

Parametrization of PHENOBMSBv.02 - A Model for Simulation of Developmental Instars of *Halyomorpha halys*

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ABSTRACT

This paper proposes an extended parametrization for a simple model for the development of the invasive brown marmorated stink bug (*Halyomorpha halys* Stål, 1855) proposed by the same authors in a previous conference. The quadratic equations for the duration of each instar under variable temperatures were obtained by regressions of datasets from a controlled temperature experiment published by other authors. Compared with the previous version of the model, in this paper was analysed the impact on the calibration of additional three different phenological data sets available in literature. 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 fulfil 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 consideration 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.

INTRODUCTION

The importance of *Halyomorpha halys*, 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 (Maistrello et al., 2017). According to CSO (2020), in 2019 losses in fruit production in northern Italy were estimated at € 588 million. Reasons for concern were the initial absence of specific natural antagonists, the low efficacy of the native ones, and the enormous increase in the use of broad-spectrum insecticides, which seriously disrupted previous IPM (integrated pest management) programs (Leskey et al., 2012). There is a progressive adaptation of local

predatory species to the BMSB in the newly invaded areas (Rot et al., 2021). Cage experiments including BMSB in various stages and generalist predators permitted a quantitative estimation of the efficiency of this type of biological control (Bulgarini et al., 2021). Modern techniques like molecular analysis of the gut content of predators opened the way for a better understanding of interaction between BMSB and the potential local predators. So for Italy, these approach was able to prove that local predators included at least 10 insects taxa and six arachnid taxa (Bulgarini et al., 2022).

There is a legitimate concern that the polyphagous *Halyomorpha halys* may extend its attacks on field crops like sweet corn (Bueno et al., 2021) and soybean (Gonzalez, 2020) in the future. It is interesting to mention that under the specific biodiversity and climatic conditions of the Switzerland [the European country where the pest bug was first reported (Wermelinger et al., 2008)]

the economic damages of the BMSB remained quite reduced (Haye et al., 2014) compared with Mediterranean countries and damages on field crops were practically absent till 2017 when the raise of temperatures were related with an increase of BMSB population, areal and crop damage. Simulations with a high-resolution CLIMEX model indicate that this trend will continue (Stoeckli et al., 2020). The expected climate changes for southern regions of Romania suggest a reduction in occurrence of severe winters, a reduction in precipitations and warmer springs (Sima et al., 2015; Caian and Amihăesei, 2023) which may favor the BMSB early development and spread. For Romania, the frame of concern is larger due to already observed changes in the incidence of diseases and pests of cultivated plants, but also the appearance of pathogens not specific to Romania. The appearance of the *Caliroa annulipes* (Klug, 1816) species has already been reported (Petcu et al., 2019) and of new fungi that cause black point disease in autumn barley (Cristea et al., 2024)

Rapid changes in EU legislation regarding registered pesticides provide an additional reason to adapt and improve IPM strategies (for example out of the nine active ingredients tested in (Nielsen et al., 2008b), only acetamiprid and lambda-cyhalothrin are currently registered (“EU Pesticides Database - Active substances, n.d.”).

BMSB which is native to China with high invasive and has a high damaging potential was first noticed in Romania in 2015 (Macavei et al., 2015). Two years later, a report on the significant negative impact of joint attack of southern green stink bug (*Nezara viridula*) and BMSB on various corn hybrids was published.

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 carried out with traps baited with aggregation pheromones. These traps have limitations, including increased damage in the vicinity of the traps (Weber et al., 2017).

An integrated approach was developed within the HalyID project (“Our Project - HALY.ID, n.d.”), that includes the detection of the target bugs by image analysis during UAV (unmanned aerial vehicles) flights (Betti Sorbelli et al., 2022), monitoring of orchard microclimate, and modeling of phenology, and epidemiology of BMSB (Kargar et al., 2022; Sava et al., 2022; Almstedt et al., 2023; Giannetti et al., 2024). In this context, this paper presents a simple model for the simulation of phenology, able to use the meteorological data flow coming from the automatic micro weather stations distributed in the orchards. A earlier version of the model was recently presented at an international conference (Lazăr et al., 2023).

The weather sensors are critical for simulating the movement between the visible sunlit areas and the shaded areas but first, their data will be used to simulate the phenology of different instars of BMSB.

Current approaches in the modeling the phenology of Pentatomyds

It was shown by Davidson (Davidson, 1944) that the Van t'Hoff-Arrhenius “equations are inadequate for relating temperature to the speed of development in poikilothermic animals” and a formula was proposed for the reciprocal value of the time required for a given stage in the life cycle of an insect (I/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 of many phenological models for *BMSB* is the calculation of a stage-specific development rates either as linear functions (Nielsen et al., 2016, 2017). These rates are valid for a range between a minimum temperature (14.17°C) and a maximum temperature (35.76°C) (Nielsen et al., 2016). The same authors considered a critical photoperiod of 13.5 h for onset and termination and initiation of diapause as a conservative option.

A linear model derived from (Davidson, 1944) combined with a Briere type non-linear model (Briere et al., 1999) (2) was used to calculate stage-specific development rates $R(T)$ and the model was tested with data from the literature and data obtained for the South Korean BMSB population under controlled temperature (Baek et al., 2017).

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

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 (Baek et al., 2017).

Chang et al. (2013) found in their study that the average TKW of Hap III was significantly different ($p < 0.05$) from those of Hap I and IV in almost all environments. Also, significant differences ($p < 0.05$) were identified in three drought-stress regimes between Hap II and Hap I. For peduncle length, Hap IV and II were longer than Hap III and I in all environments, with a significant difference ($p < 0.05$) between Hap II and I.

MATERIAL AND METHODS

In the model, a simple approach based on following three basic assumptions was used to estimate the time of completion of each developmental stage:

- The durations values for an BMSB stage at different controlled temperatures allow the calculation of the coefficients for a quadratic equation that gives the duration of that stage at any temperature within the temperatures range tested (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 fraction of D_{Topt} that is “travelled” during a period i at temperature T_x , is equal to the duration of that period (t_i) multiplied by the ratio of D_{Topt} and D_{Tx} .

- The calculation of stage advancement should be done with a reasonably small-time step. This aspect is perfectly compatible with the outputs of all automatic weather stations. Practically it is proposed, to replace the stage-specific development rates $R(T)$ by a “thermal efficiency” $TE(T_x)$ value of the considered period i and the average temperature T_x for this period (3).

$$TE(T_x) = \frac{D_{Topt}}{D_{Tx}} \quad (3)$$

when

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

the current development stage is considered terminated.

In no case, this approach can be considered as a criticism of other methods, part of them cited in this study, methods that have proven their value in different environments. The method proposed in this paper was considered advantageous for some applications related to activities of authors in HalyID project (“Our Project - HALY.ID, n.d.”).

The data for initial model calibration were derived from (Govindan and Hutchison, 2020) and the hourly weather data and oviposition days for the initial validation of the model were from (Costi et al., 2017)

Simulations, statistical analysis and graphical presentations were made in Excel (+VBA) from Microsoft 365.

Input Data and the Structure of the Model

The data for initial model calibration were derived from (Govindan and Hutchison, 2020) and the hourly weather data and oviposition days for the initial validation of the model were from (Costi et al., 2017).

The observed stage durations of BMSB for each temperature from (Govindan and Hutchison, 2020) were used to extract the coefficients A , B , and C for the quadratic function Y (5), which describes the influence of temperature x on stage duration and the minimum stage duration (D_{Topt} - the minimum of the function) (Table 1).

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

For the pre-adult stages equations derived from data on the duration of individual stages (Govindan and Hutchison, 2020) were more appropriate than the equation calculated from data on the entire pre-adult period (Govindan and Hutchison, 2020). An example is given in Figure 1 for the fifth instar and the corresponding equation is (6).

$$Y(x) = 0.06588x^2 - 4.07x + 70.23 \quad (6)$$

The coefficients of (5) for each stage extracted in this way are displayed in Table 1.

The concept of the model was tested in MS Excel with a subset of the observed data from (Costi et al., 2017) and after the final adjustments will be transcribed in Visual Basic for Applications (Figure 2). Each datalogger record is stored in a separate row and all calculations are performed for each “time slice”. Effective simulations start with the first record of the day in which the oviposition was reported (input date).

Table 1. Coefficients of the previous version for the equations describing the relation between the temperature and length of development stages of Halyomorpha Halys [Regressions from data of (Govindan and Hutchison, 2020)]

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	0.942
Pre-oviposition Period	0.25721	-15.041	228.61	8.73	0.919
Oviposition Period	0.15219	-11.867	248.37	17.02	0.984

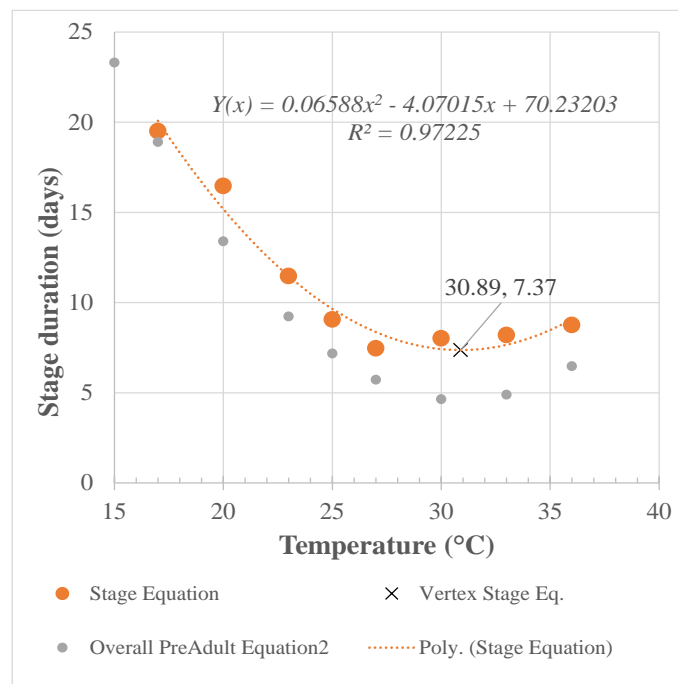


Figure 1. Relationship between temperature and duration of the fifth instar (large orange circles) and the duration of the same stage calculated with the equation (not shown) for the entire pre-adult period. Both sets of values were derived from (Govindan and Hutchison, 2020)

In order to get a better perspective of the viability of the initial calibration based on (Govindan and Hutchison, 2020), three additional phenological data sets obtained

under controlled conditions (Nielsen et al., 2008a; Haye et al., 2014; Baek et al., 2017) were used as a pooled calibration set that included all four data sets.

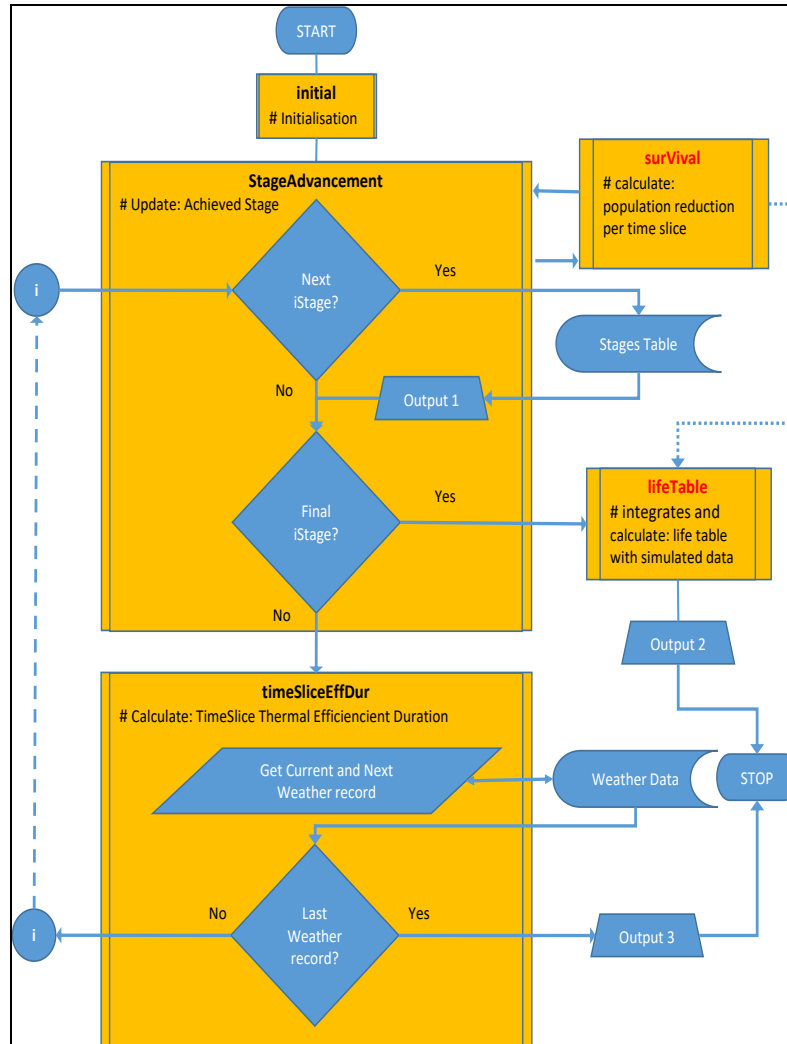


Figure 2. The general structure of the model

RESULTS AND DISCUSSION

Analysis of differences in parametrization with the initial calibration set and the pooled calibration set

The regression based on the initial calibration (Govindan and Hutchison, 2020) indicates a minimum duration of the egg stage equal to 2.8 days (optimal temperature for development is 32.2°C) compared to a minimum duration of 3.3 days (optimal temperature for development being slightly lower 31.4°C) for the same stage resulted from the pooled calibration data set (Nielsen et al., 2008a; Haye et al., 2014; Baek et al.,

2017; Govindan and Hutchison, 2020). The differences between the egg stage duration calculated with the two equations varies between 1.2 days at 17°C to 0.3 days for the 27.5 to 28.5°C range (Figure 3).

The minimum durations and optimal temperatures for first instar development calculated with both equations were quite similar 3 days at 31.3°C for the initial calibration and 2.7 days at 31.7°C for the pooled calibration data set. The differences between the first instar duration calculated with the two equations varies between 1.1 days at 17°C to 0.2 days for the 27 to 28.5°C range (Figure 4).

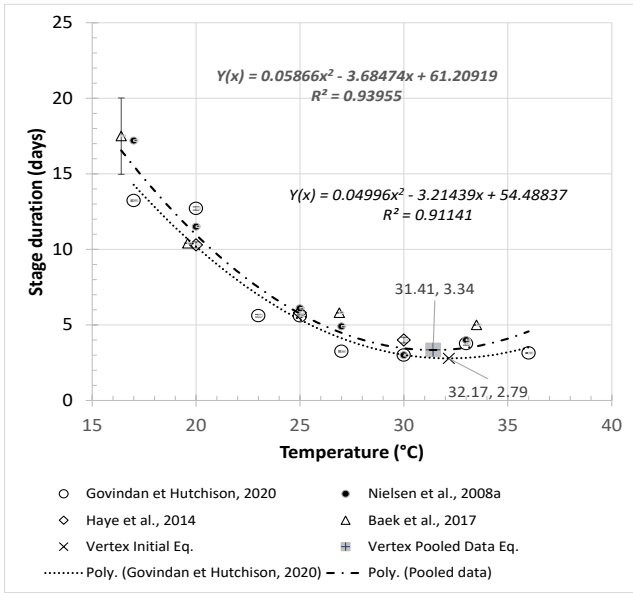


Figure 3. Relationship between temperature and duration of the egg stage. The equation for the pooled calibration data is in bold face. The vertical bars above and below each represent one standard deviation.

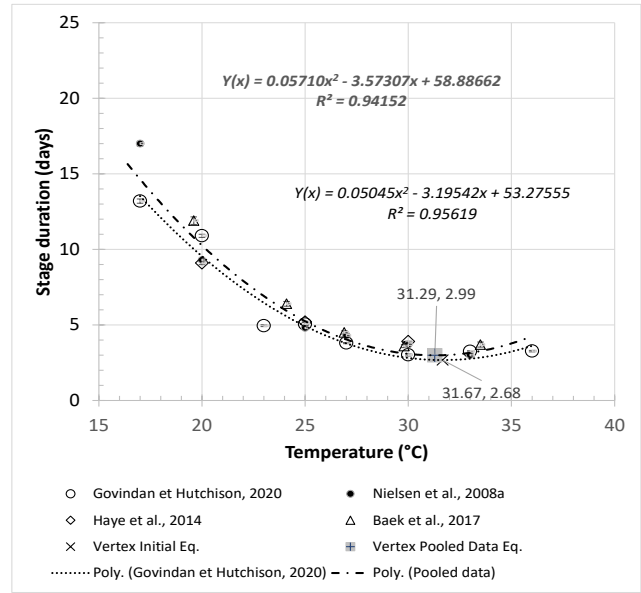


Figure 4. Relationship between temperature and duration of the first instar stage. The equation for the pooled calibration data is in bold face.

The differences between the second instar durations calculated with the two calibration sets were greater than 1.5 days outside the 18.5–34°C range, but for the 20 to 32°C range the differences were less than 0.5 days. The minimum duration (and optimal temperature) calculated with the first and the second calibration sets were 5.5 days ($T_{opt}=32^{\circ}C$) and 5.8 days ($T_{opt}=30.9$), respectively (Figure 5).

Both calculations indicate T_{opt} of about 29.6°C for development of the third instar,

but the minimum duration indicated by the calculation based on the first calibration set was 0.7 days shorter than that resulting from the pooled data set (Figure 6). The data from the South Korean experiment (Baek et al., 2017) showed a longer stage duration, and this aspect is even more evident for the fourth instar (Figure 7) and can be explained by possible differences in the genome of the stink bug populations.

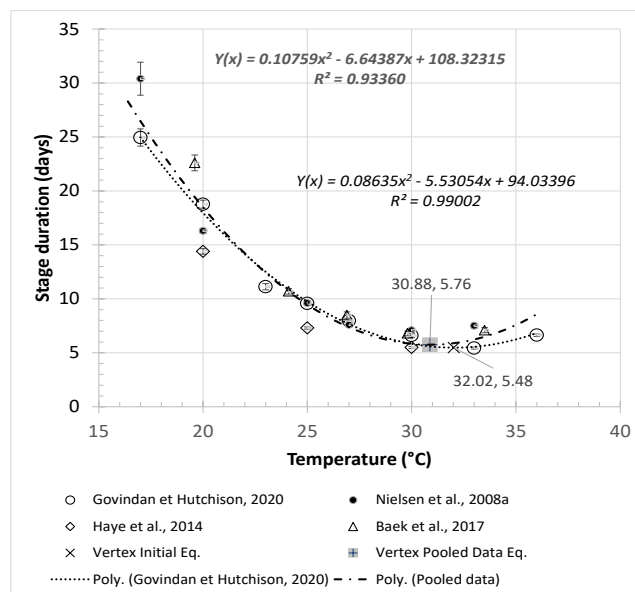


Figure 5. Relationship between temperature and duration of the second instar stage. The equation for the pooled calibration data is in bold face.

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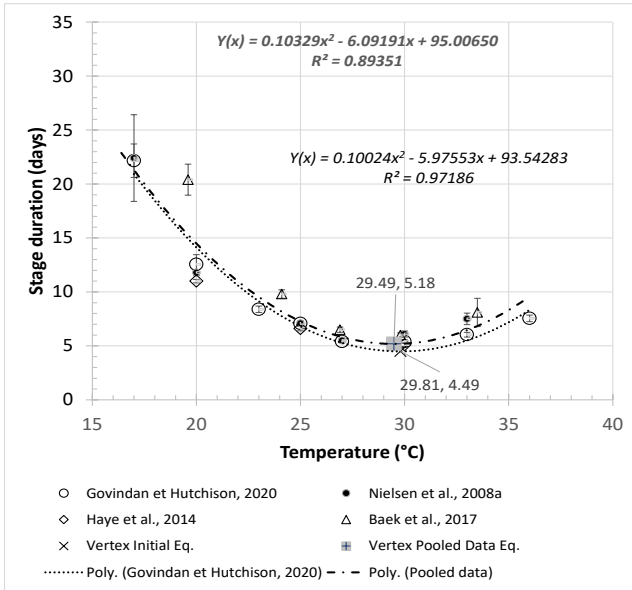


Figure 6. Relationship between temperature and duration of the third instar stage. The equation for the pooled calibration data is in bold face.

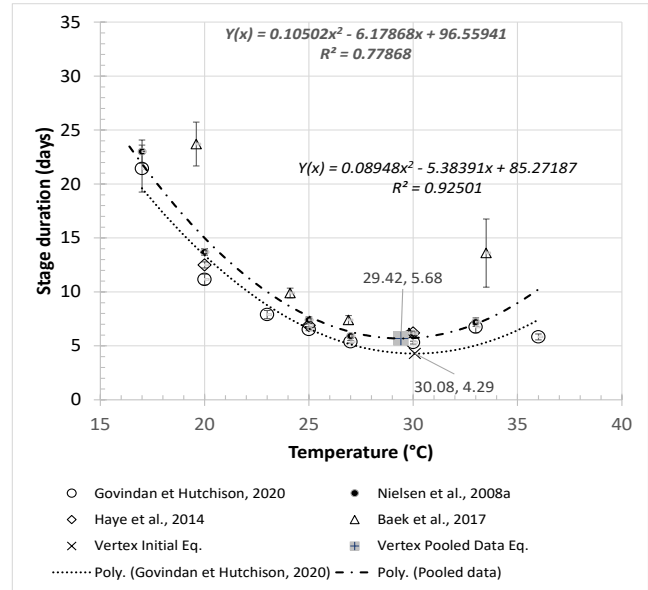


Figure 7. Relationship between temperature and duration of the fourth instar stage. The equation for the pooled calibration data is in bold face.

The T_{opt} and stage durations for the fourth instar were also close to 29.6°C and 4.3 (for initial calibration) to 5.7 days (for the calibration based on four data sets), respectively.

For the fifth instar, the optimal temperature for development (T_{opt}) was close 30.8°C and the duration of this instar was around 7.6 days for both calibration sets,

but the calibration performed with all four available data sets indicated a shorter duration for this stage at temperatures between 17°C (-4.6 days) and 20°C (-3 days) compared to the values resulting from the regression based only on first data set (Govindan and Hutchison, 2020) (Figure 8).

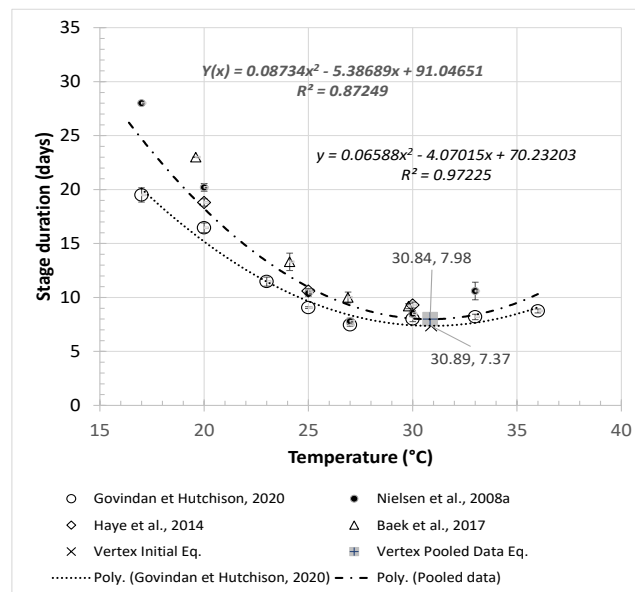


Figure 8. Relationship between temperature and duration of the fifth instar stage. The equation for the pooled calibration data is in bold face.

Simulated versus observed data from cages experiment

Analysis of the observed phenology data (days of the year when a given stage was reached) observed from the validation set (Costi et al., 2017) (obtained from a cages experiment performed in Sassuolo, Modena province, Italy) and simulated phenology based on the first calibration set (Govindan and Hutchison, 2020), indicates that the model was able to explain 97% of the variance in the observed data (R^2) (Figure 9). The regression equation (7) for observed versus simulated data has a slope close to 1.

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

It is easy to imagine that a model based on average daily temperature may calculate an optimal development rate for a day that has many hours below or above the optimal

range. A higher frequency stream of weather data will allow a more accurate integration of the thermal efficiency for each “time slice”.

The same observed versus simulated analysis was performed for the phenology simulations based on the calibration of the pooled data from the four calibration data sets already mentioned above. The new calibration showed a slight improvement in the total explained variance ($R^2=0.98$), but the simulations blocked in some cases for the last two instars (Figure 10).

Under these circumstances it is preferable, either to keep the first calibration or to try a recalibration without the South Korean data set, which may be related to a different genome of the bug. The new regression equations based on the three sources mentioned above are shown in Table 2.

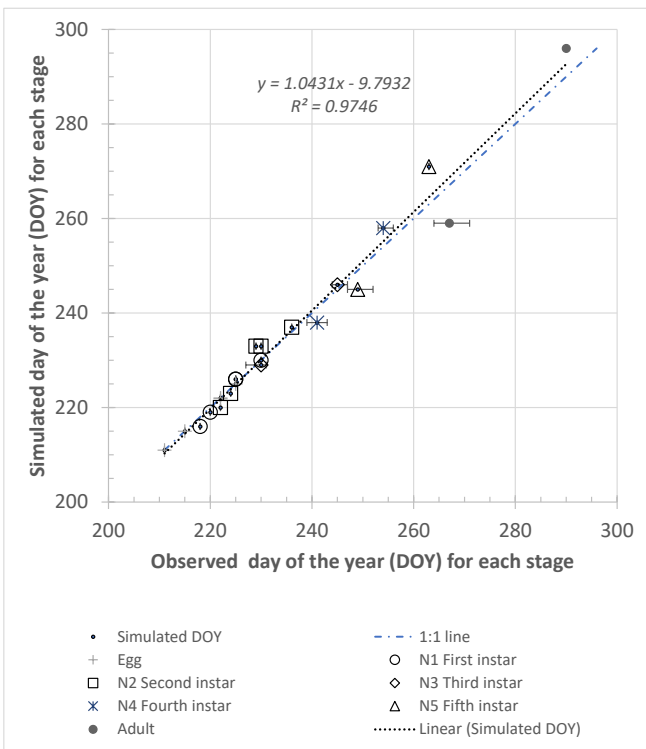


Figure 9. Relationship between observed (Costi et al., 2017) and simulated days of the year in which different developmental stages started based on the initial calibration (based on Govindan and Hutchison, 2020). Horizontal bars represent the days when the respective stage was reached.

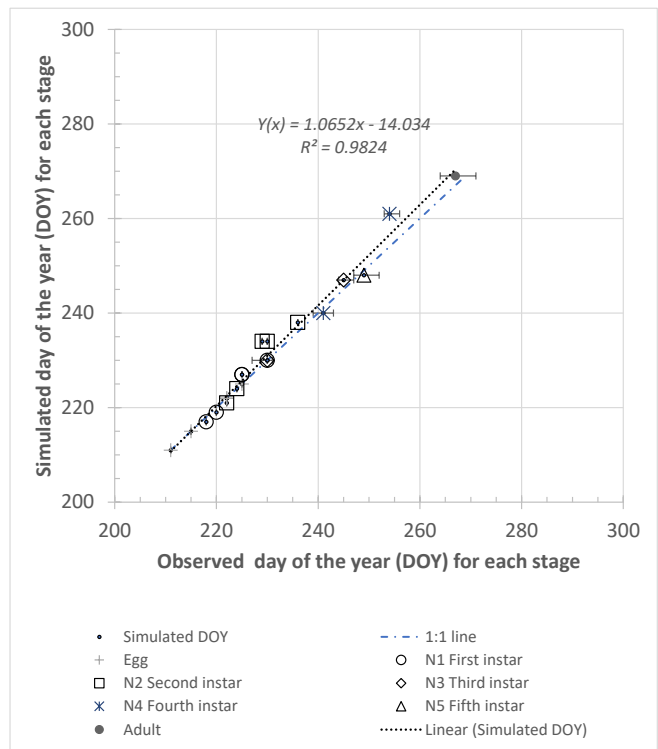


Figure 10. Relationship between observed (Costi et al., 2017) and simulated days of the year in which different developmental stages started based on the four pooled calibration data sets. Horizontal bars represent the days when the respective stage was reached.

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Table 2. Coefficients for the equations describing relation between the temperature and length of development stages of *Halyomorpha Halys* [Regressions from three pooled data sources (Govindan and Hutchison, 2020), (Nielsen et al., 2008a) and (Haye et al., 2014)]

Stage	Parameters				
	A	B	C	Duration (D) at T_{opt} (days)	R^2
Egg	0.0558	-3.55676	59.747	3.1	0.936
First instar	0.05785	-3.6083	59.104	2.8	0.94
Second instar	0.10781	-6.63681	107.65	5.5	0.937
Third instar	0.10333	-6.05508	93.477	4.8	0.941
Fourth instar	0.09527	-5.67398	89.345	4.9	0.929
Fifth instar	0.08996	-5.48176	91.252	7.7	0.885

The comparison between observed and the simulations with the parametrization based on these three calibrations set, didn't explained more than 93% of the observed variance, which is slightly below the previously presented performances, but it is still an indication in favor of model stability (Figure 11).

Compared with the non-linear model of Brière (Briere et al., 1999) (2), which describes the growth rate (the inverse of instar duration), the main differences appear at temperatures close to the lower (17°C) and

upper (36°C) thresholds for development. The non-linear model of Brière has the advantage of sharp and asymmetric decrease of the developmental rate towards the upper threshold, but there are large differences between the observed values from different calibration sets. Our approach, which imposes zero contributions for temperatures outside the range between thresholds is much easier to calibrate than Brière's non-linear model and much more flexible than its linear simplification.

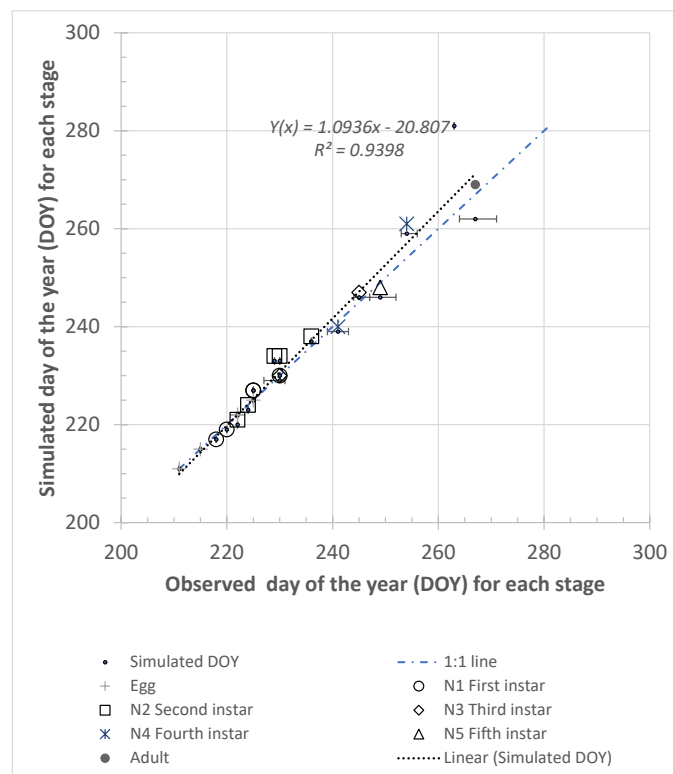


Figure 11. Relationship between observed (Costi et al., 2017) and simulated days of the year in which different developmental stages started based on the three pooled calibration data sets. Horizontal bars

Considerations regarding the time step of simulation

Regarding the situation where the weather data is only available with a daily time step, but minimum and maximum temperatures are available, it is suggested to estimate 3-hour average temperatures ($T3h(j)$) for the days when one or both of the day's extreme temperatures are outside the $T_b - T_L$ range. This can be done by calculating eight correction factors $Tcf(j)$ (8) and then $T3h(j)$ (9) (Jones and Kiniry, 1986) (j takes values from 1 to 8).

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

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

Monitoring of the BMSB population is important or technical decisions on the application of treatments (Aita, 2020). Under real production conditions the results of phenological models may be affected by other factors (like predators and parasitoid activity, nutritional status, applied treatments (Nielsen et al., 2008a), migrations, other weather factors and possibly genetic physiological differences between BMSB populations (Reznik et al., 2022), and for this reason it is preferable that the simulation model to have implemented a facility for forcing with occasional observed data from different monitoring facilities. Also the phenology of the target plant and distance to retreat areas for the bug must be considered (Zapponi et al., 2024). In addition, for the assimilation of UAV processed observations (Sava et al., 2022), it is necessary to have an estimation of the representativeness 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 microclimatic conditions at certain moments. The proposed model is open to these additional functionalities.

CONCLUSIONS

The proposed model calculates the phenological progress based on thermal efficiency (the ratio between the duration of the phase under optimal conditions and the

duration of that phase under current conditions) rather than stage-specific developmental rates. The coefficients for the second-degree polynomial functions describing the variation in phase duration under different temperatures were derived from a study conducted under controlled temperatures (Govindan and Hutchison, 2020) performed under controlled conditions and were able to reasonably simulate ($R^2 > 0.9$) the observed phenology of BMSB (Costi et al., 2017) from an experiment in cages from a very different environment. Recalibration with an extended dataset confirmed the validity of the first calibration but pointed out that at temperatures close to the lower (17°C) and upper (36°C) thresholds for development, differences between predictions based on different calibrations may appear. Some of these differences may be related to variations in the genetic structure of the bug populations. 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.

ACKNOWLEDGEMENTS

A previous calibration and the structure of this model were presented at an international conference (Lazăr et al., 2023) and the contribution of the current paper focuses on the assimilation of additional phenological data sets for a possible recalibration of the model. For the sake of clarity, the description of the model and considerations on the time step of the simulations have also been included in this paper.

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