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A phenological model for the apple and pear leaf-roller *Pandemis cerasana* (Hb.) (Lepidoptera: Tortricidae) (*)

INTRODUCTION

The leaf-roller *Pandemis cerasana* (hereinafter PC) (Lepidoptera: Tortricidae) is found throughout Europe and as far east as in Siberia and the temperate zones of Asia (northern India, China and Japan). In Europe it is particularly common in Mediterranean countries, in northern Italy, in the Rhône Valley of France and in southern Switzerland (Carter, 1984). A polyphagous species, it can live on fruit (apple, pear, plum, cherry) and forest trees (lime, oak, Coniferae etc.) (Tremblay, 1986) as well as on ornamental plants (Pollini, 1988). In Italy, it is very common in the Emilia-Romagna region, where it is considered a key-pest of apple and pear orchard and completes two generations a year, overwintering as young larva. The larvae feed on leaves, flowers and fruits, causing characteristic, superficial erosions; economic damage is high enough to justify control measures. A thorough knowledge of its phenology is essential in order to optimize pest control, whence the need for a phenological model that can forecast the development of ontogenesis on the basis of weather data.

MATERIALS AND METHODS

1. Mathematical model

This model is largely similar to the one we developed for another leaf-roller, *Argyrotaenia pulchellana* (Hw.) (De Berardinis *et Al.*, 1992). It is based on a **time-distributed delay** model (Manetsch, 1976) that describes a stochastic process, such as the development of an insect population. This model can describe the age-

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class distribution and genetic variability of poikilothermal organism populations (Baumgärtner *et Al.*, 1990). Several examples of the use of such a model can be found in literature (Welch *et Al.*, 1978; Croft & Welch, 1983; Welch, 1984; Baumgärtner & Baronio, 1988; Toole *et Al.*, 1983; Baumgärtner & Severini, 1987; Bianchi *et Al.*, 1990; Cerutti *et Al.*, 1990).

To set up the model correctly, the **ontogenetic structure of the population at the beginning of the year** must be defined. PC overwinters as second or third instar larva according to some authors (Balachowsky, 1966), or in the third or fourth instar according to others (Pollini *et Al.*, 1988). As it is not known exactly how much of their development the overwintering larvae have already completed, the larvae are assumed to be at 40% of full development at the end of diapause.

Second, the thermal response of each stage, which must be defined, has already been determined by De Berardinis *et Al.* (1992) for the developmental rates of eggs, larvae, pupae and adults reared in controlled-environment cells at constant temperature, relative humidity and photoperiod. The larval rates were determined for the first generation on the assumption that overwintering larvae do not behave differently. While validating the model, however, we noticed that actual flights always occurred later than in the forecast. A possible explanation could be that overwintering larvae had actually completed less than 40% of their development, although the difference was too high to be corrected with reasonable changes in the assumed development of overwintering larvae. Moreover, the slope of the flight curves - forecast and actual - was also different. Therefore, we assumed that overwintering larvae had a different response to temperature than spring and summer larvae. By a trial-and-error procedure, we then defined a new set of parameters (H included) for the hibernating stage. This approach proved successful and enabled us to achieve a good agreement between forecast and actual flight patterns.

To simulate the development of the early stages, we used the function of Logan *et Al.* (1976). The parameters for each stage are listed in table I.
For the female adults, a linear function was used:

$$F(t) = .004966\ t - .03976$$

The ageing rate of females was assumed to remain constant at temperatures higher than 26°C.

Another parameter that had to be defined was the **mean fecundity of females as function of age**. We fitted a modified Bieri's function (Bieri *et Al.*, 1983) to the daily fecundities observed in females reared at the 25°C optimum temperature (De Berardinis *et Al.*, 1992). The coefficients of the resulting equation are: $P1 = 36.49$; $P2 = 1.065$; $P3 = 1.489$. The mean total fecundity of the female, found by numerically integrating Bieri's function, was 213.5 eggs.

To simulate the flux of individuals of the same population through the different stages (stochastic process), we used a **time-distributed delay model** (Manetsch, 1976). This model lets the individuals flow through a series of stages, each comprising a number of substages. Therefore, the number of substages (order of the process) has to be determined. It is defined as the ratio of the squared persistence-time in a given stage and its variance. For PC, these parameters have been experimentally determined by De Berardinis *et Al.* (1992). The order of the process was greater than 50 for eggs and pupae at any temperature, although we opted to keep H = 50. For larvae, we chose H = 29, i.e. the lowest figure among those found at different temperatures. For the hibernating larvae, we empirically determined H = 80; for the adults, H = 15. The criteria adopted for the choices are those detailed for *A. pulchellana* in De Berardinis *et Al.* (1992).

The model can now simulate the development of the insect population on the basis of temperature input. It fits a sinusoid between minimum and maximum temperature and then divides each day into a number of intervals (time steps, 10 in our case), calculating via the sinusoid for each step the mean temperature and the instantaneous development of early stages, the ageing rate of the adults and their fecundity. Finally it outputs, day by day, the cumulating percentages of egg-laying, egg-hatching, pupation and adult emergence.

2. Field validation of the model

Field validation was conducted along the same guidelines as for *Argyrotaenia pulchellana* (De Berardinis *et Al.*, 1992). In order to compare the flight curves forecast by the model and those actually determined in the field, in 1990 and 1991 several apple and pear orchards with sex traps (Agrimont) were chosen in the provinces of Bologna, Ferrara, Forlì and Ravenna. Farms, farm locations and weather stations are listed in tables II (1990) and III (1991). The captured PC males were counted once a week in 1990 and twice a week in 1991. The differences between the cumulated percentages of the forecast and actual flight patterns were expressed in days, + and - sign respectively indicating an anticipation or a delay of the forecast (tables IV to VII). In some orchards and some generations of AP it proved impossible to validate the model. To make significant and reliable comparisons, we did not take into account any case in which the flight was incomplete or less than 30 males per generation had been caught. Temperatures are from weather stations, either automatic or mechanical, located very close to the farms used for validation.

RESULTS AND DISCUSSION

Field validation, which is based only on a comparison of forecast and actual flight patterns, has some limits (De Berardinis *et Al.*, 1992) but it appears overall to be fairly reliable. Tables IV to VII and figures 1 to 3 show that the actual and forecast flight curves are in good agreement in each generation and farm.

Although this particular kind of model does not output population density estimates, it can be very useful from a practical point of view to optimize both sampling and spraying schedules. Moreover, by taking into account the adults caught by sex traps (usually available within integrated plant protection programmes), we can determine not only the best moment to treat but also if spraying is needed, how many treatments are to be applied and the most suitable active ingredient. Of course, in order to achieve such a performance, we must have a thorough knowledge of the capture-infestation relationship. While this has been possible for other leaf-rollers (e.g. *Argyrotaenia pulchellana*), for this species further experimental work is needed.

Finally, starting with this model and introducing more biotic (immigration, emigration, mortality) and abiotic (effect of treatments) factors into it, we can try to set up a demographic model, an essential tool for the study and management of agroecosystems (Baumgärtner & Gutierrez, 1988; Baumgärtner & Delucchi, 1988).

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SUMMARY

A simulation model of the phenology of *Pandemis cerasana* (Hb.) (Lepidoptera: Tortricidae) is presented. A non-linear function is used to determine the temperature-dependent developmental rates of eggs, larvae and pupae; a linear equation is used for the ageing rate of females. The mean fecundity of females as a function of age is expressed by a modified Bieri's function. In order to simulate the stochastic process a time-distributed delay model is used.

Field validation was conducted by comparing the flight curves forecast by the model to the flight curves actually determined in 1990 and 1991 in several apple and pear orchards, in the provinces of Bologna, Ferrara, Forlì and Ravenna, that employ sex traps.

Forecast and actual flight curves agree fairly well in all farms and in the two generations of the insect.

Modello previsionale fenologico per *Pandemis cerasana* (Hb.) (Lepidoptera: Tortricidae)

RIASSUNTO

È stato sviluppato un modello fenologico di simulazione per *Pandemis cerasana* (Hb.) (Lepidoptera: Tortricidae). Per definire i tassi di sviluppo in funzione della temperatura di uova, larve e pupe si è usata una funzione non lineare, mentre il tasso di invecchiamento delle femmine è correttamente simulato da una retta. Per la fecondità media delle femmine in relazione all'età si è impiegata la funzione di Bieri modificata. Per simulare la natura stocastica del processo di sviluppo si è fatto ricorso ad un modello a ritardo distribuito nel tempo.

La convalida in campo è stata eseguita paragonando le curve di volo previste dal modello con quelle concretamente rilevate in diversi frutteti di Melo e di Pero, provvisti di trappole sessuali, situati nelle province di Bologna, Ferrara, Forlì e Ravenna.

Le previsioni differiscono ben poco dai dati rilevati, in tutte le aziende e nelle due generazioni dell'insetto.

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Table I - Parameters of the Logan's function.

	P1	P2	P3	Tli	Tll
Eggs	0,10546	0,17396	0,18318	8,6	34,0
Larvae	0,38163	0,14889	0,14929	4,5	34,0
Overwintering larvae	0,18324	0,15115	0,15181	4,5	34,0
Pupae	0,16001	0,15480	0,16152	8,5	35,0

Table II - Farms used for validation in 1990.

FARM	LOCATION	WEATHER STATION
Raspadori	Imola (BO)	Imola
Barbavara	Imola (BO)	Imola
Marani	Ravenna	Ravenna
Cantina s.	Conselice (RA)	Conselice
Diegoli	Castello d'Argile (BO)	S. Giovanni in Persiceto
Funi	Castello d'Argile (BO)	S. Giovanni in Persiceto
Branchini	Castello d'Argile(BO)	S. Giovanni in Persiceto
Cantelli	Bentivoglio (BO)	Altedo

Table III - Farms used for validation in 1991.

FARM	LOCATION	WEATHER STATION
Masotti	S. Pietro Capofiume (BO)	S. Pietro Capofiume
Salina	Molinella (BO)	Salina
Lessio	Marmorta (BO)	Marmorta
Franzoni	Marmorta (BO)	Marmorta
Centrale	Miravalle (BO)	Molinella
Branchini	Porotto (FE)	Vigarano
Rosati	Bulgaria (FO)	Bulgaria
Ricci	Cesena (FO)	Martorano

Table IV - Difference (days) between forecast and actual flight in 1990 (see text for details).

FARM	CUMULATED FLIGHT PERCENTAGES (1st FLIGHT)							
	0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Raspadori	+1						+1	
Barbavara	+6					+2		
	+1							
Conselice			+3				+2	
Diegoli				+5				+5
Funi I				+6				
Funi II		+4				+1		
Branchini			+8					+8
								+1
								-4
Cantelli	+3					+4		

Table V - Difference (days) between forecast and actual flight in 1990 (see text for details).

FARM	CUMULATED FLIGHT PERCENTAGES (2nd FLIGHT)							
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Raspadori	-9.5						0	
Marani	-2.5			-1.5				+5
Diegoli	-4		-4.5				-1	
Cantelli	-6.5	-3			-5			

Table VI - Difference (days) between forecast and actual flight in 1991 (see text for details).

FARM	CUMULATED FLIGHT PERCENTAGES (1st FLIGHT)							
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Masotti	-4.5			-1		-2		-3
Salina				+6	-4	+1	-4	-8
Franzoni		-7		-6.5				
Centrale	-5	-3						+2
Branchini			+4				+5	+5.5
Rosati		-7						+2
Ricci	-7			-4				0

Table VII - Difference (days) between forecast and actual flight in 1991 (see text for details).

FARM	CUMULATED FLIGHT PERCENTAGES (2nd FLIGHT)							
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Masotti	+5.5 +4	+4	+2.5	+1	0	0 -2.5	-4	-4 -5
Salina		+5			+7	+6 +5	+5	
Lessio		+2	+1	0	-2	-4	-4	-4 -4
Franzoni	-1	-1					+5	
Centrale	-2.5	-3				+4		
Branchini	+4 +2					+11		
Rosati			+4 +1	-3				+3.5
Ricci	-1	0			+1		+3	+3.5

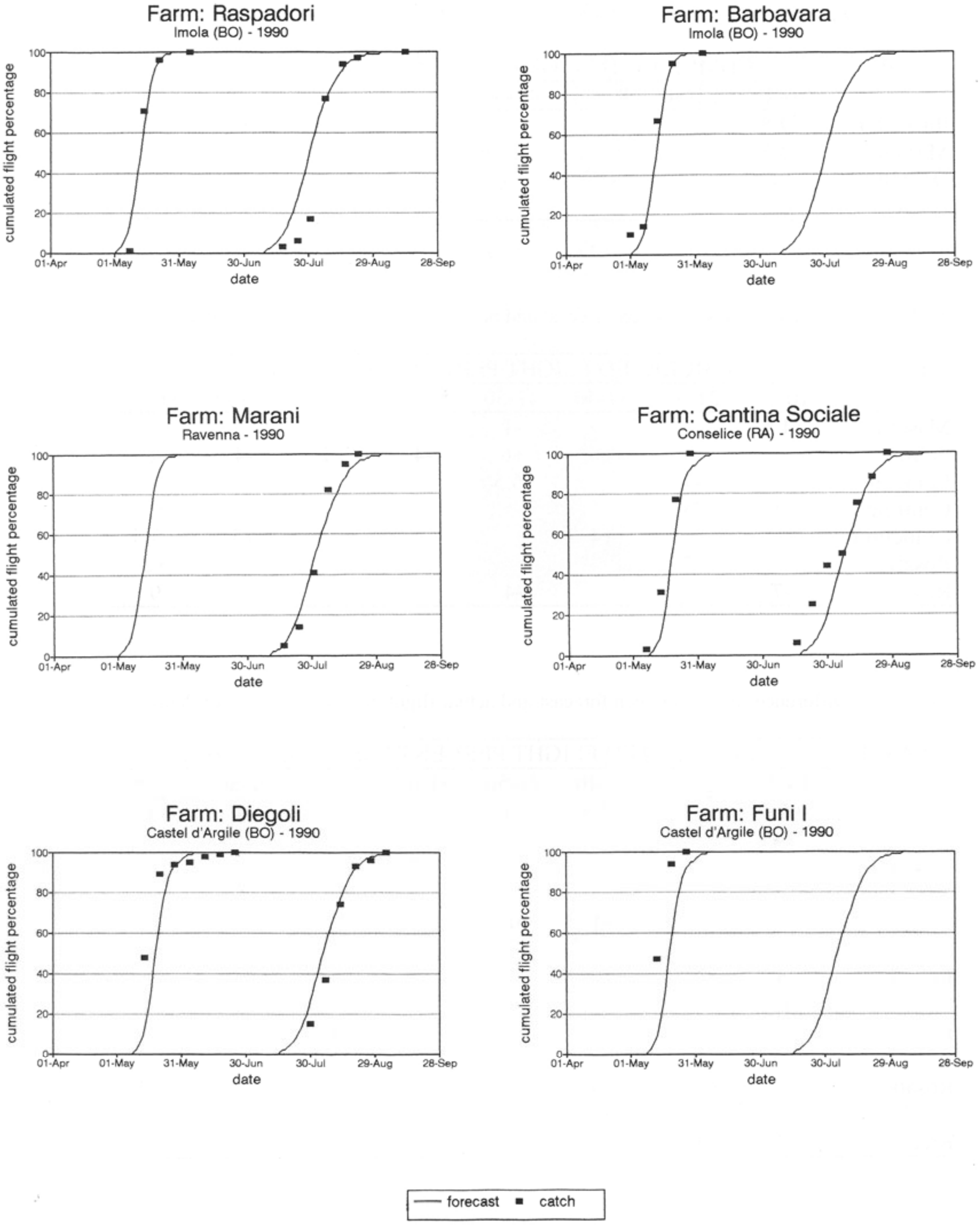
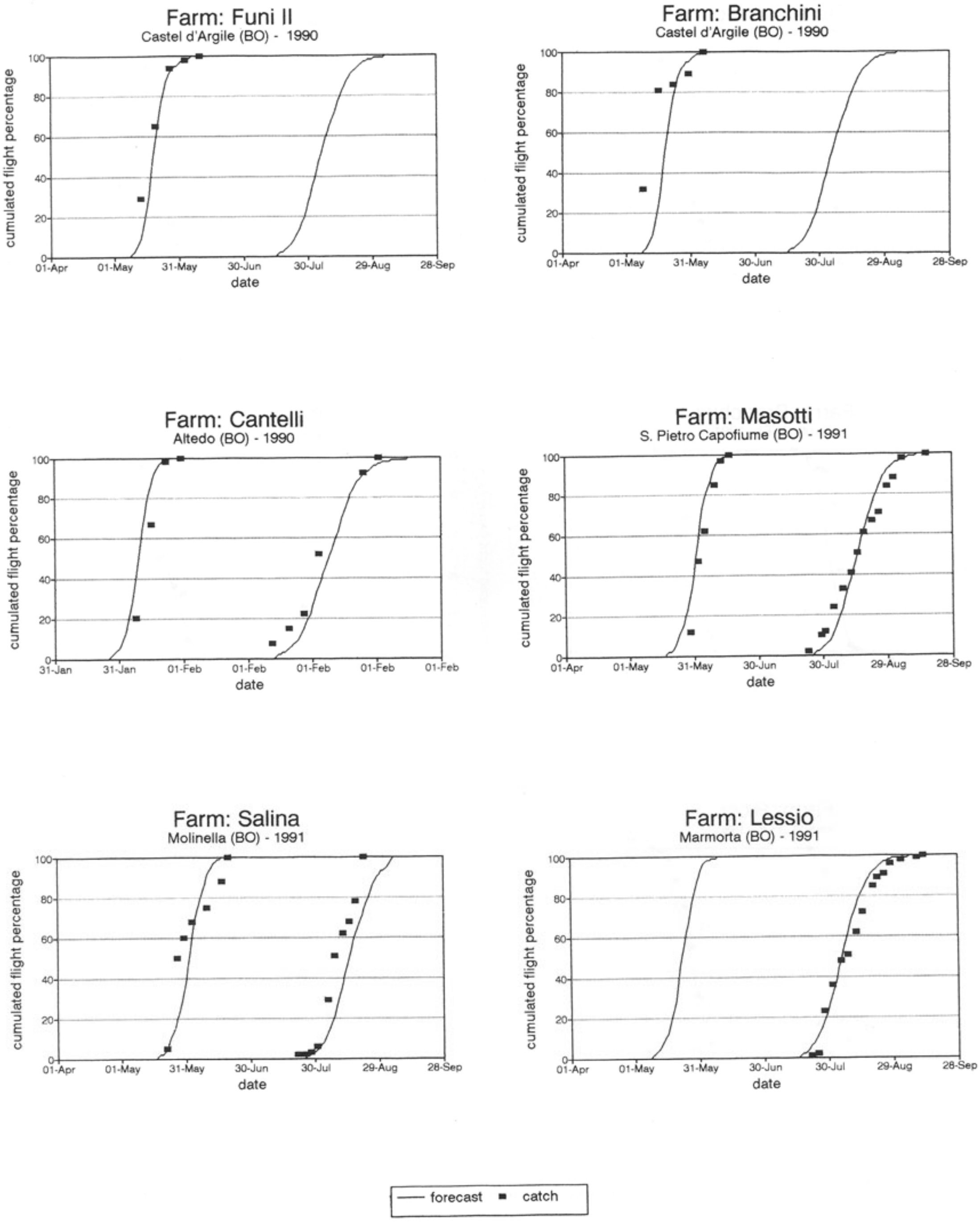


Fig. 1.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).



Farm: Funi II
Castel d'Argile (BO) - 1990

Farm: Branchini
Castel d'Argile (BO) - 1990

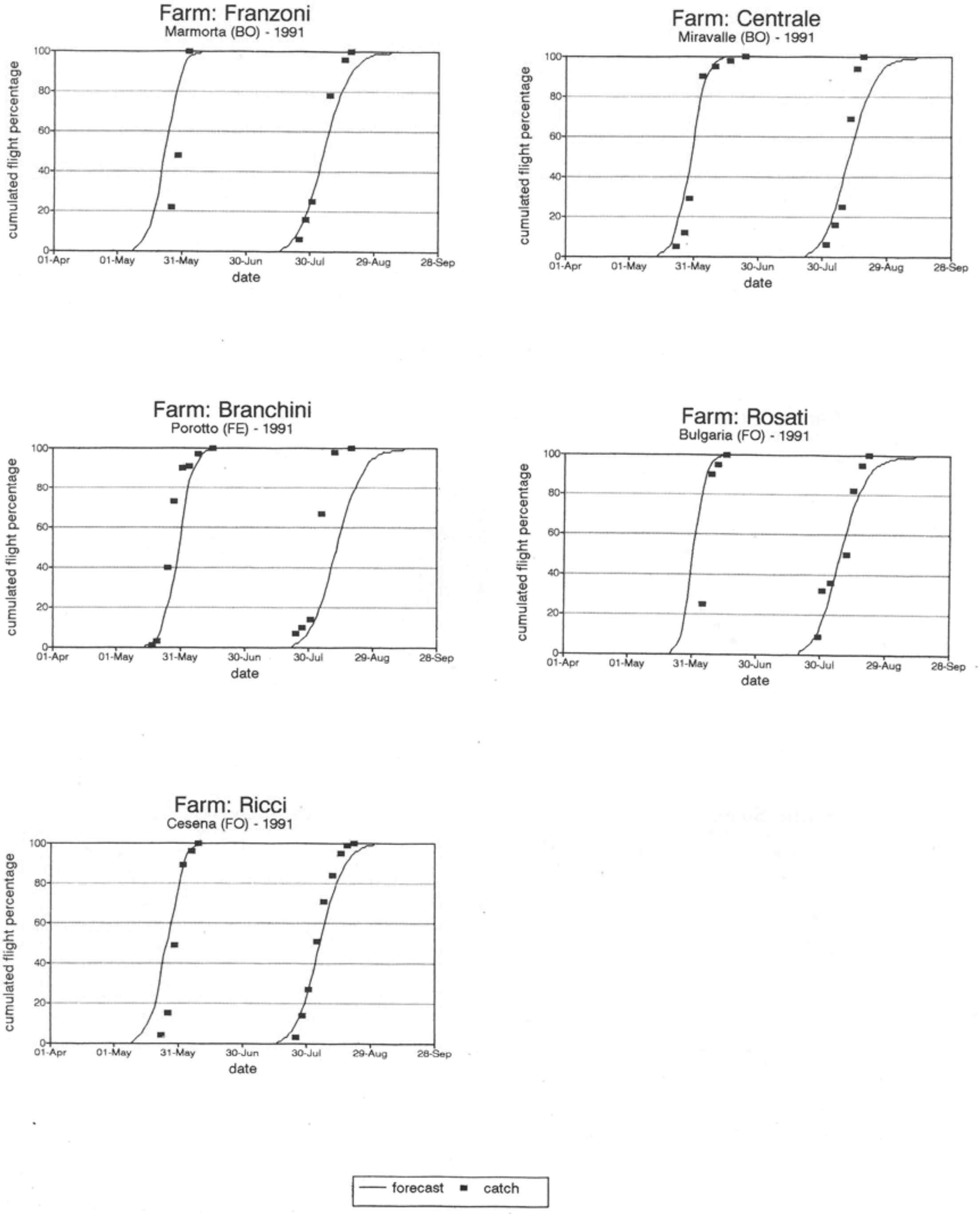
Farm: Cantelli
Altedo (BO) - 1990

Farm: Masotti
S. Pietro Capofiume (BO) - 1991

Farm: Salina
Molinella (BO) - 1991

Farm: Lessio
Marmorta (BO) - 1991

Fig. 2.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).



Farm: Franzoni
Marmorta (BO) - 1991

Farm: Centrale
Miravalle (BO) - 1991

Farm: Branchini
Porotto (FE) - 1991

Farm: Rosati
Bulgaria (FO) - 1991

Farm: Ricci
Cesena (FO) - 1991

Fig. 3.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).