A Model for Simulation of Developmental Instars of *Halyomorpha halys*

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***Abstract*—This paper proposes a simple model for the development of the invasive brown marmorated stink bug (*Halyomorpha halys*). The quadratic equations for the duration of each instar under variable temperatures were obtained by regressions of datasets from an experiment under controlled conditions published by other authors. The thermal efficiency for the development of each temperature record from a data logger is given by the ratio of the minimal duration of the considered instar (duration under optimal temperature to fulfill a specific stage) and the duration of the same stage at a recorded temperature. The simulated stage is considered fulfilled when the sum of the products between record duration and its thermal efficiency is equal to the minimal duration of the considered stage. The model was tested with experimental data obtained from a life table study performed in cages under outdoor weather conditions in the Emilia Romagna region in 2015.**

***Keywords*—Halyomorpha halys, insect development modeling, thermal efficiency, pest monitoring, orchard**

I. INTRODUCTION

The importance of *Halyomorpha halys*, also known as the brown marmorated stink bug (BMSB), stems from the high rate of spread and disastrous level of orchard yield reduction inflicted by this invasive species. BMSB was responsible for severe damage (including total yield loss) already three years after the first confirmed presence in Northern Italy (2012) and became predominant over all other *Heteroptera* species in the orchards [1]. Reasons for concern were the initial absence of specific natural antagonists, the low efficacy of the native ones, even if some show progressive adaptation to the new species [2], and, in particular, the enormous increase in the use of broad-spectrum insecticides, which seriously disrupted previous IPM (integrated pest management) programs [3].

The quick changes in EU legislation regarding approved pesticides bring out an additional reason for adaptation and improvement of IPM (integrated pest management) strategies (for example out of the nine active ingredients tested in [4], only Acetamiprid and lambda-Cyhalothrin are currently approved [5].

Dynamics of the BMSB population and its phenology are difficult to predict and there is an acute need for more performant pest monitoring methods. Currently, field monitoring of the BMSB population is performed with traps baited with aggregation pheromones, which however show limitations, also in terms of increased damage near the traps [6] and [7].

An integrated approach was developed within the HalyID project [8] including target bug detection by image analysis during flights with UAV (unmanned aerial vehicle), monitoring of orchard microclimate, and modeling of phenology, behavior, and epidemiology of BMSB [9], [10], [11]. In this context, this paper presents a simple model for the simulation of phenology, able to use the weather data flux from the automatic micro weather stations disseminated in orchards.

The weather sensors (Fig. 1) are critical for the simulation of movement between the visible sunlit areas and the shadowed areas but first, their data will be used for simulating the phenology of different instars of BMSB.

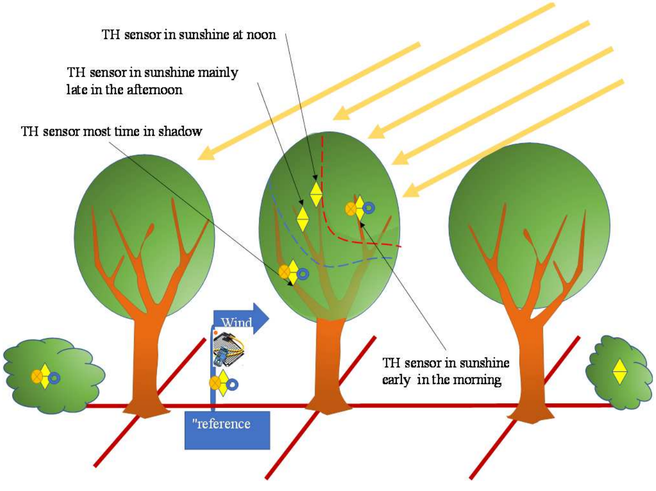

Fig. 1. The distribution of weather sensors within the orchard.

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II. CURRENT APPROACHES IN MODELING THE PHENOLOGY OF PENTATOMIDS

It has been shown by Davidson [12] that the Van t'Hoff-Arrhenius "equations are inadequate for relating temperature to the speed of development in poikilothermic animals" and it was proposed a formula for the reciprocal value of the time required for a given stage in the life cycle of an insect (*1/y*), to develop at a given temperature *x* (1).

$$\frac{1}{y} = \frac{K}{1 + e^{a-bx}} \quad (1)$$

where *a* and *b* are constants, and *K* is the asymptote of the logistic curve.

A key component for many of the phenological models for BMSB are the calculations of stage-specific development rates as linear functions [13] and [14]. These rates are valid for a range between a minimum temperature (14.17°C) and a maximum temperature (35.76°C) [13]. The same authors considered a critical photoperiod of 13.5 h for termination and initiation of the diapause as a conservative option.

A linear model derived from [12] combined with a non-linear model of Briére type [15] (2) was used to calculate stage-specific development rates *R(T)* and the model was tested with data from literature and data obtained for South Korean BMSB population under controlled temperature [16].

$$R(T) = nT(T - T_b)(T_L - T)^{\frac{1}{m}} \quad (2)$$

where *n* and *m* are constants, *T* is the current temperature (in °C), T_b is the lower developmental threshold (°C) and T_L is the upper developmental threshold [16].

In this paper, a simple approach was used to estimate the moment of fulfillment of each developmental stage based on the following basic assumptions:

- The duration values for an BMSB stage at different controlled temperatures permit the calculation of the coefficients for a quadratic equation that gives the duration of that stage at any temperature within the tested temperatures range (D_{Tx}) and the *Y* minimum for that function is the duration under optimal development conditions (D_{Topt}). It should be noted that optimum temperature for development is often different from the optimum temperature for survival.
- The part of D_{Topt} that will be "travelled" during a period *i* at temperature T_x, will be equal with the duration of that period (t_i) multiplied by the ratio of D_{Topt} and D_{Tx}.
- The calculus of stage advancement should be done at a reasonably low time step. This aspect is perfectly compatible with the outputs of all automatic weather stations.

Practically it is proposed the replacement of stage-specific development rates *R(T)* with a "thermal efficiency" value $TE(T_x)$ of the considered period *i* and average temperature T_x for that period (3).

$$TE(T_x) = \frac{D_{T_{opt}}}{D_{T_x}} \quad (3)$$

When

$$D_{Topt} = \sum_{i=1}^{n} t_i \cdot TE(T_x)_i \quad (4)$$

the current development stage is considered ended.

The method proposed in this paper was considered advantageous for some applications related within activities of the HalyID project and it could be useful in a wider range of applications [8].

III. INPUT DATA AND THE STRUCTURE OF THE MODEL

The data for initial model calibration were derived from [17] and the weather data at hour level and the oviposition days for the initial validation of the model came from [18].

The observed stage durations of BMSB for each temperature from [17] were used to extract the coefficients *A, B,* and *C* for quadratic function *Y* (5), describing the influence of temperature *x* on stage duration and the minimum stage duration (D_{Topt}- the minimum of the function) (Table I).

$$Y(x) = Ax^2 + Bx + C \quad (5)$$

For the juvenile instars, equations derived from the data of the individual stages duration [17] were more appropriate than the equation calculated from the data of the whole pre-imaginal period [17]. An example is given in Fig. 2 for the fifth instar and the corresponding equation is (6).

$$Y(x) = 0.06588x^2 - 4.0702x + 70.232 \quad (6)$$

The coefficients of (5) for each instar extracted in this way are displayed in Table I.

TABLE I. COEFFICIENTS FOR THE EQUATIONS DESCRIBING RELATION BETWEEN THE TEMPERATURE AND LENGTH OF DEVELOPMENT STAGES OF *HALYOMORPHA HALYS* (REGRESSIONS FROM DATA OF [17])

Stage	**Parameters**				
	A	***B***	***C***	***Duration (D) at Topt*** *(days)*	***R^2***
Egg	0.04996	-3.2144	54.488	2.79	0.911
First instar	0.05045	-3.1954	53.276	2.68	0.956
Second instar	0.08635	-5.5305	94.034	5.48	0.990
Third instar	0.10024	-5.9755	93.543	4.49	0.971
Fourth instar	0.08948	-5.3839	85.272	4.29	0.925
Fifth instar	0.06588	-4.0702	70.232	7.37	0.972
Adult (female)	0.83117	-50.537	851.64	83.45	0.992
Adult (male)	0.94006	-55.466	894.28	76.14	0942
Pre-oviposition[a]	0.25721	-15.041	228.61	8.73	0.919
Oviposition[b]	0.15219	-11.867	248.37	17.02	0.984

[a] period between adult female emergence and the first oviposition

[b] period between the laying of the first eggmass and the laying of the last eggmass

The concept of the model was tested in MS Excel with a subset of the observed data from [18] and after the final adjustments will be transcribed in Visual Basic for Applications (Fig. 3). Each record from the data logger is stored in a different row and all the calculations are performed for each "time slice". Effective simulations start for the first record of the day in which the oviposition was reported (input date).

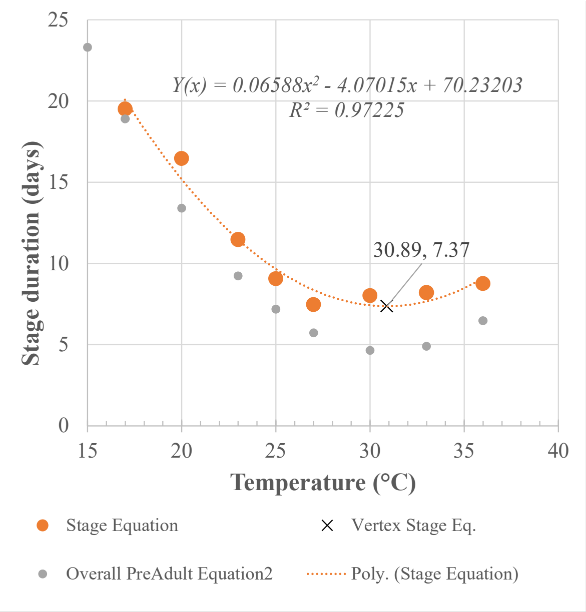

Fig. 2. Relationship between temperature and duration of the fifth instar stage (large orange circles) and the duration of the same stage calculated with the equation (not shown) for the whole pre-imaginal period. Both series of values were derived from [17].

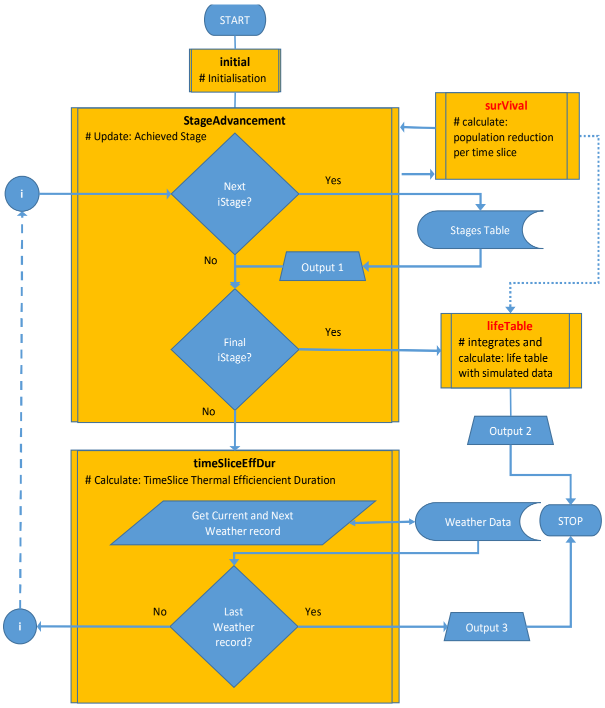

Fig. 3. The general structure of the model. "LifeTable" and "Survival" components are not discussed in this paper.

IV. Results and Discussion

The analysis of the observed and the simulated days of the year in which a certain instar was achieved indicate that the model was able to explain 97% of variance of observed data (R^2) (Fig. 4). The regression equation (7) for observed versus simulated data has a slope close to 1one.

$$Y(x) = 1.043x - 9.79 \quad (7)$$

To measure the average difference between the simulated values and observed values for attaining different stages of development the root mean square error (*RMSE*) was calculated (8).

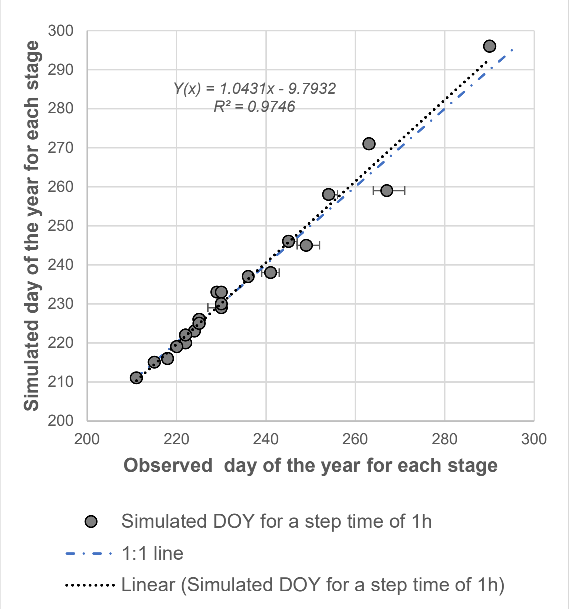

Fig. 4. Relationship between observed [18] and simulated days of the year when different development stages started. The time step of simulations was one-hour. Horizontal bars represent the days in which achievement of the given stage was recorded. (DOY = day of the year).

$$RMSE = \sqrt[2]{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}} \quad (8)$$

where n stands for the total number of pairs "simulated (S)" and "observed (O)" start days of different developmental stages (i).

The *RMSE* (8) was 0.55 when it was calculated for simulations performed with the proposed model and temperatures recorded at one-hour intervals.

It is easy to imagine that a model based on average daily temperature may calculate an optimal development rate for a day that, in fact has many hours under or over the optimal range. A flux of weather data with a higher frequency will allow a more accurate integration of the thermal efficiency for each "time slice". So, when the model was run with temperatures means for 24 hours (Fig. 5), the R^2 was also high (0.968) but the slope of the regression equation (10) was 5.7% higher than in the case when the one-hour temperatures were used. The *RMSE* (9) was in this case 1.38, which is more than double of the value obtained using the recording step of datalogger and in two cases the simulations at day level exceeded the period of record temperatures and observed data.

$$Y(x) = 1.1022x - 21.64 \quad (9)$$

Regarding the situation in which the weather data are available only with a daily time step, but if the minimum and the maximum temperature are available, it is suggested to estimate 3 hours average temperatures (*T3h(j)*) for the days when one or both extreme temperatures of the day are outside T_b - T_L range. This can be done calculating eight correction factor *Tcf(j)* (10) and then *T3h(j)* (11) [19] (*j* takes values from 1 to 8).

$$Tcf(j) = 0.931 + 0.114j - 0.0703j^2 + 0.0053j^3 \quad (10)$$

$$T3h(j) = T_{min} + Tcf(j)(T_{max} - T_{min}) \tag{11}$$

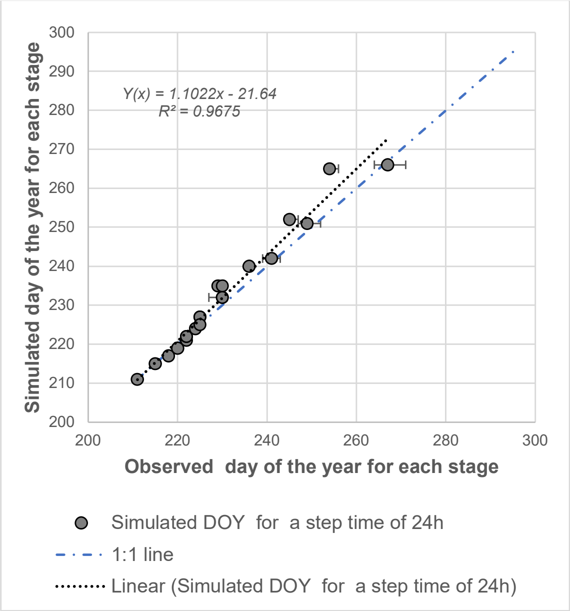

Fig. 5. Relationship between observed [18] and simulated days of the year when different development stages started. The time step of simulations was 24-hours. Horizontal bars represent the days in which achievement of the given stage was recorded. (DOY = day of the year)

The use of smaller time steps is strongly encouraged by the increasing availability of cheap and reliable data from automatic weather stations. A limited source of uncertainty may be represented by the variation of microclimate across orchard. To have an estimation of this source of variation it is useful to place weather sensors in the representative “microclimatic segments” of the orchard (Fig. 2) and to have a functional representation of the bug’s hygro-thermal preferences.

The monitoring of the BMSB population is important for technical decision to apply treatments [20]. Under field conditions the results of phenological models may be affected by other factors such as biocontrol activity from predators and parasitoids, nutrition state, applied treatments [21], migrations, other weather factors and possibly also genetic physiological differences between BMSB populations [22]. For this reason, it is preferable for the user to have the option to “force” the model to run with the estimated population from different monitoring facilities instead of using the population simulated from the previous day. In addition, for the quick new developing directions of monitoring of BMSB populations with the drones [10],[23], [24], [25] it is necessary to have an estimation of the representativity of the observed scene versus the rest of the tree crown and to estimate the preference of BMSB for the visible area under the specific microclimate conditions at a certain moment. For example, there is a specific “window of opportunity” for the UAV monitoring that begins just after sunrise, when the air temperature rises enough for the (ectotherm) bugs that are still cold from the night to move towards the leaves in sunny spots to get the energy to move and eventually fly elsewhere. The proposed model is open for these foreseen additional functionalities. This paper exemplified how developmental coefficients calculated on a BMSB data set obtained under controlled conditions may be satisfactory applied for simulating the development of this bug observed in cages under natural conditions, but having mind the costs of developmental studies under controlled conditions at various temperatures one may remark the importance of estimation of the developmental coefficients of other representatives of the *Pentatomidae* directly from cage experiments paired with automatic weather data records. Future progress regarding the theoretical basis and practical proof for this still open challenge may be expected soon.

V. CONCLUSIONS

The proposed model calculates the phenological progress based on thermal efficiency (the ratio between the duration of the stage under optimal conditions and the duration of that stage under current conditions) rather than stage-specific development rates. The coefficients for the second degree polynomial functions describing the variation of stage duration under different temperatures were derived from a study [17] performed under controlled conditions and were able to reasonably simulate ($R^2 > 0.9$) the observed phenology of BMSB [18] from an experiment in cages from a very different environment. The model can work with a variable time step according to the recording settings of the micro weather stations for monitoring of the orchard environment.

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