# MANAGING THE CABBAGE MAGGOT, Delia radicum (L.), BY MEANS OF AGROECOSYSTEM DIVERSIFICATION

CAROLYN K. PARSONS

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By

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# ABSTRACT

The cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae) is the most serious pest of brassica crops in the temperate world. Increasing plant diversity in an agricultural system can reduce cabbage maggot oviposition due to a disruption in the host plant finding behaviour. Diversification can be accomplished several ways including intercropping and undersowing. Competition between component crops in the field has been an impediment to the adoption of diversification as a management tool for cabbage maggot. The current research investigated the disruptive potential of several plant species and the effect of two different types of habitat diversification on reducing cabbage maggot oviposition while minimizing competition. Effects on the sympatric species, *Delia platura* and *D. florilega* also were examined and species compositions compared to available data from the 1950s.

Results of cage studies testing different plant species for their disruptive effects were variable, depending on year. Five non-host plant species were tested (beet, spinach, lettuce (two varieties), carrot and parsley); cabbage maggot oviposition was reduced by lettuce. The percentage of vertical profile of cauliflower covered by the non-host plant significantly influenced the numbers of eggs laid.

Although undersowing cauliflower with winter wheat reduced cabbage maggot egg numbers in one of the two years, competition was intense and cauliflower yields were compromised.

Relay cropping reduces the time that crops overlap in the field competing for resources. There were fewer *D. radicum* eggs collected from cauliflower relay cropped with lettuce than monoculture and competition was minimal. *Delia platura / D. florilega* responded similarly to *D. radicum* in 2003, but in 2004 the opposite was true. This is the first study to demonstrate that relay cropping can reduce egg-laying by *D. radicum* while minimizing competition between component crops for key resources.

Comparison of oviposition data from the 1950s to data from the diversification studies indicate that *D. platura* / *D. florilega* eggs were more prevalent than *D. radicum* in 2003-04 than fifty years earlier. In 2003-04 species proportions varied between year (2003 vs. 2004) and diversification study (undersowing vs. relay cropping).

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## Overview

## 1.1 Introduction

The current research investigates the potential of increasing the within-field vegetation of a cauliflower agroecosystem for management of the cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae). The specific objectives for Chapters 2 to 5 are outlined at the end of this chapter and Chapter 6 presents a summary and conclusions. In this chapter a review of existing information and literature relevant to the above research is presented. Topics that have been reviewed in this introduction include:

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## 1.2 The context

Consumer demand for a dependable supply of high quality, unblemished produce at low cost has made the control of pests that attack vegetable crops an essential part of production. Current vegetable production systems rely heavily on insecticide use as the primary form of pest control. This is due to a combination of demands on growers for a) low prices and b) high external cosmetic quality of produce. Only high quality products achieve the best price. A situation like this causes a high degree of risk aversion, which often results in the use of unnecessary chemical control treatments as an insurance (Theunissen 1994).

Insecticide use on vegetable crops became common place after World War II, as they became relatively easy to obtain and were very cost effective. The introduction of DDT as a commercial insecticide in 1941 brought on an era of pest control dominated by chemical insecticides (Dent 1995). As a result, some of the most important traditional methods of pest control, such as crop free periods, rotations, cultivation and various types of sanitation practices were used less and less. When insecticides became a part of the production system these cultural control methods often appeared unnecessary compared with the high level of control attained from insecticides alone and the reduction in labour costs resulting from with their use.

The overuse of pesticides, insecticides in particular, has lead to a number of biological and environmental problems. Pest resistance, killing of non-target organisms, disruption of predator/prey relationships and human exposure are just a few. Rachel Carson (1962), in her book “Silent Spring”, brought awareness to the public about the dangers of pesticide use to people and the environment. She talked about biologically based alternatives to synthetic chemicals and how they should be studied and implemented. Although much research has been done since the publication of that book few of these alternatives have been adopted commercially.

There are many changes taking place in the attitudes of consumers as well as the general public today with regards to the environment. These attitudes will directly affect the production and marketing of field vegetables; putting pressures on growers to comply with environmental standards. The demand for 'organic' produce has never been greater. This demand coupled with the threat of insect resistance and a lack of suitable insecticides, makes considerable room for the integration of non-chemical techniques into vegetable production systems. There is currently an urgent demand for alternative control strategies for such pests where insecticide control methods have failed as a result of insecticide resistance or resurgence triggered by suppression of natural enemies (Verkerk et al. 1998).

The focus of the research in this thesis stems from the need to develop ecologically based pest management systems, taking into account the delicate interactions within the agroecosystem. The remainder of this Chapter introduces the term agroecosystem diversification and explains its important role in sustainable agriculture, focusing on the theoretical basis behind the phenomenon of reduced pest numbers in diversified cropping systems. The study insect, *D. radicum*, will be introduced and its basic biology, host plant finding behaviour and management, reviewed. Finally the two topics will be combined and the effect of agroecosystem diversification on the behaviour and management of *D. radicum* discussed.

## 1.3 Agroecosystem diversification

### 1.3.1 Overview

The term "agroecosystem diversification" encompasses many crop production practices, all of which are defined by an increase in vegetation within the agricultural landscape. There has long been a link between diversity and stability within the ecological context (Elton 1958, McCann 2000). Many of the underlying processes that create this stability have been used by pest management specialists to design more sustainable pest management strategies that rely less on external inputs such as insecticides. Increased diversity can be achieved at the farm or landscape scale as well as at the field scale. Diversifying edge vegetation by planting hedgerows, maintaining weedy borders or leaving forest corridors contributes to increased biodiversity within the farming system. One benefit from a pest management perspective is the potential increase in predators and parasitoids by providing them food, shelter and hosts (Nicholls et al. 2001).

Diversity can also be increased within the field. Within-field diversification encompasses many different cropping strategies. There are various terms used in the literature to describe a diverse cropping situation, including mixed cropping, intercropping, relay cropping, living mulches and undersowing. Mixed cropping (often used interchangeably with intercropping), is a traditional method of crop production in which two or more crops are grown together in the same field with both temporal and spatial overlap (Tukahirwa and Coaker 1982). Vandermeer (1989) defined intercropping as “the cultivation of two or more species of crop in such a way that they interact agronomically”. Relay cropping is a term used to describe an intercropping situation in which there is a time lag between the planting and harvesting of the two intercropped species. Another means of diversifying the agroecosystem is through the use of undersowing and living mulches. These approaches involve planting of an uneconomic crop within or under a main (e.g. vegetable, grain, fruit tree) crop (Theunissen 1994). The purpose of the secondary plant species may include weed control and/or fertility management. The planting of a nitrogen fixing clover, for example, would improve the soil and add nutrients back into the cropping system after plough down.

Intercropping has some application and potential use in low input farming in temperate regions but is unlikely to find a place in most modern agriculture until research and technology for intercrops is as well developed as it is today for monoculture (Coaker 1990). Much of the research on intercropping in temperate regions has focused on pest suppression. The following section will discuss the mechanisms behind reduced pest numbers in intercropping systems.

### 1.3.2 Theoretical basis behind reduced pest numbers

A number of hypotheses and one theory have been proposed to help explain the reduction in pest numbers associated with diverse cropping systems. Some of the hypotheses overlap at least partially, and there is no single overlying theory that totally explains this phenomenon. The underlying ecological mechanisms behind reduced pest numbers in diverse plantings have been investigated in a number of different cropping combinations and the results are often inconsistent and contradictory likely because of differences in the scales at which studies were conducted (Bommarco and Banks 2003) as well as differences in individual insect behavioural responses (Åsman et al. 2001).

Root (1973) introduced two hypotheses to explain why insect distribution is changed when host plants are grown in diverse as opposed to bare-soil backgrounds: i) the enemies' hypothesis and ii) the resource concentration hypothesis. The enemies' hypothesis predicts that insect predators and parasitoids will be more abundant in diversified systems than in monocultures due to possible changes in the microclimate and presence of alternate prey. The resource concentration hypothesis concerns the movement and reproductive behaviour of insects themselves, and is based on an insects' ability/inability to detect its host, resulting in a lower reproductive rate on hosts surrounded by non-host plants.

Vandermeer (1989) suggested two further hypotheses to help explain the lowered incidence of pest insects in diversified systems, the 'disruptive-crop hypothesis' and the 'trap crop hypothesis". The 'disruptive-crop hypothesis' was introduced as an alternative to the 'resource concentration hypothesis' focusing on the potential of a second non-host plant species to disrupt the ability of an insect to efficiently locate its host and is largely applicable to host-specific herbivores. The 'trap crop hypothesis' states that reduced pest incidence can be achieved if the crop plant is presented with a more attractive alternative host plant.

Finch and Collier (2000) have developed the theory of 'appropriate/inappropriate landings' to explain reduced insect attack in diverse plantings. This theory is based on a disruption of the behavioural events associated with insect host-plant selection. During colonization by an insect species, host-plant selection consists of a series of actions beginning with detection of plant volatile chemicals through odour induced attraction. The insects that fly over crop plants are then stimulated by visual cues to land and make contact with a host plant. In bare ground monoculture, the insects will be stimulated to land on the only green objects available and so most landings will be on host plants and thus 'appropriate'. Insects flying over intercropped plants however, will land on any green objects available to them, whether suitable or not, and therefore some of the landings will be on non-host plants and be 'inappropriate'. The proportions of appropriate and inappropriate landings are governed by the relative areas occupied by the host and non-host plants.

The "host-plant-quality" hypothesis states that in a diverse cropping situation the nutritional quality and chemical suitability of a host plant may affect herbivore performance (Bach 1981, Bukovinszky et al. 2004). The competition between plant species growing in close proximity to one another changes the structural and physiological condition of the host plant and subsequently affects the insects' ability to find, feed and/or develop on its host.

## 1.4 The cabbage maggot, *Delia radicum* L. (Diptera: Anthomyiidae)

### 1.4.1 Taxonomy

The cabbage maggot was first described by Linnaeus in 1758 (Griffiths 1991). The taxonomical classification is as follows:

- Class Insecta
  - Order Diptera
    - Suborder Brachycera
      - Family Anthomyiidae
        - Subfamily Anthomyiinae
          - Genus *Delia*
            - Species *radicum*

### 1.4.2 Life cycle

Adult cabbage maggots emerge in the spring from overwintered pupae; the adult flies are similar in appearance to the common housefly, *Musca domestica* L., but slightly smaller (Fig. 1.1). The adult is the dispersal stage and can fly up to two kilometers to find suitable host plants (Coady and Dixon 1997). Females lay their white, elliptical eggs (Figs. 1.2 & 1.3) on the stem or in the soil around the base of the host plants. Eggs hatch within about a week, depending on the temperature, and the emerging larvae (Fig. 1.3) move to the roots of the host plant to feed. The larvae feed for three to four weeks and develop through three larval instars. The mature, third instar larvae complete feeding and pupate in the soil near the roots. The puparia (Fig. 1.3) are reddish-brown in colour, oval shaped and non-motile. In the summer months this pupal stage lasts for three to four weeks, again depending on the temperature, after which an adult fly emerges. If diapause is induced in this stage the pupae will overwinter and adults will emerge in the spring. The number of generations in a year depends on the climatic conditions and varies from one in northern Europe to as many as five in parts of Canada and the US (Finch and Thompson 1992). There are two generations of the cabbage maggot in Newfoundland (Coady and Dixon 1997).

**Figure 1.1.** Adult cabbage maggot fly, *Delia radicum*, on a cauliflower leaf.

**Figure 1.2.** *Delia radicum* eggs on the soil surface next to a cauliflower plant.

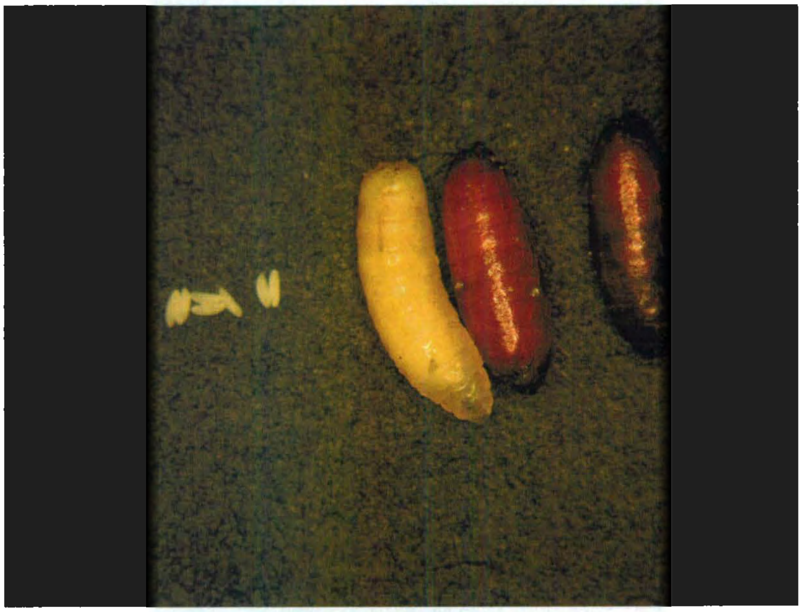

**Figure 1.3.** *Delia radicum* eggs, a third instar larva and pupae from colony maintained at St. John's, NL.

### 1.4.3 Host plant selection

Host plant selection by female *D. radicum* has been well studied. Host plant location from a distance is dominated by odour induced attraction to specific volatile chemicals produced by brassicaceous plants (Finch and Skinner 1982). At closer distances pre-alighting visual cues such as host plant colour and leaf area appear to play important roles (Prokopy et al. 1983). Final host plant acceptance is highly influenced by specific non-volatile chemicals on the host leaf surface (Baur et al. 1996). These chemicals are detected by tarsal chemoreceptors which induce the females to make short flights on and off the leaf surface. After sufficient stimulus is achieved, they walk to the stem base to assess the substrate and oviposit (Kostal et al. 2000).

### 1.4.4 Damage

The damage caused by the cabbage maggot can be classified as either direct or indirect. Crop species for which the above ground portion is consumed (cabbage, cauliflower, broccoli etc.) usually experience indirect damage and during the first 5-7 weeks of seedling growth, protection from *D. radicum* is critical. As the young plants are establishing the first generation of flies is laying eggs. The resulting larvae strip the young seedlings of their roots, leaving them unable to take up water and nutrients, and eventually, causing wilting and death. When the second generation of flies is laying eggs the plants are usually large and have well established root systems and can tolerate higher numbers of feeding larvae. Brassica crop plants that are harvested for their roots (turnip, rutabaga/swede) suffer from direct damage. Feeding by larvae from the second generation of flies damages the root directly which compromises the quality of the roots and affects its marketability. The tolerance for larval feeding damage on these root crops is very low.

### 1.5 History of cabbage maggot management

*D. radicum* is one of the most serious pests of brassica crops in temperate North America and Europe (Jukes et al. 2000). Since the 1960s, *D. radicum* larvae have been controlled by various types of applications and formulations of mainly organophophate (OP) insecticides (Finch 1993). The range of insecticides available to Brassica growers will decrease in the future (Collier 1999) due to the adverse publicity from the use of OP insecticides as well as deregistration by chemical manufacturing companies and government agencies. The need to find alternative insecticides or control measures has never been so urgent. In Canada vegetable brassica growers currently rely on one active ingredient, chlorpyrifos, for cabbage maggot control (Parsons et al. 2006).

A variety of physical and cultural methods have been used to control cabbage maggots. These include physical barriers to egg-laying adults such as tarpaper squares (Slingerland 1894, cited in Finch 1989) around the base of the plants as well as cheesecloth frames, row covers (Hough-Goldstein 1987), soil cultivation (Finch and Skinner 1980), removal of weeds that may serve as alternate hosts, and timing of plantings to avoid the peak spring emergence of adults (Coaker 1987). Over the years many of these methods have been replaced by the almost exclusive use of insecticides applied to the soil. With increased interest in more ecologically based pest management and a reduction in registered chemicals for use against the cabbage maggot, many of these practices are increasingly being incorporated into brassica research programs and production systems.

### 1.6 Sympatric *Delia* species

*Delia radicum* is one of a number of closely related anthomyiid species that feed on the roots of crop plants. *Delia floralis*, *D. platura* and *D. florilega* are three related species that have been recorded as pests of brassica crops (Miller and McClanahan 1960, Finch 1989). *Delia floralis* (Fallén) has similar host finding behaviours as *D. radicum* and is phytophagous and host specific to plants in the family Brassicaceae (Hopkins et al. 1999). *Delia floralis* is a more exclusively northern species than *D. radicum* (Griffiths 1991) and researchers have reported species compositions in northern latitudes to be predominately *D. floralis* (Shaw 1970). This species does not occur on the island of Newfoundland.

*Delia platura* (Meigen) and *D. florilega* (Zetterstedt) are often referred to as the seed corn maggot complex and have been recorded as pests on a number of different crops, including corn, bean, cucurbits and vegetable brassicas (Miller and McClanahan 1960, Parsons et al. 2007). *D. platura* is widespread and occurs on all continents except Antarctica (Griffiths 1993) and *D. florilega* is abundant in the northeast of North America, western Canada and Alaska. In the Palaearctic region, *D. florilega* is widely reported in Northern and Central Europe as well as Siberia and China (Griffiths 1993). These species are attracted to newly ploughed soil for oviposition (Miller and

McClanahan 1960, Biddle et al. 1992) and the number of generation varies depending on location ranging from 2-5 (Biddle et al. 1992).

### 1.7 Agroecosystem diversification and the cabbage maggot

Reduced oviposition by *D. radicum* has been reported when brassica plants were undersown or surrounded by other plant species, although plant yield has generally suffered. Finch and Kienegger (1997) observed an 80% reduction in *D. radicum* oviposition when brassica plants were undersown with clover and similar reduced oviposition by *D. radicum* have been reported when the brassica plants were surrounded by weeds (Smith 1976), *Spergula arvensis* (Theunissen and den Ouden 1980) and peas (Kostal and Finch 1994). This level of reduction in infestation would be an acceptable level of "control" in commercial brassica crops which are damaged indirectly (e.g. cauliflower, cabbage) but not for those damaged directly (turnip, rutabaga). Theunissen et al. (1995) demonstrated that cabbage crops of desired quality, although of slightly lower yield, have been produced in fields undersown with clovers. The reduced level of *D. radicum* infestation in a diverse planting, however, has often been associated with unacceptable levels of plant competition (Dixon et al. 2004, Hooks and Johnson 2003). According to Finch (1993) some loss of yield may be inevitable as most of the crop protection benefits occur during the time the main crop and the undersown crop are actively growing together in the field.

The observed reduction of *D. radicum* infestations in diverse plantings appears to mainly be due to 'appropriate/inappropriate landings' (Finch and Collier 2000). The distinct series of behaviours associated with *D. radicum* host plant finding is disrupted when the host brassica is planted within a diverse habitat. The subsequent chapters in this thesis investigate the effect of increasing the within-field diversity of a cauliflower cropping system on *D. radicum* oviposition and cauliflower yield.

The goal of the current research was to evaluate several methods of diversifying an agroecosystem as well as to assess various non-host plant species for use as intercrops. This was accomplished through a series of greenhouse and field studies. Specifically, Chapter 2 investigates the effect of different vegetable intercrop species on *D. radicum* oviposition in field and greenhouse cage studies with the aim of finding a method for screening suitable intercrops prior to field scale testing. Chapter 3 explores undersowing as a means to diversify the cauliflower agroecosystem. In this study cauliflower was undersown with winter wheat and the effects on *D. radicum* oviposition and cauliflower yield are discussed. Chapter 4 explores the use of relay cropping lettuce into the cauliflower cropping system as a means to disrupt *D. radicum* oviposition and reduce cauliflower yield loss by reducing the time the component crops grow together in the field. Chapter 5 is an analysis of the co-existence of *Delia florilega, D. platura* and *D. radicum* within the brassica production system. The availability of unpublished data collected from 1950-1955 from the same site provided the opportunity to investigate changes in abundance that have occurred over the past 50 years. The final chapter provides a summary, conclusions, and directions for future research.

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## 1.9 Co-authorship statement

I conducted this research independently but under the supervision of my co-supervisors Dr. Peggy L. Dixon and Dr. Murray H. Colbo and with the support of my committee members, Dr. Wilf Nicholls and Dr. Derek Lynch. I was responsible for the design and execution of the field and greenhouse studies. I had technical assistance for field and greenhouse set-up from Janet Coombes (2002-2005), Heidi Fry (2004-2005) and various staff of the Atlantic Cool Climate Research Centre. I compiled and analysed all of the data with statistical consultation from Dr. Dave Schneider, Dr. Keith Lewis and Dr. Ken McRae. Chapter 4 has been published in the Journal of Economic Entomology and the assistance of my supervisors, Dr. Peggy Dixon and Dr. Murray Colbo, as well as Rick West and two anonymous reviewers is acknowledged.

# Chapter
# 2

## Cage studies to compare candidate intercrop species for their disruptive effects on *Delia radicum* oviposition

# Cage studies to compare candidate intercrop species for their disruptive effects on *Delia radicum* oviposition

## 2.1 Abstract

Six plant species were assessed for their potential suitability as intercrops with cauliflower to disrupt *Delia radicum* oviposition. "No-choice" cage experiments were conducted in both the field and greenhouse in 2002-2005. Flies were released into cages with four potted cauliflower host plants each surrounded by bare soil or six plants of either beet, spinach, lettuce (two varieties), carrot or parsley. After 36 hours the numbers of eggs laid per cauliflower was determined. In 2004/05, intercrop size class also was considered. There were no differences in the numbers of eggs laid on cauliflower surrounded by the different intercrop species in the cages in the field in 2003. In the 2004/05 greenhouse experiment there were differences in the numbers of eggs laid around cauliflower depending on intercrop species. Of the intercrop characteristics measured the percentage of vertical profile of cauliflower covered was the only one that significantly influenced the numbers of eggs laid. The results indicate that lettuce may have potential in intercropping with cauliflower for reducing *D. radicum* oviposition.

## 2.2 Introduction

The cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), is a major pest of brassicaceous crops in the temperate world. The larvae of this insect can completely devour the root system of brassica plants. First generation *D. radicum* are especially damaging to new transplants which have yet to develop extensive root systems. Management strategies for this pest primarily rely on insecticides, but due to a reduction in available insecticides and an increased interest in ecologically based pest management systems, within-field diversification as a potential means to reduce infestation levels is being investigated.

Management of *D. radicum* through field diversification has been studied for many years (Root 1973, Theunissen and den Ouden 1980, Kostal and Finch 1994, Dixon et al. 2004). Within-field diversification can be achieved by planting two economically important crops together (intercropping) or by planting an uneconomical cover crop species within the brassica rows (undersowing or living mulch). In diverse cropping systems fewer *D. radicum* eggs are laid on brassicas grown with non-host plant species (Dempster and Coaker 1974, O'Donnell and Coaker 1975, Ryan et al. 1980, Hooks and Johnson 2003).

In a diverse cropping situation the behaviours associated with host finding and host acceptance may be disrupted resulting in fewer eggs being laid on the brassica host plant. Host plant finding by *D. radicum* from a distance is dominated by odour induced attraction to specific volatile chemicals produced by brassicaceous plants (Finch and Skinner 1982). At closer distances, pre-alighting visual cues such as host plant colour and leaf area appear to play important roles (Prokopy et al. 1983). Host plant acceptance is highly influenced by specific non-volatile chemicals on the host leaf surface (Baur et al. 1996). These chemicals are detected by tarsal chemoreceptors which induce the females to make short flights on and off the leaf surface. After sufficient stimulus is achieved, they walk to the stem base to assess the substrate and oviposit (Kostal et al. 2000). When host brassicas are growing with other non-host plant species this sequence of behaviours can be interrupted, reducing the probability that the female will successfully find a host plant and lay her eggs. The 'appropriate / inappropriate landings' theory proposed by Finch and Collier (2000) explains this as an inability of the female flies to visually discriminate between a host and a non-host plant when both are green. Therefore in the presence of another green object (a non-host plant in the case of intercropping), the series of behaviours associated with host finding is interrupted, there is an increase in the number of 'inappropriate' landings and fewer eggs are laid around the host brassica.

The 'appropriate/inappropriate landings' theory states that 'it is just the number of green surfaces surrounding a host plant that disrupts host-plant finding and colonization by phytophagous pest insects' (Finch and Collier 2000). 'Green surfaces' from a plant architectural perspective, however, come in a variety of different shapes, heights and ground covers, as well as different shades of green, influenced by leaf surface characteristics that in turn affect reflectance and appearance of the leaves. Finch et al. (2003) explored the disruptive effects of various plant species on *D. radicum* oviposition and determined that of 24 species tested, 20 disrupted oviposition. The two that reduced egg numbers to the greatest degree were the weed *Chenopodium album* and culitivated carrot, *Daucus carota*. In order to maximize the disruptive effect, the surrounding non-host plants need to cover at least 50% of the vertical profile of the host brassica (Finch and Kienegger 1997) and a 60% ground cover also is required (Theunissen and den Ouden 1980).

The objective of the current study was to develop a method for screening non-brassica plants for their suitability in disrupting *Delia radicum* oviposition. The plants chosen for screening were ones that could be practically used as intercrops in vegetable brassica production systems. Screening is required as there are a vast number of possible intercrop species that could be used and field testing of each would require considerable resources. In the present four years of cage studies, six different intercrop species along with their size and colour were assessed in an attempt to determine the effect these factors had on the oviposition behaviour of *D. radicum.*

## 2.3 Materials and methods

**2.3.1 Plant production.** All plants used in this study were started from seed obtained from Vesey's Seeds, PEI, Canada. The host plant used in this study was cauliflower, *Brassica oleracea* var. *botrytis* L. (cv. Fremont). Cauliflower seeds were sown at weekly intervals in order to have a supply of host plants of similar ages for replication over time, in plastic flats with 72 cell tray inserts in Promix BX$^{®}$ commercial potting media. Flats were placed in a temperature controlled greenhouse set at 18°C and plants were thinned to one plant per cell after germination. One week prior to testing cauliflower seedlings were transplanted into 7.5 cm round pots filled with Promix BX® potting media. This was usually around four weeks after seeding, at the two true leaf stage.

Test plants were seeded in the same manner as the cauliflower, i.e. same tray size, potting media and greenhouse. The plant species were chosen for various reasons as outlined below and summarized in Table 2.1. Carrot (*D. carota* L. cv. Chantenay Red Cored) was shown by Finch et al. (2003) to rank high in its disruptive effect on *D. radicum* and it is also an important crop to Atlantic Canada. Parsley (*Petroselinum crispum* (P. Mill.) Nyman ex A.W. Hill cv. Forest Green) was chosen as it is similar to carrot in terms of growth characteristics; however it has more aromatic leaves. It was thought that parsley may disrupt the female host finding through olfactory as well as visual means. Spinach (*Spinacia oleracea* L. cv. Bloomsdale) was chosen for its ability to grow and germinate under cool conditions and its potential to produce sufficient ground cover in a field before peak oviposition in the early spring. Beet (*Beta vulgaris* L. subsp. *vulgaris* cv. Detroit Dark Red) was also chosen for its potential growth in a cool spring as well as for its reddish leaves. The red leaves of beet allowed the opportunity to study the influence of plant colour on disruption of *D. radicum* oviposition. Other authors have reported that brassicas with reddish leaves were less attractive to *D. radicum* (Prokopy et al. 1983; Finch et al. 2003) and we thought that using an intercrop with leaves having greater anthocyanin content, the plant pigment responsible for the reddish leaves, may disrupt the female to a lesser degree than a green one. Lettuce (*Lactuca sativa* L. cv. Simpson Elite (2003) and cv. Belowa (2003/04/05) was chosen for its ability to be transplanted in early spring.

**Table 2.1: Summary of test plants screened in each year of the cage studies and rationale for selection**

| Intercrop | Year | Rationale |
|---|---|---|
| Carrot | 2003/04 | Positive results of Finch et al. (2003) |
| Parsley | 2003/04 | Positive results of Finch et al. (2003) more aromatic than carrot but with similar growth habit |
| Spinach | 2004/05 | Cool season crop – rapid growing crop for use in early cool spring to control 1st generation *D. radicum* |
| Beet | 2003/04/05 | Cool season crop – as for spinach |
| Lettuce – cv. Simpson Elite (leaf type) | 2003 | As for spinach, and to test shades of green as a lighter 'green' than oak leaf lettuce |
| Lettuce – cv. Belowa (oak leaf type) | 2003/04/05 | Cool season crop – as for spinach and to contrast with lighter green Simpson Elite Lettuce. |

**2.3.2 Experimental design.** This study was conducted over four years. Trials in 2002/03 were conducted in six screened wooden cages (90 x 90 x 90 cm) placed in a field plot at the Atlantic Cool Climate Crop Research Centre of Agriculture and Agri-Food Canada in St. John's, NL. Each cage contained four potted cauliflowers sunken into the ground spaced 40 cm from one another and treatments were randomly assigned to the six cages. Treatments were the four cauliflower plants within a cage surrounded by either bare ground, or six plants of carrot, parsley, spinach, beet or lettuce planted ~15 cm from, and evenly spaced around, the host cauliflower (Fig. 2.1). Test plant species were transplanted at three weeks of age directly into the field and cages sunken into the field soil and secured down with rope and wooden stakes. Flies (see section 2.2.3) were released one week after transplanting of the test plants. These were "no choice" experiments as each cage contained only one test species with the cauliflower plants. The experiments were replicated 6 times over 7 weeks. After the first three replicates the test plants were removed and replanted with new three week old intercrop plants and the last three replicates completed.

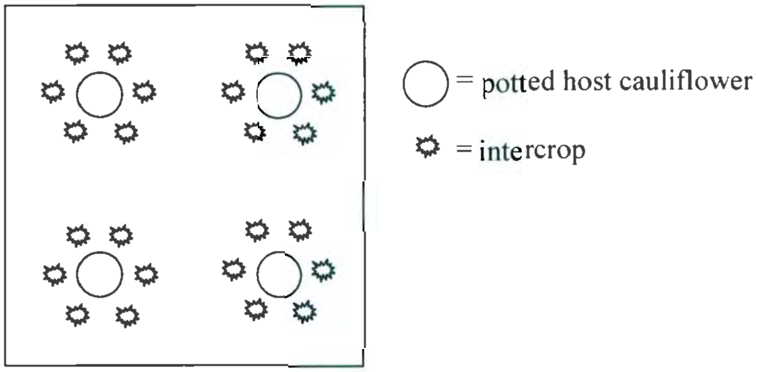

**Figure 2.1.** Illustration of experimental cage set-up used in the study. Each cage contained four host brassica plants and 24 intercrop treatment test plants of the same species (six per host brassica).

In 2004/05 the experiment was conducted as above but with the following modifications: 1) the experiment was moved into the greenhouse with test plant species transplanted into six, 10 cm x 1 m x 1 m square, Promix BX® filled boxes with permanent holes spaced as above to accommodate four potted cauliflower host plants. The cages were placed over each box with edges sunken into the potting mix. The potting mix in the experimental area (Fig. 2.1) was covered with a layer of sifted field soil to ensure similar substrate characteristics as the potted cauliflower (see Section 2.2.4 below); 2) Experiments were conducted on test intercrop plants classified as either small, medium or large. 'Small' intercrops were those that had been transplanted into the boxes at 3 weeks of age and left to grow for one week before running the experiment (4 weeks old). Medium intercrops were left for a further week and thus were 5 weeks old during the running of the experiment and 'large' intercrops were 6 weeks old. After the first set of experiments were completed, cages were replanted with three week old small transplants and experimental trials repeated after the one week post transplanting time; and 3) in 2005 only spinach, lettuce and beet were tested as these species appeared most practical for use in a field situation against first generation *D. radicum.* Also, by not testing carrot and parsley, additional experimental boxes were available to conduct two replicates at the same time with the other test plant species.

**2.3.3 Insects.** Colonies of *D. radicum* were established using pupae collected from various commercial brassica fields around St. John's, NL. Flies used for the study were reared under diapause conditions in climate-controlled chambers (20°C, 80% R.H., L12:D12) according to the method of Finch and Coaker (1969). Resultant pupae were counted and stored, 250 pupae per 250 ml plastic tub, in moist vermiculite in a 4°C refrigerator for 20 weeks to complete diapause (Collier and Finch 1983). Approximately 18-20 days before flies were needed for experiments the required number of tubs of pupae were removed from the refrigerator and placed in 30 x 30 x 30 cm cages in a separate climate controlled chamber (20°C, 80% R.H., L16:D8). After emergence, flies were randomly selected from the 30 x 30 x 30 cm cages, sexed and placed (2003: 5♀:5♂; 2004-2005: 10♀:10♂ ) into ventilated 500 ml plastic tubs. Flies were held for a maximum of 1 hour until release into the 90 x 90 x 90 cm cages. All flies were 5-9 days old.

**2.3.4 Experimental trials.** Prior to release of flies into the cages, potted cauliflower were haphazardly chosen from a series of plants which were all the same age. The pots with the cauliflower were prepared by first firming down the potting mix in the pot around the stem followed by the addition of 2 cm layer of sand. Sand was added to make the eggs easier to retrieve. Finally, a 1 cm layer of sifted field soil was sprinkled over the surface of the potting medium to maintain similar cover to the surrounding soil on the floor of the cage. Cauliflower plant height was measured and the potted plants placed in the permanent holes in the cage area. Intercrop height was taken on three of the six plants associated with each cauliflower host plant. These heights were used to determine the percent of the cauliflower vertical profile covered by the intercrop using the following equation:

% vertical profile covered = (height of intercrop / height of cauliflower) * 100

Ten leaves were randomly chosen from the six plants to assess 'greenness' using a Minolta SPAD-502 meter. SPAD readings were used as a surrogate for chlorophyll levels as they provide a quick, non-destructive method of determining leaf chlorophyll content (Chang and Robison 2003). In 2004 and 2005 digital photographs were taken of each of the cauliflower host plants with surrounding intercrops. Ground cover values were assessed using the dot-grid method which involves placing a transparent grid (grid size 8.4 x 8.4 cm with 441 smaller 4 mm squares per grid) over the photograph and counting each intersection that contains part of the plant. This number is used to obtain a percent ground cover by dividing by the total number of intersections and multiplying by one hundred.

Flies were released into cages and left for 36 hours after which the potted cauliflower were removed and the sand and sifted field soil were transferred into 250 ml plastic cups for later retrieval of eggs by floatation.

**2.3.5 Comparison of SPAD chlorophyll meter readings to extractable chlorophyll content.** As chlorophyll levels in plant leaves are often responsible for the observed 'green' colour, we wanted to ensure the relationship between the extractable chlorophyll content of intercrop leaves and the SPAD readings used in this study could be accurately related to the true chlorophyll content. A one-time assessment of this relationship was conducted on intercrops at the end of the last replicate of the cage studies in 2005. Five

SPAD readings were taken on the upper mid-section of a mature leaf of four spinach, four lettuce and four beet plants. Immediately following the SPAD measurements a single disc (~ 10 mm in diameter) was subsequently punched from these leaves and placed in sterile 2 ml centrifuge tubes, capped and placed on ice until used for analysis. The leaf disks were manually homogenized in 80% acetone using a mortar and pestle, centrifuged at 5000 rpm for 1 minute and 1 ml of supernatant was analysed using a UV/VIS spectrophotometer (Pharmacia Biotech Ultrospec 2000) at 645 nm and 663 nm for chlorophylls a and b respectively.

**2.3.6 Statistical analyses.** Data in 2003 were analyzed separately from 2004/05 due to differences in experimental procedures. All egg data were analyzed as totals per cage and subject to an Analysis of Variance (ANOVA) using MINITAB (version 13 for Windows) provided the assumptions of normality, homogeneity and independence, outlined by the general linear model, were met; alpha was set at 0.05. The 2004/05 egg data did not meet the assumption of homogeneity and thus were analyzed within the generalized linear model framework, with SAS® PROC GENMOD ( SAS Institute Inc. 2001), assuming a log link and negative binomial error distribution in order to incorporate the non-normal error structure into the analyses (Littell et al. 2002). Thus, the initial analysis involved analyzing total egg numbers per cage against intercrop species and replicate (2003) and total egg numbers per cage against intercrop species, size class (see Section 2.2, experimental set-up, 2004/05 modification 2) with replicate and year included in the model.

It was impossible to separate the effect of intercrop species and size and colour parameters, i.e. heights, ground covers, SPAD readings, due to the individual growth, shape and colour of each species. That is, the height and ground cover of carrot, for example, cannot be compared with the height and ground cover of lettuce as the two species have very different growth patterns.

Ground cover, intercrop height (vertical profile) and colour (SPAD value) were dependant on intercrop species and thus to determine if these parameters affected egg laying by *D. radicum* it was necessary to analyze these effects separately within intercrop species. Individual regression analyses of the effect of eggs on ground cover, vertical profile and SPAD were conducted on individual intercrop species using the PROC GENMOD procedure in SAS®, using a log link and negative binomial error distribution appropriate for count data (Littell et al. 2002).

## 2.4 Results

**2.4.1 *Delia radicum* egg numbers.** In each year of the study there were occasions when few or no eggs were collected in any treatment. These events were invariably associated with cold weather or extreme wind which may have influenced *D. radicum* oviposition and masked any treatment effects. Replicates in which three or more cages contained no eggs were excluded from the analyses, i.e. in replicates where no eggs were collected from any of the four host cauliflower plants in at least 3 cages.

*2003 trials.*

In the 2003 field cage experiments there were no significant differences in the total number of eggs laid around cauliflower surrounded by any of the intercrop species tested (Fig. 2.2) ($F_{5,19}$=2.57, p= 0.061). Mean total numbers of eggs per cage ranged from 183.5 ± 36.8 eggs laid on cauliflower surrounded by beet to 71.8 ± 17.9 eggs laid on cauliflower surrounded by the 'Belowa' oak leaf lettuce.

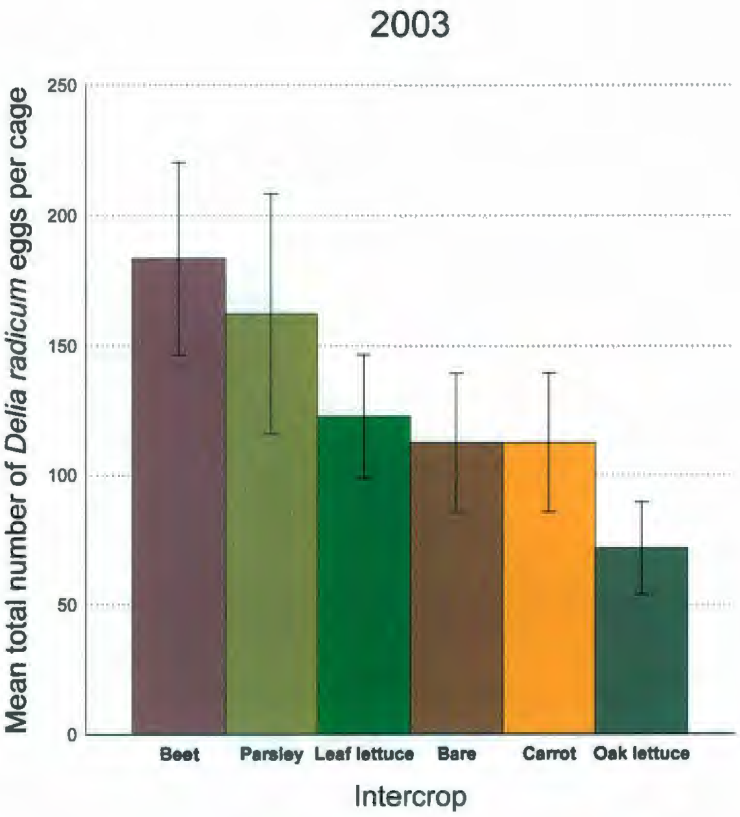

**Figure 2.2.** Effect of intercrop species on the mean total number (± SEM) of *Delia radicum* eggs laid per cage in the 2003 field cage experiments.

*2004-2005 trials.* In these trials the mean number of *D. radicum* eggs laid around the base of cauliflower host plants differed among intercrop species (Table 2.2; Fig. 2.3). The ranking of the intercrop species that reduced egg laying from the greatest to the least, varied considerably between size classes (Fig. 2.4). In all size classes tested, lettuce (var. Belowa), consistently reduced the number of *D. radicum* eggs laid on the host cauliflower to the greatest degree with beet ranking second (Fig. 2.4). Carrot, parsley, spinach and bare ground shifted ranking position depending on size.

Intercrop size class, as defined as number of weeks of growth, had a significant effect on the numbers of *D. radicum* eggs laid around the base of potted cauliflower, with larger intercrops having the greatest effect in reducing egg numbers (Table 2.2, Fig. 2.5).

**Table 2.2: Analysis of deviance table (type 3 analysis) on the effects of intercrop species and size class (small, medium, large) on *Delia radicum* egg numbers for greenhouse cage studies in 2004-2005.**

| Source | df | G | P |
|---|---|---|---|
| replicate | 3 | 25.83 | <0.0001 |
| intercrop species | 5 | 11.96 | 0.0354 |
| size class | 2 | 9.99 | 0.0068 |
| species*size | 10 | 8.04 | 0.6251 |

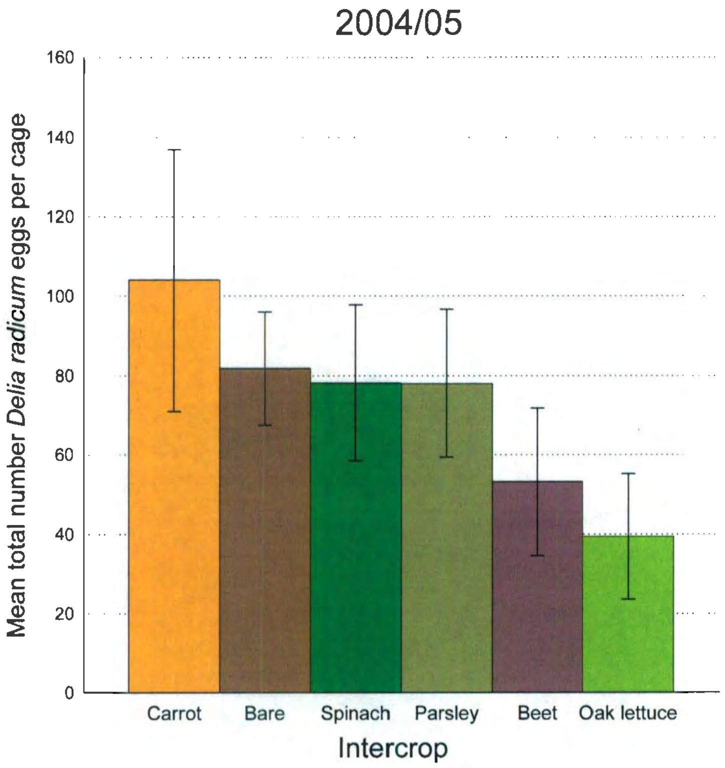

**Figure 2.3.** Effect of intercrop species on the mean total number (± SEM) of *Delia radicum* eggs laid per cage in the 2004-2005 greenhouse cage experiments.

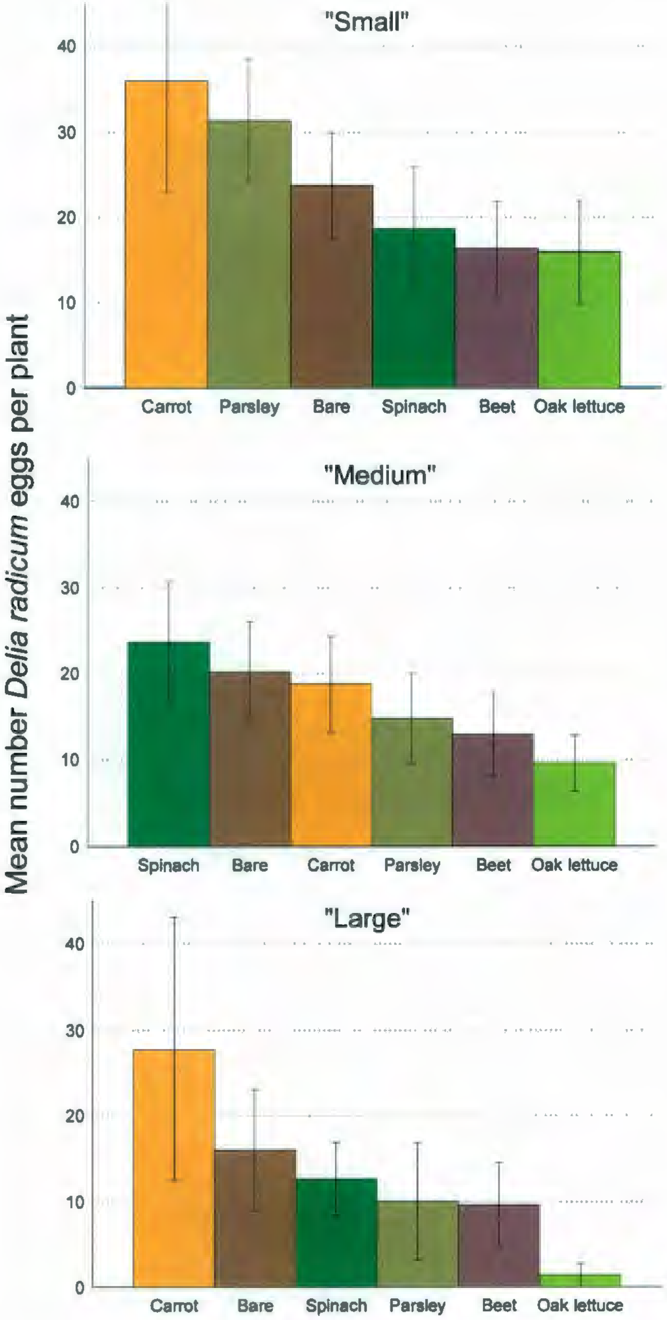

**Figure 2.4**. Mean number (± SEM) of *Delia radicum* eggs laid around the base of cauliflower plants surrounded by different intercrop species of different size classes in greenhouse cage studies in 2004-2005.

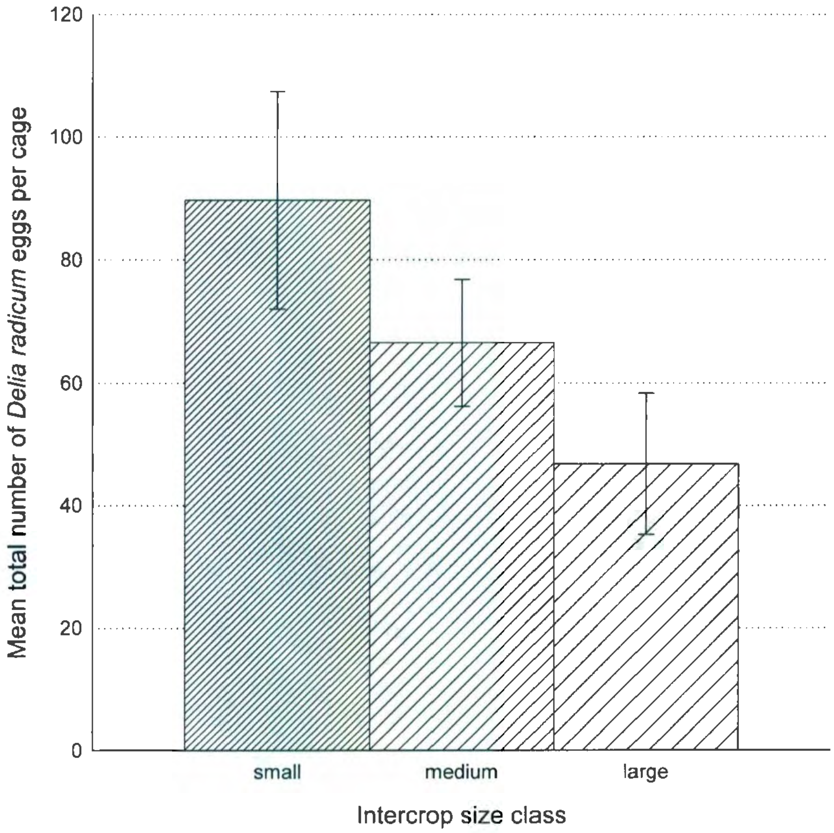

**Figure 2.5.** Effect of intercrop size class, i.e. age of intercrop plants, on the mean total number (± SEM) of *Delia radicum* eggs laid on host cauliflower surrounded by different intercrop species in greenhouse cage studies in 2004-2005.

**2.4.2 Intercrop characteristics.** In 2004-2005, the size of the intercrop species influenced the numbers of eggs laid by *D. radicum* and therefore further analyses were conducted to determine which, if any, of the intercrop size parameters measured, vertical profile and ground cover, influenced the numbers of eggs deposited per plant. Only those species that consistently reduced egg laying, lettuce (cv. Belowa) (2003 and 2004), spinach, beet and parsley were chosen for further analyses.

Vertical profile was the only size parameter that influenced the numbers of eggs laid by *D. radicum* in the cage studies in 2004/05 and this was only applicable to parsley and lettuce (Table 2.3). The mean (± SEM) percent cauliflower vertical profile covered for parsley ranged from 66.8 ± 5.06 for small parsley plants to 202.7 ± 11.7 for large parsley plants (Fig 2.6). Lettuce plants covered a larger percent of the cauliflower vertical profile with a range of 116.3 ± 9.61 for small lettuce plants to 304.6 ± 25.3 for larger lettuce plants. In all cases the mean percent vertical profile covered was over 100% indicating that the lettuce was taller than the cauliflower plants in the majority of the experimental trials.

**Table 2.3: Analysis of deviance table (type 3 analysis) of regression analysis on the effect of ground cover, vertical profile and SPAD reading on *Delia radicum* egg numbers for intercrops that reduced the number of deposited eggs per cauliflower as compared to those in bare ground control cages in 2003 and 2004/05 cage experiments.**

| Year | Intercrop species | Source | df | G | P |
|---|---|---|---|---|---|
| 2003 | Oak leaf lettuce | vertical profile | 1 | 1.68 | 0.1949 |
| | | SPAD | 1 | 0.78 | 0.3779 |
| 2004/05 | Spinach | ground cover | 1 | 0.48 | 0.4881 |
| | | vertical profile | 1 | 0.82 | 0.3645 |
| | | SPAD | 1 | 0.01 | 0.9273 |
| | Parsley | ground cover | 1 | 1.76 | 0.1842 |
| | | vertical profile | 1 | 5.13 | 0.0235 |
| | | SPAD | 1 | 0.15 | 0.6996 |
| | Beet | ground cover | 1 | 0.48 | 0.4866 |
| | | vertical profile | 1 | 0.52 | 0.4724 |
| | | SPAD | 1 | 0.02 | 0.8754 |
| | Oak leaf lettuce | ground cover | 1 | 1.19 | 0.2744 |
| | | vertical profile | 1 | 4.49 | 0.0342 |
| | | SPAD | 1 | 0.06 | 0.8070 |

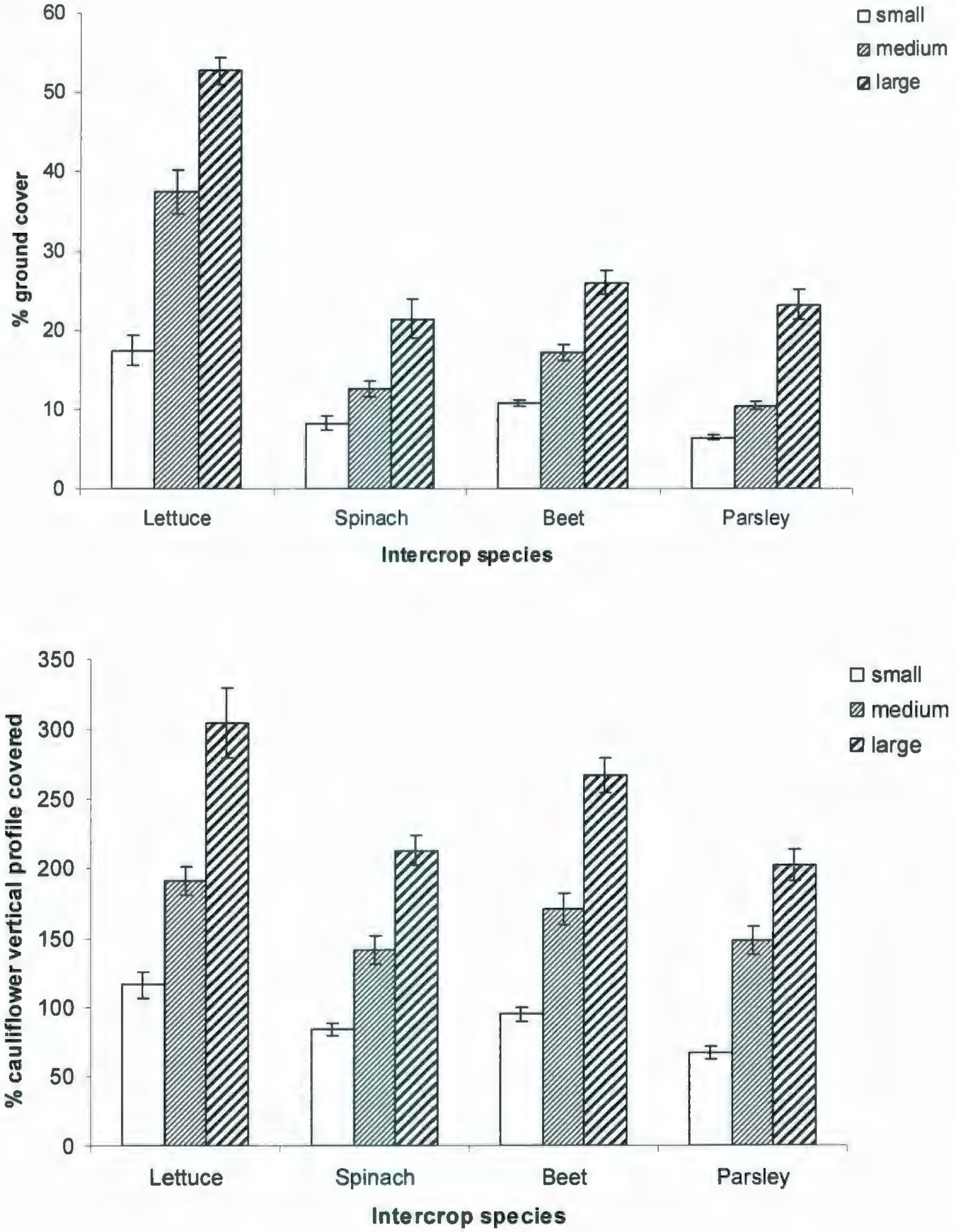

**Figure 2.6.** Mean (± SEM) percent ground cover and percent cauliflower vertical profile covered of intercrop species that reduced the numbers of eggs deposited by *Delia radicum* in the cage study experiments of 2004-2005.

**2.4.3 Comparison of SPAD chlorophyll meter readings to extractable chlorophyll content.** The SPAD readings and the spectrophotomic absorption have a similar trend over the 12 samples (Fig 2.7). The 645 absorption, however, was less in agreement with the SPAD reading particularly for spinach and beet.

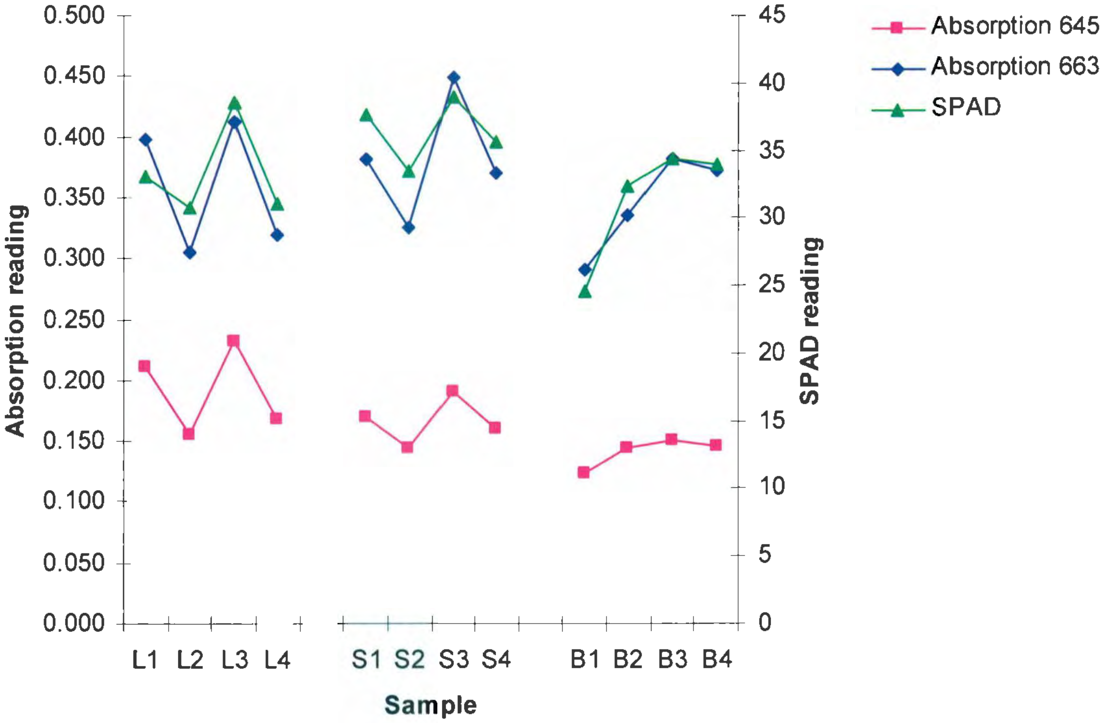

**Figure 2.7.** Relationship between SPAD readings and actual absorption values for chlorophyll a (absorbance at 663 nm) and chlorophyll b (absorbance at 645 nm) in lettuce (L1-L4), spinach (S1-S4), and beet (B1-B4).

## 2.5 Discussion

We investigated the effects of intercropping cauliflower with six different vegetable intercrop species, each with very different architectures; in the expectation of determining those intercrop characteristics most responsible for reduced *Delia radicum* egg numbers on host cauliflower. 'No-choice' cage experiments were used as a means to further explore 'appropriate/innappropriate' landings and to determine if cage screening is an effective way to quickly chose suitable intercrops for field application. Results between years and within years were highly variable and confounded by the difficulty in comparing height and ground cover of one intercrop plant to another due to differences in intercrop growth patterns.

Reduced herbivore numbers in diverse plantings have been reported in a number of different cropping systems covering insect species spanning the Orders (Andow 1991; Finch and Kienegger 1997; Hooks and Johnson 2003) and the mechanisms behind reduced attack appear to depend upon the specific cropping system being investigated as well as behavioural differences among the insect species. Reductions of the onion thrip, *Thrips tabaci* (Lindeman) (Thysanoptera: Thripidae) on leek, for example, appear to be due to changes in host plant quality (den Belder et al. 2000), whereas reductions of diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) on white cabbage appear to be explained by reduced colonization or inability to find its host in a diverse setting (Åsman et al. 2001).

The 'appropriate / inappropriate landings' theory (Finch and Collier 2000) incorporates behavioural details based on comparative observations of a number of different herbivores from several insect Orders (Finch and Kienegger 1997). The theory states that 'it is just the number of green surfaces surrounding a host plant that disrupts host-plant finding and colonization by phytophagous pest insects' (Finch and Collier 2000). The degree to which this theory applies to a particular insect species depends heavily on the specific host-finding behaviours associated with that insect. Female *D. radicum*, for example, use visual cues associated with the host brassica plant and have specific spiral flight patterns on and off the host plant leaves in order to accumulate non-volatile chemicals which induce oviposition. These series of behaviours are easily disrupted by the presence of a non-host plant species and the theory of 'appropriate / inappropriate landings' appears to explain the reduced egg numbers often observed.

Although intercropping did reduce oviposition by *D. radicum* in this study, the effect varied among vegetable species and between years. In 2003 there were no differences detected between the numbers of eggs laid around the host cauliflower surrounded by the different intercrop species, whereas in the 2004-2005 experiments intercrop species affected oviposition. Possible reasons for the inability to detect a treatment effect in 2003 include cooler/wetter weather, the fewer number of flies released as well as potential differences in attractiveness of the host cauliflower plants. Weather conditions during the 2003 field cage experiments were extremely variable with intense periods of rain and wind. The mean daily maximum and minimum temperatures during the course of the experiment were 22.61 ± 0.50°C and 13.90 ± 0.52°C with a maximum and minimum temperature reaching 29.3°C and 4.5°C respectively. These environmental conditions will affect the oviposition behaviour of *D. radicum* as this insect becomes inactive at temperatures above 21°C (Finch and Collier 1985) and will take shelter from the winds and rain, thus influencing oviposition rates. In 2004/05 when experiments were conducted in the greenhouse, the environmental conditions were constant and more suitable for *D. radicum* oviposition. In 2003, only five female flies were released per cage whereas in 2004/05 ten female flies were released. It is possible that the number of replications used was not sufficient to account for the source of variation between female egg loads (Noronha 1992). Cauliflower plants of similar size may be differentially attractive to *D. radicum* as was demonstrated by Billiald (2001). In her studies, a single plant, during the active growth phase, ranked one of the most attractive out of 42 on one day, to one of the least preferred a few days later. The potted host cauliflower used in these studies were all reared under the same environmental conditions and chosen to be a 'standard' size. This source of variation, however, cannot be overlooked. With increased replications and an increase in the number of flies released per cage, it is expected that the ability to detect a true difference would increase as was demonstrated in the subsequent greenhouse trials of 2004-2005.

The fact that our experiments were 'no-choice' cage studies may also have affected the ability to detect treatment differences. It is not known how many 'inappropriate' landings the female fly makes before leaving a diversely planted area and flies in cage studies do not have the opportunity to leave the area after repeated contact with a non-host plant. As such, confinement to cages may have affected the interpretation of oviposition response to intercropping. Also, without access to a 'choice' of a host plant surrounded by bare ground the flies' need to oviposit may have overruled the disrupted oviposition behaviour due to the presence of the intercrop species (Theunissen 1997). However, although the flies were left for only 36 hours and it is thought that the non-host plants become progressively less effective in disrupting oviposition the longer the flies are confined to cages (Tukahirwa and Coaker 1982) we did find differences among intercrop treatments in the number of *D. radicum* eggs laid in 2004-2005. This suggests that 36 hours was an acceptable amount of time to assay treatment effects.

In our study we purposely chose intercrop species varying in size, colour and plant chemistry. Our result with respect to beet, the only non-green, intercrop species used, was unexpected. Beet ranked second over all size classes in 2004-2005. It was expected that beet would have little disruptive effect due to the high anthocyanin content which gives its leaves their reddish colour. Prokopy et al. (1983) demonstrated that brassica crops with reddish leaves, such as red cabbage, are less attractive to *D. radicum* and fly landings on the leaves of these plants is reduced compared to associated green cabbage varieties. It was thought that using beet as an intercrop, with the lack of apparent 'green' in the leaves, would not disrupt the female fly in her search for the host cauliflower. The beet SPAD readings were similar to the other apparently 'green' plants tested. The SPAD meter measures the chlorophyll content of the plant leaf and is positively correlated with actual plant nitrogen content within a plant leaf (Chang and Robison 2003). The SPAD meter does not take into account other plant pigments, such as anthocyanin, that may influence the visual colour of the plant leaf. The SPAD meter may thus not be an appropriate means to measure 'greenness' per se. The perception of colour by the fly will be influenced by many leaf characteristics such as pubescence, epicuticular bloom and the presence of other colour pigments that mask chlorophyll (Prokopy et al. 1983).

We were unable to determine what architectural characteristics are best at explaining reduced egg numbers in intercropping situations. Despite the fact that the degree to which the intercrop covers the vertical profile of the host brassica was important in two of the intercrop species, lettuce and parsley, in explaining reduced egg numbers, these two plants have very different growth habits. Parsley leaves have long petioles with relatively small leaf areas as compared to the lettuce which have no petiole and a greater leaf area. The difficulty in finding an appropriate way of measuring different architectural characteristics of different plants remains a constraint in determining what architectural characteristics are important for disrupting the female fly to the greatest degree. We need a means to measure and quantify the three dimensional space occupied by the intercrop species. Until this is achieved it will be difficult to determine the specific architectural characteristics, if there are any, which will contribute to increased disruption to *D. radicum* oviposition.

There have been many studies that have demonstrated the ability of a non-host plant to disrupt female *D. radicum* egg laying on a host brassica in cage studies (Finch and Kienegger 1997; Finch et al. 2003; Kostal and Finch 1994; Tukahirwa and Coaker 1982). The present results agree with these studies with beet, parsley and lettuce reducing the numbers of eggs deposited around cauliflower as compared to bare ground cauliflower. Further work is now needed to continue the search for an appropriate method of measuring plant architecture and to assess the crops with the greatest disruptive capabilities under field conditions. Field studies will enable one to potentially investigate the effects on *D. radicum*, other pests, key predators and parasitoids as well as effects on the yields of the component crops.

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# Chapter
# 3

## Undersowing cauliflower with winter wheat: impact on cauliflower yield and oviposition of first-generation cabbage maggot (*Delia radicum* (L.) (Diptera: Anthomyiidae))

# Undersowing cauliflower with winter wheat: impact on cauliflower yield and oviposition of first-generation cabbage maggot (*Delia radicum* (L.) (Diptera: Anthomyiidae))

## 3.1 Abstract

Within-field diversification has the potential to reduce pest populations. In 2002 and 2003 field studies were conducted to investigate undersowing cauliflower (*Brassica oleracea* L.var. *botrytis*) with winter wheat (*Triticum aestivum* L.) as a means to reduce the number of eggs laid by first-generation *Delia radicum*. Effects of the wheat on cauliflower yields also were determined. In early spring of 2002 wheat was broadcast at rates of 0, 125, 250, 375 and 500 seeds $m^{-2}$. The impact on egg deposition by *Delia* spp. was evaluated by *in-situ* egg sampling, which showed no differences in the number of eggs counted among the treatments. However, it was not possible to separate among *D. radicum, Delia platura* and *Delia florilega* eggs with the sampling protocol used. All undersown plots produced no marketable cauliflower. In 2003, in an attempt to reduce competition, the wheat was seeded in rows and the cauliflower was subsequently transplanted between every fourth row of wheat. In 2003, when eggs were removed and separated by species, there were more *D. radicum* and *D. platura / D. florilega* eggs collected from cauliflower grown in bare ground as compared to cauliflower undersown with wheat. Seeding wheat in drills did not reduce competition and no marketable cauliflower were produced in the undersown plots in 2003. The potential for yield improvement through manipulation of temporal and spatial arrangements of crops in a mixed cropping system is discussed.

## 3.2 Introduction

The importance of diverse cropping systems in sustainable agricultural production, and in particular for pest management, has been well established (Root 1973; Vandermeer 1989); however, most cropping systems still rely on conventional monoculture production. In addition, most vegetable cropping systems rely on insecticides as the primary method of pest management. With the demand for more sustainable forms of crop production and an increase in organic agriculture, continued research into diverse cropping systems is necessary in order to fully understand the impact of diversification on the ecology of any given crop and its potential use in integrated pest management.

In studies of specific crop combinations the objective is to identify crops that complement one another thereby maximizing benefits, such as insect management, while minimizing negative effects such as yield loss via competition. Diverse cropping systems often possess greater richness of ecological interactions that make a positive contribution to fertility, weed, insect and disease management (Vandermeer 1989; Santos et al. 2002). One method of diversifying a cropping system is "undersowing", which involves interplanting a cover crop between the rows of an annual row crop. The cover crop is not harvested and consequently does not have any direct economic benefit, but there may be several indirect benefits, including weed control (Liebman and Dyck 1993), increased soil fertility and health (Hartwig and Ammon 2002) and a decrease in pest populations (Theunissen and den Ouden 1980; Kostal and Finch 1994; Hooks and Johnson 2004).

Undersowing for pest management purposes has been investigated in a number of different cropping systems, including vegetable brassicas. A key pest species within the brassica pest complex that has been extensively studied for its response to undersowing is the cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae) (Ryan et al. 1980; Langer 1996; Dixon et al. 2004). In undersown brassicas there is often a reduction in the numbers of eggs laid on the brassica host due to a disruption in the cabbage maggot's host selection behaviours. Host plant selection by the female fly is described as a linked chain of three events consisting of odour-induced attraction to specific volatile chemicals associated with the brassica host plant (Finch 1978), close range searching using pre-alighting visual cues associated with the color and architecture of the host plant (Prokopy et al. 1983), and an assessment of non-volatile chemicals on the host leaf surface (Baur et al. 1996). The female fly, upon successful completion of these behaviours, will proceed to the base of the brassica plant and oviposit in the soil.

The main mechanism behind the reduction in the numbers of eggs laid by *D. radicum* when its host plant is grown with an undersown crop is explained by the 'appropriate / inappropriate landings' theory (Finch and Collier 2000) and is based on the inability of the female fly, prior to alighting, to distinguish between the host brassica plant and the undersown non-host plant species, when both are green. Thus, in an undersowing situation, the female fly may land on the non-host plant species, making an 'inappropriate landing', which results in an overall reduction in the number of successful 'appropriate landings' and a reduction in the numbers of eggs laid on the host brassica.

It has been shown that for undersowing to be effective at reducing *D. radicum* egg numbers, the non-host plant must cover 50% of the vertical profile (Finch and Kienegger 1997) and 60% of the ground horizontally (O'Donnell and Coaker 1975). This requirement for extensive growth of the cover crop presents a challenge for control of the first-generation of the cabbage maggot, especially in areas with a short growing season like Newfoundland. Flies from overwintering pupae usually emerge mid-June when most brassica vegetables are being transplanted. The small seedlings, if attacked at this stage, can be killed or severely stunted by larval infestations. In areas with cool, wet spring conditions it is a challenge to find a plant species that will germinate, grow and produce the required amount of ground cover before fly emergence. A number of candidates were considered but winter wheat (*Triticum aestivum* L.) was chosen because it can be seeded early in the spring and will germinate and grow despite the cool soil conditions often present in Newfoundland at that time.

Choosing a plant species that would produce enough 'green' in early spring to disrupt oviposition behaviour of *D. radicum* is one of two requirements before use of this cropping practice can be adopted as a management tool for cabbage maggot in Newfoundland. The second requirement is little competition between the component crops, such that there is little yield loss. Competition between the crop and undersown plant species has been one of the main impediments to adoption of undersowing for insect management (Theunissen et al. 1995; Dixon et al. 2004). In this study the winter wheat was seeded as a spring crop in an attempt to render it less competitive. As spring seeded winter wheat is not vernalized it will tend to stay short, with limited tillering and little seed set.

Alternative cropping strategies, such as undersowing, are an important component of organic crop production systems. Many studies on the use of undersowing in organic systems focus on the effects on fertility and weed management (Germeier 2006; Law et al. 2006). This study assesses the potential of using undersowing as an insect management tool. The specific objectives were to determine the suitability of winter wheat as an undersown species for reducing first generation *Delia radicum* egg numbers on cauliflower and to evaluate the effects of undersowing on cauliflower yield.

## 3.3 Materials and Methods

**3.3.1 Experimental fields.** Experiments, using organic crop production practices, were conducted in 2002 and 2003 at the Atlantic Cool Climate Crop Research Centre of Agriculture & Agri-Food Canada in St. John's, Newfoundland and Labrador (47°31'N, 52°47'W). The site was established following plough-down of a three year old stand of timothy/red clover. Additional fertility, based on soil test recommendations, included the application of fish meal (P. Janes & Sons Ltd., Hant's Harbour, Newfoundland and Labrador, Canada), kelp meal (Acadian Seaplants Ltd., Dartmouth, Nova Scotia, Canada) and bone meal (C-I-L®) in the transplant furrows. We assumed 10% available N for the fish meal, 3.5% available K for the kelp meal and 14% available P for the bone meal. In 2003, 2.5 cm of fish offal/peat compost (total nitrogen, phosphorus, and potassium, 1.29, 0.07, and 0.02% respectively) was applied to the experimental area and incorporated by disking. No herbicides, fungicides or insecticides were used in this study.

**3.3.2 Transplant production.** Cauliflower, *Brassica oleracea* L.var. *botrytis* (cv. Fremont) (Vesey's Seeds, PEI) were seeded on 2002 April 30 and 2003 May 5 in 72 cell tray inserts in Promix BX® commercial potting mix. The seedlings were grown out in a greenhouse set at 18°C. After the first true leaves had emerged the plants were fertilized weekly with Alaska® organic fish fertilizer, mixed at a rate of 7.5 ml per litre of water and applied until the cells were drenched. Four to five weeks after seeding the transplants were placed outside, covered with Agribon® floating row cover to exclude insects, and left for increasingly prolonged periods of time to 'harden off' before transplanting.

**3.3.3 Broadcast experiment 2002.** On May 17, 7.0 m x 7.2 m plots were hand broadcast with winter wheat (var. Borden) (Fig. 3.1b) at treatment rates of 125, 250, 375 and 500 seeds $m^{-2}$ with a bare ground control (Fig. 3.1a). The trial was set up as a randomized complete block design with five blocks. Five-six week old cauliflower were transplanted into the plots on June 10–11 in rows spaced 75 cm apart and an in-row spacing of 40 cm.

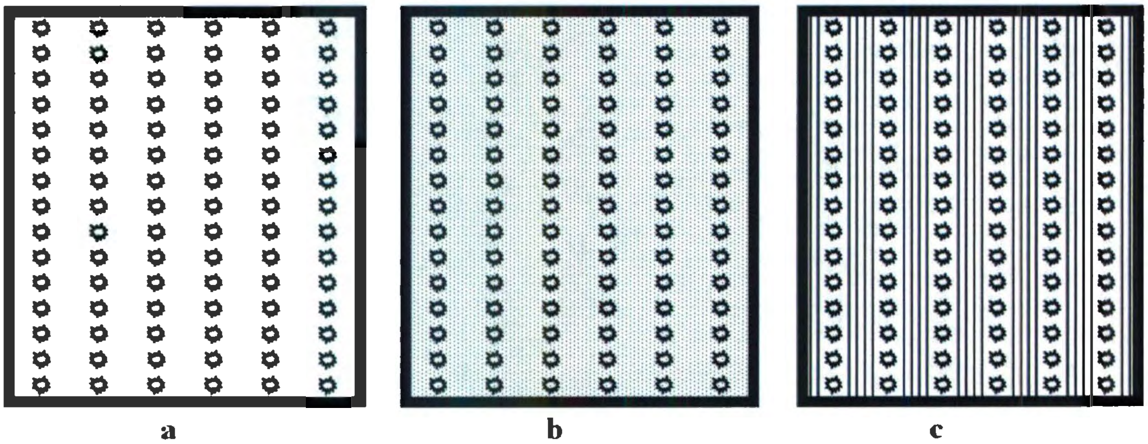

**Figure 3.1.** Schematic diagram of experimental plots illustrating the intercropping designs used in the study: a) cauliflower in bare ground monoculture (2002/03) b) cauliflower planted into broadcasted winter wheat (2002) c) cauliflower planted between winter wheat rows (2003).

One week before cauliflower transplanting, a 30 cm x 30 cm quadrat was randomly tossed into each plot five times and the numbers of winter wheat plants counted to assess stand establishment. Visual ratings of the percent ground cover were taken on June 16, June 24, July 2 and July 9. Ratings were performed by placing the 30 cm x 30 cm quadrat around 20 randomly selected cauliflower plants per plot. Ratings were made using the following scale: 1 = 0 - 20%, 2 = 20 - 40%, 3 = 40 – 60%, 4 = 60 – 80%, 5 = 80 – 100% coverage. On July 9 ground cover ratings were taken as total ground cover, winter wheat plus weeds, as well as ground cover occupied by the winter wheat only.

Twenty randomly selected cauliflower plants per plot were inspected for the presence of *Delia* spp. eggs. The top 2 cm of soil within a 5 cm radius of the cauliflower stem was gently disturbed with a spatula and numbers of *Delia spp*. eggs around the base of the cauliflower plants were visually counted. Eggs were sampled on June 16, June 24, July 2 and July 9 with new plants randomly selected for inspection on each date. This sampling period coincided with predicted peak oviposition of the first-generation of *D. radicum* based on Degree Day accumulations and forecasting data (Coady and Dixon 1997). To determine the species being counted *in situ*, eggs were sampled on June 24 and July 9 by removing a 5 cm radius, 2 cm deep volume of soil from the base of 10 randomly selected guard row plants. This soil was taken back to the lab and the eggs were removed by flotation and identified under the microscope as *D. radicum* or *D. platura / D. florilega*. *D. platura* and *D. florilega* are indistinguishable visually in the egg stage (Brooks 1951).

On 2002 August 28, ten randomly selected cauliflower plants per plot were harvested by taking all plant material from the soil surface up; this was recorded as an "above ground weight". Wrapper leaves were removed and "trimmed curd weights" taken. Curd diameter at widest point was also determined. The number and fresh weight of marketable and unmarketable curds per plot also were determined. Marketable cauliflower are those that fall into Canada No. 1 and Canada No. 2 standards according to the Canadian Food Inspection Agency, Vegetable Inspection Manual (Anon. 2002). Under these standards cauliflower that have a curd diameter > 102 mm and are free of hollow stem, decay, mold and insect frass are deemed marketable.

**3.3.4 Row planting experiment 2003.** In 2003, there were two treatments, cauliflower grown in bare ground (Fig. 3.1a) and cauliflower grown with rows of winter wheat (Fig. 3.1c). The trial was set up as a randomized complete block design with four blocks. Winter wheat was seeded at a rate of 450 seeds $m^{-2}$ (153 kg/ha) on May 22 in 6 m x 6.8 m plots. The rate used to seed the winter wheat in 2003 was in between the two highest rates used in 2002 as this rate appeared to provide a good level of weed control. Cauliflower seedlings were transplanted on June 17 in rows spaced 1 m apart with an in-row spacing of 40 cm. The wider between row spacing accommodated four rows of winter wheat spaced 20 cm apart between cauliflower rows. In both years the winter wheat was mowed when it exceeded a height of ~ 20 cm. The control plots and in-row cauliflower (2003) were hand weeded. Cauliflower were hand watered at transplanting and when necessary throughout the growing season.

A high proportion of *Delia platura / D. florilega* eggs were observed in the 2002 species assessment, thus in 2003 all eggs sampled were returned to the laboratory for identification. Egg sampling involved the removal of a 5 cm radius and 2 cm deep volume of soil from around the base of 10 randomly selected cauliflower plants per plot on June 23, June 27 and July 2. The same plants were used for egg sampling over all dates and the hole was filled back in with surrounding soil. Eggs were removed from the soil by floatation, placed on moist black filter paper, counted and identified under the microscope as above.

On 2003 July 17, 10 randomly selected plants per plot were harvested to assess mid-season dry matter production. Above ground portions of the cauliflower were weighed, dried in a 70°C oven for 48 hrs and weighed again to determine dry matter content. On 2003 August 5, chlorophyll readings were taken on 10 randomly selected plants per plot using a MINOLTA- SPAD 502 chlorophyll meter. The upper mid section of an actively growing leaf was used for the measurements. SPAD meters provide a rapid and non-destructive measurement of leaf chlorophyll content and SPAD readings have been positively correlated to foliar-N (Chang and Robison 2003) and have been used to assess nitrogen deficiencies in crops (Wood et al. 1992). SPAD readings were not taken in 2002 due to the unavailability of the SPAD meter.

Cauliflower yields were determined as in the 2002 experiment; 15 plants per plot were harvested on 2003 August 25.

**3.3.5 Statistical Analysis.** For the *Delia* spp. (2002) and *D. radicum* (2003) and *D. platura / D. florilega* (2003) egg data, total eggs laid per plot were analysed with an Analysis of variance (ANOVA) using MINITAB (version 13 for Windows). Residuals were checked for the assumptions of normality, homogeneity and independence; alpha was set at 0.05. The influence of block and treatment on the incidence of egg laying was analyzed using logistic regression, a special case of the generalized linear model appropriate for analyzing binary data (Agresti 1996) using PROC GENMOD (SAS Institute Inc. 2001). All results are reported as Type III analyses (analogous to adjusted sums of squares).

ANOVAs also were completed on the ground cover ratings and SPAD readings to determine if there were differences between treatments. The above ground weights, trimmed curd weights, and yield per plot of cauliflower also were subjected to ANOVA to determine if there were differences between cauliflower grown in bare ground and cauliflower undersown with winter wheat.

## 3.4 Results

**3.4.1 Observations.** By the end of July in 2002 larvae of the purple backed cabbage worm, *Evergestis pallidata* (Hufnagel) (Lepidoptera:Pyralidae), were present in large numbers in all plots and were removed by hand. The purple backed cabbage worm was not present in plots in 2003. Few other insect pests were present in plots in either year.

**3.4.2 Broadcast experiment 2002.** With *in situ* egg sampling, there were no differences in mean total *Delia* spp. eggs per plot collected from cauliflower in the bare ground control versus cauliflower undersown with the different rates of winter wheat ($F_{4,16}$ = 0.16, $P = 0.942$). The two egg samples taken to determine egg species composition on the cauliflower showed there were varying proportions of eggs from different *Delia* species in the root maggot complex. On June 24, 52.5% of the eggs were identified as *D. radicum* with the remaining 47.5% determined to be *D. platura / D. florilega*. Two weeks later on July 9, 89.1% were identified as *D. radicum*, with the remaining 10.9 % *D. platura / D. florilega*.

The treatment quadrat counts of winter wheat, taken one week prior to transplanting in 2002, determined mean (± SEM) plant counts to be 0, 76.9 ± 9.0, 165.8 ± 21.1, 284.4 ± 27.2 and 373.7 ± 44.2 plants $m^{-2}$. The broadcast seeding of the wheat made hand weeding /hoeing difficult and it was not possible to maintain the lower treatment rates at the initial wheat plant densities because of weed growth. Weeds were not identified to species and are classified as any plants growing in the plots that were not winter wheat or cauliflower. There was a significant difference between the ground cover ratings at the four seeding rates on the first three sampling dates; however, by the fourth sampling date, because of more weed growth in the low density plots, the ground cover ratings were not different between the seeding rates (Table 3.1). On 2002 July 9 total ground cover ratings ranged between three and four (Fig. 3.2). Ratings for winter wheat alone in these same plots were lower (1.5 to 3.5). As the season progressed all treatments reached similar ground cover ratings with differences only in the wheat:weeds ratio (Table 3.1; Fig. 3.2). Actual differences in the effect of varying rates of winter wheat alone could not be determined as the weed growth resulted in similar total ground cover ratings in all treatments.

**Table 3.1. Mean ground cover ratings on each egg sampling date in the 2002 undersown plots. The five rating categories were based on 20% cover intervals starting with 1=0-20% and ending with 5=80-100% cover. Ratings include all vegetative cover with winter wheat and weeds combined.**

| | Ground cover rating | | | |
|---|---|---|---|---|
| Treatment | 16 June | 24 June | 2 July | 9 July |
| 125 seeds/$m^2$ | 1.02 ± 0.02 | 1.03 ±0.02 | 1.08 ± 0.04 | 3.32 ± 0.34 |
| 250 seeds/$m^2$ | 1.30 ± 0.09 | 1.34 ± 0.10 | 1.44 ± 0.15 | 3.46 ± 0.07 |
| 375 seeds/$m^2$ | 1.64± 0.11 | 1.94 ± 0.14 | 2.28 ± 0.26 | 3.55 ± 0.32 |
| 500 seeds/$m^2$ | 1.94 ± 0.21 | 2.08 ± 0.21 | 2.44 ± 0.14 | 4.10 ± 0.06 |
| $F_{3,12}$ | 11.36 | 17.08 | 27.67 | 2.18 |
| $P$ | <0.001 | <0.001 | <0.001 | 0.1430 |

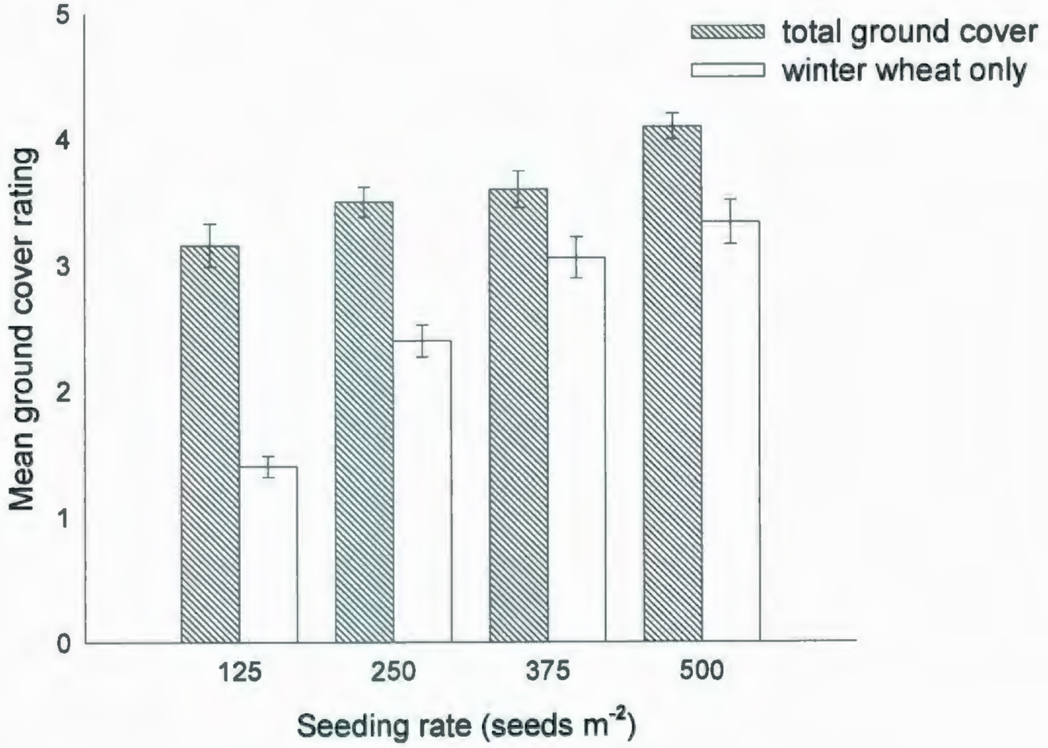

**Figure 3.2.** Mean ground cover ratings (± SEM) of the four undersown plots showing the relation between winter wheat seeding rate, total cover and the proportion of cover resulting from weeds for each seeding rate. Note: Readings taken on 9 July 2002, the last egg sampling date.

There were, in 2002, more marketable curds produced in the bare ground plots than in the undersown plots (Table 3.2). No marketable cauliflower was produced in the plots that were undersown with wheat; even at the lowest seeding rate of 125 seeds $m^{-2}$, as curds were too small. There were significant reductions in all cauliflower yield parameters measured, above ground weight, trimmed curd weight and curd diameter, when the cauliflower was undersown with winter wheat (Table 3.3). In 2002, the plots undersown with winter wheat produced curds between 10.1 ± 2.2 g with an average diameter of 3.3 ± 0.3 cm in the high seeding rate treatment and 12.7± 2.3 g with an average diameter of 3.8 ± 0.3 cm in the low seeding rate treatment. This compares to bare plots where curds weighed 230.9 ± 49.0 g and were 11.2 ± 0.9 cm in diameter.

**Table 3.2. Mean marketable fresh weight harvested ha$^{-1}$ (±SEM) of cauliflower grown in bare ground and undersown with winter wheat (varying rates in 2002).**

|  |  | Marketable curd | Unmarketable curd |
|---|---|---|---|
| Year | Treatment | Fresh weight (t ha$^{-1}$) | Fresh weight (t ha$^{-1}$) |
| 2002 | Bare ground | 5.59 ± 1.75 | 1.539 ± 0.369 |
|  | 125 seeds/m$^2$ | – | 0.388 ± 0.064 |
|  | 250 seeds/m$^2$ | – | 0.324 ± 0.096 |
|  | 375 seeds/m$^2$ | – | 0.393 ± 0.139 |
|  | 500 seeds/m$^2$ | – | 0.278 ± 0.061 |
|  |  |  | $F_{4,16} = 6.22$<br>$P = 0.003$ |
| 2003 | Bare ground | 8.55 ± 1.30 | 2.193 ± 0.587 |
|  | Undersown | 0.38 ± 0.260 | 0.785 ± 0.250 |
|  | $F_{1,3}$ | 38.15 | 8.79 |
|  | $P$ | 0.009 | 0.059 |

**Table 3.3: Above ground weight, trimmed curd weight and curd diameter of individual cauliflower (means ± SEM) grown with winter wheat or in bare ground.**

| Year | Treatment | Above ground weight (g) | Trimmed curd weight (g) | Curd diameter (cm) |
|---|---|---|---|---|
| 2002 | | | | |
| | 0 seeds $m^{-2}$ | 538.0 ± 107.0 | 230.9 ± 49.0 | 11.2 ± 0.9 |
| | 125 seeds $m^{-2}$ | 43.4 ± 4.4 | 12.7 ± 2.2 | 3.8 ± 0.3 |
| | 250 seeds $m^{-2}$ | 42.3 ± 8.2 | 10.5 ± 2.8 | 3.4 ± 0.6 |
| | 375 seeds $m^{-2}$ | 47.1 ± 9.0 | 12.9 ± 4.2 | 3.6 ± 0.5 |
| | 500 seeds $m^{-2}$ | 37.7 ± 5.0 | 10.1 ± 2.3 | 3.3 ± 0.3 |
| | $F_{4,16}$ | 24.42 | 21.52 | 73.18 |
| | $P$ | <0.001 | <0.001 | <0.001 |
| 2003 | | | | |
| | Bare | 1179 ± 78.9 | 406.7 ± 55.7 | 11.6 ± 0.81 |
| | Undersown | 280.52 ± 46.4 | 82.4 ± 13.6 | 7.0 ± 0.49 |
| | $F_{1,3}$ | 99.49 | 35.72 | 35.06 |
| | $P$ | 0.002 | 0.009 | 0.010 |

**3.4.3 Row planting experiment 2003.** In 2003, when species were considered separately, there were significant differences in the total numbers of *D. radicum* eggs laid between the bare ground and undersown plots ($F_{1,3} = 12.78$, $P = 0.037$) (Fig. 3.3). *D. platura* and/or *D. florilega* responded similarly to cropping treatment with more eggs collected from cauliflower in bare ground than on cauliflower in the undersown plots ($F_{1,3} = 36.22$, $P = 0.009$) (Fig. 3.3). On two of the three sampling dates there were more cauliflower plants with *D. radicum* eggs in the bare ground plots than in the undersown plots (Table 3.4). The incidence of plants with *D. platura* / *D. florilega* eggs, however, was similar between treatments (Table 3.4).

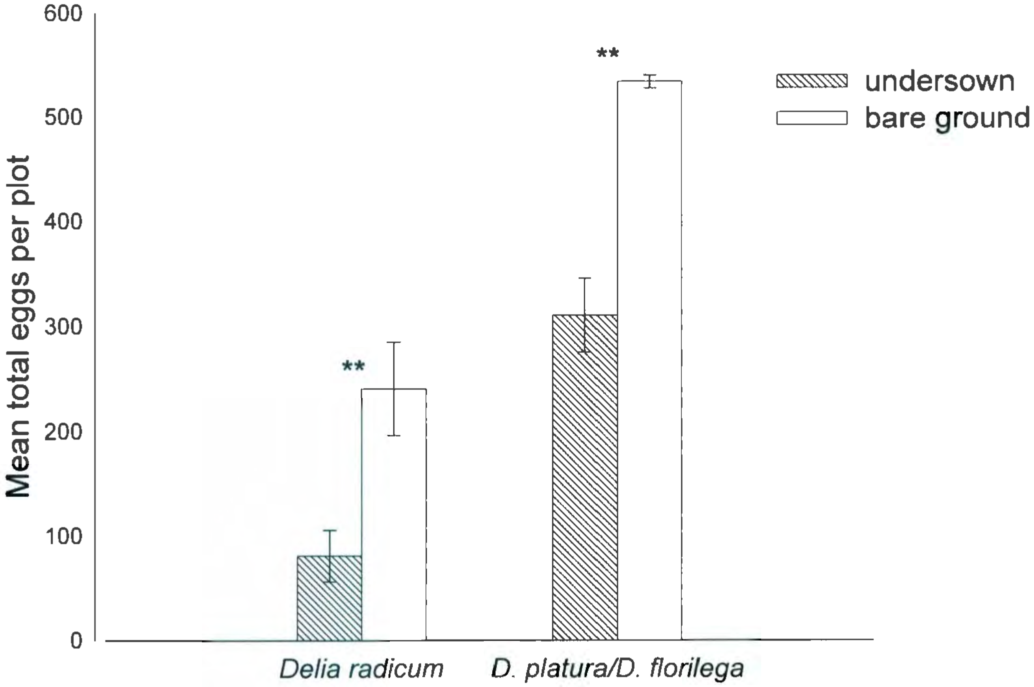

**Figure 3.3.** Mean total number eggs per plot (± SEM) of *Delia radicum* and *Delia* spp. (*D. platura / D. florilega*) collected from cauliflower undersown with winter wheat and in bare ground in 2003. Numbers are mean total eggs collected from the base of ten cauliflower plants per plot over three sampling dates.
(**, significant at $p < 0.001$)

**Table 3.4: Analysis of deviance table (type 3 analysis) of logistic regression analysis on the incidence of eggs on cauliflower grown in bare ground compared to cauliflower undersown with winter wheat in 2003.**

| Root maggot species | Sample date | Source | df | G | P |
|---|---|---|---|---|---|
| *Delia radicum* | 23-June | Treatment | 1 | 0.00 | 1.000 |
| | | Block | 3 | 0.92 | 0.821 |
| | 27-June | Treatment | 1 | 10.23 | 0.001 |
| | | Block | 3 | 0.20 | 0.978 |
| | 2-July | Treatment | 1 | 4.41 | 0.036 |
| | | Block | 3 | 10.61 | 0.014 |
| *Delia platura / D. florilega* | 23-June | Treatment | 1 | 1.01 | 0.316 |
| | | Block | 3 | 3.76 | 0.288 |
| | 27-June | Treatment | 1 | 0.36 | 0.550 |
| | | Block | 3 | 1.77 | 0.622 |
| | 2-July | Treatment | 1 | 1.40 | 0.237 |
| | | Block | 3 | 2.85 | 0.415 |

The winter wheat in 2003 was seeded into the field approximately two weeks before the cauliflower was transplanted. After 5 weeks in the field, on July 17, cauliflower plants in the undersown plots were stunted and showing signs of nutrient deficiencies such as greying and purpling of the leaves. There was also a significant reduction in the dry weights of cauliflower in the undersown plots (6.32 ± 0.55 g) as compared to cauliflower in the bare ground plots (7.99 ± 0.46 g) ( $F_{1,3} = 31.18$; $P = 0.0114$) on this date. Chlorophyll content of cauliflower leaves, as measured through SPAD readings taken on Aug. 5, also were significantly lower in the undersown plots ($F_{1,3} = 18.65$, $P = 0.023$).

In 2003 there were more marketable curds produced in the bare ground plots than in the undersown plots (Table 3.2). Seeding the winter wheat in drills increased the value of cauliflower yield parameters measured with trimmed curd weights and diameter averaging 82.4 ± 13.6 g and 7.0 ± 0.49 cm respectively (Table 3.3); however these were still below marketable size. Curds from bare plots weighed 406.7 ± 55.7 g and were 11.6 ± 0.881 cm in diameter.

### 3.5 Discussion

As previous studies have reported reduced *D. radicum* egg numbers in undersown brassica cropping systems (Smith 1976; Theunissen et al. 1995; Dixon et al. 2004), we explored undersowing using winter wheat as a management strategy for cauliflower production in the cool climate of Newfoundland. There were no differences in the total number of *Delia* spp. eggs collected from cauliflower undersown with winter wheat and cauliflower planted in bare ground in the 2002 broadcast seeding study. In the 2003 experiment, when the winter wheat was planted in rows between the cauliflower, the total numbers of *D. radicum* eggs laid on cauliflower undersown with winter wheat were significantly less than the numbers of eggs on cauliflower in bare ground. In both studies, cauliflower undersown with winter wheat did not grow to marketable size.

A high proportion of *D. platura* and/or *D. florilega* eggs were found in the 2002 samples and may have confounded the egg caounts and thus interfered with the ability to assess the effects of undersowing on *D. radicum* oviposition. The effect of undersowing on *D. platura / D. florilega* is not documented in the literature; however, Parsons et al. (2007) demonstrated that the effect of relay cropping on these species was inconsistent suggesting that these species may not respond to within field diversification in the same manner as *D. radicum*. Moreover, the 2002 undersowing experiment did not involve removal of eggs from the cauliflower plants and it is possible that the presence of eggs may have also influenced oviposition by other *Delia* spp. females as it is known that the presence of *D. radicum* eggs and larvae on a host brassica may induce conspecific females to oviposit on the same plant (Gouinguené et al. 2006; Baur et al. 1996). Whether there is a similar effect on congeners is, however, unknown. The complex oviposition interactions between these three species of *Delia* root maggots requires further investigation.

The reduction of *D. radicum* oviposition in undersown plots in the 2003 study supports the 'appropriate/inappropriate landings' theory of Finch and Collier (2000). According to the theory, when host plants are grown in a diverse setting there is a reduction in the number of successful ('appropriate') landings or oviposition experiences. This was demonstrated in this study through the reduction in the number of plants infested with eggs in the undersown plots i.e. the incidence of plants sampled that had *D. radicum* eggs present was reduced in the undersown plots. Other studies have reported reduced *D. radicum* egg numbers when the host brassica is undersown with clover (Theunissen et al. 1995; Dixon et al. 2004), growing in a weedy background (Dosdall et al. 2003; Smith 1976), or intercropped with other vegetable species (Parsons et al. 2007; Kostal and Finch 1994; Ryan et al. 1980).

Although the 'appropriate / inappropriate landings' theory appears to be the primary mechanism explaining the reduced egg numbers obtained from cauliflower plants undersown with winter wheat, the intense competition as shown by reduced dry matter production and reduced chlorophyll levels, may have negatively affected the quality of the cauliflower as a host; thereby influencing the decision by the females to oviposit (or not) on cauliflower grown in undersown plots. The indirect effect of plant competition on the 'quality' of the host plant and subsequent choice by *D. radicum* to oviposit has not been documented. It is possible that competition between the winter wheat and cauliflower changed not only the structure and size, but also the physiological condition of the cauliflower, which may have made it less attractive/suitable for oviposition by *D. radicum.*

The reduction in *D. platura / D. florilega* egg numbers in the 2003 undersown plots suggests that these species may respond to increased within-field diversification in a manner similar to *D. radicum*; however reports from other studies on diversification effects on *D. platura / D. florilega* showed a varied response depending on year (Parsons et al. 2007). The former two species have similar life histories to one another but very different from that of *D. radicum.* Females of *D. platura / D. florilega* are attracted to newly ploughed soil for oviposition (Eckenrode et al. 1975) rather than by specific cues associated with brassica plants as is the case with *D. radicum*. The incidence of cauliflower plants with *D. platura / D. florilega* eggs was not different between the treatments which suggests that the mechanism behind reduced oviposition may not be due to 'appropriate / inappropriate landings'. *D. platura / D. florilega* are considered pests on a number of different plant species including brassicaceous vegetables (Miller and McClanahan 1960). There have been a number of cases in which *D. platura* and *D. florilega* appear to be primary pests in certain cropping systems (Parsons et al. 2006). Further investigation is needed to assess the ecology of the co-occurrence of these three species on brassicaceous vegetables, as well as their responses to within-field diversification. It will be necessary to understand this relationship before diversification can be considered as a pest management tool against *D. radicum* in areas where *D. platura* and *D. florilega* also occur.

Although the winter wheat was seeded early in the spring rather than the fall in an attempt to reduce competition, it produced enough growth to reduce first generation *D. radicum* egg numbers, at least in 2003. However, competition still was intense and cauliflower yield severely compromised in both years. The switch from broadcasting the winter wheat in 2002 to row planting in 2003 where the cauliflower rows were maintained weed free was not sufficient to reduce competition between the component plant species. By mid-season in the undersown plots, cauliflower dry weights and chlorophyll readings were reduced and the cauliflower plants were stunted and showing signs of nutrient deficiencies, indicating severe competition for mineral nutrients with winter wheat. This issue of reduced yields in undersown systems has been one of the main impediments to their use in pest management, with documented yield losses in many of the crops investigated (Lotz et al. 1997; Dixon et al. 2004). It may be possible to decrease the amount of competition and still provide a degree of crop protection from *D. radicum* by ploughing under or chemically removing the between row winter wheat after peak oviposition, and allowing the cauliflower to continue as a monoculture. Care needs to be taken, however, as this practice may influence other pests.

This study investigated the possibility of undersowing winter wheat as a pesticide free, sustainable method for root maggot management in cauliflower. In one of two years, reduced egg numbers on cauliflower were obtained. This, however, was offset by a significant decrease in cauliflower yield. The cauliflower and winter wheat were incompatible at the planting times used in this study; further investigation is needed into the temporal and spatial arrangements used in mixed cropping to optimize both pest management benefits as well as crop yield.

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# Chapter
# 4

# Relay cropping cauliflower with lettuce as a means to manage first-generation cabbage maggot (*Delia radicum*) and minimize cauliflower yield loss[1]

C.K. Parsons[2, 3], P.L. Dixon[2] & M.H. Colbo[3]

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[2] Agriculture & Agri-Food Canada, PO Box 39088, St. John's, Newfoundland and Labrador, Canada, A1E 5Y7. [3] Memorial University of Newfoundland, St. John’s, Newfoundland and Labrador, Canada, A1B 3X9

## Relay cropping cauliflower with lettuce as a means to manage first-generation cabbage maggot (*Delia radicum*) and minimize cauliflower yield loss

### 4.1 Abstract

First-generation cabbage maggot, *Delia radicum* (L.), can cause extensive damage to newly transplanted brassica crops. This study investigated the use of relay cropping, a form of intercropping that involves overlapping two crops in the same field for a short period, as a means to: 1) reduce first-generation *D. radicum* egg numbers by disrupting female host finding and 2) minimize yield loss by reducing the time that crops overlap. Due to the high incidence of two other *Delia* species, *D. platura* (Meigen) and *D. florilega* (Zetterstedt), treatment effects on these insects was also considered. In both years there were fewer *D. radicum* eggs collected from the base of cauliflower plants relay cropped with lettuce than in monoculture. *D. platura* / *D. florilega* also laid fewer eggs on cauliflower in the relay crop than in monoculture in 2003, but in 2004 the opposite was true, there were more *D. platura* / *D. florilega* eggs laid on the relay cropped cauliflower. After peak *D. radicum* oviposition the lettuce was harvested. Cauliflower curd weights and diameters were comparable between treatments in both years. Plant loss due to *D. platura* / *D. florilega* feeding in the 2004 relay cropped plots resulted in reduced yields in these plots compared to the monoculture. Although further investigation is needed into the effects of relay cropping on other pests within this system, this is the first study to demonstrate that relay cropping can reduce egg-laying by *D. radicum* at the scale studied while minimizing competition between component crops for key resources.

## 4.2 Introduction

The role of diversity in agricultural systems is an area of research that has received increased attention as the search for more sustainable forms of crop production continues. Intercropping is the practice of growing multiple crops on the same area of land at the same time. One type of intercropping is relay cropping, which involves overlapping the two crops in the field for a short period of time, usually combining an early maturing crop with a crop that requires a longer period in the field to reach maturity. The indigenous peoples of the Americas, for example, grew beans relay cropped with maize, and this diversified system continues to be used today in many parts of Latin America (Guldan and Martin 1998). The long-term use of bean-maize relay cropping demonstrates the potential for sustainable production of certain intercropping combinations. Successful intercropping systems use complementary crops that make efficient use of available resources, often reducing reliance on external inputs (Vandermeer 1989, Santos et al. 2002).

Intercropped systems have been associated with the potential for pest and disease reduction (Root 1973, Vandermeer 1989, Andow 1991, Trenbath 1993, Åsman et al. 2001, see Hooks and Johnson 2003 for review specific to Brassicas). The cabbage maggot, *Delia radicum* L. (Diptera: Anthomyiidae), has consistently shown reductions in infestation levels when host plants are grown in diverse cropping systems (Dempster and Coaker 1974, O'Donnell and Coaker 1975, Ryan et al. 1980, Hooks and Johnson 2003). This root-feeding insect feeds on plants within the Brassicaceae and is an economically important pest in many parts of the temperate world. In Newfoundland, *D. radicum* overwinters as pupae with adult flies emerging around the middle to end of June. The resulting larvae, from eggs laid by these first generation flies, can often cause significant damage to newly transplanted brassica seedlings as the young plants are unable to withstand high levels of larval feeding. A second generation of flies will emerge around the end of August and complete a partial generation before entering diapause to overwinter as pupae. Management of the cabbage maggot is mainly through the use of insecticides; however, many of the currently available chemicals may be lost for use on brassica crops due to de-registration (Dixon et al. 2004), leaving growers with few alternative management options.

The primary mechanism underlying reduced *D. radicum* numbers in intercropping situations is a disruption of the host plant selection behaviors associated with the female fly. Host plant selection by *D. radicum* involves a three-linked chain of events consisting of: 1) odor induced attraction to specific volatile chemicals associated with the brassica host plant (Finch 1978), followed by 2) close range searching using pre-alighting visual cues associated with the color and architecture of the host brassica plant (Prokopy et al. 1983), and 3) an assessment of non-volatile chemicals on the host leaf surface (Baur et al. 1996a). Once the female has assessed the suitability of the host brassica plant and has accumulated sufficient non-volatile cues she is induced to proceed to the base of the plant to lay eggs in the soil near the base of the stem. Finch and Collier (2000) proposed the 'appropriate/inappropriate landings' theory to explain the disruption to the host selection process provided by the presence of a non-host plant. In an intercropped situation the female fly during the second stage of host selection cannot visually discriminate between a host plant and non-host plant when both are green. Thus, the probability of making an 'appropriate landing' on a host brassica is reduced. After a female fly successfully contacts a host brassica plant she makes an average of four spiral flights on and off the host plant leaf, assessing suitability and accumulating sufficient non–volatile stimuli to induce oviposition (Kostal and Finch 1994). In a situation where the host brassica is planted with a non-host intercrop it is possible that during the spiral flights, the female will lose contact with the host plant, landing on the intercrop. This disrupts the accumulation of non-volatile cues and reduces oviposition. Morley et al. (2005) described how the female fly, after making an 'inappropriate landing', stops her search for a suitable host for prolonged periods of time. The reduced oviposition in diverse plantings may be due to increased tenure time on non-hosts and the subsequent need to 're-start' the behaviors associated with host plant selection. Although this behavioral disruption appears to be the principal mechanism behind reduced infestation levels for this insect, other mechanisms may play important roles in certain cropping situations. These include changes in the quality of the host brassica plant due to competition (Bukovinszky et al. 2004), and differences in natural enemy activity (Root 1973, Theunissen and den Ouden 1980, Parajulee and Slosser 1999). The spatial scale of vegetation plots may also influence herbivore response in some diversified systems (Bommarco and Banks 2003).

The timing of intercrop establishment is particularly important if the main purpose of within-field diversification is pest management. The early planting of the intercrop relative to the main brassica crop can contribute to better control of targeted pest organisms (Hooks and Johnson 2003) as the intercrop will have reached the critical size to affect the pest populations (Finch and Kienegger 1997, Åsman et al. 2001). This early planting, however, often has negative effects on the growth and development of the main brassica crop. With regards to management of first-generation *D. radicum* on brassica seedlings, relay cropping may be one approach that provides a solution to both the issues of needing an intercrop of sufficient size for disruption of egg-laying and reducing competition between the component crops.

This field study was initiated to investigate the use of relay cropping as a possible alternative management strategy for *D. radicum*. Although the principal pest under investigation was *D. radicum* and previous records indicate that the key root maggot causing damage to brassicas in Newfoundland is *D. radicum* (Morris 1952 unpublished data, Dixon et al. 2004), two other *Delia* species, *D. platura* (Meigen) and *D. florilega* (Zetterstedt), were also present in the study area and the effect of relay cropping on these species also was assessed.

Intercropping and undersowing have the potential to reduce *D. radicum* levels in certain cropping situations; however yield losses associated with these cropping techniques often counteract the pest management benefits. This study assesses relay cropping as a means to alter the time the component crops overlap in the field to examine whether competition with the intercrop can be reduced but also maintain the pest management benefits of intercropping. The specific objectives were to: 1) assess the use of relay cropping with lettuce as a means to reduce first generation *D. radium* egg numbers on cauliflower and 2) assess the potential of relay cropping as a means to minimize competition between the intercrops.

## 4.3 Materials and Methods

The brassica crop used in the study was cauliflower (*Brassica oleracea* var. *botrytis* cv. Fremont) and it was relay cropped with lettuce (*Lactuca sativa* L. cv. Belowa). Lettuce was chosen as the intercrop for two main reasons. First, it was able to be transplanted into the field early in the season and provide enough 'green' to disrupt the host finding behavior of the female fly and second, cauliflower and lettuce have differing resource-use patterns and growth habits (Gliessman 1998).

**4.3.1 Transplant production.** Cauliflower, *Brassica oleracea* var. *botrytis* (cv. Fremont) (Vesey's Seeds, PEI, Canada) were seeded in size 48 plastic flats with 72 cell tray inserts on 5 May 2003 and 11 May 2004 in Promix BX® commercial potting mix. Flats were placed in a temperature controlled greenhouse set at 18°C. Plants were thinned to one plant per cell after germination and fertilized weekly with Alaska® organic fish fertilizer, at a rate of 7.5 ml per liter of water, after the first true leaves had emerged. When plants were 4-5 weeks old they were placed outside to 'harden off' before transplanting. Flats were covered with Reemay® floating row cover to exclude insects. Lettuce (var. Belowa) (Vesey's Seed, PEI) were started on the same days as the cauliflower and raised under the same protocol.

**4.3.2 Experimental fields.** Experiments were conducted in 2003 and 2004 at the Atlantic Cool Climate Crop Research Centre of Agriculture & Agri-Food Canada in St. John's, Newfoundland and Labrador, Canada (47°31'N, 52°47'W). Experiments were conducted using organic crop production practices. Fertility was supplied by plough-down crops of timothy/red clover (2003, three year old stand) and oat/red clover (2004, one year old stand), a fish offal/peat compost (total nitrogen, phosphorus, and potassium, 1.29, 0.07, and 0.02% respectively) spread to a depth of 2.5 cm over each plot, as well as fish meal (P. Janes & Sons Ltd., Hant's Harbour, Newfoundland and Labrador, Canada), kelp meal (Acadian Seaplants Ltd., Dartmouth, Nova Scotia, Canada) and bone meal (C-I-L®) broadcast over the plots at rates based on soil test recommendations. The organic amendments were applied assuming a 10% available N for the fish meal, 3.5% available K for the kelp meal and 14% available P for the bone meal. The compost and fertilizer were applied and rototilled into the soil two weeks prior to the transplanting of the lettuce.

**4.3.3 Plot layout and experimental design.** This study used an additive intercropping design with one row of lettuce planted on each side of the cauliflower. Plot size was 3 m x 3.2 m in 2003 and 4 m x 3.2 m in 2004. Lettuce were transplanted into the field on 5 June 2003 and 7 June 2004 with an in-row spacing of 15 cm (Fig. 2). Cauliflower were transplanted approximately one week later (13 June 2003 and 15 June 2004) with an in-row spacing of 45 cm and a between-row spacing of 60 cm (2003) and 80 cm (2004) (Fig. 1). The cauliflower between-row spacing was increased in 2004 to increase air flow in order to reduce the incidence of a lettuce wilt (*Sclerotinia sclerotiorum*) observed in 2003. Bare plots and in-row areas were maintained weed free and thus are true representatives of bare ground conditions.

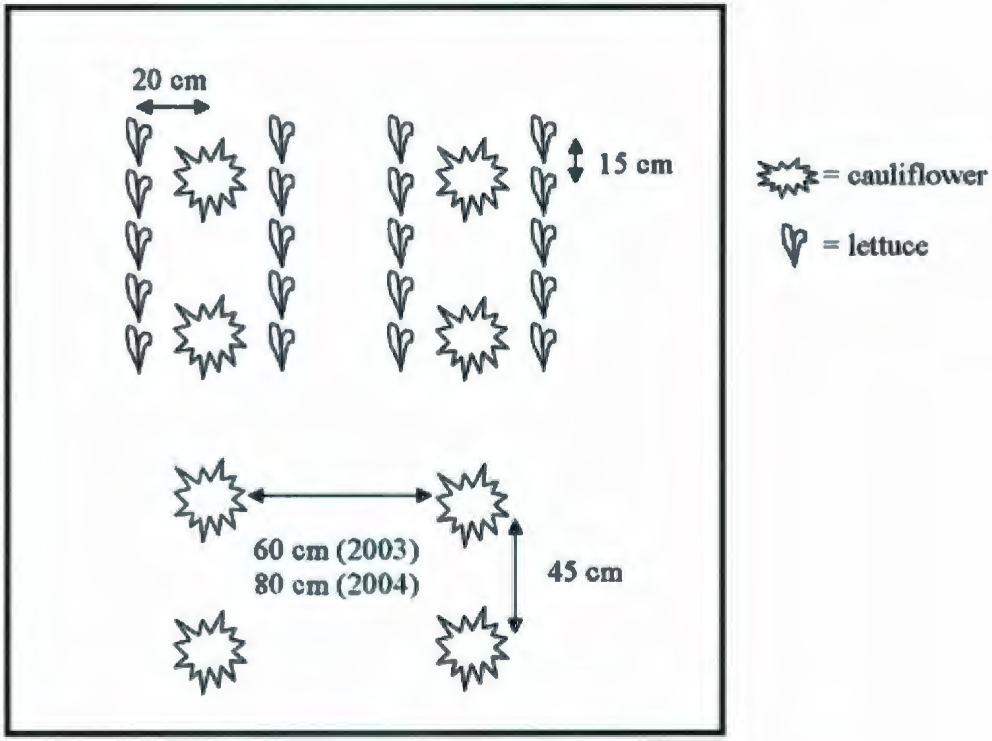

**Figure 4.1.** Schematic diagram illustrating the layout of plants within the cauliflower/lettuce relay cropped plots.

**4.3.4 *Delia* spp. egg counts.** Ten randomly selected cauliflower plants per plot were repeatedly sampled for *Delia* spp. eggs. Sampling involved removing soil from around the base (5 cm radius, 2 cm deep) of the cauliflower and placing it into 250 ml plastic containers. The area was then filled in with surrounding soil. In 2003, eggs were sampled on 23 June, 27 June and 2 July; inclement weather prohibited the extension of egg sampling beyond these dates. In 2004, eggs were sampled from cauliflower on 18 June, 22 June, 27 June, 1 July and 6 July. Sampling began when degree-day accumulations reached 220 DD (base 4.4°C) from 1 April, coinciding with expected peak oviposition of the first generation of *D. radicum* (Coady and Dixon 1997). In the laboratory, eggs were extracted from the soil by floatation, placed on moist black filter paper and identified as *D. radicum* or *D. platura / D. florilega*; *D. platura* and *D. florilega* are indistinguishable in the egg stage (Brooks 1951). In 2004, some of the *D. platura / D. florilega* eggs from the samples were reared on a mixture of rutabaga, fish meal and sand. Twenty five of the resulting flies were sent to a specialist for identification. If time was limited, egg samples were stored in the freezer until they were processed.

**4.3.5 Vertical profile and ground cover of lettuce.** Height of the tallest leaf on 10 randomly selected cauliflower and 10 randomly selected lettuce plants per plot were measured using a 30 cm ruler placed at soil level. This was repeated on 10 different plants on each sampling date to determine the percent of the cauliflower vertical profile covered by the lettuce using the following formula:

% vertical profile covered = (height of lettuce / height of cauliflower) * 100

Digital photographs of two randomly selected cauliflower plants per plot, with their associated lettuce plants, were taken on each sample date and used to determine a percent lettuce ground cover using a dot-grid method. A transparent grid (grid size 8.4 x 8.4 cm with 441 smaller 4 mm squares per grid) was placed over the photo and the number of intersected lines that contained lettuce were counted, divided by the total number of intersections and multiplied by 100 to produce a percent lettuce ground cover value.

**4.3.6 Chlorophyll measurements.** A MINOLTA- SPAD 502 chlorophyll meter was used to non-destructively measure chlorophyll content of the cauliflower leaves on each of the sampling dates in 2004. SPAD readings have been positively correlated to the actual foliar-N content of plant leaves (Chang and Robison 2003) and often used to non-destructively assess nitrogen deficiencies (Wood et al. 1992). Readings were taken from the upper-mid section of an inner mature leaf on ten randomly selected cauliflower plants per plot per date.

**4.3.7 Yield.** On 15 July (2003 and 2004), after peak fly oviposition was complete and the lettuce had reached maturity, all lettuce plants in each plot, excluding guard rows, were harvested at soil level, weighed using a Sartorius LP 34000 P model scale and reported on a yield per hectare basis. The guard row lettuce plants were harvested but not used in the lettuce yield analysis. After the lettuce was removed from the field, both treatments were bare ground cauliflower monocultures.

All cauliflower plants, excluding guard rows, in each plot were harvested on 22 August 2003 and 20 August 2004. Harvest involved removing all plant material above the soil level. Individual plants were weighed, using the same scale as above, to determine an aboveground weight; wrapper leaves removed and a subsequent trimmed curd weight taken. Curd diameter at the widest point was also determined. The number and fresh weight of total marketable and unmarketable curds per plot were determined. Marketable cauliflower are those that fall into both Canada No. 1 and Canada No. 2 standards according to the Canadian Food Inspection Agency, Vegetable Inspection Manual (Anon. 2002). Under these standards cauliflower that have a curd diameter > 102 mm and free of hollow stem, decay, mold and insect frass were deemed marketable.

**4.3.8 Statistical analysis.** All *D. radicum* and *D. platura / D. florilega* egg counts were analyzed as total eggs laid per plot with an Analysis of variance (ANOVA) using MINITAB (version 13 for Windows). Residuals were checked for the assumptions of normality, homogeneity and independence; alpha was set at 0.05. Incidence, as measured by the number of plants sampled with eggs, was analysed using binary logistic regression (SAS Institute Inc. 2001) to determine if more plants within the bare ground plots contained eggs than plants in the relay cropped plots.

Cauliflower SPAD, above ground weights, trimmed curd weights, and yield per plot of cauliflower also were subject to ANOVA to determine if there were differences between cauliflower grown in bare ground and cauliflower relay cropped with lettuce.

## 4.4 Results

**4.4.1 Egg counts.** The date when 220 degree days (DD), above base 4.4°C, were accumulated and egg sampling began was similar in both years of the study. In 2003 egg sampling began on 23 June with a DD accumulation of 217 compared with 2004 in which sampling began on 18 June with a DD accumulation of 226.

*D. radicum* egg numbers differed between years. In 2003 a total of 3113 *D. radicum* eggs were collected from 240 samples over three sampling dates, compared with 726 eggs collected from 400 samples in 2004 over five sampling dates; thus, egg numbers were analyzed separately by year. Egg numbers collected from cauliflower in 2003 ranged from 1-33 eggs per plant, whereas in 2004, collected egg numbers ranged from 1-18 eggs per plant. In both years there were fewer *D. radium* eggs laid on cauliflower grown in the relay cropped plots than on cauliflower grown in bare ground plots (Fig 4.2) with a 66% and 74% reduction in the numbers of eggs in 2003 and 2004 respectively. There were more cauliflower plants infested with *D. radicum* eggs in the bare ground plots than in the relay cropped plots on all three sampling dates in 2003 (Table 4.1) and on four of the five sampling dates in 2004 (Table 4.2).

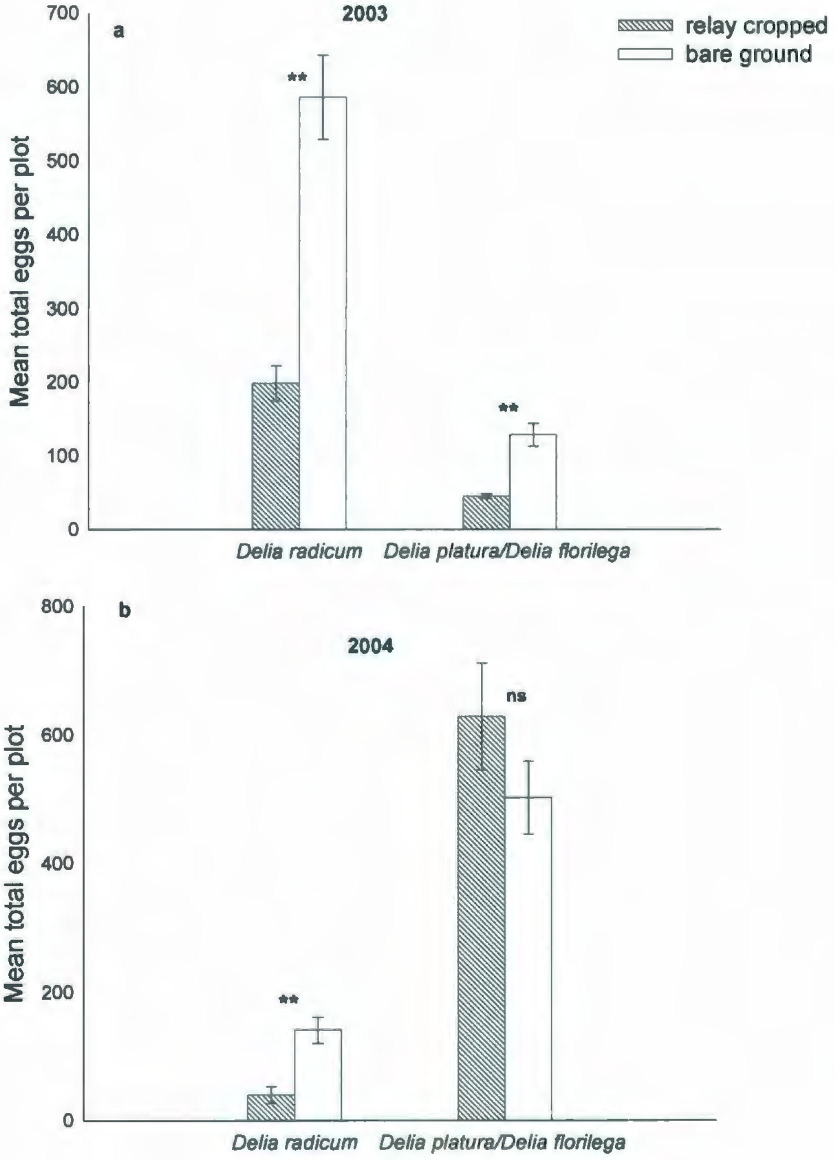

**Figure 4.2.** Mean total number of *Delia radicum* and *D. platura / D. florilega* eggs (± SEM) collected from cauliflower grown relay cropped with lettuce and in bare ground monoculture in a) 2003 and b) 2004.
(**, ns, significant at $p < 0.001$ and not significant respectively)

**Table 4.1: Analysis of deviance table (type 3 analysis) of logistic regression analysis on the incidence of eggs on cauliflower grown in bare ground compared to cauliflower relay cropped with lettuce in 2003.**

| Root maggot species | Sample date | Source | df | G | P |
|---|---|---|---|---|---|
| *Delia radicum* | 23 - June | Treatment | 1 | 8.51 | 0.004 |
| | | Block | 3 | 2.65 | 0.449 |
| | 27-July | Treatment | 1 | 15.68 | <0.001 |
| | | Block | 3 | 2.80 | 0.424 |
| | 2-July | Treatment | 1 | 9.01 | 0.003 |
| | | Block | 3 | 2.09 | 0.553 |
| *Delia platura /*<br>*D. florilega* | 23 - June | Treatment | 1 | 0.21 | 0.647 |
| | | Block | 3 | 2.90 | 0.408 |
| | 27-July | Treatment | 1 | 1.89 | 0.169 |
| | | Block | 3 | 6.59 | 0.09 |
| | 2-July | Treatment | 1 | 15.66 | <0.001 |
| | | Block | 3 | 1.41 | 0.704 |

**Table 4.2: Analysis of deviance table (type 3 analysis) of logistic regression analysis on the incidence of eggs on cauliflower grown in bare ground compared to cauliflower relay cropped with lettuce in 2004.**

| Root maggot species | Sample date | Source | df | G | P |
|---|---|---|---|---|---|
| *Delia radicum* | 18-June | Treatment | 1 | 15.65 | <0.001 |
| | | Block | 3 | 11.10 | 0.011 |
| | 22-June | Treatment | 1 | 16.86 | <0.001 |
| | | Block | 3 | 13.18 | 0.004 |
| | 27-June | Treatment | 1 | 30.90 | <0.001 |
| | | Block | 3 | 1.55 | 0.671 |
| | 1-July | Treatment | 1 | 15.92 | <0.001 |
| | | Block | 3 | 5.18 | 0.159 |
| | 6-July | Treatment | 1 | 5.08 | 0.024 |
| | | Block | 3 | 8.13 | 0.043 |
| *Delia platura / D. florilega* | 18-June | Treatment | 1 | 0.59 | 0.441 |
| | | Block | 3 | 6.02 | 0.111 |
| | 22-June | Treatment | 1 | 4.43 | 0.035 |
| | | Block | 3 | 4.80 | 0.187 |
| | 27-June | Treatment | 1 | 0.57 | 0.451 |
| | | Block | 3 | 1.17 | 0.761 |
| | 1-July | Treatment | 1 | 4.91 | 0.027 |
| | | Block | 3 | 3.84 | 0.279 |
| | 6-July | Treatment | 1 | 0.00 | 1.00 |
| | | Block | 3 | 1.16 | 0.763 |

*D. platura / D. florilega* responded differently to the relay cropping treatment depending on year. In 2003 *D. platura / D. florilega* showed similar patterns to that of *D. radicum* with significantly higher numbers of eggs on cauliflower in the bare ground plots as compared to the relay cropped plots (Fig. 4.2). In 2004 there were no differences in the total number of *D. platura / D. florilega* eggs laid around the cauliflower in the relay cropped plots compared to cauliflower in bare ground plots (Fig. 4.2). On one of the three (2003) and two of the five (2004) sampling dates there were differences in the numbers of plants infested with *D. platura / D. florilega* eggs (Tables 4.1 & 4.2).

Of the twenty five flies sent for identification in 2004, 56% were *D. florilega* and 44% were *D. platura.*

**4.4.2 Vertical profile and ground cover of lettuce.** The variety of leaf lettuce chosen for this study (Belowa) initially had a horizontal growth pattern, followed by vertical growth. Seven days after the cauliflower were transplanted, 18 June 2004, the lettuce covered 64% of the vertical profile of the cauliflower with a 12 % ground cover; by the last sampling date, 6 July 2004, the lettuce covered 96 % of the vertical profile of the cauliflower with a 52% ground cover (Table 4.3).

**4.4.3 Crops.** *Mid-season assessment of competition.* As the chlorophyll content of a plant is expected to change over time the SPAD readings between treatments were analyzed separately by date. On all sampling dates the SPAD values of cauliflower grown in bare ground and cauliflower relay cropped with lettuce were similar (Table 4.4).

**Table 4.3. Comparison of the % vertical profile of cauliflower covered by lettuce and the % lettuce ground cover on each sample date in 2003 and 2004.**

| | Sample date | % vertical profile covered by lettuce | % ground covered by lettuce |
|---|---|---|---|
| 2003 | 23-June | DNA* | 12.1 |
| | 27-June | DNA | 24.6 |
| | 2-July | DNA | 39.6 |
| 2004 | 18-June | 64 | 11.9 |
| | 22-June | 65 | 23.3 |
| | 27-June | 62 | 30.9 |
| | 1-July | 87 | 48.0 |
| | 6-July | 96 | 52.0 |

*DNA = Data not available

**Table 4.4. Chlorophyll levels (SPAD value ± SEM) of cauliflower grown in bare ground monoculture and relay cropped with lettuce in 2004**

| Treatment | Sample date | | | | |
|---|---|---|---|---|---|
| | 18-June | 22-June | 27-June | 1-July | 6-July |
| Bare ground | 34.49±1.27 | 34.24±0.77 | 46.24±0.88 | 56.39±2.04 | 58.58 ± 1.42 |
| Relay cropped | 34.86±1.26 | 35.54±0.79 | 46.88±0.66 | 57.08±0.76 | 57.74 ± 0.93 |
| $F_{1,3}$ | 0.15 | 3.18 | 0.70 | 0.07 | 0.33 |
| P | 0.72 | 0.17 | 0.46 | 0.81 | 0.61 |

*Lettuce.* Approximately three weeks before lettuce harvest in 2003, approximately 10% of the lettuce plants and <5% the cauliflower were determined to be infected with a pathogen (*Sclerotinia sclerotiorum*). Between-row spacing was increased in 2004 and <1% lettuce plants were diseased. There was no incidence of the disease in the cauliflower in 2004. Lettuce yields averaged 7.2 t ha$^{-1}$ and 10.2 t ha$^{-1}$ in 2003 and 2004 respectively.

*Cauliflower.* Relay cropping cauliflower with lettuce did not affect above ground weights, trimmed curd weights and curd diameters in both years of the study (Table 4.5) and yield of marketable curds also did not differ between treatments in 2003. However, yields of marketable curd were significantly lower in the intercrop treatment in 2004.

**Table 4.5. Above ground weight, trimmed curd weight and curd diameter (means ± SEM) of individual cauliflower grown without (bare ground) and with lettuce (relay cropped)**

| Year | Treatment | Above ground weight (g) | Trimmed curd weight (g) | Curd diameter (cm) |
|---|---|---|---|---|
| 2003 | Bare ground | 1326.0 ± 138.0 | 416.0 ± 83.6 | 12.7 ± 0.73 |
| | Relay cropped | 1124.4 ± 87.2 | 433.5 ± 45.0 | 13.0 ± 0.44 |
| | $F_{1,3}$ | 6.78 | 0.17 | 0.42 |
| | P | 0.08 | 0.68 | 0.56 |
| 2004 | Bare ground | 1147.5 ± 43.3 | 292.8 ± 16.2 | 10.59 ± 0.28 |
| | Relay cropped | 1170.1 ± 62.6 | 274.5 ± 24.1 | 10.00 ± 0.70 |
| | $F_{1,3}$ | 0.64 | 0.29 | 0.87 |
| | P | 0.48 | 0.63 | 0.42 |

**Table 4.6. Number and fresh weight harvested per ha (means ± SEM) of marketable and unmarketable cauliflower grown without (bare ground) and with lettuce (relay cropped)**

| | | Marketable curds | | Unmarketable curds | |
|---|---|---|---|---|---|
| Year | Treatment | No. ha$^{-1}$ ( x 10$^{3}$) | Fresh weight (t ha$^{-1}$) | No. ha$^{1}$ ( x 10$^{3}$) | Fresh weight (t ha$^{-1}$) |
| 2003 | Bare ground | 16.4 ± 0.89 | 7.5 ± 1.85 | 1.75 ± 0.85 | 0.21 ± 0.15 |
| | Relay cropped | 16.7 ± 0.43 | 7.5 ± 0.53 | 1.25 ± 0.45 | 0.11 ± 0.07 |
| | $F_{1,3}$ | 0.05 | < 0.001 | 0.33 | 0.65 |
| | P | 0.84 | 0.98 | 0.60 | 0.49 |
| 2004 | Bare ground | 7.8 ± 0.64 | 2.85 ± 0.24 | 4.75 ± 0.63 | 0.38 ± 0.07 |
| | Relay cropped | 4.5 ± 0.67 | 1.79 ± 0.23 | 3.50 ± 0.65 | 0.20 ± 0.09 |
| | $F_{1,3}$ | 288.48 | 13.4 | 1.12 | 0.37 |
| | P | < 0.001 | 0.04 | 1.25 | 0.35 |

### 4.5 Discussion

The reduction in the number of *D. radicum* eggs laid around the base of cauliflower in the relay cropped plots was consistent with the results of earlier studies that examined the effect of increasing within-field vegetation on this pest. Reductions in egg numbers have been observed when the host brassica is surrounded by weeds (Smith 1976), including corn spurry (Theunissen and den Ouden 1980), clover (Theunissen et al. 1995, Dixon et al. 2004) and other vegetables such as peas (Kostal and Finch 1994) and lettuce (Ryan et al. 1980). According to the 'appropriate/inappropriate landings' theory (Finch and Collier 2000) insects flying over host brassicas surrounded by non-host plants will land in proportion to the relative areas occupied by leaves of the host and non-host plants. The area occupied by lettuce in this study was approximately three times that of the cauliflower and as a result the female flies made more 'inappropriate' landings as the number of plants infested with eggs was reduced in these relay cropped plots. It is not known, however, how many times a female fly will make an 'inappropriate' landing before leaving the diversely planted area altogether. The research plots in this study were relatively small and the reduced *D. radicum* egg numbers on cauliflower in the relay cropped plots could have been a consequence of increased emigration out of these plots.

In order for the intercrop to affect pest populations it often needs to be a critical size with regard to height (Finch and Kienegger 1997, Åsman et al. 2001) and ground cover (Theunissen and den Ouden 1980). Transplanting lettuce into the field before the cauliflower allowed a certain level of control over the size of the intercrop in this system. Finch and Kienegger (1997) stated that in a diversified system the associated plant has to cover at least 50% of the vertical profile of the host brassica in order to maximize the disruptive effect of intercropping on *D. radicum.* The vertical coverage that lettuce provided in this study was between 64 and 96 % of the cauliflower, sufficient for reducing *D radicum* oviposition according to Finch and Kienegger (1997). A minimum ground cover of 60% has been suggested by O' Donnell and Coaker (1975) as the level required to achieve reductions in *D. radicum* egg numbers in diverse plantings. In the current study the percent ground cover varied considerably, from 12 – 52%, and there were fewer *D. radicum* eggs even with a 12% ground cover. This discrepancy could be due to the different methods of ground cover estimation used. Many authors use visual ratings to assess vegetation ground cover which are known to be highly variable and overestimate the actual percent cover (Olmstead et al. 2004). The present study used a dot-grid method, which gives a more accurate representation of the actual plant cover and the digital images provide a permanent record for storage and reevaluation if necessary.

Many studies have concluded that in diverse brassica plantings there are often reduced brassica yields (Theunissen et al. 1995, Dixon et al. 2004). In this study the lettuce and the cauliflower overlapped in the field, and competed for resources, for only four weeks. SPAD readings taken during this time indicate that there were no differences in leaf chlorophyll content of cauliflower grown in bare ground compared to cauliflower relay cropped with lettuce. This suggests minimal competition occurred between the two crops when they were growing together.

The harvested lettuce provided an additional marketable crop, averaging 8.7 t $ha^{-1}$ from the same land area, thus increasing the land use efficiency of the system. From an economic standpoint, based on local crop prices, averaged over the two years, the potential market value of the cauliflower monoculture was \$30,250 per hectare compared with \$126,890 per hectare for the cauliflower / lettuce relay crop. These values assume full sale of marketable product, do not account for input costs and are based on the cropping pattern used in the present study. In commercial practice slight modification of the cropping pattern may be needed to fit with current production practices.

The number and fresh weight of marketable curds produced between bare ground and relay cropped plots in 2003 were comparable. The lack of yield reduction of cauliflower may be attributed to the complementary growing patterns of cauliflower and lettuce. This complimentarity has been discussed by Vandermeer (1989) and Altieri and Nicholls (2004) and is based on "two crops using different components of the ecosystem, using the same components in different ways or in some way [they] exploit different ecological niches". Planting lettuce, a short season crop, harvestable within 45 days of being transplanted, into a cauliflower crop that is grown over the entire growing season, makes efficient use of available resources. During early spring the cauliflower puts energy into developing leaves and a deep root system, while the lettuce, with shallow roots, uses the available resources for above ground growth (Gliessman 1998). Around the time the lettuce is harvested the cauliflower directs its energy towards curd development. Yildirim and Guvenc (2005) found that cauliflower yield was not significantly affected when intercropped with cos or leaf lettuce, attributing the lack of yield loss to the differing patterns of maturity and resource use.

Of the three individual cauliflower yield parameters measured, above ground weight, trimmed curd weight and curd diameter, the above ground weight was the only parameter affected by relay cropping, and then only in the first year of the study. This may be explained by the fact that early in the season, when cauliflower is directing energy towards leaf and root growth, the two intercrops are competing for resources. Although this reduction in above ground weight did not translate into a reduction in the marketable portion of the plant, the trimmed curd weight, it does suggest that there may be a critical period of harvest for the lettuce. If the lettuce and cauliflower are left growing together past a certain point and leaf growth is further reduced, there may be an associated cauliflower yield loss.

In 2004, there was a significant reduction in the number and fresh weight of marketable curds produced in the relay cropped plots. We attribute this decrease to a higher incidence of *D. platura* and/or *D. florilega* and the consequent increased death of cauliflower plants in the relay plots. *D. platura* and *D. florilega* have similar life histories and have been recorded as pests in many different cultivated crops such as corn, beans, wheat and canola, as well as different vegetable brassicas (Miller and McClanahan 1960). It is unclear whether this was just a sporadic year when these species were unusually abundant, whether they were attracted by the decomposing green manure after plough-down (Eckenrode et al. 1975, Hammond and Jeffers 1983), or whether they are beginning to play a larger role within the root feeding maggot complex. The ecology of the co-occurrence of the three species (*D. radicum*, *D. platura* and *D. florilega*) is complex and not well-known. Gouinguené et al. (2006) demonstrated that the presence of *D. radicum* eggs stimulated oviposition by other D. *radicum* females and Baur et al. (1996b) have shown *D. radicum* females prefer to lay eggs on plants damaged by conspecific larvae to undamaged controls. The presence of *D. platura / D. florilega* eggs and larvae may also influence host choice by *D. radicum*; however, this has never been established.

The current study is the first to demonstrate the ability, through relay cropping, to both minimize egg-laying by *D. radicum* and minimize competition for key resources, by varying planting times of component intercrops in this system. Further work is needed to evaluate this practice on a larger scale. The design of an intercropping system must take into account many different factors including the resource use of the two (or more) crops, effects on potential pests of all component crops and the effects on the natural enemies within the system. It is expected that the unique nature of each agroecosystem with its complex array of interactions will prevent the development of sustainable cropping practices that will work in every system and therefore regional testing of different practices is required.

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# Chapter
# 5

## Co-existence of three sympatric root feeding pest species, *Delia radicum, D. platura* and *D. florilega*

## Co-existence of three sympatric root feeding species, *Delia radicum, D. platura* and *D. florilega*

### 5.1 Abstract

The co-existence of *Delia radicum, D. platura* and *D. florilega*, three sympatric brassica root feeding pests is discussed. Emphasis is placed on differences in species composition in general between the early 1950s and the early 2000s. Data from the 1950s were collected during a study investigating the life history of *D. radicum*. The 2003-2004 data were collected during a series of experiments designed to investigate the effect of crop diversification (undersowing and relay cropping) on *D. radicum*. The dates of first oviposition for *D. radicum* in the early 2000s were similar to those observed in the early 1950s. *D. platura* / *D. florilega* eggs however were detected several weeks later in the spring during the 1950s than in 2003 and 2004; possible reasons are discussed. Eggs collected during the 1950s were comprised predominantly of *D. radicum* with very low proportions of *D. platura* / *D. florilega*. *D. platura* / *D. florilega* eggs were more prevalent in the diversification studies of 2003 and 2004 than in the life history studies of the 1950s; however their proportions varied between year (2003 vs. 2004) and diversification study (undersowing vs. relay cropping). Current studies suggest proximity to source populations and crop production practices appear to play important roles in the *Delia* species composition present. In order to continue development of ecologically based pest management systems for *D. radicum* further investigation into changes in species composition and interspecific competition with *D. platura* and *D. florilega* under field conditions is warranted.

## 5.2 Introduction

Root maggots are economically important pests of brassica crops in many parts of the world. The main dipteran species involved in temperate regions all belong to the family Anthomyiidae and include *Delia radicum* (L.), *D. floralis* (Fallén) and the *D. platura* (Meigen) / *D. florilega* (Zetterstedt) complex. The former two species are considered monophagous, primary pests, attacking only plants within the family Brassicaceae. The latter two species are often, but not always, considered saprophagous, secondary pests, ovipositing alongside decomposing plant material. However, after the larvae start feeding they may move onto living seedlings (Finch 1989).

The relative abundance of these species varies with geographic area (Shaw 1970). In Ontario, *D. platura* and *D. florilega* have been recorded as secondary pests of crucifers (Miller and McClanahan 1960), whereas in British Columbia, they are considered primary pests. The primary anthomyiid pest species attacking vegetable brassicas in Newfoundland and Labrador is the cabbage maggot, *D. radicum* (Morris 1960, Dixon et al. 2004). The turnip maggot, *D. floralis*, does not occur on the island of Newfoundland and *D. platura* and *D. florilega* are not considered economically important. Specific agricultural practices associated with crop production will affect relative species abundance as well. Incorporating a green manure before seeding or transplanting, for example, can increase damage caused by *D. platura* and/or *D. florilega* (Hammond and Jeffers 1983).

Of the species present in Newfoundland, only *D. radicum* is host specific as it oviposits and feeds exclusively on plants in the family Brassicaceae. *D. florilega* is extremely polyphagous, feeding on corn seedlings, roots of brassica plants, beans, peas and other vegetables (Miles 1950, Brooks 1951). Oviposition by both *D. florilega* and *D. platura* increases in the presence of certain microbes (Eckenrode et al. 1975, Kim and Eckenrode 1987). These species are also highly attracted to newly disturbed soil which stimulates oviposition (Miller and McClanahan 1960).

Correct identification of pest species is fundamental to any integrated pest management strategy, especially when dealing with sympatric species that occupy the same ecological niche. These root feeding maggots, although having some common host plants, often have different emergence patterns and life histories that need to be fully understood before a truly integrated management plan can be successfully developed. Management of the root maggots associated with vegetable brassicas has, in the past, focused primarily on management of the cabbage maggot, *D. radicum*, as it has been considered the major pest. Insecticides have been the mainstay of *D. radicum* management for the past 50-60 years and their use for cabbage maggot subsequently controlled the other species of root maggots present. Recent reductions in the numbers of available insecticides and an interest in ecologically based pest management strategies, has steered research back to more biologically and behaviourally based pest management. These management strategies; however, require detailed knowledge of the life histories of all root maggot species involved, how and if these sympatric species share the same resources, as well as the conditions that encourage oviposition and host selection. This will ensure that a management practice to reduce one species does not encourage another.

The objectives of this chapter are: 1) to compare differences in *Delia* species composition observed in 2003-2004 with life history data compiled from 1950-1955 from the same site and 2) to explore differences in *Delia* species composition and abundance in the two years of diversification studies.

## 5.3 Materials and Methods

The data reported in this Chapter have been collected from three studies on *D. radicum* oviposition in St. John's, NL. The first set was compiled from unpublished data collected from 1950 to 1955 by Ray Morris, Entomologist at the Agriculture and Agri-Food Canada Research Centre in St. John's (1948-1982), who investigated the life history of the root maggots *D. radicum* and *D. platura / D. florilega* in cabbage. The second and third data sets are from the two diversification studies discussed in Chapters 3 and 4 of this thesis.

### 5.3.1 Seasonal life history data: 1950-1955.

Eggs were collected twice per week in each year from 5 cabbage plants (var. Golden Acre) randomly chosen from a small cabbage plot at the Atlantic Cool Climate Research Centre, Agriculture and Agri-Food Canada, St. John's, NL. Over the five years the plots contained 400-500 cabbage plants transplanted between May 30th and June 11th. Egg sampling began approximately one week after transplanting and involved careful examination of the soil around the root of each plant; all eggs were collected and preserved for species identification. Eggs were separated as *D. radicum* and *D. platura / D. florilega* using the keys of Brooks (1951).

### 5.3.2 Diversification studies: 2003 & 2004.

Details pertaining to site and plot preparation for the diversification studies are available in Chapters 3 and 4. The host brassica used was cauliflower (var. Fremont). Egg sampling involved removing soil from around the base, 5 cm radius, 2 cm deep, of each cauliflower sampled and placing it into 250 ml plastic containers. The area was then filled in with surrounding soil. Eggs were sampled during peak oviposition on the following dates: 23 June, 27 June and 2 July (2003) and 18 June, 22 June, 27 June, 1 July and 6 July (2004). Eggs were removed from the soil samples by flotation and identified to species using the keys of Brooks (1951).

### 5.3.3 Day Degree Accumulations.

Day degree accumulations (ADD) for all years were calculated using max-min daily temperatures, beginning in March, using Environment Canada's weather data collected at the AAFC Research Centre in St. John's, NL. Calculations used a base development temperature of 4.4°C (Coady and Dixon 1997).

## 5.4 Results

### 5.4.1 Date of first oviposition.

*Delia radicum.* Over the two years of the diversification studies *D. radicum* eggs were present on the date of first egg sampling, 23 June and 18 June in 2003 and 2004 respectively. These dates corresponded with ADDs of 250.8 and 276.1 (Table 5.1).

The date of first oviposition of *D. radicum* in the early 1950s ranged from 14 June (1952) to 30 June (1953); approximately two weeks difference. Day degree accumulations indicate that during the 1950s eggs first appeared in the samples when ADD's were between 164.5 and 292.4 (Table 5.1).

*Delia platura / Delia florilega.* Eggs of *D. platura / D. florilega* were also present on the first sampling dates in 2003 and 2004, 23 June and 18 June respectively, corresponding to ADDs of 250.8 and 276.1 (Table 5.1). Of the five years of egg collection in the 1950s the earliest that *D. platura / D. florilega* were detected was on the 30 June in 1954, corresponding to an ADD of 322.2 (Table 5.1). The average date of first collection was 12 July with a mean (± SEM) ADD of 349.5 ± 15.6.

**Table 5.1: Date of first incidence of *Delia* spp. eggs in the 2003 & 2004 diversification experiments compared to life history data from the early 1950s and accumulated degree days ($ADD_{air}$) using a base threshold of 4.4°C.**

| Year | *Delia radicum* | ADD | *Delia platura / Delia florilega* | ADD |
|---|---|---|---|---|
| 2004 | 18 June | 250.8 | 18 June | 250.8 |
| 2003 | 23 June | 276.1 | 23 June | 276.1 |
| 1955 | 29 June | 202.2 | 11 July | 353.0 |
| 1954 | 16 June | 164.5 | 30 June | 322.2 |
| 1953 | 30 June | 292.4 | 8 July | 358.9 |
| 1952 | 14 June | 166.2 | 12 July | 400.8 |
| 1951 | 15 June | 171.7 | 3 July | 312.4 |

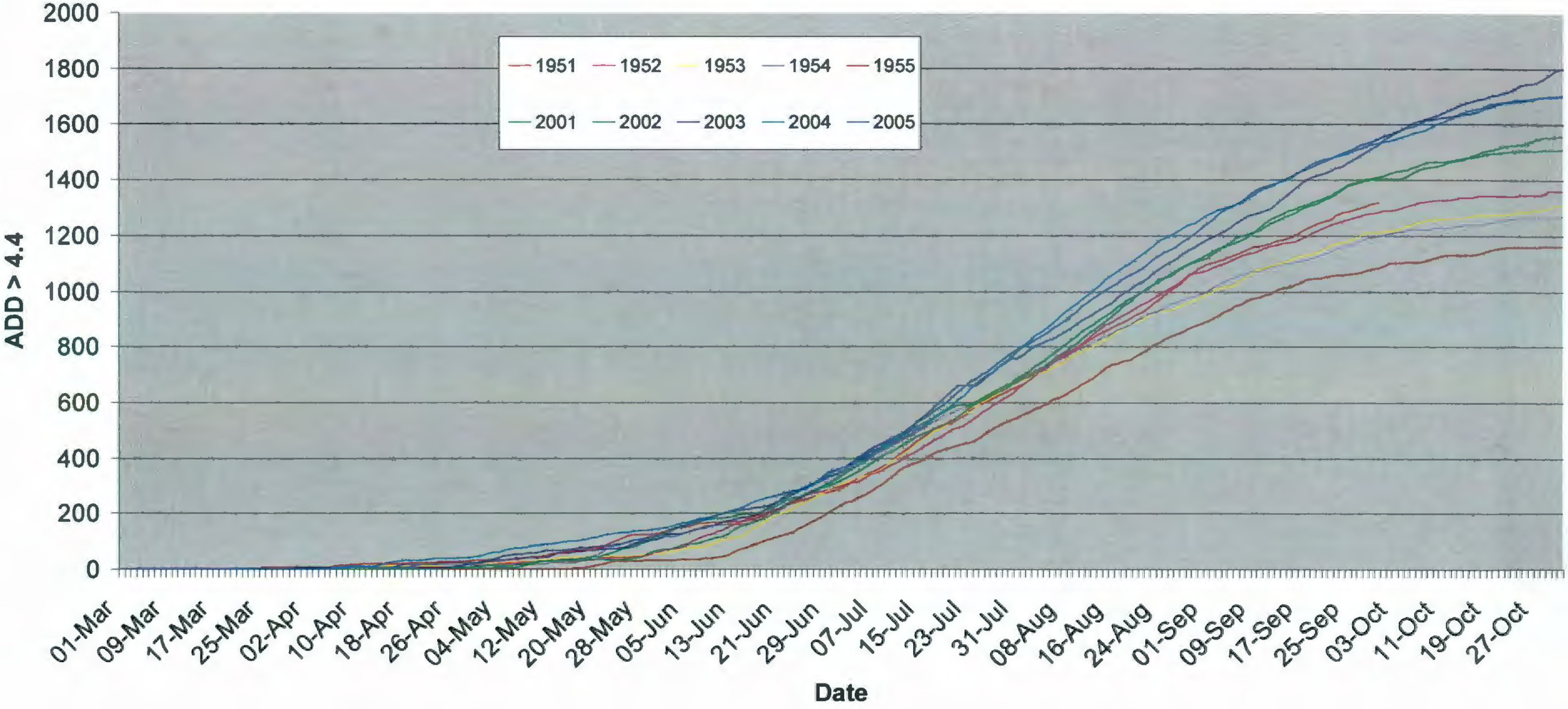

**Figure 5.1**. Accumulated day degrees (ADD) above base temperature 4.4°C from 1951-1955 and 2001-2005.

### 5.4.2 Day Degree accumulations.

The pattern of day degree accumulations during 2001-2005 differed from that in the early 1950s (Fig. 5.1), particularly in the increase in total day degrees accumulated during a growing season (defined as the ADD 1 March – 31 Oct, except for 1955 where weather data were only available until 3 Oct). During the course of collecting the life history data in the 1950s, there was a minimum of 1162.6 DD accumulated in 1955 to 1358.9 DD in 1951. This is in contrast to the early 2000's, where the ADD ranged from 1508 DD in 2002 to 1800.1 DD in 2003. Spring temperatures, which would influence insect emergence dates, were slightly cooler during the early 1950s compared to the early 2000s. The five years with the least ADDs accumulated by mid-June, were 1951, 1953, 1954, 1955 and 2001 (Fig. 5.1).

### 5.4.3 Species proportions.

The data from the early 1950s indicate that the majority of eggs collected from the base of cabbage plants grown in monoculture were *D. radicum* with less than 10% of the eggs identified as *D. platura* / *D. florilega* (Fig. 5.2). This is in contrast to the species proportions observed in the diversification studies of 2003 and 2004. Eggs from the bare ground cauliflower plots of the diversification studies show that the proportion of eggs belonging to *D. radicum* and *D. platura* / *D. florilega* varied depending on diversification study (undersowing or relay cropping in 2003), and between years in the relay cropping experiments (Fig. 5.2). Eggs collected from cauliflower in the bare ground control of the relay cropping trial were predominately *D. radicum* compared to eggs collected from cauliflower in the bare ground control plots of the undersowing trial in 2003 and the relay cropping control plots of 2004 which were predominately *D. platura / D. florilega* (Fig. 5.2).

### 5.4.4 Species composition in diversification studies.

*Relay cropping cauliflower with lettuce.* The relay cropping experiment of 2003 yielded species proportions that were similar over all three dates and between cropping treatments. There were approximately 80% *D. radicum* and 20% *D. platura / D. florilega* (Fig. 5.3a & b).

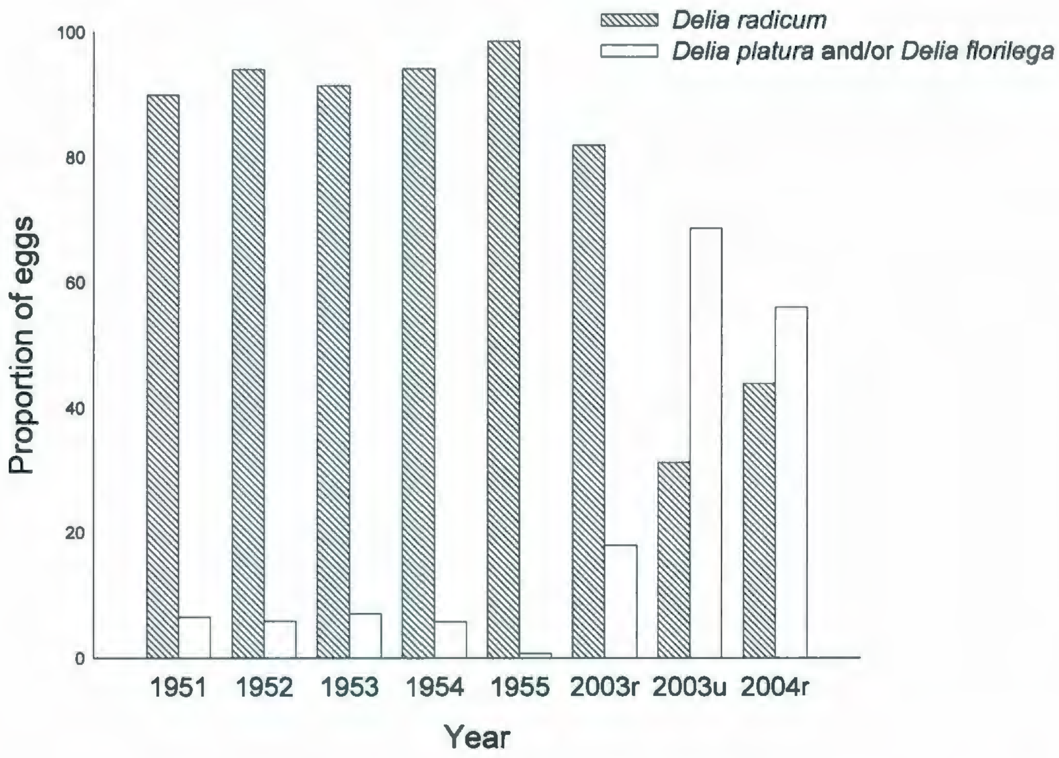

**Figure 5.2.** Proportion of eggs identified as *Delia radicum* or *D. platura* / *D. florilega* collected from cabbage plants grown in monoculture 1951-1955 and from cauliflower monoculture control plots in diversification studies of 2003 and 2004. (r= relay cropping diversification study; u= undersowing diversification study)

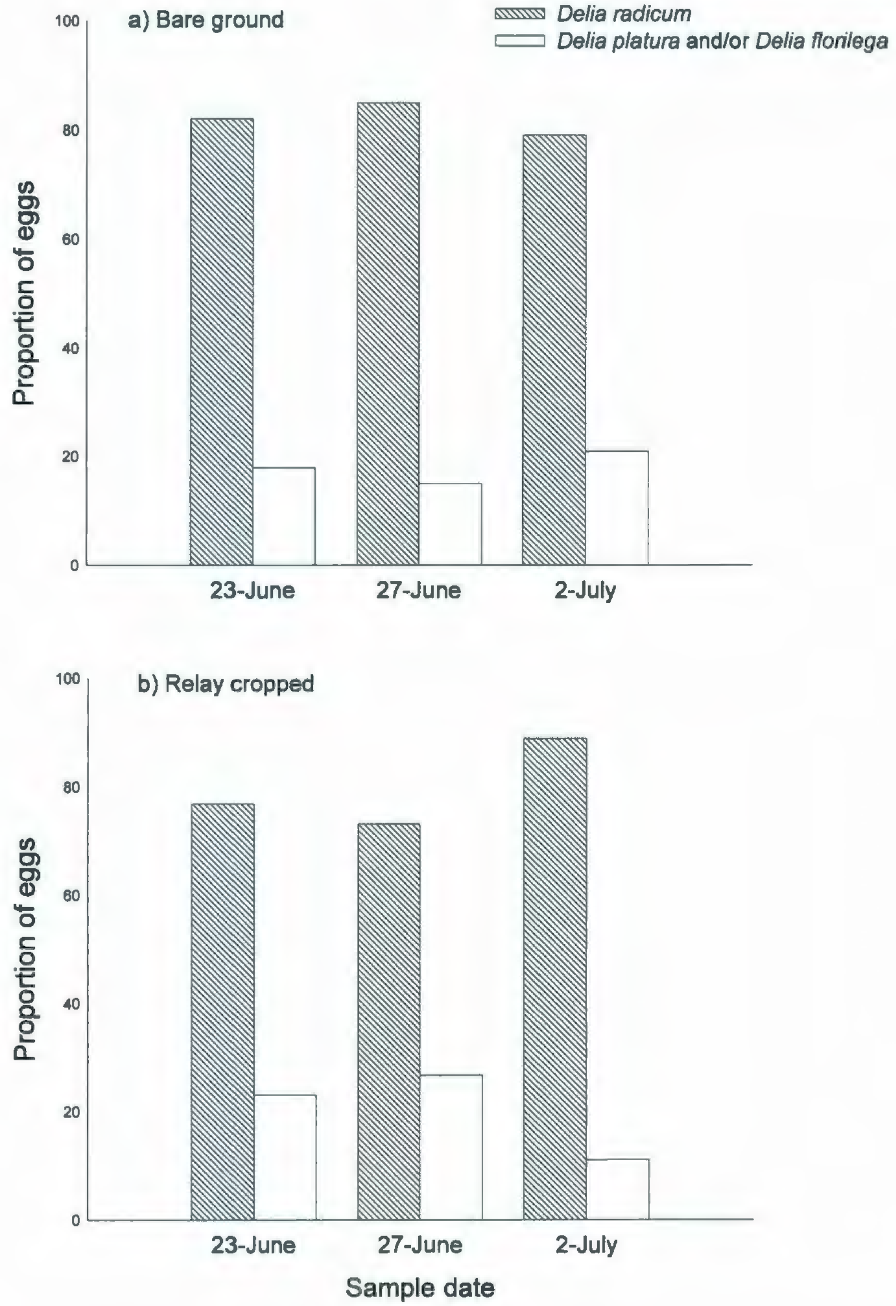

**Figure 5.3.** Proportion of *Delia radicum* or *D. platura / D. florilega* eggs collected from cauliflower grown in a) bare ground and b) relay cropped with lettuce, over three sample dates in 2003.

In 2004, however, there were differences in species proportions both over the sampling dates and between treatments (Fig. 5.4a & b). In the relay cropped plots, the eggs collected from the cauliflower on all sample dates were predominately *D. platura / D. florilega*, with *D. radicum* composing at most, 32% of the total eggs collected (July 1, Fig. 5.4b). The proportions of eggs collected in the bare ground plots also contained more *D. platura / D. florilega* except on 27 June and 1 July when there were more *D. radicum* (Fig. 5.4a).

*Undersowing cauliflower with winter wheat.* In the undersown plots in 2003 approximately equal numbers of *D. radicum* and *D. platura / D. florilega* eggs were collected from cauliflower in both cropping treatments on 23 June (Fig. 5.5a & b). On the next two sample dates, 27 June and 2 July, the majority (80-90 %) of the eggs collected from the bare ground and undersown cauliflower were *D. platura / D. florilega* (Fig. 5.5a & b).

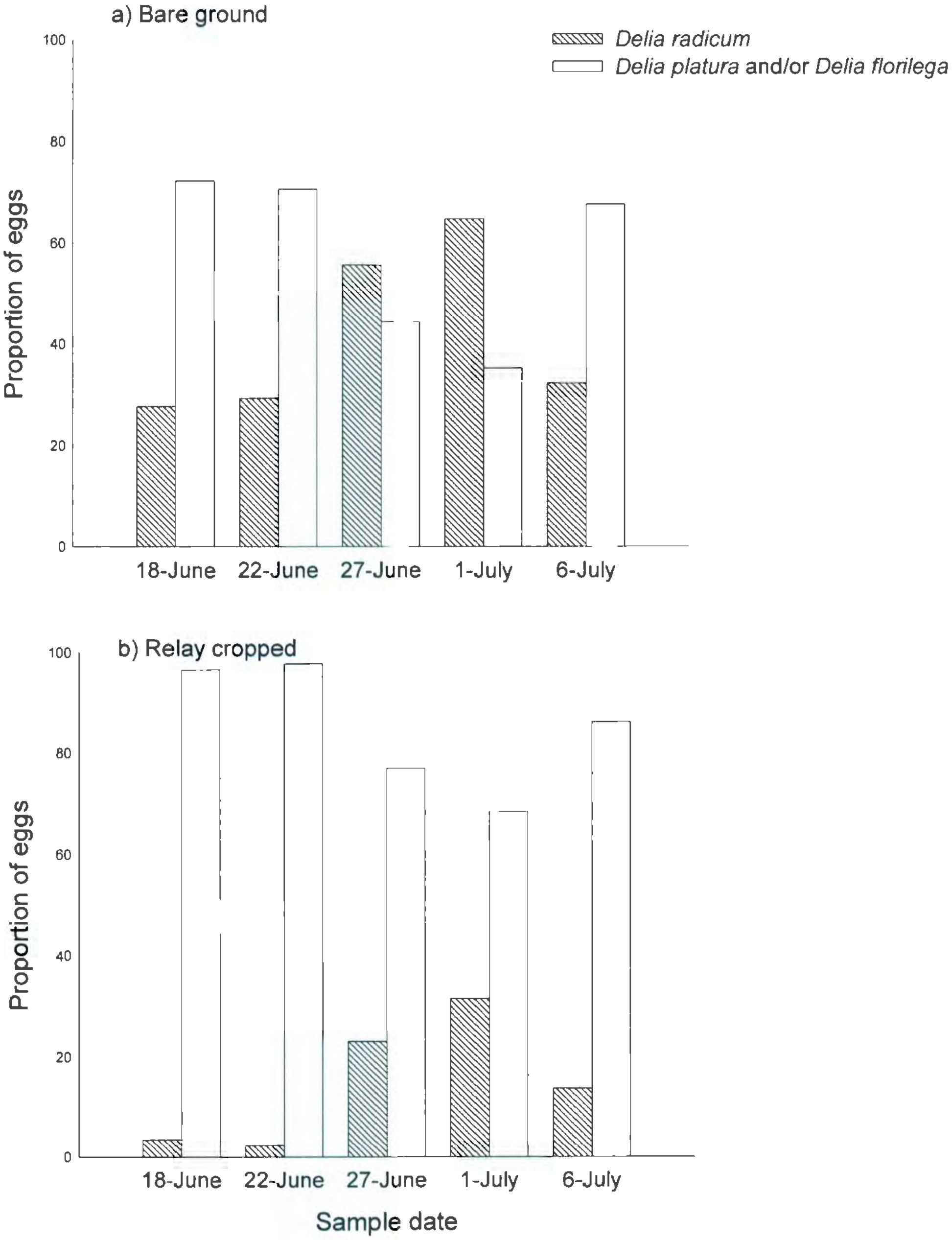

**Figure 5.4.** Proportion of *Delia radicum* or *D. platura* / *D. florilega* eggs collected from cauliflower grown in a) bare ground and b) relay cropped with lettuce, over five sample dates in 2004.

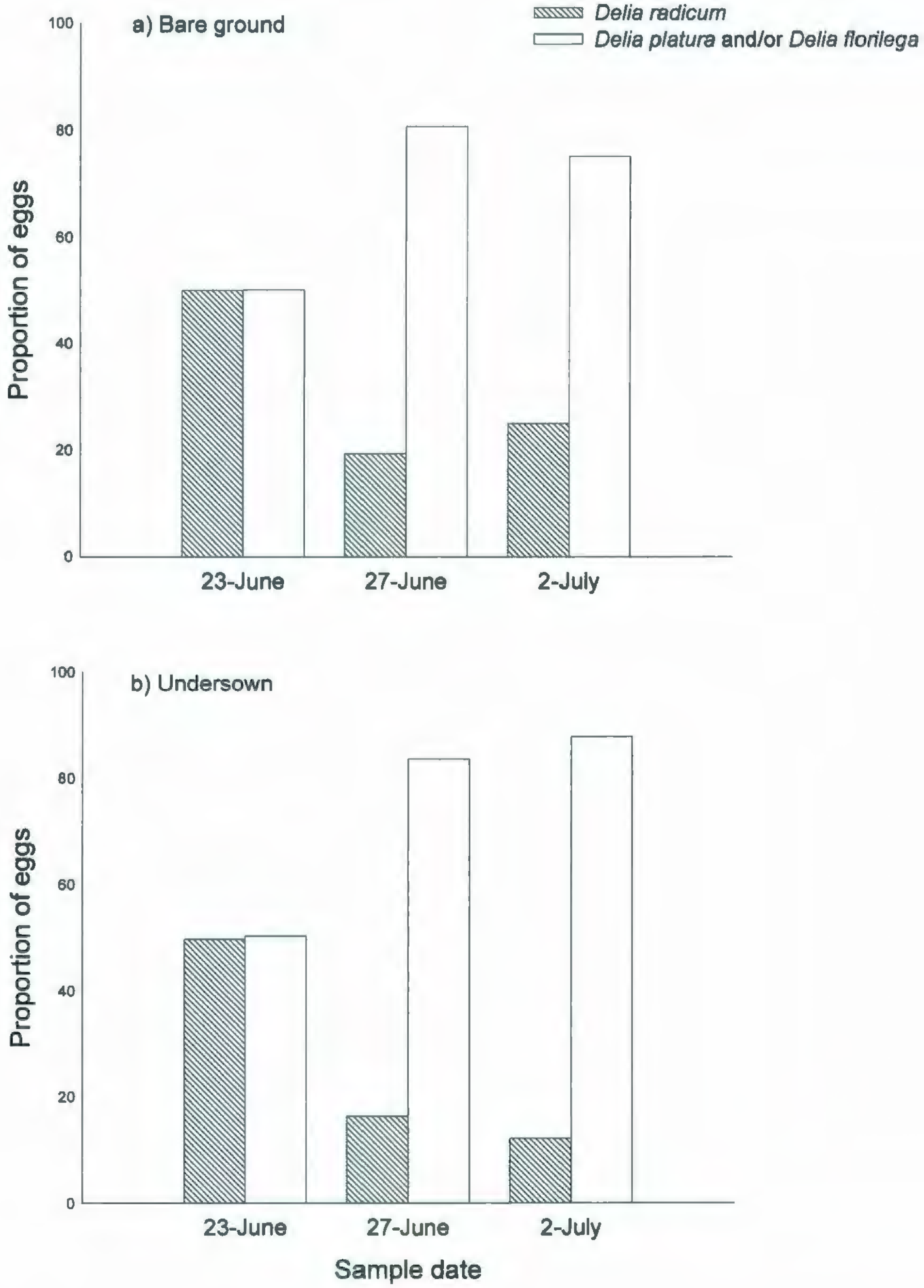

**Figure 5.5.** Proportion of eggs identified as *Delia radicum* or *D. platura* / *D. florilega* collected from cauliflower grown in a) bare ground and b) undersown with winter wheat, over three sample dates in 2003.

### 5.4.5 Abundance in diversification study experiments.

There were more *D. radicum* than *D. platura / D. florilega* eggs in 2003, with 12.97 ± 0.84 eggs per cauliflower as compared to 2.89 ± 0.31 *D. platura / D. florilega* eggs per plant. In 2004, the opposite was true with more *D. platura / D. florilega* eggs, 4.05 ± 0.18 eggs per plant, compared to *D. radicum* with 1.83 ± 0.16 eggs per plant.

## 5.5 Discussion

The date of first recorded oviposition of *D. radicum* in the two years of the diversification studies corresponded to predicted peak flight activity of the cabbage maggot in Newfoundland (Coady and Dixon 1997). Peak flight activity is approximately 220 ADD above base 4.4°C. In both years there were *D. radicum* eggs present on the first sample dates with corresponding ADDs of 276.1 and 250.8 in 2003 and 2004 respectively. Although the model uses 220 DD as a prediction of peak flight activity it is expected that egg laying will begin shortly after this period as the flies usually mate at 4 - 6 days of age (Swailes 1961). The data from the 1950s indicate that ADDs at the time of first oviposition ranged from 164.5 in 1954 to 292.4 in 1953 with a mean ADD of 199.4. The DD accumulations when first *D. radicum* eggs were detected are slightly less in the early 1950s than in 2003 and 2004; except for 1953 when eggs were not detected until 292.4 DD had accumulated corresponding to a calendar date of June 30. A cool spring in 1953 would have both delayed and prolonged emergence and thus oviposition.

Although the ADD of first egg detection in 2003 and 2004 are slightly higher than the early 1950s it is possible that the date of first oviposition during the course of the diversification studies was missed. The life history studies of the early 1950s were designed specifically to look at the life history of *D. radicum* in cabbage under usual production protocols of the region at the time. As a result egg sampling was initiated with intent to capture the beginning of the oviposition period of the different species. In the diversification experiments conducted in 2003 and 2004, the primary purpose was to determine differences in oviposition by the cabbage maggot as a result of changes in within-field diversification. Sampling was intended to catch the peak oviposition and we do not know whether the first sampling dates were the actual dates of first oviposition. According to the ADDs however, first emergence was probably just a couple of days before the sampling period began and thus a close approximation of the date of first oviposition.

The date of first oviposition of *D. platura* and *D. florilega* was later in the season in the early 1950s than in 2003 and 2004. Eggs of these species in 2003 and 2004 were present on the first sampling dates, 23 and 18 June respectively, with 250.8 and 276.1 ADD. During the 1950s, eggs of these species were not observed on cabbage, until approximately a month later after an additional 100 DD had accumulated. Data from the Czech Republic (Kostal 1992) also suggests an earlier activity period for *D. platura* and *D. florilega*; the onset of activity for *D. radicum* in the Czech Republic is 185 ± 31.8 DD compared to 156 ± 10 and 118 ± 41.5 DD for *D. platura* and *D. florilega,* respectively. Kostal's (1992) data were collected using yellow water pan traps, sticky traps and a base temperature of 6°C for Degree Day calculations. Although there were different methods used, the study demonstrates that the latter two species began activity earlier than *D. radicum* similar to what has been observed during 2003 and 2004 in Newfoundland.

It should be noted that the life history studies of the 1950s and the diversification studies of the 2000s measured oviposition, not fly emergence. The later detection of *D. platura* / *D. florilega* oviposition observed in the early 1950s could be a consequence of the flies having to travel further to find oviposition sites as source populations could have been some distance away; however this is not known as cropping history at the AAFC Research Centre during this time is not well documented. The 2003 and 2004 diversification studies were in an area that regularly used green manures and it is known that fields with decomposing organic material are suitable for oviposition of these species (Miller and McClanahan 1960). It is possible that in 2003 -2004 the surrounding area had a large source population of *D. platura* / *D. florilega* flies present and once the cauliflower were transplanted the flies subsequently used this as a host plant.

There was a higher proportion of *D. platura* / *D. florilega* eggs collected from the bare plots in 2003 and 2004 diversification studies compared to the eggs collected during the life history studies of the 1950s. These species comprised less than 10% of the total eggs collected in 1951 through to 1955. Although in the 2003 relay cropping study there were greater proportions of *D. radicum* eggs collected in the bare plots, *D. platura* / *D. florilega* eggs still constituted 20% of the total eggs collected. It is possible that a larger source population of *D. platura* / *D. florilega* in 2003-2004 could also have contributed to this change in root maggot species composition.

In 2003 there were differences in the species composition between the relay cropping and undersowing diversification studies. The egg samples in the relay cropping study were composed predominately of *D. radicum* eggs; however, less than 100 m away in the undersowing experiment, the eggs were predominantly *D. platura* / *D. florilega*. The primary difference between the experimental set-ups was the placement of the organic amendments used as a fertility source. In the relay cropping study the organic amendments, fish meal, bone meal and kelp meal, were broadcast by hand and rototilled into the entire plot before transplanting. In the undersowing experiment, however, the amendments were placed directly into the transplant furrow and a small volume of soil was scratched into the bottom of the furrow before transplanting of the cauliflower. This direct placement of the organic amendments close to the root system of the cauliflower may have increased the number of *D. platura* / *D. florilega* attracted to and ovipositing on the cauliflower in this area. These amendments and/or the decomposition of these amendments may create conditions favorable to ovipositing *D. platura* / *D. florilega* females. Fish meal, for example, is often used in the rearing media for *D. platura* (Harris et al. 1966). The broadcasting of the amendments and deep incorporation through rototilling would disperse the amendments throughout a greater volume of soil and make them less concentrated and presumably less noticeable to the female flies seeking suitable oviposition sites. *Delia platura* and *D. florilega* also have been known to mine the roots of cereals (Griffiths 1993) and it is possible that these species were attracted to the winter wheat used in the undersowing plots.

The 2003 and 2004 relay cropping study also revealed differences in total abundance of each species depending on year. *Delia radicum* egg numbers were higher than *D. platura* / *D. florilega* in 2003; however in 2004, the opposite was true with more *D. platura* / *D. florilega* eggs per plant, compared to *D. radicum.* There were no obvious differences in weather, plot preparation or distance to source populations that readily explain these differences. Spring temperatures and rainfall were similar; the experiments were conducted in different areas of the same field, set-up using the same production protocols and there would have been source populations of all species in the area. The increased occurrence of *D. platura* and *D. florilega* however, cannot be overlooked. There have been several reports from across Canada that damage by the seed corn maggot complex is increasing (J. Broatch and M. Roy, pers. comm.). In order to develop sound IPM systems for *D. radicum* we may instead need to focus on IPM systems for *Delia* spp. which will entail a greater understanding of how the three species co-exist together.

Damage to brassica crops by *D. platura* and *D. florilega* was once thought to occur following primary invasion by *D. radicum* (Brooks 1951, Miles 1952), however primary attack does occur by these species and they are capable of surviving and completing development on brassicas in the absence of *D. radicum* (Nair and McEwen 1973, Noronha 1992). Sympatric species occupying the same ecological niche often have specific strategies to reduce competition for the common resource. In the case of the brassica feeding root maggots, *D. radicum, D. platura* and *D. florilega*, these strategies have not been well investigated. Noronha (1992), however, investigated interspecific competition between *D. radicum* and *D. platura* under laboratory conditions and demonstrated that these two species will oviposit on the same plant when present in a mixed population with no effect on either female fecundity or the time to 50% oviposition as compared to single species populations.

*Delia floralis* (Fallén) is another closely related species that is often present in mixed populations with *D. radicum* in other parts of the world. Certain populations of *D. radicum* and *D. floralis* have shown bimodal emergence patterns, in which a proportion of the population will emerge earlier or later than others within the population. Biron et al. (2003) have speculated that this adaptation may be a strategy to reduce interspecific competition between sympatric species feeding on the same plant. Bimodal emergence has been documented in Newfoundland populations of *D. radicum* (Dixon, unpublished); however investigations into emergence and oviposition patterns of *D. platura* and *D. florilega* have not been done. Detailed studies of how the presence of one or more *Delia* spp. affects the other under field conditions are warranted.

The increased occurrence of *D. platura* and *D. florilega* feeding on vegetable brassicas warrants further investigation. With the interest in more ecologically based production and pest management practices these species may prove to play a larger role in brassica production than they have in the past. Root maggot management may have to switch from a focus on *D. radicum* to inclusion of all *Delia* spp. present in a particular geographic region. Detailed knowledge of how these species co-exist and compete for a common resource is needed as well as further investigation into how each responds to changes in crop production practices. In order for an integrated pest management program to be successful, it is imperative that the life history and ecology of the pest species be fully understood. In the case of the cabbage maggot, *D. radicum*, the presence of the sympatric species *D. platura* and *D. florilega*, and the life histories of these species in a particular region may influence the management strategies employed.

The ability to predict the emergence and oviposition times of the cabbage maggot, *D. radicum*, has been a major advance in the management of this pest. Day degree models are used to predict emergence and peak activity times, to adjust planting and harvesting schedules, and to time application of insecticides and the placement of row covers. In many regions, however, the presence of sympatric species may complicate forecasting as an effective pest management tool. All three of the root maggot species discussed, *D. radicum, D. platura* and *D. florilega* are known to exist in different proportions and have varying life histories depending on geographic region (Matthewman et al. 1950, Kostal 1992, Coady and Dixon 1997, Dreves et al. 2006). Therefore it is not always appropriate to assume similar emergence times between regions and regional assessments of population differences are required. Also, it may be necessary to revisit these emergence and peak activity times as changes in climatic conditions over time may limit their effectiveness as monitoring tools.

## 5.6 Literature cited

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# Chapter
# 6

# Summary, conclusions and future directions

## 6.1 Summary

The importance of increasing diversity in agricultural systems, especially from a pest management perspective, has long been recognized (Gliessman 1998, Nicholls and Altieri 2004). Although populations of many insect pest species are reduced when crop plants are grown in diverse cropping situations, responses to diversification need to be assessed on a local level (Nicholls and Altieri 2004). In a general sense, the development of ecologically based pest management strategies such as plant diversification have become more important as we search for alternatives to current insecticide based systems.

*Delia radicum,* the cabbage maggot, is an introduced economically important pest of brassica crops in Newfoundland and Labrador, and has been extensively studied throughout its range. The host finding process used by the female fly is well understood and the behaviours associated with successful location of suitable oviposition sites well documented (Finch and Collier 2000, Baur et al. 1996). This detailed knowledge has enabled pest management specialists to exploit these behaviours to their advantage and develop crop production methods that reduce the probability that the female will find her host plant.

This thesis explores the use of agroecosystem diversification as a pest management tool for *D. radicum*. The effect of intercrop species and intercrop size on *D. radicum* egg laying was first examined in cage studies (Chapter 2). The purpose of this study was to find an efficient method to screen suitable crops for use in field application. However, unforeseen issues with weather and insect rearing resulted in large variation and low sample sizes for statistical analyses which in turn affected the ability to detect differences between intercrop treatments. Despite these problems the trends observed were that cauliflower plants surrounded by lettuce consistently had fewer eggs than cauliflower surrounded by bare ground. Also, intercrop size influenced the numbers of eggs laid by *D. radicum*, with larger intercrops reducing egg laying to the greatest degree.

Another question to be addressed in using diversification as a pest management tool for the cabbage maggot is how to avoid reduced yields often associated with competition between the component plant species (Theunissen et al. 1995, Dixon et al. 2004). Hooks and Johnson (2003) suggest five possible solutions to reduce yield loss due to competition. They are: 1) proper fertilization and water management, 2) use of vigorous / rapidly growing cultivars, 3) optimal spacing, 4) adjusting planting times of the component crops and 5) suppression of background vegetation (mowing, rototilling). The winter wheat undersowing study (Chapter 3) examined competition by sowing winter wheat in the spring as well as by changing from broadcasting the winter wheat in 2002 to row seeding in 2003. Broadcasting the winter wheat resulted in no marketable cauliflower being produced in 2002. *Delia radicum* egg numbers were reduced in 2003, but the competition still prevented the production of any marketable cauliflower yield in the undersown plots. Whether rototilling or ploughing under the winter wheat after peak egg laying would have improved cauliflower yields is a question that needs to be addressed.

The relay cropping study (Chapter 4) addressed the question of competition via adjusting the planting and harvesting times of the component crops. Planting lettuce in the field with the cauliflower reduced the numbers of eggs laid by *D. radicum*. After peak egg laying by the first-generation *D. radicum* the lettuce was harvested.

Cauliflower yields were not compromised in the relay cropped plots and the lettuce provided a second crop off of the same area of land.

Further findings during the course of the field studies showed that the co-existence of *D. platura / D. florilega*, two sympatric root feeding species, may influence the use of agroecosystem diversification as a management tool for *D. radicum*. The effect of diversification on *D. platura / D. florilega* was explored in Chapter 5; where examining available data from the early 1950s provided the opportunity to explore the possible changes in species composition over time. The date of first oviposition of *D. platura / D. florilega* was later in the 1950s than in the early 2000s. It also appears that these species may be becoming more abundant than in the 1950s, however further work is needed to verify this.

## 6.2 Conclusion

The results from this thesis demonstrate that it is possible use agroecosystem diversification as a means to manage the cabbage maggot, *Delia radicum*. However, careful selection of the component crops is needed to avoid competition. Relay cropping cauliflower with lettuce reduced oviposition but did not affect cauliflower yields. It is necessary, however, to take into account the specific agroecological situation of the region. *Delia platura / Delia florilega* are two sympatric species that played a minor role in the pest complex associated with *Brassica* crops in Newfoundland under conventional monoculture management. This study demonstrates that these two species may have to be considered when switching to an organic and/or diverse cropping situation.

Diversification shows promise as a suitable management tool for cabbage maggot in leafy Brassicas.

### 6.3 Future directions

The unexpected presence and abundance of *Delia platura* and *D. florilega* encountered during the course of these studies highlights the importance of understanding how changes in production practices will affect all key pests within a particular pest complex. It is not known whether *Delia platura* and *D. florilega* were more abundant because organic management practices were used, whether they are becoming more abundant on Brassicas in this region, or whether this reflects normal population variation over time. A closer investigation into the life history of these species on Brassicas in this region is warranted.

Research is also needed on how diversification will affect other key pests of Brassicas as well as their natural enemies. In many cases response to diversification by both pests and natural enemies depends upon the specific host finding mechanisms used by the insects.

Before relay cropping can be adopted on a commercial level research is needed to assess how this cropping practice will fit with the production practices used by local farmers.

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