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Development and Evaluation of Degree-Day Models for *Acrolepiopsis assectella* (Lepidoptera: Acrolepiidae) Based on Hosts and Flight Patterns

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Abstract

The leek moth, *Acrolepiopsis assectella* (Zeller), was first discovered in Ottawa, Canada, during the 1993 growing season, representing the first known occurrence of this species in North America. Since then, it has become a significant concern in *Allium* vegetable production including garlic, leeks, and onions. *Acrolepiopsis assectella* was first detected in the contiguous United States during the 2009 growing season in northern New York. In this study, we evaluated the development of the US *A. assectella* population in the laboratory and commercial onion fields. Our results showed that this population required 443.9 degree-days to complete its life cycle on onions in the laboratory. The development of *A. assectella* on onion did not significantly differ from populations reared on garlic or leeks. Field studies revealed three distinct flight periods for overwintered, first- and second-generation adult males in northern New York. Life cycle duration in the field ranged from 4 to 8 wk. The degree-day prediction model evaluated in this study provided accurate estimates of the occurrence of the following generation. We conclude that this model can help growers to implement appropriate management strategies for different life stages in a timely manner and lessen damage by this new invasive pest.

Key words: *Acrolepiopsis assectella*, *Allium* spp., development, degree-day, flight activity

Acrolepiopsis assectella (Zeller), the leek moth, is a microlepidopteran pest that attacks cultivated *Allium* plants including garlic (*Allium sativum* L.), leek (*Allium porrum* L.), and onions (*Allium Cepa* L.) (Garland 2002). Larvae feed on leaves, stems, flower stalks, inflorescences, and, occasionally, bulbs of plants. *Acrolepiopsis assectella* injury rarely kills the host, but plant growth can be diminished and subsequently reduce the economic value of *Allium* vegetable crops. For example, leeks, chives, and green onions have high cosmetic standards, and there is no consumer tolerance for visual insect damage or frass (Huang 1996).

Acrolepiopsis assectella has been a pest of *Allium* crops in >30 countries, and its distribution ranges from Portugal to Russia moving from east to west, and from Angola to Sweden moving south to north (Åsman 2001, Garland 2002, Jenner et al. 2010a). The first North American detection occurred in 1993 near Ottawa, Canada (Landry 2007), and was first detected in the United States in 2009 in Plattsburgh, New York. As of 2015, *A. assectella* is well-established in four counties of northern New York and five counties of northern Vermont. Among sites in the United States, *A. assectella* has only been found in small, diversified farms and home gardens in New York and Vermont where garlic, leeks, and onions have been grown. But, the distribution of *A. assectella* has expanded southward and threatens large-scale commercial onion production areas in New York. Thus, it is considered a major threat to the New York onion industry whose economic value exceeds US$54 million (United States Department of Agriculture–Economic Research Service [USDA-ERS] 2011).

Few natural enemies have been reported for *A. assectella* (Garland 2002; Jenner et al. 2010b, 2010c). Mason et al. (2010) identified five parasitoid species in Ontario, Canada, and all are generalists with a wide host range. Mason et al. (2013) subsequently released the European parasitoid *Diadromus pulchellus* (Wesmael) (Hymenoptera: Ichneumonidae), as a classical biological control agent to control *A. assectella* in Canada. While they reported that *D. pulchellus* successfully overwintered in the region, intraguild competition with the hyperparasitoid *Conura albifrons* (Walsh) (Hymenoptera: Chalcididae) hindered the establishment of *D. pulchellus* (Miall et al. 2014). At present, it is unclear whether *D. pulchellus* is an effective biological control agent for *A. assectella* in commercial *Allium* vegetable production. For this reason, it is important to identify other options that can supplement biological control agents, including the judicious use of well-timed applications of selective insecticides. Olmstead and Shelton (2012) found several insecticides suitable for control of *A. assectella* as a preventive strategy. Because *A. assectella* neonates mine into their host plants within 24 h of emergence and are physically well-protected until

pupation (Bouchet 1980), it is critical to accurately time treatments against susceptible life stages.

To accurately predict the presence of specific *A. assectella* life stages susceptible to chemical control, modeling the rate of insect development is required (Wagner et al. 1984). Degree-day (DD) models have been developed for *A. assectella* in Europe (Bouchet 1973, Åsman 2001) and Canada (Mason et al. 2010). However, DD requirements to complete the *A. assectella* life cycle varied among regions (450 DD in France, 630 DD in Sweden, and 445 DD in Canada). Different insect life-history traits, such as developmental rate, diapause intensity, body size, critical photoperiod, are frequently influenced by geographic location and latitude (Masaki 1961, 1972, 1979; Danilevsky 1965; Bradshaw and Lounibos 1977). Host species also influences developmental rate, body weight, survivorship, and reproduction of lepidopteran species (Liu et al. 2004). Previous studies of *A. assectella* evaluated leek and garlic as developmental hosts but not onions, which differ in plant architecture from other *Allium* spp. Specifically, onions leaves are hollow, and this may affect the environment to which the larvae are subjected and hence their development. Furthermore, the exterior leaf surface which the larvae encounter before entering the hollow leaf possess epicuticular wax that has been shown to be associated with significant resistance to *Thrips tabaci* Lindeman (Thysanoptera: Thripidae) (Damon et al. 2014; Diaz-Montano et al. 2010, 2012). A better understanding of *A. assectella* development in onion host plants is important because of the threat they pose to large-scale onion production in the northeastern United States. For this reason, it is important to study development of the current *A. assectella* population established in New York, and to examine its development on other host *Allium* crops.

The objectives of this study were to 1) develop a DD model for *A. assectella* development on onions in New York, comparing it to previously described models from other regions, 2) compare development of New York *A. assectella* on three different *Allium* host plants each with multiple cultivars, 3) describe seasonal population dynamics of *A. assectella* in New York onion fields, and 4) present guidelines for predicting *A. assectella* activity in the field as part of a larger integrated pest management (IPM) strategy.

Materials and Methods

Colony Establishment and Maintenance
A laboratory colony of *A. assectella* was established in 2012 from samples collected at northern NY field sites in Heuvelton (44.5313, −75.4891), Peru (44.5628, −73.4528), and Wellesley Island (44.3102, −76.0043). These sites contained the first *A. assectella* discovered in New York, and individuals from the sites were considered the founding population of *A. assectella* in New York. However, no genetic analysis of this population has been conducted. The colony was supplemented with adults from these same sites annually. The colony was reared on store-bought, USDA organic leek plants in a walk-in chamber at $27 \pm 0.5°C$, 70% relative humidity (RH), and a photoperiod of 18:6 (L:D) h.

Degree-Day Modeling
To study development on onions, groups of 30 individuals from the colony were reared from egg to adult at five different temperatures (7, 10, 15, 20, and 25°C). Cohorts of 10 males and 10 females were released together in a cage containing 8-wk-old onion plants (cultivar 'Braddock,' Bejo Seed, Geneva, NY). After adults laid eggs, plants were maintained at one of the five designated temperatures,

70% RH, and a photoperiod of 18:6 (L:D) h. Soon after the larvae hatched, each individual was transferred with a fine paintbrush to a 100-ml centrifuge tube that contained trimmed onion leaves (5–7 cm long). The tubes were maintained at the designated temperatures. Daily observations on development were made, and the time of each life-cycle event at each temperature, including hatching, pupation, and eclosion, were recorded. Onions in the tubes were replaced every 2 d. Three replicates were run at each temperature.

To compare the development of *A. assectella* on different *Allium* vegetables and their different cultivars grown in New York, groups of 10 individuals from the colony were reared on cultivars of garlic (var 'German Red' and 'Music'), elephant garlic (*Allium ampeloprasum* L.), cultivars of leek (var 'Lancelot,' 'Lincoln,' 'Striker,' and 'Surfer'), and cultivars of onions ('Braddock,' 'Crocket,' 'Delgado,' 'Exhibition,' 'Red Angel,' 'Red Wing,' and 'Safrane'), using the same protocol described above for the onion variety 'Bradock.' Each group was reared from egg to adult in a incubator (Percival model I-30BL, Percival Scientific, Inc., Perry, Iowa) at 25°C, 70% RH, and a photoperiod of 18:6 (L:D) h. The number of days required by each individual to complete development was recorded. Three replicates were run for each cultivar. Although Elephant garlic is not a true garlic but a variant of leek, it was grouped with garlic for analysis because its leaf is similar to garlic, and its cultivation is similar to garlic. Post hoc comparisons were conducted to evaluate the significance of species effect. Also, one-way ANOVA between cultivars within species was conducted to compare the effect of cultivars. For each statistical analysis, a statistical significance of $P < 0.05$ was employed.

The DD model we developed assumed a linear relationship between the rate of insect development (1/d) and the temperature above a certain base temperature (minimum developmental threshold, MDT) that is unique for the species. To determine the MDT and the temperature sum required to complete development (thermal constant, K), the linear model $y = \alpha + \beta T$ was employed, where y = the rate of development at temperature T, and α and β are constants. MDT was determined by extrapolating y = 0, i.e., the temperature at which there is no development. K was determined by calculating the reciprocal of the slope β. To determine the rate of development in the field, summation of DD exceeding MDT was compared with K (Dent 1997). Regression analyses were executed using R (R Core Team 2015). The standard errors of K and MDT were calculated using the method of Campbell et al. (1974).

Activity of *A. assectella* in Onion Fields
To document the periods of flight activity of *A. assectella* in the field, adults were monitored using pheromone traps (Scentry Delta Traps, Great Lakes IPM Inc., Vestaburg, MI) and *A. assectella* pheromone septa (AgBio, Inc., Westminster, CO). At each experimental site, three 100-foot rows were planted with a total of 3,600 onions. A trap was placed at each end of the rows. The traps were set on a post at plant canopy height, and the position was raised as the plants grew. Three times a week, the sticky inserts were recovered and replaced with new ones, and the number of moths trapped on each card was recorded. Pheromone septa were replaced every 2 wk. Traps were monitored from early April until the beginning of October. In 2013, the study was conducted at four locations in northern NY: Heuvelton (44.5313, −75.4891), Lisbon (44.7838, −75.2398), Peru (44.5628, −73.4528), and Wellesley Island (44.3102, −76.0043). In 2014, the study was conducted at three locations in northern NY: Lisbon, Peru, and Wellesley Island, and one location in northern VT near Burlington (44.4961, −73.2069).

At each site, local temperature data were recorded using a Hobo data logger (Onset Computer Cooperation, Bourne, MA).

In both years, at experimental sites in New York, larval populations on plants were monitored to confirm the progression of population development. Five plants were randomly sampled from each site twice weekly. Sampling began the day of planting and ended on the day of harvest. Sampled plants were removed and placed in airtight plastic bags, put into coolers, and transported to the laboratory. Plant samples were dissected to determine the presence of life stages, and the number of individuals in each stage was recorded.

Model Validation

Mason et al. (2010) proposed a life-cycle model to predict *A. assectella* life stages on garlic fields in Ontario, Canada. The life-cycle model assumed that oviposition began ca 1 wk after the male moths were first caught in pheromone traps and reached a maximum ca 1 wk after male flights peaked. This assumption was based on studies showing female *A. assectella* lay most of their eggs in the first 10 d of adulthood (Allison et al. 2007), within which mating happens in the first 4 d after emergence (Plaskota and Dabrowski 1986), oviposition starts 2–4 d after mating, and ca. 70% of egg laying takes place within the first 3 d after the initiation of oviposition (Auger and Thibout 1983, Plaskota and Dabrowski 1986). We employed this life-cycle model to validate how accurately the model relates the timing of accumulated population (25, 50, and 75%) of the observed male flight peaks to the flight peaks of the following generation by using the temperatures recorded in the field. DD accumulation was calculated using the average method (mean of high and low temperatures) with MDT 7°C.

Results

Degree-Day Modeling

A. assectella development times on onions from egg to adult at four different temperatures were 115.5 ± 1.0 d at 10°C, 54.3 ± 1.2 d at 15°C, 33.8 ± 0.9 d at 20°C, and 23.7 ± 0.9 d at 25°C (mean $\pm$ SE). Although eggs hatched at 7°C, no further development was observed at the temperature.

A. assectella development times on different *Allium* vegetable at 25°C were 24.0 ± 0.1 d on garlic, 23.2 ± 0.2 d on leeks, and 23.6 ± 0.1 d on onions (Fig. 1). There was a significant effect of *Allium* species on *A. assectella* development ($F = 5.11$; df = 2, 123; $P = 0.007$). Post hoc comparisons showed that mean developmental time on leeks was significantly less than on garlic. However, the mean developmental time on onions did not significantly differ from those on leeks and on garlic. The effect of cultivars was only significant among onion varieties ($F = 5.96$; df = 6, 58; $P < 0.001$). Developmental time on 'Safrane' (22.7 ± 0.8) was significantly less than those on 'Braddock' (24.1 ± 0.8, $P < 0.01$), 'Crocket' (24.4 ± 0.7, $P < 0.01$), 'Delgado' (24.6 ± 0.5, $P < 0.01$), and 'Exhibition' (24.0 ± 0.9, $P = 0.02$), but it was not significantly less than those on 'Red Angel' (23.6 ± 1.0, $P = 0.27$) and 'Red Wing' (23.3 ± 1.3, $P = 0.80$).

The laboratory developmental data described above were used to construct a DD model (Fig. 2). A linear regression of developmental rates at the four temperatures produced $y = -0.014792 + 0.002253\,T$ and $R^2 = 0.9915$. Thus, MDT was calculated as 6.6 ± 0.2°C and K as 443.9 ± 5.1°D.
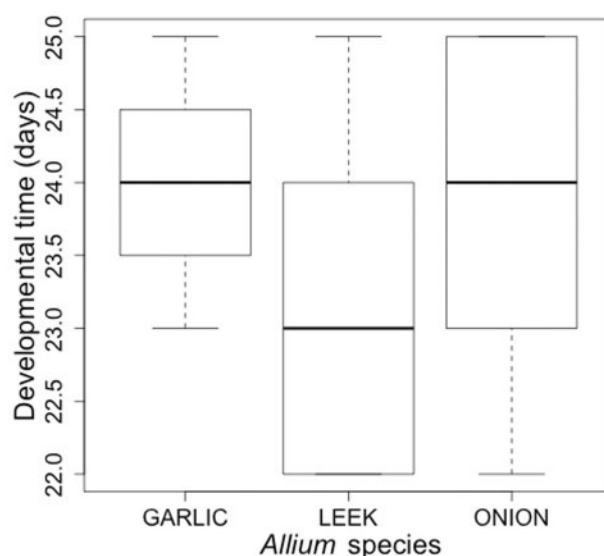

Fig. 1. Number of days required for *A. assectella* collected in New York on three different *Allium* species to complete its life cycle at 25°C under a photoperiod of 16:8 (L:D) h.
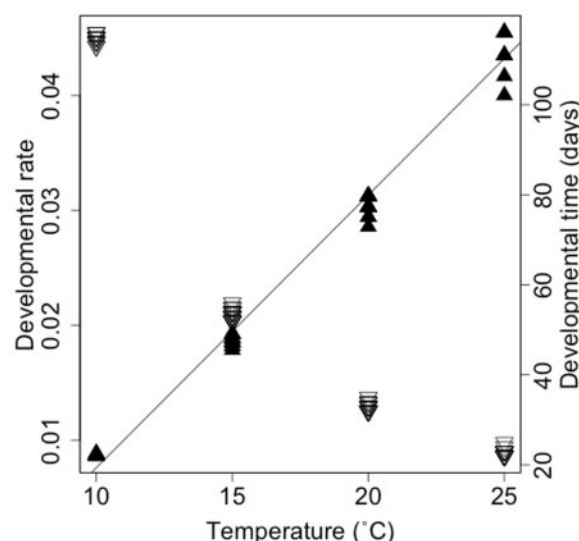

Fig. 2. DD model for development of *A. assectella* collected in New York on onion. The threshold for development was 7°C and the thermal constant K was 443.85°DD (reciprocal of slope). (▲—developmental rate, ▽—developmental time)

Activity of *A. assectella* in Onion Fields

Based on pheromone trap catch data and examination of field collected plant samples, we identified three flight periods and two cohorts of immature *A. assectella* larvae at all sites both in 2013 (Fig. 3) and 2014 (Fig. 4). The first flight resulted from the emergence of overwintering adults (OWA). First emergence of OWA were detected between mid-April and mid-May in both years. The first flight ended between mid-May and early June, lasting 4–8 wk. The second flight period, composed of first-generation adults, occurred from mid-June to mid-July for 4 wk across all sites. The third flight, composed of second-generation adults, occurred from late July to late August over 4 wk across all sites.

Abundance and duration of *A. assectella* generations varied by sites and year (Figs. 3 and 4; Table 1). The number of peaks (a data
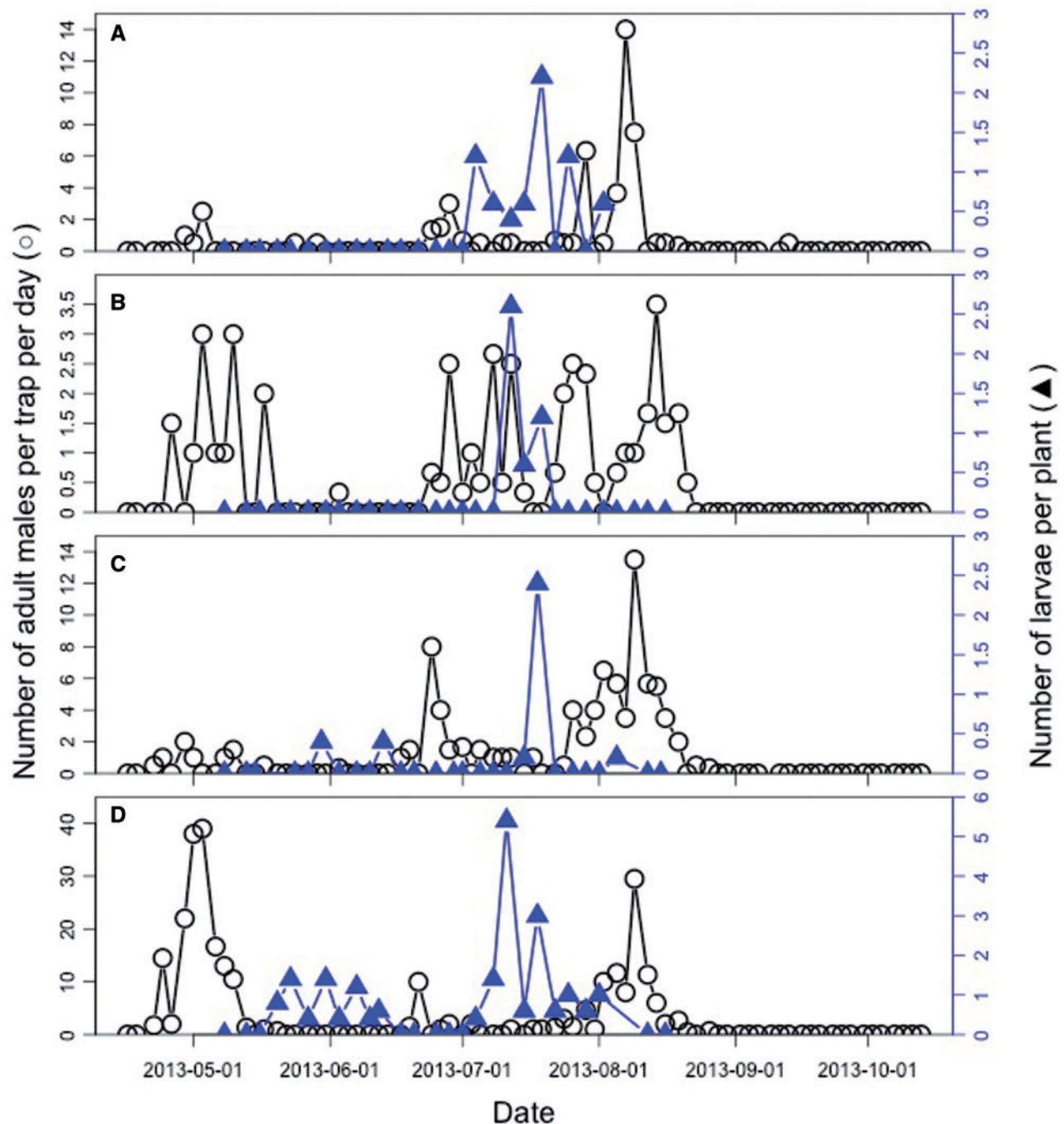
Fig. 3. Mean number of adult male *A. assectella* captured per day in pheromone traps and *A. assectella* larvae collected from plant samples at (A) Heuvelton, (B) Lisbon, (C) Peru, and (D) Wellesley Island, NY, in 2013.

point that is more than the preceding and less than the following ones) described during each flight period ranged from two to eight (Table 1). The maximum mean number of male adult moths captured on pheromone traps per day across sites was >30-fold (1.3–39.0). The timing of 50% population accumulation (Table 2) ranged from 1–5 May in 2013 and from 23 April–23 May in 2014 for the overwintered male moth flight activity, from 21–27 June in 2013 and 29–30 June in 2014 for the second flight period, and from 6–7 August in 2013 and 1–13 August in 2014 for the third flight. Days between the dates of 50% population accumulation for male adult

moth trap catch data ranged from 37 to 67 d between first and second flights (mean 52.3 ± 3.4 d), and from 32 to 47 d between second and third flights (mean 40.6 ± 1.7 d; Table 2).

Validation of the Model

We assumed that population accumulation patterns in flight activity observed in early season corresponded with those of the following generation despite the difference in the number of peaks and the variation in emergence timing of the overwintered adults. From the
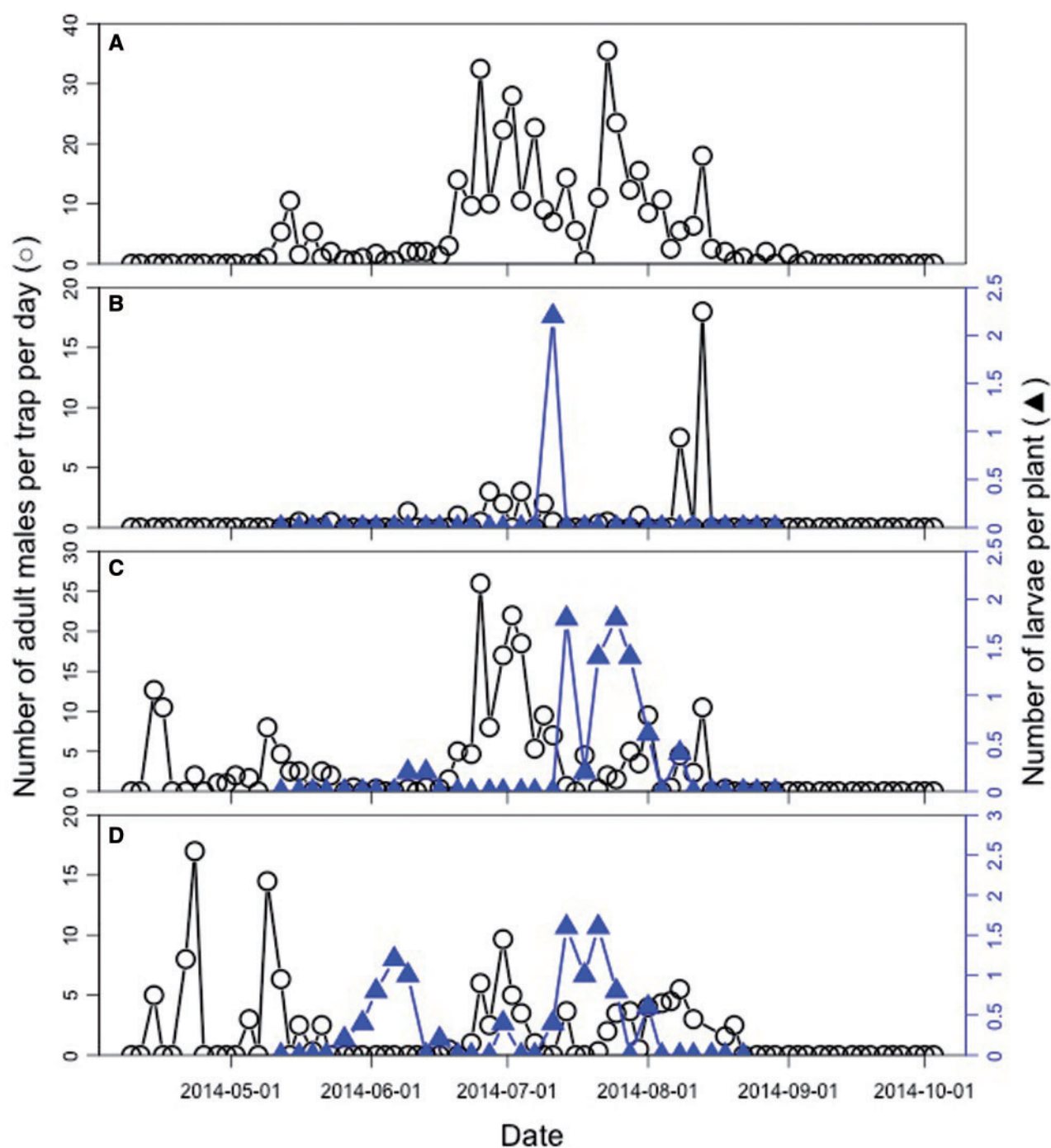
Fig. 4. Mean number of adult male *A. assectella* captured per day in pheromone traps and *A. assectella* larvae collected from plant samples at (A) Burlington, VT (no larval data), (B) Lisbon, (C) Peru, and (D) Wellesley Island, NY, in 2014.

date of 25, 50, and 75% population accumulation of males captured in the pheromone trap identified during the first flight period, predicted dates for the date of 25, 50, and 75% population accumulation within the second flight period was calculated with the life-cycle model (predicted date is [7 d + 443.9°D]) from peak date (Table 2). For example, 50% population accumulation within the first flight was 2 May 2013 in Heuvelton. The predicted date for the date of 50% population accumulation in the following generation was identified as the date that is 443.9°D from 9 May 2013 (Table 2). The average predictions for all locations in 2013 and

2014 were 3.1 ± 0.7 d different from the actual dates for the second flight, and 4.9 ± 0.9 d apart from the actual dates for the third flight.

Discussion

The DD model developed for *A. assectella* in New York yielded a good estimate of their development time and predictions of the first and second generations, based on the trap catch data of OWA.

Table 1. Start and end date of flight periods for *A. assectella* in New York and Vermont, 2013 and 2014

Year	Site	First flight				Second flight				Third flight			
		Start	End	No. of peaks	Max. trap catch	Start	End	No. of peaks	Max. trap catch	Start	End	No. of peaks	Max trap catch
2013	Heuvelton	04–29	05–29	4	2.5	06–24	07–12	3	3.0	07–22	08–19	3	14.0
	Lisbon	04–26	06–03	5	3.0	06–24	07–15	5	2.7	07–22	08–21	2	3.5
	Peru	04–22	06–03	5	2.0	06–17	07–17	5	8.0	07–24	08–26	4	13.5
	Wellesley Island	04–22	05–20	3	39.0	06–19	07–12	4	10.0	07–17	08–26	7	29.5
2014	Burlington (VT)	05–09	06–13	5	10.5	06–18	07–16	5	32.5	07–21	09–01	6	35.5
	Lisbon	05–16	06–09	3	1.3	06–20	07–11	4	3.0	07–21	08–13	4	18.0
	Peru	05–14	06–09	8	12.7	06–13	07–18	6	26.0	07–23	08–18	6	10.5
	Wellesley Island	04–14	05–21	6	17.0	06–18	07–14	4	9.7	07–21	08–20	3	5.5

Table 2. DD model prediction of accumulated abundance of *A. assectella* flight and its difference from the observed dates in the field in New York and Vermont

		2013						2014			
Site		Accumulated population	Predicted	Actual	Difference	Site		Accumulated population	Predicted	Actual	Difference
Heuvelton	First flight	25%	–	04–30	–	Burlington	First flight	25%	–	05–13	–
		50%	–	05–02	–			50%	–	05–16	–
		75%	–	05–03	–			75%	–	05–29	–
	Second flight	25%	06–25	06–25	0		Second flight	25%	06–30	06–24	6
		50%	06–27	06–27	0			50%	07–01	06–30	1
		75%	06–27	06–29	–2			75%	07–10	07–05	5
	Third flight	25%	08–02	08–02	0		Third flight	25%	08–11	08–13	–2
		50%	08–05	08–06	–1			50%	08–17	08–13	4
		75%	08–08	08–07	1			75%	08–25	08–27	–2
Lisbon	First flight	25%	–		–	Lisbon	First flight	25%	–	05–18	–
		50%	–		–			50%	–	05–23	–
		75%	–		–			75%	–	06–02	–
	Second flight	25%	06–27		1		Second flight	25%	07–01	06–26	5
		50%	07–05		8			50%	07–04	06–29	5
		75%	07–10		11			75%	07–13	07–03	10
	Third flight	25%	07–26		–10		Third flight	25%	08–08	08–05	3
		50%	08–07		0			50%	08–11	08–09	2
		75%	08–13		0			75%	08–16	08–11	5
Peru	First flight	25%	–		–	Peru	First flight	25%	–	04–14	–
		50%	–		–			50%	–	04–29	–
		75%	–		–			75%	–	05–10	–
	Second flight	25%	06–22		0		Second flight	25%	06–26	06–25	1
		50%	06–24		0			50%	06–28	06–30	–2
		75%	06–28		–2			75%	06–30	07–03	–3
	Third flight	25%	07–29		–3		Third flight	25%	08–05	07–29	7
		50%	07–31		–7			50%	08–11	08–01	10
		75%	08–07		–4			75%	08–14	08–11	3
Wellesley	First flight	25%	–		–	Wellesley	First flight	25%	–	04–21	–
		50%	–		–			50%	–	04–23	–
		75%	–		–			75%	–	05–09	–
	Second flight	25%	06–24		4		Second flight	25%	06–20	06–26	–6
		50%	06–26		5			50%	06–25	06–29	–4
		75%	06–27		0			75%	06–28	07–02	–4
	Third flight	25%	07–27		–6		Third flight	25%	08–09	07–27	13
		50%	07–28		–10			50%	08–12	08–04	8
		75%	08–04		–5			75%	08–16	08–07	9

MDT estimated in our study, which is 6.6 ± 0.2°C, is similar to 7°C that was suggested for a Canadian population (Mason et al. 2010). Our estimate of the thermal constant K as 443.9 ± 5.1°D is also close to the Canadian model, 444.6 ± 19.8°D, with a nearly identical K value. These similarities are reasonable because a Canadian *A. assectella* population is likely the origin of our New York population because the distance between New York collection sites and

known Canadian populations was only 40 km. Although the Canadian population was collected from garlic fields, and the New York population was collected from onion fields, the difference in host plants did not affect the development rate of the moth. This fact was supported by the results of the developmental study on different *Allium* spp. (Fig. 1). Both populations were collected from areas that are in USDA plant hardiness zone 4a or 4b; thus, it is

unlikely that there are significant differences in local climate conditions to alter the moth's developmental rate. Our estimate of K is slightly lower than that of the French population, 450°D (MDT 6°C; Bouchet 1973), but is significantly different from the Swedish population's 630°D (MDT 6°C; Åsman 2001). Campbell et al. (1974) hypothesized that temperature requirements of species development vary among locations. DD requirements for organisms from higher latitudes tend to have lower MDT and higher K values than those from lower latitudes (Trudgill et al. 2005). Also, latitudinal differences occasionally result in significant differences in growth rate and response to photoperiod (Sniegula et al. 2012). The New York *A. assectella* population was collected from locations that were lower in latitude (44°N) than any populations used in previously published *A. assectella* developmental studies (ca 45°N in Canada and France, and 59°N in Sweden). In addition to the differences in latitude, insects used in prior studies were collected from either leek or garlic fields. Local adaptation to the host plant and trophic specializations may influence DD requirements for an insect (Gilbert and Coaker 1988, Honek 1999). These factors might explain the low K for *A. assectella* calculated in our study but should be investigated further.

Acrolepiopsis assectella feeds on a wide variety of *Allium* vegetables (Garland 2002). *Allium* vegetables have two distinct plant architectures: folded-leaf type (leek, garlic) and hollow-leaf type (onions, shallots). We assumed these differences might affect the DD requirement considering the softer tissue of onion leaves and the enclosed microenvironments for insects may provide more buffered temperature and moisture conditions. Therefore, we conducted comparative feeding studies. *A. assectella* developed significantly faster on leeks than on garlic in our study, but the development on onions was not significantly different from leeks and garlic. From a pest management perspective, there would likely not be any practical difference between the developmental time on leeks (23.18 ± 0.18 d) and on garlic (24.00 ± 0.14 d). Thus, the model should be applicable to similar *Allium* crops. Gilbert and Coaker (1988) suggested that adaptation to host plants in the same family, but different genera, would affect insect development. There is no report of *A. assectella* feeding on plants in genera other than *Allium* (Garland 2002). Our results support hypothesis suggested by Gilber and Coaker (1988), showing that *A. assectella* developmental rate remains unchanged across plant species within this genus.

Onion fields in northern New York experienced three distinct flight periods during the periods of observation in this study. Flight patterns, abundance, and duration of each generation varied by location and year (Figs. 3 and 4; Table 1). Mason et al. (2010) reported similar patterns in Canadian garlic fields and suggested such inconsistencies were due to localized differences in temperature accumulation. We did not detect significant differences in temperature accumulation patterns across sites, yet observed diverging population patterns. Therefore, localized differences in temperature accumulation fail to explain the variation in population patterns across sites and years observed in our study. Each experimental site has a unique soil type, wind condition, vegetation surrounding fields, localized precipitation pattern, and topography. These might explain the variability among the different sites, but not within the sites across years (Wallner 1987).

Small farms in northern New York grow leek, garlic, and onion crops close together in the agricultural landscape, both spatially and temporally. Garlic, seeded in the fall, emerges in March, while leeks and onions are planted in April. Garlic is harvested in July, while onions mature in August. Leeks often grow well into the fall. For this reason, *A. assectella* may move from one host plant to the next,

from overwintering garlic to summer and fall crops, back to overwintering garlic hosts. This complicates management of *A. assectella.*

In contrast to adult populations, *A. assectella* larval populations consistently increased throughout the season across sites and years. This phenomenon was also observed in prior studies by Bouchet (1973) and Åsman (2001). Mason et al. (2010), however, reported inconsistent larval abundance across garlic fields, attributing this to variation in localized developmental conditions including landscape composition and grower management practices.

Our DD model could relate the timing of the first flight activity to that of second flight activity, and the second flight activity to the third flight activity (Table 2), despite large variation in adult flight patterns and abundance across sites and years (Table 1). As the growing season progressed, mean days between the dates of 50% population accumulation point for male adult moth trap decreased from 52.3 ± 3.4 d between the first and second flights to 40.6 ± 1.7 d between second and third flights (Table 2). This likely occurred because daily temperature accumulation increases toward the end of the onion growing season, and, as a result, it shortens the developmental time of the insect. As the life-cycle model automatically added 7 d for prediction, the actual life-cycle period in the field would range from 33.6 to 45.3. Based on the results from our study and Mason et al. (2010), we can divide the stages as: 6–10 d (eggs) + 16–25 d (larvae) + 8–12 d (pupae). Using this information, growers can target a specific life stage using judicious, well-timed insecticide or other control methods.

Olmstead and Shelton (2012) identified several insecticides that remained effective against *A. assectella* neonates up to 8 d after treatment. Based on the results of our population studies and DD modeling, we hypothesized that these chemistries can be utilized as foliar applications immediately after flight peak to prevent newly hatched larvae from infesting plants. More research is needed, however, to test such an assumption.

Our study shows the presence of multiple adult emergence peaks during each of three flight periods within a growing season. Realistically, spraying after each peak may not be feasible or advisable. For this reason, a management decision must be made to determine which peak to target. Based on our larval population data (Figs. 3 and 4), first larval emergence occurred in mid-May. Working backward, overwintering adults from which the F₁ field generations were derived showed flight peaks 45 d prior. Assuming a 10-d gestation period for eggs, an insecticide reported by Olmstead and Shelton (2012) applied soon after flight peaks in late April or early May might be ideal for targeting larvae from the first generation. Using similar logic, larvae from the generation could be targeted by spraying after the flight peaks in late June. Additional field research is needed, however, to test these assumptions.

Few studies investigating the curative treatment of *A. assectella* larvae, after infestation of host *Allium* plants, have been reported either using biological control methods or chemical insecticides. García del Pino and Morton (2008) reported that foliar application of the entomopathogenic nematode *Steinernema feltiae* to leek plants infested with *A. assectella* caused a 90% reduction of larvae on infested host plants. The efficacy of *S. feltiae* against *A. assectella* larvae in onions is unknown, however. Studies evaluating curative treatments with chemical insecticides are also lacking. In order to understand the relevance of *A. assectella* population dynamics to curative chemical control, more research is needed.

Floating row covers have been recommended to effectively intercept *A. assectella* oviposition in garlic fields (Allen et al. 2008), although field data are lacking. Although row covers might provide

season-long protection, their application is likely to be feasible only for small-scale growers. Furthermore, there is a concern among farmers that row covers would prevent proper plant growth by physically suppressing the plants and yields might decline. DD models may help time when row covers would be most effective.

Factors influencing the emergence of adult overwintering *A. assectella* into agricultural landscapes have not been identified. For management, this is a key time period. If overwintering adults are effectively targeted, season-long control becomes much easier. Future studies need to consider the effect of environmental factors including ambient and soil temperature at overwintering sites, environmental conditions of the sites, mortality of OWA, timing of initiating overwintering activity in the previous year, etc.

Accurate and precise prediction of pest occurrence is the foundation of IPM. Using pheromone traps with high frequency sampling (three times per week) was an effective way to monitor flight activity of male *A. assectella* adults and predict emergence of the next adult generation. The life-cycle model proposed by Mason et al. (2010) was effective when used with average daily ambient temperature. To properly time the application of effective management methods, it is necessary to relate the timing with insect life stage and DD accumulations. Future research should include refinement of the timing for currently available management methods, development of curative treatment methods, and identification of insecticide chemistries that are effective against *A. assectella* in curative treatments.

Acknowledgments

References Cited

Allen, J., H. Fraser, and M. Appleby. 2008. Leek moth — a pest of Allium crops. (http://www.omafra.gov.on.ca/english/crops/facts/08–009.pdf)

Allison, J., W. Jenner, N. Cappuccino, and P. G. Mason. 2007. Oviposition and feeding preference of *Acrolepiopsis assectella* Zell. (Lep., Acrolepiidae). J. Appl. Entomol. 131: 690–697.

Åsman, K. 2001. Effect of temperature on development and activity periods of the leek moth *Acrolepiopsis assectella* Zell. (Lep., Acrolepiidae). J. Appl. Entomol. 125: 361–364.

Auger, J., and E. Thibout. 1983. Spécificité des substances non volatiles des *Allium* responsables de la ponte de la teigne du poireau, *Acrolepiopsis assectella* (Lepidoptera). Entomol. Exp. Appl. 34: 71–77.

Bouchet, J. 1973. La prevision des attaques de la teigne du poireau a la station d'avertissements agricoles des pays de la loire. Phytoma Defens Des Cultures 25: 24–28.

Bouchet, J. 1980. The leek tineid. A pest of vegetable crops undergoing a renewed outbreak. Phytoma 319: 8–9.

Bradshaw, E., and P. L. Lounibos. 1977. Evolution of dormancy and its photoperiodic control in pitcher-plant mosquitoes. Evolution 31: 546–567.

Campbell, A., B. D. Frazer, N. Gilbert, A. P. Gutierres, and M. MacKauer. 1974. Temperature requirements of some aphids and their parasitoids. J. Appl. Ecol. 11: 431–438.

Damon, S. J. 2014. Quantitative trait loci controlling amounts and types of epicuticular waxes in onion. J. Am. Soc. Hortic. Sci. 139: 597–602.

Danilevsky, A. S. 1965. Photoperiodism and seasonal development of insects. Oliver and Boyd, Edinburgh, Scotland.

Dent, D. R. 1997. Quantifying insect populations: estimates and parameters, pp. 57–109. *In* D. R. Dent and M. P. Walton (eds.), Methods in ecological and agricultural entomology. CABI, Wallingford, United Kingdom.

Diaz-Montano, J., M. Fuchs, B. A. Nault, and A. M. Shelton. 2010. Evaluation of onion cultivars for resistance to onion thrips (Thysanoptera: Thripidae) and iris yellow spot virus. J. Econ. Entomol. 103: 925–937.

Diaz-Montano, J., J. Fail, M. Deutschlander, B. A. Nault, and A. M. Shelton. 2012. Characterization of resistance, evaluation of the attractiveness of plant odors, and effect of leaf color on different onion cultivars to onion thrips (Thysanoptera: Thripidae). J. Econ. Entomol. 105: 632–41.

García del Pino, F., and A. Morton. 2008. Efficacy of *Steinernema feltiae* against the leek moth *Acrolepiopsis assectella* in laboratory and field conditions. BioControl 53: 643–650.

Garland, J. 2002. Pest facts sheet—leek moth *Acrolepiopsis assectella* (Zeller, 1839). Bull. Entomol. Soc. Canada 34: 129–153.

Gilbert, N., and T. H. Coaker. 1988. Differential survival of British and Mediterranean strains of *Pieris rapae* (L.) (Lepidoptera: Pieridae) on different brassica cultivars. Bull. Entomol. Res. 78: 669–671.

Honek, A. 1999. Constraints on thermal requirements for insect development. Entomol. Sci. 2: 615–621.

Huang, C. L. 1996. Consumer preferences and attitudes towards organically grown produce. Eur. Rev. Agric. Econ. 23: 331–342.

Jenner, W. H., U. Kuhlmann, N. Cappuccino, and P. G. Mason. 2010a. Prerelease analysis of the overwintering capacity of a classical biological control agent supporting prediction of establishment. BioControl 55: 351–362.

Jenner, W. H., U. Kuhlmann, P. G. Mason, and N. Cappuccino. 2010b. Comparative life tables of leek moth, *Acrolepiopsis assectella* (Zeller) (Lepidoptera: Acrolepiidae), in its native range. Bull. Entomol. Res. 100: 87–97.

Jenner, W. H., P. G. Mason, N. Cappuccino, and U. Kuhlmann. 2010c. Native range assessment of classical biological control agents: impact of inundative releases as pre-introduction evaluation. Bull. Entomol. Res. 100: 387–94.

Landry, J.-F. 2007. Taxonomic review of the leek moth genus *Acrolepiopsis* (Lepidoptera: Acrolepiidae) in North America. Can. Entomol. 139: 319–353.

Liu, Z., D. Li, P. Gong, and K. Wu. 2004. Life table studies of the cotton bollworm, *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), on different host plants. Environ. Entomol. 33: 1570–1576.

Masaki, S. 1961. Geographic variation of diapause in insects. Bull. Fac. Agric. Hirosaki Univ. 34: 66–98.

Masaki, S. 1972. Climatic adaptation and photoperiodic response in the bandlegged ground cricket. Evolution (N. Y) 26: 587–600.

Masaki, S. 1979. Climatic adaptation and species status in the lawn ground cricket. Oecologia 43: 207–219.

Mason, P. G., M. Appleby, S. Juneja, J. Allen, and J.-F. Landry. 2010. Biology and development of *Acrolepiopsis assectella* (Lepidoptera: Acrolepiidae) in eastern Ontario. Can. Entomol. 142: 393–404.

Mason, P. G., A. M. Brauner, J. H. Miall, and A. M. R. Bennett. 2013. *Diadromus pulchellus* in North America: field release against leek moth and new characters to distinguish it from *Diadromus subtilicornis*, a native diamondback moth parasitoid. Biocontrol Sci. Technol. 23: 260–276.

Miall, J. H., P. K. Abram, N. Cappuccino, and P. G. Mason. 2014. Potential impact of the native hyperparasitoid *Conura albifrons* (Hymenoptera: Chalcididae) on the exotic biological control agent *Diadromus pulchellus* (Hymenoptera: Ichneumonidae). Biocontrol Sci. Technol. 24: 611–624.

Olmstead, D. L., and A. M. Shelton. 2012. Evaluation of insecticide chemistries against the leek moth (Lepidoptera: Acrolepiidae), a new pest in North America. Fla. Entomol. 95: 1127–1131.

Plaskota, E., and Z. T. Dabrowski. 1986. Biological principles of leek moth (*Acrolepia assectella* Zeller, Lepidoptera: Plutellidae) control. 1. Host plants, damage caused by leek larvae and leek moth parasites. Ann. Warsaw Agric. Univ. SGGW-AR. Hortic. 13: 27–34.

R Core Team. 2015. R Foundation for Statistical Computing. R: A language and environment for statistical computing.

Sniegula, S., V. Nilsson-Örtman, and F. Johansson. 2012. Growth pattern responses to photoperiod across latitudes in a northern damselfly. PLoS ONE 7: e46024.

Trudgill, D. L., A. Honek, D. Li, and N. M. Van Straalen. 2005. Thermal time – concepts and utility. Ann. Appl. Biol. 146: 1–14.

(USDA-ERS) United States Department of Agriculture–Economic Research Service. 2011. U.S. onion statistics (94013) Table 24 onions: area, yield, production & value, 1960–2010. (http://usda.mannlib.cornell.edu/usda/ers/94013/Table24.xls) Last accessed 9 December 2015.

Wagner, T., H. Wu, P. Sharpe, R. Schoolfield, and R. Coulson. 1984. Modeling insect development rates: A literature review and application of a biophysical model. Ann. Entomol. Soc. Am. 77: 208–220.

Wallner, W. 1987. Factors affecting insect population dynamics: Differences between outbreak and non-outbreak species. Annu. Rev. Entomol. 32: 317–340.