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Research Article

Field-based thermal requirements study to improve *Tuta absoluta* (Lepidoptera: Gelechiidae) management

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Abstract: For effective integrated pest management (IPM) programs, it is essential to determine the thermal requirements and apply an accurate forecasting method based on daily degree units of pests. The present study investigated the physiological time (Degree-Days) and the number of generations of tomato leaf miner (TLM), *Tuta absoluta* (Meyrick) in Varamin region (Tehran, Iran) on two tomato cultivars (Cal JN3 and Early Urbana Y) under field-cage and open-field conditions during tomato growing seasons in 2015 and 2016. The environmental temperature was recorded hourly using an electronic data logger. The results indicated that TLM completed three generations during tomato growing seasons on the two tomato cultivars in both years. Degree-days for each generation and the thermal requirements of immature stages were a little different under field-cage and open-field conditions in 2015 and 2016. Furthermore, the pest completed each generation, one to three days earlier in the open-field conditions depending on tomato cultivars. On the whole, findings of this study can improve monitoring and forecasting phenological events of *T. absoluta* and thereby assist in timely adoption of management practices in IPM programs.

Keywords: Degree-day, Integrated pest management, Physiological time, Tomato leaf miner

Introduction

Tomato crop is one of the most important vegetables worldwide which is attacked by a wide range of insect and mite pests. The tomato leaf miner (TLM), *Tuta absoluta* (Meyrick) (Lepidoptera: Gelechiidae) is one of the most destructive pests that reduces tomato yield in many parts of the world (Biondi *et al.,* 2018). TLM also infests other solanaceous crops such as potato, pepper, and eggplant in all developmental stages and causes 55-100% loss in tomato as a main host in many regions of the world (Desneux *et al.*, 2010; Balzan and Moonen, 2012). Using microsatellite markers, researchers found that the central region of Chile is the origin of pest population (Guillemaud *et al.*, 2015). It is estimated that 84.9% of tomato growing areas and 87.4% of total tomato production throughout the world are directly threatened by this pest and other areas are already infested or may be in the near future (Desneux *et al.*, 2011). A recent study showed that *T. absoluta* increased from infesting 3 to 60% of the tomato-cultivated area

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worldwide in 10 years and some of major tomato producing areas, such as China, Mexico, and the USA which produce 42% of the world's tomatoes, are at high risk of being invaded by TLM (Biondi *et al*., 2018). Evaluation of the effect of climatic variables, especially temperature on the biological characteristics of TLM is crucial to provide comprehensive data allowing for better design and timing application of management strategies against this noxious pest on tomato crop. Despite some studies on thermal requirement for development of TLM under laboratory conditions (Krechemer and Foerster, 2015; Martins *et al*., 2016), its determination under natural conditions is not well studied.

Temperature is the main abiotic factor among the climatic variables that can affect directly or indirectly insects' biological characteristics such as population dynamics, activity, geographical distribution, development, generation numbers and life history (Wallner, 1987; Cui *et al*., 2008; Ju *et al*., 2011). These effects vary on different species, but overal, lower and higher temperatures result in decreasing and increasing the rate of insect development, respectively (Andrewartha and Birch, 1973). Physiological time for an organism is the heat unit accumulation to develop in life cycle between the lower and upper temperature thresholds which is calculated as degree-day (DD) or more accurately degree-hour (DH) units (Taylor, 1981; Howell and Neven, 2000). The degree-day accumulation monitoring can be considered as a useful tool to timing of sampling, management events and predicting pest activity based on weather trends in agricultural systems (Murraym, 2008). The biofix point (first trap catch or first occurrence of the pest) should be determined to start degree-day accumulation in field study (Alston, 2006). Some mathematical methods are developed to estimate degree-day; the daily average temperature is the simplest one (Roltsch *et al*., 1999; Aghdam *et al*., 2009; Mirhosseini *et al*., 2017). The other ways are single triangle (Lindsey and Newman, 1956), double triangle (Sevacherian *et al*., 1977), and single and double sine wave (Allen, 1976) which are based on the daily minimum and maximum temperatures. Finally, the hourly-recorded real weather data is the most accurate method to estimate degree-days (Cesaraccio *et al*., 2001; Aghdam *et al*., 2009). The present study was carried out to determine TLM physiological time based on hourly recorded real temperature under field-cage and open-field conditions in order to improve its monitoring and forecast phenological events to utilize in integrated TLM management programs.

Materials and Methods

Experimental design

The study was conducted in two scenarios, field-cage and open-field zones in Varamin county (35° 19' 31" N, 51° 38' 44" E, 918 m above sea level), Tehran province in 2015 and 2016. Two tomato cultivars, Cal JN3 (susceptible) and Early Urbana Y (resistant) were used in the experiments (Ghaderi *et al*., 2017). The temperature was recorded hourly using a digital data logger (Testo, 175-H_2, Germany) positioned inside a cage in the trial site and kept away from direct sunlight. The TLM individuals were collected from infested tomatoes in the Varamin region and were reared on tomato cultivars in a growth chamber at 25 ± 1 °C, 60 ± 5 %RH and a photoperiod of 16: 8 (L: D) h, to release in related cages (Ghaderi *et al*., 2017).

In the open-field study, five-leaf tomato seedlings were transplanted on 11 and 27 April 2015 and 2016, respectively in a randomized complete block design. No fertilizers or pesticides were applied and the experimental zone was not surrounded by other TLM host plants. Larval population density was recorded for the both tomato cultivars during growing seasons in the two years (Ghaderi *et al*., 2018; Ghaderi *et al*., 2019). Delta-shaped traps equipped with sticky surface and pheromone capsules (AgriSense, UK) were installed 0.5 m above the ground and monitored daily to determine the biofix date. Biofix was confirmed when at least two males were trapped in twocosecutive days. After the biofix date, the traps were observed and renewed weekly to count the captured TLM adult males. Trap monitoring was continued until the end of September, when tomato plants were harvested. To calculate physiological time, cumulative degree-hours were measured, between the lower (8 °C) and upper (≈37 °C) temperature thresholds as proposed by Krechemer and Foerster (2015), from the date of biofix.

To calculate physiological time under field-cage conditions, two mated TLM females (three-day-old) were released in each experimental unit made up of three six-week-old tomato plants in tulle net cages (1.2 × 1.2 × 1.2 m); three cages for each cultivar. From the day after the release, the duration of egg, larval and pupal stages were recorded until adult emergence.

Data analysis

Both scenarios were continued during the tomato growing season and physiological times for immature stages and generations were calculated by accumulation of data-logger-recorded degree-day (degree-hour / 24) data. The Excel 2013 software was used for degree-day data accumulation and drawing the graphs.

Results

Thermal requirements of *T. absoluta* under field cage and open-field conditions are shown in Tables 1 and 2, respectively. Based on the results, TLM had three generations on tomato cultivars under field cage and open-field conditions in both years. In both scenarios, TLM needed more thermal units to complete each generation on Early Urbana Y compared with Cal JN3 cultivar. In the open-field condition, the lowest thermal requirement on both cultivars belonged to second generation of TLM. Also the highest mean environmental temperature was recorded in third generation (Table 2).

Table 1 Sum of effective temperature (Degree-day) for development of *Tuta absoluta* under field cage conditions in 2015 and 2016.

Year	Cultivar	Immature stage	1st generation (DD)	2nd generation (DD)	3rd generation (DD)
2015	Cal JN3	Egg	98.91	98.12	99.10
		Larva	248.52	247.53	248.23
		Pupa	123.81	122.20	123.47
		Total	471.24	467.85	470.80
	Early Urbana Y	Egg	120.91	119.12	119.78
		Larva	290.43	289.87	290.10
		Pupa	136.50	135.65	136.98
		Total	547.84	544.64	546.86
2016	Cal JN3	Egg	99.80	98.93	99.53
		Larva	249.47	247.82	248.91
		Pupa	123.76	122.61	122.81
		Total	473.03	469.36	471.25
	Early Urbana Y	Egg	121.62	119.93	120.24
		Larva	293.21	291.35	291.87
		Pupa	137.03	135.53	137.63
		Total	551.86	546.81	549.74

The TLM larval density and trapped males (from biofix to harvest date) are shown in Figure 1. The number of captured males at the beginning and end of the season was lower and the larval population increased during growing season while decreased at the end of season. April 28, 2015 and May 15, 2016 were considered as the biofix dates based on captured males. During tomato growing season in 2015, the total male captured in pheromone trap were 2,741 in 20 weeks from April 14 to August 25, ranging from 10 to 409 males/trap/week that increased in late June when the cumulative degree-day was 1168.15 (Fig. 1). Considering the slow development of immature stages at the beginning of season, larval density was 0.23 and 0.18 larvae/plant on Early Urbana Y and Cal JN3, respectively, which was raised with increasing temperature under favorable climatic conditions and reached to the maximum density on both cultivars in late June. On May 1 to August 28, 2016, the total captured males were 2,439, ranging from 3 to 483 males/trap/week in 18 weeks during the growing season. The first

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peak of captured males was observed when cumulative degree-day reached 639.46 DD on June 19 (Fig. 1). The larval population density was 0.11 larvae/plant on Early Urbana Y and 0.15 larvae/plant on Cal JN3 at the beginning of the season due to low temperature which increased in the middle of the season as temperature increased.

Table 2 Mean environmental temperature and thermal requirements (Degree-day) of *Tuta absoluta* under open-field conditions in 2015 and 2016.

Year	Cultivar	Mean environmental temperature (°C)			Thermal requirements (DD)		
		Generation			Generation		
		1st	2nd	3rd	1st	2nd	3rd
2015	Cal JN3	27.54	29.31	30.63	461.66	412.58	421.52
	Early Urbana Y				521.65	511.48	519.87
2016	Cal JN3	25.61	27.98	30.59	454.83	420.98	423.56
	Early Urbana Y				508.64	497.10	502.32

DD: Degree-day.

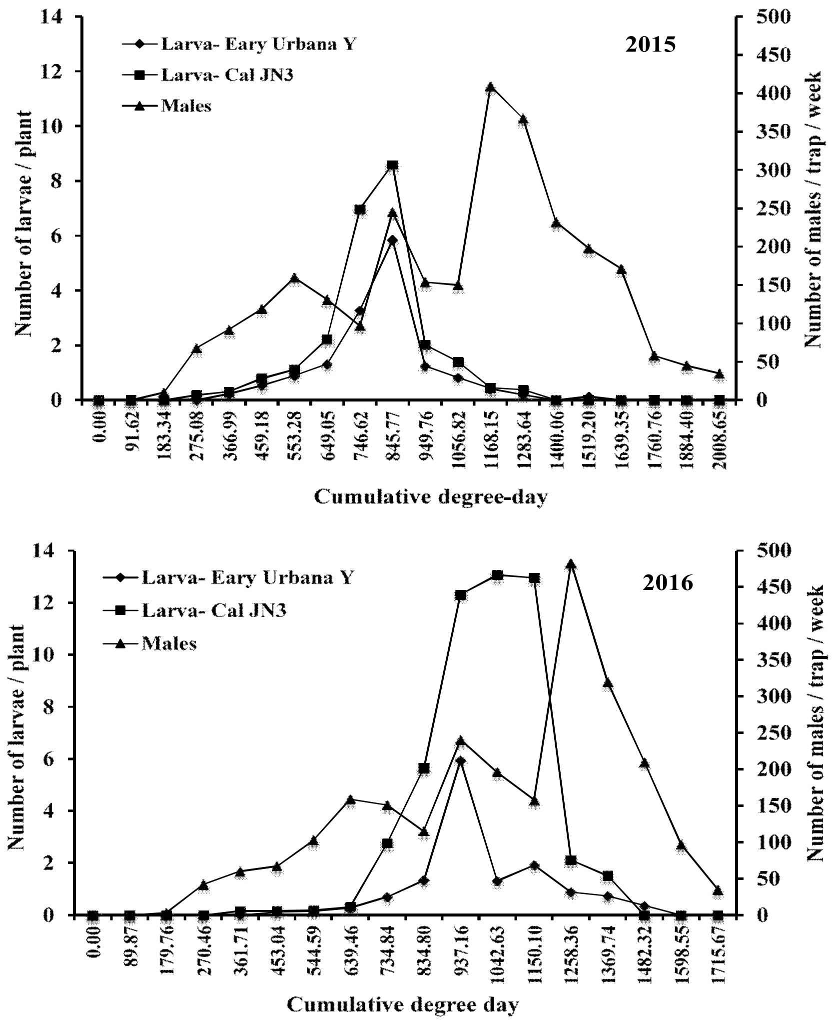

Figure 1 Mean number of larva and captured *Tuta absoluta* males with pheromone trap in tomato growing season in 2015 and 2016.

The first generation activity began in late May 2015 and June 2016, which were the first peak of trapped males (Fig. 1). Second and third peaks were observed for these generations on July 16 and August 9, 2015 and July 10 and August 4, 2016, respectively. Although based on accumulated degree-days in 2015 and 2016 (2008.65 and 1715.67 DD) four generations can be predicted for TLM under open-field conditions, the fourth generation was not completely developed due to tomato plant removal.

Discussion

Temperature affected development time of TLM under field cage and open-field conditions the same as other lepidopteran species (Koda and Nakamura, 2012; Park *et al*., 2014). Although results showed that different plant cultivars can influence the development time of herbivore (Baker *et al*., 2002; Ghaderi *et al*., 2017), TLM had three generations on both tomato cultivars in both years. On Early Urbana Y, TLM needed more thermal units to complete each generation compared with Cal JN3 cultivar in both years, which can be due to TLM-resistance of this cultivar (Ghaderi *et al*., 2017).

Although TLM thermal requirements have been studied in laboratory conditions, researchers argue that thermal constants suffer from a great amount of uncertainty under laboratory conditions which should be used with caution in practice (Bergant and Trdan, 2006). Under the open-field conditions, TLM thermal requirements on sensitive cultivar (Cal JN3) depending on the number of generations ranged between 461.66 and 412.58 DD in 2015 and 454.83 and 420.98 DD in 2016, which are slightly different from field cage conditions due to reduction of sunlight intensity in cage with tulle net (Connor and Taverner, 1997; Pincebourde and Casas, 2006; Pincebourde and Woods, 2012). In a similar study, Unlu (2012) reported three generations for TLM in Turkey. Polat *et al*. (2016) reported that the field thermal requirements to complete development period of *T. absoluta* was 468.13 DD at 28 °C, 463.54 DD at 29 °C, and 461.02 DD at 26 °C for the first, second and third generation, respectively, which is approximately in line with the current study. According to Barrientos *et al*. (1998), the total TLM degree-day was 459.6 DD and for eggs, larvae and pupae were 103.8, 238.5 and 117.3 DD, respectively. However, Krechemer and Foerster (2015) recorded 416.7 DD for TLM development. These differences are not surprising since different experimental conditions were used to calculate thermal requirements, population genetics, microclimate (i.e. photoperiod and humidity) which have major effect on insect development (Pitcairn *et al*., 1992). Furthermore, thermal requirements for insect development may vary depending on various ecological factors including availability, quality and efficiency of food resources (Gilbert and Raworth, 1996; Trudgill *et al*., 2005), as it is shown that different tomato cultivars can affect TLM development time (Gharekhani and Salek-Ebrahimi, 2014; Ghaderi *et al*., 2017). In another study, Mamay and Yanik (2012) determined the emergence of TLM adults in tomato fields in July, August, September and October, corresponding to four generations per year in Turkey.

In conclusion, researchers' findings have shown that a rise in global temperatures, has triggered development of pests, by extension of their activity period and change in population growth rates (Rodhe, 1990; Mahlman, 1997). Therefore, as essential tools for evaluating and understanding population dynamics of insect pests, phenological models can predict generation time, emergence of adults, eggs hatching, larval and pupal development using physiological time data. These models can determine the best time for insecticide application if they are validated under open-field conditions based on real data (Pitcairn *et al*., 1992; Howell and Neven, 2000). The main goal of IPM programs is providing systems based on physiology which include all aspects of crop protection rather than calendar-based systems. However, timely application of different pest management strategies such as pesticide treatments and releasing natural enemies based on physiological time data can improve their success. This study develops practical insight into the population emergence of TLM, the most important tomato pest in many parts of the world. Consequently, the study findings include essential implications for improved management of the pest.

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Statement of Conflicting Interests

The authors declare that there is no conflicts of interest.

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مطالعه نیازهای گرمایی صحرایی برای بهبود مدیریت *Tuta absoluta* (Lepidoptera: Gelechiidae)

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چکیده: در برنامه‌های مؤثر مدیریت تلفیقی آفات، اندازه‌گیری نیازهای گرمایی و به‌کارگیری روش‌های دقیق پیش‌بینی ظهور آفات براساس دمای روزانه ضروری است. در پژوهش حاضر زمان فیزیولوژیکی (روز-درجه) و تعداد نسل‌های مینوز برگ گوجه‌فرنگی (TLM)، *Tuta absoluta* (Meyrick)، با تغذیه از دو رقم گوجه‌فرنگی (Cal JN3 and Early Urbana Y) در شرایط نیمه مزرعه‌ای و مزرعه‌ای در سال‌های ۲۰۱۵ و ۲۰۱۶ در منطقه ورامین استان تهران مورد بررسی قرار گرفت. دمای محیط در هر ساعت توسط دستگاه الکترونیکی ثبت دما، ضبط شد. نتایج نشان داد که این آفت دارای سه نسل در طول مدت رشد گوجه‌فرنگی روی هر دو رقم در هر دو سال می‌باشد. میزان روز-درجه برای هر نسل و نیازهای گرمایی مراحل نابالغ آفت دارای تفاوت ناچیزی در شرایط نیمه مزرعه‌ای و مزرعه‌ای در هر دو سال بودند. علاوه بر این، هر نسل آفت در شرایط مزرعه‌ای بسته به نوع رقم گوجه‌فرنگی یک تا سه روز زودتر از شرایط نیمه مزرعه‌ای کامل شد. به‌طور کلی، یافته‌های این مطالعه با بهبود پیش‌بینی وقایع فنولوژیکی این آفت، می‌تواند تأثیر به‌سزایی در مدیریت به‌موقع آن داشته باشد.

واژگان کلیدی: روز-درجه، مدیریت تلفیقی آفت، زمان فیزیولوژیکی، مینوز برگ گوجه‌فرنگی

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