

Incidence of cabbage maggot (Diptera: Anthomyiidae) infestation and plant damage in seeded Brassica fields in California's central coast



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ARTICLE INFO

Article history:

Received 21 February 2014

Received in revised form

10 April 2014

Accepted 11 April 2014

Available online

Keywords:

Delia radicum

Brassicaceae

Root maggot

Broccoli

Salinas Valley

Reduced-risk insecticide

ABSTRACT

The temporal incidence of cabbage maggot, *Delia radicum* L. was investigated using three exclusion cage experiments, one each during spring, summer and fall, in broccoli fields as well as two surveys, one each in three broccoli fields, and sixteen turnip plantings in central coast of California. In the cage experiments, sets of broccoli plants were exposed to natural populations of *D. radicum* flies for ~14-d periods after plant emergence throughout the growing season. For the surveys, soil, root samples, and yellow sticky traps were collected every week from broccoli fields to determine number of eggs, maggots, feeding-injury and adults. Only roots were sampled from turnip plantings to determine feeding-injury. In all three cage experiments, feeding injury from *D. radicum* maggot was less during the first 14-d than ~15–28 d after plant emergence (DAE). In the summer and fall, feeding injury by *D. radicum* was less during 29–42 and 43–56 DAE than it was 15–28 DAE. In the survey of broccoli fields, a greater number of *D. radicum* eggs were detected starting the fourth week after planting (WAP). Similarly, an increase in number of *D. radicum* maggots and feeding injury was observed at fifth and sixth WAP, respectively. However, adults were abundant throughout the growing period. In the turnip survey, increase in injury from *D. radicum* feeding did not appear until the fifth WAP. Overall, these studies indicate that increased incidence of *D. radicum* was delayed by about two to three weeks after plant emergence. The implications of these results for timing of insecticide application for *D. radicum* in the central coast of California are discussed.

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1. Introduction

Cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae) is one of the most destructive pests of cruciferous crops in North America and Europe (Coaker and Finch, 1971) and has become the major persistent pest of cruciferous crops in the central coast of California. *D. radicum* causes severe yield losses to cruciferous crops in the central coast of California. The value of cruciferous crops is estimated at ~1 billion USD in California (U.S. Department of Agriculture, NASS, 2013). In the Salinas Valley of California, cruciferous crops are grown in more than 34,398 ha and are valued at >\$485.5 million USD (Monterey County Crop Report, 2012). The majority of this acreage has been affected by cabbage maggot. Important crops that are at-risk from cabbage maggot include broccoli (*Brassica oleracea* var. *italica* Plenck), cauliflower (*B. oleracea* L. var. *botrytis*), cabbage (*Brassica oleracea* L. var. *capitata*

L.), broccoli raab (*Brassica rapa* L. subspecies *rapa*), and Brussels sprouts (*Brassica oleracea* L. var. *gemmifera*). Because cruciferous crops are produced year round in the California central coast, cabbage maggot could persist in the agricultural crops. They could persist in weeds even when there are no crops under favorable conditions (Johnsen and Gutierrez, 1997).

Cabbage maggot flies lay eggs in the soil around the base of the plant. A single female can lay about 300 eggs under laboratory conditions (Finch, 1974). Legless, 8-mm long white-maggots feed on the taproot and affect normal plant development. After about 3 weeks of feeding, the maggot pupates in the surrounding soil and remains at this stage for 2–4 weeks before emerging into an adult fly (Harris and Svec, 1966). The most common above-ground feeding symptoms of cabbage maggot are yellowing, stunting and slow growth (Natwick, 2009).

In other Brassica growing regions where cabbage maggot is known to cause economic injury to roots, pupae undergo diapause during the winter, which enabled several studies to accurately determine emergence of overwintering adult flies in the spring and precise timing of subsequent generations (Baok et al., 2012; Broatch

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et al., 2006; Coaker and Wright, 1963; Collier et al., 1988; Collier and Finch, 1985; Dreves et al., 2006; Eckenrode and Keith, 1972; Finch et al., 1986; Finch and Collier, 1983, 1985; Jyoti et al., 2003; Walgenbach et al., 1993). However, unlike other regions where cabbage maggot is a serious pest, the winter weather in California's central coast is mild and rarely goes below freezing point, thereby failing to trigger diapause in most of the cabbage maggot population (Johnsen and Gutierrez, 1997). It is proposed that this unique environment enables cabbage maggot flies to remain active even in winter months, producing multiple overlapping generations throughout the year. In order to determine and implement appropriate integrated pest management (IPM) tactics for cabbage maggot, it is critical to understand the biology of the cabbage maggot on cruciferous crops in California's central coast.

Current management practices for cabbage maggot in Brassica crops mainly involved the use of soil-applied organophosphate insecticides, such as chlorpyrifos and diazinon (Natwick, 2009), which rarely provides 100% control. This persistent use of organophosphate insecticides has resulted in higher concentrations of insecticide residues in the water bodies of California's central coast (Hunt et al., 2003), which pose risks to non-target organisms and public health through contaminated water. It is likely that this widespread use potentially provided the opportunity for cabbage maggot to develop resistance to broad-spectrum insecticides. Since 2008, regulatory agencies in the state have enforced stringent restrictions to curb the use of organophosphate insecticides in commercial Brassica crop production, leaving growers with limited options to combat cabbage maggot infestation (CEPA, 2013). Because of the fewer effective IPM options, widespread crop losses to cabbage maggot have been reported from 2008 to the present.

In this post organophosphate era with reduced-risk, less persistent insecticides being available for cabbage maggot management, knowledge of field-level incidence of cabbage maggot infestation is critical to determine precise timing for insecticide applications in Brassicas. The major objective of the study is to determine the temporal incidence of cabbage maggot relative to seeded broccoli and turnip in California's central coast. Our hypothesis is that seasonal periods in the field crop cycle can be identified that represent greater susceptibility to cabbage maggot damage which will help to temporally target insecticide treatments.

2. Materials and methods

2.1. Exclusion cage experiments

A pest exclusion approach was used to assess the effects of selective exposure of broccoli (*B. oleracea* var. *italica* Plenck) plants to natural cabbage maggot populations for discrete intervals through three growing seasons in 2013. Spring and summer experiments were conducted in Chualar, CA, whereas the fall experiment was conducted in Soledad, CA. One broccoli field each was selected during spring (cultivar 'Heritage'), summer (cultivar 'Imperial') and fall (cultivar 'Imperial') which had a history of persistent cabbage maggot infestation. The broccoli beds (two seed lines per bed) used in each field were not exposed to insecticide for the entire duration of the experiment.

Skinner and Finch (1986) showed that cabbage maggot females laid fewer eggs at the base of the stem when the base was protected with carpet-underlay discs made of foam rubber. Following this principle, cylindrical sleeve cages were constructed using translucent polypropylene cups (6 cm diam. wide and 7.1 cm long) and a fabric mesh (No-see-um nylon netting, BioQuip, Rancho Dominguez, CA) sleeve (~18 cm wide and ~28 cm long). The bottoms of plastic cups were cut and removed to allow the plants to grow

through them and a transverse cut was made to each cup to facilitate placement and removal of cups (Fig. 1b and c). The fabric was glued length-wise around the cup from end to end of the transverse cut and the rest of the fabric was wrapped around the cup. The fabric roll formed on the top of the cage was tied using a twist-tie.

Within ~7-d after planting, seeds germinated and emerged out of the soil surface. At the cotyledon stage (Fig. 1a), cages were deployed over individual broccoli plants (Fig. 1b). As the plant grew in size, the rolled fabric on the top of the sleeve cage was untied and carefully re-tied to the base of the stem, leaving the growing point outside the cage (Fig. 1c) but preventing cabbage maggot fly oviposition at the base of the plant. The cages were secured by pushing the bottom edges into the soil. Treatments included plants ($n = 50$ /treatment) that were never exposed (i.e. always caged), always exposed (i.e. never caged), or exposed to natural cabbage maggot populations by selective cage removal in ~14-d intervals starting from plant emergence. All treatments were blocked along the beds. The number of beds used was 12 with 57.3 m between blocks and 8.1 m between cages for spring; 5 with 29.3 m between blocks and 4.2 m between cages for summer; and 5 with 22.3 m between blocks and 3.2 m between cages for fall experiments. Seeds were planted on 27 February, 14 May and 28 August and the plants were caged on 7 March, 23 May, and 28 August 2013 for spring, summer, and fall experiments, respectively. Exposure periods began on 25 March, and 15 and 24 April for spring; 1 May, 7 and 21 June, and 5 and 19 July for summer; and 20 September, 4 and 18 October, and 1 and 14 November for fall experiments. All the exposure periods lasted 14 days except for those deployed on 15 and 24 April, which exposed plants for 19 and 13 days, respectively. Following each treatment (exposure period), plants were re-caged and remained in the field for another 14-days until harvested; however, the set of plants in the last exposure treatment in all three experiments was harvested once the exposure period was completed along with harvest of never and always exposed treatments.

2.2. Survey of commercial broccoli

A survey was conducted in three commercial broccoli fields in the Salinas Valley (one field in Chualar [cultivar 'Durapak'] and two fields [cultivars 'Durapak', and 'Imperial'] in Gonzales CA) during May, June, and July 2013. In all sites, broccoli seeds were planted on 101.6 cm wide beds with two seed lines per bed at 12.7–15.2 cm spacing between seeds. Two fields were planted on 11 May, whereas the third field was planted on 17 May 2013. The criteria for selection of blocks included: 1) blocks >1 ha in size, 2) intensely managed crop, and 3) a history of cabbage maggot infestation. Within each field, two 'zones', each consisting of 2–3 beds selected for sampling, were designated as the border zone (adjacent to the road/canal/neighbor field) and the interior or center zone (near the center of the block). In the three fields, rows were 208.2 m, 406.9 m and 331.6 m long in the border zone whereas, 212.8 m, 273.4 m, and 301.4 m long in the center zone, and the distance between zones (border and center) were at 103.9 m, 126.8 m, and 57.9 m, respectively. All three fields received insecticide sprays at various intervals including those targeting for cabbage maggot control. The insecticides used for cabbage maggot management were applied at planting and included chlorpyrifos, a granular formulated material, and clothianidin and zeta-cypermethrin, which were applied as banded sprays over the seed lines.

Samples were collected at weekly intervals starting at plant emergence (~7-d after planting) and continuing until near commercial harvest to evaluate for cabbage maggot eggs, maggots, and flies as well as root injury. Because most of the eggs are oviposited on the soil surface and in soil around the plant base, soil within



Fig. 1. Exclusion sleeve cage (a) newly emerged plant at cotyledon stage and (b) sleeve cage deployed when plant at cotyledon stage, and (c) sleeve cage deployed when plant at advanced development stage.

~ 10 cm diameter of the plant base and 2.5 cm deep was sampled. Fifteen such soil samples were collected per zone. Eggs were extracted from the soil using a floatation method where soil was agitated in water for five minutes. Those floating eggs were collected after decanting. All soil samples were subjected to floatation method two times to ensure complete egg recovery. For maggots, 20 random roots with associated soil were collected from each zone using a scoop or shovel depending on root size and maggots were extracted from the roots using forceps. To determine cabbage maggot root injury, 100 root samples per zone were randomly collected. In addition, five 18 × 14 cm yellow sticky cards (Alphascent Inc, West Linn, OR) with the sticky surface on both sides were placed 9.1 m apart on one bed in each zone to trap adult *Delia* spp. Sticky traps were changed twice a week to reduce overcrowding of flies but the flight activity was calculated on weekly basis.

2.3. Survey of commercial turnip

This study was conducted in a commercial planting of baby turnip (*Brassica rapa* var. *rapa* L.) 'Tokyo' at Prunedale, CA where turnip seeds were planted in blocks every week in a sequential pattern. Turnip root samples (ca. 100) were collected every week until harvest from sixteen distinct plantings starting December 2012 to July 2013. Samples were transported to the laboratory in plastic bags where the roots were evaluated for cabbage maggot injury.

2.4. Statistical analyses

Categorical data of the exclusion cage experiments, number of injured roots per exposure period were analyzed using a nominal logistic regression (JMP 10Pro, SAS Institute, 2010b). When there was a significant overall treatment effect (exposure period) in each experiment, treatments were compared by examining the odds ratio between two treatments i.e., probabilities of finding an injured root were compared between two treatments by examining a chi-square value of odds ratio. For the broccoli field survey, the effects of sample date and location on cabbage maggot life stages as well as root feeding injury were analyzed as a factorial experiment

with interaction using the general linear model procedure in SAS (SAS Institute, 2010a). The three broccoli fields were treated as replicates. Cabbage maggot fly count data from five yellow sticky traps were averaged to provide a single value per zone (location effects) and sample date. Similarly, number of eggs, maggots from 15 soil samples, and maggots from 20 plant-root samples each were combined per zone. These independent variables, which included number of eggs, maggots, and adults, were log-transformed ($\ln [x + 1]$) to establish homogeneity of variance using the PROC Univariate procedure of SAS. Percentage injury data were arcsine square root transformed. Survey data on broccoli fields are presented by sample week and location. To determine location effects for each sample date, one-way ANOVA was conducted on sample date data. For survey of cabbage maggot injury on turnip roots, data were aligned by week after planting (WAP) regardless of sample date. The number of samples within each WAP served as replicates. These data were subjected to a one-way ANOVA after arcsine square root transformation as indicated above where the WAP was a treatment. Transformed data for each sample date were examined using the PROC GLM procedure of SAS and means were separated using the Tukey's HSD method ($\alpha = 0.05$).

3. Results

3.1. Exclusion cage experiments

3.1.1. Spring experiment

Incidence of cabbage maggot root injury was significantly less common on plant roots exposed during 1–14 days after plant emergence (DAE) than exposed during 15–34 DAE ($\chi^2 = 135.4$; $df = 4$; $P < 0.001$) (Fig. 2). However, incidence of feeding injury during the 35–48 DAE exposure period was significantly less than the 15–34 DAE exposure period. Injury on roots between 1–14 and 35–48 DAE was not significantly different. The plants exposed continuously showed greatest number of injured plants than any other exposure treatment (Fig. 2).

3.1.2. Summer experiment

Eggs were detected at the base of the plant starting four WAP and were collected continuously for the rest of the growing period

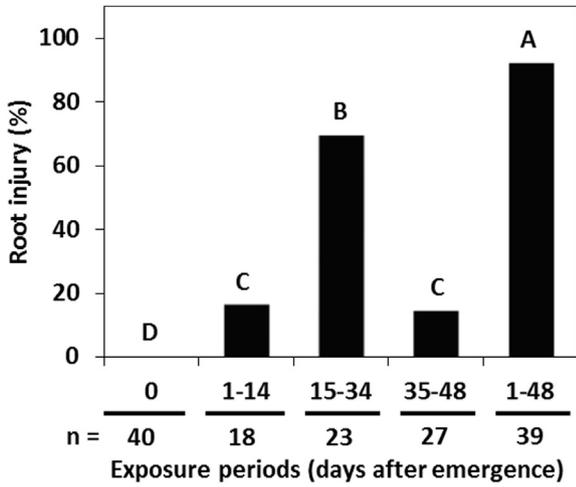


Fig. 2. Cabbage maggot feeding injury on broccoli roots when exposed to natural populations of flies for discrete periods during spring season in 2013. Symbols with similar case letters are not significantly different (comparing χ^2 of odds ratio, $\alpha = 0.05$).

(Fig. 3a). Feeding injury on the broccoli roots appeared three WAP (Fig. 3b). In the exclusion experiment, root injury from cabbage maggot feeding was significantly less during the first 14-d exposure period after plant emergence when compared with the feeding injury during the second exposure period, 15–28 DAE ($\chi^2 = 105.1$;

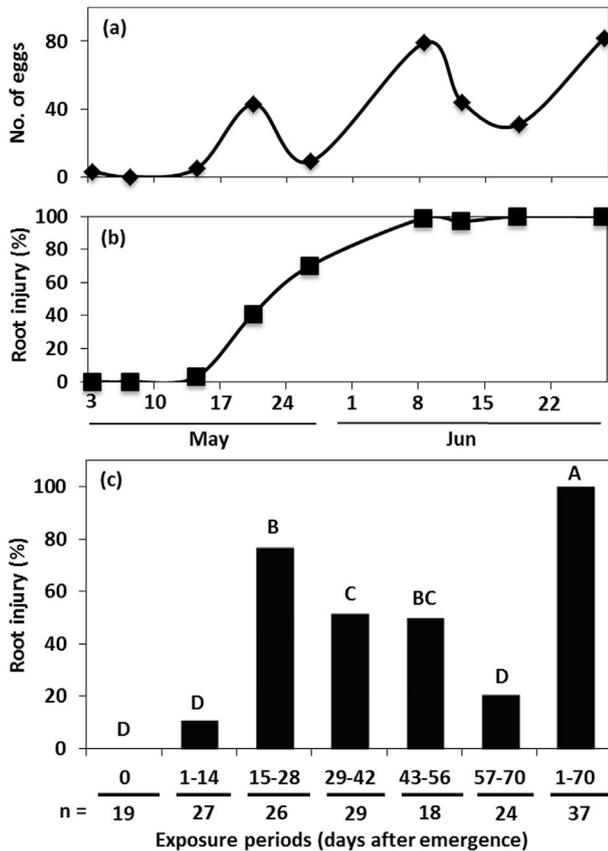


Fig. 3. Cabbage maggot (a) eggs and (b) feeding injury quantified based on weekly 30 basal-soil and 100 broccoli root samples, and (c) feeding injury on broccoli roots when exposed to natural population of flies for discrete periods during summer season in 2013. Symbols with similar case letters are not significantly different (comparing χ^2 of odds ratio, $\alpha = 0.05$).

df = 6; $P < 0.001$) (Fig. 3c). Feeding injury on roots from cabbage maggot was significantly lower during 29–42 than 15–28 DAE. There was no significant difference in incidence of injury between 29–42 and 43–56 DAE. Similarly, number of injured plants during 1–14, or 57–70 DAE was not significantly different from never exposed plants. Number of plants exposed always had greatest root injury from cabbage maggot than any other exposure treatment.

3.1.3. Fall experiment

Although eggs were not sampled for a few weeks after planting, later sampling indicated that eggs were present in the field through the fall growing period (Fig. 4a). Unlike in the summer experiment, cabbage maggot feeding injury on the roots did not increase sharply but increased steadily throughout the growing period (Fig. 4b). Similar to previous exposure experiments, root injury was greater in the second 14-d exposure period (15–28 DAE) than the first 14-d exposure period ($\chi^2 = 120.0$; df = 6; $P < 0.001$) (Fig. 4c). In the following exposure periods (29–42 and 43–56 DAE), feeding injury by maggots was lower than the second exposure period (15–28 DAE) in the roots. The plants that were never exposed to adult flies had no cabbage maggot injury in roots. However, root injury was greatest and not significantly different in the plants that were exposed continuously and during 15–28 DAE.

3.2. Survey of commercial broccoli

The number of eggs sampled from the base of the plant increased, especially in the border zone, starting the fourth WAP

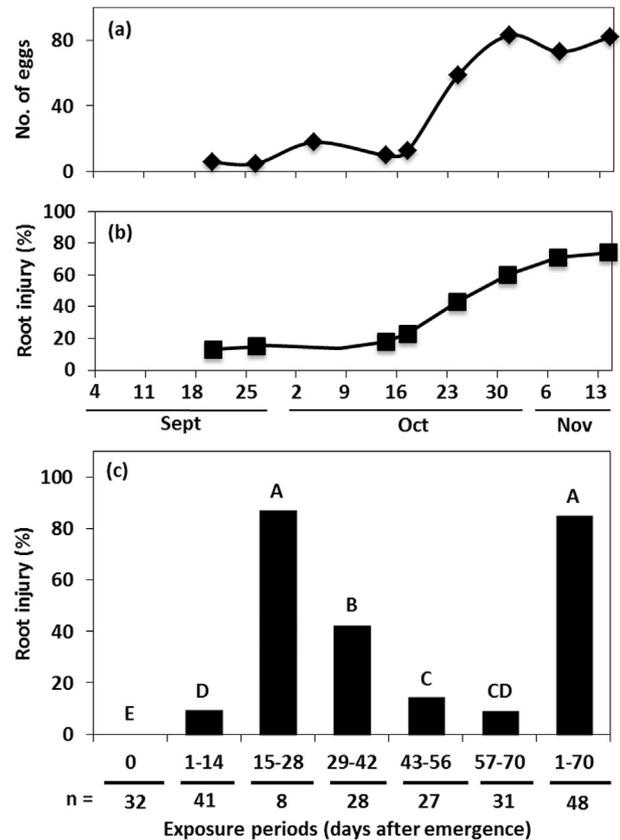


Fig. 4. Cabbage maggot (a) eggs and (b) feeding injury quantified based on weekly 30 basal-soil and 100 broccoli root samples, and (c) feeding injury on broccoli roots when exposed to natural population of flies for discrete periods during fall season in 2013. Symbols with similar case letters are not significantly different (comparing χ^2 of odds ratio, $\alpha = 0.05$).

Table 1
Analysis of variance of effects of sample date, location, and its interaction on cabbage maggot life stages and injury in 2013.

Cabbage maggot stages/injury	Sample date			Location ^a			Sample date × location interaction		
	F	df	P	F	df	P	F	df	P
Egg	9.8	9, 38	<0.001	7.7	1, 38	0.008	1.0	9, 38	0.459
Maggot	25.4	9, 38	<0.001	8.4	1, 38	0.006	0.6	9, 38	0.767
Adult	1.3	9, 38	0.255	0.7	1, 38	0.425	0.5	9, 38	0.845
Feeding injury	73.4	9, 38	<0.001	7.6	1, 38	0.009	0.8	9, 38	0.800

^a Zones within the field (border and center).

and was consistently detected through the rest of the growing period (Table 1; border: $F = 7.2$; $df = 9, 18$; $P < 0.001$; center: $F = 3.7$; $df = 9, 18$; $P = 0.009$, Fig. 5a). Overall, the number of eggs laid by cabbage maggot flies was significantly greater in the border zone than in the center zone (Table 1; border = 20.0 ± 5.8 ; center = 10.0 ± 3.4 [mean \pm SE]). However, no interaction effects correlations were observed between sample date and location on cabbage life stages or feeding injury (Table 1, $P > 0.05$).

Starting 6 WAP, the incidence of maggots, mostly second and third-instars, was both significantly and consistently greater than previous sample dates (Table 1; border: $F = 15.9$; $df = 9, 18$; $P < 0.001$; center: $F = 9.1$; $df = 9, 18$; $P < 0.001$; Fig. 5b). Conversely, significant injury on broccoli roots from cabbage maggot feeding was detected beginning the fifth WAP (Table 1; border: $F = 41.5$; $df = 9, 18$; $P < 0.001$; center: $F = 41.9$; $df = 9, 18$; $P < 0.001$; Fig. 5c). Overall, a greater number of maggots (border = 22.7 ± 5.9 ; center = 9.1 ± 2.6 [mean \pm SE]) and higher percentage of feeding injury (border = 43.9 ± 8.0 ; center = 36.3 ± 6.9 [mean \pm SE]) was found in the border than in the center zone (Table 1).

Interestingly, adult flies were captured throughout the entire growing period even during early periods of plant development (Table 1; Fig. 5d). These captures were similar between the zones. Flies were not categorized by gender or whether females were gravid or non-gravid.

3.3. Survey of commercial turnip

Turnip roots collected starting at plant emergence indicate that cabbage maggot injury was detected starting the third WAP (Fig. 6). However, significant increases in injury from cabbage maggot feeding did not appear until fifth WAP ($F = 18.9$; $df = 8, 44$; $P < 0.001$). Injury steadily increased and was $>40\%$ by the seventh WAP.

4. Discussion

Exclusion cage data suggest that severe injury from cabbage maggot did not appear during the first 14-d exposure period after plant emergence but was greater during the second exposure period (15–28 DAE). Similarly, survey in broccoli fields indicates that cabbage maggot flies did not oviposit a substantial number of eggs at the base of the plant until three weeks after plant emergence, despite presence of the adult cabbage maggot in the field during the early stages of plant development. On turnip, notable injury from cabbage maggot did not appear until five WAP. This is important information because typically insecticides targeting cabbage maggot were applied mostly at planting. Researchers (Chapman and Chapman, 1986; Getzin, 1985) showed that cabbage maggot infestation could be suppressed by using organophosphate insecticides, particularly chlorpyrifos, for more than a month after

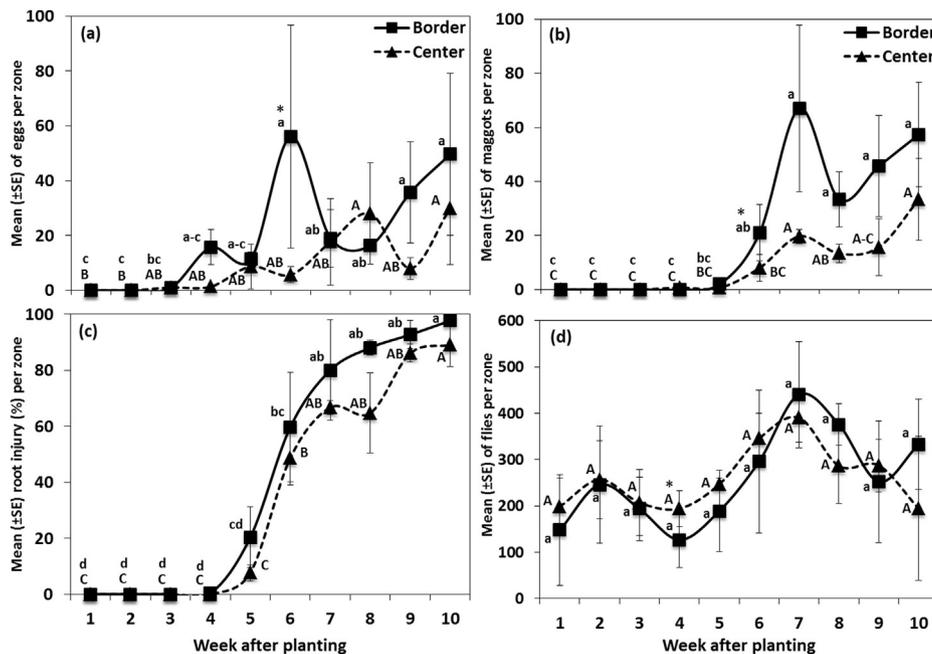


Fig. 5. Cabbage maggot (a) eggs, (b) maggots, (c) feeding root injury, and (d) flies quantified from border and central zones of commercial broccoli fields during summer in 2013. Lower case letters indicate cabbage maggot life stages/injury from border zone, whereas upper case letters indicate cabbage maggot life stages/injury from center zone. Presence of asterisk (*) suggest significant difference in number of cabbage maggot life stages between zones at a given sample date. Symbols with similar case letters (upper or lower) are not significantly different (Tukey's HSD Test, $\alpha = 0.05$).

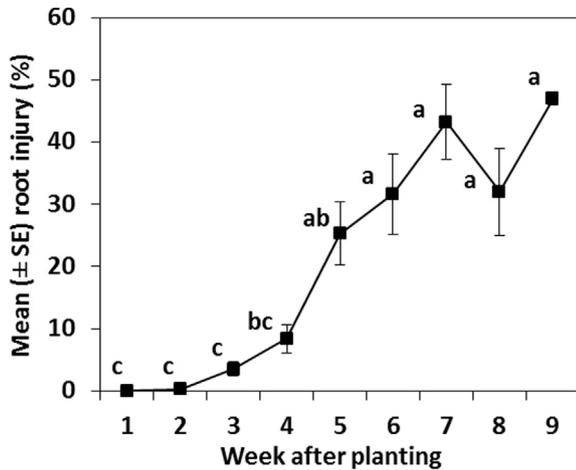


Fig. 6. Cabbage maggot feeding root injury on turnip planted in a sequential pattern from November 2012 to June 2013. Symbols with similar case letters are not significantly different (Tukey's HSD Test, $\alpha = 0.05$).

planting because product residues persisted for an extended period. In the Salinas Valley, consistent cabbage maggot control using organophosphate insecticides was never attained. With stringent restrictions in place on the use of organophosphate insecticides, applications of reduced-risk insecticides such as clothianidin, spinetoram, or chlorantraniliprole are being implemented mostly applied as banded sprays at planting. It is unclear whether application of reduced-risk insecticides at planting would provide adequate cabbage maggot control to seeded broccoli because most of the new generation insecticides are less persistent in their activity. Moreover, they are either partially soluble in water or practically immobile in the soil profile as they strongly bind to soil organic matter once in contact. Additionally, data suggest that greater levels of cabbage maggot infestation on broccoli was only observed a month after planting.

It is unclear why increased cabbage maggot oviposition did not occur during the early stages of plant development. It is possible that the invading cabbage maggot flies cannot distinguish the young seedlings at a certain size relative to the surrounding area of bare soil. Cabbage maggot flies use both volatile and visual cues to locate cruciferous hosts (Hawkes et al., 1978; Prokopy et al., 1983). Researchers suggested that volatiles released from these small plants, primarily isothiocyanates (Finch and Skinner, 1982), might not provide enough directional information for flies to precisely land on host plants (Finch and Collier, 2000). Perhaps, plants at early growth stages might be releasing weak volatile signals thus making them less attractive to flies. A second possible reason for the lack of oviposition could be related to the smaller surface area, surface characteristics (leaf color or texture), and orientation of the leaves of young (<3 leaves) plants. These factors are known to affect host finding (Prokopy et al., 1983; Roessingh and Städler, 1990). Third, chemical signals on the leaf surface, primarily glucosinolates, stimulate gravid cabbage flies to lay eggs (Städler, 1978). It is possible that younger leaves are not producing levels of glucosinolates sufficient to stimulate gravid females to lay eggs when they come in contact with leaves at the plant base. Fourth, leaf color of young plants is less attractive to cabbage maggot flies than the leaf color of intermediate or mature plants, causing adult flies to miss the young seedlings (Prokopy et al., 1983; Roessingh and Städler, 1990). Finally, in the Salinas Valley, Brassica plants are heavily irrigated to ensure uniform plant establishment and subsequent vigorous growth early in the crop cycle. Such irrigations could possibly deter flies from egg laying. As plants develop and grow

larger, intervals between irrigations become longer, resulting in longer periods in which foliage is dry. Because ovipositing female flies prefer dry surfaces within a humid, moist microclimate, it is more likely that the older, larger plants become more heavily infested (Kostal et al., 2000).

A partial or complete synchronized emergence of cabbage maggot flies from overwintering pupae has been widely reported from various regions of the United States where cabbage maggot is a persistent pest (Dreves et al., 2006; Jyoti et al., 2003; Walgenbach et al., 1993); this phenomenon helped researchers develop degree-day models to determine the precise emergence of adults. However, in California's central coast, continuous overlapping generations have been observed due to no or limited diapause (Johnsen and Gutierrez, 1997). Results from this current study provide essential information on cabbage maggot phenology relative to the development of seeded broccoli, regardless of planting time or season. The data also indicate that the use of reduced-risk insecticides should be timed early to maximize their activity against the most vulnerable life stages of cabbage maggot.

Cabbage maggot populations and crop injury from this pest tend to be more abundant in the border than the interior zone of the field; this invasion pattern continues throughout the growing period. Previous research showed that cabbage maggot female flies exhibit a diurnal cyclical pattern of behavior in feeding; oviposition flights to and from the field with more flies coming into the field during afternoon hours from hedges and leaving the field before dark to the hedges (Hawkes, 1972). The gravid females occur more uniformly through the field than non-gravid females or males as they tend to be more abundant in the border areas. In the central coast of California, weeds in close proximity to field are uncommon as they are rigorously managed and hedges are not maintained as a cultural practice. However, it is not known if a pattern of cyclic movement of gravid females made border plants more vulnerable to infestation than the plants in the interior zones of the field. More research is needed for monitoring cabbage maggot infestation in the field to determine if sampling the border zone would effectively quantify overall cabbage maggot infestation.

Invasion by cabbage maggot is continuous throughout the growing period. Cruciferous weed species surrounding the cultivated field could harbor cabbage maggot populations (Finch and Ackley, 1977). However, the cruciferous weed complex in California's central coast differs from the regions in England where Finch and Ackley (1977) conducted their study. In California's central coast, weed plants are sometimes found in ditches or water channels. If found, the common cruciferous weeds in the central coast are shortpod mustard [*Hirschfeldia incana* (L.) Lagr.-Foss.], broadleaved pepperweed (*Lepidium latifolium* L.), wild radish (*Raphanus sativus* L.), black mustard (*Brassica nigra* L.), field mustard (*B. rapa* L.) and shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.] (R. Smith, personal communication). All these species could serve as reservoirs for the cabbage maggot and allow them to persist year long. Besides cole crops, other Brassica crops including bok choy, napa cabbage, rappini, mizuna mustard, turnip and arugula; many of these are also grown all year in the Salinas Valley. Gravid female flies of cabbage maggot could disperse about 1000 m per day in search of host plants (Finch and Skinner, 1975). It seems that overlapping generations of gravid flies are developing outside the field on Brassica hosts if present and then continuously invade the field from surrounding areas.

In conclusion, our data suggest that the important seasonal periods in the central coast vegetable production area to consider targeting cabbage maggot control are three to four weeks after planting the seeds. Research will continue focusing on identifying effective insecticides against cabbage maggot as well as modes of insecticide placement during critical periods of cabbage maggot

infestation in seeded Brassicas. At this point, economic or action thresholds for cabbage maggots have not been developed in the central coast area. Future research will investigate regional distribution of cabbage maggot in order to develop thresholds for cabbage maggot management and will examine the feasibility of cultural, biological and host-plant mediated strategies for cabbage maggot management.

Acknowledgments

I appreciate the technical assistance provided by J. Zarate, L. Reyes, C. Bettiga, and S. Cosseboom in sample collection, R. Smith, S. Koike, S. Muralidhara, L. Godfrey and three anonymous reviewers for comments on this manuscript, and UC IPM for providing funding for this project.

References

- Baok, R., Cerani-Serti, M., Bari, J.I., Kozina, A., Kos, T., Lemi, D., Aija, M., 2012. Seasonal flight, optimal timing and efficacy of selected insecticides for cabbage maggot (*Delia radicum* L., Diptera: Anthomyiidae) control. *Insects* 3, 1001–1027. <http://dx.doi.org/10.3390/insects3041001>.
- Broatch, J.S., Dossdall, L.M., Clayton, G.W., Harker, K.N., Yang, R., 2006. Using degree-day and logistic models to predict emergence patterns and seasonal flights of the cabbage maggot and seed corn maggot (Diptera: Anthomyiidae) in canola. *Environ. Entomol.* 35, 1166–1177.
- California Environmental Protection Agency (CEPA), Central Coast Water Board. 2013. Agricultural Order adopted. http://www.waterboards.ca.gov/rwqcb3/water_issues/programs/ag_waivers/ag_order.shtml.
- Chapman, R.A., Chapnan, P.C., 1986. Persistence of granular and EC formulations of chlorpyrifos in a mineral and an organic soil incubated in open and closed containers. *J. Environ. Sci. Health B: Pest. Food Contam. Agric. Wastes* 21, 447–456.
- Coaker, T.H., Finch, S., 1971. The cabbage root fly, *Erioischia brassicae* (Bouché). *Rep. Natl. Veg. Res. Stn.* 1970, 23–42.
- Coaker, T.H., Wright, D.W., 1963. The influence of temperature on the emergence of the cabbage root fly (*Erioischia brassicae* (Bouché)) from overwintering pupae. *Ann. Appl. Biol.* 52, 337–343.
- Collier, R.H., Hommes, M., Finch, S., Birch, A.N.E., Brunnel, E., Freuler, J., Den Ouden, H., 1988. Induction of diapause in populations of cabbage root fly pupae; relationship between site latitude and critical day length. *WPRS/OILB Bull.* XI (1).
- Collier, R.H., Finch, S., 1985. Accumulated temperatures for predicting the time of emergence in the spring of the cabbage root fly, *Delia radicum* (L.) (Diptera: Anthomyiidae). *Bull. Entomol. Res.* 75, 395–404.
- Dreves, A.J., Dalthorp, D., Stone, A.G., Fisher, G., 2006. Spring emergence and seasonal flight of *Delia radicum* L. (Diptera: Anthomyiidae) in western Oregon. *Environ. Entomol.* 35, 465–477.
- Eckenrode, C.J., Keith, C.R., 1972. Seasonal adult cabbage maggot populations in the field in relation to thermal-unit accumulations. *Ann. Entomol. Soc. Am.* 65, 151–156.
- Finch, S., 1974. Feeding and associated behaviour of the adult cabbage root fly *Erioischia brassicae* (Beh.) (Dipt., Anthomyiidae) under laboratory conditions. *Bull. Entomol. Res.* 63, 661–671.
- Finch, S., Skinner, G., 1975. Dispersal of the cabbage root fly. *Ann. Appl. Biol.* 81, 1–19.
- Finch, S., Ackley, C.M., 1977. Cultivated and wild host plants supporting populations of the cabbage root fly. *Ann. Appl. Biol.* 85, 13–22.
- Finch, S., Skinner, G., 1982. Trapping cabbage root fly in traps baited with plant extracts and with natural and synthetic isothiocyanates. *Entomol. Exp. Appl.* 31, 133–139.
- Finch, S., Collier, R.H., 1983. Emergence of flies from overwintering populations of cabbage root fly pupae. *Ecol. Entomol.* 8, 29–36.
- Finch, S., Collier, R.H., Skinner, G., 1986. Local population differences in emergence of cabbage root flies from south-west Lancashire: implications for pest forecasting and population divergence. *Ecol. Entomol.* 11, 139–145.
- Finch, S., Collier, R.H., 1985. Forecasting the times of attack of the cabbage root fly (*Delia radicum*) on vegetable Brassica crops. *Asp. Appl. Biol.* 12, 37–46.
- Finch, S., Collier, R.H., 2000. Host-plant selection by insects – a theory based on appropriate/inappropriate landings by pest insects of cruciferous plants. *Entomol. Exp. Appl.* 96, 91–102.
- Getzin, L.W., 1985. Factors influencing the persistence and effectiveness of chlorpyrifos in soil. *J. Econ. Entomol.* 78, 412–418.
- Harris, C.R., Svec, H.J., 1966. Mass rearing of the cabbage maggot under controlled environmental conditions, with observations on the biology of cyclodiene-susceptible and resistant strains. *J. Econ. Entomol.* 59, 569–573.
- Hawkes, C., 1972. The diurnal periodicity and cycle of behaviour of the adult cabbage root fly (*Erioischia brassicae*). *Ann. Appl. Biol.* 70, 109–118.
- Hawkes, C., Patton, S., Coaker, T.H., 1978. Mechanism of host plant finding in adult cabbage root fly, *Delia brassicae*. *Entomol. Exp. Appl.* 24, 419–427.
- Hunt, J.W., Anderson, B.S., Phillips, B.M., Nicely, P.N., Tjeerdema, R.S., Puckett, H.M., Stephenson, M., Worcester, K., de Vlaming, V., 2003. Ambient toxicity due to chlorpyrifos and diazinon in a central California coastal watershed. *Environ. Monit. Assess.* 82, 83–112.
- Johnsen, S., Gutierrez, A.P., 1997. Induction and termination of winter diapause in a Californian strain of the cabbage maggot (Diptera: Anthomyiidae). *Environ. Entomol.* 26, 84–90.
- Jyoti, J.L., Shelton, A.M., Bernard, J., 2003. Evaluation of degree-day and Julian-day logistic models in predicting cabbage maggot (Diptera: Anthomyiidae) emergence and flight in upstate New York. *J. Entomol. Sci.* 38, 525–532.
- Kostal, V., Baur, R., Stadler, E., 2000. Exploration and assessment of the oviposition substrate by the cabbage maggot, *Delia radicum* (Diptera: Anthomyiidae). *Eur. J. Entomol.* 97, 33–40.
- Monterey County Crop Report, 2012. Office of Agricultural commissioner-Monterey County, California. http://ag.co.monterey.ca.us/assets/resources/assets/334/CropReport_2012.pdf?1371573041.
- Natwick, E.T., 2009. Cabbage Maggot. UC IPM Pest Management Guidelines: Cole Crops UC ANR Publication 3442. <http://www.ipm.ucdavis.edu/PMG/r108300111.html>.
- Prokopy, R.J., Collier, R.H., Finch, S., 1983. Leaf color used by cabbage root flies to distinguish among host plants. *Science* 221, 190–192.
- Roessingh, P., Städler, E., 1990. Foliar form, colour and surface characteristics influence oviposition behaviour in the cabbage root fly *Delia radicum*. *Entomol. Exp. Appl.* 57, 93–100.
- SAS Institute, 2010a. SAS Version 9.3. SAS Institute Inc., Cary, NC.
- SAS Institute, 2010b. JMPPro10. SAS Institute Inc., Cary, NC.
- Skinner, G., Finch, S., 1986. Reduction of cabbage root fly (*Delia radicum*) damage by protective discs. *Ann. Appl. Biol.* 108, 1–10.
- Städler, E., 1978. Chemoreception of host plant chemicals by ovipositing females of *Delia brassicae*. *Entomol. Exp. Appl.* 24, 511–520.
- U.S. Department of Agriculture, NASS, 2013. 2012 California Agricultural Statistics, Vegetable Summary. United States Department of Agriculture, National Agricultural Statistics Service, Pacific Region-California, Sacramento, CA. http://www.nass.usda.gov/Statistics_by_State/California/Publications/California_Ag_Statistics/Reports/2012cas-all.pdf.
- Walgenbach, J.F., Eckenrode, C.J., Straub, R.W., 1993. Emergence patterns of *Delia radicum* (Diptera: Anthomyiidae) populations from North Carolina and New York. *Environ. Entomol.* 22, 559–566.