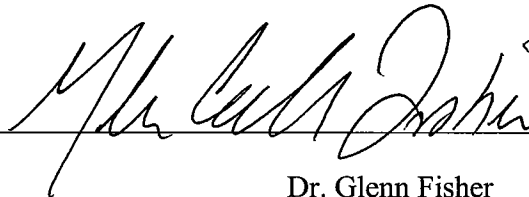


AN ABSTRACT OF THE DISSERTATION OF

Amy J. Dreves for the degree of Doctor of Philosophy in Crop Science presented on
May 26, 2006.

Title: Phenology and Monitoring of the Cabbage Maggot, *Delia radicum* (L.), in Brassica
Root Crops

Abstract approved:



Dr. Glenn Fisher

In Oregon's northern Willamette Valley, cabbage maggot (CM), *Delia radicum* (L.) (Diptera: Anthomyiidae) often renders Brassica root crops unmarketable. Scheduled insecticides are the only current control. Studies were conducted to: 1) describe and characterize spring emergence of CM flies and their seasonal flight activity relative to degree-day (DD) accumulations; 2) measure impact of CM by assessing crop damage; 3) define influence of seasonal planting and harvest dates relative to root damage; 4) identify the occurrence of ovipositional activity in relation to time of season, age of crop, distribution in field; and 5) study relationships among flight activity, oviposition, and crop damage.

Commercial rutabaga and turnip fields were studied from 2001 through 2005. Spring emergence from overwintering puparia was monitored using emergence cages. A bimodal spring emergence pattern for CM was observed: approximately 70% of the overwintering population peaked in late March. A second smaller peak was observed at the end of May.

The mean DD accumulations at 10, 50, and 95% of spring emergence using a lower and upper developmental threshold of 4.3°C and 30°C beginning January 1 had corresponding DD values of 200 ± 50.2 (8 March), 330 ± 22.2 (4 April) and 762 ± 60.1 (28 May), respectively. Spring flight patterns, monitored with yellow water traps, mirrored the bimodal emergence pattern but with an apparent lag.

Rutabaga crops sustained 1.7x higher damage levels than did turnip crops. Damage caused by CM was significantly greater (37-52%) in spring crops planted prior to an accumulated 900 DD, than in summer crops planted after 900 degree-days or in fields planted in the fall after 1500 DD. Maggot damage is abated by planting after the spring flight (> 900 DD) and harvesting before the relative peak of fall flight (< 2600 DD).

Fields documented with less than an average of 100 flies collected in a water trap over a crop's duration in the field, had the lowest sum of percent weekly egg assessments (38.6 ± 6.1 ; based on 7 weekly egg level assessments), and the least amount of root infestation by CM ($< 20\%$ per 60 root samples). Fields with greater than 100 flies per trap over crop duration in the field had the greatest sum frequency of plants with eggs (95.6 ± 6.7), and the most CM root infestation ($> 20\%$).

Oviposition significantly increased in fields at $30.9 (\pm 1.1)$ days after seeding. Large plants with > 5 leaves, root diameter of > 6 mm, and increased crop canopy were more heavily infested with CM eggs than smaller plants. A strong relationship was seen between the frequency of older plants with eggs (> 9 leaves, > 19 mm root size and partially-closed

canopy) and crop damage at harvest ($r^2 = 0.83$). Egg incidence was significantly higher (46%) on plants located on the outside periphery of fields than on plants located in the field centers.

Spring monitoring of emergence and flight arrival, and density of *D. radicum* allows useful predictions of oviposition and crop damage. Appropriate oviposition assessment, combined with timely planting and harvesting schedules, and use of egg thresholds to time treatments could greatly reduce maggot populations.

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May 26, 2006

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Phenology and Monitoring of the Cabbage Maggot, *Delia radicum* (L.),
in Brassica Root Crops

by
Amy J. Dreves

A DISSERTATION

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the requirements for the
degree of

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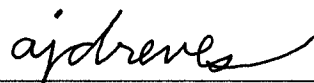
APPROVED:

Major Professor, representing Crop Science

Head of the Department of Crop and Soil Science

Dean of the Graduate School

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Amy J. Dreves, Author

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LIST OF ACRONYMS

CM	Cabbage Maggot
DD	Degree-Day
PGS	Plant Growth Stage
NWREC	Northwest Research Extension Center
EST	Egg Scrape Technique

1 GENERAL INTRODUCTION

A. J. DREVES

Department of Crop and Soil Science

Oregon State University

1.1 Distribution, Crop Hosts and Taxonomy

Cabbage maggot (CM), *Delia radicum* (L.) (Diptera: Anthomyiidae), is a world-wide pest of commercial Brassicas grown in the northern latitudes of the Holarctic region from approximately 35 to 60°N (Fig. 1.1). This exotic, multi-generation pest of European origin was first reported in north-eastern North America in the early 1800's and has since become established in crop producing regions from coast to coast (Biron et al. 2000). Its crop host range includes: rutabagas, turnips, canola, broccoli, cauliflower, Brussel sprouts, kale, collards, and cabbage. It is a key pest of rutabaga and turnip production in the Willamette Valley of western Oregon. Cruciferous weeds, including yellow rocket, wild radish, wild mustard, and black mustard are also larval host plants that are likely involved in maintaining populations of *Delia* spp. (Finch and Ackley 1977, Todd 1998).

This pest was first collected with notes on its description by Linneaus in 1758. He described the species as *Musca radicum* (Griffiths 1996). Unfortunately, Weidemann (1817) overlooked this reference when he described the species as *brassicae* and placed it in the genus, *Hylemya*. The last definitive revision of the *Hylemya* was by Robineau-Desvoidy in 1830. He constructed the genus *Delia* in which he placed *brassicae* and many of its congeners. Today the species is appropriately referred to as *Delia radicum* (L.) in recognition of Linneaus' initial description. World literature has referenced this species in many different genera: *Hylemya* and *Phorbi* in the United States and Canada, *Chortophila* in France, Germany, and Russia; and *Delia* and *Erioeschia* in Belgium and England.

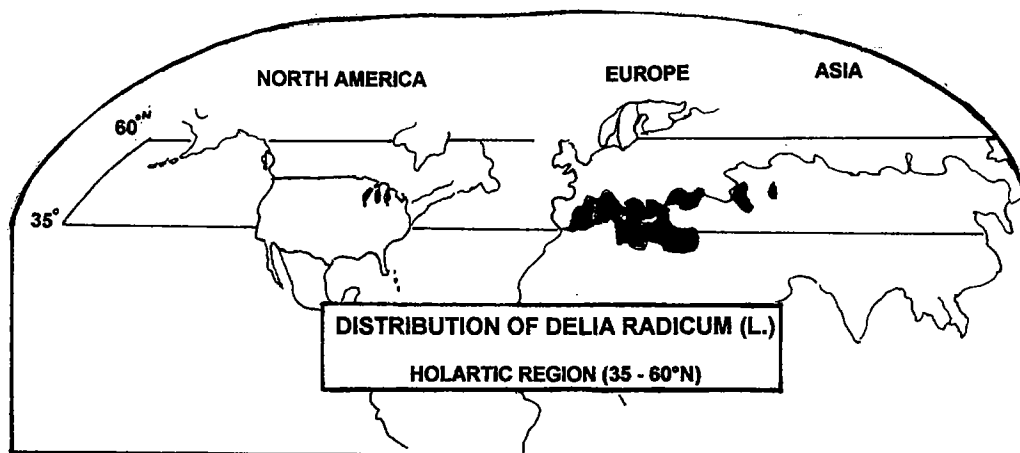


Fig. 1.1. Distribution of *Delia radicum* (L.) in the Holartic region.

1.2 Pest Status

In western Oregon, Brassica crops are grown commercially on more than 8,000 hectares for fresh market, processing, and seed production, and are valued in excess of \$20 million annually (2005). Approximately 809 hectares are planted in fresh market root Brassicas, including turnips, rutabagas, radishes, and daikon. There are over 100 Brassica growers in Oregon trying to manage *D. radicum*. The larva is the damaging stage and injury from a single maggot can render edible root produce unmarketable. Maggot injury provides entryways for pathogens causing black leg (*Phoma lingam*), bacterial soft rot (*Erwinia carotovora*), and root rot (*Fusarium* spp.) (Griffiths 1986, McDonald and Sears 1992). Long-term root crops are vulnerable to root damage from two generations of CM. Direct-seeded and transplanted above-ground Brassica crops such as cabbage, cauliflower, and broccoli are also vulnerable to CM injury, especially during early growth stages, and infestation can result in partial to complete losses and/or yield reductions (Read 1970, Getzin 1978, Bligaard 1999). There is a constant threat of damage from spring, summer and

fall CM populations. Insecticide treatments used by growers are generally preventative and routinely applied. Growers currently use no monitoring system for detecting presence of CM.

Scheduled application of an organophosphate insecticide, chlorpyrifos (*e.g.*, Lorsban®), is the most widely used treatment for control of *Delia radicum* (McGrath et al. 2006). Despite control efforts, crops are still damaged, resulting in significant economic losses (Getzin 1985, Bracken 1988, McDonald and Sears 1992, Stark 1993, Walgenbach et al. 1993, Dreves et al. 2006). Insecticide resistance as well as poor application methods and poor timing are often identified as reasons for inadequate CM control (Doane and Chapman 1962, Getzin 1985, Stark 1993). These problems, as well as environmental concerns, reduced-use programs, and governmental restrictions and cancellations of insecticides, have created the need to better understand the phenology of CM, and relationships between flight, oviposition, and crop damage.

The Brassica industry, including fresh market and processed vegetable, will benefit tremendously from the valuable inputs from the wide range of research and development tools provided by the following research. While the following work was conducted on root crops, these findings will be directly applicable to above-ground Brassica crops around the world. In addition, the findings may also be applicable to closely related fly species with similar phenologies such as seed corn maggot (*Delia platura*), onion maggot (*Delia antiqua*), and the carrot rust fly (*Psila rosae*).

1.3 Pest Biology

In early spring after emergence from puparia and prior to mating, flies seek nectar and pollen from the bloom of many different plants (Harris and Svec 1966, Finch and Coaker 1969). Mating occurs within 4-5 days of emergence (Swales 1961). The average time between CM activity peaks at temperatures of 19-22°C ranges from 41-65 days, depending on weather and soil conditions (Harris and Svec 1966, Bracken 1988).

Females search for Brassica crops by keying into leaf color and area (Prokopy et al. 1983) as well as volatile isothiocyanates and other glucosinolates produced by Brassicaceae plants (Traynier 1967, Coaker and Smith 1968, Nair and McEwen 1975, Stadler 1978). Females lay white 1mm long, oblong eggs, on soil near the crown of a host plant down to 2.5 cm below the soil surface and sometimes up the stem (Fig. 1.2).

Oviposition typically occurs during afternoon hours (Hawkes 1972), approx. 6 days after adult emergence (Harris and Svec 1966). Eggs hatch within 3 to 7 days. The neonate larvae begin feeding on lateral and main roots. After feeding for 2-3 weeks, larvae pupate in the soil around the plant root and emerge as dark grey flies 1-2 weeks later. Harris and Svec (1966) and Finch and Collier (1985) believed that fly emergence is sometimes suppressed during warm summer months because of pupal aestivation. In the later fall when periods of low temperatures occur and the photoperiod shortens, puparia diapause (McLeod 1964, Read 1965, Johnsen and Gutierrez 1997).

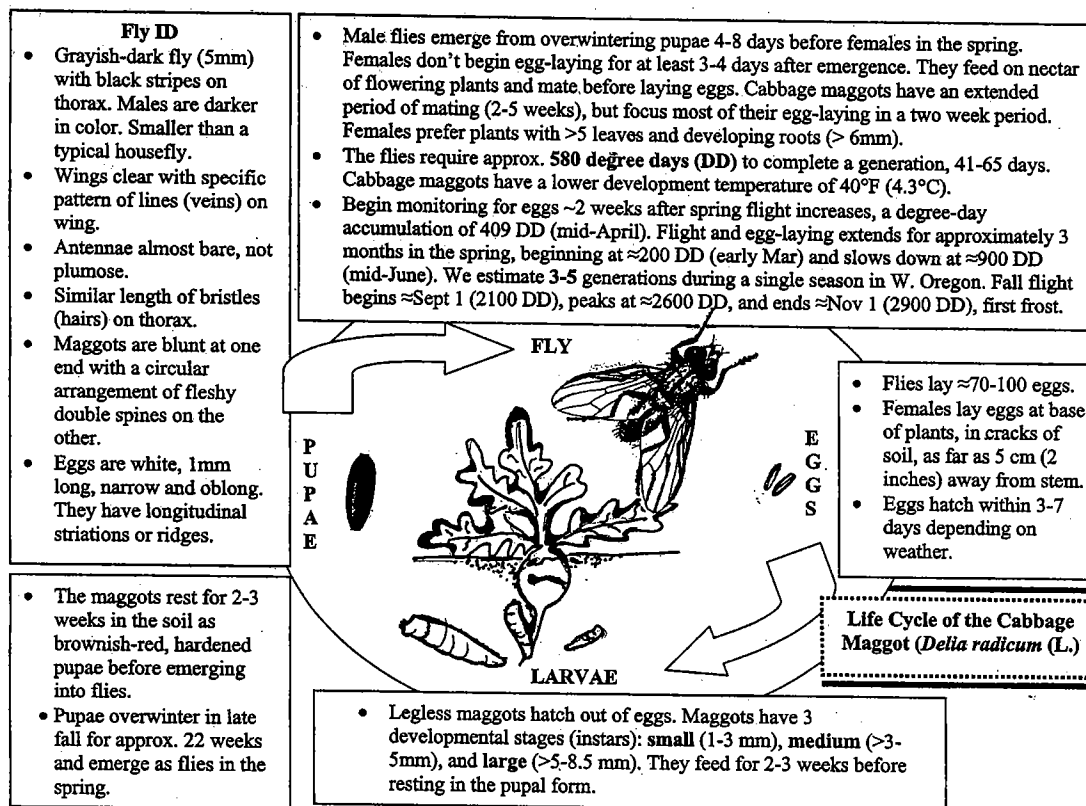


Fig. 1.2. Life cycle of the cabbage maggot (*Delia radicum* (L.))

Generation time and number of generations have not been studied for Oregon fly populations specifically. Todd (1998) has suggested that 3 to 4 CM generations were most likely characteristic of the Pacific Northwest. However, Forbes (1955) and Getzin (1978) report only three generations of CM in the Pacific Northwest. Other researchers describe up to 5 generations per year in Washington State (Carlson 1947). Three to four generations per year are reported for southwestern Ontario and southern British Columbia (Mukerji and Harcourt 1970, Nair and McEwen 1975).

1.4 Cabbage Maggot Monitoring

Growers of Oregon's Brassica root crops do not currently monitor fly activity to determine the need or timing for CM control measures in commercial fields. Seasonal field phenology of CM has not been well documented in the Pacific Northwest. Detecting and/or forecasting spring emergence of adults and seasonal flight can provide useful information to help forecast these activities and lead to timely application of controls against this pest. In addition, monitoring can lead to the identification of relationships between flight, egg levels, and subsequent crop damage and can help establish baselines for management decisions about control of CM. Economic thresholds have been identified for above-ground Brassicas (cauliflower, cabbage, and broccoli) (Anonymous 1985, Bligaard 2001), but little has been done to establish thresholds for below-ground Brassica crops (turnips and rutabagas).

1.4.1 Spring Emergence

Degree-day models have been developed worldwide for predicting spring emergence (Coaker and Wright 1963, Eckenrode and Chapman 1972, Nair and McEwen 1975, Wyman et al. 1977, Vincent and Stewart 1981, Collier and Finch 1985, Bracken 1988, Walgenbach et al. 1993, Jyoti et al. 2003, Dreves et al. 2006). Specific plant bloom periods (Miles 1951, Matthewman and Harcourt 1963), genetic variability (Finch and Collier 1983, Biron et al. 2002), and most importantly, seasonal temperature (Wymann et al. 1977) have been key factors in understanding CM phenology.

Miles (1951) suggested that *Delia* flies depend on nectar-producing flowers in the spring for survival, and for this reason timing of spring emergence can be associated with

blossoming of fruit trees and shrubs. From 1946 to 1962, Matthewman and Harcourt (1963) conducted a series of investigations at Ottawa on CM phenology including spring flight. They found flight to be correlated with weather data and specific plant blossoming periods. In addition to temperature, Sharpe and DeMichele (1977) implied that rainfall and/or other factors may affect emergence. Nair and McEwen (1975) also believed that soil moisture may be another important factor, along with temperature, regulating emergence

Timing of phenological events (such as initiation of the spring emergence period) have also been based on temperature (Read 1962, Eckenrode and Chapman 1972, Nair and McEwen 1975, Wyman et al. 1977, Vincent and Stewart 1981, Collier and Finch 1985, Walgenbach et al. 1993, Jyoti et al. 2003). Temperature is typically expressed as accumulation of degree-days with temperatures between lower and upper developmental thresholds (Wilson and Barnett 1983). Johnsen and Gutierrez (1997) reported a general agreement that 4.3°C works well as the lower development temperature (or base temperature) in northern temperate regions for CM, although other base temperatures between 4 and 6°C have been used as well (Eckenrode and Chapman 1972, Vincent and Stewart 1981, Pruess 1983, Collier et al. 1989) (Table 1.1). Collier and Finch (1985) observed that few to no flies emerge at temperatures above 30°C.

Location	Latitude-Longitude	Degree-Days (DD °C)	Lower Temp Biofix Date	Source
Oregon, Canby	45° 15'N, 122° 46'W	S1(10%): 200.25 ± 50.23 (50%): 329.8 ± 22.2 (95%): 761.5 ± 60.1	4.3 °C Jan 1	Dreves et al. 2006
UK, Wellesbourne	52° 11'N, 36° 52'W	S1 (1 st): 150 - 170 (50%) = 243 F1: 1176	4.4 °C ?	Coaker and Wright 1963
UK, Wellesbourne	52° 11'N, 36° 52'W	S1 (50%): 230 ± 10 320 DD between early and late above 6C	4.3 °C Feb 1	Collier and Finch 1985
New York, Geneva	42° 44'N, 76° 54'W	S1(1 st): 160 ± 8.1 (10%): 176.6 ± 3.8 (50%): 251.3 ± 3.5 (95%): 390.9 ± 10.1 Complete 449.2 ± 1.4 F1: +508.4 ± 32.9 F2: +465.3 ± 21.5 F3: +399.1 ± 3.1	4 °C Jan 1	Jyoti et al. 2003
North Carolina, Fletcher and Scaly Mountain	35° 52'N, 78° 47'W	S1 (50%): 198-351 (275) F1: 1248	6.1 °C ?	Walgenbach et al. 1993
Wisconsin, Arlington and Kenosha	48° 08'N, 89° 20'W	S1 (50%): 135.0 F1: +617.8	6.1 °C ?	Eckenrode and Chapman 1971
Canada, SW Ontario	45° 19'N, 75° 40'W	S1 (1 st): 174-199 (50%) 283-567; avg 342 F1: 627-1010; avg 839 F2: 1030-1463; avg 1275	6 °C ?	Nair and McEwen\ 1975
Canada, Ste. Anne de Bellevue, Quebec	45° 29'N, 73° 52'W	S1 (10%): 192 (50%): 314 - 398 S2 (50%): 565 - 716 F1: 847 - 960 F2: 1446 - 1604 F3: 2602 - 2887	6.1 °C ?	Vincent and Stewart 1981
Canada, E. Ontario, Ottawa	45° 19'N, 75° 40'W	S1(10%): 174-199 (50%): 57	4.4 °C Mar 1	Matthewman and Harcourt, 1963

Table 1.1. Phenology models developed worldwide predicting cabbage maggot spring emergence and degree-day accumulations necessary to complete seasonal generations.

Finch and Collier (1983) reported early- and late- spring emerging genetic biotypes from overwintering generations in some areas of the UK. Others have since described this

bimodal emergence pattern revealing varied and extended spring emergence (Walgenbach et al. 1993, Biron et al. 2003). Walgenbach et al. (1993) described cabbage maggot populations from western North Carolina as predominately of the late-emerging biotype and New York populations as predominately early-emerging individuals. Biron et al. (2003) showed variation in relative numbers between two spring peaks corresponding to early- and late-emerging phenotypes in Swedish fly populations versus Finnish populations. Harris & Svec (1966) and Finch and Collier (1985) believed that fly emergence is sometimes suppressed during warm summer months because of aestivation of the pupae, so flight activity may be shown as less or absent. Canadian researchers (Wyman et al. 1977) reported that to determine periods of fly emergence and flight, seasonal temperature using DD models along with fly trapping (using water traps) are the best methods to forecast phenological events.

1.4.2 Seasonal Flight

Description of seasonal flight activity is based on fly counts in yellow water traps throughout the season (Finch and Skinner 1975, Finch 1992, Kostal and Finch 1996). Water trap efficiency is heavily influenced by trap placement and weather conditions (Wyman et al. 1977), so trap counts may not accurately represent fly population densities (Griffiths 1986). Also, fly counts from water traps depend on location of traps within a field because many factors can affect trap catch, including: 1) proximity to larval infestations (Coaker and Smith 1968, Dingle 1972), 2) presence of sheltered field margins (Griffiths 1986), 3) prevailing wind direction (Banks et al. 1988), and 4) exposure to sunlight (Hawkes 1972, Klingen et al. 2000). Banks et al. (1988) suggest that *Delia* fly upwind in the presence of Brassica odors. Traps in the path of flight would theoretically catch more flies than those

away from an odor source (Nottingham and Coaker 1987). Dispersal of flies is not obligatory and when they search for a host they fly into the wind in a series of short flights (Coaker and Smith 1968, Dingle 1972, Hawkes et al. 1978, Finch and Skinner 1982), so larval infestations in close proximity to new Brassica plantings would have a higher infestation levels than distant plantings when positioning a trap for maximum fly catch. Finch and Skinner (1975) reported that: 1) generally most flies were caught within 100-200 meters of their emergence site, 2) flies were captured at a maximum distance of 2000-3000 meters from a known maggot source, but found that very few of these were males, and 3) 50-80% of the females were recaptured at their release site and few dispersed. Hawkes (1972) showed that CM is attracted to yellow water traps only within a range of about one meter when they enter a field. Adjacent crops, hedgerows, tall grasses and other features that shelter field borders influence trap catch as they attract CM by providing shelter and floral food (Hawkes 1972, Finch and Skinner 1973, Griffiths 1986). Griffiths (1986) placed traps along sheltered field margins from early to mid season to maximize trap catches. He reported that as the crop canopy closed, placement of traps near sheltered field margins was less critical to trap catch, as at that time the crop provided both food and shelter. Also, traps exposed to the sun catch significantly more flies than those in the shade (Hawkes 1974, Klingen et al. 2000).

1.4.3 Oviposition

Identifying relationships between egg levels and subsequent crop damage helps establish baselines for CM management decisions (Dapsis and Ferro 1983). Sears and Dufault (1986) did report a positive correlation between CM egg numbers and subsequent damage on rutabagas. Rutabaga plants with less than two cumulative eggs per plant resulted

in a 10 to 21% larval infestation level, and higher egg levels (three to six) yielded 59 to 63% larval infestation.

Understanding factors that influence the degree of oviposition and damage is also essential when developing an effective CM monitoring program. Researchers have noted levels of oviposition by CM populations to be influenced by: 1) crop variety type (Doane and Chapman 1962, Vandermeer 1989, Baur et al. 1996, Dossall et al. 2000), 2) morphological stages of plant growth (Coaker and Finch 1971, Hardman and Ellis 1978, McDonald and Sears 1992), 3) precipitation (Bracken 1988), 4) season (Finch and Collier 1985, McDonald and Sears 1992, Todd 1998), 5) biotic and abiotic factors such as natural enemies and natural mortality (Mukerji 1971), 6) fly activity in field (Sears and Dufault 1986), and 7) spatial distribution (Mukerji and Harcourt 1970, Finch and Skinner 1975). This list is not exhaustive.

1.4.4 Crop Damage

Many studies that have assessed crop damage in aboveground Brassicas have done so using yield data (Bevins and Kelly 1975), number of tunnels (Eckenode and Chapman 1971), and rankings of crop damage severity (Stitt 1953). Skinner and Finch (1986) estimated CM damage by taking six 10-plant samples at random across a field of 5-10 hectares and evaluating the presence or absence of CM. A binomial (presence-absence) sampling plan has been noted to be a cost efficient sampling method for CM (Bligaard 2001).

Calculated alterations in planting date and harvest date can influence level of crop damage (Buntin et al. 1990, Voss and Ferro 1990). Delayed planting, based on an understanding of seasonal influences, may reduce the likelihood of eggs being laid in the

emerging spring crop. For example, potatoes planted late in non-rotated fields in Massachusetts suffer less damage from Colorado potato beetle than do crops planted on conventional earlier dates (Voss and Ferro 1990). Similarly, Buntin et al. (1990) showed that delaying the planting date of wheat meant that fall wheat seedlings were not present for oviposition by the Hessian fly. Infestations of fall and winter wheat by this pest declined, without enhancing spring infestations or reducing wheat yields. Another example is pink bollworm, which overwinters as larvae. Harvesting early before diapause induction reduces the number of overwintering larvae to low levels (Ramalho 1994). These studies draw heavily on inference to suggest that planting and harvesting dates can be manipulated to reduce damage. But there is little or no information in the literature, inferential or otherwise, about manipulating planting and harvesting date to reduce CM damage.

1.5 Research Objectives

The primary goal of this research is to examine the usefulness of a monitoring program in order to help reduce dependence on chemicals for CM control. Therefore, studies were conducted to meet the following objectives: 1) describe and characterize spring emergence periods and seasonal flight activity of CM relative to DD accumulations; 2) measure impact of CM by assessing crop damage, 3) determine if planting and harvest dates influence root damage from CM, 4) identify the occurrence of ovipositional activity in regard to time of season, age of crop and distribution within a fields, and 5) study critical relationships among flight activity, oviposition, and crop damage.

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**2 SPRING EMERGENCE AND SEASONAL FLIGHT OF *DELIA RADICUM* (L.)
(DIPTERA: ANTHOMYIIDAE) IN WESTERN OREGON**

A. J. DREVES, D. DALTHORP, A. G. STONE, G. FISHER

Environmental Entomology
Entomological Society of America
10001 Dereckwood Lane, Suite 100, Lanham, MD 20706-4876
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2.1 Abstract

Field research was conducted to describe and characterize spring emergence and seasonal flight activity of the cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), in relationship to degree-day (DD) accumulations. Turnip and rutabaga fields were monitored in the northern Willamette Valley in western Oregon from 2001 through 2004. Spring emergence from overwintering puparia was monitored using emergence cages. A bimodal spring emergence pattern was observed, with approximately 70% of the spring population emerging in an early peak in late March, two months before a later peak near the end of May. The mean DD accumulations at 10, 50, and 95% of spring emergence using a lower and upper developmental threshold of 4.3°C and 30°C beginning 1 January had corresponding DD values of 200 ± 50.2 (8 March), 330 ± 22.2 (4 April) and 762 ± 60.1 (28 May), respectively. Seasonal flight activity was monitored using yellow water traps. Spring flight patterns mirrored the bimodal emergence patterns but with a delay of 3 days to 5 weeks between emergence and detection of flies in the water traps. The mean DD accumulations recorded from the beginning to the end of spring flight had corresponding DD values of 303 ± 61.5 (31 March) to 839 ± 51.9 (4 June). Fly activity was lower over the summer from the beginning of June until the end of August (2138 ± 82.3 DD). A fall flush of activity was observed each year beginning in late August to early September and extending through October (2860 ± 170.6 DD).

2.2 Introduction

The cabbage maggot, *Delia radicum* L. (Diptera: Anthomyiidae), also known as the cabbage root fly throughout Europe, Canada and England, continues to be a major pest of Brassicaceae crops in the northern latitudes (40-60 N) (Getzin 1985, Bracken 1988, McDonald and Sears 1992, Walgenbach et al. 1993). In western Oregon, Brassica crops are seeded at regular intervals throughout the growing season on over 20,000 acres and valued in excess of \$20 million annually. Cabbage maggot larvae feed on the roots of all Brassica crops, but the root crops such as turnips and rutabagas are especially vulnerable because even superficial damage to the roots can render the crop unmarketable. Root injury also provides entryways for pathogens causing diseases such as black leg (*Phoma lingam*), bacterial soft rot (*Erwinia carotovora*), and root rot (*Fusarium* and *Rhizoctonia* spp.) (Griffiths 1986, McDonald and Sears 1992).

The cabbage maggot is a multi-generation pest in western Oregon. Cabbage maggots overwinter under the soil surface as pupae and adult flies begin to emerge in early spring. Researchers from various regions around the world have reported a bimodal spring emergence pattern, with distinct early and late peaks, that extends over several months (Read 1958, Finch and Collier 1983, Walgenbach et al. 1993, Biron et al. 2003). After emergence, flies feed on protein and carbohydrate sources such as flowering fruit trees and other nectar-producing plants before mating (Harris and Svec 1966, Finch and Coaker 1969), which occurs within 4-6 days of emergence (Swales 1961). They search for *Brassica* plants by keying into leaf color and area (Prokopy et al. 1983) as well as volatile isothiocyanates and other glucosinolates produced by Brassica plants (Traynier 1967, Stadler 1978, Hawkes and Coaker 1979). Females lay white oblong eggs about 1 mm long

at the base of host plants (Miles 1951). The eggs hatch within 3 to 9 days, and the neonate larvae begin feeding on lateral and main roots. Larvae feed for 2 to 3 weeks, then pupate in the soil and emerge as flies one to two weeks later. Some researchers have shown that fly emergence is reduced during warm summer months of prolonged temperatures greater than 21°C due to aestivation (Harris and Svec 1966, Finch and Collier 1985). Puparia enter diapause in the late fall after the onset of lower temperature and shortened photoperiod (McLeod 1964, Johnsen and Gutierrez 1997).

Growers treat prophylactically for cabbage maggot as there is currently no commercially viable monitoring system for *D. radicum*. Scheduled applications of chlorpyrifos (e.g., Lorsban®; Dow AgroScience, Indianapolis IN), an organophosphate insecticide, are the most widely relied-on treatment used by growers to control cabbage maggot (Getzin 1981, Stark 1993, Todd 1998, Jyoti et al. 2001). In many cases, crop roots are still damaged by maggots even after chemical treatments and growers in western Oregon have suffered substantial crop losses of up to 90% in fields treated with chlorpyrifos. Ineffective *D. radicum* control may be attributed partly to poor application timing in relation to *D. radicum* development (Getzin 1985).

Planting and harvest schedules could be adjusted to avoid crop exposure to periods of high risk fly activity, and pest management practices (e.g., chemicals, row covers, exclusion fences) could be timed to be most effective if cabbage maggot phenology in the Willamette Valley was better understood. The objective of this research was to describe and characterize spring emergence and seasonal flight activity of *D. radicum* adults in relationship to DD accumulations and precipitation in the Willamette Valley of western Oregon.

2.3 Materials and Methods

2.3.1 Description of Research Sites

Research was conducted from January 2001 through November 2004 in the northern Willamette Valley, Oregon where over ninety percent of Oregon's commercial Brassica crops are grown. Our research sites consisted primarily of commercial fields of rutabaga (*Brassica napus* cv. Laurentian Purple Top) and turnip (*Brassica campestris* cv. White Globe Purple Top) within 2 km of the Willamette, Pudding, and/or Molalla rivers; however, data was also collected from rutabaga and turnip fields at Oregon State University's Northwest Research and Extension Center (NWREC) located in Aurora, Oregon. The fields were representative of the area and varied in size from \approx 1 to 4 hectares. Associated border vegetation, which may provide both food and shelter for the fly (Griffiths 1986), included trees (predominantly ash (*Fraxinus*), white oak (*Quercus*), cottonwood (*Populus*), maple (*Acer*), and Douglas fir (*Pseudotsuga*)), understory perennials (wild blackberry (*Rubus*), wild rose (*Rosaceae*), grasses (*Graminaceae*), sedges (*Carex*), and rushes (*Juncus*)), and herbaceous annuals (including wild cucumber (*Echinocystis*) and mustards (*Brassica*) and others). In addition, nurseries, hazelnut orchards, and housing developments bordered many of the fields. Soil types varied but were predominantly loams (Quatama, Newberg, Latourell) and silty loams (Willamette, Woodburn, Cloquato, and Amity). These soils are partially drained to well drained with pH between 5.5 and 7.0.

Annual precipitation in the northern Willamette Valley is typically 110 cm with over half falling during the period December through February. Summer precipitation averages only about 8 cm. Because of light rainfall during the summer months, Brassica fields must be irrigated, mostly via overhead sprinkler irrigation. Mean daily high temperatures in the

summer reach 27°C in July, with average lows of 10°C. In winter months the average daily maximum temperature is around 10°C with daily lows averaging about 2°C. The first frost is typically around 1 November. Snow and extended periods of sub-freezing temperatures are not common in the region. Four distinct seasons can be characterized by differences in precipitation, photoperiod, and temperature in the Pacific Northwest as shown in Fig. 2.1.

2.3.2 Weather Data

Weather data used in this research (air temperature and precipitation) was provided by the Pacific Northwest Cooperative Agricultural Weather Network from an agrometeorological weather station (AgriMet; #356151, latitude 45° 15 N, longitude 122° 46W, elevation 45.7 m) located at NWREC, approximately 10 km from the farthest research field. Daily minimum and maximum air temperatures recorded at 1.8 meters were used for computations in the degree-day model described below. Cumulative precipitation was collected daily for a 24 h period with a non-heated tipping bucket.

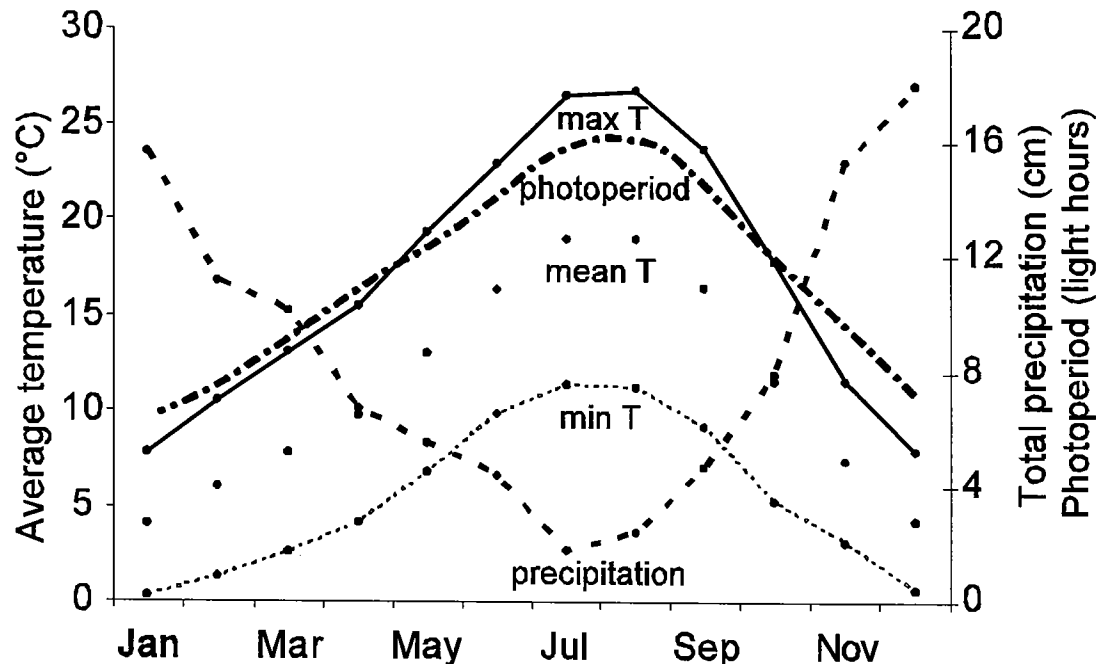


Fig. 2.1. Thirty year average weather patterns provided by the Pacific Northwest Cooperative Agricultural Weather Network, AgriMet Station #356151 (Aurora, OR).

2.3.3 Degree-Day Model

Degree-day accumulations (DD) were used as a proxy for physiological time to predict emergence and flight activity (Pruess 1983). We assumed a lower development threshold of 4.3°C, which is generally accepted in cabbage maggot models for the northern United States (Johnsen and Gutierrez 1997, Jyoti et al. 2003), and an upper development threshold of 30°C because very few flies emerge at higher temperatures (Collier and Finch 1985). Daily DD accumulations were estimated using the single sine approximation (Baskerville and Emin 1969, Wilson and Barnett 1983). Thermal units were accumulated beginning on 1 January.

2.3.4 Spring Fly Emergence

Emergence cages were used to monitor spring emergence of adult flies from overwintering puparia collected the previous fall (Finch and Collier 1983). The Boll Weevil Trap® (Hercon Environmental Corporation, Emigsville PA) was used as the

emergence cage. The cage is a plastic cylinder, 15 cm in height and 11 cm in diameter. An inverted fine-meshed (1 mm) metal screen cone, 12 cm tall, sits on top of the cylinder with a small plastic cup fitted securely over the cone. Two emergence cages were placed in each field studied in 2001–2004; there were 3, 6, 10, and 3 fields, respectively, with each field representing a different geographic area in the production region. For each cage, ten *D. radicum* puparia were collected in the late fall and placed 5–6 cm below the surface of the soil with an emergence cage placed on the surface directly above the puparia. Puparia used in the emergence study were collected from a number of fall-planted Brassica fields and a wide assortment of plants within each of these fields. Cages were monitored weekly for cabbage maggot flies from 5 January through 30 June. Each week the number of flies that were recovered from the cages was recorded and cages were re-fitted with empty retaining cups.

2.3.5 Seasonal Flight Activity

Cabbage maggot flight activity was monitored throughout the growing season with yellow water traps (Finch 1992). Traps were fluorescent yellow plastic buckets (AmLoid Corp, standard ASTM F-963; Monterrey, Mexico), measuring 18 cm in diameter, 30 cm in depth, and a volume of 5 liters. Buckets were filled with water to within 3 cm of the rim. Two ml of 6% liquid sodium hypochlorite and a few drops of detergent were added to prevent microbial growth and reduce surface tension. Buckets were set on the soil initially and raised slightly above the plant canopy as the season progressed. Buckets were replaced with new buckets after 3 or 4 months. Fly activity was monitored in 10, 19, 30, and 12 commercial fields in 2001 through 2004, respectively. In each field, one water trap was placed along the border of the north to northeast side of the field in the upwind direction of

the prevailing wind (Finch and Skinner 1982, Banks et al.1988). Vegetation was removed from an area immediately around the trap of radius 0.5 m (Griffiths 1986).

In 2001 through 2003 water traps were placed in the field on approximately 28 February and serviced weekly through 31 October, 29 October, and 4 November. In 2004, water traps were placed in fields 25 January and removed 3 December. Flies were collected weekly, counted, preserved in 70% EOH and later identified with a key (Brooks 1951). Traps were cleaned and refilled after each collection.

2.4 Statistical Analysis

2.4.1 Spring Fly Emergence

A suite of descriptive and inferential statistical tools was used to characterize the spring emergence patterns of the adult flies captured in emergence cages. These tools address: *i.* variability of emergence patterns among fields, and *ii.* whether emergence patterns were bimodal, as is sometimes observed in the literature.

i. Variation Among Fields. A Kolmogorov/Smirnov-type (KS) statistical test (Conover 1999) was performed to determine whether there was significant variation in emergence patterns among fields within a given year (see appendix for details). The null hypothesis is that the distributions of emergence times did not vary among fields in a given year. Non-rejection of the null hypothesis does not necessarily imply that the distributions were indeed the same. Therefore, we also conducted two tests of whether the distributions among fields differed. The null hypothesis for the first test was that the distribution of emergence times in a field is random and independent of the other fields. A measure of the degree of

concordance between the distributions was used as a test statistic. The hypothesis was tested by a standard bootstrap simulation (Efron and Gong 1983). Details of the test are provided in the appendix. In a second test of independence among fields, the null hypothesis was that the temporal structure of the emergence times within a field was assumed to be as observed but that the starting times of the emergence patterns in the various fields were independent. Then, a permutation test was performed. Details are given in the appendix.

ii. Bimodal Emergence Pattern. To model spring emergence patterns, we devised a "bimodal gamma" probability distribution, which is a flexible smooth curve with two peaks and fits the observed patterns well. Each peak resembles a gamma distribution with its own shape parameter α and scale parameter β . The likelihood of a fly being caught in a trap at

time t is assumed to be: $f(t) = w \frac{t^{\alpha_1-1} e^{-t/\beta_1}}{\Gamma(\alpha_1)\beta_1^{\alpha_1}} + I_{\{t \geq \delta\}} (1-w) \frac{(t-\delta)^{\alpha_2-1} e^{-(t-\delta)/\beta_2}}{\Gamma(\alpha_2)\beta_2^{\alpha_2}}$, where $\alpha_1, \beta_1, \alpha_2,$

and β_2 are the shape and scale parameters for the two peaks, δ is the starting point of the second peak, and w is the proportion of flies that are caught in the first peak. The factor

$I_{\{t \geq \delta\}} = \begin{cases} 0 & \text{if } t < \delta \\ 1 & \text{if } t \geq \delta \end{cases}$ is included so that the second gamma distribution is evaluated only when

$t \geq \delta$, i.e. after the beginning of the second peak. The model was fit by maximum likelihood (details in the appendix).

A likelihood ratio test comparing the bimodal gamma with the standard gamma distribution was performed for each year's emergence trap catch data to determine whether the bimodal model provided a significantly better description of the emergence pattern than the unimodal model. According to the likelihood ratio test, the quantity

$\Lambda = -2(L_{\text{bimodal}} - L_{\text{unimodal}})$, where L_{bimodal} and L_{unimodal} are the sum of the negative log-

likelihoods for the maximum likelihood estimators for the bimodal and unimodal gamma distributions, is distributed as a chi-squared random variable with 3 degrees of freedom.

2.4.2 Seasonal Flight Activity

Fly counts in the yellow water traps tended to have large peaks in the spring and fall with a smaller peak in the summer, thus resembling a tri-modal distribution. For this reason, we devised a tri-modal gamma distribution to model trap catches through the whole growing season:

$$f(t) = w_1 \frac{(t - t_0 + 1)^{\alpha_1 - 1} e^{-(t - \delta_1)/\beta_1}}{\Gamma(\alpha_1)\beta_1^{\alpha_1}} + I_{\{t \geq \delta_2\}} w_2 \frac{(t - \delta_2)^{\alpha_2 - 1} e^{-(t - \delta_2)/\beta_2}}{\Gamma(\alpha_2)\beta_2^{\alpha_2}} + I_{\{t \geq \delta_3\}} (1 - w_1 - w_2) \frac{(t - \delta_3)^{\alpha_3 - 1} e^{-(t - \delta_3)/\beta_3}}{\Gamma(\alpha_3)\beta_3^{\alpha_3}}$$

with parameter interpretations and estimation analogous to the bimodal case.

The bi- and tri-modal gammas were used to:

- i. estimate the dates of flight activity peaks,
- ii. estimate the time lag between emergence and flight,
- iii. estimate and compare the “widths” of various activity peaks,
- iv. estimate the proportions of a population that belong to each activity period, and
- v. create simplified graphs of fly activity through time.

The first and second peaks of a bimodal gamma distribution are at $t = \beta_1(\alpha_1 - 1)$ and $t = \beta_2(\alpha_2 - 1) + \delta$, and the three peaks of a tri-modal gamma distribution are at $t = \beta_1(\alpha_1 - 1)$, $t = \beta_2(\alpha_2 - 1) + \delta_2$, and $t = \beta_3(\alpha_3 - 1) + \delta_3$. As a measure of the width of an activity peak, we use the standard deviation of the associated gamma distribution, $\beta_j \sqrt{\alpha_j}$. The proportion of a population that belongs to a given peak is given by the weight w_j associated with the peak.

2.4.3 Delineation of Seasons

Each year the spring emergence period was defined as the period between the times when 10% of the flies had emerged ($T_{0.1}$) and ending when 95% had emerged ($T_{0.95}$). Bimodal gamma curves were also calculated for spring flight activity (i.e., fly catches in yellow water traps) from the 1 January through the accumulation of 1000 DD. From these bimodal gammas, the times of spring flight peaks were computed.

The beginning of the fall flight was estimated statistically using a simple model that assumes low activity in the summer, high activity in the fall, and low activity again in the winter. The period that begins with the end of the spring emergence and extends to the end of the year can be split into three seasons delineated by any two given times t_0 and t_f , with "summer" defined as the period before t_0 , "fall" as the period between t_0 and t_f , and "winter" as the period after t_f . Values of t_0 and t_f are chosen to minimize the deviations of trap

catches from their seasonal means, i.e., t_0 and t_f are the values that minimize the function

$$SSE(t_0, t_f) = \sum_{t < t_0} (x_t - \bar{x}_{\text{summer}})^2 + \sum_{t_0 \leq t < t_f} (x_t - \bar{x}_{\text{fall}})^2 + \sum_{t \geq t_f} (x_t - \bar{x}_{\text{winter}})^2, \text{ where } x_t \text{ is the number of flies}$$

recovered in a water trap at time t , \bar{x}_{summer} is the average trap catch prior to time t_0 , \bar{x}_{fall} is the average trap catch between times t_0 and t_f , and \bar{x}_{winter} is the average trap catch after t_f . The end of the fall flight was defined as the date of the first frost after 1 September (typically around 1 November).

2.5 Results

2.5.1 Weather Data

Yearly air temperature (used for DD calculations) and precipitation records (used to describe emergence patterns) were examined for the spring emergence period of January through June over the four years of study. Two time periods around spring emergence were explored, which included: 1) pre-emergence (January and February), and the 2) emergence period ($T_{.10}$ to $T_{.95}$; March through June).

1) *Pre-emergence*. Winter temperatures and precipitation levels were quite different between years 2001 and 2003 (Table 2.1. Degree-day accumulations (A) and precipitation levels (B) during spring emergence period for 2001 through 2004. In 2001, both temperature and precipitation were significantly lower (139 DD and 72 mm, respectively) than in 2003. In 2003, temperature and precipitation were above average (217 DD and 298 mm, respectively). Because of the warm temperatures in January 2003, the monthly DD accumulated were twice (119 DD) the mean DD of the other three years (mean of 58 DD). In 2002 and 2004, winter temperatures were about average for that time of year (145 and 156 DD, respectively) and precipitation slightly above average (292 and 260 mm, respectively).

Table 2.1. Degree-day accumulations (A) and precipitation levels (B) during spring emergence period for 2001 through 2004.

(A) Temperature: degree-day (DD) accumulations						
Year	Jan 1 through Jan 31	Feb 1 through Feb 28	$T_{0.1}$ through early peak	Early peak through $T_{0.95}$	Average DD/day from $T_{0.1}$ through $T_{0.95}$	Duration of emergence period ($T_{0.01} - T_{0.95}$)
2001	63	76	14 (3 d)	525 (67 d)	7.0	539 (70 d)
2002	57	88	57 (18 d)	442 (60 d)	7.0	499 (78 d)
2003	119	98	112 (28 d)	492 (65 d)	7.1	604 (103 d)
2004	53	103	12 (2 d)	591 (73 d)	8.0	603 (75 d)

(B) Precipitation (mm)						
Year	Jan 1 through Jan 31	Feb 1 through Feb 28	$T_{0.1}$ through early peak	Early peak through $T_{0.95}$	Jan 1 through $T_{0.95}$	Total during emergence period ($T_{0.01} - T_{0.95}$)
2001	39	33	3	101	262	104
2002	195	97	46	97	533	143
2003	222	76	172	254	651	426
2004	157	103	0	78	348	78

2) *Emergence*. Above average air temperatures were reported during the spring months (March through May) in the years 2003 and 2004, totaling 604 and 603 DD, respectively. Precipitation was above average during the spring emergence period in 2003 (426 mm), but significantly lower in 2004 (78 mm). In 2001 and 2002, temperatures and precipitation were normal (539 and 499 DD; 104 and 143 mm, respectively). However, the total cumulative precipitation for the period 1 January through 1 June in 2001 and 2004 was below average and almost half the values of years 2002 and 2003. Over this same time period, DD had accumulated in 2003 and 2004 (843 and 905 DD, respectively), and much lower DD values were reported in years 2001 and 2002 (767 and 711 DD, respectively).

2.5.2 Spring Fly Emergence

The spring emergence period begins as soils warm up and overwintering pupae emerge as adults in significant numbers. Although temperature and moisture regimes do vary geographically, we found that in each year of the study spring emergence patterns did not vary significantly from field to field (Fig. 2.2). In particular, the null hypothesis that the distribution of emergence times was the same in each field could not be rejected in any year of the study, according to our Kolmogorov-Smirnov-type simulation (Conover 1999) (P -values of 0.74, 0.93, 0.26, and 0.49 for 2001-2004, respectively). In addition, a bootstrap test (Efron and Gong 1983) revealed a higher degree of synchronization of emergence times among the fields than would be expected under a hypothesis of independence between fields (P -values of 0.004, 0.034, 0.01, and 0.10 for 2001-2004, respectively). The more specific and powerful permutation tests of the null hypothesis that the timing of the emergence peaks differed among fields was rejected with P -values of < 0.004 , < 0.001 , < 0.001 , and 0.014 for 2001-2004. In other words, the observed degree of synchronization between fields is greater than would be expected if the timing of the peaks varied between fields. Because the degree of synchronization was significant and the hypothesis that the distributions of emergence times among fields were the same could not be rejected, trap counts were pooled across fields within each year. The remainder of the results is for the pooled data.

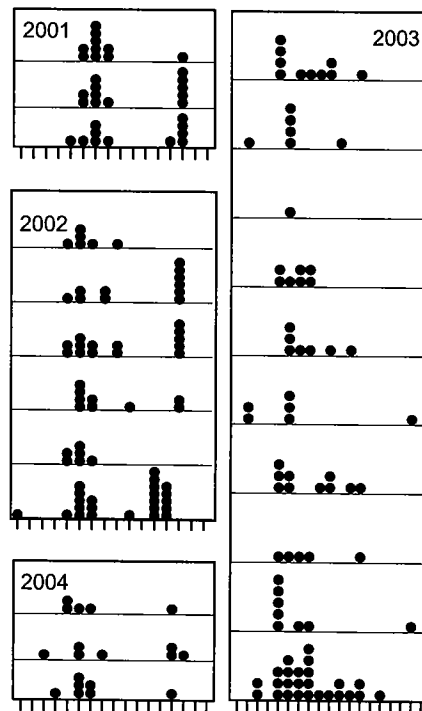


Fig. 2.2. Dot plots of fly emergence data by field and year. Tick marks on the x -axis indicate weekly trap counts between mid-February and early June. Subplots within each year represent trap catches in different fields. Each dot represents a single fly.

It is not uncommon for flies to emerge in small numbers during warm spells in winter (primarily February), but these flies are not considered economically important and do not mark the start of the spring flight. In delineating the spring emergence period, we effectively ignore these winter emergers by defining the beginning of spring emergence as the date by which 10% of the total fly catch in the emergence cages has been reached. The end of the spring emergence period is defined as the date at which 95% of the total fly count in the emergence cages has been reached.

Spring emergence patterns were similar each year. The emergence extended over a period of nearly three months, beginning after accumulation of 200 DD (early March) and ending after accumulation of approx. 800 DD (late May). A distinctly bimodal emergence

pattern was observed in 2001, 2002, and 2004 but not in 2003 (Fig. 2.3; P -values for likelihood ratio tests comparing bimodal to unimodal models were $< 10^{-16}$, 0.0025, and 0.00008 for 2001, 2002, and 2004, respectively, but only 0.13 for 2003). Each year, the early peak occurred at approximately 250 DD (mid- to late March) (Fig. 2.3; Table 2.2). The dates of the early emergence peak ranged from 9 March (in 2004) to 31 March (in 2001). The late spring peak occurred around 24 May, averaging 715 ± 95.1 DD, with dates ranging from 17 May to 2 June. The early and late peaks were separated by 473 ± 90.4 DD, or approximately two months. In the three years that had two distinct peaks, the early emerging flies constituted approximately 70% (± 3.5) of the spring population, while only about 30% were late emerging (Table 2.2).

Table 2.2. Summary of spring emergence peaks where T_p represents the degree-day accumulations (and date) required for 100 p % of the population to emerge. Timing of the early and late peaks in emergence rates are also reported in accumulated degree-days.

Year	Emergence degree-day accumulation					Time lag between peaks	Fraction in early peak
	$T_{0.1}$	$T_{0.5}$	$T_{0.95}$	Early peak	Late peak		
2001	273 (3/28)	325 (4/14)	812 (6/6)	287 (3/31)	784 (6/2)	497 (63 d)	0.67
2002	176 (3/11)	355 (4/13)	675 (5/28)	233 (3/29)	606 (5/22)	373 (54 d)	0.71
2003	160 (2/12)	337 (3/26)	764 (5/26)	272 (3/12)	—	—	—
2004	192 (3/7)	302 (3/24)	795 (5/21)	204 (3/9)	753 (5/17)	549 (69 d)	0.74
Mean	200 (3/8)	330 (4/4)	762 (5/28)	249 (3/23)	715 (5/24)	473 (62 d)	0.70
\pm SD	50.2	22.2	60.1	42.1	95.1	90.4	0.04

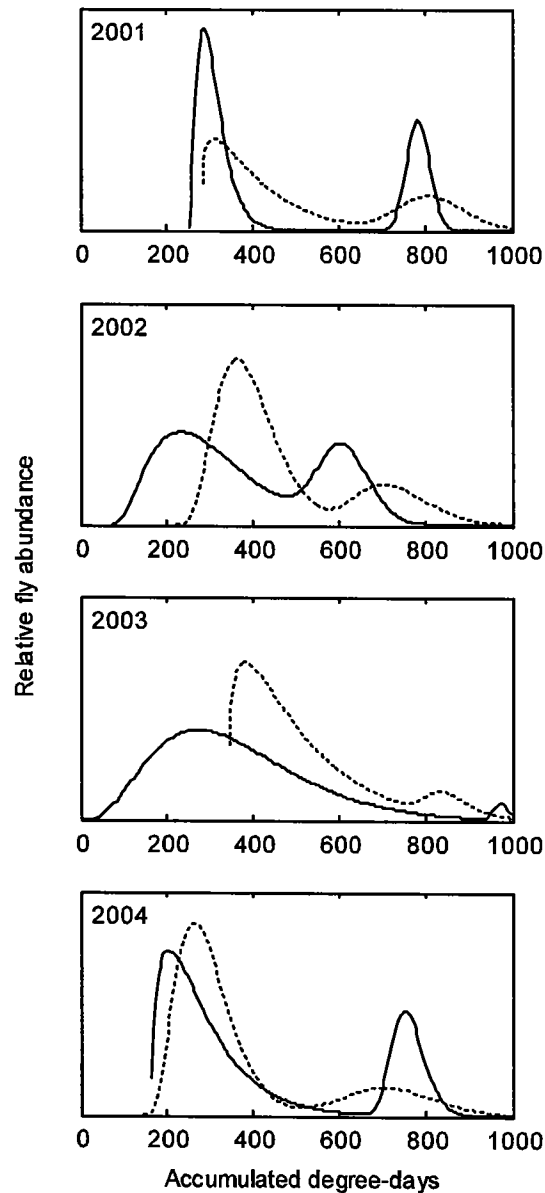


Fig. 2.3. Bimodal models of the timing of *D. radicum* spring fly emergence (solid lines) and spring flight activity (dashed lines) from yearly, pooled Brassica field data collected in the northern Willamette region, Oregon from 2001 to 2004.

In the four years of the study, the beginning of spring emergence occurred at 200 ± 50.2 DD (mean \pm SD). The standard deviation of 50.2 DD corresponds roughly to 9 days at that time of the year. Calendar dates for the start of spring emergence were substantially more variable, ranging from mid February in 2003 (the year with the warmest January and

February and wettest January), to late March in 2001 (the year with the coolest January and February and driest January and February) with a standard deviation of 18 days (Table 2.1 and Table 2.2)

The midpoint of the fly emergence period (i.e., the point at which 50% of the overwintering flies had emerged, denoted by $T_{0.5}$) occurred approximately one month after the initiation of spring emergence. The timing of the midpoint was fairly predictable, ranging from 302 DD in 2004 to 355 DD in 2002 (mean of 330 and standard deviation of 22.2 DD) (Table 2.2). The standard deviation of 22.2 DD corresponds to roughly 4 days at that time of year. Winter temperatures were cooler early in 2001 and 2002 than in early 2003 and 2004 (Table 2.1A). As a result $T_{0.5}$ was delayed three weeks compared to 2003 and 2004. Therefore, the calendar dates of $T_{0.5}$ varied widely, ranging from 24 March to 14 April, with a standard deviation of 11 days.

The end of spring emergence from remaining overwintering puparia occurred at DD accumulations of 762 ± 60.1 , corresponding to the end of May and ranging from third week in May 2004 (the highest accumulation of DD at this time of year) to first week in June 2001 (the driest and coldest winter) (Table 2.1 and Table 2.2). The standard deviation of 60.1 DD corresponds to approximately 6 days at that time of the year.

2.5.3 Spring Flight Activity

The spring pattern of flight activity mirrored the bimodal emergence pattern but with an apparent lag between emergence (as detected in emergence traps) and flight (as detected in yellow water traps) (Fig. 2.3 and Fig. 2.4). On average, the time lag between the early emergence peak and the early flight peak was 71 ± 54.2 DD, corresponding to approximately 16 ± 12 days (Table 2.3). In 2001 and 2004, the lags between early

emergence and flight peaks were substantially shorter (23 and 60 DD) than in 2002 and 2003 (130 and 109 DD). The DD lag between the late emergence peak and the late flight activity peak was 27 ± 74.7 DD, corresponding to approximately 4 ± 7 days in the three years with two distinct emergence peaks. The early and late flight peaks were separated by 437 ± 65.8 DD, or approximately 56 days. The fraction of early flight peak catch was approximately 80% of the total spring population, while only about 20% were late flight peak catch.

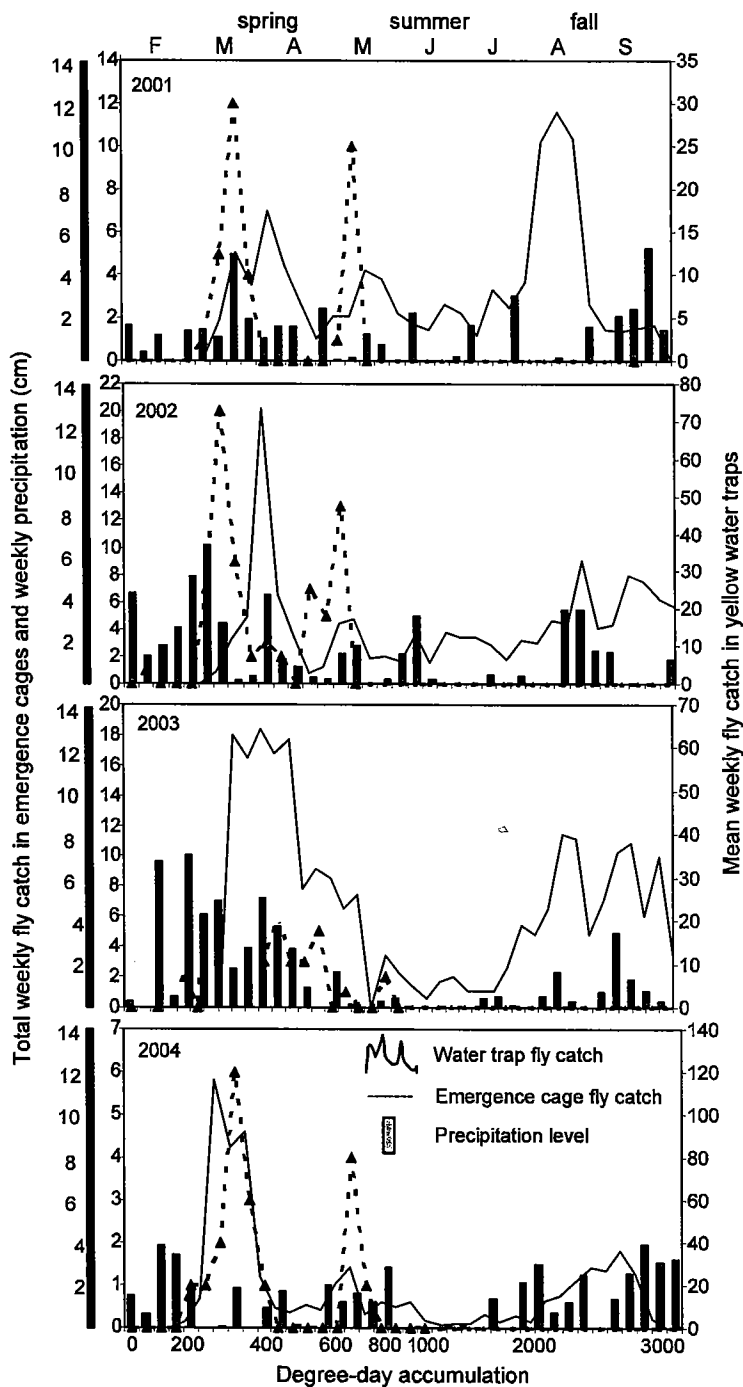


Fig. 2.4. Weekly fly trap catches in emergence cages (dashed line) and in yellow water traps (solid grey shaded area) from selected Brassica fields in northern Willamette Valley, Oregon during 2001 to 2004. Temperature (for degree-day accumulations; x-axis) and weekly rainfall (centimeters; solid bars) were obtained from the regional AgriMet weather station (NWREC; Aurora OR; #35151) during the monitoring period. Note the different y-scales used for emergence and flight over the years.

Table 2.3. Summary of spring flights where T_p represents the degree-day (DD) accumulations (and date) required to reach 100 p % of the total flies caught in the spring; timing of the early and late flight peaks in trap catch rates are also reported in accumulated degree-days (DD).

Year	Flight degree-day accumulations				DD lag between emergence and flight		
	$T_{0.1}$	$T_{0.5}$	$T_{0.95}$	Early flight peak	Late flight peak	Early peak	Late peak
2001	308 (4/8)	440 (4/29)	896 (6/13)	310 (4/9)	810 (6/6)	23 (9 d)	26 (4 d)
2002	314 (4/9)	411 (4/25)	800 (6/9)	363 (4/14)	708 (5/31)	130 (16 d)	102 (9 d)
2003	370 (3/31)	478 (4/19)	869 (6/3)	381 (4/2)	841 (5/31)	109 (21 d)	—
2004	221 (3/12)	305 (3/24)	790 (5/20)	264 (3/19)	705 (5/12)	60 (10 d)	-48 (-5 d)
Mean	303 (3/31)	409 (4/17)	839 (6/4)	329 (4/2)	766 (5/28)	71	27
\pm SD	61.5	74.3	51.9	53.1	69.7	54.2	74.7

The beginning of the spring flight occurred at 303 ± 61.5 DD, which was about three weeks after the beginning of the emergence period. The standard deviation of 61.5 DD corresponds to approximately 10 days at that time of year. Calendar dates for the beginning of the flight ranged from 12 March in 2004 (221 DD) to 9 April in 2002 (314 DD), with an average date of 31 March (Table 2.3). The early calendar date for the initiation of the spring flight in 2004 cannot be wholly attributed to a relatively warm winter and rapid accumulation of DD because the emergence began after a substantially lower DD accumulation than in prior years.

The end of the spring flight occurred at 839 ± 51.9 DD, lagging behind the end of the emergence period ($T_{0.95}$) by approximately 7 days. The standard deviation of 51.9 DD

corresponds to roughly 4 days at that time of year. Calendar dates ranged from 20 May to 13 June, with an average date of 4 June.

2.5.4 Summer Flight Activity

The cabbage maggot summer flight, a time of reduced activity, begins after 900 DD (early June) and ends at approximately 2100 DD, an average calendar date of 28 August (Fig. 2.5). The endpoints of this period correspond to the average DD accumulation that marks the end of the spring flight and the DD that marks the initiation of the fall flight (as described below). In some fields relatively large numbers of flies were caught during the summer months (Fig. 2.5), but on average, summer fly activity was significantly lower than in the spring and fall (Table 2.4).

Table 2.4. Relative proportion of fly population captured in water traps by season, for year 2001 – 2004.

Year	Seasonal trap catch		
	Spring (proportion)	Summer (proportion)	Fall (proportion)
2001	9.0 (0.33)	5.7 (0.21)	12.6 (0.46)
2002	20.1 (0.40)	10.3 (0.21)	19.8 (0.39)
2003	40.6 (0.53)	9.1 (0.12)	26.9 (0.35)
2004	32.4 (0.55)	7.8 (0.13)	18.0 (0.31)
Avg proportion	0.45 ± 0.11 (mean ± SE)	0.17 ± 0.05 (mean ± SE)	0.38 ± 0.06 (mean ± SE)

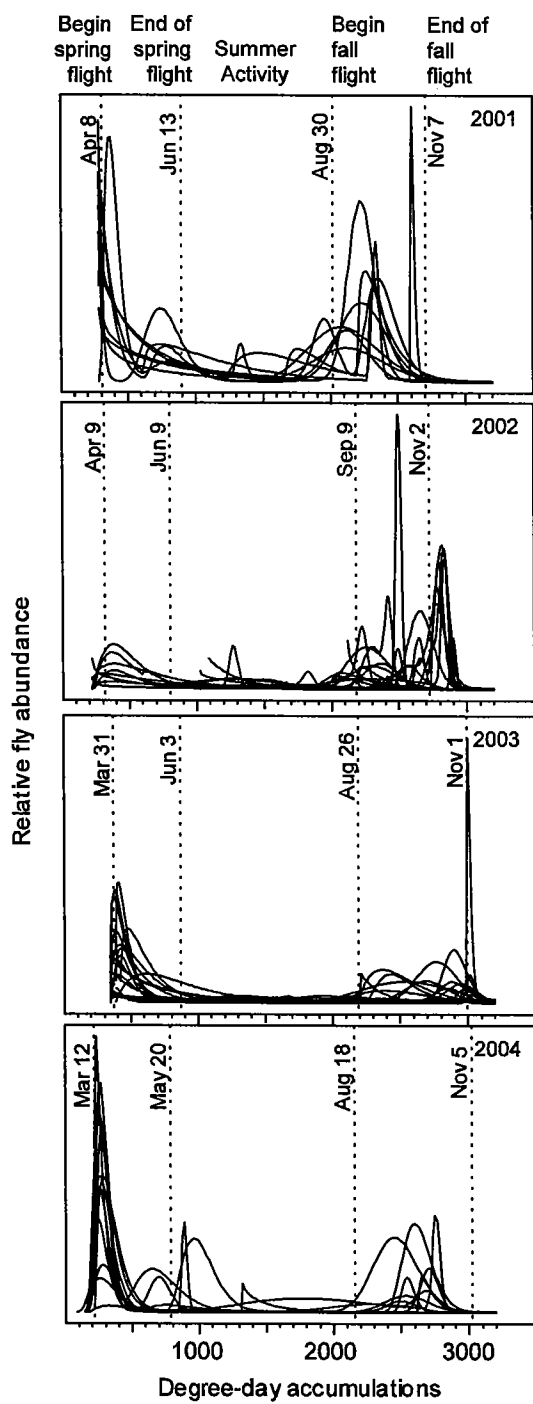


Fig. 2.5. Yearly relative flight activity (using yellow water traps) delineated by phenological seasons by field for 2001- 2004.

2.5.5 Fall Flight Activity

Each year, elevated fly catch rates began in the late summer, roughly coinciding with the onset of fall rains (Fig. 2.4). The fall flush of activity began in mid August to early September (Table 2.5), with an average calendar date over the four years of the study of 28 August, corresponding to DD accumulations of 2138 ± 82.3 (mean \pm SD). The standard deviation of 82 DD corresponds to approximately 5 days at that time of year.

Table 2.5. Summary of fall flights. The beginning and end of the fall flight in degree-days and calendar date.

Year	Initiation of fall flight	End of fall flight (first frost)
2001	2016 (8/30)	2703 (11/7)
2002	2185 (9/9)	2723 (11/2)
2003	2191 (8/26)	2993 (11/1)
2004	2159 (8/18)	3022 (11/5)
Mean	2138 (8/28)	2860 (11/4)
\pm SD	82.3	170.6

Elevated fly catches were greatly reduced as days became shorter (<11 hr), air temperatures cooled, and precipitation increased in November. The end of the fall period is defined as the approximate time of first frost, corresponding to a mean DD accumulation of 2860 ± 170.6 . The standard deviation of 170.6 corresponds to approximately 4 days at that time of year. After that date, adult activity is still possible, but temperatures are too cool to allow significant development of eggs and larvae. The progeny of these late autumn flies

are unlikely to survive through the winter because only pupae have been documented to undergo diapause.

2.6 Discussion

The four seasons in the northern Willamette Valley of western Oregon are characterized by differences in precipitation, photoperiod and temperatures (Fig. 2.1). The seasons coincide closely with distinct phases in the cabbage maggot life cycle as seen in this study:

Spring: emergence of overwintering puparia,

Summer: reduced flight activity,

Fall: flush of flight activity,

Winter: puparia undergo diapause.

In each of the four years of the study, CM flight activity (as measured by numbers of flies caught in yellow water traps) was highest in the spring (45%) and fall (38%) and lower (17%) in the summer (Table 2.4), and close to zero in the winter (data not included). These general patterns of flight broadly coincided with seasonal changes in weather conditions and were consistent among fields and through the years (Fig. 2.5), but more precise descriptions of the emergence and flight activity patterns, delineations of the phenological seasons, and understanding of the dependence of fly activity on environmental factors are discussed below.

2.6.1 Spring Fly Emergence

The bimodal spring emergence pattern that we observed in 2001, 2002, and 2004 has also been noted by other researchers. Such a pattern may be driven by 1) genetic variability

(Collier and Finch 1985, Kostal 1993), 2) differences in climatic and environmental field conditions (Read 1958, Nair and McEwen 1975, Bracken 1988, Tauber et al. 1998), 3) an adaptive response in order to minimize natural enemy pressure, optimize resources and ensure survival during atypical years (Biron et al. 2002), or perhaps 4) the difference in timing of diapause and nutritional status among pupae in the fall. It is not known for certain why a distinct late emergence peak was not observed in spring 2003. Possibly, the late-emerging flies emerged shortly after the early-emergers, so that the late peak partially merged with the early peak. The rival hypothesis that the late peak was decimated by unfavorable weather or some other catastrophe can be discounted because the emergence rate (i.e., the proportion of fall pupae recovered from emergence traps as flies in the spring) was higher in 2003 (72%) than it was in 2001, 2002, and 2004 (55%, 65%, and 63%, respectively). In addition, if it is assumed that there was only one peak in 2003, then the width of that peak (as defined in Materials and Methods) would be 182 DD compared with the much narrower peaks in 2001, 2002, and 2004, which had an average width of 88 DD (Fig. 2.2). An earlier-than-usual emergence of the late-emergers in 2003 would explain the lack of a distinct bimodal pattern and the unusually broad "early" peak in 2003.

It is possible that the environmental conditions in spring 2003 accelerated emergence of the late-emerging pupae, with the result that the second peak occurred early enough to be indistinguishable from the first peak. In particular, a relatively warm January and February in 2003 and abundant rainfall continuing through the onset of emergence (Table 2.1) may have contributed to the relatively early emergence of the late-emerging flies in 2003. The environmental conditions that serve as proximal cause of the breaking of diapause in overwintering *D. radicum* pupae are not known precisely. However, for some insects

moisture-related cues can stimulate emergence or mark the end of aestivation or diapause (Tauber et al. 1998), and *D. radicum* development may be stimulated by rainfall (Nair and McEwen 1975). By contrast, it has also been suggested that greater than normal soil moisture can reduce *D. radicum* development rates, even when temperatures are adequate (Bracken 1988). A possible resolution of this paradox would be that high levels of soil moisture can retard developmental rates but also act as an environmental cue for breaking diapause. We found that despite the abundant rainfall in spring 2003, the end of the spring emergence period required substantially smaller DD accumulation after initiation of emergence than in the other years (Table 2.1A). This suggests: i. *D. radicum* spring emergence may be governed in part by environmental conditions that trigger the breaking of diapause in addition to a DD accumulation that is sufficient for completion of physiological development, and ii. abundant moisture may result in earlier emergence than predicted by DD accumulations.

A comparison of emergence patterns in 2001, 2002, and 2004 also suggests that moisture played a role in governing the timing of emergence. The lags between the first and second peaks were substantially longer in 2001 (497 DD) and 2004 (549 DD) than in 2002 (373 DD). Although DD accumulations in March-May were similar each year (Fig. 2.6) precipitation was near normal in 2002 but substantially lower in 2001 and 2004, suggesting that the second peak may have been delayed by lower than normal precipitation.

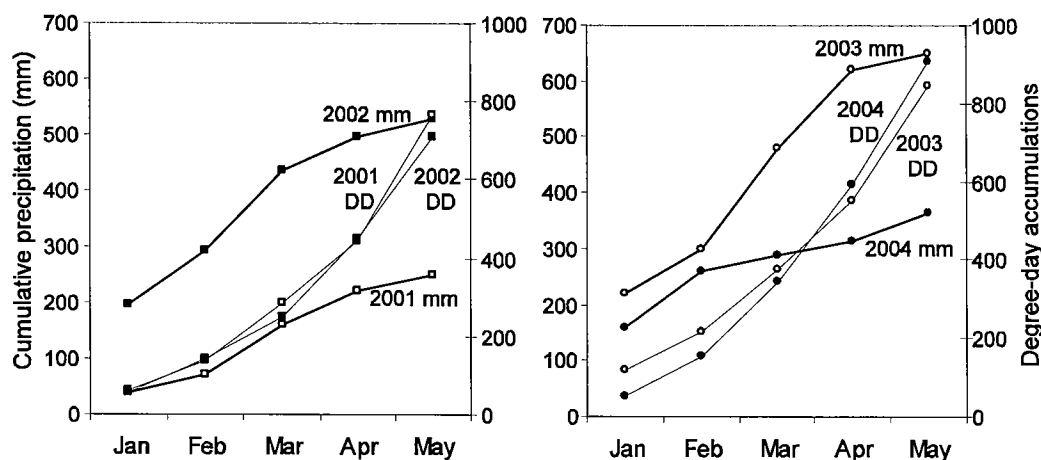


Fig. 2.6. Yearly spring comparisons of cumulative precipitation (mm; solid bold lines) and degree-day accumulations (DD; thinner lines) for (A) 2001 (□) and 2002(■), and (B) 2003(○) and 2004(●).

In the three years that had two distinct peaks, the early-emerging flies constituted approximately 67-74% of the spring population, while only about 29% were late-emerging (Table 2.2). The fraction of flies emerging early in our study was slightly lower than what has been observed in New York, where 71–98% were determined to be early emergers, and slightly higher than reported in North Carolina, where 47–71% of flies emerging in 1987-1990 were in the early peak (Walgenbach et al. 1993). Biron et al. (2003) also reported a predominance of early-emergers (71.4%) in their study of *D. radicum* in Finland.

2.6.2 Spring Flight Activity

We observed delays of 5 days to 3 weeks between fly emergence and flight activity (Fig. 2.3 and Fig. 2.4; Table 2.3), which was similar to observations of other researchers (Collier and Finch 1985; Nair and McEwen 1975). Coaker and Wright (1963) suggested that the magnitude of the time lag between emergence and flight may depend on spring temperature and precipitation regimes, with cool, wet weather delaying flight, which fits

with our observations. In 2002 and 2003, there was substantially more rainfall between emergence and flight than in 2001 and 2004 (Fig. 2.4), and, accordingly, the time lags between emergence and flight were longer (Table 2.3). Interestingly, the lag between the late emergence peak and the late flight activity peak was not apparent in 2004. The unusually dry months and higher spring temperatures during emergence may have facilitated fly movement and maturation and greatly reduced the lag between spring emergence and flight.

2.6.3 Summer Flight Activity

As the spring flight activity of *D. radicum* tapers off in early June, precipitation rates decline substantially and the average daily maximum daytime temperatures rise above 21° C (Fig. 2.1 and Fig. 2.4). Factors possibly contributing to the low trap catch in the summer include: i. aestivation of pupae at high temperatures (> 21° C) (Finch and Collier 1985; Harris and Svec 1966), ii. insufficient soil moisture for pupal development (Nair and McEwen 1975), iii. increased predator, parasite and pathogen activity (Nair and McEwen 1975, Eckenrode and Chapman 1972), and iv. reduced attractiveness of yellow water traps to flies because of increased floral competition (e.g., from wild *Brassicacae*, *Umbelliferae*, etc.).

2.6.4 Fall Flight Activity

An increase in adult activity near the end of August has also been observed by other researchers (Walgenbach et al. 1993). It is unknown whether the beginning of the fall flight is triggered by declining temperatures, shortening of photoperiod, onset of fall rains, sufficient DD accumulation for full physiological development of the fall population,

change in the quality of host plants, other environmental factors, or some combination of these. Nair and McEwen (1975) suggest that high temperatures and dry weather may delay the fall flight. Our data do not show such a relationship. In particular, in 2002 and 2003 trap catches began to rise before significant rainfall was recorded, indicating that the initiation of the fall flight did not depend strongly on rainfall. However, our study was limited to irrigated fields that may have had sufficient moisture even when the weather was relatively dry. Thus, although in some situations precipitation may be a factor, in irrigated fields other factors appear to play a significant role in determining the initiation of the fall flight. Photoperiod is another possible factor (Johnsen and Gutierrez 1997), but because the calendar dates of the initiation of the fall flight were so variable (Table 2.5), it is unlikely that the fall flight depends solely on photoperiod. Also possible is that the fall flight begins as temperatures drop sufficiently below 21°C to bring pupae out of aestivation; however, temperatures in the field during the years of the study were too variable to arrive at a firm conclusion about the role of temperature.

We use the first frost as an environmental indicator for the onset of diapause and the end of the fall flight, but what triggers diapause in the field appears to be some combination of short photoperiod and cool temperatures. Johnsen and Gutierrez (1997) showed that diapause could be induced in the lab by photoperiod dropping below 11 h light at constant temperatures, and Zabiroy (1961) discusses how low temperature can induce diapause directly and can also modify the effect of photoperiod on diapause induction.

2.7 Conclusion

Broad seasonal patterns of adult *D. radicum* activity were similar from year to year: a bimodal emergence pattern in the spring with approximately 45% of total annual of flight activity, lower levels of activity in the summer with approximately 17% of total annual of flight activity, and increased activity again in the fall, with 38% of total annual flight activity. However, the timing of spring emergence and fall flight as a function of DD accumulations can vary widely, even within a relatively small region like the northern Willamette Valley. In our 4-year study of *D. radicum* populations in the Willamette Valley, timing of spring emergence and initiation of fall flight of *D. radicum* adults could be predicted with a simple DD model only to within about 10 days; however, the DD-based predictions were substantially more precise than those based on calendar date alone. A simple DD model omits important primary variables such moisture, photoperiod, and average daily maximum temperatures, and these omissions contribute to the degree of uncertainty in predicting the timing of adult activity. Some variables with indirect effects on *D. radicum* phenology are also likely to contribute to the variability. For example, heavier soils tend to warm up more slowly than lighter textured soils, so flies emerge earlier in sandy loam soils than clay loam soils (Read 1958). It is possible that variation could be reduced somewhat by basing DD models on soil temperatures at individual sites rather than air temperatures at a central regional location (Collier and Finch 1985); however, because of the many sources of variation, it is questionable how valuable more accurate measures of temperature would be in terms of predicting adult activity. In addition, the difficulty of obtaining such data would preclude the development of practical, region-wide alert systems for fly emergence based on soil temperatures.

Despite the imprecision of DD accumulation as a predictor of the timing of activity peaks, DD accumulations provide valuable information that complement flight activity collected from yellow water traps. For example, after water trap counts indicate the beginning of the spring emergence period, the flight activity levels may drop rapidly. However, the DD model predicts a late peak in activity at around 750–800 DD and therefore a continuing threat of high fly activity until DD accumulation of around 900. In addition, the precise timing of the peak and end of the flight can only be confirmed by the water trap data. When the spring flight slows down at approximately mid June, low adult activity levels can be expected until the onset of the fall flight near the end of August.

Understanding flight behavior of *D. radicum* adults is a potentially valuable first step towards managing CM populations in Brassica crops. However, the relationships between adult flight activity, oviposition, crop damage, and environmental conditions must be better understood before specific management recommendations can be made. Some possible management strategies would be to use monitoring and modeling to optimize the timing of: (i) planting and harvesting to avoid high adult activity peaks and oviposition, (ii) insecticide treatments to coincide with high adult flight and subsequent oviposition activity, or (iii) the application of physical barriers such as row covers or exclusion fences just prior to flight activity peaks.

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2.9 Appendix

KS Test for Similarity of Emergence Time Distributions in Different Fields. For each field j , the empirical cumulative probability distribution function (CDF) was constructed as $P_j(T \leq t) = \frac{\text{number of flies emerging in field } j \text{ prior to time } t}{\text{total number of flies caught in field } j}$. Differences in emergence patterns among fields are then reflected in differences in their respective CDFs. The sum of the differences between max and min of the fields' respective CDFs at each sampling date (Δ_{sum}) was used as test statistic to measure the degree of similarity among fields. Smaller values of Δ_{sum} indicate a higher degree of similarity in emergence patterns between fields. Thus, using Δ_{sum} we were able to test the null hypothesis that the distribution of fly emergence times was the same for all fields within a given year using simulation as follows. First, the fly counts from all fields were pooled, and the empirical cumulative probability distribution function of the pooled data was constructed as

$$P(T \leq t) = \frac{\text{number of flies emerging prior to time } t}{\text{total number of flies caught in emergence traps}}$$

empirical CDF was used to simulate the emergence times of the n_j flies captured in the field, and the Δ_{sum} value was calculated for each set of simulated fields. The p -value was then calculated as the proportion of simulated years ($n = 1000$) that had Δ_{sum} value smaller than the observed.

Bootstrap Test of Independence Among Emergence Times in Different Fields. On a given day the standard deviation of trap catches among fields with independent emergence times would be expected to be greater than it would be if the emergence times in the

different fields were synchronized. Thus, a measure of the degree of synchronization between emergence times among fields in year y is the sum of the standard deviations in daily trap counts through the season, or $S_y = \sum_{t=1}^{m_y} s_t$, where s_t is the standard deviation of trap counts among fields on date t and m_y is the number of sampling dates in year y . For each year, the fly catch distribution in each field was simulated via random bootstrap sampling ($n = 1000$) (Efron and Gong 1983) of the trap counts in each field j at each sampling date t . Then, $S_{y(\text{simulated})}$ was calculated for each bootstrap sample. The p -value was then calculated as the proportion of times the observed S_y exceeded $S_{y(\text{simulated})}$.

Permutation Test of Synchronization Among Emergence Times in Different Fields.

As with the bootstrap test described above, the degree of synchronization between fields was measured as the standard deviations of fly emergence trap counts in different fields on a given date were summed over all sampling dates. A permutation test was performed to determine whether the observed degree of synchronization was greater than would be expected if emergence times among the fields were independent but the temporal correlation structure of fly counts within each field was preserved. For each field the order of the trap counts through time was preserved, but the starting date of the emergence pattern was allowed to vary. As the start and end times are allowed to vary, the sampling periods in different fields in the permutations would no longer be synchronized as they are in the original data set. To preserve the original lengths of the time series and to avoid loss of data, the end points of the series were linked to the starting points so that the permutations were conducted with the topology of a circle rather than a line. The average daily standard deviation of starting times among fields was calculated for all permutations of starting dates among the fields. The p -value was then the proportion of the permutations for which the

simulated average standard deviation was less than the observed average standard deviation. In 2003, though, there were emergence cages in 10 fields with 18 sampling dates. Because of the relatively large number of fields, the number of possible permutations is prohibitive (18^{10}), so a random sample of 10,000,000 permutations was used in the test instead of the full set of permutations.

Maximum Likelihood Estimation (MLE) of Bimodal Gamma Distributions. Fitting the bimodal gamma model by maximum likelihood entails finding the parameter values that maximize the product of the likelihoods evaluated at the times that each fly was caught.

Equivalently, the maximum likelihood estimates can be determined by finding the values

$\hat{\alpha}_1, \hat{\alpha}_2, \hat{\beta}_1, \hat{\beta}_2,$ and δ that minimize function $L = -\sum_{i=1}^n \log[f(\hat{\alpha}_1, \hat{\alpha}_2, \hat{\beta}_1, \hat{\beta}_2, \delta | T)]$, where $T =$

{times of emergence of flies caught in the trap}. Since the traps were checked only once per week, the time any given fly emerged is not known precisely. Instead of using precise emergence times, we estimated the time of emergence by assuming that the flies recovered from a trap on a given date were captured at equal intervals since the previous time the trap was checked. For example, if 35 flies were recovered from a trap on 4 March after they had been found empty on 26 February — a period in which 25 DD were accumulated — then individual flies were assumed to emerge at intervals of $25/35 = 0.71$ DD beginning on 26 February. Parameter estimation was done through non-linear optimization using the Matlab[®] function `fmincon`.

**3 MONITORING CROP LOSS BY CABBAGE MAGGOT (DIPTERA:
ANTHOMYIIDAE) IN OREGON BRASSICA ROOT CROPS**

A. J. DREVES, D. DALTHORP, D. BRUCK

Refining and preparing for Journal of Environmental Entomology

3.1 Abstract

Field research conducted from 2001 through 2005 evaluated impact of the cabbage maggot, *Delia radicum* (L.) on Brassica root-crop production. Damage was assessed using a binomial sampling procedure on fields of rutabaga and turnip crops, ranging from 0.8 to 4 hectares. Crop damage, caused by *Delia radicum*, progressively increased by 3.5 times, from a mean CM infestation of 11.9% (± 2.5) in 2001 to 41.4% (± 5.5) in 2005.

Degree-day accumulations in Oregon's northern Willamette Valley were based on the cabbage maggot's lower and upper air temperature threshold of 4.3°C and 30°C using the single sine approximation, starting January 1. A significant correlation was discovered between crop damage and the timing of planting and harvesting. Crop damage was significantly higher: 37 to 52% greater, in crops planted during spring months (< 900 degree-day) compared to summer (> 900 degree-day) or fall months (> 1500 degree-day), respectively. Results validate prior assumptions that cabbage maggot damage is abated by planting after the spring flight (> 900 degree-days) and harvesting before the peak of fall flight (< 2600 degree-days). Rutabaga crops sustained 1.7x higher damage levels (37.9 ± 3.4) than did turnip crops (22.9 ± 1.8). And, in some cases, holding rutabaga crops in the field yielded less damage perhaps due to rutabagas capacity to heal superficial tunneling.

Fly catch, assessed with yellow water traps, was correlated with crop damage at harvest ($r = 0.41$; $P < 0.0001$). Fewer than 100 flies trapped over a root crop's lifetime in a field (≈ 60 -100 day crop) equated to < 20% plants with damage, while > 100 flies resulted > 20% damage (12% error rate). While providing only estimates of seasonal pest population variation, water traps allow useful projections of damage potential.

3.2 Introduction

Cabbage maggot (CM), *Delia radicum* (L.) (Diptera: Anthomyiidae), is the key pest of Brassica root crops (e.g., daikon, rutabaga, turnip, and radish) in northwestern Oregon. Over the course of the five-year study, economic losses attributable to *D. radicum* steadily increased, a situation exacerbated by lack of effective controls and incomplete understanding of contributing ecological and environmental factors. Turnips and rutabagas, the focal crops of this research, are cool season fresh market vegetables planted and harvested from spring through fall months. One maggot tunnel can render an edible root crop unmarketable, resulting in lost income. The injury provides entryways for pathogens, including blackleg (*Phoma*), bacterial soft rot (*Erwinia*), and root rot fungi (*Fusarium* spp.) (Doane and Chapman 1964, Griffiths 1986, Carisse et al. 1998). The long-season Brassicas, such as turnips and rutabagas, are at risk from two generations of CM maggots. In contrast, direct-seeded and transplanted Brassica crops, such as cabbage, cauliflower, and broccoli whose roots are not consumed, are vulnerable to CM injury primarily during the early stages of plant growth. They become increasingly tolerant of later CM attack as root weight and volume increase (Read 1970, Getzin 1978).

In northwestern Oregon, Brassica crops are grown commercially on more than 8,000 hectares and are valued in excess of \$20 million annually (Burt 2005). Approximately 800 hectares of the total are planted in fresh market belowground Brassicas. The potential for damage exists from early- and late-emerging spring CM populations, unpredictable summer populations, and fall-emerging populations in the northern regions of the Valley. Profitable returns on Brassica root crops are directly proportional to yield of roots free from damage.

Host selection by CM females relies on recognition of leaf color and area (Prokopy et al. 1983) as well as volatile chemicals produced by Brassicas (Traynier 1967, Coaker and Smith 1968, Nair and McEwen 1975, Stadler 1978). Females lay white oblong eggs about 1 mm long at the base of host plants (Miles 1951). Eggs hatch within 3 to 7 days, and neonate larvae begin feeding on lateral and main roots. Larvae feed for 2 to 3 weeks, then pupate in the soil and emerge as grey flies, one to two weeks later. A laboratory-controlled study in western Ontario, Canada documented the completion of a single fly generation in 41–65 days (Harris and Svec 1966). However, generation time and number of generations have not been documented in the field for Oregon fly populations.

Todd (1998) has suggested that three to four CM generations occur in western OR and WA, similar to findings reported in southwestern Ontario and southern British Columbia (Mukerji and Harcourt 1970, Nair and McEwen 1975). Earlier both Forbes (1955) and Getzin (1978) reported three generations of CM in the Pacific Northwest, while other researchers located in northwest Washington state described up to 4 or 5 CM generations per year (Carlson 1947). Monitoring CM generations throughout a season will be of critical importance in developing and applying proper management practices for this pest.

Previously, monitoring of *D. radicum* has concentrated on degree-day modeling of the spring emergence period and the seasonal flight as determined by fly trap catches (Coaker and Wright 1963, Eckenrode and Chapman 1972, Nair and McEwen 1975, Wyman et al. 1977, Vincent and Stewart 1981, Collier and Finch 1985, Bracken 1988, Walgenbach et al. 1993, Jyoti et al. 2003, Dreves et al. 2006). Puparia of the fall generation overwinter in the soil. Flies emerge in the spring over a three month period (Read 1958, Finch and Collier 1983, Walgenbach et al. 1993, Biron et al. 2003, Dreves et al. 2006). In the northern

Willamette Valley, spring emergence occurs after an accumulation of 200 air °C degree-days. This value is obtained by using a lower and upper developmental threshold of 4.3°C and 30°C, respectively, starting Jan 1st (Collier et al. 1989, Dreves et al. 2006). A bimodal spring emergence pattern occurs here with 95% of spring flight having occurred by \approx 900 degree-days (approximately early- to mid-June). Flight activity, assessed using water traps, is greatly reduced over the summer months (Harris and Svec 1966, Eckenrode and Chapman 1972, Nair and McEwen 1975, Finch and Ackley 1977, Finch and Collier 1985, Dreves et al. 2006). Flight increases again in the fall after a degree-day accumulation of \approx 2100 (a calendar date of \approx Sept 1) and peaks at \approx 2600 degree-days (Dreves et al. 2006). Puparia produced from this flight enter diapause in the late fall, a result of lower temperature and shortened photoperiod (McLeod 1964, Read 1962, Johnsen and Gutierrez 1997).

Prior to this study, Oregon growers did not monitor CM activity in *Brassicas*. At planting time, application of chlorpyrifos (Lorsban®, organophosphate), is the most widely used method for suppressing damage from *D. radicum* (McGrath et al. 2006). Despite these applications, substantial damage and economic losses continue today (Getzin 1985, Stark 1993, Dossdall et al. 1998).

Effective CM control can be enhanced by a monitoring program. However to be effective, it involves understanding key factors influencing degree of injury. Researchers have cited four: 1) fly activity in field (Sears and Dufault 1986), 2) Brassica crop type (Doane and Chapman 1962, Vandermeer 1989, Dossdall et al. 1994, Baur et al.1996), 3) proximity to a maggot source (Collier et al.1989), and 4) time of season (McDonald and Sears 1992, Todd 1998).

The significance of fly activity, typically assessed from yellow water traps placed near a newly-planted field (Finch 1992, Kostal and Finch 1996), can be difficult to interpret (Bracken 1988). High fly catch numbers in water traps does not necessarily indicate females are going to lay eggs, resulting in crop damage (Sears and Dufault 1986, Bracken 1988). This does not imply that, if few or no flies are caught in a water trap, no flies are in the area and no oviposition will occur (Wyman et al. 1977, Griffiths 1986). Further investigation of the relationship between fly catch and damage will be useful.

Studies have shown significant differences in CM's preference for certain crops. Baur et al. (1996) described CM flies being more attracted to rutabagas than to kales. Host attractiveness to CM continually diminished sequentially from rutabaga, turnip, black mustard, radish through cauliflower (Doane and Chapman 1962). Dossdall et al. (1994) attributed differences in CM's oviposition preference between cultivars of mustards and canola to the fly's relative attraction to variations in volatile chemical stimuli among the plants. A more "attractive" host plant can draw flies away from a less-attractive host (Vandermeer 1989, Boucher et al. 2003). Consequently, improved knowledge of crop attractiveness could lead to improved development of effective trap cropping techniques (Rousse et al. 2003).

Alterations in planting dates and/or harvest dates can be significant in allowing crops to escape damage. Delayed planting has been used since the 1800's to avoid Hessian fly damage in susceptible cereal crops (Buntin et al. 1990). Potatoes planted late in non-rotated fields in Massachusetts suffer less damage from Colorado potato beetle than do crops planted on conventional earlier dates (Voss and Ferro 1990). Early harvest of certain crops has been shown to have a profound effect in reducing subsequent populations of pests. Harvesting early before diapause induction occurs in larvae of pink bollworm and reduces

the number of overwintering larvae to significantly low levels (Ramalho 1994). There is little substantive data in the literature referencing planting and harvest dates as an effective tool for reducing damage from cabbage maggots (Coaker 1987, Collier et al. 1989).

This research presents the impact of CM on turnip and rutabagas in the Willamette Valley. Parameters for a monitoring program to reduce dependence on chemical control are presented. Primary objectives are to: 1) measure the impact of CM by assessing crop damage; 2) define the influence of seasonal planting and harvest dates as they relate to root damage; 3) identify factors influencing crop damage; and 4) present the relationship between flight activity and crop damage.

3.3 Materials and Methods

3.3.1 Site Description

Seasonal root infestation by cabbage maggot, *D. radicum* L., was studied over a 5-year period (2001 through 2005) in the northern Willamette Valley of western Oregon (south of Portland in Clackamas and Marion Counties) (Fig. 3.1), where the core area (> 90%) of Oregon's commercial *Brassica* crops are grown. Monitoring, as described below, was conducted in commercial fields of two long-season root crops, rutabaga (*Brassica napus* cv. Laurentian and American Purple Top) and turnip (*Brassica campestris* cv. Purple Top White Globe). The fields, managed by two growers, were located within 11 km of Oregon State University's Northwest Research Extension Center (NWREC), which houses the regional AgriMet weather station (lat 45°16'55"; long 122° 45'01"; elevation 140') used to collect weather data for this research. The crops were planted on ≈1.6 m wide beds, four

rows per bed in accordance with standard commercial practices. The fields were representative of the region, varying in size from 0.8 to 4 hectares, averaging ≈ 2 hectares. All fields received registered and labeled applications of chlorpyrifos (Lorsban 4E; Dow AgroSciences, Indianapolis, IN; 1.12 kg ai/ha) for maggot control and were fertilized and treated for weeds at planting. Periodic insecticide sprays targeting cabbage flea beetle and aphids were applied.

Because surrounding vegetation may provide both food and shelter for *D. radicum* (Griffiths 1986), it is reported here. The overstory at the field sites was comprised mainly of ash (*Fraxinus*), white oak (*Quercus*), cottonwood (*Populus*), maple (*Acer*), and Douglas fir (*Pseudotsuga*), and understory perennials included wild blackberry (*Rubis*), wild rose (*Rosaceae*), grasses (*Graminaceae*), and herbaceous annuals like wild cucumber (*Echinocystis*) and mustards (*Brassica*). Nurseries, hazelnut orchards, and housing developments bordered many of the fields. Soil types varied but were predominantly loams (Quatama, Newberg, Latourell) and silty loams (Willamette, Woodburn, Cloquato, and Amity). These soils are partially to well drained, with pH's of 5.5 to 7.0.

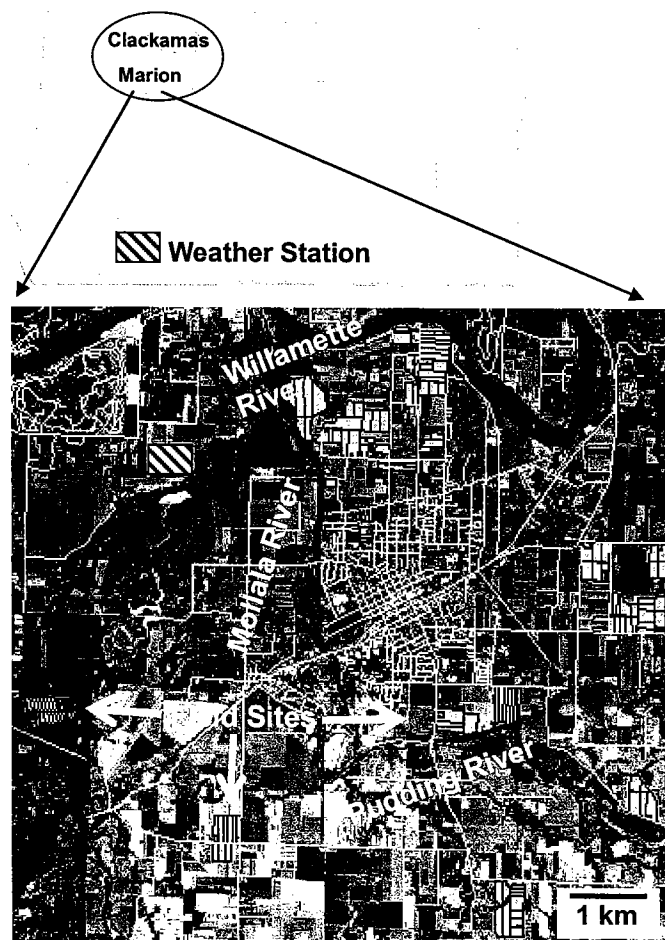


Fig. 3.1. Map of field study sites in northern Willamete Valley, Oregon (Clackamas and Marion counties). Pacific Northwest Cooperative Agricultural Weather Station is located in Aurora Oregon.

Annual precipitation in the northern Willamette Valley is typically 100 cm of which \approx 50 % falls between the four months of November and February. Spring and fall precipitation totals are similar, averaging 24 and 20cm, respectively. Summer precipitation is slight, about 8 cm. Therefore, summer Brassica fields must be irrigated, generally by overhead sprinklers. In the spring and fall, the average daily high temperatures were 17°C

and 24°C, respectively; and daily lows averaged 5°C and 7°C, respectively. Mean daily high temperatures in the summer can reach 27°C in July, with average lows of 10°C. In winter months, the average daily maximum temperature is approximately 10°C with daily lows averaging about 2°C. The first frost is typically around November 1. Snow and extended periods of sub-freezing temperatures are not common in the region.

3.3.2 Crop Damage

To measure crop loss from CM, a total of 180 fields were assessed for damage. The number of fields examined varied annually: 34, 39, 44, 43, and 20 fields in year 2001 through 2005, respectively.

Many studies have assessed crop damage in aboveground *Brassicas* using yield data (Bevins and Kelly 1975), numbers of tunnels (Eckenode and Chapman 1971), and rankings of damage severity (Stitt 1953). Skinner and Finch (1986) estimated CM damage by taking six 10-plant samples at random across a field of 5.0-10 hectare and evaluating the presence or absence of CM.

In this study, a damage assessment was designed for the belowground Brassica crops, similar to the Skinner and Finch (1986) method, but modified as follows. Each field, regardless of size, was divided into six sections: four outside corner locations (NE, SE, NW, SW) and 2 middle locations (midNE, midSW). To minimize edge effect, five meters of buffer row were excluded from samples. Ten plants at each location were randomly selected along a zig-zag (“M”) transect of ≈15 meters into the field. The damage assessment, referred to as “M60”, was initiated at harvest. Sixty plants were removed from the field and their roots inspected for CM tunneling. The proportion of damaged roots was calculated.

3.3.3 Chemical Efficacy

The effectiveness of chlorpyrifos in reducing damage from CM was determined over a five year period by comparing treated plants to untreated plants in 32 commercial growers' rutabaga and turnip fields in the northern Valley. Each treatment consisted of three beds, four rows per bed, nine meters long, replicated two to three times. Chlorpyrifos (Lorsban 4E) was applied at a rate of 0.10 lb ai/1000 row feet, beginning with a broadcast band, not incorporated on seeded rows at planting and 3 additional foliage sprays 14 days apart. Sixty plants from each treatment were randomly selected from the center bed. Roots were examined for the presence/absence of cabbage maggot damage and the proportion of plants with damage was calculated. Pair-wise comparison t-tests ($\alpha = 0.05$) were performed on treated and untreated beds in these commercial fields. The GLM procedure (ANOVA, SAS 9.1 Institute, Inc. 2003-2004) was used to test if any other factors such as crop type, year, season, and planting time affected damage levels.

3.3.4 Weather Conditions

Air temperature (used for degree-day (DD) calculations) and precipitation records (used to help describe flight and explore weather effects on damage levels) were obtained from the regional AgriMet weather station. They were referenced over the 5-year study using three periods, including: 1) previous winter (November and December), 2) pre-flight (January and February), and 2) spring flight period (March through June 1). Degree-day accumulations were calculated for CM development using a lower and upper developmental threshold of 4.3°C and 30°C, respectively, starting January 1st (Dreves et al. 2006). Seasonal field plantings with varying flight and weather conditions included: 23 spring (< 900 DD), 25 summer (900-1500 DD), and 24 fall (> 1500 DD) (Fig. 3.2).

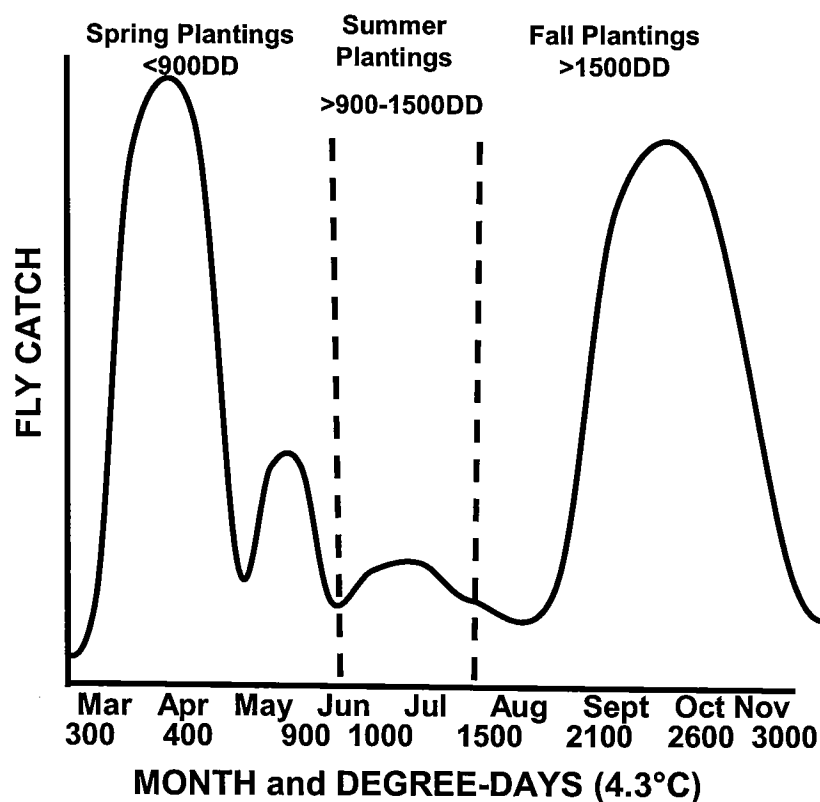


Fig. 3.2. Generalized flight pattern for *Delia radicum* with associated month and degree-days (based on a lower and upper pest developmental temperatures of 4.3°C and 30°C starting January 1 using single sine approximation method) in western Oregon. This pattern can change with weather and location. Three seasonal planting times (spring, summer, and fall) are shown, which are based on flight and oviposition patterns in the northern Willamette Valley.

3.3.5 Planting and Harvest Date

Each year, Brassica field plantings were selected over three distinguished seasons based on CM flight (Dreves et al. 2006): 1) spring plantings (high flight; before ≈ 900 DD; $n = 61$); 2) summer plantings (low flight; 900 DD to 1500 DD; $n = 75$); and 3) fall plantings (after 1500 DD and high flight initiated at 2100 DD; $n = 47$). Further, the early planted fields ($n = 61$) were designated as those crops planted before 95% spring CM flight (< 900 DD), (according to double gamma model from yellow water trap flight data; Dreves et al.

2006) and late-planted fields ($n = 119$) were those planted after 900 DD. Early harvested fields were designated as those crops harvested before the relative minimum peak of fall flight, ≈ 2600 DD and late harvest fields were designated as those crops harvested after the fall peak flight, a DD accumulation of greater than ≈ 2600 . The amount of time a crop remained in the field was calculated by accumulating DD from the elapsed time between planting of the crop until harvest. Damage accumulation rate, or amount of damage sustained per DD in the field, was computed by dividing the time (DD) in the field by the damage level at crop harvest.

3.3.6 Seasonal Flight Activity

Cabbage maggot flight activity was assessed in 71 fields over five years with the use of yellow water traps (Finch 1992). Traps were fluorescent yellow plastic buckets (AmLoid Corp, standard ASTM F-963; Monterrey, Mexico), measuring 18 cm in diameter, 30 cm in depth, and a volume of 5 liters. Buckets were filled with water to within 3 cm of the rim. Two mls of 6% liquid sodium hypochlorite, and a few drops of detergent were added to minimize microbial growth and reduce surface tension. Initially, buckets were set on the soil but later the rim was raised slightly above the plant canopy as the season progressed to harvest. Fly activity was monitored weekly in 9, 21, 23, 14, 4 commercial fields from 2001–2005, respectively. Seventeen of the fields were fall-planted; 26 summer-planted, and 28 spring-planted. One water trap was placed at planting along the border of the north to northeast windward side of each field (Finch and Skinner 1982, Banks et al. 1988). All vegetation was removed from an area of 0.5 meters immediately around the trap (Griffiths 1986). Flies were collected weekly, counted, preserved in 70% EOH and later identified

(Brooks 1951). Traps were cleaned and refilled after each collection. Trap catches were summed across weeks at each field from planting until crop harvest.

3.3.7 Data Analysis

Relationships with damage and effects from year, season crop types, planting dates, harvest dates, and flight activities were analyzed using regression analysis. Percent damage data was analyzed using a linear analysis of variance model (ANOVA, Proc GLM; SAS 9.1 Institute, Inc. 2003-2004). To improve normality and homogenize variances, arcsine-square root transformations were used on damage proportions. For multiple mean comparison of year, season, early and late plantings and harvestings, Tukey's honestly significant difference (HSD) was used. Significance was established at $\alpha = 0.05$. In all cases, actual, rather than transformed data are presented. Independent sample t-tests were used to determine differences in population parameters and to compare damage between crop types, (rutabagas and turnips). Relationships between damage level (function of number of infested roots per field), year, season, crop type, planting date, harvest date, time in field were tested using regression analyses (SAS 9.1 Institute, Inc. 2003-2004). Correlations were tested between planting date, harvest date, and time in field using a Pearson correlation coefficient.

3.4 Results

3.4.1 Crop Damage

Cabbage maggot damage levels steadily increased over the five year study period (Fig. 3.3). Yearly differences in damage levels were significant ($F = 10.31$; $df = 5, 175$; $P <$

0.0001) (Table 3.1). Damage increased by 3.5x, from a mean damage of 11.9 ± 2.5 (mean \pm SEM) in 2001 to 41.4 ± 5 in 2005. Within a given year, damage levels varied among fields with significant dependence on planting date ($P < 0.0001$), harvest date ($P < 0.0001$), crop type ($P < 0.0001$). Damage levels were not significantly different between the two growers' fields ($F = 1.03$; $df = 2, 174$; $P = 0.31$). Differences in field sizes yielded no apparent differences in damage levels ($F = 0.87$; $df = 1, 174$; $P = 0.39$). This non-significance allowed data for the different growers and different field sizes to be combined for data analysis.

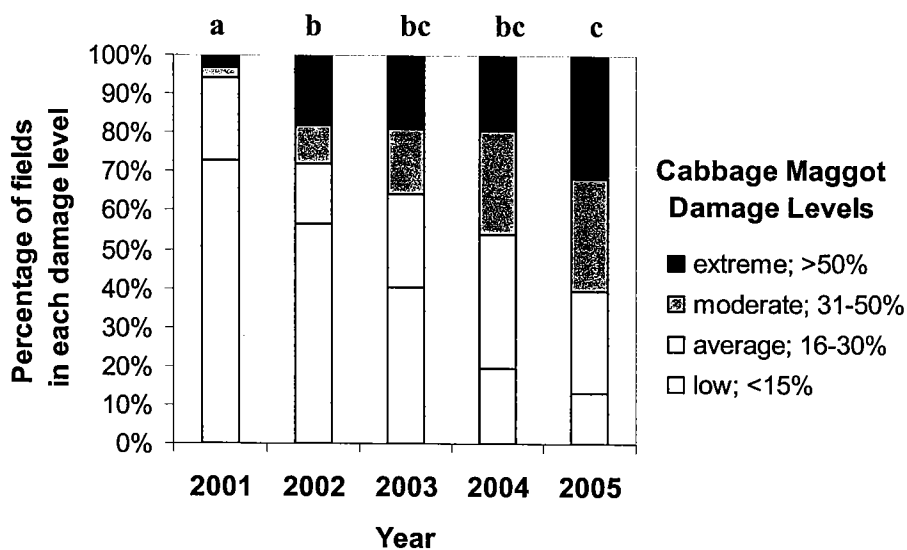


Fig. 3.3. Yearly comparison of crop damage levels caused by *Delia radicum* (L.) in commercial Brassica root crops (rutabaga and turnip) in the northwestern Willamette Valley, Oregon, 2001-2005.

Table 3.1. Comparison of cabbage maggot damage by crop type in the northern Willamette Valley over a 5-year study period.

Percent root damage by <i>Delia radicum</i> affecting rutabaga and turnip crops						
Crop Type	All years	2001	2002	2003	2004	2005
Rutabaga	37.2 ± 3.4a	16.2 ± 6.3a	37.4 ± 7.3a	37.2 ± 6.1a	45.4 ± 6.7a	57.6 ± 10.3a
Turnip	23.0 ± 1.8b	9.9 ± 2.2a	18.5 ± 4.3b	24.3 ± 3.3b	30.4 ± 3.4b	34.5 ± 4.9b
# fields: R, T	57, 123	11, 23	13, 26	14, 30	13, 30	6, 14
<i>t</i> -test	4.16	1.29	2.68	2.05	2.26	2.32
Df	178	32	37	45	41	18
<i>P</i>	< 0.0001	0.207	0.011	0.047	0.029	0.033

3.4.2 Chemical Efficacy

To evaluate the effectiveness of chemicals used for control of CM, thirty-two on-farm commercial plot studies (each replicated 2-3x) were established in the Brassica growing region. Factors such as year ($P = 0.36$), crop type ($P = 0.54$), season ($P = 0.20$), and planting and harvesting date ($P = 0.11$) showed no effect on differences in damage levels between treated and untreated plots in these small-scale plot studies, so data were pooled. There were no significant differences between the untreated (28.2 ± 4.2) and treated plots (26.1 ± 4.1) of turnips and rutabaga crops ($t = 0.75$; $df = 31$; $P = 0.46$) (Table 3.2). However, yearly damage levels were 35% higher in the untreated plots in 2001 and 2002, and 10% higher in the treated plots in 2003, 2004, and 2005; none of these differences were significant. No significant differences in damage between untreated and treated plots were seen in 2002 ($P = 0.06$) and in 2005 ($P = 0.08$).

Table 3.2. Mean damage comparison (\pm SEM) for chlorpyrifos-treated and untreated Brassica root crops located at commercial farms in northwestern Willamette Valley.

Year	# of fields	Mean percent cabbage maggot damage (\pm SEM) (60 roots sample / treatment/ 2-3 reps)		t statistic p value
		Untreated beds	Treated beds	
2001	5	21.7 \pm 7.8a	13.8 \pm 5.5a	$t = 1.76$ $P = 0.15$
2002	7	39.0 \pm 7.9a	26.7 \pm 6.4a	$t = 2.27$ $P = .06$
2003	10	24.9 \pm 8.5a	28.5 \pm 8.3a	$t = 1.47$ $P = 0.18$
2004	7	23.8 \pm 1.1a	24.9 \pm 1.1a	$t = 1.15$ $P = 0.29$
2005	3	35.0 \pm 1.6a	40.3 \pm 1.8a	$t = 3.27$ $P = 0.08$
Mean \pm SEM	32	28.2 \pm 4.2a	26.1 \pm 4.1a	$t = 1.0$ $P = 0.46$

3.4.3 Weather Conditions

Temperature (expressed as pest DD accumulation) and precipitation (mm) were examined for yearly differences in flight activity, and, ultimately, on damage levels (Table 3.3). The first year of study (2001) occurred during an exceptionally dry and cool year and initiation of spring flight was delayed compared to the ensuing years. Flight in 2002 was also delayed perhaps due to the cool temperatures and low degree-day accumulation during the pre-flight (Jan-Feb) and spring flight period (Mar-May). Crop damage caused by CM in 2001 and 2002 were lower in comparison to the other 3 years. In 2005, CM damage was significantly higher ($P < 0.0001$). Temperature was warm during the spring flight period (with a high accumulated DD value) and precipitation fell during initiation of flight, most likely stimulating pupal emergence. In 2003 and 2004, ample moisture and high DD accumulations were acquired through the spring period resulting in early emergence and

flight. Crop damage was not statistically different between 2002 (24.8 ± 4.0), 2003 (28.4 ± 3.1), and 2004 (34.9 ± 3.2), however damage continued to increase during each consecutive year of the study.

Table 3.3. Yearly total precipitation (mm) and degree-day accumulation (DD) documented for 3 time periods of overwintering puparia development: 1) previous winter (Nov-Dec); 2) pre-flight (Jan-Feb); and 3) spring flight (Mar-May). A low (L), average (A), and high (H) code relative to the 30-year average of precipitation and temperature are listed next to the actual values.

Year	Precipitation (mm)			Degree-day accumulation (4.3°C)		
	Previous Winter (Nov – Dec)	Winter Pre-Flight (Jan – Feb)	Spring Flight (Mar – May)	Previous Fall (Nov – Dec)	Winter Pre-Flight (Jan – Feb)	Spring Flight (Mar – May)
2001	L - 157	L - 72	L - 177	L - 138	L - 139	A - 628
2002	H - 389	H - 292	A - 234	H - 255	A - 145	L - 566
2003	A - 336	H - 298	H - 305	H - 234	H - 217	A - 626
2004	H - 384	A - 260	L - 103	L - 154	A - 156	H - 749
2005	L - 164	L - 62	H - 330	A - 172	H - 173	H - 711

3.4.4 Planting Date (Degree-Day Accumulation)

The date of planting had a significant influence on damage levels in all years ($F = 15.27$; $df = 1, 178$; $P < 0.0001$), except in 2005 ($P = 0.37$). Crops planted early in the spring (before 95% spring flight; < 900 DD) had significantly more damage than did late-planted crops (after 95% spring flight; ≥ 900 DD) ($F = 19.62$; $df = 2, 178$; $P < 0.0001$) (Fig. 3.4). The mean percent damage reported on crops planted early ($n = 60$) was 37.5 ± 2.9 (mean \pm SEM), while crops planted later, after spring flight, ($n=120$) averaged 22.5 ± 1.9 . Crops planted early in the season had 38% more damage than did late-planted crops.

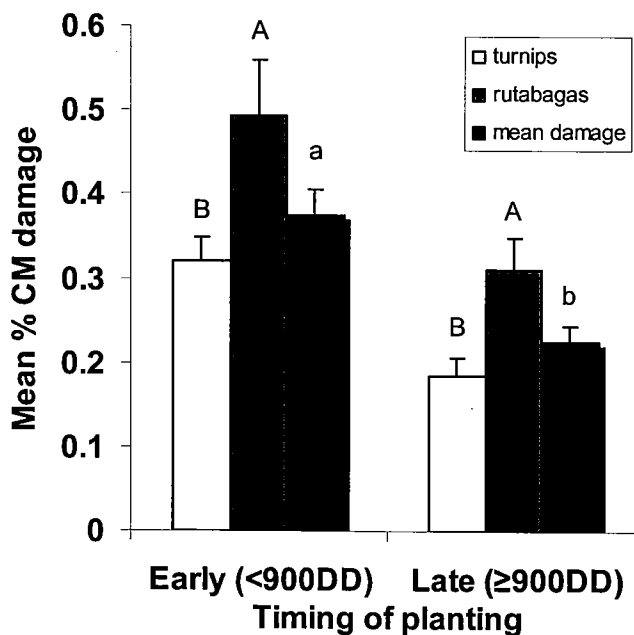


Fig. 3.4. Mean crop damage comparison between rutabaga and turnip crops planted at early and late seasons in western Oregon.

Three planting seasons (spring, summer, and fall) were investigated to determine variations in crop impact caused by *D. radicum*. Differences in damage were apparent between planting seasons ($F = 12.89$; $df = 3, 177$; $P < 0.00091$) (Fig. 3.5). Overall, crops planted in the spring season (before 95% spring flight was completed; < 900 DD) had significantly higher damage levels than did summer-planted and fall-planted crops. Damage to spring-planted crops was 34% higher than summer-planted crops, and 52% higher than fall-planted crops. Crop damage to summer-planted crops, a mean damage of 25.0 ± 2.5 , was not significantly different than damage occurred by fall-planted crops, with a mean damage of 18.4 ± 2.8 . Significant yearly variations in seasonal damage were revealed ($F = 13.73$; $df = 7, 173$; $P < 0.0001$) (Fig. 3.5). No significant differences in seasonal damage were found in 2005 ($P = 0.88$), and significant differences in 2001 ($P = 0.05$); but highly

significant differences in damage were reported between seasonal plantings in 2002, 2003, and 2004 ($P = 0.03, 0.0015, 0.0006$, respectively). In these same three years, mean damage in spring-planted Brassica was 13-52% higher than in summer plantings; and summer plantings were 30–60% higher in damage than were fall plantings. In 2003, damage in fall-planted crops was slightly greater (9%) than in summer-planted crops, but the difference was not significant. In 2002, damage levels between spring and fall-planted crops only were significantly different ($P = 0.03$).

Table 3.4. Yearly comparison of cabbage maggot damage between early and late plantings of Brassica root crops.

Planting Date	Percent Root Damage by <i>Delia radicum</i> affecting Brassica Root Crops				
	2001 (N)	2002 (N)	2003 (N)	2004 (N)	2005 (N)
Early planting < 900 DD	(12) 19.9 ± 6.1a	(13) 33.9 ± 5.9a	(16) 40.4 ± 5.1a	(15) 50.0 ± 6.6a	(4) 43.3 ± 5.8a
Late Planting ≥ 900 DD	(22) 7.5 ± 1.6b	(26) 20.2 ± 5.0a	(28) 21.5 ± 3.3b	(28) 26.9 ± 2.8b	(16) 41.0 ± 6.3a
<i>F</i>	5.95	3.50	10.73	15.72	0.04
<i>df</i>	1, 32	1, 37	1, 42	1, 41	1, 18
<i>P</i>	0.02	0.07 NS	0.002	0.0003	0.84 NS

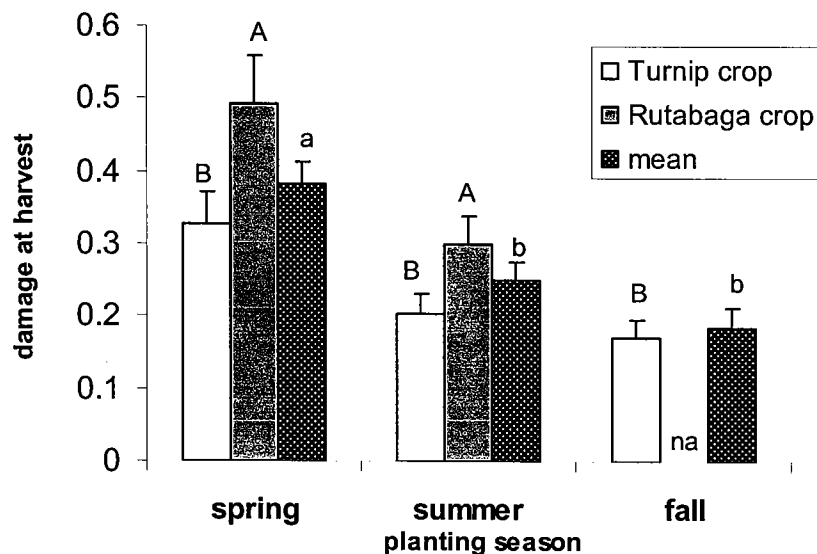


Fig. 3.5. Mean comparison of cabbage maggot damage affecting turnip and rutabaga crop plantings at three different seasons collected over a 5- year period, 2001-2005.

3.4.5 Crop Type

There were significant differences in damage between the two crop types studied at each planting season ($F = 17.3$; $df = 1, 178$; $P < 0.0001$) (Fig. 3.5). Rutabaga crops matured in ≈ 100 days after seeding, three weeks longer than for turnip crops. Root damage in rutabaga crops ($n = 57$ fields) was found to be significantly higher, averaging 37.2 ± 3.4 , while turnip crop damage ($n=123$) averaged 23.0 ± 1.8 ($t = 4.16$; $df = 178$; $P < 0.0001$). Rutabaga crops had 38% greater damage levels at harvest than did turnip crops.

Table 3.5. Yearly seasonal differences in crop damage caused by cabbage maggots.

Season	Seasonal % Root Damage by <i>Delia radicum</i> affecting Brassica Crops				
	2001 (N)	2002 (N)	2003 (N)	2004 (N)	2005 (N)
Spring	(12) 19.9 ± 6.1a	(13) 33.9 ± 5.9a	(15) 42.8 ± 4.9a	(15) 50.0 ± 6.1a	(3) 47.8 ± 5.3a
Summer	(14) 8.7 ± 2.1b	(14) 27.9 ± 7.8ab	(18) 20.1 ± 3.7b	(17) 30.1 ± 3.5b	(12) 40.6 ± 7.6a
Fall	(8) 5.5 ± 2.3b	(12) 11.3 ± 5.4b	(11) 22.3 ± 6.0b	(11) 21.8 ± 4.5b	(5) 39.6 ± 9.6a
<i>F</i>	3.31	4.06	7.61	8.93	0.13
df	2, 31	2, 36	2, 41	2, 40	2, 17
<i>P</i> -value	0.050	0.026	0.0015	0.0006	0.88

Damage found in rutabaga crops was significantly higher than that found in turnip crops, averaging 1.6x higher in 2002 through 2005 (P values = 0.01, 0.04, 0.02, 0.03, respectively); while no differences in damage were observed between crop types in 2001 (P = 0.20). After accounting for planting date (P < 0.0001), year (P < 0.0001), and crop type (P < .0021), differences in crop damage were highly significant. The mean damage reported in rutabaga crops was suggestively but inconclusively affected by planting date (P = 0.06), and only in 2003 and 2004. However, turnip crops were significantly effected by the planting date (P = 0.0023). The later turnip crops were planted, the less damage. No significant interactions were seen between planting date and crop type (F = 0.82; df = 4, 176; P = 0.366), so in fact both crops were affected by planting date in a similar same way, viz. higher damage in crops planted earlier.

Crop damage was significantly different between crop types at two different seasons of planting, spring and summer (F = 12.89; df = 2, 177; P < 0.0001) (Fig. 3.5; Table 3.6). Fall planting season was not analyzed for crop type comparisons, as rutabagas — due to their slow maturation — are rarely planted that late in the year. Significant differences between crop types were observed both in the spring (P = 0.018) and summer planting season (P =

0.026). Rutabaga damage was significantly higher (35%) than turnip damage in spring-planted crops; and 33% higher than turnip damage in summer-planted crops.

Table 3.6. Seasonal differences in crop damage between rutabaga and turnip crop from year 2001 through 2005.

Crop Type	Seasonal Mean Root Damage (± SEM)		
	Spring	Summer	Fall
Rutabaga	49.36 ± 6.53a	30.09 ± 3.81a	NA
Turnip	32.72 ± 4.56b	20.23 ± 2.84b	16.96 ± 2.71
N (Ruta, Turn)	19, 39	38, 39	na, 43
df	1, 56	1, 76	-
F	5.95	1.75	-
P-value	0.018	0.026	-

Also, rutabaga damage was 39% higher in spring plantings ($F = 3.38$; $df = 1, 56$; $P = 0.04$); and turnip damage was 38 and 48% higher in spring plantings than in summer and fall plantings, respectively ($F = 9.45$; $df = 2, 120$; $P = 0.0002$). However no damage differences were seen between summer- and fall-planted turnips. When studying effects from early and late-plantings, damage was significantly higher in both early-planted (49.8 ± 6.5) and late-planted rutabaga crops (29.9 ± 3.4) compared to turnip crops, a mean damage of 32.0 ± 2.8 and 18.5 ± 2.1 , respectively ($t = 2.65$; $df = 56$; $P = 0.0095$, $t = 3.28$; $df = 120$; $P = 0.0014$, respectively).

3.4.6 Crop Type Comparison

Damage comparisons between rutabaga crops versus turnip crops were analyzed in 28-paired fields over a course of five years. The pairs of rutabaga and turnip crops were planted in close field proximity to one another (within <15 meters), treated similarly throughout the growing season, planted on approximately the same date (± 4 days), and

assessed on the same date. Yearly variation ($F = 1.89$; $df = 4, 28$; $P = 0.15$) and season of planting ($F = 1.19$; $df = 2, 28$; $P = 0.29$) did not show any effect on differences in damage between crop types. A paired t-test showed significant differences in damage levels between rutabaga and turnip crops ($t = 5.34$; $df = 27$; $P < 0.0001$). Rutabaga crops had almost twice the damage than turnip crops, averaging 37.6 ± 4.6 compared to 19.0 ± 2.2 , respectively.

3.4.7 Harvest Date

Cabbage maggot damage levels were not only affected by yearly variation, planting date, season, and crop type, but also by timing of harvest. Timing of harvest date had a significant effect on level of crop damage ($F = 12.07$; $df = 1, 178$; $P = 0.0006$). Damage levels increased by 34% with later harvest dates (after the relative fall peak flight; > 2600 DD) compared to early harvest dates (before fall peak flight; < 2600 DD).

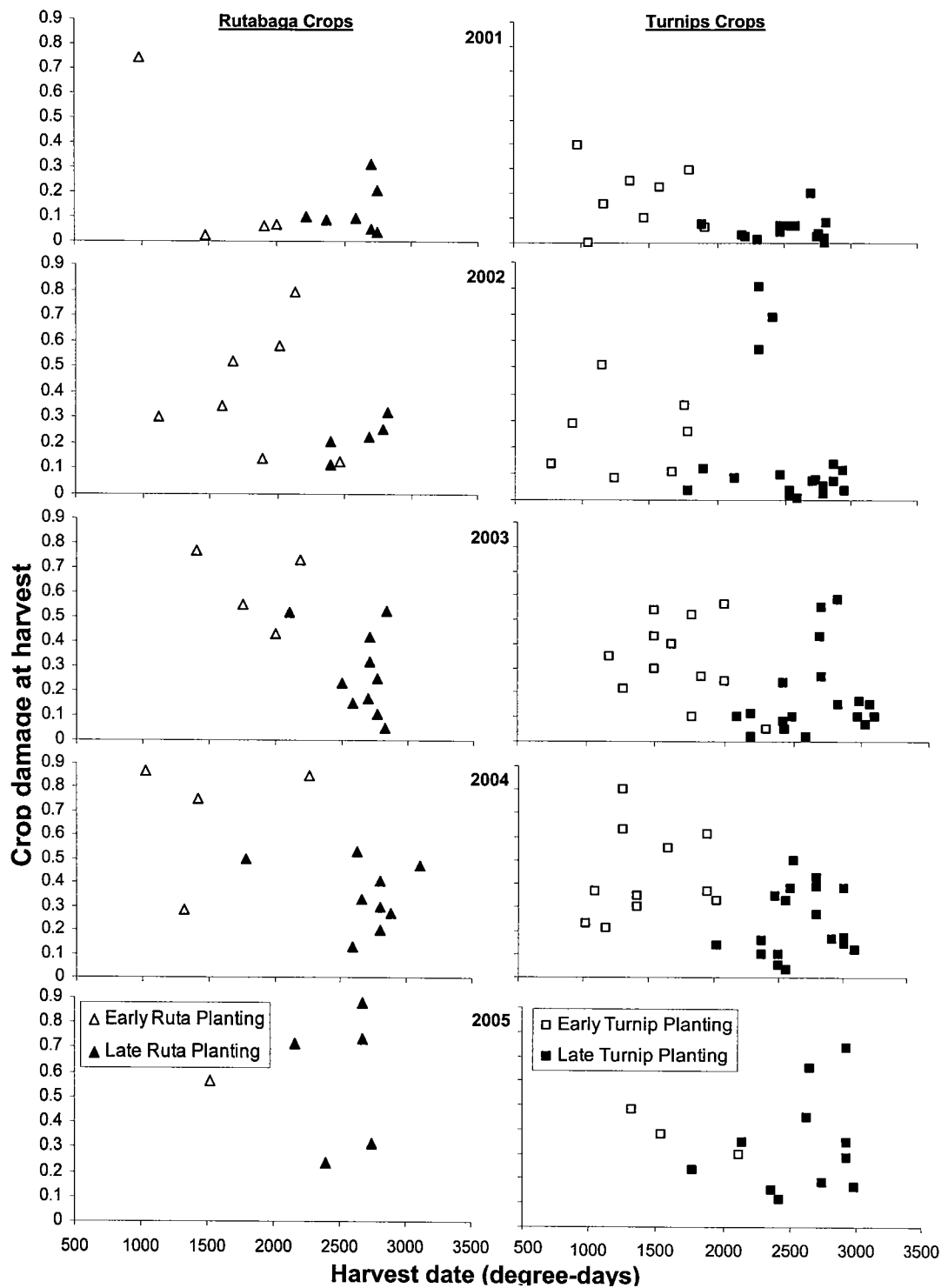


Fig. 3.6. The effect of early and late planting and harvest dates of turnip and rutabaga crops on damage at harvest in yr 2001 through 2005.

The effect of planting date and early and late harvest date (>2600 DD) on crop damage was significant ($F = 25.95$; $df = 3, 177$; $P < 0.0001$), specifically turnip crops planted in 2003 and 2004 ($F = 174.2$; $df = 3, 120$; $P < 0.0001$) (Fig. 3.6). Turnips planted later during the summer season (> 900 DD) had less than one third the damage (11.2 ± 3.3 (mean \pm SEM), compared to early spring plantings (38.4 ± 5.3), unless harvested after the relative fall flight peak (≈ 2600 DD); in which damage increased by 2x, averaging 27.2 ± 4.9 (Fig. 3.7) as shown in three turnip fields in 2003. In the two years that was significant, planting late and harvesting early revealed 70% less damage than reported in crops planted over the spring season.

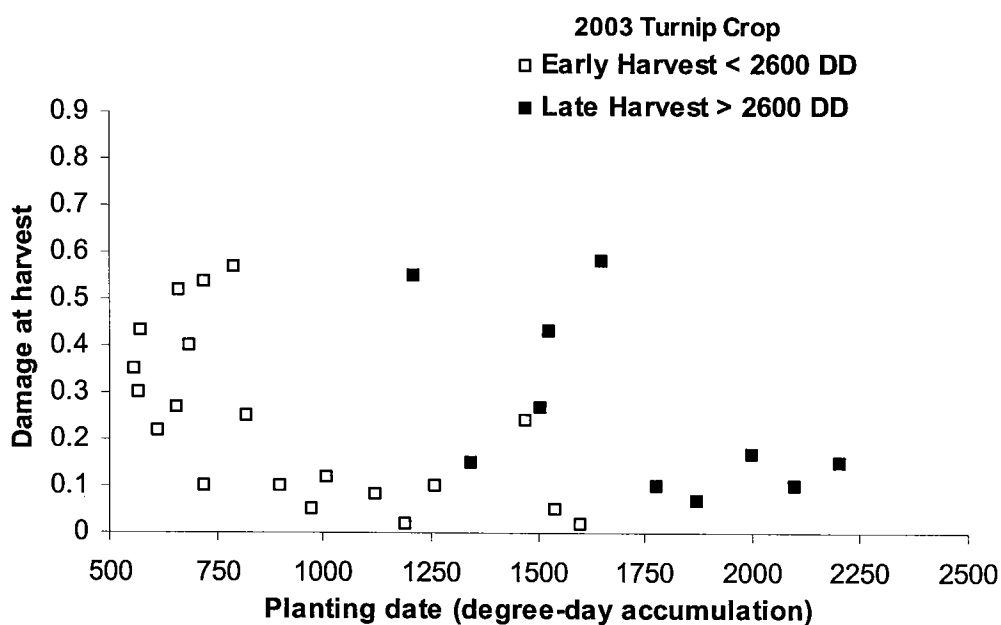


Fig. 3.7. Effect of early and late harvest dates on maggot damage in relationship to early and late planting dates as seen in turnip crops planted in 2003.

However, in some cases (2003) the longer amount of time rutabaga crops were in the ground, little to no increase in damage resulted. Harvest time had no significant effect on rutabaga crops ($P = 0.88$). In fact, less damage was observed in many cases for turnip crops. No differences in damage between early and late harvest resulted. However, crop damage was less than half, averaging 65.5 ± 10.8 (early planting, early harvest date) to 30.0 ± 4.3 (late planting, late harvest date) in years 2003 and 2004.

Damage was lower for crops planted after spring period (> 900 DD), but harvested before fall flight (< 2600 DD; relative minimum of fall phenology curve). Damage was lower when crops were planted after midsummer 1500 DD, a calendar date of about August 1. Less damage was observed when crop was harvested early (before initiation of fall flight; ≈ 2100 DD) than if harvested late after relative minimum of fall flight (2600 DD). Fig 3.8 and Fig. 3.9 are visual displays of crop damage at harvest in 2001 and 2003 showing differences in planting date and harvest date and their affect on damage levels for crop types. The dashed lines in Fig. 3.8 and Fig. 3.9 point back from harvest date to the plant date for each field.

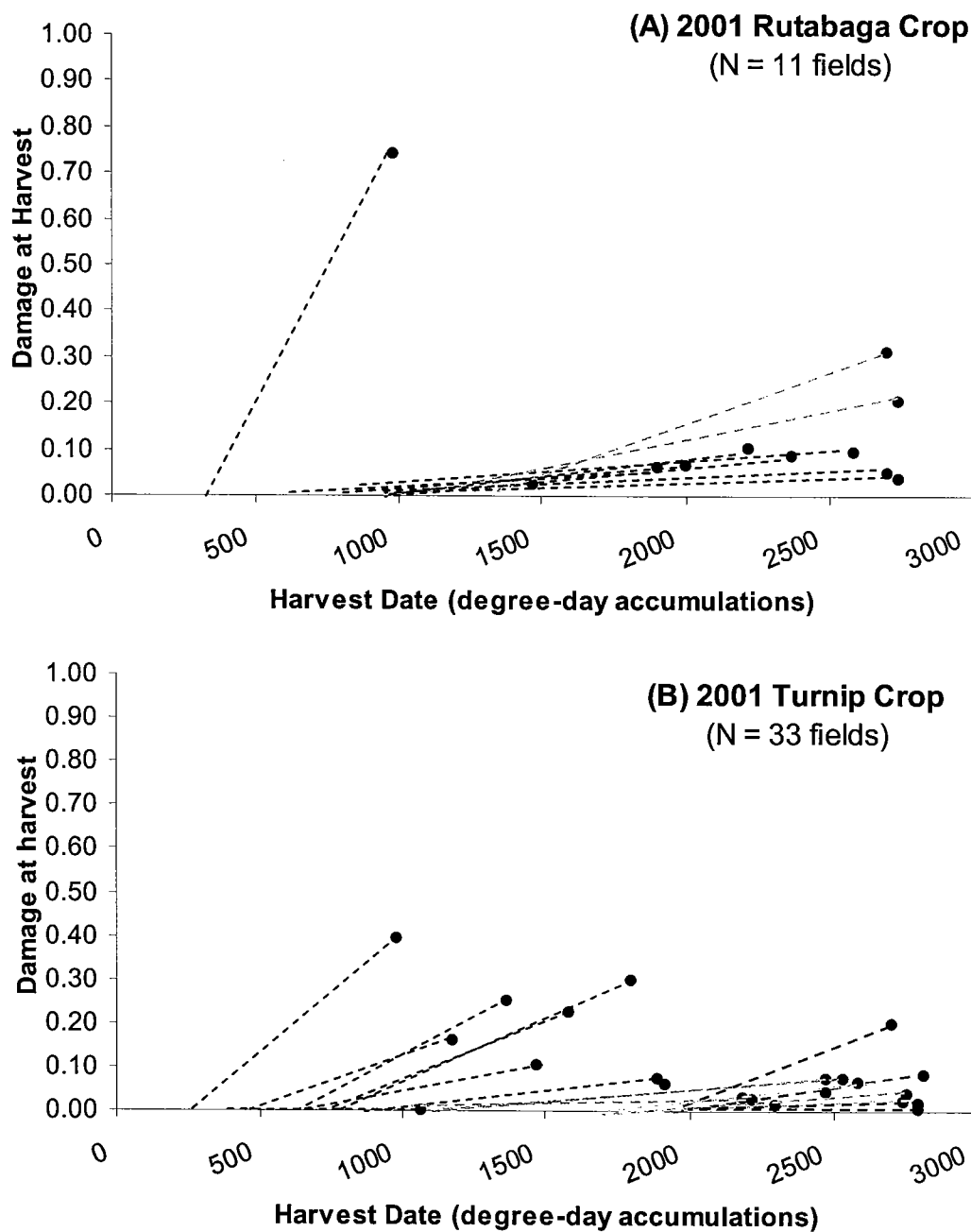


Fig. 3.8. Relationship of planting and harvesting dates to *D. radicum* damage at harvest of (A) rutabaga crops and (B) turnip crops in 2001. Dotted lines run from planting date on x-axis to harvest date.

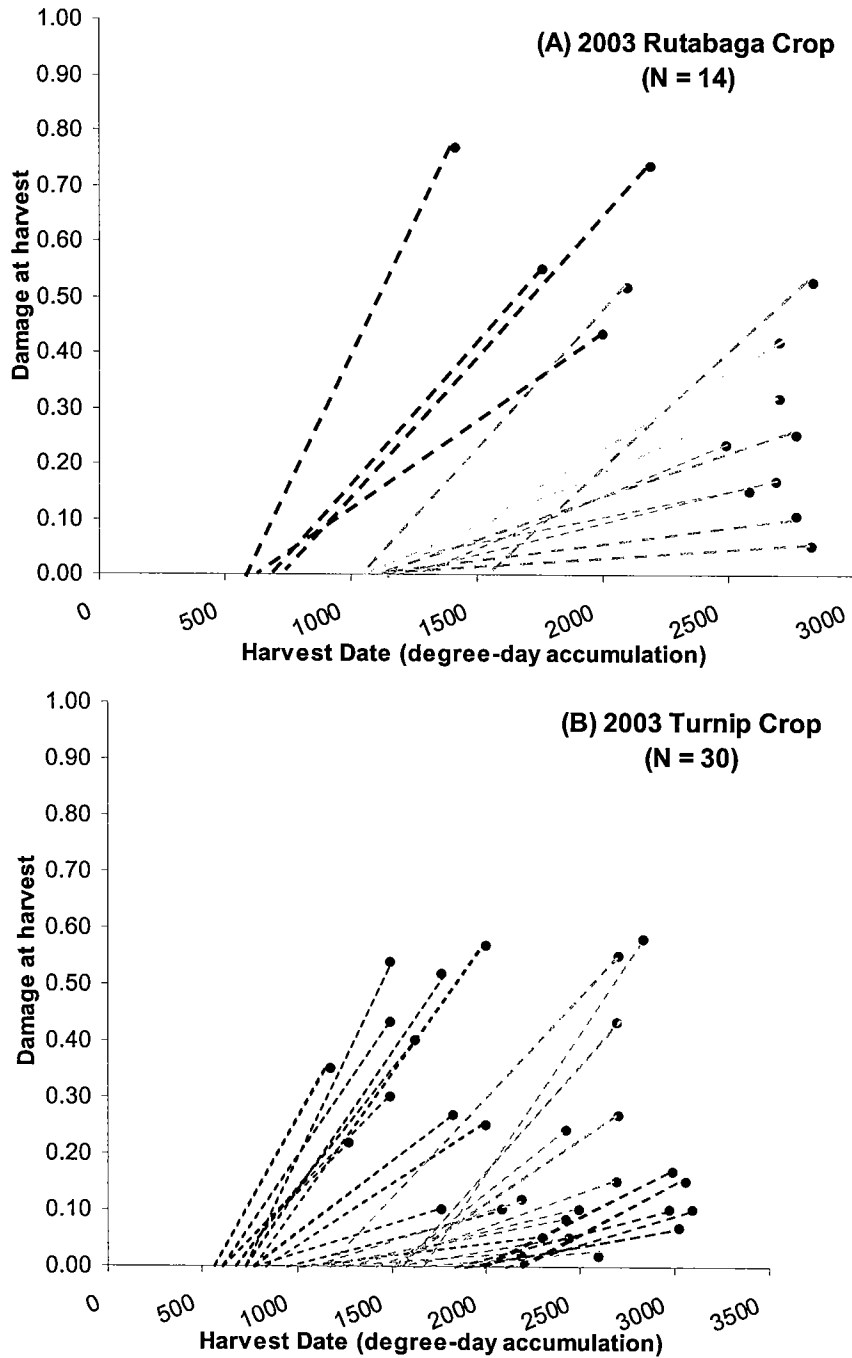


Fig. 3.9. Relationship of planting and harvesting dates to *D. radicum* damage at harvest of (A) rutabaga crops and (B) turnip crops in 2003. Dotted lines run from planting date on x-axis to harvesting date.

3.4.8 Damage Accumulation Rate and Time in the Field

Turnips planted later showed a significantly slower damage accumulation rate (amount of damage sustained per degree day in the field), unless harvested after the start of the fall flight peak, in which case planting date was less pronounced (Fig. 3.10). This interaction was not seen in turnips planted in 2004 ($P = 0.12$). Overall, the length of time (DD accumulation) a Brassica crop is in the field did not significantly affect damage levels ($t = 0.95$; $df = 1, 178$; $P = 0.346$). However, the length of time a crop remains in a field affects damage levels of crop types differently. Rutabaga crops required a mean DD accumulation for maturity of 1362 DD (equivalent to ≈ 100 days), while turnips only required 988.6 DD (equivalent to ≈ 78 days). Rutabaga damage was significantly affected by the length of time crop was present in the field ($t = 2.26$; $df = 1, 55$; $P = 0.028$). The longer rutabaga crops were in the field the lower the damage ($t = 3.14$; $df = 1, 12$; $P = 0.0085$). When analyzing the combined effects of planting date and time in the field on damage level, significant effects were specifically observed in rutabagas in 2003 ($F = 12.62$; $df = 2, 177$; $P < 0.0001$) (Fig. 3.11). Later plantings of rutabagas (> 900 DD) had comparable low damage levels when the crop remained in the field longer (mean 1552 DD; about 107 days) compared to an earlier harvest at 1302 DD (≈ 84 days), from 26.11 to 30.0%. No significant effect from length of time in field on damage was reported in turnip crops ($t = 0.08$; $df = 1, 121$; $P = 0.936$). Damage in late plantings of turnips increased with increasing DD accumulation, from 9.1% crop damage (1094 DD; 69 days) to 25.6 % (1172 DD; about 88 days). Pearson correlation coefficient was used to look at rutabaga crop damage as a measure of strength of the linear relationship between variables including harvest date, time in the field and planting date. Harvest date was strongly correlated with both crop time in the field ($r = 0.75$; $P = 0.0017$;

$r^2 = 0.58$) and planting date ($r = 0.81$; $P = 0.0004$; $r^2 = 0.66$), but planting date was not correlated with time in the field ($r = 0.24$; $P = 0.40$; $r^2 = 0.06$).

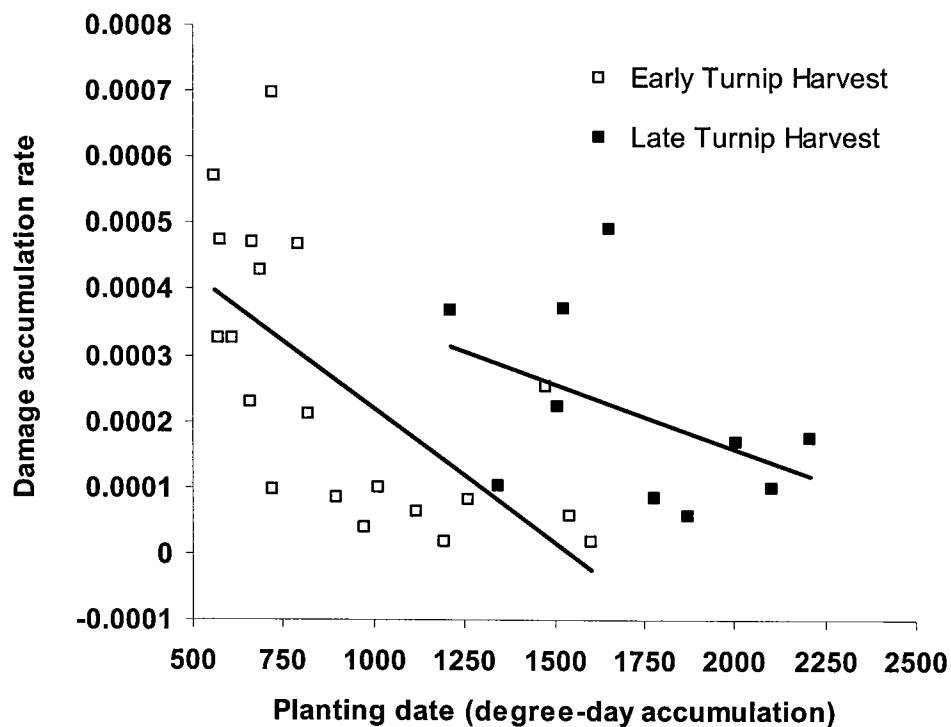


Fig. 3.10. Effect of early and late harvest dates on amount of damage crop sustains per degree day in the field (damage accumulation rate) in relationship to early and late planting dates, shown in turnip crops planted in 2003.

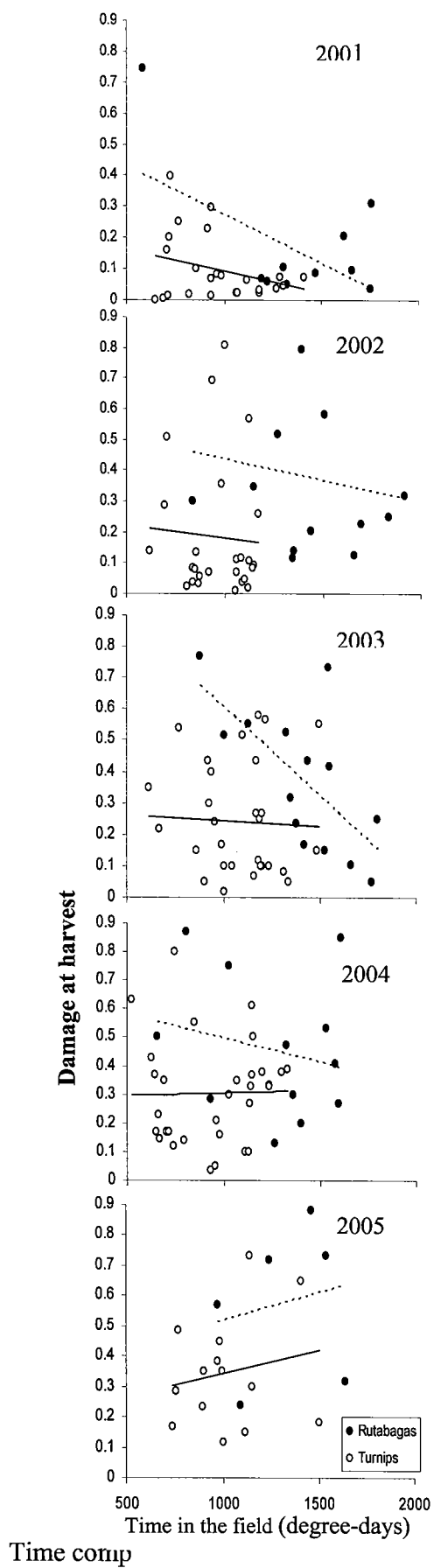


Fig. 3.11. Damage comparison of rutabaga (solid dots) and turnip crops (open dots) in relationship to their time in the field in years 2001 through 2005.

arin of rutabaga and turnip crops in

3.4.9 Planting and Harvesting Schedule

Different combinations of planting and harvesting times in fields significantly affected crop damage levels over the five years studied ($F = 16.39$; $df = 3, 177$; $P < 0.0001$). Damage levels were higher in fields planted in spring (< 900 DD) and harvested in the summer (< 2600 DD), an average damage level of 38.6 ± 3.0 (mean \pm SEM). Fields planted in the summer and harvested in the summer had an average damage of 16.5 ± 2.7 ; fields planted in the summer and harvested in the fall (> 2600 DD), had an average crop damage of 24.8 ± 2.4 . However, fields planted in the summer and harvested in the summer were not significantly different than fields planted in the summer and harvested in the fall as shown by Tukey's mean separation test ($P = 0.05$). In 2003 and 2004, differences in the timing of planting and harvest dates both clearly showed dissimilarity in damage levels as described above ($F = 9.13$; $df = 3, 41$; $P = 0.0005$, $F = 10.51$; $df = 3, 40$; $P = 0.0002$). In 2003, a mean damage of 42.8 ± 4.9 was monitored in fields planted in early spring and harvested over the summer. The damage level decreased when planting and harvesting date occurred over the summer, averaging 15.1 ± 4.2 , and increased when harvest date was deferred until fall, a mean damage of 24.5 ± 4.3 . In 2004, there was close to the same trend as 2003, but with slightly higher damage rates. The spring-planted fields revealed a mean damage of 50.0 ± 6.1 , when harvested in the summer and a mean damage of 30.4 ± 2.9 when harvested in the fall. Damage was significantly lower when fields were planted and harvested in the summer, averaging 17.9 ± 5.7 . In 2002, significantly higher damage, averaging 35.0 ± 6.5 , was found in spring-planted and summer-harvested fields compared to summer-planted and fall-harvested fields, averaging 11.8 ± 2.8 ($F = 3.79$; $df = 3, 36$; $P = 0.0321$). In 2001 and 2005, no significant differences in damage were apparent whether a field was planted in the

spring or summer, or harvested in the summer or fall ($F = 2.91$; $df = 3, 31$; $P = 0.0696$ or $F = 2.55$; $df = 3, 17$; $P = 0.10$, respectively).

3.4.10 Flight Effect

The relationship between crop damage and fly catch, detected in yellow water traps placed on the north-northeast side of fields, was assessed using the linear regression model. A total of 71 water traps associated with field sites were analyzed. A significant relationship was found between fly catch and crop damage level ($F = 6.64$; $df = 1, 69$; $P < 0.0001$) (Fig. 3.12). Fly catch (based on a total of 7 assessments) was moderately correlated with damage at harvest ($r = 0.64$; $P = 0.0001$; $r^2 = 0.41$). Total fly catch in fields with less than 20% damage, averaged 70.8 ± 7.1 ($n = 36$), while fields with greater than 20% damage, averaged a fly catch of 248.6 ± 30.3 ($n = 35$) (Fig. 3.13). In four of the 71 fields, fly catch detected in water traps was low, underestimating damage; and in another four fields, fly catch in water traps was high, overestimating crop damage according to this predictive model. A 12% margin of error was calculated when predicting low ($< 20\%$) and high ($> 20\%$) damage levels by fly catch. No seasonal differences affected the relationship between fly catch and damage ($F = 1.56$; $df = 2, 68$; $P = 0.2169$).

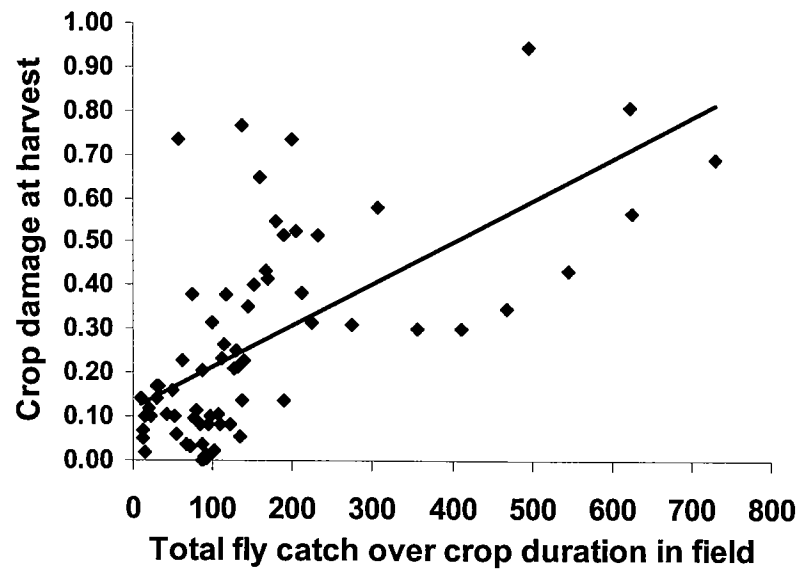


Fig. 3.12. Total fly catch from 71 different fields of rutabaga and turnips and relationship of flight to crop damage at harvest.

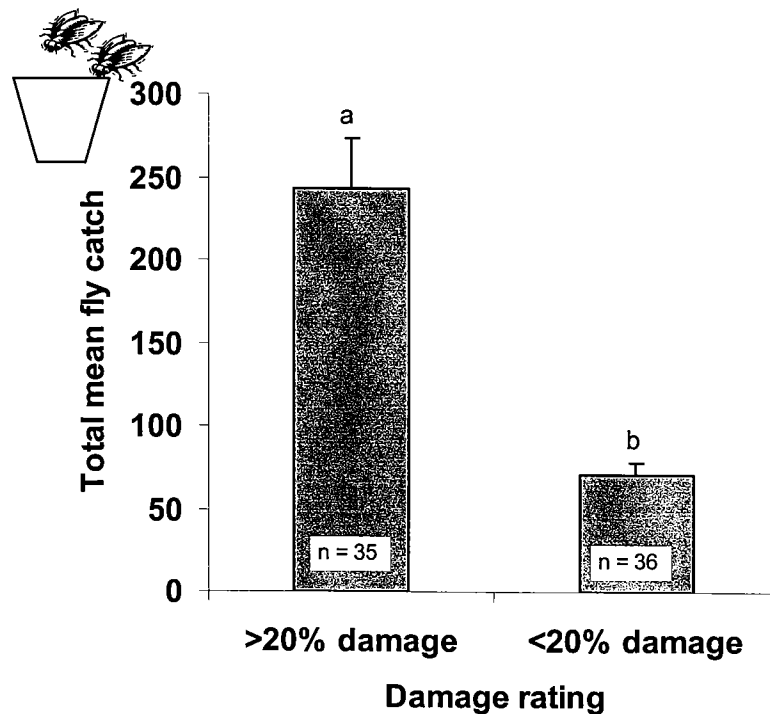


Fig. 3.13. Total mean fly catch (collected from yellow water traps) from growers' fields assessed with less than and greater than 20% cropdamage from cabbage maggots.

3.5 Discussion

3.5.1 Crop Damage

D. radicum crop damage increased over the years of study perhaps in response to favorable wintering conditions; yearly differences in environmental conditions (e.g., temperature and precipitation), reduction of natural enemies due to overuse of chemical treatment, response to a pest's periodic cycle, and as a result of global warming (Collier et al. 1990). A history of CM outbreaks has been documented throughout the world in spite of attempts at controlling the pest with chemicals (Bracken 1988, McDonald and Sears 1992, Walgenbach et al. 1993). This lack of control often is related to implied resistance, poor timing or ineffectiveness of soil insecticide applications (Harris 1972, Getzin 1985, Stark 1993).

3.5.2 Weather Conditions

Populations of *D. radicum* were intensified by winter rains when followed by warm temperatures in February and March, which induced early general emergence of overwintering flies and their migration to fields of *Brassicas*, primarily seen in 2003. In 2001, cool and dry weather began the previous winter (Nov – Dec), and continued over the pre-flight and spring flight period delaying flight activity in the spring by ≈ 3 wks. First generation emerged later in the spring into the summer season, resulting in lower damage levels. As a consequence of the late emergence, mid-summer generations rather than the spring generation of flies produce the first infestations, but considerably lower damage levels were seen, perhaps due to the summer environmental conditions as also noted by Finch and Collier (1985) in Wellesbourne, England studies. The number of generations may

have been reduced in 2001, as spring flight was delayed and the second late fall peak (≈ 2600 DD) was not apparent, as seen in the other 4 years. Miles (1954) reported reduced generation time and decline in oviposition when springtime temperatures were below 15°C. The elimination of this second fall oviposition period, most likely contributed to low damage levels in 2001.

In 2002, precipitation levels were average to high, but temperature was low during pre-flight and flight period which could be part of the cause of a delayed spring flight. Not only was temperature low over the summer, precipitation was below average July through October, and when the rains finally came, a huge spike in fly catch was seen at late peak.

In 2005, the year of highest damage levels, precipitation was also lower than average from November – February like 2001. However the difference was the above average precipitation fell over the spring emergence period and temperature was average to above average. Temperature and precipitation are only a few of the factors affecting damage.

There were an increasing higher relative spring proportion of flies caught in the traps from 2001 to 2005, average proportion of (33, 40, 53, 55, and 73%, respectively). The average weekly fly catch in the spring increased from 9 flies in 2001 to 75 flies in 2005. In fact there were decreasing fall proportions of flies caught in traps from 45% in 2001 to 15% caught in the fall of 2005. Again perhaps the warmer fall and spring temperatures (highest degree-day accumulations) as seen in 2003, 2004, 2005 encouraged survival of overwintering puparia and larger spring populations, causing higher damage levels.

Field size affected damage levels in only 2003, however after close examination a large percentage of smaller fields (< 1 hectare) were planted during the rainy spring season, so higher damage would be expected in the spring regardless of field size. Damage assessments can help with management decisions such as determining when > 40 % of

plants have maggot injury, a point in which PNW growers would find it more economical to replant rather than treat the field. A field that has a maggot infestation should be disked immediately to reduce future generations.

3.5.3 Chemical Efficacy

Broadcast application use of chlorpyrifos is questionable, as these study results showed no significant differences between treated and untreated plots. However, still the question of interest is whether the ineffectiveness of the chemical is misuse with the end result being resistance, poor application, lack of chemical persistence required to provide protection throughout a growing season for a long-lived crop, or unnecessary treatments at times when the pest is not present. Yellow water sensitive papers were used at base of plants to determine adequate insecticide coverage. Little to no insecticide reached the egg target, especially once crop canopy had closed. In-furrow application provides longer protection with less damage (unpublished data) and should be more widely used by growers. More research on appropriate application equipment is needed to tackle later season fly populations once canopy has closed. In addition, soil type has been noted to have a major influence on the effectiveness of insecticides, however in this study, fields with a range of soil types were used and no differences were apparent in damage levels.

3.5.4 Planting and Harvesting Schedule

It was clearly evident that cabbage maggot damage was significantly higher in fields planted early in the season (before 95% spring flight; < 900 DD), a favorable time for optimum cabbage maggot development. The data suggests that when spring flight takes on an early start and favorable environmental conditions of warmer winter weather mixed with

precipitation for puparia stimulation continues, damage levels increase. Damage can persist through subsequent seasons if spring populations are not controlled as shown in 2005. No differences were seen between early and late planting during 2005, most likely due to the heavy pressure and lack of control of the spring cabbage maggot populations. If growers have the liberty to plant their crops after the spring season, this practice alone could bypass some of the overwintering populations and greatly reduce damage in future plantings. Forecasting flight activity with the degree-day model could help identify this 'low risk window', where less maggot presence exists so fewer treatments would be required (Dreves et al. 2006). An additional low risk window was not consistently identified between early- and late-emerging spring peaks, as too many factors affect the timing of these peak flights.

Not only should a grower be aware of low risk planting times, but know that harvest time is crucially as important. Cabbage maggots are a multi-generation pest and long-season crops can be exposed to two generations of flies. Damage levels greatly increased on crops left in the field in the fall and exposed to CM peak fall flight. It was observed that some of the last crops left in the field in the fall were even more vulnerable to late CM injury from harvested neighboring fields, and especially vulnerable to neighboring fields assessed with high damage levels. Crop damage almost doubled in some cases. However rutabaga plantings in 2003 showed less damage from later plantings, while in the ground for a longer period of time extending into fall flight. Rutabagas have a denser, tougher root than turnips and less deep wounds and larval tunnels penetrate the center of these roots, so conceivably the roots might compensate for damage by a significant increase in root weight and heal the superficial tunneling. In addition, they have multiple roots originating from the underside of the edible root as well as from the taproot perhaps creating a barrier to new damage. Also precipitation was unusually dry from May through September, allowing for

surface tunnels to dry out and mend. Carefully chosen planting dates and harvesting dates, which must take local ecological conditions into account, can reduce the damage inflicted by *D. radicum*.

3.5.5 Crop Type

Rutabaga crops could have experienced higher damage (38.9% higher) compared to turnip crops simply by the fact that they are planted earlier in the season and damage is associated primarily by planting date. No differences were seen between crop types in 2001, as CM pressure was too low to see differences. The average planting date for rutabagas was 324 degree-days earlier than the average turnip planting dates. So the effect of planting date was more pronounced for rutabagas than for turnips. The early-planted rutabagas were hit especially hard and in most years, the intercept for rutabagas was significantly greater and slope steeper than for turnips. Not only did rutabagas get planted earlier, but they take longer to mature so are exposed longer to an increased number of fly generations. However after comparing damage between 28 paired fields of rutabaga and turnips planted on nearly the same date and assessed for damage on the same date, rutabaga damage was significantly higher suggesting that rutabagas are the more attractive plant species to ovipositing flies as claimed by Doane and Chapman (1962). Chemical cues given off by *Brassica* plants are important for oviposition of these pests. Rutabagas might produce more glucosinolate and isothiocyanate chemicals from their actively-growing roots than turnips (Sang et al. 1984), providing an increased host-plant finding cue for *D. radicum*. Knowing that *Delia* typically moves into its environment and penetrates crops along the edge of fields (at least initially), allows the use of perimeter trap cropping. Researchers have explored trap cropping to reduce CM (Pats and Vernon 1999, Rousse et al. 2003). In Oregon, a few rows of rutabagas

were planted on the perimeter of a main crop, turnip, to protect the main crop from the pest in an unreplicated study. The trap crop had 3x more CM damage than the main crop (unpublished data). It might be interesting to explore rutabagas as trap crops along field edges that border known sources of overwintering infestations to serve as a sink for emerging pests in the spring (Shelton and Badenes-Perez 2006).

3.5.6 Seasonal Flight Activity

The spring arrival of CM determined by use of a degree-day model (Dreves et al. 2006) can be a good warning device for growers in order to better time treatments. The actual appearance of flies in the field was determined by setting out yellow water traps at the border of the prevailing wind side of fields. A significant relationship was observed between crop damage and fly catch, however the r^2 value showed only 41% of the variation in fly catch was related to the variation in damage ($P < 0.0001$), implying other factors can influence fly catch. Forecasting the actual severity of the infestation level can be difficult. In several cases in this study, the water trap catch can give an incomplete picture of the size of flight and level of infestation. It was observed that water traps in summer-planted fields appeared less efficient in trap catch relative to the degree of crop damage. The discrepancy in trap catch amongst fields is uncertain. Possible reasons include: varying levels of canopy and increased flora making the trap less noticeable or less desirable, excessive rainfall, therefore a lack of fly movement; or just poor trap placement. In this study, only one trap was placed on the corner of the prevailing wind which might not be enough to give us an adequate reading of activity. Perhaps two or three traps per field would have more adequately assessed fly activity. Water trap efficiency is heavily influenced by field placement and weather conditions, so trap catch may not accurately represent fly population

densities or damage levels (Griffiths 1986, Sears and Dufault 1986). Other factors affecting trap catch include: 1) prevailing wind direction (Banks et al. 1988), 2) proximity to larval infestations (Coaker and Smith 1968, Dingle 1972), 3) presence of sheltered field margins and wooded borders (Griffiths 1986), 4) exposure to sunlight (Hawkes 1972, Klingen et al. 2000), and unfavorable weather such as heavy precipitation (Wyman et al. 1977). Banks et al. (1988) suggested that *Delia* fly upwind in the presence of *Brassica* odors. Traps in the path of flight would theoretically catch more flies than those away from an odor source (Nottingham and Coaker 1987). Dispersal of flies is not obligatory, however when they search for a host it has been noted that they fly into the wind in a series of short flights (Coaker and Smith 1968, Dingle 1972, Hawkes et al. 1978, Finch and Skinner 1982), so larval infestations in close proximity to new *Brassica* plantings would be more important than distant infestations when positioning a trap for maximum fly catch. Finch and Skinner (1975) reported that most flies were generally caught within 100-200 meters of their emergence site and flies were captured at a maximum distance of 2000-3000 meters from a known maggot source, but very few of them. Hawkes (1972) showed that CM is attracted to yellow water traps only within a range of about 1 m when they enter a field. Adjacent crops, hedgerows, tall grasses and other features that shelter field borders influence trap catch as they attract CM by providing shelter and floral food (Hawkes 1972, Finch and Skinner 1973, Griffiths 1986). Griffiths (1986) placed traps along sheltered field margins from early to mid season to maximize trap catches. He reported that as the crop canopy closed, placement of traps near sheltered field margins was less critical to trap catch, as at that time the crop provided both food and shelter. Also, traps exposed to sun catch significantly more flies than those in the shade (Hawkes 1974, Klingen et al. 2000). Because of the many factors that influence trap catch, fly catch in water traps may not be reliable indicators of

estimating crop damage; however, fly counts in the same trap at different times over the crop's duration in the field can give an indication of the relative size of the population at the different times and can be used to determine periods of high and low flight activity. This tool may be good predictors of activity, but unreliable as numerical estimators of damage expected in a Brassica field.

Increased environmental concern and potential loss of the organophosphate insecticide has emphasized a need for a monitoring program. As an aid in field management decisions, the binomial damage assessment ("M60") was adequate for estimating root damage attributed to cabbage maggot. The estimate of damage incorporated a standard error approximately 15% of the mean by sampling 60 plants in any size field which is quite within the range for the needs of a root crop grower (Strickland 1961).

Better knowledge of CM damage levels could: 1) reduce insecticide use, 2) determine low and high risk pest activity periods, 3) estimate damage in relationship to seasonal market demands, 4) measure crop loss for evaluating new management strategies (e.g., alternative chemicals), 5) identify present and immigrating populations, and in the end 6) aid in better management decisions. Further research is needed to examine spatial distribution of oviposition and damage in the field, *Delia*'s ovipositional preference, egg-damage threshold levels, and relationship of flight to oviposition.

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**4 SEASONAL OVIPOSITION BY *DELIA RADICUM* L. IN RUTABAGA AND
TURNIP CROPS IN OREGON**

A. J. DREVES, D. DALTHORP, G. FISHER

Refining and preparing for Journal of Environmental Entomology

4.1 Abstract

Oviposition of cabbage maggot, *Delia radicum* (L.), on rutabaga and turnip root crops was investigated in 90 fields during 2001 through 2005. A binomial sampling plan was designed to estimate the proportion of plants with cabbage maggot eggs and crop damage. Over three seasons, planting date (expressed in degree-day accumulation based on *D. radicum* phenology) had a greater influence on oviposition occurrence than did flight events. Water trap catch was unreliable as a predictor of actual timing of oviposition in Brassica root fields. Oviposition significantly increased in fields at an average of 30.9 (\pm 1.1) days after planting. However, several summer-planted fields experienced a delay in oviposition until the later flight of the fall-generation. Precipitation did not appear to be a significant factor in this delayed oviposition.

Significantly more eggs were observed on older plants with 5 -15 leaves, root diameter of 6 - 32mm, and increased crop canopy. In any given field, there was a significant correlation between the proportion of plants with eggs and damage levels at harvest ($r^2 = .84$); in particular, plants with higher egg counts at later growth stages showed significantly higher damage levels. Egg incidence levels sampled on plants located in outside periphery of fields were significantly higher (46%) than in centrally located plants. In addition, increased egg-laying occurred in locations closest to the windward side of the prevailing wind.

4.2 Introduction

The cabbage maggot (CM), *Delia radicum* (L.) (Diptera: Anthomyiidae), an injurious and exotic pest of Brassica crops, has been reported in United States since the mid-1800s (Whistlecraft et al. 1985). Growers of Brassica root crops such as daikon, turnip, radish, rutabaga, consider CM to be the key pest. Brassica root crops valued in excess of \$4 million annually are grown in Oregon on approximately 810 hectares (Burt 2005). Long-season, belowground crops, such as turnips and rutabagas, are susceptible to CM damage from early spring through fall (Dreves et al. 2006). A single larval tunnel found in an edible root leaves the product unmarketable. Maggot injury also provides entryways for pathogens (Doene and Chapman 1964, Griffiths 1986, Carisse et al. 1998).

D. radicum has a pre-oviposition period ranging from 4 to 8 days (Miles 1951, Swailes 1961, Coaker and Finch 1971). Full reproductive maturity is attained by feeding on protein and carbohydrate sources, such as flowering fruit trees and other nectar-producing plants (Harris and Svec 1966, Finch and Coaker 1969). Mating takes place before the females enter a crop for oviposition (Finch and Skinner 1973, Hawkes 1974).

Flies rely on both visual and chemical cues to locate their host (Traynier 1967, Coaker and Smith 1968, Nair and McEwen 1975, Stadler 1978, Prokopy et al. 1983). Females deposit 1 mm long white, oblong eggs in the upper soil layer at the base of host plants (Miles 1951). Fecundity of CM is variable as reported in previous literature. Swailes (1961) documented an average of 78 eggs during a typical life span of 22 days. Finch (1970) reported 63 eggs per female in the field. Biron et al. (2002) reported an average of 113 eggs, with a range of 56 to 144 eggs per female.

Eggs hatch in three to seven days. Larvae feed on both lateral and main roots, maturing in two to three weeks. Adults emerge one to two weeks later. A laboratory-controlled study in western Ontario, Canada documented a single CM generation time in 41–65 days (Harris and Svec 1966). Researchers have suggested that three to five CM generations occur annually in the Pacific Northwest (Forbes 1955, Mukerji and Harcourt 1970, Nair and McEwen 1975, Getzin 1978, Todd 1998).

Control of CM in commercial edible Brassica root crops relies heavily on insecticides. This is attempted with pre-plant and post emergence applications. Despite control efforts, Brassica crops suffer increasing damage resulting in significant economic losses (Dreves et al. 2006, unpublished data). Insecticide resistance as well as poor application methods and their timing are often identified as reasons for poor CM control (Doane and Chapman 1962, Getzin 1985, Stark 1993). These problems, environmental concerns, and potential governmental restrictions on organophosphate insecticides have created the need to understand the ovipositional behavior and phenology of CM in these crops as essential to the development of successful management techniques.

Oregon growers do not monitor oviposition activity in Brassicas to time insecticide applications. A degree-day model recently developed for CM activity in Oregon predicts spring emergence and flight (Dreves et al. 2006). This model coupled with data from water traps provide estimates of seasonal variation in pest populations and allow growers to verify the actual beginning and ending of flight periods; and begins to provide a framework for estimating damage potential and control timing. Unfortunately, arrival of flies in water traps can be unpredictable and sometimes gradual and prolonged, which necessitates the need to monitor for the occurrence of oviposition in fields (Sears and Dufault 1986, Bracken 1988).

Previous research has not clearly defined when to begin monitoring for CM eggs. It is clear that an understanding of ovipositional behavior of CM and factors that influence the degree of oviposition in commercial plantings is essential to an effective CM monitoring and management program. Literature suggests that oviposition can be influenced by: 1) crop and variety (Doane and Chapman 1962, Vandermeer 1989, Dossall et al. 1994, Baur et al. 1996); 2) stage of plant growth (Coaker and Finch 1971, Hardman and Ellis 1978, McDonald and Sears 1992); 3) spatial distribution (Finch and Skinner 1975); 4) precipitation (Bracken 1988); 5) season (Finch and Collier 1985); and 6) various biotic and abiotic factors (Mukerji 1971). Researchers reported that egg and larvae survivorship in summer is greatly reduced. They cite various reasons including desiccation from higher daily temperatures and direct sun exposure (Harris and Svec 1966, Finch and Collier 1985); insufficient soil moisture for successful egg eclosion (Zabirov 1961, Nair and McEwen 1975); increased predation, parasitism and disease (Nair and McEwen 1975, Eckenrode and Chapman 1972). Knowledge of egg survivorship or successful establishment rate helps in understanding damage potential.

The use of egg monitoring techniques in Brassica root crops could be useful if relationships exist between egg numbers and subsequent crop damage (Dapsis and Ferro 1983). Economic thresholds have been identified for aboveground Brassicas (cauliflower, cabbage, and broccoli) (Anonymous 1985, Bligaard 2001), but little has been done to establish thresholds for belowground Brassica crops (turnips and rutabagas). Sears and Dufault (1986) reported a positive correlation between CM egg numbers and subsequent damage on rutabagas. They found that rutabaga plants in commercial fields with less than two cumulative eggs per plant resulted in crop infestation levels from 10-to-21%. Whereas, fields with plants of three to six eggs, resulted in overall infestations of 59 to 63%.

The primary objectives of the research were: 1) to understand seasonal CM egg levels and describe significant ovipositional periods; 2) to determine numerical relationships between flight activity, oviposition, and crop damage; and 3) identify factors influencing oviposition.

4.3 Materials and Methods

4.3.1 Research Study Site

Seasonal oviposition and root damage caused by *D. radicum* (L.) was monitored over a five-year period from 2001 through 2005. Monitoring, as described below, was conducted in 90 commercial fields of long-season root crops, including rutabaga (*Brassica napus* cv. Laurentian and American Purple Top) and turnip (*Brassica campestris* cv. Purple Top White Globe). The fields, managed by two growers, were located in the northern Willamette Valley near Oregon State University's Northwest Research Extension Center (NWREC) in Aurora, Oregon, where the core area (> 90%) of Oregon's commercial *Brassica* root crops is grown. The crops were direct-seeded in accordance with standard commercial practices on ≈ 1.6 m wide beds, four rows per bed. Soil types varied but were predominantly loams (Quatama, Newberg, Latourell) and silty loams (Willamette, Woodburn, Cloquato, and Amity). These soils are partially to well-drained; pH varied from 5.5 to 7.0. The fields were representative of the region, varying in size from 0.8 to 4 hectares, averaging ≈ 2 hectares. All fields received labeled rates of chlorpyrifos (Lorsban 4E; Dow AgroSciences, Indianapolis, IN; 1.12 kg ai/ha) for CM control, and were fertilized

and treated for weeds at planting. Insecticide sprays targeting cabbage flea beetle and aphids were periodically applied.

4.3.2 Weather

Air temperature (used for degree-day (DD) calculations based on the local phenology model described below) and precipitation records (used for understanding the influence of precipitation on oviposition) were obtained from the regional AgriMet weather station (lat 45° 16' 55"; long 122° 45' 01"; elevation 140') located at Oregon State University's NWREC.

Annual precipitation for the northern Willamette Valley is typically 100 cm, of which \approx 50 % falls between November and February. Spring, summer, and fall precipitation approaches 24, 8, and 20 cm, respectively. Because of light summer rainfall, Brassica fields must be irrigated, usually by overhead sprinklers. Mean daily high temperatures in the summer can reach 27 °C in July, with average lows of 10 °C. In spring and fall, daily high temperatures average 17 °C and 24 °C, respectively; and daily lows average 5 °C and 7 °C respectively. In winter months, the average daily maximum temperature is approximately 10 °C, with daily lows averaging about 2 °C. The first frost is typically around November 1. Snow and extended periods of sub-freezing temperatures are not common in the region.

4.3.3 Degree-Day Model

In the northern Willamette Valley, overwintering CM puparia produce first generation adults after a degree-day accumulation of 200 °C (air). This value is obtained by using the lower and upper developmental thresholds of 4.3 °C and 30 °C, respectively, starting January 1 (Dreves et al. 2006) (Fig. 4.1). Spring activity extends over a three month period

and spring has proven to be the season with greatest crop damage caused by CM. Bimodal spring emergence of adults was reported for the northern Willamett Valley with spring flight activity declining after ≈ 900 degree-days (calendar date of approximately early to mid-June). Flight activity (assessed by water-trap fly catch) is reduced over the summer months (Harris and Svec 1966, Eckenrode and Chapman 1972, Nair and McEwen 1975, Finch and Ackley 1977, Finch and Collier 1985, Dreves et al. 2006). Flight activity increases again in the fall following a degree-day accumulation of ≈ 2100 (a calendar date of \approx Sept 1) and peaks at ≈ 2600 DD (Dreves et al. 2006). Puparia enter diapause in the late fall after the onset of lower temperatures and a shortened photoperiod (McLeod 1964, Read 1965, Johnsen and Gutierrez 1997). Each year, *Brassica* were seeded over three distinct seasons of CM flight activity and accumulated pest DD (Dreves et al. 2006). These plantings include: 1) spring plantings before 900 DD; 2) summer plantings after 900 DD; and 3) fall plantings after 1500 DD.

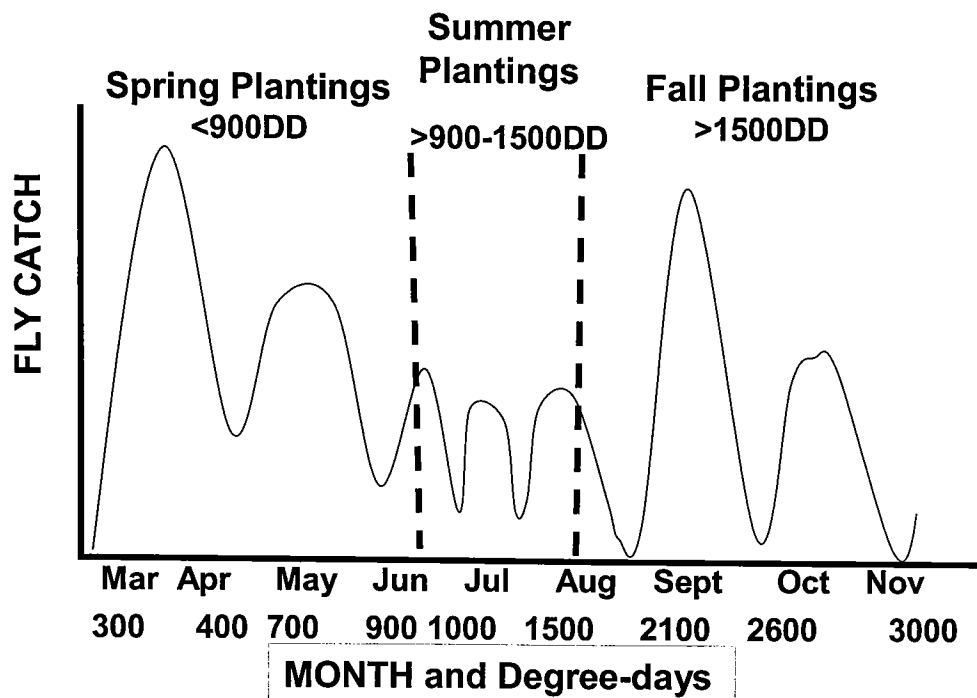


Fig. 4.1. Generalized flight pattern with associated degree-days for *Delia radicum* (based on a lower and upper developmental temperatures of 4.3°C and 30°C starting Jan 1; single sine approximation) in northwestern Oregon. This pattern can change with weather and location. Three seasonal planting times (spring, summer, and fall) are shown which are based on flight patterns and weather.

4.3.4 Oviposition Activity

Fields were inspected weekly for CM eggs using the egg-scrape technique (EST), similar to that described by Skinner and Finch (1986). It was modified as follows: Each field, regardless of size, was divided into six locations: four outside corners (NE, SE, NW, SW) and two central locations (midNE, midSW) (Fig. 4.2).

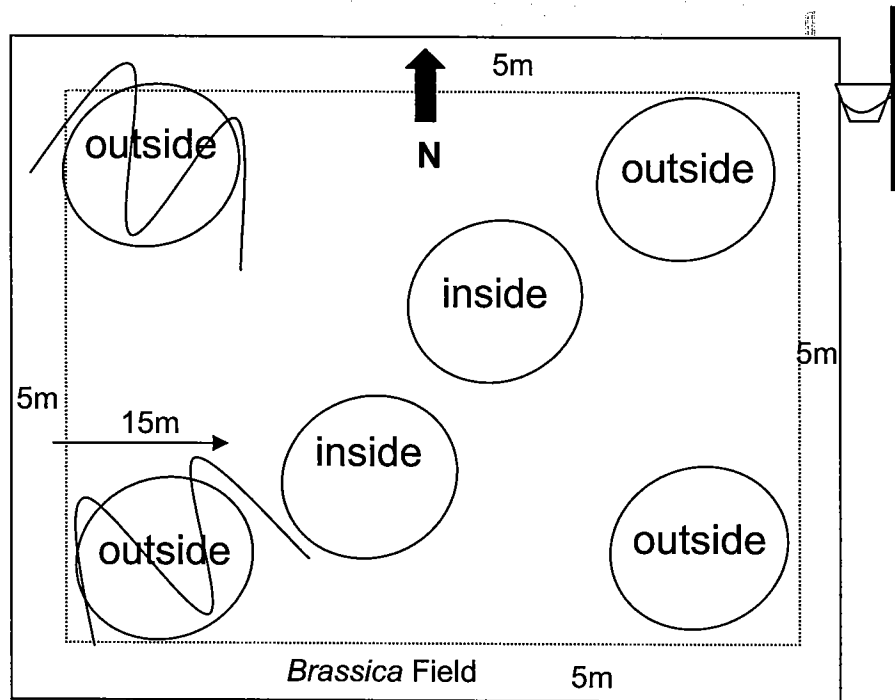


Fig. 4.2. Egg incidence and damage assessments were performed by randomly selecting plants at six sampling locations in commercial Brassica field. Samples were collected along a “M” transect at each location. A yellow water trap was set up on north-northeast border of the field to detect seasonal fly activity.

Egg sampling began when plants reached the cotyledon stage. Preliminary surveys in these fields determined that oviposition did not occur prior to cotyledon stage. To minimize edge effect, five meters of buffer rows around the perimeter of each field were excluded from sampling. At each of the six locations, plants were selected along five points of a M-shaped transect within a 15 m² area. At each point, three neighboring plants were randomly selected, totaling 15 plants per location. A total of 90 plants per field were inspected for eggs. Around each plant, a 5 cm radius of soil was scraped away to a depth of 2 cm. The

numbers of plants with eggs present were recorded. Thus, the proportion of plants with eggs present (egg incidence) could be determined. The occurrence of plants with eggs for each field was analyzed to determine for each field when egg levels significantly increased, or “spiked”. Spike dates were then plotted and analyzed to determine when increased oviposition occurred. In addition, weekly egg incidence assessments were summed to determine relationships with crop damage at harvest.

4.3.5 Plant Growth Stage

Prior to monitoring a field for egg incidence, a plant growth stage was documented based on a 1-4 rating index of four plant growth stages (PGS). The rating was based on number of leaves, root development, and crop canopy coverage. The plant growth stages consisted of:

PGS 1: cotyledon to four developing true leaves, root diameter less than 6 mm, canopy coverage open, bare ground exposed;

PGS 2: 5-8 leaves, root diameter >6 to 19 mm, canopy coverage open, and >50% bare ground exposed;

PGS 3: 9-15 leaves, root diameter >19 to 32 mm, canopy coverage partially-closed, and < 50% bare ground exposed; and

PGS 4: 9-15 leaves, root diameter >32 mm, canopy coverage closed (typically).

The number of fields assessed yearly was: 16, 34, 20, 14, and 6, respectively. The mean number of assessments per field was seven. Mean egg incidence was computed for each plant growth stage per field.

4.3.6 Seasonal Flight

Flight activity was monitored with yellow water traps in 34 fields: 5 in 2001, 14 in 2002, 11 in 2003, and 4 in 2004. Traps were fluorescent yellow plastic buckets (AmLoid Corp, standard ASTM F-963; Monterrey, Mexico), measuring 18 cm in diameter, 30 cm in depth, and 5 L in volume. Buckets were filled with water within 3 cm of the rim. To minimize microbial growth and reduce surface tension, 2 ml of 6% liquid sodium hypochlorite and a few drops of detergent were added. Initial placement of traps was on the soil. As plants grew traps were raised so rims were above the canopy. At planting, one water trap was located in each field along its north-northeast (windward) border (Finch and Skinner 1982, Banks et al.1988). Vegetation was removed from an area 0.5 meters immediately around the trap (Griffiths 1986). Flies were collected and counted weekly. Specimens were preserved in 70% EOH, and later identified (Brooks 1951). Traps were cleaned and refilled after each collection. Trap catch was totaled for the duration a crop was in the field.

4.3.7 Crop Damage Assessment

Crop damage was assessed at harvest. This was done in the proximity of the same six locations (Fig. 4.2) as the egg incidence assessment. Ten plants were randomly selected along a M-shaped transect at each location, for a total of 60 plants per field. Plants were pulled and roots inspected for the presence of CM injury. The proportion of damaged roots was calculated. A standard error less than 15% of the mean was estimated for the 60 plant sample size (Strickland 1961).

4.3.8 Data Analysis

Data, collected over the five year period, were analyzed for significant relationships among planting date, water trap fly catch, egg incidence, and root injury. Ninety fields representing spring, summer, and fall plantings were studied. A total of 678 evaluations of egg incidence were analyzed. Significant increases in oviposition (egg spikes) were determined using Regression Analysis Procedure (REG; SAS Institute 9.1.3 2002-2003). Statistical comparisons of yearly and seasonal mean egg incidence assessed at different plant growth stages were performed by analysis of variance (ANOVA) procedure of SAS (PROC GLM; SAS 9.1.3 Institute 2002-2003) to test relationships with planting date and trap catches. Tukey's honestly significant difference (HSD) test was used to determine if significant differences in egg incidence occurred between plant growth stages. Egg incidence values were transformed by arcsine-square-root transformations to equalize variances among fields. Egg incidence by plant growth stage in 77 fields was compared to harvest damage, using the REG procedure. Egg incidence assessments within ten days before harvest were not included in the data sets because any resultant larval feeding would not be detectable on the harvested root crop. Using the REG procedure, relationships were analyzed among total fly catches per trap per field from planting to harvest and egg incidence (proportion of plants with eggs), including: the sum of weekly egg incidence assessments (avg 7 assessments), the sum of egg incidence assessment from the mean assessment at each plant growth stage; and the sums of egg incidence assessments from a combination of different plant growth stages. The percentage of cumulative plants with eggs per field resulting in damage at harvest was computed.

To determine if level of egg incidence was correlated with location of the sample in the field, three years of egg location data (2003 to 2005) were analyzed by planting time and year. Seasonal plantings included: 23 spring fields (<900 DD), 25 summer fields (900-1500 DD), and 24 fall fields (>1500 DD). For each field, the proportion of plants with eggs present through harvest in each sample location was averaged. Two-sample paired t-tests were used to determine significant differences between sample locations at 5% probability level. Location data from 72 fields, with a mean of five evaluations per field, were compared.

4.4 Results

4.4.1 Oviposition Activity

D. radicum oviposition was significantly higher in spring plantings (<900 DD) of rutabaga and turnip crops, a mean egg incidence (proportion of plants with eggs per evaluation \pm SEM) of 14.0 ± 0.77 ; compared to egg incidence assessed in summer (9.40 ± 0.67) and fall plantings (6.46 ± 0.64) ($F = 30.1$; $df = 3$; $P < 0.0001$) (Fig. 4.3). No difference in egg incidence was detected between summer and fall plantings.

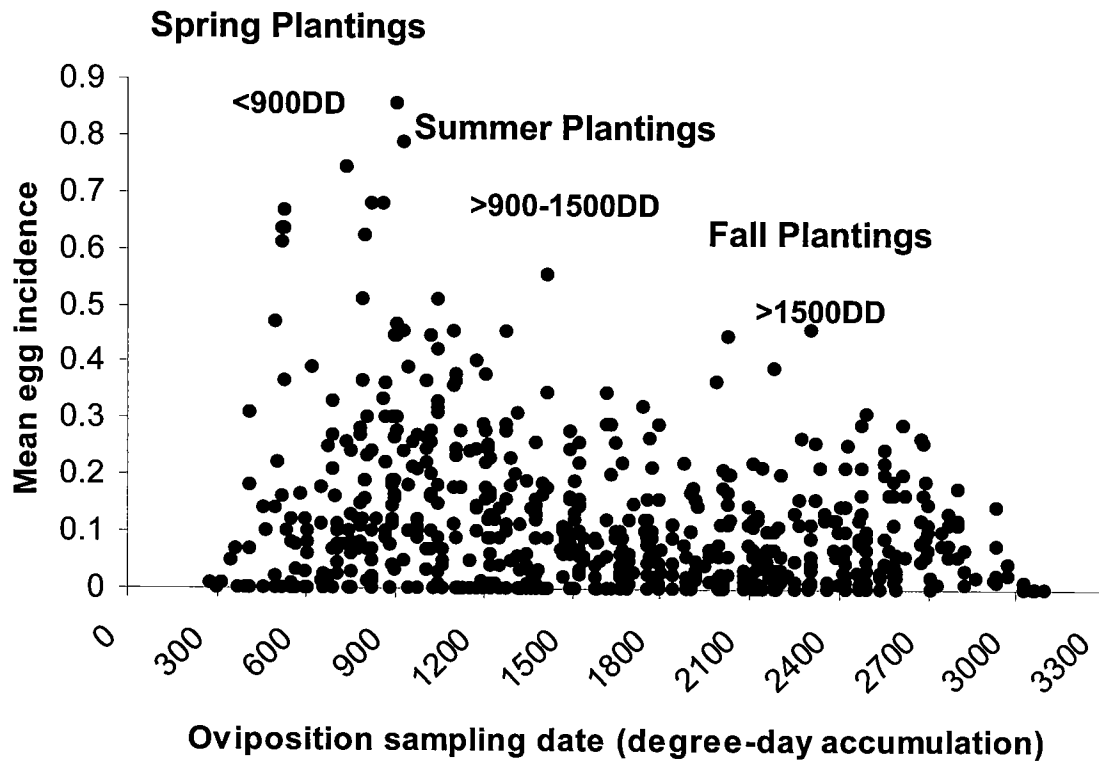


Fig. 4.3. Seasonal egg incidence evaluated from 2001 through 2005 in rutabaga and turnip crops in the northern Willamette Valley, OR (n = 672 evaluations).

4.4.2 Seasonal Flight

Few to no eggs (< 5% mean egg incidence per evaluation) were reported on rutabaga and turnip crops planted before 50% spring flight peak (a mean degree-day accumulation of 409 DD and mean calendar date of April 17) (Fig. 4.4). The DD phenology model, based on 4 years of data, estimated that 70% of flies emerged and 80% spring flight was detected in water traps by this time of the year (Dreves et al. 2006). Increased oviposition (> 10% mean egg incidence per evaluation) was observed in crops after the 50% spring flight peak at 409 DD, 27 days (+127 DD) after the early-emerging peak flight (mean 329 DD and mean

calendar date of April 2). Greatest percentages of oviposition (averaging 16.3 to 23.1% mean egg incidence) occurred after a degree-day accumulation of 800 DD (mid-May) to 1100 DD (early- to mid-June) and diminished (averaging 7%) around 1300 DD (end of June). Sporadic increases in oviposition occurred in fields over the summer months and no concerted oviposition time could be identified across the region most likely due to the polymodal patterns of activity. Oviposition was significantly lower between 1800 to 2000 DD (< 5% egg incidence), the warmest time of the year in the Willamette Valley (> 27°C). Oviposition increased during fall flight, after 2000 DD with highest oviposition occurring between 2500 and 2600 DD (a mean egg incidence of 15%), and then greatly declined after first frost in November.

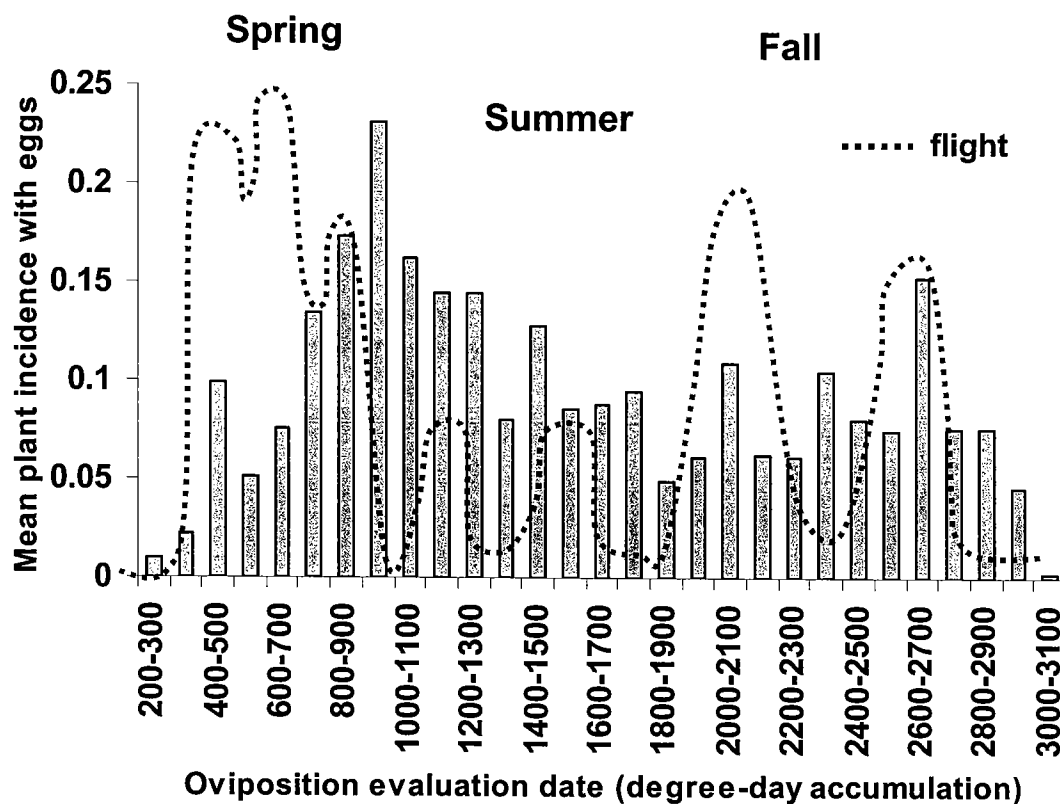


Fig. 4.4. Mean egg incidence assessed at seasonal evaluation dates (described in degree-day accumulation from pest phenology) ($n = 672$ evaluations). Regional flight activity (dotted line) overlays evaluation dates and includes early and late spring flights, sporadic summer flights, and bimodal fall flights.

4.4.3 Planting Date

Planting date (expressed in DD accumulation based on CM phenology) influenced oviposition activity in all seasonal plantings of rutabaga and turnip crops during this study ($F = 22.1$; $df = 86$; $P < 0.0001$); and was highly related to oviposition “spikes” or significant increases in egg incidence ($r^2 = 0.80$; $P < 0.0001$) (Fig. 4.5). Significant and consistent oviposition spikes occurred at 30.8 days (± 1.2) after seeding in the spring, an accumulation

of 305.7 ± 13.7 DD; 43.8 ± 3.9 days after summer plantings, a mean accumulation of 682.11 ± 118.74 DD ($F = 24.95$; $df = 2$; $P < 0.0001$); and 31.5 ± 2.9 days after fall plantings, an accumulation of 453.69 ± 43.5 DD. Timing of oviposition spikes was not significantly different between spring plantings and fall plantings; however both seasons were significantly lower in number of days between spike and planting date compared to summer plantings. Eight fields seeded in the summer did not have the significant oviposition spikes at \approx one month after seeding, that were observed in the other 80 fields. Most notably, these eight summer-seeded fields experienced egg spikes after an additional accumulation of 300 DD (46 calendar days later). No significant differences in number of days from planting date to oviposition spike were seen between crop types in spring, summer, or fall plantings ($P = 0.47$; $P = 0.23$, $P = 0.95$, respectively).

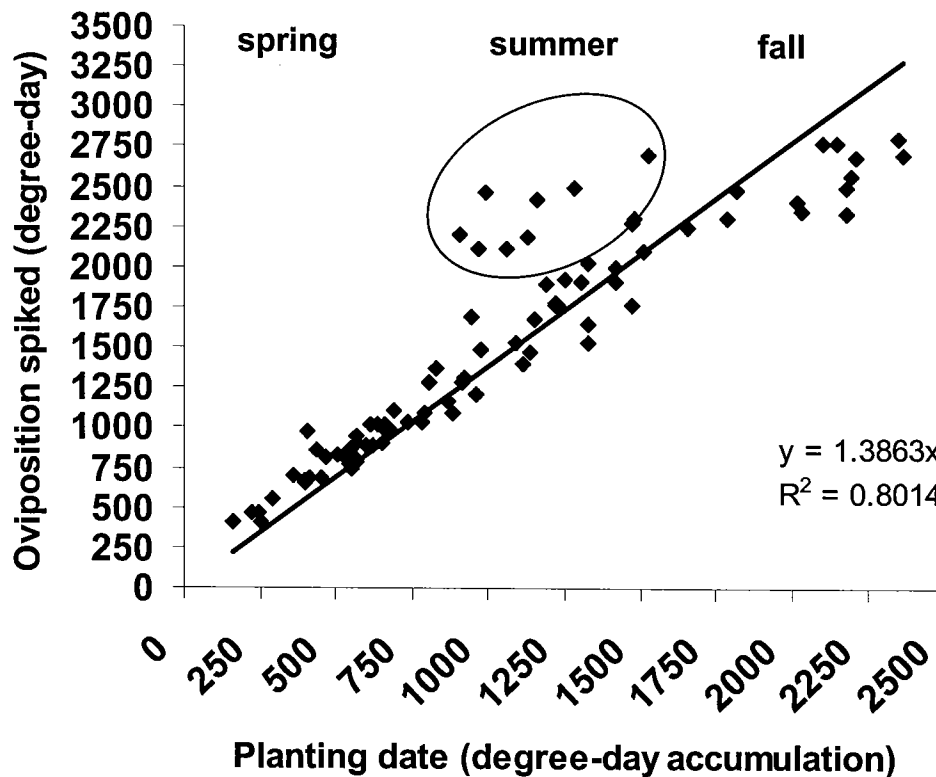


Fig. 4.5. Occurrence of oviposition “spike” or significant increase in egg incidence (proportion of plants with eggs) after seeding. Circled group of summer-planted fields exhibited a delay in oviposition spike.

4.4.4 Precipitation

There was no differences in precipitation level among the 28 fields with oviposition spikes that occurred at approx. one month after seeding (mean precipitation total of 1.45cm), and the 8 fields that experienced a significant delay in oviposition (mean precipitation total of 2.21 cm) ($t = 1.29$; $df = 31$; $P = 0.20$) (Fig 4.6). Four of the eight fields received less than 2 cm of precipitation at 31 days after planting and the other four had higher levels of precipitation (>3 cm) during the time the crop was in the field.

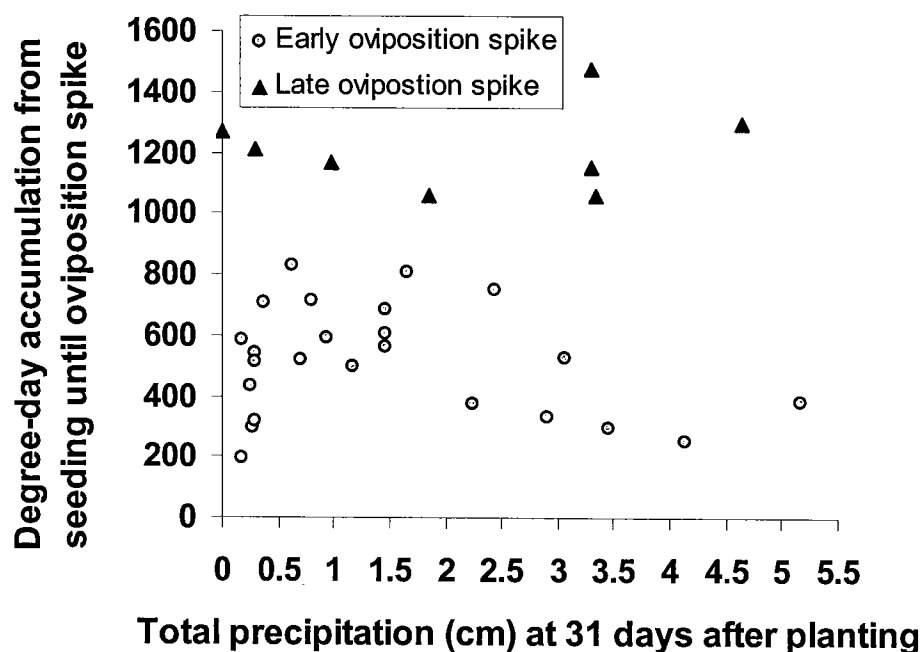


Fig. 4.6. Precipitation (cm) comparison (from seeding to 31 days after) between fields with a delay in oviposition spike (\blacktriangle) versus fields without delay in oviposition spike (\bullet).

4.4.5 Plant Growth Stage

From 2001 to 2005, overall egg levels increased significantly (50%, hence crop damage also significantly increased over the five years (Table 4.1). The three seasonal plantings (spring, summer, and fall), all showed significant increases in egg levels beginning at the 5-leaf stage and root size of 6 mm. Higher levels of egg incidence occurred at every plant growth stage in the spring, as compared to the other two planting seasons ($F = 24.7$; $df = 2$; $P < 0.0001$) (Table 4.2). There were significant differences in the proportional egg incidence at different plant growth stages ($F = 35.94$; $df = 3, 356$; $P < 0.0001$) (Fig. 4.7). Significantly more plants with eggs (12.0 ± 1.2 ; mean \pm SEM) were oviposited on older

rutabaga and turnip plants (PGS 2, 3, and 4) with developing roots (> 6 mm), > 5 leaves, and expanding plant canopy. Comparatively lower egg incidence (3.7 ± 1.2) were found on younger plants at cotyledon to 4-leaf stage with little root development. Increase in egg incidence on older plants (PGS 2, 3, 4) compared to younger plants (PGS 1) ranged from 64 to 92% and a mean increase of 75 % more plants with eggs were found at the base of older plants. In 2001 and 2004, the oldest mature plants with a PGS rating of 4, revealed no differences in the proportion of CM eggs in comparison to the youngest developing plants with PGS rating of 1.

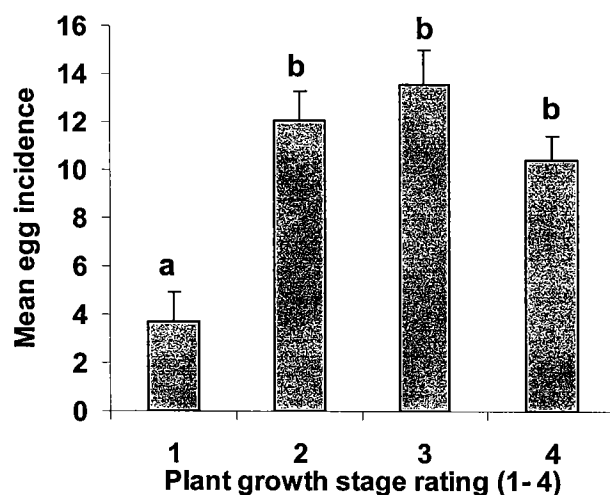


Fig. 4.7. Mean egg incidence at four plant growth stages over 5 years of study in rutabaga and turnip crops. The plant growth developmental rating scale consisted of: 1 = cotyledon to 4 developing leaves, root diameter less than 6 mm, canopy coverage open, bare ground exposed; 2 = 5 -8 leaves, root diameter 6-19mm, canopy coverage open and bare ground exposed; 3 = 9-15 leaves, root diameter >19mm-32mm, canopy coverage partially closed (only 75 to 175mm of exposed bareground; and 4 = 9-15+ developed leaves, root diameter >32 mm-100mm, canopy coverage typically closed, mature crop.

Table 4.1. Yearly mean egg incidence at four different plant growth stages from 2001 through 2005.

Yearly mean egg incidence (\pm SEM) at four different plant growth stages ^{x,y}					
Plant growth stage rating ^z	2001	2002	2003	2004	2005
1	0.8 \pm 0.29b	1.9 \pm .64b	1.9 \pm 0.59b	6.3 \pm 1.4b	5.6 \pm 2.1b
2	10.6 \pm 2.0a	9.4 \pm 1.7a	12.3 \pm 2.9a	17.2 \pm 3.6a	18.2 \pm 2.5a
3	11.9 \pm 3.9a	9.9 \pm 1.7a	11.7 \pm 2.4a	22.2 \pm 5.0a	26.0 \pm 2.7a
4	7.4 \pm 1.9ab	8.4 \pm 1.7a	10.4 \pm 2.5a	13.1 \pm 1.9ab	22.7 \pm 3.1a
F	10.41	12.44	7.82	5.54	12.48
N	16	34	20	14	6
p	<0.0001	<0.0001	<0.0001	<0.0022	<0.0001

^x Original means (based on 90 plants per field) within columns followed by the same letter are not significantly different at $\alpha = 0.05$, detected by ANOVA test using the Tukey's HSD multiple comparison.

^y Original means are presented in table, however data were transformed using arcsin squareroot to equalize variances before analysis with ANOVA.

^zThe plant growth developmental rating scale consisted of: **1** = cotyledon to 4 developing leaves, root diameter less than 6 mm, canopy coverage open, bare ground exposed; **2** = 5 -8 leaves, root diameter 6-19 mm, canopy coverage open and bare ground exposed; **3** = 9-15 leaves, root diameter >19 mm-32 mm, canopy coverage partially closed (only 75 to 175mm of exposed bareground; and **4** = 9-15+ developed leaves, root diameter >32 mm-100 mm, canopy coverage typically closed, mature crop.

Table 4.2. Seasonal differences in egg incidence at four different plant growth stages in rutabaga and turnip crops.

Mean egg incidence (\pm SEM) at 4 plant growth stages and 3 seasonal plantings^{x,y}			
Plant growth stage^z	Spring N = 41	Summer N = 29	Fall N = 20
1	3.9 \pm 0.7c	1.5 \pm 0.58b	1.6 \pm 0.66b
2	18.3 \pm 1.9ab	7.1 \pm 1.3a	6.4 \pm 1.5a
3	19.3 \pm 2.4a	9.5 \pm 1.8a	8.1 \pm 1.8a
4	12.7 \pm 1.6b	10.8 \pm 1.9a	4.9 \pm 1.2a
<i>F</i>	23.72	16.17	6.64
df	3, 37	3, 25	3, 16
<i>P</i>	< 0.0001	< 0.0001	< 0.0005

^x Original means (based on 90 plants per field) within columns followed by the same letter are not significantly different at $\alpha = 0.05$, detected by ANOVA test using the Tukey's HSD multiple comparison.

^y Original means are presented in table, however data were transformed using arcsin squareroot to equalize variances before analysis with ANOVA.

^z The plant growth developmental rating scale consisted of: 1 = cotyledon to 4 developing leaves, root diameter less than 6 mm, canopy coverage open, bare ground exposed; 2 = 5-8 leaves, root diameter 6-19 mm, canopy coverage open and bare ground exposed; 3 = 9-15 leaves, root diameter >19mm-32mm, canopy coverage partially closed (only 75 to 175mm of exposed bareground; and 4 = 9-15+ developed leaves, root diameter >32 mm-100mm, canopy coverage typically closed, mature crop.

4.4.6 Fly Catch, Damage, and Oviposition Relationships

A significant relationship existed between fly catch and crop damage in fields monitored for weekly egg incidence ($n = 34$) ($F = 3.55$; $df = 1, 32$; $P < 0.0012$). Fields assessed with greater than 20% damage ($n = 18$) had higher fly counts in water traps, a mean cumulative fly count over the duration a crop was in the ground, of 286.13 ± 52.7 , compared to fields with less than 20% damage ($n = 16$), a mean count of 84.7 ± 10.8 ($F =$

14.45, $df = 2,32$; $P < 0.0006$). After assessing numbers of fly catch in the lowest damaged fields ($< 20\%$) and numbers in the highest damaged fields ($> 40\%$, the grower's economic threshold), crop damage was significantly higher in fields with greater than 100 flies detected in water traps over the duration a field was in the ground, field damages averaging 36.9 ± 4.7 , compared to lower numbers of fly catch (< 100 flies), a crop damage averaging 14.1 ± 4.2 (two-sample t test = 4.5; $df = 32$; $P < 0.0001$).

A significant relationship also existed between crop damage and proportion of plants with eggs (egg incidence) ($F = 34.8$; $df = 1, 32$; $P < 0.0001$). Fields with less damage ($< 20\%$) and less fly catch (< 100 flies), had significantly less oviposition. In fields with low damage levels ($< 20\%$), the sum of weekly egg incidence assessments (7) averaged 38.6 ± 6.1 compared to 95.6 ± 16.7 , in highly damaged fields ($t = 3.60$, $df = 32$, $P = 0.001$).

Fields documented with less than 100 flies detected in water traps had lower sums of weekly egg incidence, averaging 44.0 ± 1.3 ; whereas fields with more than 100 flies had higher sums of egg incidence, averaging 84.5 ± 1.3 over crop duration ($t = 2.2$; $df = 32$; $P = 0.03$) (Fig. 4.8). However no significance was detected between fly catch and sum of weekly egg incidence assessments across years and seasons when using REG analysis procedure ($t = 1.59$; $df = 1, 32$; $P = 0.12$) (Fig. 4.9).

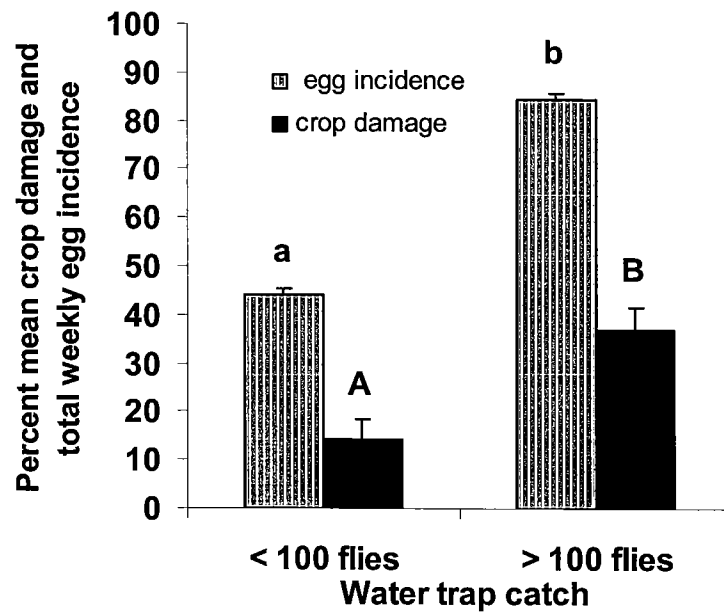


Fig. 4.8. Sum of weekly egg incidence (proportion of plants with eggs) and crop damage at harvest in relation to fly catch at less than and greater than 100 flies.

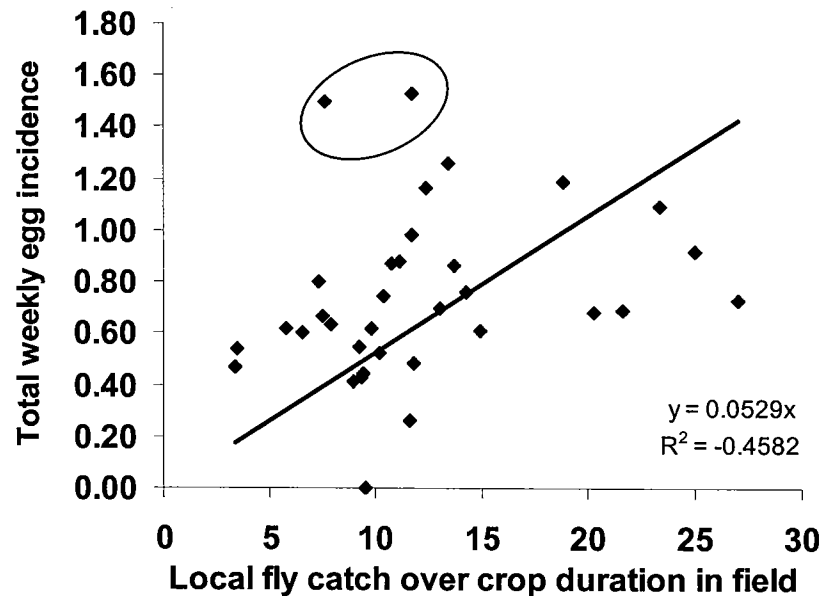


Fig. 4.9. Relationship between fly catch over crop duration in field and sum of weekly egg incidence assessments (7) in rutabaga and turnip crops. Two field outliers were identified with low fly catch detected in water trap, but high total weekly egg incidence.

Fields assessed with low damage levels (< 20%) yielded a maximum of one weekly evaluation with > 10% egg incidence and all other crop evaluations during the monitoring period were assessed at less than 10% egg incidence. Whereas, fields with high damage levels (> 40 % loss) yielded at least three weekly evaluations of > 15% egg incidence reported over the duration of egg monitoring.

It is important to note that in this study, there is not was not a one-to one relationship between cumulative egg incidence in a field and ultimate crop damage. Only 57.1% (a range of 26.1 to 80.1%) of plants with eggs counted yielded actual crop damage. And this difference between incidence and damage varies seasonally, because the causal factors vary. For example, egg incidence varied in reduction from spring plantings (60.3 ± 3.0), to summer (49.7 ± 4.1) to fall plantings (59.2 ± 5.1) ($F = 3.43$; $df = 2, 32$; $P = 0.04$).

There was a strong relationship between the sum of weekly egg incidence assessed at the later growth stages (PGS 3 and PGS 4) and crop damage ($r^2 = 0.84$)(Fig. 4.10). Other egg-to-damage relationships reported were: the sum of egg incidence over the duration a crop was in field and damage ($r^2 = 0.67$) (Fig. 4.11); the sum of mean egg incidence from each plant growth stage and damage ($r^2 = 0.60$); the sum of the egg incidences at PGS 2 and PGS 3 only and crop damage ($r^2 = 0.43$).

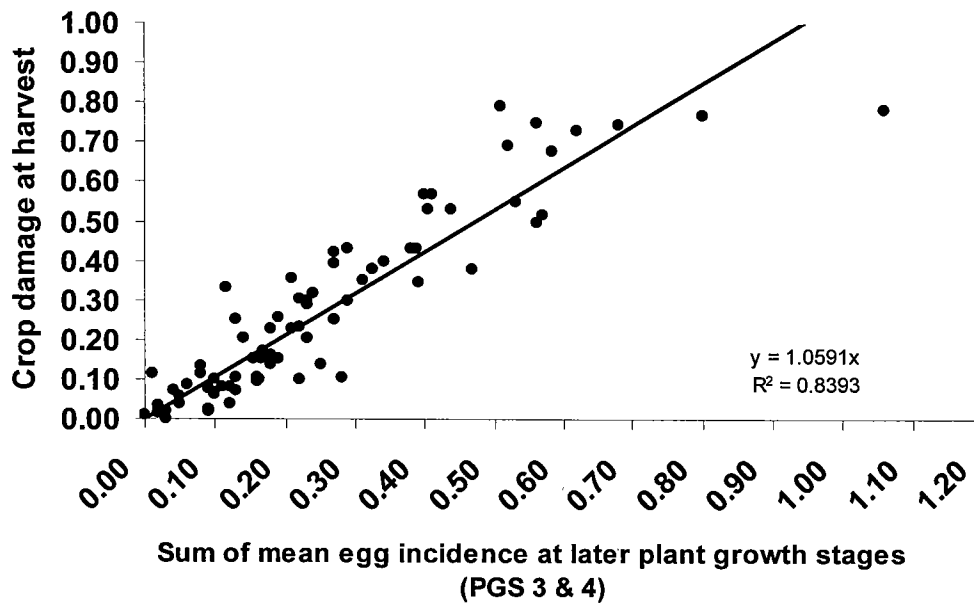


Fig. 4.10. Relationship between the sum of egg incidence assessed at later plant growth stages (PGS 3 and PGS 4) of rutabaga and turnip crops to crop damage at harvest.

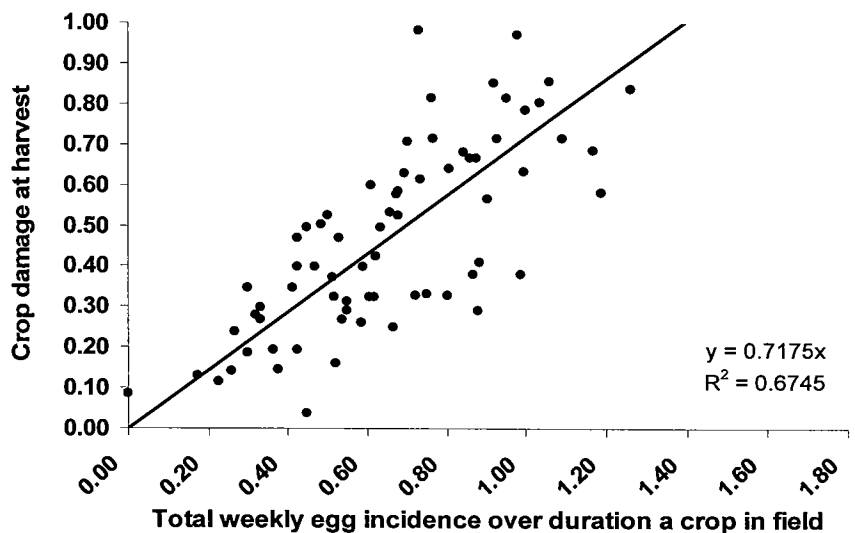


Fig. 4.11. Relationship between the sum of egg incidence assessed over duration a crop is in field and crop damage at harvest.

4.4.7 Spatial Distribution of Eggs

There were significant differences in number of plants with CM eggs depending on the sample location within the field ($F = 13.05$; $df = 5$; $P < 0.0001$). The outside perimeter, extending 15 meters into the field, had significantly higher levels of egg incidence than the locations inside the fields of any-size. Egg incidence increased by approximately 46% on plants located on the outside of the field compared to levels found at central locations. Also, oviposition was higher in fields planted in the spring, than summer or fall-planted fields ($F = 39.76$, $df = 71$, $P < .0001$) (Table 4.3). No significant differences in egg incidence were seen between summer and fall-planted fields. In fields planted in spring, summer, and fall, there was a respective egg incidence increase of 38, 54, and 52%, in the outside sampling locations compared with interior locations ($t = 12.54$; $df = 71$; $P < 0.0001$).

Table 4.3. Comparison of seasonal mean egg incidence located on central and periphery of 72 fields. A total of 90 plants per evaluation, approx. 6 evaluations per field.

Seasonal mean egg incidence (\pm SEM)				
Sample location	All Seasons	Spring <900DD	Summer >900-1500DD	Fall >1500DD
Outside	16.8 \pm 1.3a	24.6 \pm 2.5a	14.6 \pm 1.7a	11.5 \pm 1.4a
Inside	9.0 \pm 1.0b	15.3 \pm 2.2b	6.7 \pm 1.4b	5.5 \pm 1.0b
t	12.54	7.15	7.44	8.39
df	71	22	24	23
P <	0.0001	0.0001	0.0001	0.0001

Differences in oviposition levels were also reported between years ($t = 3.10$; $df = 2$; $P = 0.05$) and between yearly sampling locations ($t = 4.7$; $df = 71$; $P < 0.0001$) (Table 4.4).

Overall, significantly more egg incidence occurred throughout the field in the 2005 fields (16.1 ± 2.2) than 2003 (9.2 ± 1.7), however no differences existed between 2004 (12.7 ± 1.6) and 2005 or 2003. Egg incidence in all years was significantly higher in outside sampling locations than in interior locations. Egg levels on periphery plants had increased proportions of 48, 52, and 65% in 2003, 2004, and 2005, respectively. There was no differences in egg incidence between the two central locations ($t = 0.010$; $df = 71$; $P = 0.99$) (Table 4.5). However, significant differences were observed among the four outside locations. In fall-planted fields, the NW corner had significantly less oviposition than the NE ($P = 0.0019$), SE ($P = 0.02$) and marginally but inconclusively less than the SW corner ($P = 0.08$). The NE location had higher egg levels than the SW prevailing wind corner, as well as the east side of the field had increased oviposition levels than the west side. In summer-planted fields the opposite occurred. The southern outer peripheries of the fields had increased egg incidence compared to the northern side, and the SW location yielded greater egg incidence than the NE side, as seen in 2003 ($P = 0.01$) and 2005 ($P = 0.005$).

Table 4.4. Comparison of yearly mean egg incidence of *D. radicum* at inside and outside sampling locations in a field.

Sample Location	Yearly mean egg incidence (\pm SEM)			
	All Years	2003	2004	2005
Outside	16.8 \pm 1.3a	12.2 \pm 2.0a	17.2 \pm 2.0a	20.1 \pm 2.3a
Inside	9.04 \pm 1.0b	6.3 \pm 1.4b	8.3 \pm 1.4a	12.2 \pm 2.3b
<i>t</i>	4.7	6.9	7.4	8.6
df	71	19	27	23
<i>P</i> <	0.0001	0.0001	0.0001	0.0001

Table 4.5. Seasonal and yearly mean egg incidence at different sampling locations in the field.

Sample Location	(t, df, P)	Seasonal and yearly mean (\pm SEM) egg incidence					
		All Seasons	Spring	Summer	Fall	2003	2004
Inside							
Location	(0.010, 71, 0.99)	(0.93, 22, 0.36)	(1.03, 23, .31)	(1.74, 22, 0.10)	(.41, 19, .68)	(.59, 27, .56)	(.10, 23, .92)
5SW	9.0 \pm 1.1	14.8 \pm 2.1	6.6 \pm 1.4	4.8 \pm 0.8	6.4 \pm 1.5	8.1 \pm 1.4	12.3 \pm 2.6
6NE	9.0 \pm 1.0	15.8 \pm 2.5	7.4 \pm 1.5	6.7 \pm 1.4	6.1 \pm 1.4	8.4 \pm 1.4	12.1 \pm 2.3
North side	(2.4, 71, 0.03)	(.47, 22, 0.64)	(.70, 24, 0.48)	(3.5, 23, .0019)	(.33, 19, .90)	(4.3, 27, .0002)	(.13, 23, .90)
1NE	17.5 \pm 1.5	25.3 \pm 3.1	13.6 \pm 1.6	14.1 \pm 1.9	12.0 \pm 1.8	19.4 \pm 2.2	19.8 \pm 3.0
4NW	15.0 \pm 1.5	24.2 \pm 3.2	12.5 \pm 2.1	8.9 \pm 1.3	12.2 \pm 2.3	12.8 \pm 2.0	20.1 \pm 3.2
South side	(0.83, 71, .93)	(3.27, 22, .24)	(1.7, 24, 0.11)	(1.2, 22, .24)	(.90, 19, .38)	(1.4, 27, .17)	(.39, 22, .70)
2SE	17.1 \pm 1.3	24.8 \pm 2.7	14.9 \pm 1.8	11.9 \pm 1.5	13.1 \pm 2.8	17.4 \pm 2.1	20.3 \pm 2.0
3SW	17.2 \pm 1.4	24.1 \pm 2.4	17.1 \pm 2.3	10.4 \pm 1.4	11.5 \pm 1.6	19.2 \pm 2.6	19.7 \pm 2.1
East side	(0.25, 71, .81)	(.24, 22, .81)	(.95, 24, .35)	(1.3, 22, .20)	(.87, 19, .40)	(1.7, 27, .11)	(.36, 22, .72)
1NE	17.4 \pm 1.5	25.3 \pm 3.1	13.6 \pm 1.6	14.1 \pm 1.9	12.0 \pm 1.8	19.4 \pm 2.2	19.5 \pm 3.1
2SE	17.1 \pm 1.3	24.8 \pm 2.7	14.9 \pm 1.8	11.9 \pm 1.5	13.1 \pm 2.8	17.4 \pm 2.1	20.3 \pm 2.0
West side	(1.95, 71, .05)	(.01, 22, .99)	(2.29, 24, .03)	(1.8, 23, .08)	(.72, 19, .48)	(3.5, 27, .0015)	(.17, 23, .86)
3SW	17.2 \pm 1.3	24.1 \pm 2.4	17.1 \pm 2.3	10.8 \pm 1.4	11.5 \pm 1.6	19.2 \pm 2.6	19.7 \pm 2.0
4NW	15.0 \pm 1.5	24.2 \pm 3.2	12.5 \pm 2.1	8.9 \pm 1.3	12.2 \pm 2.3	17.4 \pm 2.1	20.1 \pm 3.2
Prevailing Wind							
1NE	(.248, 71, .81)	(.61, 22, .55)	(2.15, 24, .04)	(2.5, 23, .02)	(.44, 19, .67)	(.097, 27, .92)	(.06, 23, .96)
3SW	17.5 \pm 1.5	25.3 \pm 3.1	13.6 \pm 1.6	14.1 \pm 2.0	12.0 \pm 1.8	19.2 \pm 2.6	19.8 \pm 3.0
3SW	17.2 \pm 1.3	24.1 \pm 2.4	17.1 \pm 2.3	10.8 \pm 1.4	11.5 \pm 1.6	19.4 \pm 2.2	19.7 \pm 2.0
Corners	(1.8, 71, .07)	(.24, 22, .81)	(1.1, 24, 0.27)	(2.6, 22, .02)	(.55, 19, .59)	(2.5, 27, .02)	(.09, 22, .93)
4NW	14.9 \pm 1.5	24.2 \pm 3.2	12.5 \pm 2.1	8.9 \pm 1.3	12.2 \pm 2.3	12.8 \pm 2.0	20.1 \pm 3.4
2SE	17.1 \pm 1.3	24.8 \pm 2.7	14.9 \pm 1.8	11.9 \pm 1.5	13.1 \pm 2.8	17.4 \pm 2.1	20.3 \pm 2.0
Side NS	(1.17, 71, .25)	(.15, 22, .88)	(1.9, 24, .06)	(.07, 23, .95)	(.30, 23, .75)	(1.7, 27, .10)	(.03, 23, .93)
North	16.3 \pm 1.4	24.7 \pm 2.9	13.0 \pm 1.7	11.5 \pm 1.3	12.09 \pm 1.0	16.1 \pm 2.0	20.7 \pm .03
South	17.2 \pm 1.3	24.5 \pm 2.3	16.0 \pm 2.0	11.5 \pm 1.5	12.30 \pm 1.0	18.2 \pm 2.0	20.2 \pm 2.0
Side EW	(.010, 71, .99)	(.59, 22, .56)	(.51, 24, .61)	(3.3, 23, .003)	(.56, 23, .56)	(2.1, 24, .05)	(.22, 23, .83)
East	17.4 \pm 1.3	25.0 \pm 2.7	14.2 \pm 1.6	13.3 \pm 1.7	12.56 \pm 2.0	18.39 \pm 2.0	20.65 \pm 2.0
West	16.1 \pm 1.3	24.1 \pm 2.5	14.8 \pm 1.9	9.9 \pm 1.3	11.53 \pm 1.0	16.00 \pm 2.0	20.33 \pm 2.0

4.5 Discussion

4.5.1 Oviposition Activity

Results affirmed research reporting that *D. radicum* egg-laying increased in the spring, with increased moisture and cooler temperatures (Sears and Dufault 1986, McDonald and Sears 1992, Todd 1998). However, flight can be delayed, as seen in 2001, most likely due to an unusually cool and dry spring causing decreased DD accumulations. Under these conditions, oviposition can extend into late June (≈ 1100 DD). Previous findings that ≈ 600 DD are required for each generation, suggests that first-generation flies, produced from the overwintering population (estimated at 329 DD), begin to oviposit in early to mid-June (900 -1100 DD) (Eckenrode and Chapman 1972). Oviposition overlap is common in spring, making it difficult to predict the timing of oviposition in a field based on a single spring flight event.

Oviposition levels also differed between crops. The severity of oviposition on the different crops may be related to the relative attractiveness of the crop at oviposition. Rutabagas are known for their rich source of oviposition stimulants found in the roots (de Jong 2000). Known differences in oviposition levels between crop types could provide a management tool for turnip growers. For example, preliminary and unreported data revealed that planting 2–3 rows of rutabagas, a crop more attractive to *D. radicum* females, on the periphery of a turnip field may reduce oviposition in the turnip field (Rouse et al. . Border rows could then be treated with chemicals for control of CM or destroyed before larval emergence (unpublished data). Trap cropping needs further investigation.

4.5.2 Seasonal Flight.

Distinct emergence and more consistent flight patterns in the spring enhances estimates of initial oviposition increases, which occurred at greater than 409 DD. However, the value of employing spring flight events to predict timing of increased oviposition in each field was not clear in this study. The degree-day model could predict the start of oviposition and peak of activity but could not predict the spread of activity. Previous research has not clearly defined when to begin field monitoring for detecting increases in CM eggs in the spring, but has simply related initiation of spring oviposition to flight activity. Coaker and Wright (1963) documented a three-to-ten-day lag between the date of first fly emergence and the initiation of CM oviposition. Other researchers observed that oviposition by the spring generation of flies occurred in a four-day span, two weeks after detection of adults (Matthewman and Harcourt 1963, Griffiths 1986). Sears and Dufault (1986) also found a correlation and two-week lag between increased fly catch and oviposition. In this study, the first fields were not planted until an accumulation of 162 DD (early March). Increased fly movement occurred in the spring as fly populations move around to locate newly-planted Brassica crops, delaying their arrival into fields. Increased egg-laying was not observed until 50 days after planting in fields planted before early-emerging peaks. Initial increases in egg levels were not seen until 3–4 weeks after the early emerging peak flight (> 329 DD). So in contrary to what other researchers have found, no correlation between increased flight activity and increased oviposition was identified. Most importantly, planting date and plant growth stage — as will be explained later — appeared to play a greater role in the timing of oviposition spikes in individual fields in the spring.

In the fall, no clear relationship between timing of oviposition and initiation of fall generation flights was observed. Others reported initiation of oviposition when fall generation flights began (Sears and Dufault 1986). Increased fly movement was apparent in the fall as detected in water traps, and Brassica crops still left in the ground were at risk to high oviposition from emerging fly populations. Flies most likely redistribute themselves in the region to find the last of the Brassica crops for oviposition purposes. No pattern of oviposition could be linked to increased flight. In addition, a large number of late fall-collected flies after 2900 DD were not accompanied by increased oviposition, also confirmed by Sears and Dufault (1986), and Bracken (1988). In comparison to the spring and fall, reduced fecundity occurred in the summer and flight was variable and dependent on locality. Lower oviposition has been explained by: 1) reduced nectar in flower blossoms (Miles 1951) and 2) unfavorable weather for *D. radicum* (Bracken 1988).

4.5.3 Planting Date

Planting date was significantly correlated with increased oviposition. No research has documented this correlation. The plant growth stage of the crop at ≈ 1 month after planting had a rating of PGS 2 and PGS 3, the ovipositional preference of females as reported in this research and others. Knowing the expected timing of oviposition helps determine when monitoring should begin. However, eight summer-planted crops did not see increases in egg levels at ≈ 1 month after planting, and experienced an oviposition delay of ≈ 46 additional days. All eight fields were close-by to recently harvested, neighboring maggot sources (within 400 meters). These eight fields became the only known available food source for *D. radicum*. Summer-planted fields, may miss the first oviposition cycle, but may be at risk, especially those in close proximity to harvested maggot-infested fields, by fall generation

flies. Further research is needed to understand why some fields escape oviposition increases. There are many factors that may contribute to increased oviposition levels in a field, including: 1) proximity to overwintering and seasonal maggot sources; 2) level of fly pressure in the spring and lack of ability to control the overwintering and first generation population; and 3) stage of plant growth relative to other surrounding fields (as explained below). Spatial relationships need further investigation.

4.5.4 Plant Growth Stage

D. radicum preferred four-week-old root crops with developing roots as ovipositional sites. Females preferentially laid more eggs at the base of plants with more than five leaves, \approx 30 days after planting. Differences in oviposition levels at different plant growth stages may be due to differences in root size, plant architecture (increased leaf surface area), and chemical cues (Prokopy et al. 1983, Griffiths 1986, Baur et al. 1996). Changes in glucosinolate chemicals in relationship to plant development from seed, to foliage development, and to initiation of root growth can help explain the differences in egg incidence (de Jong 2000).

This study was in agreement with Liu and Butts (1982) who reported that young *Brassica* plants (two weeks old) are less susceptible to ovipositing females than are older plants (five weeks old). These findings were confirmed by Ontario researchers who found that oviposition rarely occurs on plants with fewer than six to eight leaves (McDonald and Sears 1992). This research also show increased oviposition on rutabaga plants five days earlier than turnip crops, perhaps because these crops were planted 200 DD earlier, a higher egg-laying period, and the crop growth stage was advantageous. However, *D. radicum* laid eggs on later plant stages (PGS 4) in cases when the younger, more preferred stages, PGS 2

and PGS 3, were not available. It was also noted that, if summer-planted crops were not harvested until after fall flight, oviposition increased in later plant stages (PGS 4), most likely because these fields were the only ovipositional sites available.

4.5.5 Fly Catch, Damage, and Oviposition Relationships

Typically low fly catch (< 107 flies over crop duration in field) equated broadly to a low sum of weekly egg incidence assessments per field (mean 44.0; a sum of 7 weekly egg incidence), hence lower damage levels (< 20% loss). However, this study replicated what others have found: the arrival of flies in water traps can be unpredictable, sometimes gradual and prolonged, so monitoring for oviposition is essential (Sears and Dufault 1986, Bracken 1988). Increasing the numbers of water traps in field borders may increase the efficacy of fly catch and yield better estimates of potential oviposition, but they will remain estimates.

Egg incidence assessments taken at early growth stages (PGS 1 and PGS 2) did not appear to contribute to damage accumulation. At planting, all fields were treated with a persistent chemical. This may have increased protection through the first two stages of plant growth, but the protection most likely did not last through the growing season. Oviposition continued, and later growth stages sustained damage. The degree of chemical persistence depends on soil type and moisture (Harris 1969; Getzin 1981). Moist soils, water applications, and sandy to silt loam soils, as found in this study can reduce the chemical activity of chlorpyrifos, 36 hours to 30 days (Exttoxnet 2000). Also, when eggs are oviposited early in crop development, before the plant canopy closed, eggs are more exposed to broadcast chemicals. Later in the season, the canopy closes and chemical controls do a poorer job of penetrating to the potentially damaging target eggs.

Less than 50% of the total sum of weekly egg incidence assessments per field resulted in actual larval damage at harvest. The establishment of larvae in a root can be greatly affected by biotic and abiotic causes, including desiccation, natural enemies, and natural egg or larval mortality. Mukerji (1971) report a 15% natural mortality of eggs upon eclosion. Biron et al. (2002) reported natural mortality of CM eggs and larvae during spring emergence averaging 2–5 % and 43–56 %, respectively, and resulted in 37–40 % survival from egg to adult. In Holland, researchers described 97.5% egg mortality was due to natural enemies, and 75% mortality at eclosion and establishment of newly-emerged larvae (Abu Yaman 1960, Hughes and Salter 1959). Due to similar biotic and abiotic causes, Nair and McEwen (1975) reported egg mortality from 36.2% to 76%. They also reported high mortality between eclosion and second larval molt. When designing a monitoring program with appropriate egg-incidence thresholds, egg and larval must be considered to accurately reflect subsequent damage.

4.5.6 Spatial Distribution of Eggs

Incidence of plants with eggs was often greater along field peripheries compared to field centers; in many cases, eggs were more prevalent on the windward sides of fields. However, surrounding hedgerows, prevailing wind direction and housing developments may affect fly activity and hence oviposition levels on the different borders (unpublished data). Knowledge of this negative binomial spatial pattern (Mukerji and Harcourt 1970) is an essential piece of knowledge for developing a precise and efficient sampling design and can be exploited to: 1) reduce broadcast spraying of insecticides by limiting insecticide application to areas of high oviposition activity, and 2) encourage alternative control methods, like perimeter trap cropping (Hokkanen 1991), that draw flies away from a less-

attractive main crop and concentrating them in a trap crop on the borders of the field. Also, it was observed that in fields with increased egg incidence assessments and larval injury, oviposition pressure was more pronounced and consistent throughout the field season as reported in other studies (Baur et al. 1996). Baur et al. (1996) reported that increased root damage can induce preference for oviposition. At very low or extremely high densities, aggregate distributions can diminish, nearly approaching the Poisson distribution.

4.6 Conclusion

It is recommended to begin weekly egg monitoring prior to expected oviposition increase, approximately two-three weeks after planting, at the five-leaf stage of rutabaga and turnip crops. Considerable amounts of further basic research will be required to produce a robust monitoring program that will forecast accurately the crop damage, but this research has generated a foundation to build from. High fly counts in water traps can alert a grower to potential oviposition, but traps are not foolproof. The egg-scrape technique (consisting of a total of 90 plants) employed a binomial sampling procedure to estimate the number of plants with eggs (standard error was less than 15%). For egg sampling to be considered viable by growers, it must be fast, easy, and cost effective. A shortcut or “speed-scouting” sampling method like sequential sampling could be designed to meet growers’ needs and still yield accurate egg-levels and damage estimates. When samples are drawn sequentially, in field locations where population density is clearly defined, one or two samples often suffice; but, at locations near borderlines between two classes of population density, more samples must be

drawn to achieve accurate placement. And growers might consider treating field borders differently than central locations.

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5 GENERAL CONCLUSION

A. J. DREVES

Department of Crop and Soil Science

Oregon State University

5.1 General Conclusion

Cabbage maggots frequently require management in areas of intensive Brassica crop production, as seen in northwestern Oregon. Growers of root crops in the northern Willamette Valley are challenged to produce a crop economically, when *Delia* spp. are problematic through the season for rutabaga and turnip crops. This research was developed to investigate strategies for reducing the cabbage maggot, *Delia radicum* L., which most importantly includes monitoring. Currently growers do not monitor for presence of maggot, but prophylactically treat fields, regardless of the actual level of oviposition. This research promotes monitoring: 1) to assess a pest situation and determine what sort of pest activity is occurring; 2) to predict pest problems before they occur; 3) for wiser decision-making; and 4) ultimately, to reduce pesticide use. The study investigated spring emergence and seasonal flight, pest impact, relationships between flight, damage and oviposition, and timing of planting and harvesting to avoid high risk peaks of fly activity.

Spring emergence of CM flies in field emergence cages indicated a bimodal spring emergence pattern. Approximately 70% of the overwintering population emerges and displays an early peak in late March, while the remainder of flies emerge later in the spring, displaying a smaller peak in late May. The mean degree-day (DD) accumulations at 10, 50, and 95% of spring emergence using a lower and upper developmental threshold of 4.3°C and 30°C beginning 1 January had corresponding DD values of 200 ± 50.2 (8 March), 330 ± 22.2 (4 April) and 762 ± 60.1 (28 May), respectively.

Flies caught in yellow water traps mirrored the bimodal emergence pattern, but with a delay of 3 days to 5 weeks. The mean DD accumulations recorded from the beginning to the end of spring flight had corresponding DD values of 303 ± 61.5 (31 March) to $839 \pm$

51.9 (4 June). Fly activity was lower over the summer from the beginning of June until the end of August (2138 ± 82.3 DD). A fall emergence of flies was observed each year beginning in late August to early September and extending through October (2860 ± 170.6 DD).

Overall, crop damage from CM was assessed using a binomial sampling procedure of 60 roots per field. During the course of the study harvest damage increased from a mean damage of 11.9% (± 2.5) in 2001 to 41.4% (± 5.5) in 2005. Rutabaga crops sustained greater percent root damage (37.9 ± 3.4) than did turnip crops (22.9 ± 1.8). Crop damage was significantly greater (37-52%) in crops planted during the spring before an accumulated 900 degree-days, when compared to crops planted in the summer (>900 DD) or fall (>1500 DD). When planting occurs after 900 DD, and the crop is harvested prior to the peak of fall flight (< 2600 degree-days), damage from maggots is reduced substantially.

A significant relationship was seen between fly catch and crop damage observed at harvest ($r^2 = 0.64$; $P < 0.0001$). Fields with seasonal counts of fewer than 100 flies per trap over a crop's duration in the field had a lower sum of weekly assessments (avg. 6) of plants with one or more eggs, averaging 38.6 ± 6.1 , and had less than 20% crop damage. Fields with seasonal counts greater than 100 flies per trap had a higher sum of weekly assessments of plants with eggs, averaging 95.6 ± 6.7 and greater than 20% damage at harvest. Data showed that if greater than 10% egg incidence is reported at any given evaluation, control should be considered. It is felt that fly counts in water traps are not reliable indicators of a potential problem, and egg monitoring is essential to verify arrival of ovipositing females in a field. Interestingly in this study, the sum of weekly egg incidence assessments per field resulted in half the amount of actual damage recorded at harvest.

Planting date predicted occurrence of oviposition better than did flight events.

Oviposition significantly increased in fields at 30.9 (\pm 1.1) days after planting. However, some summer-planted fields were without a significant number of plants with eggs until the later flight of the fall generation. Precipitation did not appear to be a significant factor affecting the oviposition timing in these eight fields. Water trap catch was unreliable as a predictor of actual timing of oviposition in the Brassica field but can alert growers of potential damage and oviposition levels.

Increased egg incidence was recorded on older plants with > 5 leaves, root diameters of > 6 mm, and an increased crop canopy. There was a significant correlation between egg incidence and damage at harvest; in particular the sum of weekly egg incidence assessments from later plant growth stages showed the strongest relationship with crop damage ($r^2 = .84$). Egg incidence was significantly higher (46%) on plants located on the outside periphery of fields than centrally-located plants.

Spring monitoring of emergence, flight patterns, arrival, and density of *D. radicum* allows useful predictions of oviposition and crop damage. Appropriate oviposition and distribution assessments, combined with improved spatial and temporal field management, timely planting and harvesting schedules, and use of egg thresholds to time treatments could greatly reduce maggot populations.

In addition to the findings presented in this study, other factors that affect CM damage in commercial Brassica root crops in need of study include: influence of crop rotations, distance from sources of CM infestation, usefulness of trap cropping; selection of and timing for insecticide applications, most effective application equipment, selective location spraying, and sequential sampling.

The following list of recommendations will help reduce levels of cabbage maggots in rutabaga and turnip crops:

1. In the spring, develop a seasonal planting and harvesting schedule of an anticipated number of field plantings. Avoid planting near overwintering and seasonal maggot sources. If possible, evade planting during peak egg-laying periods in the spring (before 900 DD). Acknowledge that a field is at risk if left in the ground through fall flight.
2. Set up several yellow water traps on border areas (corners of prevailing windward wind) of newly-planted fields. Document weekly trap catches and pay attention to low and high patterns of fly catch. Water traps are not foolproof. If >100 flies are caught in traps, potential for greater damage (> 20%) is possible.
3. Predict emergence and flight by using the Oregon degree-day model and record daily degree-days and number of flies in water traps to verify actual arrival of flies in the field.
4. Monitor weekly for egg levels to verify oviposition in field. Begin sampling at ≈ 3 weeks after planting (>5 leaf stage; >6 mm roots) to detect increases in oviposition, which is essential to time treatments and effectively target eggs at the base of plants. If greater than 10% of plants are assessed with eggs (egg incidence) in a field, consider treatment. This research showed that less than half the sum of plants assessed weekly with eggs actually acquired damage.
5. Rutabaga crops obtained more damage in this study. Consider planting 2 – 3 rows of rutabagas on border of fields to attract flies away from main crop but remember to destroy those rows before that next generation of flies reproduces. However,

damage leveled off the longer the rutabaga crop was in the field perhaps due to the roots' ability to heal.

6. Assess fields periodically for damage levels using the binomial procedure (60 roots) to confirm level of damage relative to oviposition in order to meet market demands.
7. Consider destroying a highly-damaged root crop ($> 40\%$) early to avoid fly movement into nearby fields.

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