary and Conclusions

The pheromone trap is probably the most specific, economical, and convenient biological monitoring tool available today and is, therefore, ideally suited to be used in a pest management program for a multiple pest species complex. For its effective and confident use it is necessary to understand the relationship of catch to phenological phenomena (emergence, oviposition, damage, etc.) under various climatic situations and population densities.

At the onset of spring flight, trap efficiency was highest, but dropped off with increasing ovipositional activity. During the summer generation, trap efficiency showed a general decline. Evidence presented in this study suggests that competition is a likely factor which might contribute to the high variability in trap efficiency during both generations and cause the unique relationships of catch to oviposition and emergence.

Three points in a seasonal trapping record, first catch and peak catches in both generations, which are readily identifiable as the season progresses, were investigated in their relationship to key phenological events which are critical for the timing of control measures. First catch (Biofix 1) appeared to give a reliable estimate for first emergence and could be used therefore as a biological reference point. Peak catch during spring flight (Biofix 2) as an indicator for 50% emergence and peak catch during the summer generation (Biofix 3) as it relates to 50% second generation egg hatch require further study.

The combination of biological monitoring with the pheromone trap and environmental monitoring for dd forecasting which Hagley (1973) found also very promising can be easily integrated in a pest management system for deciduous fruit as outlined by Croft *et al.* (in press). The implementation and the success of such a program will depend heavily on the establishment of a fine-meshed environmental monitoring network so that predictions can be made for individual orchards as well as for larger regions.

This study was carried out in abandoned orchards because the authors intended to clarify the inherent properties of the pheromone trap as they relate to moth phenology undisturbed by artificial mortality factors. Second, since codling moth is a direct fruit pest, moth populations in well-managed orchards are almost totally suppressed and therefore difficult to study. However, the question arises: Are the results obtained in abandoned orchards relevant and applicable to the commercial orchard with standard spray programs? The frequent application of insecticides will undoubtedly alter the seasonal phenology of an indigenous moth population since certain proportions of the various life stages are eliminated depending on frequency and timing of applications. Unless the effect of control measures on the moth population is quantitatively understood and incorporated in a population model which will track stage mortalities and stage distribution it is difficult to predict within-generation and even more difficult to predict between-generation shifts in moth phenology. Experiments are necessary to show if the pheromone trap can be a valid indicator of moth activity and egg laying in orchards with indigenous moth populations whose phenology is disturbed by routinely applied sprays. However, the phenology in a commercial orchard would be similar to that of abandoned orchards if the major part of an infestation is caused by moths immigrating from unsprayed trees or wild hosts. In these cases which are quite frequent in Michigan and other eastern apple growing areas, the forecasting methods developed herein should prove useful.

References

- Baker, H. 1942. The relation between bait-trap catches and codling moth emergence and egg laying. *Bien. Rep. Kans. Hort. Soc.* **46**: 31–35.
- Baskerville, G. L. and P. Emin. 1969. Rapid estimation of heat accumulation from maximum and minimum temperatures. *Ecology* **50**(3): 514–517.
- Batiste, W. C., A. Berlowitz, and W. H. Olson. 1970. Evaluation of insecticides for control of codling moth on pears in California and their usefulness in an integrated control program. *J. econ. Ent.* **63**: 1457–1462.
- Batiste, W. C., A. Berlowitz, W. H. Olson, J. E. DeTar, and J. E. Joos. 1973. Codling moth: estimating time of first egg hatch in the field — a supplement to sex-attractant traps in integrated control. *Environ. Ent.* **2**: 387–391.
- Croft, B. A., R. L. Tummala, H. Riedl, and S. M. Welch. Modeling and management of 2 prototype apple arthropod pest subsystems. In R. L. Tummala *et al.*, (Eds.), Modeling for pest management: Concepts, techniques and applications. *Proc. 2nd Ann. USSR/USA Symp. on Integrated Pest Management*, Michigan St. Univ., E. Lansing (1974) (in press).
- Glenn, P. A. 1922. Relation of temperature to development of codling moth. *J. econ. Ent.* **15**: 193–198.
- Hagley, E. A. C. 1973. Timing sprays for codling moth (Lepidoptera: Olethreutidae) control on apple. *Can. Ent.* **105**: 1085–1089.

- Hall, J. A. 1929. Six years' study of the life history and habits of the codling moth (*Carpocapsa pomonella* L.). *A. Rep. ent. Soc. Ont.* **59**(1928): 96-105.
- Haynes, D. L., R. K. Brandenburg, and P. D. Fisher. 1973. Environmental monitoring network for pest management systems. *Environ. Ent.* **2**: 889-899.
- Headlee, T. J. 1931. Performance of the thermal constant as an indicator of the time to apply cover sprays for codling moth. *J. econ. Ent.* **24**: 291-296.
- MacLellan, C. R. 1972. Sex ratio in three stages of field collected codling moth. *Can. Ent.* **104**: 1661-1664.
- Madsen, H. F. and J. M. Vakenti. 1972. Codling moths: female-baited and synthetic pheromone traps as population indicators. *Environ. Ent.* **1**: 554-557.
- . 1973. Codling moth: use of Codlemone-baited traps and visual detection of entries to determine need of sprays. *Environ. Ent.* **2**: 677-679.
- Mani, E., Th. Wildbolz and W. Riggenschach. 1972. Die Männchenfalle, eine neue Prognosemethode für den Apfelwickler; Resultate 1969-1971. *Schweiz. Z. Obst- u. Weinb.* **108**: 337-344.
- Morris, R. F. and W. C. Fulton. 1970. Models for the development and survival of *Hyphantria cunea* in relation to temperature and humidity. *Mem. ent. Soc. Can.*, No. 70. 60 pp.
- Peterson, A. 1928. Determination of the spring brood emergence of oriental peach moths and codling moths by various methods. *J. agric. Res.* **37**(7): 399-417.
- Riedl, H. and B. A. Croft. 1974. A study of pheromone trap catches in relation to codling moth (Lepidoptera: Olethreutidae) damage. *Can. Ent.* **106**: 525-537.
- Roelofs, W. L., E. H. Glass, J. Tette, and A. Comeau. 1970. Sex pheromone trapping for red-banded leaf roller control: theoretical and actual. *J. econ. Ent.* **63**: 1162-1167.
- Roelofs, W. L., A. Comeau, A. Hill, and G. Milicevic. 1971. Sex attractant of the codling moth: characterization with electroantennogram technique. *Science* **174**: 297-299.
- Shelford, V. E. 1927. An experimental investigation of the relations of the codling moth to weather and climate. *Ill. nat. Hist. Surv.*, Vol. XVI, Art. V.
- Tadic, M. 1963. The biology of the codling moth (*Carpocapsa pomonella* L.) as the basis for its control. U.S. Dep. Commerce, Office of Technical Services; OTS 60-21681, 97 pp. (Translation of 1957 paper: University of Belgrade.).

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