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A phenological forecasting model for the apple and pear leaf-roller *Argyrotaenia pulchellana* (Hw.) (Lepidoptera: Tortricidae)(*)

INTRODUCTION

Argyrotaenia pulchellana (Hw.) (Lepidoptera: Tortricidae), hereinafter AP, is a very common polyphagous leaf-roller that feeds on leaves, flowers and fruits of several trees and shrubs (Balachowsky, 1966). In Italy this species first became a pest of fruit-plants in the area near Ferrara (Bongiovanni, 1954) and then near Verona (Ivancich Gambaro, 1959). Its distribution in the Emilia-Romagna region has recently been studied by Pasqualini *et Al.* (1982), who found it in the provinces of Bologna, Ferrara, Forlì, Modena and Ravenna.

AP in this region overwinters as pupa and can usually complete three generations a year. Larvae feed on leaves and fruits, gnawing them superficially and causing typical injuries. Young fruits heal but are permanently deformed whereas ripe fruits usually rot (Ivancich Gambaro, 1962). At present, damage to pome fruits is high enough to justify control treatments. In an integrated plant protection programme treatments have to be carefully timed in order to limit their number and increase mortality, and products with minimal impact on environment are to be preferred.

Such a strategy makes a thorough knowledge of insect phenology very important. The key environmental factor influencing the phenology of most insect pests is temperature. Thus the forecasting model reported and discussed in the present paper is based on temperature and can forecast in real time the presence of each developmental stage (eggs, larvae, pupae and adults).

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Material and Methods

1. Mathematical model

To simulate the phenology of the pest, a time-distributed delay model based on the mathematical background developed by Manetsch (1976) was employed. Such a model is generically suitable to describe a stochastic process, such as the development of an insect population. Each individual in a population goes through the same stages at different times (Curry & Feldman, 1987) as a result of genetic variability, microclimate and food supply. In other words, a time-distributed delay model can describe the age-class distribution and genetic variability of poikilothermal organism populations (Baumgärtner *et Al.*, 1990), and 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).

We employed the time-distributed delay algorithm to implement a phenological model for AP similar to that used by Baumgärtner & Baronio (1988) for the grape moth. The basic elements of our model are:

1. **Ontogenetic structure of the population at the beginning of the year**. As the exact percentage of pupal development at the beginning of the year is not known, it is assumed that the insect overwinters as newly-formed pupa.

2. **Mean temperature at each time-interval.** A sinusoid is fitted between the minimum and maximum temperature. The day-length is divided into 10 equal intervals and for each one the mean temperature is calculated based on the sinusoid. Of course, if hourly temperatures are available, it is best to use them.

3. **Instantaneous development of each stage**. This parameter is calculated on the basis of the thermal-response curves as determined by Tiso *et Al.* (1992) using the developmental rates of eggs, larvae, pupae and adults reared in controlled-environment cells at constant temperature, relative humidity and photoperiod. For the early stages, we use the function given by Logan *et Al.* (1976):

$$F(t) = P1 \cdot (\exp (P2 \cdot (t-Tli))-\exp(P2 \cdot (Tll-Tli)-P3 \cdot (Tll-t)))$$

where:

P1, P2, P3 are function parameters;
t is the actual temperature;
Tli is the lower temperature threshold;
Tll is the upper temperature threshold (lethal temperature).

The parameters of the curves, evaluated with the least-squares method, are listed in Table 1.

The following linear equation was used for the female adults:

$$F(t) = .005113\ t - .02024$$

The ageing rate of females is assumed to remain constant at temperatures higher than 26°C, as adults are supposed to be able to find shelter where temperature is close to the optimum.

4. **Mean fecundity of females as a function of age**. This parameter is used to calculate the daily egg-laying rate, i.e. the input of the egg stage. The fecundity rate is thus expressed by a modified Bieri's function (Bieri *et Al.*, 1983):

$$F(x) = (P1 \cdot (x - P2))/(\exp(\ln(P3) \cdot (x - P2)))$$

The parameters of the curve (P1 = 62.001, P2 = 1.2741, P3 = 1.4567) were estimated with the least squares method from daily fecundity data of females kept at the 26°C optimum temperature (Tiso *et Al.*, 1992). The mean total fecundity per female given by numerically integrating Bieri's function is 302.46 eggs/female.

5. The **Time-distributed delay model** simulates the flux of individuals belonging to the same population through the different phenophases (stochastic process). This process, which is represented by letting the individuals flow through a series of sub-stages, is described by a simultaneous equation set:

$$dr_h(t)/dt = H/DEL[T(t)]\ [r_{h-1}(t)-(1+1/H\ DEL[T(t)/dt)_{rh}(t)]$$

$$h = 1, 2, ..., H$$

where:

H is the number of sub-stages, thereby representing the dispersal in time of the individuals coming out of a given stage and hence determining the stochastic nature of the development;

$r_0(t)$ is the input flux (function of time) of individuals into the developmental process;

$r_h(t)$ is the output flux (function of time) of individuals from the developmental process;

DEL[T(t)] is the expected value of the transit time of individuals through the same phenophase, expressed as function of temperature which in turn is a function of time.

The number of sub-stages (order of the process) was calculated as the ratio of the squared permanence-time in a given stage and its variance. For AP, these parameters have been experimentally determined by Tiso *et Al.* (1992). The order of the process was greater than 100 for eggs and pupae at any temperature, although we decided to keep H = 50 as greater values only slightly modify the distribution of the individuals exiting the process, thereby needlessly increasing computing time. For larvae, we employed H = 19, i.e. the lowest found among those for different temperatures. For the adults the persistence time in a given stage and its variance are not reliable as in this case individuals die instead of going on to the subsequent stage. In other words, it is impossible to make a distinction between mortality due to external factors and mortality due to the natural ageing process. Therefore, for the adults the order of the process is arbitrarily determined: we adopted H = 50.

From a practical point of view the simulation model works as follows. It starts with a population of overwintering pupae (point 1 *supra*). At each time step, as per the mean temperature of the interval (point 2), the instantaneous development (point 3) and fecundity (point 4) of each stage are calculated. The instantaneous development is then "delayed" (point 5) to simulate the genetic variability of the individuals as well as random differences in microclimate. At the end of every day the input and the percent of presence in each stage is calculated. This procedure is repeated for each day of the simulated time. The cumulative egg-laying, egg-hatching, pupation and eclosion curves (output of the model) are expressed as percentages. Moreover, this model does not take into account any mortality factor but natural death of adults.

2. Field validation of the model.

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 (Agrimont). The captured AP males were counted once a week in 1990 and twice a week in 1991. In order to compare the forecast flight curves (cumulated and percentage) to the field curves, the following were calculated for each orchard:

- the total number of males caught per generation;
- the percentage (referred to the generation total) of males caught on each sampling date;
- the cumulated percentage of males caught on each sampling date.

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 VIII). 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. Farms, farm locations and weather stations are listed in tables II (1990) and III (1991).

Result and discussion

Altogether, forecast and actual flight curves agree fairly well in all farms and in the three generations of the insect (tables IV-VII, figures 1-3). However, we must point out that validation regarded only adults, the earlier stages being omitted, as the test would have required much more time and manpower. However, if the forecast and actual flight figures agree in the three generations, as in fact they do, then egg-laying, egg-hatching and pupation curves should also agree. Of course, sex traps give an estimate of the number of flying males, while the model outputs the number of males that were newly produced every day. Moreover, only males are caught in sex traps, while our model uses an average developmental rate determined for males and females together. In spite of these limits, our validation of the model, though based only on flight figures, appears fairly reliable: an analysis of the results shows that the model correctly simulates the phenology of the pest. While the model does not forecast any change in population density, it does give a good estimate of the dynamics of ontogenesis and, hence, can be used to optimize the timing of treatments in an integrated plant protection programme.

A plant protection tool based both on phenological estimates provided by the model and on demographic estimates from sex-trap captures is currently being developed. It will give farmers advice on how many treatments are needed in each orchard, when to apply them, and which chemical or biological pesticides to use. In the future, it will perhaps be possible to improve the model by introducing more biotic (immigration, emigration, mortality) and abiotic (effect of treatments) factors. An essential tool for the study and management of agroecosystems will then become available (Baumgärtner & Gutierrez, 1988; Baumgärtner & Delucchi, 1988).

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SUMMARY

A simulation model of the phenology of *Argyrotaenia pulchellana* (Hw.) (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 three generations of the insect.

Modello previsionale fenologico per *Argyrotaenia pulchellana* (Hw.) (Lepidoptera: Tortricidae)

RIASSUNTO

È stato sviluppato un modello fenologico di simulazione per *Argyrotaenia pulchellana* (Hw.) (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 tre generazioni dell'insetto.

LITERATURE CITED

BALACHOWSKY A.S., 1966. - Entomologie appliquée a l'agriculture, Tome II: 497-500. - *Masson*, Paris.

BAUMGÄRTNER J., BARONIO P., 1988. - Modello fenologico di volo di *Lobesia botrana* Den. & Schiff. (Lep. Tortricidae) relativo alla situazione ambientale dell'Emilia-Romagna. - *Boll. Ist. Ent. Univ. Bologna*, 43: 157-170.

BAUMGÄRTNER J., DELUCCHI V., 1988. - Vom integrierten Pflanzenschutz zur optimalen Bewirtschaftung landwirtschaftlicher Kulturen. - *Schweiz. Ldw. Fo.* 27: 77-90.

BAUMGÄRTNER J., GUTIERREZ A. P., 1989. - Simulation techniques applied to crops and pest models. - In: CAVALLORO R., DELUCCHI V. (eds.): PARASITIS 88. *Proceeding of a scientific congress*, Barcelona, 25-28 October 1988. *Boleton de Sanidad Vegetal*, Fuera de Serie 17: 175-214.

BAUMGÄRTNER J., SEVERINI M., 1987. - Microclimate and arthropod phenologies: the leaf miner *Phyllonorycter blancardella* F. (Lep.) as an example. - *Inter. Conf. on Agrometeorology, Cesena 1987*. Fondazione Cesena Agricoltura: 225-243.

BAUMGÄRTNER J., SEVERINI M., TAMO'M., 1990. - Modelli matematici demografici per la fenologia e l'interazione fra specie nella gestione dei sistemi agricoli. - *Atti del Convegno "Modelli euristici e operativi per la difesa integrata in agricoltura", Caserta*, 27-29 settembre 1990.

BIANCHI G., BAUMGÄRTNER J., DELUCCHI V., RAHALIVAVOLOLONA N.,1990. - Modèle de population pour la dynamique de Maliarpha *separatella* Ragonot (Pyralidae, Phycitinae) dans les rizières malgaches du Lac Alaotra. - *J. Appl. Entom.* 110: 384-397.

BIERI M., BAUMGÄRTNER J., BIANCHI G., DELUCCHI V., VON ARX R., 1983. - Development and fecundity of pea aphid (*Acyrtosiphon pisum* Harris) as affected by constant temperatures and pea varieties. - *Mitt. Schweiz. Ent. Ges.* 56: 163-171.

BONGIOVANNI G. C., 1954. - A proposito del Tortricide rinvenuto sui meli del Ferrarese. - *Informatore Fitop.* IV, 4, Bologna, 59.

CERUTTI F., BAUMGÄRTNER J., DELUCCHI V., 1990. - Ricerche sull'ecosistema "vigneto" nel Ticino: IV. Modellizzazione della dinamica di popolazione di *Empoasca vitis* Goethe (Homoptera, Cicadellidae, Typhlocybinae). - *Boll. Ist. Ent. Univ. Bologna* (in press).

CROFT B., WELCH S. M., 1983. - Implementation research on on-line apple IPM. In: CROFT B. A., HOYT S. C. (eds.): Integrated management of insect pests of pome and stone fruits. *Wiley*, New York, 456 pp.

CURRY G., FELDMAN R. M., 1987. - Mathematical foundations of population dynamics. - *Texas Engineering Exp. Sta.*, monograph series N° 3, 246 pp.

IVANCICH GAMBARO P., 1959. - Due nuovi particolari insetti minacciano i nostri frutteti. - *L'informatore agrario*, 15, 519.

IVANCICH GAMBARO P., 1962. - Osservazioni sulla biologia di *Argyrotaenia pulchellana* Hw. (= *Eulia politana* Auct.) e di *Adoxophyes reticulana* Hb. (= *Capua reticulana* Auct.) nel Veronese

(Lepidoptera, Tortricidae). - *Boll. Zool. agr. e Bachic.* (Ser. II), 4: 1-20.

LOGAN J. A., WOLLKIND D. J., HOYT S. C., TANIGOSHI L. K., 1976. - An analytic model for description of temperature dependent rate phenomena in arthropods. - *Environ. Entomol.* 5: 1133-1140.

MANETSCH T. J., 1976. - Time-varying distributed delays and their use in aggregative models of large systems. - *IEEE Trans. Sys. Man. Cybern.*, 6: 547-553.

PASQUALINI E., BORTOLOTTI A., MAINI S., BRIOLINI G., CASTELLARI P. L., 1982. - Distribuzione spaziale e fenologia degli sfarfallamenti di tre specie di Lepidotteri Tortricidi ricamatori in Emilia-Romagna. - *Boll. Ist. Ent. Univ. Bologna*, 37: 109-121.

TISO R., DE BERARDINIS E., BUTTURINI A., BRIOLINI G., 1992.- Influenza della temperatura sullo sviluppo di *Argyrotaenia pulchellana* (Hw.) (Lepidoptera: Tortricidae). - *Boll. Ist. Ent. Univ. Bologna*, 46: 161-172.

TOOLE J. L., NORMAN J. M., HOLTZER T. O., PERRING T. M., 1983. - Simulating Banks grass mite (Acari: Tetranychidae) population dynamics as a subsystem of a crop canopy-microenvironment model. - *Environ. Entomol.* 13: 329-337.

WELCH S. M., CROFT B. A., BRUNNER J. F., MICHELS M. F., 1978. - PETE: an extension phenology modelling system for management of multispecies pest complex. - *Environ. Ent.* 7: 482-494.

WELCH S. M., 1984. - Developments in computer-based IPM extension delivery systems. - *Ann. Rev. Entomol.*, 29: 359-381.

Table I - Parameters of the Logan's function.

	P1	P2	P3	Tli	Tll
Eggs	0,13289	0,16517	0,17339	8,7	34,5
Larvae	0,03234	0,20724	0,21613	8,5	32,0
Pupae	0,10414	0,17465	0,18388	8,5	33,5

Table II - Farms used for validation in 1990.

FARM	LOCATION	WEATHER STATION
Gandolfi	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Luberti	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Diegoli	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Cristofori	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Mandrioli	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Govoni	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Funi	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Baldo	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Stagni	S. Giovanni in Persiceto (BO)	San Giovanni in Persiceto
Raspadori	Imola (BO)	Imola
Marani	Ravenna	Marani

Table III - Farms used for validation in 1991.

FARM	LOCATION	WEATHER STATION
Serpieri	Bologna	Serpieri
Bonora	S. Pietro Capofiume (BO)	S.Pietro Capofiume
Baroni	Bologna	Baroni
Carlina	S. Romualdo (RA)	S. Romualdo
Fossatone	S. Romualdo (RA)	S. Romualdo
Branchini	Porotto (FE)	Vigarano

Table IV - 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
Gandolfi	+8					+6		+2.5
Luberti	+5		+2				+1	
Diegoli		+6		+2			0	
Cristofori		+6				+6		+3.5
Mandrioli				+9			+8	+3.5
Govoni	+3		+2		-3			-2
Funi							+8	
Baldo				+8				+10
Stagni				+8			+6	+2.5
Raspadori		+4					-1	-5
Marani						-1		-3

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

FARM	CUMULATED FLIGHT PERCENTAGES (3rd FLIGHT)							
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Cristofori	+10			+12			+10	-1
Mandrioli	+1.5			+3			+3	-1

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
Serpieri	+1		-3.5		-6		-5	-6
Serpieri	-2							
Branchini	-1	-1	-3		-6.5	-7	-8	

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
Serpieri		-1		-1		-2		+1
Bonora	0		+1		+1	+.5		
Baroni (m)	+2	+4		+5		+3.5		+4
								+3
Baroni (p)		+2	+2		+1	0	-1.5	-1.5
Branchini	+2			+2		+3		+3.5
Carlina	+2	+4			+5			+8.5
Fossatone	+3			+6		+4.5	+4	

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

FARM	CUMULATED FLIGHT PERCENTAGES (3rd FLIGHT)							
	10-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90
Serpieri	-1	-1				-.5	-1	-5
Fossatone			+2		+2		+2	0
Baroni (m)	+11	+9		+6		+4	-2	-.5
Baroni (m)		+6						-2
Baroni (p)	+11	+8		+2		+3	0	+1.5
Baroni (p)		+6				0		
Baroni (p)		+1						

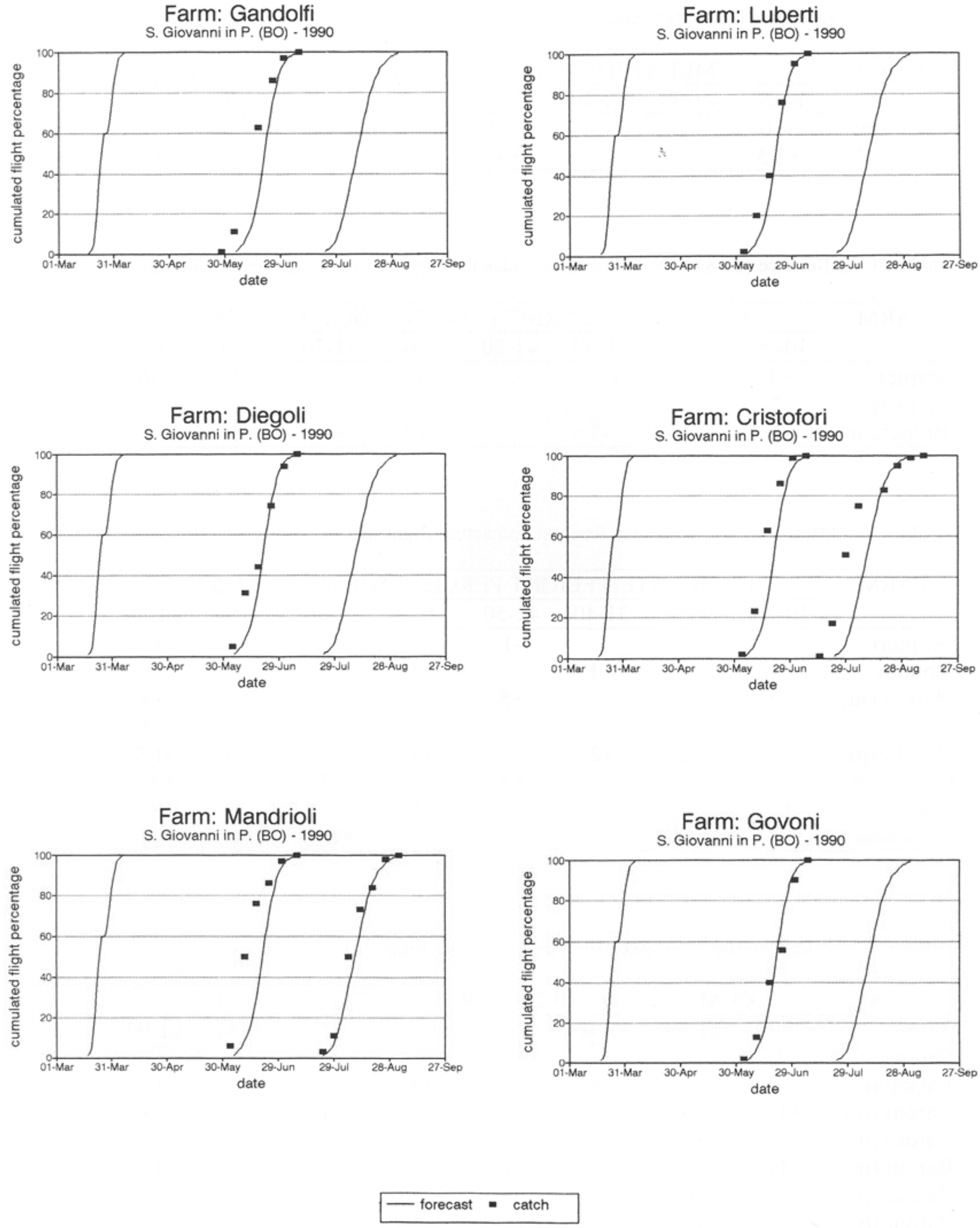

Fig. 1.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).

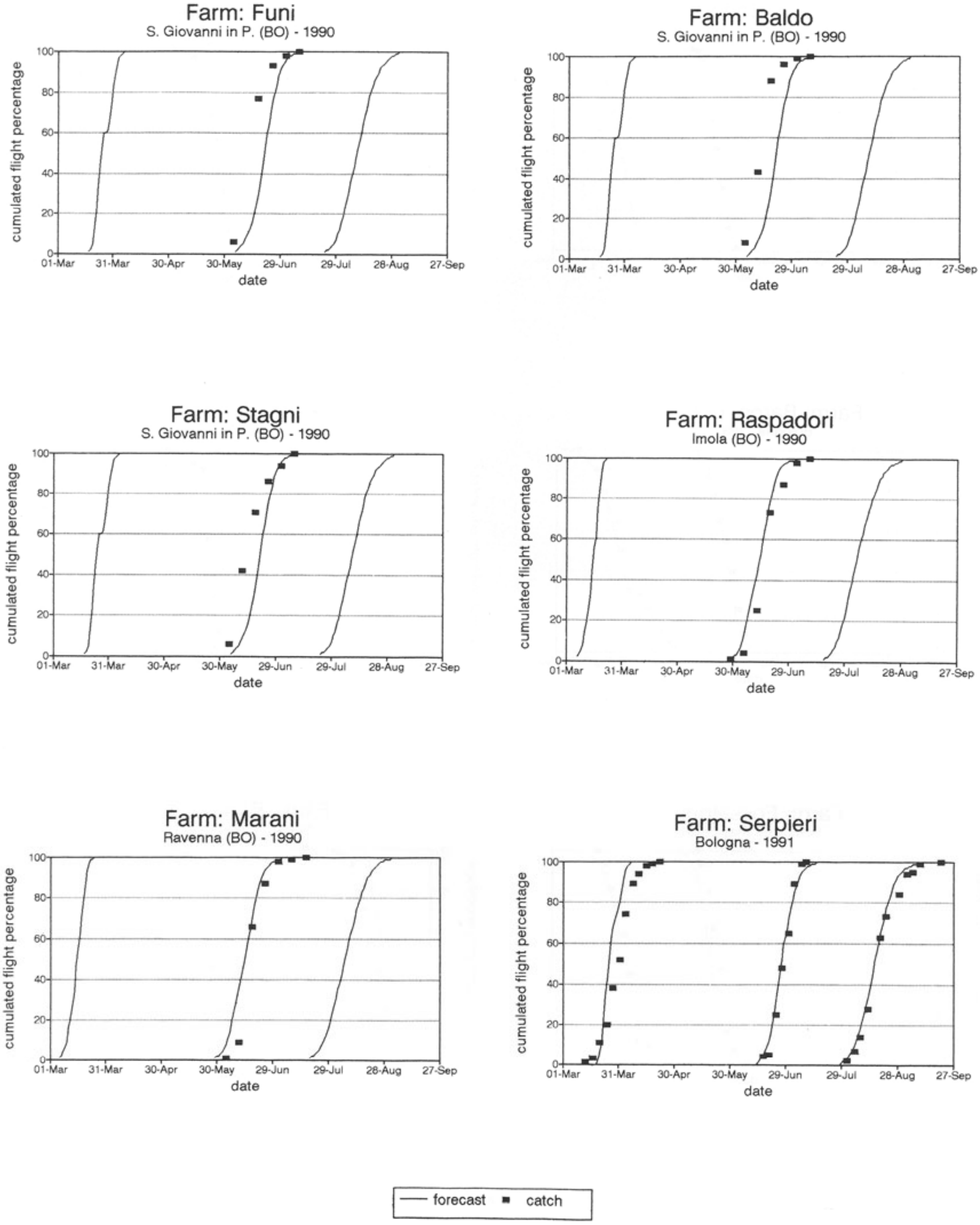

Fig. 2.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).

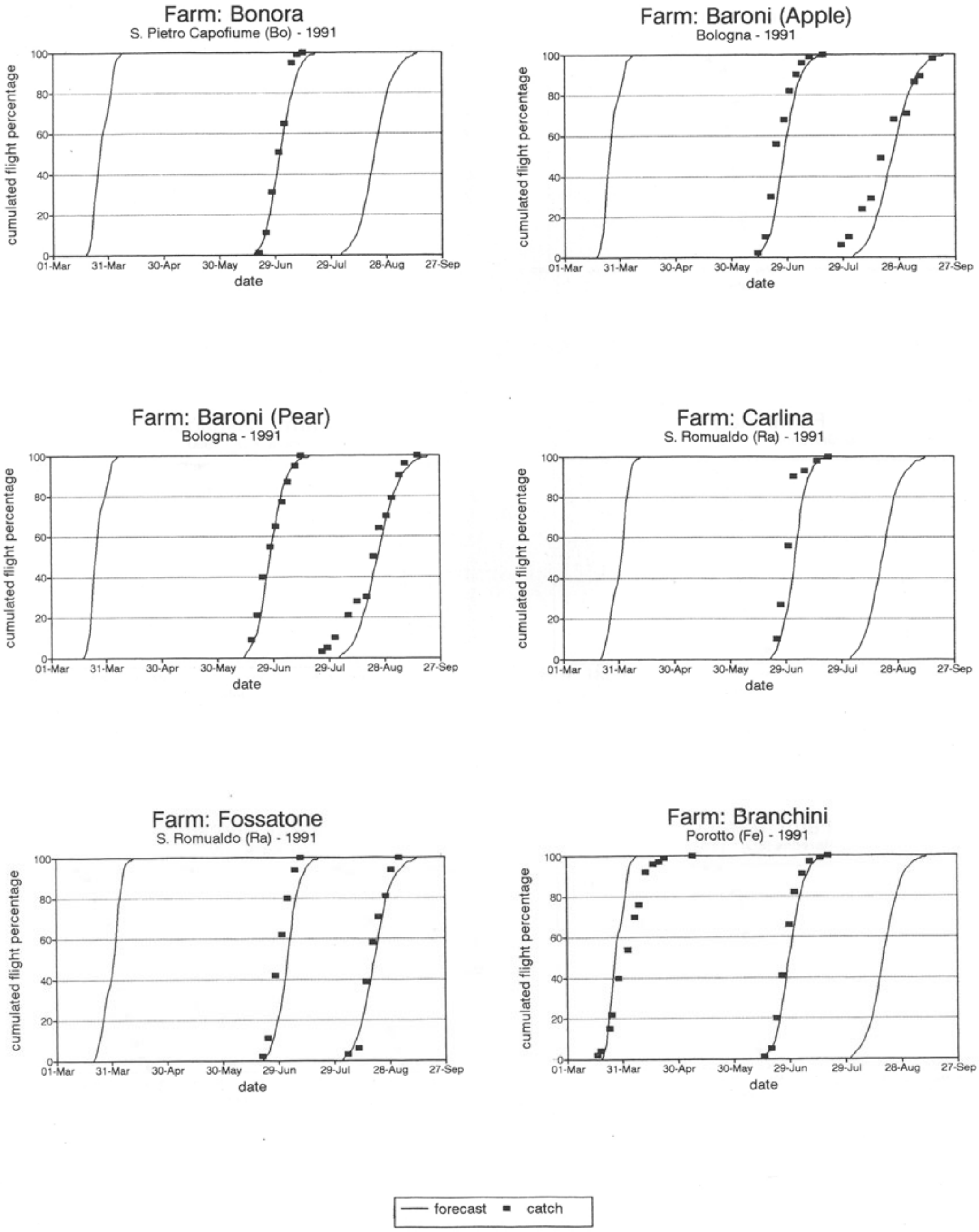

Fig. 3.- Flight patterns forecast by the model (solid lines) and actually observed in the field (dots).