Validation of an insect pest phenological model for the European corn borer (Ostrinia nubilalis Hbn) in the Po Valley in Italy

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Validation of an insect pest phenological model for the European corn borer (*Ostrinia nubilalis Hbn*) in the Po Valley in Italy

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Abstract: *The European corn borer (ECB)* Ostrinia nubilalis *Hb. is one of the most important insect pests of maize. The chemical treatment by means of self-powered spraying machines is the main strategy adopted in Northern Italy to control the pest. The success of the treatment mostly depends on the timing of its application. Phenological models can be successfully used for identifying the right application period for the treatments. The main objectives of this work were the validation of an existing ECB phenological model and evaluating its possible future use as a management tool in Northern Italy. Model accuracy was tested against data collected from traps placed in 26 collaborating maize farm fields in Northern Italy from 2010 to 2012. The ECB adult flight activity was monitored and the model was tested for its accuracy in simulating the occurrence of the first generation adult flight peak. The model resulted accurate in the explored conditions, unbiased (negligible tendency to overestimation), and it was able to explain 76% of variation. The model was able to predict the occurrence of the adult peak with an error of ±4.3 days (Root Mean Square Error). The observed level of error can be considered acceptable for effective chemical treatments.*
Keywords: *european corn borer, model software components, maize, insect pest phenology, validation.*

Riassunto: *La piralide del mais* Ostrinia nubilalis *Hb. è uno dei più importanti insetti dannosi del mais. Una delle strategie di difesa più utilizzate in Nord Italia è il trattamento chimico distribuito con macchine irroratrici. Il successo del trattamento dipende principalmente dal momento di applicazione. I modelli fenologici possono rappresentare un utile strumento per la sua identificazione. Il principale obbiettivo del lavoro è stato la validazione di un modello fenologico per la piralide per l Nord Italia e la sua valutazione come strumento decisionale. L'accuratezza del modello è stata testata utilizzando trappole in 26 campi di mais di aziende sparse nella Valle del Po, in Nord Italia nel triennio 2010-2012. Il modello è stato testato per la sua accuratezza nel simulare il picco di volo degli individui adulti della prima generazione. Il modello è risultato accurato nelle condizioni esplorate, equilibrato (trascurabile tendenza alla sovrastima), è stato capace di spiegare il 76% della variazione, ed ha predetto il picco di volo con un errore di ±4.3 giorni (considerando il Root Mean Square Error). Il livello di errore osservato può essere considerato accettabile per l'utilizzo del modello nell'individuazione del momento migliore per il trattamento.*
Parole chiave: *piralide del mais, modello a componenti software, mais, fenologia di insetti dannosi, validazione.*

1. INTRODUCTION

The European corn borer (ECB) *Ostrinia nubilalis* Hb. is one of the most important insect pests of maize especially in USA and Southern Europe (Mason *et al.,* 1996). Nevertheless, its spread is large and its presence has been reported also in Canada, Northern Europe, Northern Africa, Middle East, China, and Russia (www.plantwise.org, accessed 12 October 2013). The ECB is a holometabolic insect and each generation consists of four phenological stages: the egg, larva, pupa, and imago or adult stages. The larval stage goes through five developmental phases called instars (first to fifth instar) (Magai *et al.,* 1997). Each generation starts from the deposition of new cohorts of eggs. This insect overwinters as a diapausing fifth instar larva in above or below ground debris. Beck (1980) defines diapause as a physiological, genetically determined state, which is programed into the life cycle of the ECB as an adaptive mechanism that ensures survival during periods of adverse conditions. Diapause termination (in spring) and induction (in late summer) are regulated by both intrinsic (genetic make-up) and extrinsic factors, predominantly expressed by light (daylength), temperature, food, and water availability (Magai *et al.,* 1997). In particular, the ECB diapause termination is controlled by the length of the scotophase (i.e., the dark phase of photoperiod) and temperature, the latter having a secondary importance (Beck 1985). Under the effect of these factors diapausing larvae terminate diapause,

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resume development and undergo pupation in spring. The adults emerging from these pupae give origin to the flight of the wintering generation and depose the eggs of the first generation. The number of generations can vary from one to five depending on climate and genetic factors (Mason *et al.,* 1996). In Italy the number of generations varies from two to three in warmer years (Alma and Lessio 2005). In Northern Italy the activity of the first generation adult fly is usually monitored to manage the treatments against this insect. Therefore, the modelling approach used in this work considered the development of the European corn borer from diapause termination to the adult flight of the first generation.

European corn borer larvae damage leaves, stalks and ears causing damages that have direct consequences on yield and grain quality (Labatte and Got 1991). In fact larvae feeding activity is crucial on maize grain mycotoxin contamination. Damaged ears can suffer mycotoxin contamination at rates 40 times higher than healthy ones (Alma and Lessio 2005). Methods that have been suggested for the control of ECB population and damage include the planting of genetically engineered maize hybrids, crop techniques like shredding and ploughing, and the chemical treatment by means of self-powered spraying machines applying organophosphates and pyrethroids (Mazurek *et al.,* 2005; Papst *et al.,* 2005; Folcher *et al.,* 2009). This last method is the main strategy adopted in Northern Italy. Results of the chemical treatment can be quite good in terms of higher yield and lower mycotoxin grain contamination (Maiorano *et al.,* 2009a; Maiorano *et al.,* 2009b). The success of the treatment mostly depends on the timing of its application (Mason *et al.,* 1996). The best timing of application is determined by monitoring the adult flight activity. This is done by means of blacklight or pheromone net traps which give an estimation of the starting and peak of the adult flight activity. The suggested timing of treatment is approximately at 10 to 14 days after initiation of egg lying, which is 0–4 days after the adult flight peak (Mason *et al.,* 1996). In practice, the timing of the chemical treatment is further complicated by the availability of spraying machines. In Northern Italy spray machines are not owned by farmers and the treatments are made by private contractors serving many farmers during the treatment period; the risk of making late treatments can be high.

Mathematical models that predict the phenological development of insect pests can be successfully adopted in management strategies (Di Lena *et al.,* 2013). For instance they can be of great help for scheduling scouting activities in the field and/or identifying the right application period for the chemical treatments. Degree-day based models helps predicting the time of occurrence of biological events such as the appearance of specific insect pest phenological stages. The phenological model presented in Maiorano (2012) was preliminary

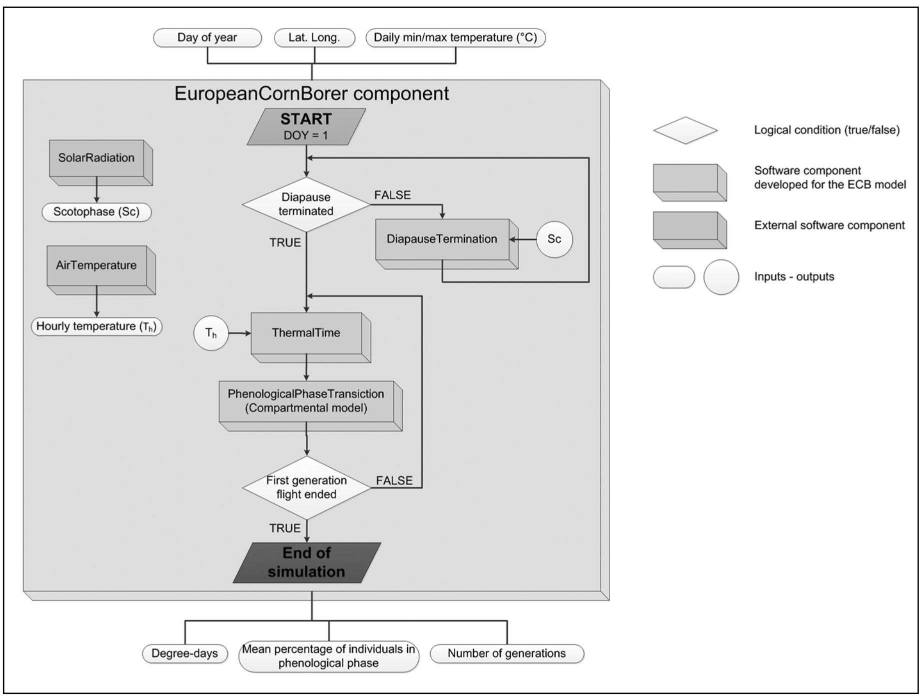

Fig. 1 - Phenological model component diagram and relationships between the sub-components.
Fig. 1 - Diagramma dei componenti del modello fenologico e relazioni tra i sub-componenti.

applied using data from the Piemonte region, in Northern Italy. In the tested conditions the model showed appreciable results above all when compared with the more common degree-day linear model usually used to simulate ECB development.
The aims of this work were:
implementing the model presented by Maiorano (2012) as an independent model software component and presenting the structure of the component extending the test of the model and evaluating perspectives for its use as a management tool for one of the most important maize areas in Europe, the Po Valley in Northern Italy.

2. MATERIALS AND METHODS

The work was carried out in 3 phases: (I) model implementation in independent software components integrated in a modelling solution, (II) collection of data from traps located in the Po Valley, in Northern Italy, (III) evaluation of the model.

2.1 Phenological model, model implementation and software component diagram

The model used in this work is the phenological model presented in Maiorano (2012). The model is based on a degree-days compartmental system developed by Brown (1982). The original model by Brown was based on a linear relationship between temperature and development, and on the use of daily temperatures as input. The disadvantages of using a linear approach and daily temperatures are well known (Curry and Feldman 1987; Worner 1992; Roltsch *et al.,* 1999; Logan *et al.,* 2003; Maiorano *et al.,* 2012). Maiorano (2012) improved the model by Brown by using a non-linear response to temperature (using the equation by Yin *et al.,* 1995) including a minimum, an optimum, and a maximum temperature for development (respectively T_{min}, T_{opt}, and T_{max}), and running the model at an hourly time step. Moreover, in the model by Maiorano (2012) the date to begin accumulating degree-days (i.e. biofix) is not an arbitrarily fixed day (e.g. 1 January); instead, it is determined according to the scotophase (i.e., dark phase of photoperiod excluding twilights) length (h). According to the studies of Skopik and Bowen (1976) the ECB diapause termination starts after 4 days with scotophase < 10h. Furthermore, if during the period up to the stage of the first flight initiation (flight of the overwintering generation) the temperature drops below 0 °C the thermal time calculation is reset. The model requires as input parameters the degree-days for reaching the beginning and ending of the ECB phenological phases. As done in Maiorano (2012), the reference degree-days obtained in laboratory condition by Bessin (2003) and Brown (1982) were used (Table 1). As a result of the work by Maiorano (2012), following optimization the optimal values for the parameters of the non-linear degree-day model were T_{min} = 8 °C, T_{opt} = 35.0 °C, T_{max} = 41,0 °C, shape parameter c=1.47. Compared to the linear version, the non-linear model obtain better results for all the accuracy indicators (linear model: root mean square error = 6.524, coefficient of residual mass = 0.03, model efficiency = -1.282; non-linear model: root mean square error = 3.092, coefficient of residual mass = -0.003, model efficiency = 0.487) (Maiorano 2012).
The model was implemented according to the component architecture proposed by Donatelli and Rizzoli (2008). Components were composed of discrete model units of fine granularity called *Strategies*. They were developed using the software component-oriented paradigm which allows the reusability either as standalone models, or composed with other models for the development of new modelling solutions. The fine granularity of model implementation allows an easier verification and maintenance, and allows composition using the same interface but keeping a solid and transparent underlying modelling structure. The clear separation between data and algorithms, the fine granularity, the attributes defined for each variable used make this type of implementation a way to share modelling knowledge via operational software units. The components implemented in this work can be easily re-used in any platform based on Microsoft®.NET platform and they were implemented as modelling solutions for the BioMA platform of the European Commission (http://bioma.jrc.ec.europa.eu/).
A modelling solution is a discrete simulation engine where different models are selected and composed in order to carry out simulations for a specific goal. The modelling solution presented in this work was implemented in the component *EuropeanCornBorer* for the estimation of the ECB phenological development. Figure 1 shows the modelling solution component diagram and the relationship between the components. The component included the sub-components *AirTemperature* for the estimation of hourly temperature (Donatelli *et al.*, 2010), *SolarRadiation* (Donatelli *et al.*, 2006) for the estimation of the scotophase, and the sub-components, *DiapauseTermination* simulating diapause termination, *ThermalTime* including the

calculation of the ECB thermal time, and *PhenologicalPhaseTransition* simulating the transition from one phenological phase to the other according to a compartmental model. Inputs needed are daily air temperatures, day of the year (Julian day), and geographic coordinates in decimal degrees. Outputs are accumulated degree-days, estimated mean percentage of ECB individuals in the different ECB phenological phases (total individuals = 100), and number of generations. It must be pointed out that in this work only the occurrence of the first generation adult flight peak was tested.

2.2 Data source and model testing

The area of study was included in the Po Valley (including the Piedmont, Lombardy, and Emilia-Romagna regions) and the flatlands of the Veneto and the Friuli-Venezia-Giulia Regions. According to the Köppen climate classification (Kottek *et al.,* 2006) this area is characterized by a humid subtropical climate marked by hot and wet summers and moderately cold winters. Mean annual temperatures are around 13°C. The data source used to test the model consisted of dates and the number of moths caught in pheromone cone traps (Coretrap®, Riff98, Bologna, Italy) baited with sex pheromones (E and Z lures, E:Z=97:3) and phenylacetaldehyde (Pelozuelo and Frerot 2006). Traps (3 traps per field) were placed in collaborating maize farms fields located in Northern Italy from 2010 to 2012. Data from 4 fields were used during the first year, 12 during the second year, and 10 during the third year for a total figure of 26 monitored fields. Traps were placed at the beginning of June and checked every 2-3 days from 1 June to 31 August of each year. Data from the Piemonte region (North-Western Italy) already used in Maiorano (2012) were added to the dataset.

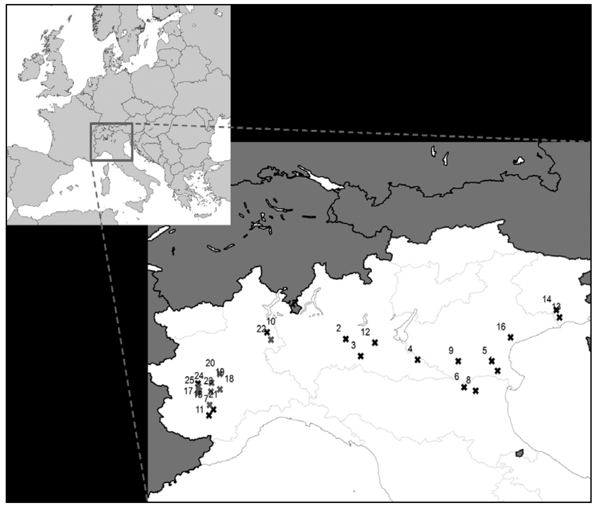

Fig. 2 - Locations and ID (see Table 2) of pheromone traps and weather stations in the Po Valley (northern Italy) used for validating MIMYCS.Borers.
Fig. 2 - Siti e codice ID (vedere Tabella 2) delle trappole a feromoni e delle stazioni meteorologiche nella Valle del Po (Nord Italia) usate per la validazione del modello EuropeanCornBorer.

Data from this dataset were added in order to increase the density of data point in the analysed region (Po Valley), and to balance the high number of data point that were collected mainly in North-Eastern Italy during the 2010-2012 period. Fig. 2 and Tab. 2 shows information about the locations considered for this work.
In most of the cases number of captures in the single traps during the three years were rather low (daily number of captures statistics: median=3, mean = 5.5, maximum = 88, total number of

	Insect stages								
		Larval stages							
	Egg	1	2	3	4	5	Pupa	Adult	Flight
Winter generation									
Bi	Diapause						139	233	306
Ei						250	311	422	500
First generation									
Bi	339	417	539	633	717	789	800	900	922
Ei	550	606	672	750	828	900	961	1078	1217
Second generation									
Bi	967	1033	1094	1189	1250	1317			
Ei	1311	1383	1439	1511	1578	1944			

Tab. 1 - Accumulated degree-days necessaries to reach the beginning (*Bi*) and the ending (*Ei*) of different European Corn Borer phenological stages (Bessin, 2003; Brown, 1982).
Tab. 1 - Somme termiche cumulate necessarie per raggiungere l'inizio (Bi) e la fine (Ei) dei diversi stadi fenologici della piralide del mais (Bessin, 2003; Brown, 1982).

ID	Location	Province	Lat	Long	Years	Note
1	Adria	Rovigo	45.05	12.12	2011 – 2012	Syngenta dataset
2	Barbata	Bergamo	45.48	9.77	2011	Syngenta dataset
3	Campagnola	Cremona	45.25	10.00	2010 – 2011 – 2012	Syngenta dataset
4	Castelbelforte	Mantova	45.20	10.88	2011	Syngenta dataset
5	Cona	Venezia	45.18	12.03	2011 – 2012	Syngenta dataset
6	Ferrara	Ferrara	44.83	11.60	2012	Syngenta dataset
7	Fossano	Cuneo	44.53	7.72	2012	Syngenta dataset
8	Masi torello	Ferrara	44.78	11.78	2011	Syngenta dataset
9	Megliadino S. vitale	Padova	45.18	11.51	2011 – 2012	Syngenta dataset
10	Momo	Novara	45.57	8.55	2012	Syngenta dataset
11	Montanera	Cuneo	44.45	7.65	2011	Syngenta dataset
12	Montirone	Brescia	45.43	10.22	2011	Syngenta dataset
13	Palazzolo dello Stella	Udine	45.77	13.08	2010 – 2011	Syngenta dataset
14	Rivignano	Udine	45.87	13.03	2012	Syngenta dataset
15	Scalenghe	Torino	44.88	7.48	2010 – 2011 – 2012	Syngenta dataset
16	Tessera	Venezia	45.50	12.32	2011 – 2012	Syngenta dataset
17	Cardè	Cuneo	44.75	7.48	2005 - 2008	Maiorano, 2012 dataset
18	Ceresole Alba	Cuneo	44.80	7.82	2005	Maiorano, 2012 dataset
19	Carmagnola	Torino	44.89	7.69	2008, 2009	Maiorano, 2012 dataset
20	Chieri	Torino	45.01	7.82	2005, 2006	Maiorano, 2012 dataset
21	Genola	Cuneo	44.59	7.66	2005	Maiorano, 2012 dataset
22	Novara	Novara	45.47	8.61	2006	Maiorano, 2012 dataset
23	Racconigi	Cuneo	44.77	7.68	2005, 2006	Maiorano, 2012 dataset
24	Vigone	Torino	44.84	7.49	From 2004 to 2008	Maiorano, 2012 dataset
25	Villafranca	Torino	44.78	7.50	2005, 2006, 2008	Maiorano, 2012 dataset

Tab. 2 - Locations, geographic coordinates (decimal degrees), years and reference dataset of traps and weather stations.
Tab. 2 - Siti, coordinate geografiche (gradi decimali), anni e dataset di riferimento delle trappole e delle stazioni meteorologiche.

captures=1708). Therefore, for each field the sum of the three traps were considered for validating the model. A field was considered for validation only if at least 10 captures (sum of 3 traps) were taken at the peak. When the same number of individuals were recorded at the peak on two consecutive surveys, the date of the first survey was considered as the peak.

Daily temperatures data (maximum and minimum temperature) from 1 January of each year for each field were taken from weather stations placed close to the fields (≤1km).

The model was tested for its accuracy in simulating the peak of the first generation adults. The accuracy of the model was evaluated by using the root mean square error (RMSE, dimensionless, 0 to + ∞, optimum=0; Fox, 1981), modelling efficiency (EF, dimensionless, – ∞ to 1, optimum = 1; where a negative value indicates that the average of observations is a better predictor than the model; Nash and Sutcliffe, 1970), and the coefficient of residual mass (CRM, dimensionless, – ∞ to + ∞, optimum = 0, where a positive value indicates model underestimation, and negative indicates model overestimation; Loague and Green, 1991). Performance indicators were calculated for the Syngenta dataset and the whole dataset (Syngenta + Maiorano 2012 datasets – Tab. 1).

3. RESULTS AND DISCUSSION

Fig. 3 shows the adult moth captures compared to the simulated development of adult flight. In the first graph (ID 1, year 2010) of Fig. 3, despite a number of captures >10 the black arrow was not drawn as it was difficult to discriminate between the overwintering, the first and the second generation adult flight (Fig. 4). The observed distribution of the flights can indicate an overlapping of three flights (winter, first and second generation) or it is related to an univoltine ecotype of *O. nubilalis*. Even though the multivoltine is the most frequent ecotype in Northern Italy, the monovoltine ecotype is not absent and can be predominant in some years and locations (Alma and Lessio 2005). Observed flight peak ranged from day of year (DOY) 192 (11 July) in 2011 at location ID 5 (North-Eastern Italy), to DOY 223 (11 August) in 2010 at location ID 15 (North-Western Italy). The highest recorded number of captures at the second flight peak was 120 in 2010 at location ID 15.

Fig. 5 shows the predictive capability of the model in terms of observed vs. predicted day of occurrence of the first generation adult flight peak. Most of the points of the Syngenta dataset were recorded in the 190-205 DOY range and just 5 points were recorded in the 205 – 225 range. These points appear homogeneously distributed around the 1:1 line.

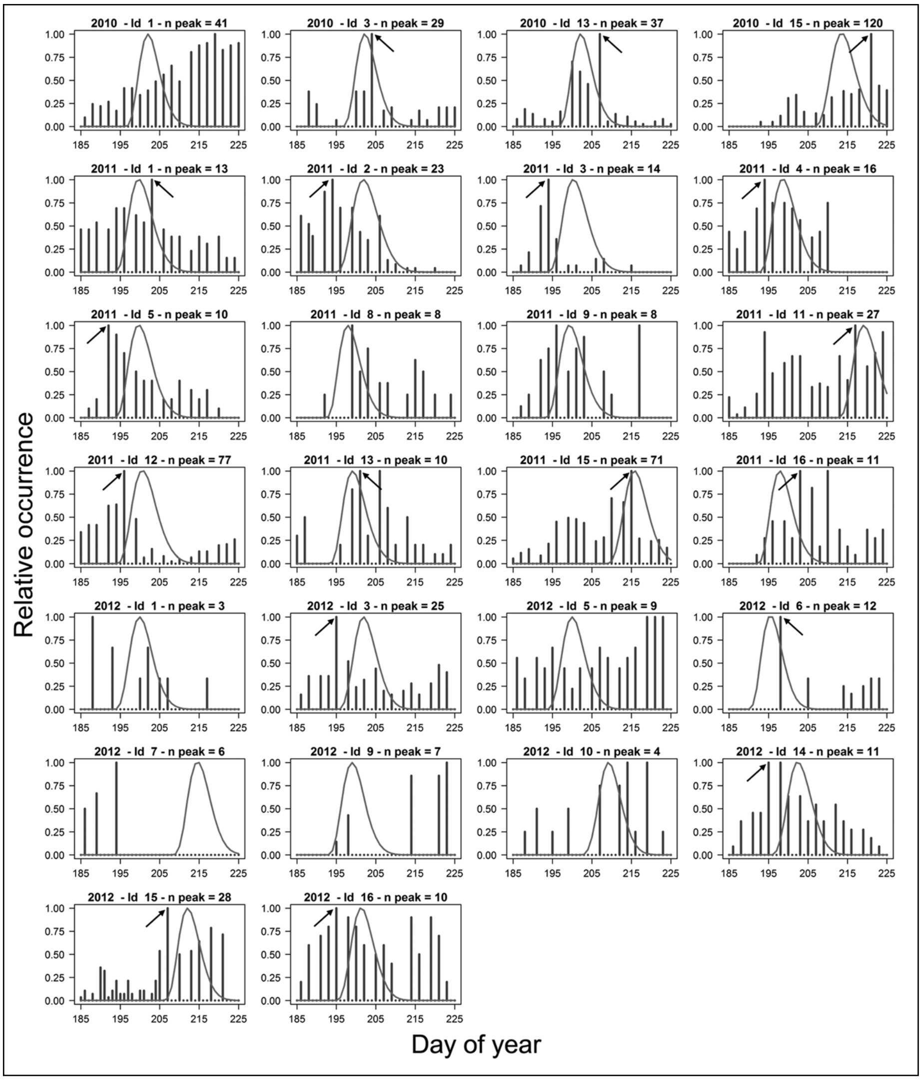

Fig. 3 - Adult moth captures (bars) and simulated development of the first generation adult flight (solid line) in each location (Syngenta dataset) and year. The black arrows indicate the observed first generation adult flight peak. The graphs where the black arrow is absent are locations/years where the number of moth captured at the peak where <10.

Fig. 3 - Catture degli adulti (barre) e sviluppo simulato del volo della prima generazione (linea intera) per tutti i siti (dataset Syngenta) e anni. Le frecce nere indicano il picco osservato del volo della prima generazione. I grafici in cui la freccia è assente indicano siti/anni in cui il numero degli adutli catturati è stato <10.

According to the Pearson's coefficient the model explains 66% of variation. The CRM indicates a very slight overestimation tendency. The EF is positive and satisfactory close to the optimum value. The RMSE indicates that the model is accurate at a level of ±5 days from the simulated peak. Differently from the Syngenta dataset, the Maiorano 2012 dataset included data points entirely recorded in the range 205-225 DOY range. Data from this dataset were recorded in the Piemonte region in North-Western Italy. This region is characterized by cooler temperatures and slower thermal accumulation compared to central and eastern regions of the Po Valley included in the Syngenta dataset. In these way the two dataset completed each other. The addition of the Maiorano 2012 dataset substantially improved all the performance indicators showing that the model I) is capable of explaining a high percentage of variation (76%), II) is unbiased and with a negligible tendency to overestimating the peak (CRM=-0.006), III) can predict the occurrence of the peak with an estimated error of ±4.3 days (considering RMSE). This can be considered a satisfactory level of error considering the low number of moth captured during the years of observation in the Syngenta fields, the 2-3 days between each observation, and the monitoring traps intrinsic error.

This level of error can be considered compatible with the length of the best window of application for pyrethroids reported by Mason *et al.*, (1996) and Blandino *et al.*, (2009). They reported that the chemical treatment should be applied from the beginning of consistent adult flight activity (steady increase in adult captures) and up to 4 days after the flight peak. This time window lasting around 10 days can be identified by the model with a good level of reliability.

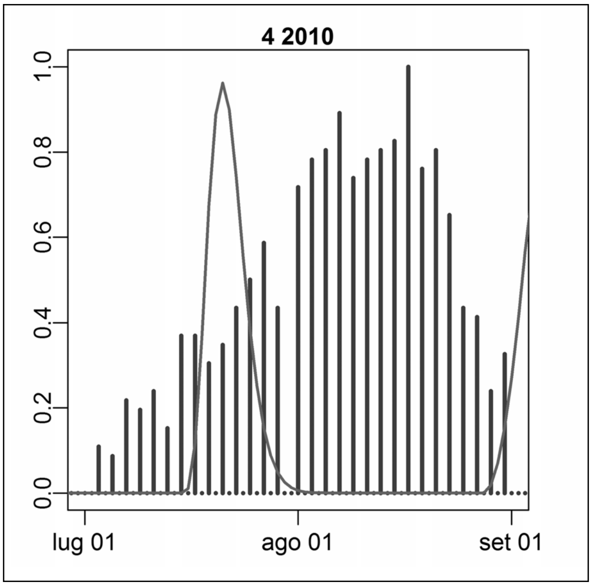

Fig. 4 - Pattern of adult moths captured in field ID1 in 2010 (bars) and simulated adult flight peak (solid line). From this pattern it was impossible to discriminate between the overwintering, the first and the second generation adult flight.
Fig. 4 - Andamento delle catture degli adulti nel campo ID1 nel 2010 (barre) e picco simulato (linea intera). Da questo andamento non è stato possibile discriminare tra il volo della generazione svernante, quello della prima e della seconda generazione.

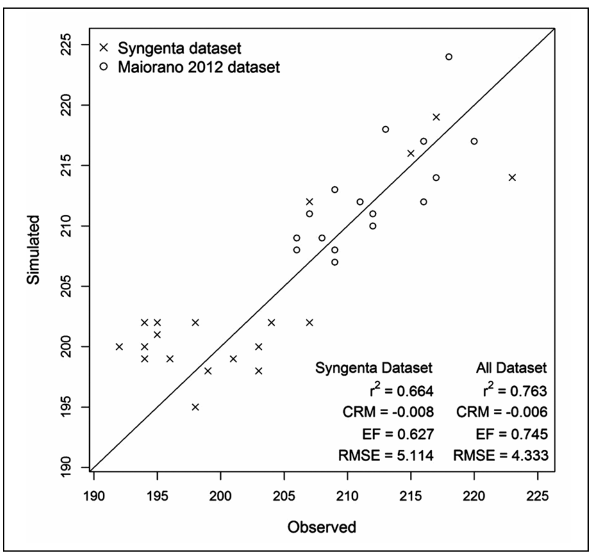

Fig. 5 - Observed vs predicted day (days from 1 January) of occurrence of the first generation adult flight peak. The solid line is the 1:1 line. Black dots are from the Maiorano 2012 dataset. Black crosses are from the Syngenta dataset Accuracy indicator values are shown for both the datasets.
Fig. 5 - Giorno (giorni dal 1 gennaio) osservato vs simulato del picco di volo della prima generazione. La linea in grassetto è la linea 1:1. I punti neri sono relativi al dataset Maiorano 2012. Le croci sono relative al dataset Syngenta. I valori degli indicatori di accuratezza del modello sono mostrati per entrambi i dataset.

4. CONCLUSIONS

The main goal of this work was to implement in an independent software component and to validate a phenological model for the European Corn Borer in Northern Italy and evaluate its potential use for management purposes. The model was adequately accurate in the explored conditions, reproducing correctly the occurrence of the adult flight peak. The observed level of error can be considered acceptable for the chemical treatments usually applied on the ECB. The model can be used as an useful tool to replace the use of monitoring traps and the scouting activity in the field. Furthermore, using short term forecast of temperatures (3-5 days) the model can be used to predict the days when the insect is expected to be in the target phenological stage. In this way the chemical treatment can be planned in advance minimizing the risk of late treatments. The approach followed in this work was not designed and it is not able to explain population dynamics or even to forecast population densities. However, the model can guide to targeted in-field sampling to make a decision, given the number of insects collected, if spraying, thus limiting the number of in field data collections. Also, the model could be used as a management tool to understand not only the best period for a treatment but also if it is too late for it. In such case the farmer might decide not to cancel the treatment by the contractor.
Further studies should be conducted to verify if the parameters by Bessin (2003) can be considered reliable also on the egg and larval phenological phases. In this way the simulation and prediction of the appearance of the phenological phases sensitive to the chemical treatment might increase its accuracy.

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