

Predictive Modelling of Adult Emergence in a Polyphagous *Eucolaspis* (Chrysomelidae: Eumolpinae) Leaf Beetle

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ABSTRACT *Eucolaspis* sp. (Chrysomelidae: Eumolpinae) is a pest that inflicts huge economic loss in many organic apple (*Malus domestica* Borkh.) orchards in New Zealand. The timing of control methods for this pest has been shown to be crucial for success. To aid in planning control programs, we studied threshold temperature and degree-days required for the development of *Eucolaspis* sp. pupae and modeled adult emergence in the field. Pupal development was observed at three constant temperatures. Pupae required 237.0–21.67 degree-days above lower threshold temperature of 4.7–0.89°C to develop into adults. The emergence of adults was modeled with these thermal values and the model was tested for accuracy with field data. The model performed well with a precision of ±4 d. The proposed phenology model has wide applicability in monitoring and planning pest control measures.

KEY WORDS bronze beetle, Chrysomelidae, degree-day, phenology model, temperature

Eucolaspis Sharp 1886 (Coleoptera: Chrysomelidae: Eumolpinae), commonly referred as bronze beetle, is a New Zealand native polyphagous leaf beetle genus. Recent taxonomic findings support only three mainland and one offshore species (Doddala 2012). One of these species, *Eucolaspis* sp. (Doddala 2012) is a pest on many economically important fruit crops in New Zealand. This species also infests other crops and native shrubs of the region. Damage by *Eucolaspis* sp. results in loss of up to 40% of the yield in infested organic apple (*Malus domestica* Borkh.) orchards (Rogers et al. 2006). Limited options are currently available to organic growers for the control of this beetle.

All immature stages in *Eucolaspis* life cycle live exclusively underground, whereas adults live above ground (Miller 1926, Doddala et al. 2010). The larvae seem to undergo winter diapause in deep soil layers (450–600 mm) (Kay 1980, Rogers et al. 2008). Once soil temperatures are sufficiently high during late winter (August), larvae terminate their diapause and move upward, seeking food and shelter to pupate (Kay 1980). Thus, during spring (September and October), most larvae are found at a depth of ~70 mm in the soil (Rogers et al. 2007, 2009). Pupation occurs in earthen cells in the upper soil layers during spring (Lysaght 1930, Rogers et al. 2006). So, this period provides

Table 1. Parameters for calculation of thermal requirements for the emergence of *Eucolaspis* sp. "Hawke's Bay" adults from pupae, at three constant temperature regimes (12, 15, and 18°C) in the laboratory

T	n _p	n _a	N (SE)	V	VT	V ²	T	(T - T _c) ²	(V - V _c) ²
12	54	15	33.2 (0.9)	0.03	0.361	0.0009	11.88	0.01334	0.00015824
15	50	16	22.8 (0.6)	0.044	0.658	0.00192	15.27	0.07117	0.00000169
18	61	16	18.4 (0.7)	0.054	0.978	0.00295	17.85	0.02289	0.00013567
			74.4	0.128	1.998	0.00578	45.00	0.10739	0.00029561

T is the experimental temperature; n_p is number of pupae monitored; n_a is number of adults emerged, N is the mean pupal duration; V is the mean developmental rate and equals 1/N; VT, V², T, (T - T_c)², and (V - V_c)² are the other parameters used in calculation of threshold temperature and degree-days by using method 2 following Zong et al. (2004) and Ma et al. (2008); V_c = V/n = 0.0428; n = 3 is the number of temperature regimes in the experiment (12, 15, and 18 C); T_c is the calculated value of temperature (or effective temperature) and equals T_c = KV.

tory, and effective in modeling phenology of target insects (Delahaut 2003, Jarosik et al. 2004, Trudgill et al. 2005). The other crucial parameter in phenology models, thermal constant, or the sum of effective temperatures (usually expressed in degree-days), is the total amount of heat required for an organism to develop from one stage to another in its life cycle (Honek and Kocourek 1990, Honek 1996) and has been used to predict phenology of insects and other ectotherms (Schwartz 2003).

Phenology models that predict seasonal occurrence of a particular growth stage are available for a range of coleopteran crop pests, including Western corn root-worm, *Diabrotica virgifera virgifera* LeConte (Jackson and Elliott 1988, Stevenson et al. 2008); bark beetle, *Ips typographus* (L.) (Wermelinger and Seifert 1998); mountain pine beetle, *Dendroctonus ponderosae* Hopkins (Logan and Powell 2004); *Semanotus bifasciatus* (Motschulsky) (Ma et al. 2008); bamboo powderpost beetle, *Dinoderus minutus* (F.) (Garcia and Morrell 2009); pine sawyer, *Monochamus galloprovincialis* Olivier, 1795 (Naves and de Sousa 2009); and brassica leaf beetle, *Phaedon brassicae* Baly (Wang et al. 2009).

To provide support for *Eucolaspis* sp. "Hawke's Bay" control programs, development of beetle pupae was studied in the laboratory. We used laboratory studies to assess lower threshold temperature and degree-days required for development of pupae into adults. The data were used to develop and test a phenology model for adult emergence in the field. Linear model was used to describe pupal development in bronze beetle, to calculate threshold temperatures, and to model adult emergence. Both linear and nonlinear models are in practice to describe insect development (Herrera et al. 2005). Nonlinear models enable description of insect development over a wide range of temperatures, but they may not be practically relevant (Jarosik et al. 2002). Linear models usually give a good fit for the rate of development over a range of ecologically relevant temperatures, and they are usually sufficient to predict insect development in the field (Campbell et al. 1974, Jarosik et al. 2002, Garcia and Morrell 2009). We believe that the linear model is appropriate here, as the temperature extremes near lower and upper developmental thresholds are unlikely to be experienced during the active growth period of *Eucolaspis* sp. "Hawke's Bay" in temperate New Zealand climate.

Materials and Methods

Insects and Incubators. Fully grown *Eucolaspis* sp. "Hawke's Bay" larvae that have terminated diapause and moved to the upper layer of the soil to pupate were collected during the last weeks of September 2009 and September 2010 from an organic apple orchard in Havelock North, New Zealand. Soil samples were taken below tree branches and hand-sorted (Rogers et al. 2006, Doddala et al. 2010). The larvae were collected individually into vented 1.5-ml micro-centrifuge vials (Eppendorf AG, Hamburg, Germany) along with a small amount of soil. The larvae were kept cool and transported to the laboratory where they were maintained at controlled conditions (18 C, photoperiod of 0:24 [L:D] h) until they pupated. Care was taken that humidity did not fall below 80% by occasional water spraying and leaving water in open containers. The larvae were observed daily in the morning for pupation. Each new pupa was allocated randomly to one of three constant temperature treatments and transferred immediately to its respective incubator.

Three incubators were used for the experiment; each incubator was set at a constant temperature of 12, 15, or 18 C. These temperatures were within 1 C of the mean monthly soil temperatures of the Hawke's Bay region during September, October, and November in the 3 yr (2006-2008) immediately preceding the year of experiment. Incubators were kept dark to simulate the conditions in soil where pupation occurs in nature. Humidity was not controlled but monitored with digital hygrometers. The vials were sprayed with distilled water if humidity fell below 80%. Temperatures were monitored using data loggers. The entire experiment was repeated in 2009 and 2010. Care was taken to have similar numbers of adults emerged from each temperature regime by adding more pupae depending on mortality in individual incubators (see Table 1 for details). The pupae were observed daily at noon for adult emergence. Adult status was accepted when the beetles achieved darker pigmentation (Lysaght 1930). Pupal duration was calculated as the number of days between the date of pupation and the date of adult emergence.

Calculation of Thermal Requirements. Lower threshold temperature and thermal constant (degree-days) required for *Eucolaspis* pupae to develop into adults were calculated based on two methods. For

method 1 (Campbell et al. 1974, Naves and de Sousa 2009), rate of pupal development (y), the inverse of pupal duration (N) at a particular constant temperature, was regressed against temperature (T) as $y = a + bT$, where y is the rate of development, T is temperature in Celcius, a is the intercept, and b is the slope of the regression line. Rates of development of individual insects were used rather than the mean, in fitting regression model, to minimize error in estimation of thermal values (Kipyatkov and Lopatina 2010). The program Proc REG in SAS version 9.2 (SAS Institute, Cary, NC) was used for the regression analysis.

Threshold temperature, C_t , was calculated according to the formula $C_t = -a/b$ the temperature at which the regression line intercepts x-axis. The thermal constant, K , degree-days required, was calculated as the inverse of the slope of the regression line $K = 1/b$. Standard errors for threshold temperature (SE_{C_t}) and degree-days (SE_K) were calculated from the following formulae (Campbell et al. 1974, Walgama and Zalucki 2007):

$$SE_{C_t} = \frac{y}{b} \sqrt{\frac{s^2}{n - y^2}} = \frac{SE_{.b}}{b} \cdot SE_{.K}$$

in the season (late spring), whereas they hatched in only 15 d later in summer, when temperatures were higher. Acceleration of development with increase in temperature within an optimal range is typical of ectotherms (Jarosik et al. 2002, 2004; Trudgill et al. 2005).

Developmental thermal values (threshold temperatures and degree-days) are usually taxon-specific, and they represent the evolutionary adaptations of an organism to its thermal environment (Trudgill et al. 2005). We believe that the 4.7 °C lower threshold temperature calculated for *Eucolaspis* sp. •Hawke's Bay, which temperature seems to be much lower than the observed average for Coleoptera (13.6 °C) (Nietschke et al. 2007), is an ecological adaptation to New Zealand's temperate climate. Similar lower threshold temperatures for pupal development (–5 °C) were observed in other coleopterans, such as strawberry root weevil, *Otiorynchus ovatus*

spectively (Table 1). The sex of emerging adults was not recorded.

Threshold Temperature and Degree-Days Required. Lower threshold temperature for development of *Eucolaspis* sp. •Hawke's Bay pupae was found to be 4.7 ± 0.89 °C, when calculated using method 1 as (x; 0) intercept of the regression line in the Fig. 1. The threshold temperature was 4.5 ± 0.84 °C when calculated using method 2 (using parameters in Table 1).

Degree-days (Celsius days) required for completion of pupal development were equal to the inverse of the slope of the regression line (Fig. 1) and were 237.0 ± 21.67 according to method 1 and 246.2 ± 19.06 according to method 2 (using parameters in Table 1).

Phenology Model. Lower threshold temperature and degree-days calculated using the two methods did not differ greatly; 4.7 °C and 237 degree-days obtained from the more widely referenced method 1 (linear regression model) were used to predict adult beetle emergence.

Among the different biofix dates compared for the accuracy of prediction, 11 September gave the best fit model with the least mean absolute deviation (5 d) between predicted and actual emergences, compared with the other dates tested (1 September, 9.25 d; 6 September, 6.5 d; 16 September, 7.5 d).

The predicted and actual emergence dates when 11 September was used as the biofix date were within 4 d for all the years except for 2005, where the difference between the two dates was 10 d (Fig. 2). Among the investigated years, 2006 and 2007 had the earliest predicted emergence date due to high soil temperatures, and 2009 had the latest predicted emergence date due to low soil temperatures.

Discussion

As found in the current study (Fig. 1), increased rate of development at higher temperatures also was observed in eggs of *Eucolaspis* by Lysaght (1930), who observed that eggs hatched after 21–22 d during early

emergence) and 90% of the adults had emerged by the first week of December (Table 2). If these crucial events (50 and 90% emergence) were back-calculated

Jackson, J. J., and N. C. Elliott. 1988. Temperature-dependent development of immature stages of the Western corn rootworm, *Diabrotica virgifera virgifera*