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Temperature models for predicting the flight activity of local populations of *Cydia funebrana* (Lepidoptera: Tortricidae) in Central Europe

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Abstract. Temperature models for predicting the flight activity of the plum fruit moth, *Cydia funebrana*, were developed using male catches in pheromone traps at four locations in the Czech Republic and one in the Slovak Republic. A method of nonlinear regression by means of Richard's formula was used. Total catches of moths from the overwintering and the summer (second) generations were strongly correlated. The regression equation proposed can be used to forecast the expected number of individuals in the summer generation. Whereas the flight curves of the overwintering generation were similar for all populations and years in this study, flight curves of the summer generation differed markedly among populations from different localities. Degree-days from initiation to the peak of flight during the summer were significantly higher at warmer localities, than at the coldest locality. Year to year differences of up to 30 days were found among the flight peaks of the summer generation at the same locality. Regression models proposed for each local population can be used to forecast the phenology of the pest within a year, and together with other knowledge, they can be used for timing pesticide treatments.

INTRODUCTION

Pheromone traps have been used for monitoring a number of lepidopteran pests of fruit orchards and together with the method of temperature summation, they are important components of phenological models (Croft et al., 1976; Riedl et al., 1976). Models utilizing temperature summation are a useful tool for forecasting the presence of a specific stage of a pest (Mols, 1992).

Cravedi & Molinari (1993) reported that pheromone traps are commonly used in Italy for monitoring the flight activity of the plum fruit moth, *Cydia funebrana* (Treitschke), but interpretation of the data seems ambiguous and needs further study. A strong correlation between temperature sums and pheromone trap catches of *C. funebrana* was demonstrated in earlier experiments (Beránková et al., 1991). A temperature-based model predicting activity of a population of *C. funebrana* in a single commercial plum orchard in Central Bohemia was devised by Kocourek et al. (1995); however, it was never established whether this model could be used at different locations. This paper reports the development of a temperature model for predicting flight activity of *C. funebrana* at different locations of the Czech and the Slovak Republic.

MATERIAL AND METHODS

We obtained records of male *C. funebrana* catches in pheromone traps at several sites and in different years as specified: 1) Heřmanice near Nová Paka, north-western Bohemia, was the coldest locality under investigation. Pheromone traps were placed in plum tree canopies in a mixed fruit tree orchard during 1976–1991 (with exception of the year 1980); 2) in Zbraslav, a suburb of Prague, Central Bohemia, traps were placed in plum tree canopies in a backyard orchard during 1985–1991; 3) in Roudnice, one of the warmest regions in Bohemia, traps were placed in commercial plum orchards (11.04 hectares), with Chachanska Lepotica and Chachanska Naibolia cultivars during 1988–1992; 4) in Pasohlávky, a very warm part of southern Moravia, traps were placed in approximately 60 hectares of peach orchards with sporadic presence of plum trees in immediate vicinity during 1988 only, and 5) in Borovce, traps were placed in a research orchard of the breeding station at Veselé near Piešťany, West Slovakia, consisting of large apricot and peach stands, and also some plums during 1987–1989.

Climatic and topographical data for each study site are given in Table 1.

TABLE 1. Topographical and climatic data at each locations under investigation.

Location	Altitude (m)	Average temperatures (°C)		Average annual rainfall (mm)	Pesticide applications [2]
		annual	growing season [1]		
(1) Heřmanice	449	7.00	13.4	756	–
(2) Zbraslav	190	8.70	14.6	521	–
(3) Roudnice	187	8.70	15.2	488	+
(4) Pasohlávky	164	9.10	15.8	540	+
(5) Borovce	165	9.05	15.0	625	+

[1] Average temperature during the growing season (April–September).
[2] Pesticide applications: – none; + applied regularly.

Three trap types were used in this study: modified flower pots (Neuffer, 1974), Etokap tube traps (Chemika, Bratislava), and finally cardboard delta traps with glue inserts (glue: Bird Tanglefoot, Tanglefoot Comp., Grand Rapids, MI, USA, or Chemflor, Chemika, Bratislava, Slovak Republic). The binary mixture of (*Z*)-8-dodecen-1-yl acetate and (*E*)-8-dodecen-1-yl acetate (approx. 4%) was used in the earlier experiments. The five component sex pheromone blend (Guerin et al., 1986) was used in 1983 and later. In the earlier experiments different rubber substrates were used as pheromone dispensers because standardized pheromone caps were not yet available. Starting 1985 caps made of non-sulphur-cured rubber (Vrkoč et al., 1988) loaded with 334 to 5,010 mg of the attractant were used. The same pheromone baits and traps of the same type were employed at each particular location during the same season.

Pheromone traps were hung 160 cm above ground on the eastern side of tree canopies. Traps were positioned at each location before the overwintering generation flew and remained until the end of the summer generation flight. Catches were recorded once or twice a week, except at the Zbraslav location where they were recorded daily. Pheromone baits were replaced at 5 to 7 week intervals and sticky inserts as necessary.

Catches from the Pasohlávky and Borovce sites, where *Cydia molesta* Busck is common and cannot be distinguished from *C. funebrana* in pheromone traps, were separated in the laboratory on the basis of differences in genitalia (Hrdý et al., 1979a). In catches from the Roudnice and Zbraslav locations where *C. molesta* occurrence is less frequent, potential capture of non-target species was confirmed by occasional checks of genitalia of trapped specimens. *C. molesta* does not occur in Heřmanice and surrounding areas (Hrdý et al., 1993).

Starting January 1, daily maximum and minimum air temperatures were used to calculate the degree-days (DD) above a threshold of 10°C.

Relative trap catches at each site were converted to cumulative catch curves. Cumulative percentages were transformed to probits and plotted against DDs from January. Two regression methods were used to analyze the flight curves. When using a linear regression method, parameters a and b of the equation y = a + bx were determined, where y stands for probit transformation of the cumulative percentage of moth catches, and x stands for DD. When using the nonlinear regression method, parameters c_1, c_2, and c_3 of the Richard's formula (Fircks & Verwijst, 1993) in the form

$$y = \frac{100}{\left(1 + c_3 \cdot e^{-c_1\left(x - c_2\right)}\right)^{\frac{1}{c_3}}}$$

were determined, where y is the cumulative percentage of the moth catch, and x is the DD calculated for the day of pheromone trap check. The parameters were determined by fitting the above equation using the Statgraphic program. A DD of 280°C after January (Kocourek et al., 1995) was used to differentiate between the two generations.

Analysis of variance (ANOVA) was used for assessing differences among the flight curve parameters. Linear regression was employed to estimate the effect of meteorological factors and the effect of the population density on the variability of flight curves.

RESULTS

Fluctuations in population density

Relative population densities, as measured by catches of males in pheromone traps, during the first (overwintering) and second (summer) generations from different locations are summarized in Table 2. The proportion of the first to the second generation is higher at the coldest locality (Heřmanice) than on other locations. The proportions of moths of the summer generation substantially decreased in years with below-average temperatures in May, June and July.

TABLE 2. Mean numbers of *Cydia funebrana* moths caught per trap and percentages of moths in each generation at each site as calculated from data obtained in all years under investigation.

Location	Number of years under investigation	Mean number of moths of the overwintering generation	%	Mean number of moths of the summer generation	%
Heřmanice	14	76.1	31.3	167.2	68.7
Zbraslav	7	110.5	21.5	432.8	78.5
Roudnice	5	175.9	21.5	642.5	78.5
Borovce and Pasohlávky	3 1	54.3	22.8	183.3	77.2

Total male catches in particular generations are presented in Fig. 1. Long-term cyclic fluctuation in trap catches is apparent at Heřmanice locality but it does not correspond to temperature fluctuations in particular years. While trap catches were on the decrease at Zbraslav (location without insecticide treatment), increases in trap catches occurred at Heřmanice (without insecticide treatment) and Roudnice (orchard with regular chemical pest control).

Using catches from all locations and years a highly significant correlation y = 27.25 + 2.77x ($r = 0.844$; $P < 0.0001$) was found between the total number of males caught during the overwintering generation (x) and the total number of males caught during the summer generation (y). Using this regression equation, the catches of the summer generation within a year can be forecast regardless of locality if one knows the total catch of males of the overwintering generation. This forecast can be made even more accurate at specific locations. For example, the above relationship was quantified for the Heřmanice locality as follows: y = –22.85 + 2.49x ($r = 0.920$; $P < 0.0001$).

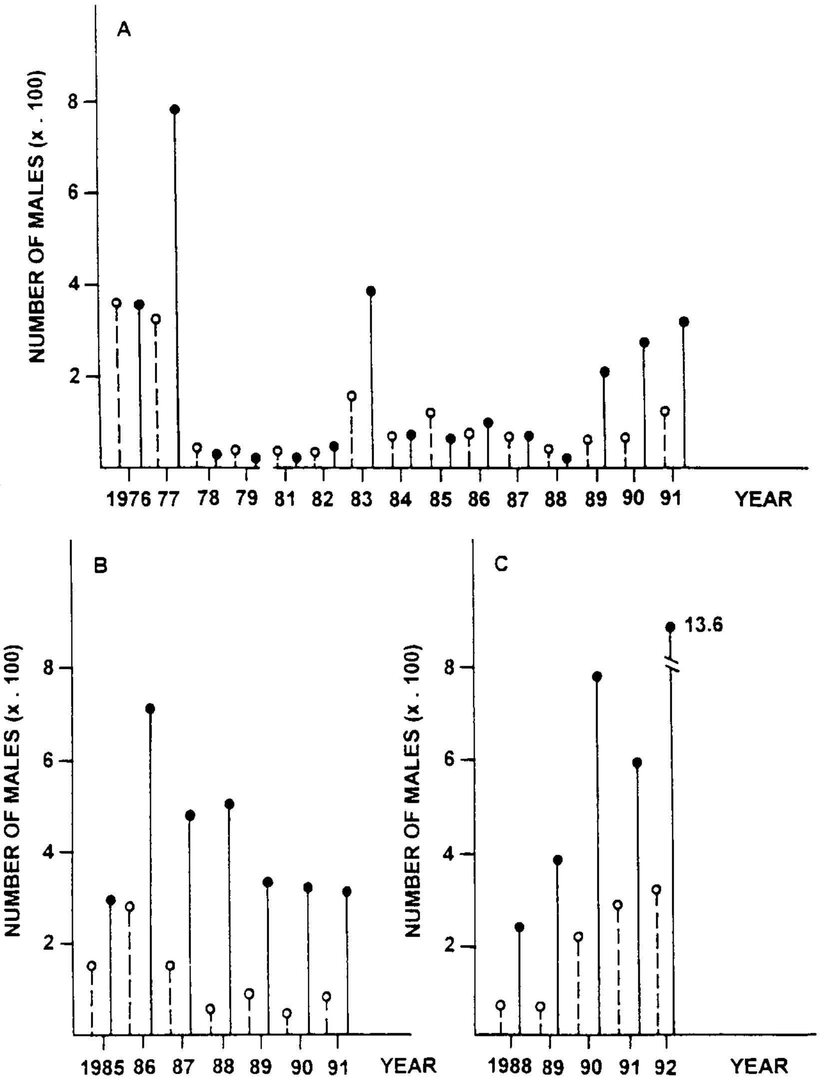

Fig. 1. Total number of males of *Cydia funebrana* caught in pheromone traps for overwintering (broken line) and summer (solid line) generations; A – Heřmanice (1976–1991), B – Zbraslav (1985–1991), C – Roudnice (1988–1992).

Temperature models for local populations

The parameters of nonlinear models for particular locations are presented in Table 3. Data presented in Fig. 2 indicate the time necessary for the development of a given plum fruit moth generation. The difference between values of DD for the emergence of 10% of males of a given population, i.e., the difference between the first and second generation shows that DD needed for development of a generation is about 390 to 410°C.

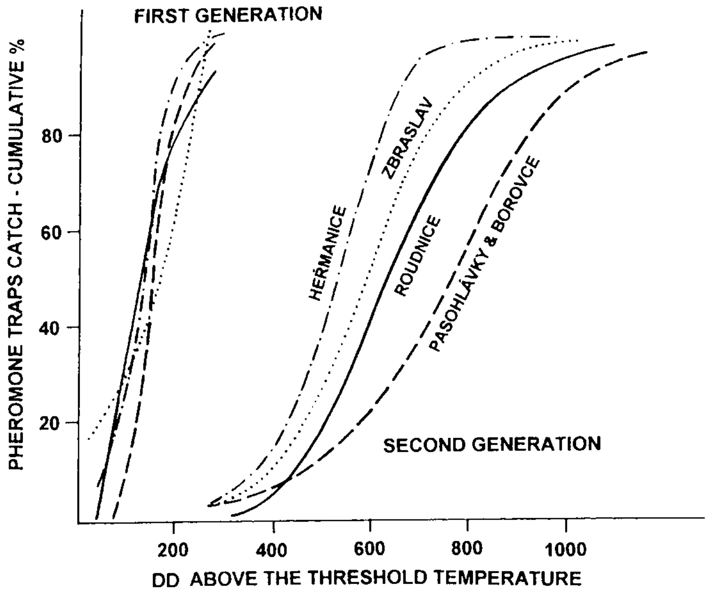

Fig. 2. Flight curves for the overwintering and summer generations of *Cydia funebrana* based on pheromone trap catches of males. Curves fitted using Richard's formula: % – cumulative percentage of trapped males, degree-days (DD) above the threshold of 10°C from January 1.

TABLE 3. Parameters (c_1, c_2, c_3) of nonlinear models describing flight activity of *Cydia funebrana* and coefficients of determination (r^2) for particular locations.

A – overwintering generation							
Location	c_1	Standard error (c_1)	c_2	Standard error (c_2)	c_3	Standard error (c_3)	r^2
Heřmanice	0.034	0.01	143.15	13.1	1.44	0.99	0.824
Zbraslav	0.270	1.40	258.80	53.6	36.70	191.300	0.686
Roudnice	0.012	0.002	85.09	16.2	-0.525	0.277	0.887
Borovce and Pasohlávky	0.025	0.003	140.5	7.72	0.063	0.310	0.964
B – summer generation							
Location	c_1	Standard error (c_1)	c_2	Standard error (c_2)	c_3	Standard error (c_3)	r^2
Heřmanice	0.018	0.004	567.4	18.87	1.760	0.769	0.850
Zbraslav	0.011	0.001	609.5	9.92	1.020	0.212	0.956
Roudnice	0.008	0.0005	616.7	13.50	0.273	0.168	0.970
Borovce and Pasohlávky	0.009	0.001	812.9	21.30	1.630	0.423	0.939

Variability in flight curves is indicated by differences in coefficients of determination (r^2) (Table 4). Substantially higher r^2 values in nonlinear models when compared with linear models show that the nonlinear model describes the data in a more precise way.

Regression analysis has further shown that r^2 values of the nonlinear models appeared independent of the population density in contrast to r^2 values of linear models.

TABLE 4. Mean coefficients of determination (r^2) computed from linear and nonlinear models for all the years under investigation. According to analysis of variance, differences between means are statistically significant ($P < 0.01$), with the exception of those followed by the same letter.

Location	Overwintering generation Linear model	Summer generation	
		Linear model	Nonlinear model
Heřmanice	0.632 a	0.679 a	0.988 a
Zbraslav	0.746 b	0.867 b	0.996 a
Roudnice	0.922 c	0.974 b	0.988 a
Borovce and Pasohlávky	0.750 b	0.870 b	0.988 a

With the overwintering generation, minimal differences exist in patterns of male flight curves among populations from different locations. The DD values for 50% emergence of males of the overwintering generation are very similar, even at localities which differ substantially in temperature characteristics. However, male flight curves of the summer generation are specific to particular local populations. While the onset of flight in the summer generation is similar at all locations (290 to 320°C DD), it is a slower increase in cumulative catch rate at warmer locations. Consequently, the DD for catches of 50% of the males is shifted to higher values at warmer localities. When compared with the Heřmanice population (530°C), the Zbraslav population shows a DD of 550°C, the Roudnice population 640°C, and the Borovce population 760°C. The flight ends at substantially lower DD at colder localities than at warmer localities.

Flight activity models were devised using the Richard's formula and parameters, presented in Table 3. By this method, it is possible to forecast for a given year and a given locality, by substituting the DD (x) at the date of trap checking, the cumulative percentage (y) of male occurrence within particular generations.

The dates indicating the beginning and the peak, respectively, of the flight of particular generations differ considerably depending on location and year. The differences in flight peaks among particular years range up to 30 days at the same location. Thus, the determination of flight peaks of *C. funebrana* in terms of calendar dates is not possible. Flight peaks for particular generations, as well as for timing pesticide treatments can be determined by using the above temperature model.

The causes of different patterns of flight curves of the summer generation

When considering potential causes of different flight-curve patterns, three tentative hypotheses were examined and tested by regression analysis using parameters of nonlinear models. The hypotheses were based on the premises: (1) the shape of flight curve is determined by parameters of the Richard's curve, (2) these parameters may be correlated to other factors which are different in respective years. The tests were conducted for all the locations and years under investigation (28 cases in total).

The regression analysis demonstrated the following:

1) The correlation has not been found for parameters of nonlinear model for the overwintering and the summer generation. The summer generation flight curve pattern as

related to DD for a given year and locality does not duplicate the overwintering generation flight curve pattern.

2) The correlation has not been found for parameters of nonlinear model for the overwintering generation and for the total number of moths of the overwintering (or summer) generation. The pattern of the summer generation flight curve is not dependent on population density of either the first or second generation.

3) The correlation has been found for parameters of nonlinear model for the summer generation and values of DD for the given period of time. Results of regressions between DD and parameters of nonlinear flight curve models for all locations and years are presented in Table 5. Significant values of correlation coefficients for all three parameters show that individual parameters of the nonlinear model vary depending on DDs reached both in the period preceding flight peaks (up to July 1) and in the period during which summer generation flight takes place (from July 1 to August 10). The pattern of the summer generation flight curve is dependent on the DD reached at July 1 from the beginning of the year, and also on the DD for the period from July 1 to August 10.

TABLE 5. Linear regression of parameters of Richard's formula for the 2nd generation of *Cydia funebrana* on DD summed over two periods.

	DD June 1–June 30			DD July 1–August 10		
	a	b	r	a	b	r
c_1	0.158	−0.00003	-0.514^{++}	0.190	−0.0004	0.533^{++}
c_2	516.9	0.395	0.347^{n}	429.0	0.466	0.466^{+}
c_3	19.3	−0.041	-0.423^{+}	21.9	−0.051	-0.484^{+}

a, b – regression parameters; r – correlation coefficient; ^{n} not significant, $^{+}$ $P < 0.05$, $^{++}$ $P < 0.01$, data from all localities and years (n = 28).

DISCUSSION

The plum fruit moth is a chronic pest of plums and damsons in Central Europe but knowledge of its population dynamics is limited. *C. funebrana* was monitored by means of pheromone traps and different blends, loads and formulations of the synthetic pheromone were screened parallelly (partially published by Hrdý et al., 1979b, 1989). In present study we considered using data covering very long period of investigation (1976–1992) reasonable, in spite of the fact that standardized pheromone dispensers for *C. funebrana* were not available at the beginning. Monitoring at several locations of the former Czechoslovakia (Novák & Hrdý, 1986) resulted in the differentiation of two regularly occurring flight peaks considered to represent generations. The second generation is less numerous in sub-highland regions in cold years. The occurrence of only a single generation recorded in Great Britain (Vernon, 1971) was not confirmed in Central Europe. A partial third generation – up to 10% of the total male catch in pheromone traps for a year – occurs in southern parts of Moravia in very warm years. Molnár (1991) also reported the occurrence of a partial third generation in Slovakia. The number of individuals in the third generation of *C. funebrana* increases with decreasing latitude in the southern parts of Europe (Deseö et al., 1971; Vernon, 1971; Karadzhov et al., 1992).

The data obtained in our study show that the catches of plum fruit moths at a particular location can increase for several years, while catches at another locality can decrease within the same period. A similar situation was reported from Yugoslavia by Stamenkovic et al. (1984). Population density regulation is probably dependent on factors other than climatic differences among years. *C. funebrana* does not show marked changes in relative population densities among years, which corresponds to the characteristics of K-life-history strategy (Pianka, 1970; Southwood, 1977). Using a regression model it is possible to forecast catches of summer generation moths from catches of the overwintering generation. In commercial plum orchards, the population density of the plum fruit moth is usually higher than the economic injury level in spite of the previous insecticide treatments. The long term population trends are probably not drastically affected in insecticide treated orchards because of prevailing incorrect timing of sprays. Control measures must be applied in commercial orchards in the Czech Republic each year, like in regions further south (Deseö et al., 1971). Infestation rate is usually low with early fruit varieties (Zivanovič & Pavicevič, 1954; Cvetkov et al., 1961) but it depends also on other than variety factors (Deseö, 1967).

If we compare DDs between the flight peaks of the two generations (Fig. 2), then an DD value of 387°C (Deseö, 1971) corresponds only at the coldest locality Heřmanice (400°C), whereas it is higher at the other localities (Zbraslav 430°C, Roudnice 510°C, Borovce and Pasohlávky 610°C). Increased development time occurs at warm locations, especially in warm years, presumably because development of that part of the population which does not enter diapause, is delayed.

Flight curve patterns of the summer generation were quite diverse. Generally, the warmer the location (or the warmer the year), the higher DDs were reached at the date of the emergence of summer generation moths. According to our data, the pattern of the summer generation flight curve depends on the temperature course within the preceding period, i.e., during the development of preadult stages. We present two hypotheses to explain this observation. According to Blago (1992), the increase in DD for populations from warm localities is explained in terms of non-adequate input into the model. Temperatures measured during summer in a standard meteorological box are substantially lower than temperatures within the microenvironment in which the plum fruit moth development takes place (Blago & Dickler, 1990). As the larval development is slowed down at temperatures exceeding 30°C, the male flight peak is forecasted for an earlier period, than the real situation in the orchard. The warmer the location, the greater are differences between the model and real situation.

The second hypothesis assumes that changes in the patterns of the flight curve of summer generation are influenced by differences in diapause incidence in populations occurring at warm locations or in warm years. According to Sáringer (1967), the critical photoperiod for the incidence of diapause starts on July 20, and diapause begins in all larvae within a period from August 10 to August 15. A higher proportion of larvae within a population develops faster, thus ending development earlier, and those larvae do not enter diapause. In populations from warmer localities, the period of flight activity of the summer generation as expressed in terms of DD is prolonged, and the flight curves become flatter (Fig. 2). This may be caused also by presence of some early individuals of the third generation. Less numerous second generation at subhighland regions, especially in cold years, may be caused by the more individuals of the summer generation going into diapause.

Regression models for any particular situation (locality, year) can be used to indicate the date when control measures should be initiated. The timing of treatments of the summer generation depends on DD reached at the beginning of massive oviposition. The critical period is, according to our experience, at DD of 290–400°C, or immediately following the first marked flight of males in pheromone traps. Precise timing of treatments is extremely important when biorational insecticides (juvenoids, chitin synthesis inhibitors) are used.

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