PHYSIOLOGICAL ECOLOGY

Effects of Temperature on the Immature Development of the Stone Leek Leafminer *Liriomyza chinensis* (Diptera: Agromyzidae)

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ABSTRACT The effect of nine constant temperatures (15, 17.5, 20, 22.5, 25, 27.5 30, 32.5, and 35°C) on the development of the stone leek leafminer, *Liriomyza chinensis* (Kato), on Japanese bunching onion, *Allium fistulosum* L., was studied in the laboratory. Developmental times for immature stages were inversely proportional to temperature between 15 and 30°C but increased at 32.5°C. Total developmental times from egg to adult emergence decreased from 69.6 to 17.1 d for temperatures from 15 to 30°C, with pupae requiring more time for development than the combined egg and larva stages. Both linear and nonlinear (Logan equation VI) models provided a reliable fit of development rates versus temperature for all immature stages. The lower developmental thresholds that were estimated from linear regression equations for the egg, first, second, and third instars, total larva, egg-larval, pupa, and total combined immature stages were 12.1, 10.6, 13.6, 8, 9.6, 11.3, 11.2, and 11.4°C, respectively. The degree-day accumulation was calculated as 312.5 DD for development from egg to adult emergence. By fitting the nonlinear models to the data, the upper and optimal temperatures for egg, larva, pupa, and total immature stages were calculated as 37.8 and 31.7, 34.9 and 30.1, 35.8 and 30.6, and 35.0 and 30.9°C, respectively. These data are useful for predicting population dynamics of *L. chinensis* under field conditions and determining the maximum proportion of susceptible individuals for facilitating improved timing of application of control measures.

KEY WORDS *Liriomyza chinensis*, temperature, development, threshold, degree-day

The stone leek leafminer, *Liriomyza chinensis* (Kato) (Diptera: Agromyzidae), is a specialist pest on *Allium* spp. Damage caused by *L. chinensis* to onion plants is very similar to other *Liriomyza* species: female flies puncture the leaves with their ovipositor for feeding and oviposition, larvae mine and feed within the leaves. The leafminer has become a serious pest on onion crops in many countries including China, Japan, Malaysia, Singapore, Thailand (Spencer 1973, 1990, Chen et al. 2003), Korea (Hwang and Moon 1995), Vietnam (Andersen et al. 2002, Tran and Takagi 2005a), and Taiwan (Shiao 2004). Recent outbreaks of the leafminer in onion crops across Vietnam were treated by a wide range of conventional insecticides, but control was unsatisfactory (Tran and Takagi 2005a). Frequent applications of these broad-spectrum insecticides can adversely affect parasitoid abundance in the vegetable agroecosystem (Johnson et al. 1980, Saito et al. 1996, Thang 1999), can promote the development of pesticide resistance within fly populations (Keil et al. 1985, Johansen et al. 2003), and frequently lead to an increase in leafminer density (Oatman and Kennedy 1976, Murphy and LaSalle 1999).

The development of forecasting systems for use in pest management programs depends on determination of temperature-dependent developmental rates and threshold temperatures for the target species (Palumbo 1995). However, to date, only limited data on the developmental biology of *L. chinensis* have been published (Hwang and Moon 1995, Tagae and Ohtomo 2002). The objectives of this study were to determine the effect of selected constant temperatures on development rate of the eggs, larvae, and pupae of *L. chinensis* on Japanese bunching onion, and from these data, estimate lower and upper developmental thresholds, optimum temperature for development, and thermal constant (degree-day) for each stage.

Materials and Methods

Insect Rearing. *Liriomyza chinensis* used for this study came from a culture reared by the Fukuoka Agricultural Research Center, Fukuoka, Japan, since 2002 from flies collected from commercial onion fields in Fukuoka Prefecture. The leafminer was reared on Japanese bunching onion, *Allium fistulosum* L., as de-

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scribed by Tran and Takagi (2005b). Seeds of this plant were sown in a tray (20 by 60 by 15 cm) in soil mixture (40% water content, pH = 5.5–6.5, 0.035% N, 0.123% P, 0.018% K). Two months after germination, single plants were transplanted in plastic pots (9 cm in diameter). A tray (32 by 44 by 6 cm) containing 15 potted plants was placed in a small greenhouse at 20 ± 5°C and 60 ± 10% RH.

Six potted plants at the two to three leaf stage were exposed to 50 mixed sex *L. chinensis* adults (≈1:1 sex ratio) in a plastic cage (45 by 30 by 25 cm) covered with a fine nylon mesh. After exposure for 24 h, the flies were removed, and the plants were maintained in the MIR-253 Sanyo incubator chamber at 25 ± 0.5°C and a photoperiod of 16 L:8 D until all leafminer larvae pupated. Before plants were placed in the environmental chamber, the upper opening of each pot was covered with a piece of reversed funnel-shaped filter paper (11 cm in diameter), which prevented leafminer larvae from pupating on the soil. Larvae were collected immediately after emergence from leaves and placed in a plastic box (23 by 17 by 6 cm) containing moistened tissue paper and covered with a fine nylon mesh. After pupation, they were transferred to petri dishes (9 cm in diameter) containing moist filter paper and maintained at the same conditions until adult flies emerged.

Immature Development. Six potted plants at two to three leaf stage were exposed to 50 mixed sex *L. chinensis* adults (≈1:1 sex ratio) in a plastic cage (45 by 30 by 25 cm) covered with a fine nylon mesh. After exposure for 6 h, the flies were removed, and the plants were subsequently placed in each of eight in MIR-253 Sanyo incubator chambers set at 15.0 ± 0.5, 17.5 ± 0.5, 20.0 ± 0.5, 22.5 ± 0.5, 25.0 ± 0.5, 27.5 ± 0.5, and 30.0 ± 0.5°C, 70 ± 10% RH, and a 16 L:8 D photoperiod. Light was provided by a 15-W fluorescent lamp (Toshiba FL15D). A second experiment was conducted at 32.5 ± 0.5 and 35 ± 0.5°C using the same equipment to provide a meaningful estimate of optimum temperature and upper temperature threshold. Eggs, which became clearly visible after a few days, were individually marked by circling that area of the leaf with a felt marker under a microscope. Egg hatch was determined by inspecting the leaves with the microscope every 12 h. Only the larvae that hatched at the same time were monitored for larval development time. Larvae that hatched at different times were removed with an insect pin. Because there was no overlap in size of mouth hooks and the cephalopharyngeal skeleton lengths occurred among three instars of *L. chinensis,* measuring the sizes of mouth hooks (0.021 ± 0.0003, 0.054 ± 0.0004, and 0.092 ± 0.0012 mm for first, second, and third instars, respectively) and the cephalopharyngeal skeleton (0.089 ± 0.0014, 0.165 ± 0.0018, and 0.261 ± 0.0037 mm for first, second, and third instars, respectively) enabled the three instars to be easily distinguished (Tran and Takagi 2005b). Measurements of the length of mouth hooks and the cephalopharyngeal skeleton were made in the same manner as described by Tran and Takagi (2005b). When the mines became visible on the plants a few

Table 1. Developmental times (days) of *L. chinensis* at different constant temperatures on Japanese bunching onion

Temperature (°C)	Stage							
	Egg	First instar	Second instar	Third instar	Total larva	Egg-larva	Pupa	Total development
15	11.3 ± 0.05a (195)[b]	4.7 ± 0.06a[a] (19)	4.4 ± 0.11a (11)	6.6 ± 0.27a (14)	14.7 ± 0.29a (14)	26.6 ± 0.13a (92)	43.8 ± 0.58a (5)	69.6 ± 0.93a (5)
17.5	7.4 ± 0.04b (175)	4.3 ± 0.07b (65)	2.9 ± 0.12b (34)	4.2 ± 0.09b (74)	10.4 ± 0.13b (74)	19.7 ± 0.07b (222)	31.8 ± 0.09b (139)	51.8 ± 0.13b (139)
20	5.5 ± 0.02c (224)	2.3 ± 0.06c (43)	2.6 ± 0.05b (48)	3.4 ± 0.06c (98)	7.5 ± 0.08c (98)	14.7 ± 0.12c (401)	22.9 ± 0.06c (289)	37.4 ± 0.08c (289)
22.5	4.4 ± 0.02d (519)	2.0 ± 0.02c (24)	1.9 ± 0.05c (29)	2.6 ± 0.08cd (78)	6.7 ± 0.09d (78)	10.6 ± 0.16d (127)	16.4 ± 0.08d (91)	26.8 ± 0.12d (91)
25	3.4 ± 0.02d (519)	1.5 ± 0.06d (35)	1.7 ± 0.05c (72)	2.3 ± 0.07de (61)	5.4 ± 0.09e (61)	9.1 ± 0.07e (250)	14.1 ± 0.04e (180)	22.9 ± 0.07e (180)
27.5	2.8 ± 0.0e (150)	1.3 ± 0.05d (21)	1.2 ± 0.05d (23)	2.2 ± 0.04de (45)	4.4 ± 0.04f (45)	7.7 ± 0.08f (161)	12.4 ± 0.08f (85)	19.9 ± 0.12f (85)
30	2.3 ± 0.02fA (339)	1.2 ± 0.03dA (39)	0.8 ± 0.03eA (44)	1.9 ± 0.07eA (58)	4.0 ± 0.06fA (58)	6.3 ± 0.04gA (136)	10.6 ± 0.06gA (104)	17.1 ± 0.06gA (104)
32.5	2.6 ± 0.01B (466)	1.6 ± 0.03B (31)	1.1 ± 0.04B (30)	2.1 ± 0.07A (69)	4.8 ± 0.05B (69)	6.7 ± 0.04B (350)	11.1 ± 0.08B (52)	17.3 ± 0.12B (52)
35	2.8 ± 0.04 (127)	-	-	-	-	-	-	-

[a] Mean ± SE. Means with the same small letters within the same stage and different temp (15 to 30°C) are not significantly different by Tukey's HSD test after one way ANOVA, $P < 0.05$. Means with the same capital letter within the same stage and different temp (30 and 32.5°C) are not significantly different by unpaired t-test, $P < 0.05$.

[b] Values in parentheses are no. of tested individuals.

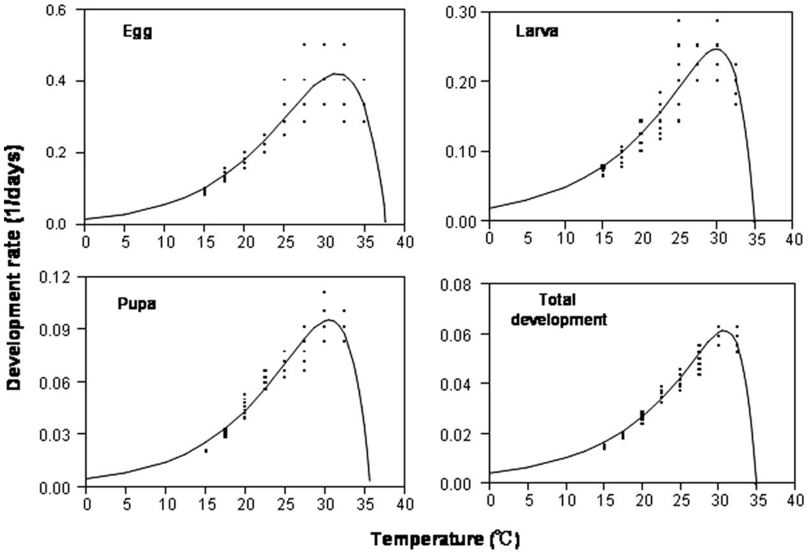

Fig. 1. Development rate (Logan VI model) of egg, larva, pupa and total immature stages of *L. chinensis* as a function of temperature.

days after oviposition, larvae were collected from primary leaves every 12 h and preserved in 70% ethanol until examination. The larvae were dissected and examined under a stereomicroscope (SMZ1000; Nikon Intech Co., Tokyo, Japan). The end of larval development was assessed by collection of pupae from the plants at 12-h intervals.

For determining combined egg-larva, pupa, and total immature development time, another six leafminer-infested plants were maintained in each of the eight environmental chambers until all leafminer larvae feeding on the plants had pupated. Pupae were collected once per day in the afternoon. The development time of egg-larva stages was defined as the time from oviposition until pupa collection. The pupae were individually placed in petri dishes (6 cm in diameter) lined with filter paper. These dishes were placed at the same experimental conditions and supplied daily with some drops of water for maintaining appropriate humidity. Pupae were observed daily to check for adult emergence. The development time and sex for each fly was recorded.

Statistical Analysis. The effect of temperature (15–30°C) on development time was analyzed by one-way analysis of variance (ANOVA). The means were separated by Tukey's honestly significant difference (HSD) test (SAS Institute 1998). The development time at 30 and 32.5°C were compared using an unpaired *t*-test. The effect of temperature on the developmental rate of various stages (i.e., egg, first instar, second instar, third instar, pupa, and total development) was tested by linear regressions using the model $Y = bX + a$, where Y is developmental rate (1/developmental time), X is temperature, and a and b are the regression parameters obtained from the regression. The lower developmental thresholds (T_0) and the thermal constant (DD) requirement were estimated using the parameters: $T_0 = -a/b$ and $DD = 1/b$ (Campbell et al. 1974). Estimation of constants was based only on data obtained at 15–30°C. The relationships between temperature (15–35°C) and rate of development were also fitted by the nonlinear Logan model VI (Logan et al. 1976).

$$Y = P_1 \times \{\exp[P_2 \times (X - T_0)] - \exp[P_2 \times (T_{max} - T_0) - P_3 \times (T_{max} - X)]\}$$

where X is the temperature, T_0 is the lower developmental threshold, T_{max} is the upper (lethal) temperature threshold, and P_1, P_2, and P_3 are coefficients. The optimum temperature for development was calculated after setting the first derivative of the Logan equation equal to zero. The curves were fitted with nonlinear regression using JMP IN software (SAS Institute 2005).

Results

Developmental time for *L. chinensis* at different temperatures is summarized in Table 1. The duration of egg stage decreased significantly as the temperature increased from 15 to 30°C ($P < 0.0001$). The total larval development time decreased significantly when temperature was increased up to 27.5°C ($P < 0.0001$). There was no significant difference in total larval development duration at 27.5 and 30°C ($P > 0.05$). The duration of the first-instar stage decreased significantly ($P < 0.0001$) as temperature increased to 25°C. However, there were no significant differences in development period between 25 and 30°C ($P > 0.05$). The second-instar development period decreased significantly ($P < 0.0001$) from 15 to 30°C, although no significant difference was observed between 22.5 and 25°C ($P > 0.05$). The third-instar development period

Table 2. Linear regression equations of development rate vs temperature and estimated lower developmental threshold (T_0; °C) and thermal constant (DD) for the immature stages of *L. chinensis*[a]

Stage	Slope ± SE	Intercept ± SE	ANOVA parameters			r^2	T_0	DD
			F	df	*P*			
Egg	0.0236 ± 0.00018	−0.2855 ± 0.0043	16985.9	1,1844	<0.0001	0.902	12.1	42.4
First instar	0.0430 ± 0.0019	−0.4544 ± 0.0431	512.1	1,244	<0.0001	0.677	10.6	23.3
Second instar	0.0644 ± 0.0032	−0.8748 ± 0.0761	414.9	1,258	<0.0001	0.617	13.6	15.5
Third instar	0.0256 ± 0.0009	−0.2050 ± 0.0218	735.9	1,424	<0.0001	0.634	8	39.1
Total larva	0.0123 ± 0.0002	−0.1180 ± 0.0054	2835.6	1,413	<0.0001	0.873	9.6	81.3
Egg-larva	0.0083 ± 0.00006	−0.0935 ± 0.0013	18322.2	1,1387	<0.0001	0.929	11.3	120.5
Pupa	0.0051 ± 0.00002	−0.0570 ± 0.0006	32904.4	1,898	<0.0001	0.973	11.2	196.1
Total development	0.0032 ± 0.00001	−0.0364 ± 0.0003	47030.9	1,891	<0.0001	0.981	11.4	312.5

[a] Data were obtained from experiments conducted at seven constant temperatures (15, 17.5, 20, 22.5, 25, 27.5, and 30°C).

decreased from 15 to 30°C ($P < 0.0001$), although no difference was found between 20 and 22.5, and 22.5 and 27.5°C ($P > 0.05$). Instar-specific larval developmental duration also varied significantly with temperature ($P < 0.0001$; Table 1). The first-instar stage had the shortest development period at 20°C ($P < 0.0001$), whereas the second-instar stage was shortest at 17.5 and 30°C ($P < 0.0001$). The third-instar stage was the longest for all tested temperatures ($P < 0.0001$) except for at 17.5°C ($P > 0.05$).

Developmental time for the combined egg-larva, pupa, and total immature stages decreased as temperature increased from 15 to 30°C (Table 1). Development of combined egg-larva stages varied from 26.6 d at 15°C to 6.3 d at 30°C. Pupal development varied from 43.8 to 10.6 d at 15 and 30°C, respectively. In general, pupal development lasted slightly longer than the combined egg and larval stages. Total developmental time from oviposition to adult emergence declined from 69.6 d at 15°C to 17.1 d at 30°C. Developmental time was longer at 32.5°C than at 30°C ($P < 0.001$) for all immature stages except for the third instar ($P = 0.057$). Although some egg hatched, no larvae succeeded in completing development at 35°C.

Development rate of *L. chinensis* from oviposition to completion of egg, egg-larva, pupa, and total immature stages increased with temperature within the temperature range of 15–30°C but declined at 32.5°C (Fig. 1). Significant linear relationships were indicated for the regressions of individual development rate on temperature for each life stage period (Table 2). From these equations, a lower developmental threshold was estimated at 12.1, 10.6, 13.6, 8, 9.6, 11.3, 11.2, and 11.4°C for the egg, first instar, second instar, third instar, total larva, egg-larva, pupal, and total immature stages, respectively. A thermal constant (DD) of 42.4, 23.3, 15.5, 39.1, 81.3, 120.5, 196.1, and 312.5 DD was estimated as the effective temperature sums for the development of the egg, first instar, second instar, third instar, total larva, egg-larva, pupal, and total development periods, respectively.

The nonlinear Logan model gave a good fit (R^2 between 0.9839 and 0.9966) to the data sets of developmental rate for the range of temperature used (Fig. 1; Table 3). The optimal developmental temperatures estimated for egg, larva, pupa, combined egg-larva, and total immature stages were 31.7, 30.1, 31.0, 30.6, and 30.9°C, respectively. The upper limit temperatures for immature development of *L. chinensis* ranged between 34.9 and 37.8°C (Table 3).

Discussion

The lower threshold temperature for total development of *L. chinensis* estimated in this study (11.4°C) is similar to that calculated by Tagae and Ohtomo (2002) (11.5°C), but is higher than that of Wang et al. (2000) (10.3°C). The thermal constant estimated from our data for total development (312.5 DD) was lower than the estimate by Tagae and Ohtomo (2002) (345.5 DD) but was higher than estimate by Wang et al. (2000) (257.5 DD; Table 4). Methodological factors may account for these differences. In the previous studies, estimation was only based on data attained from three temperatures (16.8, 20.5, and 24.6°C) (Wang et al. 2000) and four temperatures (15, 20, 25, and 30°C) (Tagae and Ohtomo 2002). These numbers are considered insufficient for accurate estimation of

Table 3. Parameters of Logan VI equation, upper temperature thresholds, and optimum development temperature for immature stages of *L. chinensis*[a]

Stage	P1	P2	P3	R^2	Upper threshold (°C)	Optimum temperature (°C)
Egg	0.2319 (0.00000)	0.1564 (0.00119)[b]	0.1709 (0.00101)	0.9839	37.8 (0.07)	31.7
Larva	0.0469 (0.00172)	0.0958 (0.00335)	0.3698 (0.01548)	0.9879	34.9 (0.01)	30.1
Egg-larva	0.0299 (0.00045)	0.0967 (0.00127)	0.5168 (0.00985)	0.9889	35.0 (0.29)	31.0
Pupa	0.0168 (0.00028)	0.1143 (0.00362)	0.2993 (0.01693)	0.9958	35.8 (0.11)	30.6
Total development	0.0119 (0.00012)	0.0947 (0.00092)	0.5007 (0.00839)	0.9966	35.0 (0.00)	30.9

[a] Data were obtained from experiments conducted at nine constant temperatures (15, 17.5, 20, 22.5, 25, 27.5, 30, 32.5, and 35°C).

[b] Values in parentheses are standard errors of each parameter.

Table 4. Lower developmental threshold (T_O; °C) and the thermal constant (DD) of *L. chinensis* compared with other *Liriomyza* species

Species	Host plant	T_0	DD	References
L. chinensis	Japanese bunching onion	11.4	312.5	Present study
	Japanese bunching onion	11.5	345.5	Tagae and Ohtomo (2002)
	Not stated	10.3	257.3	Wang et al. (2000)
L. sativae	Kidney bean	10.7	248.1	Tokumaru and Abe (2003)
	Lettuce	9.4	285.7	Palumbo (1995)
	Kidney bean	11.1	223.7	Sakamaki et al. (2003)
L. trifolii	Kidney bean	9.8	251.3	Tokumaru and Abe (2003)
	Kidney bean	9.5	257.0	Saito et al. (1995)
	Kidney bean	11.2	204.1	Sakamaki et al. (2003)
	Kidney bean	10.5	233.9	Lanzoni et al. (2002)
	Tomato	9.1	264.6	Minkenberg (1988)
L. bryoniae	Kidney bean	8.1	316.5	Tokumaru and Abe (2003)
	Tomato	8.1	295.9	Minkenberg and Helderman (1990)
L. huidobrensis	Kidney bean	8.1	280.3	Lanzoni et al. (2002)
	Lettuce	5.7	312.5	Head et al. (2002)

the lower developmental threshold and the thermal constant using the linear model (Campbell et al. 1974, Jervis and Copland 1996). The development times of immature stages of *L. chinensis* were similar to those of *L. bryoniae* and *L. huidobrensis,* but slightly longer than observed for *L. sativae* and *L. trifolii* (Table 4). This study showed that the egg development time increased with decreasing temperature. There is no deviation from linearity in egg development rate in *L. chinensis,* whereas with *L. trifolii,* increases in egg development rate dropped off sharply above 25°C (Leibee 1984). The lower threshold temperature of egg development was 12.1°C, which was much higher than estimated for *L. trifolii* (6.9°C) (Minkenberg 1988) and *L. sativae* (10°C) (Petitt et al. 1991).

No significant deviation from linearity in larval development rate was observed with *L. chinensis* over the temperature range tested. This result is consistent with previous studies indicating that, at an intermediate range of temperatures (e.g., 15–30°C), the rate of development of most *Liriomyza* leafminers is approximately linearly related to ambient temperature (Leibee 1984, Palumbo 1995, Minkenberg and Helderman 1990, Head et al. 2002, Lanzoni et al. 2002). The total larval development durations decreased significantly as rearing temperature increased until 30°C. We observed the development durations for *L. chinensis* to be slightly longer than observed for *L. trifolii* but shorter than for *L. huidobrensis* (Lanzoni et al. 2002). The relationship of temperature with instar-specific larval durations was described by the general linear equations. However, previous studies reported that instar-specific larval development period varied with temperature (Petitt et al. 1991). Our study also indicates that the influence of temperature differs by development stages of the larvae in *L. chinensis.*

The estimated lower threshold temperatures for egg, larval, pupa, and total development of *L. chinensis* (Table 2) were similar to that for *L. trifolii* and *L. sativae* developing on the kidney bean, *Phaseolus vulgaris* (Sakamaki et al. 2003). This suggests that *L. chinensis* may colonize areas with climatic condition similar to those of *L. trifolii* and *L. sativae.*

Palumbo (1995) reported that there were significant differences between estimated DD values for total development from egg deposition to adult eclosion of *L. sativae* based on laboratory data and observed DD values under fluctuating temperature conditions in the greenhouse. Therefore, to predict population dynamics of *L. trifolii* under field conditions at fluctuating temperatures, interpolation from data measured in the laboratory at constant temperatures is only possible when the life history variables react instantaneously to temperature (Minkenberg 1988).

We applied the nonlinear Logan model to study the adverse effect of extreme temperatures on developmental rate. The Logan model has certain advantages over linear regression, including good estimates of upper threshold and optimum temperature and a description of the nonlinear response to temperature. The model fit the data well and predicted values for the upper temperature ranged between 34.9 and 37.8°C, and the optimum temperature ranged between 30.0 and 31.7°C. These values were slightly higher than those of *L. trifolii* and *L. huidobrensis* (Lanzoni et al. 2002).

The mathematical description of the development rate of *L. chinensis* from our study can help underpin the study of the population dynamics of this pest. Linear or nonlinear models can be used to predict the rate of growth and development of the leafminer population in the field and also to optimize control decisions by identifying when the maximum proportion of susceptible individuals is present. For example, delaying application of larval insecticides such as cyromazine or abamectin until eggs are hatching (Parrella et al. 1982). Timing is also important in terms of augmentative biological control. For example, the potential use of parasitoids (Petitt and Wietlisbach 1993) or entomophathogenic nematode (Head et al. 2000) would require precise timing for success.

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References Cited

Andersen, A., E. Nordhus, V. T. Thang, T.T.T. An, H. Q. Hung, and T. Hofsvang. 2002. Polyphagous *Liriomyza* species (Diptera: Agromyzidae) in vegetables in Vietnam. Trop. Agric. (Trinidad). 79: 241–246.

Campbell, A., B. D. Frazer, N. Gilbert, A. P. Gutierrez, and A. P. Mackauer. 1974. Temperature requirements of some aphids and their parasites. J. Appl. Ecol. 11: 431–438.

Chen, X. X., X. Y. Lang, Z. H. Xu, J. H. He, and Y. Ma. 2003. The occurrence of leafminers and their parasitoids on vegetables and weeds in Hangzhou area, Southeast China. BioControl 48: 515–527.

Head, J., K.E.A. Walter, and S. Langton. 2000. The compatibility of the entomophathogenic nematode, Steinernema feltiae, and chemical insecticides for the control of the South Am. leafminer, *Liriomyza huidobrensis.* BioControl 45: 345–353.

Head, J., K.E.A. Walter, and S. Langton. 2002. Utilisation of morphological features in life table studies of *Liriomyza huidobrensis* (Dipt., Agromyzidae) developing in lettuce. J. Appl. Entomol. 126: 349–354.

Hwang, C. Y., and H. C. Moon. 1995. Effect of temperature on the development and fecundity of *Liriomyza chinensis* (Diptera: Agromyzidae). Korean J. Appl. Entomol. 34: 65–69.

Jervis, M. A., and M.J.W. Copland. 1996. The life cycle, pp. 63–161. *In* M. A. Jervis and N. Kidd (eds.), Insect natural enemies: practical approaches to their study and evaluation. Chapman & Hall, London, UK.

Johansen, N. S., M. T. Tao, T.K.O. Le, and E. Nordhus. 2003. Susceptibility of *Liriomyza sativae* (Diptera: Agromyzidae) larvae to some insecticides scheduled for their control in North Vietnam. Grønn Kunnskap. 7: 157–165.

Johnson, M. W., E. R. Oatman, and J. A. Wyman. 1980. Effects of insecticides on populations of the vegetable leafminer and associated parasites on summer pole tomatoes. J. Econ. Entomol. 73: 61–66.

Keil, C. B., M. P. Parrella, and J. G. Morse. 1985. Method for monitoring and establishing baseline data for resistance to permethrin by *Liriomyza trifolii* (Burgess). J. Econ. Entomol. 78: 419–422.

Lanzoni, A., G. G. Bazzocchi, G. Burgio, and M. R. Fiacconi. 2002. Comparative life history of *Liriomyza trifolii* and *Liriomyza huidobrensis* (Diptera: Agromyzidae) on beans: effect of temperature on development. Environ. Entomol. 31: 797–803.

Leibee, G. L. 1984. Influence of temperature on development and fecundity of *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae) on celery. Environ. Entomol. 13: 497–501.

Logan, J. A., D. J. Wollkind, S. C. Hoyt, and L. K. Tanigoshi. 1976. An analytic model for description of temperature dependent rate phenomena in arthropods. Environ. Entomol. 5: 1133–1140.

Minkenberg, O.P.J.M., and C.A.J. Helderman. 1990. Effect of temperature on the life history of *Liriomyza bryoniae* (Diptera: Agromyzidae) on tomato. J. Econ. Entomol. 83: 117–125.

Minkenberg, O.P.J.M. 1988. Life history of the agromyzid fly *Liriomyza trifolii* on tomato at different temperatures. Entomol. Exp. Appl. 48: 73–84.

Murphy, S. T., and J. LaSalle. 1999. Balancing biological control strategies in the IPM of New World invasive *Liriomyza* leafminers in field vegetable crops. Biocontrol News Inform. 20: 91–104.

Oatman, E. R., and G. G. Kennedy. 1976. Methomyl induced outbreak of *Liriomyza sativae* on tomato. J. Econ. Entomol. 69: 667–668.

Palumbo, J. C. 1995. Developmental rate of *Liriomyza sativae* (Diptera: Agromyzidae) on lettuce as a function of temperature. Southwest. Entomol. 20: 461–465.

Parrella, M. P., K. L. Robb, and P. Morishita. 1982. Response of *Liriomyza trifolii* (Diptera: Agromyzidae) larvae to insecticides, with notes about efficacy testing. J. Econ. Entomol. 75: 1104–1108.

Petitt, F. L., and D. O. Wietlisbach. 1993. Effects of host instar and size on parasitization efficiency and life history parameters of *Opius dissitus.* Entomol. Exp. Appl. 66: 227–236.

Petitt, F. L., J. C. Allen, and C. S. Barfield. 1991. Degree-day model for vegetable leafminer (Diptera: Agromyzidae) phenology. Environ. Entomol. 20: 1134–1140.

Saito, T., F. Ikeda, and A. Ozawa. 1996. Effect of pesticides on parasitoid complex of serpentine leafminer *Liriomyza trifolii* (Burgess) in Shizuoka Prefecture. Jpn J. Appl. Entomol. Zool. 40: 127–133.

Saito, T., T. Oishi, A. Ozawa, and F. Ikeda. 1995. Effects of temperature, photoperiod, and host plants on development and oviposition of *Liriomyza trifolii* (Burgess) (Diptera: Agromyzidae). Jpn. J. Appl. Entomol. Zool. 39: 127–134.

Sakamaki, Y., Y. Chi, and K. Kusigemati. 2003. Lower threshold temperature and total effective temperature for development of *Liriomyza sativae* Blanchard on kidney beans. Bull. Fac. Agric. Kagoshima Univ. 53: 21–28.

SAS Institute. 1998. StatView 5.0.J. SAS Institute, Cary, NC.

SAS Institute. 2005. JMP IN 5.1. SAS Institute, Cary, NC.

Shiao, S. F. 2004. Morphological diagnosis of six *Liriomyza* species (Diptera: Agromyzidae) of quarantine importance in Taiwan. Appl. Entomol. Zool. 39: 27–39.

Spencer, K. A. 1973. Agromyzidae (Diptera) of economic importance. Dr. W. Junk B.V., Publishers, The Hague.

Spencer, K. A. 1990. Host specialization in the world Agromyzidae (Diptera). Series Entomologica. Kluwer Academic Publisher, Dordrecht.

Tagae, M., and R. Ohtomo. 2002. Developmental zero and effective accumulative temperature of the Allium leafminer, *Liriomyza chinensis.* Proc. Soc. Plant. Prot. North Japan 53: 245–247.

Thang, V. T. 1999. Surveys of leafminers (*Liriomyza*) and their parasitoids on vegetable in Vietnam, pp. 42–53. *In* L. G. Soon, S. S Sastroutomo, and L. W. Hong (eds.), Workshop on leafminers of vegetables in Southeast Asia. CAB International, Southeast Asia Regional Centre (SEARC), Serdang, Selangor, Malaysia.

Tokumaru, S., and Y. Abe. 2003. Effects of temperature and photoperiod on development and reproductive potential of *Liriomyza sativae*, *L. trifolii*, and *L. bryoniae* (Diptera: Agromyzidae). Jpn J. Appl. Entomol. Zool. 47: 143–152.

Tran, D. H., and M. Takagi. 2005a. Susceptibility of the stone leek leafminer *Liriomyza chinensis* (Diptera: Agromyzidae) to insecticides. J. Fac. Agr. Kyushu Univ. 50: 383–390.

Tran, D. H., and M. Takagi. 2005b. Developmental biology of the stone leek leafminer *Liriomyza chinensis* (Diptera: Agromyzidae) on onion. J. Fac. Agr., Kyushu Univ. 50: 375–382.

Wang, L. X., Y. J. Zhang, and Y. W. Jiang. 2000. Bionomics of *Liriomyza chinensis* (Kato). Entomol. Knowl. 37: 214–217.

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