

**THE EFFECT OF TILLAGE AND SEEDING RATE ON INFESTATIONS OF
CABBAGE ROOT MAGGOTS, *DELIA RADICUM* (L.)
(DIPTERA: ANTHOMYIIDAE) IN CANOLA, *BRASSICA NAPUS* (L.), IN
MANITOBA**

**A Thesis
Submitted to the Faculty**

of

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by

Amy K. Hawkins-Bowman

**In Partial Fulfillment of the
Requirements for the Degree**

of

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The Effect of Tillage and Seeding Rate on Infestations of Cabbage Root Maggots, *Delia radicum* (L.) (Diptera: Anthomyiidae) in Canola, *Brassica napus* (L.), in Manitoba

BY

Amy K. Hawkins-Bowman

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of
Manitoba in partial fulfillment of the requirement of the degree

Of

Master of Science

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Dedication

I would like to dedicate this document
to my husband, Patrick and
to my two bright and wonderful children, Katie and Elias.

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Abstract

Amy Hawkins-Bowman. University of Manitoba, 2005. **THE EFFECT OF TILLAGE AND SEEDING RATE ON INFESTATIONS OF CABBAGE ROOT MAGGOTS, *DELIA RADICUM* (L.) (DIPTERA: ANTHOMYIIDAE) IN CANOLA, *BRASSICA NAPUS* (L.), IN MANITOBA**

Advisor: Dr. N.J. Holliday

Delia radicum (L.) is an important pest of canola on the Canadian prairies, feeding on the roots of canola and other Brassica crops. In both vegetable and canola crops *D. radicum* can cause significant yield losses. Natural controls, predators and parasitoids, have not been reducing the populations sufficiently to prevent yield losses in canola. No insecticides are registered for use on *D. radicum* in canola. Agronomic practices may be the best method of reducing yield loss associated with this pest.

Two management practices tillage treatment and seeding rate were applied to experimental fields of canola at the Carman Research Station in Manitoba. Tillage treatment was applied as zero tillage or conventional tillage. Seeding rate treatment was applied as high or low seeding rates. Results show that zero tillage systems have lower root damage ratings then conventionally tilled systems in Manitoba. Also that lower seeding rates have lower root damage ratings then higher seeding rates in Manitoba.

Currently in Manitoba, *D. radicum* is not affecting yield. This study supported the recommendations that zero tillage or minimal tillage should be implemented when growing canola in Manitoba and canola should be seeded at higher rates to reduce damage associated with this pest.

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Chapter I: Introduction

Canola became the recognized name for low erucic acid rapeseed in 1980 (Daun 1986). This name has been registered across the world and the crop is now important in many countries (Daun 1986). Specifically, canola is a vital part of the Canadian agricultural economy and since 1983, more than 90% of the rapeseed grown in Canada meets the canola requirements. *Brassica napus* (L.) is the predominant species of canola grown in the Eastern Prairies. Canola oil is used for human consumption, and canola meal is used as a feed supplement for livestock, including cattle, pigs, and chickens (Daun 1986).

The first report of cabbage root maggot, *Delia radicum* (L.) on oilseed rape in Manitoba was in 1958 (Allen 1964). Since this time, the area seeded to canola has increased and reports of cabbage root maggot in canola have also increased. Research on cabbage root maggots on canola in Manitoba has not been exhaustive; however since the early 1990s research has been occurring in Alberta (Dosedall *et al.* 1998). While yield losses are not commonly associated with this pest in Manitoba (Turnock *et al.* 1992), they are of great economic significance in Alberta (Dosedall *et al.* 1994). Surveys of this pest in canola have shown that 96% of fields surveyed in Manitoba and Saskatchewan were infested by cabbage root maggots (Soroka *et al.* 2004).

The cabbage root maggot is a common pest of many vegetable brassica crops, such as, broccoli and rutabaga. In Manitoba, there is only one pesticide registered for use on this pest and only in vegetable crops (Manitoba Agriculture, Food and Rural Initiatives 2005). With no registered insecticides to control *D.*

radicum in canola it is necessary to find other methods to help reduce yield loss resulting from root maggot infestations.

Over the past twenty-five years, agronomic methods have changed. Zero tillage has been recommended to producers as a way to reduce soil erosion, lower fuel consumption and improve soil moisture retention (Borstlap and Entz 1994). Research has been conducted in Alberta for the past decade to determine how management practices affect populations of cabbage root maggot in canola (Dosdall *et al.* 1998 and 2003). Minimal research has been conducted in Manitoba to explore the effects of agronomic practices on cabbage root maggot.

Changing plant density can affect many different levels of agro-ecosystems, potentially altering carabid abundance and movement, cabbage root maggot oviposition, and crop yield, to name a few (Dosdall *et al.* 1996b). In Alberta, research has been conducted on the effects of seeding rate and row spacing on cabbage root maggot damage (Dosdall *et al.* 1998). Results from these and other studies show the potential importance of plant density on populations of cabbage root maggots (Dosdall *et al.* 1998; Finch *et al.* 1976).

The need for research conducted under Manitoba conditions on cabbage root maggots in canola led to the development of this study. The overall objectives for this research were three fold:

1. Develop a better understanding of the effects of tillage and seeding rate on immature *Delia radicum* infestations and the subsequent

changes (if any) of root damage ratings, yield and seed quality for canola in Manitoba;

2. Develop a better understanding of the effects of tillage and seeding rate on mature *D. radicum* numbers in canola in Manitoba;
3. Develop a better understanding of the effects of tillage and seeding rates on the numbers of predators of *D. radicum* in canola in Manitoba.

Chapter II: Literature Review

INTRODUCTION

Delia radicum (L.) is a member of the order Diptera (true flies) and the family Anthomyiidae and is commonly known as cabbage root maggot or cabbage maggot (Griffiths 1991a). Diptera are one of the largest orders of insects and can be distinguished from other insects by the presence of only one pair of functional flight wings, the front wings (Borror *et al.* 1989). For a detailed description of this order and the family Anthomyiidae please refer to Borror *et al.* (1989).

Throughout the Holarctic region, *Delia* spp. are pests of cruciferous crops (Dufault and Sears 1982) or phytophagous on other plant species (Griffiths 1991a). A large number of publications have been written regarding root maggot attacks on a variety of host plants (Brooks 1951); many of these papers concern *Delia radicum* (Linnaeus) (Diptera: Anthomyiidae). This pest feeds on a number of crop plants including: rutabaga, cauliflower, cabbage, and oil seed rape (Bracken 1988; Liu and Butts 1982; Miles 1952; Nair and McEwen 1975).

Delia radicum has four life stages: egg, larva, pupa, and adult . Damage to brassica crops is caused by the three larval instars feeding, primarily but not exclusively, on the roots. To understand the significance of this pest in western Canada, it is essential to understand the status of the pest across the northern hemisphere. In this review I strive to develop a better understanding of the

ecology, the wide variety of potential control tactics, and the status of the pest's effects on horticultural crops and canola (oil seed rape) in western Canada.

ROOT MAGGOTS

***Delia* spp. in Canada**

Three major economic pest *Delia* spp. (Griffiths 1991a) will be discussed: *Delia radicum* (Linnaeus), *Delia floralis* (Fallén), and *Delia planipalpis* (Stein). *Delia radicum* originated in Europe and was introduced to North America (Griffiths 1991a). In the early 1950s, *D. radicum* had been reported in 8 out of the 10 provinces (Brooks 1951). As of the early 1990s populations of *D. radicum* were present in all 10 provinces in Canada (Griffiths 1991a). The apparent changes in distribution could be attributable to a change in host and the expansion of area in which host crops are grown. The natural enemies and voltinism for *D. radicum* will be discussed in more detail later in this review.

Delia planipalpis has been recorded in Alberta, British Columbia, Manitoba, Northwest Territories, Ontario, Saskatchewan and Yukon (Griffiths 1991a). The principal host of this root maggot is radish (*Raphanus sativus* L.); however, it has been found on many other brassica crops (Kelleher 1958), including cabbage, canola, cauliflower, rutabaga, mustard, Brussels sprouts, and turnip (Griffiths 1991a). This root maggot is considered native to western North America because it occurs in areas remote from cultivation as well as in agricultural regions (Griffiths 1991a). It is parasitized and preyed on by the same

species of Coleoptera as *D. radicum* (Kelleher 1958). *Delia planipalpis* may have three generations per year in the southern portion of its range; however it is univoltine in the more northern portion of the range (Kelleher 1958).

Delia floralis has been recorded in Alberta, British Columbia, Labrador (Newfoundland), Manitoba, Northwest Territories, Ontario, Quebec, Saskatchewan, and Yukon (Griffiths 1991a). Host plants of this species are mostly the same as those of *D. radicum* and *D. planipalpis*. Some weed plants have been listed as hosts for *D. floralis*: *Thlaspi arvense* (L.), stinkweed; *Sisymbrium altissimum* (L.); and *Brassica kaber* (DC)(Griffiths 1991a). Staphylinidae species found to parasitize *D. radicum* and *D. planipalpis* are also reported to be parasitoids for *D. floralis* (Griffiths 1991a). This root maggot is univoltine through out its North American range. The remainder of this review will focus on *D. radicum*.

DELIA RADICUM

Nomenclature

Linnaeus first described *Delia radicum* (Linnaeus) in 1758 as *Musca radicum* (Griffiths 1991a). Since that time, due to ignorance of Linnaeus' description, *D. radicum* has had seventeen different synonyms. Pont (1981) was the first to resolve this nomenclatural confusion (Griffiths 1991a). In most of the literature reviewed, three different names were used: *Hylemya* (*Hylemyia*) *brassicae* (Bouché), *Erioischia brassicae* (Bouché), and *Delia radicum*

(Linnaeus). For the purpose of this review *Delia radicum* will be used regardless of the nomenclature the author of individual papers used.

Biology

Adult *Delia radicum* feed on nectar from flowers to obtain energy and nutrients (Finch 1971). In western Canada on canola, *D. radicum* is generally univoltine or bivoltine (Turnock *et al.* 1992). On vegetables, this pest has been known to complete two or three generations in Manitoba, depending on how early the crop is sown and on weather conditions (Allen 1964, Bracken 1988). In Wellesbourne, England two generations are usually observed. Once diapause has been terminated a further 14 days at 20°C is needed for flies to emerge (Finch and Collier 1983). In parts of Canada such as in Ontario, Manitoba and Alberta, adult emergence begins in May and continues into June (Kelleher 1958; Nair and McEwen 1975); some degree of variation occurs in this timing depending on geographic location (Miles 1952; Nair and McEwen 1975; Turnock *et al.* 1992), and phenotypic polymorphism (Muona and Lumme 1981). Under laboratory conditions, emergence continues for 10-11 days (Whistlecraft *et al.* 1985).

In the field, mating occurs near the site of emergence and gravid females seek appropriate host plants and lay eggs at the base of brassica plants (Finch 1971; Finch and Skinner 1973). Male flies are either blown or actively disperse into areas with a greater amount of nectar producing plants (Finch and Skinner 1975). Females are not blown by the wind, but actively disperse in search of appropriate oviposition sites (Finch and Skinner 1975). Dispersal is upwind or at

a small angle to the wind (Finch and Skinner 1982a). Laboratory studies confirm that gravid females use upwind orientation and show that flight is stimulated by host plant odour plumes; this behaviour allows females to locate host plants (Hawkes *et al.* 1978). Under field conditions host plant odour also acts as an attractant and aggregator (Hawkes 1974). Female flies exhibit specific flight patterns once plants have been located, and contact and re-contact with the host plant is necessary to stimulate oviposition (Kostal and Finch 1994); to induce oviposition, plants must contain active glucosinolates (Nair and McEwen 1976). Isothiocyanates, which are break-down products of glucosinolates, are important in attracting females to the host plant (Nair *et al.* 1976). In Wisconsin, females will lay eggs for up to 21 days under field conditions (Eckenrode and Chapman 1971). In June, in Manitoba, six to seven days after adults emerge, oviposition in canola (oilseed rape, *Brassica napus* L.) begins and may continue for up to 3 weeks (Turnock *et al.* 1992). The time of oviposition depends on the crop, soil temperature, and accumulation of degree-days (Eckenrode and Chapman 1971; Whistlecraft *et al.* 1985). Females lay an average of 41 eggs over 16 days (Kelleher 1958) at the base of cruciferous plants. Females are more uniformly distributed throughout crops and disperse more actively than males (Finch and Skinner 1973).

Using what is known about oviposition requirements for *D. radicum*, research has been conducted on oviposition deterrents; these are chemicals that hinder the gravid female's egg laying choices (Jones and Finch 1987). These chemicals may be an important source of protection for vulnerable plants. One

such chemical was extracted from the frass of the garden pebble moth caterpillar, *Evergestis forficalis* (L.) and was found to deter oviposition when applied to any cruciferous plant species (Jones and Finch 1987). When monoterpenes, alone or blended with other chemicals were applied to rutabaga, oviposition was deterred. Some of the chemical blends used for this research were terpinolene, γ -phellandrene, and myrcene (Ntiamoah and Borden 1996). Long chain fatty acids act as oviposition deterrents; these may also provide some protection for vegetable fields (Cole *et al.* 1989). The presence of aphids also deters oviposition. Approximately 250 cabbage aphids, *Brevicoryne brassicae* (L.) or peach-potato aphids, *Myzus persicae* (Sulz.) on a brassica plant are sufficient to deter oviposition by *D. radicum*. While this may be an effect of alarm pheromones, it is more likely the result of physical disruption of host-plant selection for the flies. Gravid females probe the leaves of host plants before moving down the plant stem to lay eggs in the soil; when this probing was disrupted by physical contact with an aphid the fly would stop probing for a short period, preventing sufficient positive stimuli to induce oviposition (Finch and Jones 1989).

Time of egg hatching is a function of accumulated thermal units both in the soil and in the air (Eckenrode and Chapman 1972). Darker soils warm up faster in the spring, and accumulate thermal units faster than lighter coloured soils or those soils, such as on zero tillage fields, with crop stubble. These warmer soils, therefore, let eggs hatch earlier than lighter coloured soils or soils with crop stubble. In Manitoba on canola, hatch generally begins in the last week of June

or the first week in July (Allen 1964) and larvae proceed to develop through three instars.

Rate of larval development depends on temperature and quality of food source (Whistlecraft *et al.* 1985; Griffiths 1991a). Under standard rearing conditions ($19 \pm 1^{\circ}\text{C}$; $60 \pm 5\%$ RH; LD 16:8 h) larval development lasts 18-22 days (Whistlecraft *et al.* 1985). In fields of canola in Manitoba, female flies were collected in June and first-generation adults were found in August of that same year, and the duration of immature stages (egg-larva-pupa) totals approximately 2 months (Turnock *et al.* 1992).

The length of the pupal period is affected by diapause cues (Nair and McEwen 1975), thermal accumulation, and moisture (Whistlecraft *et al.* 1985; Eckenrode and Chapman 1971). In laboratory studies, newly hatched larvae were exposed to three different temperatures (10.5°C , 12°C and 14°C) and photoperiods of 10:14, 11:13, 12:12, 13:11, 14:10, and 15:9 h L:D to determine the effect of temperature and photoperiod on induction and duration of diapause (Johnsen and Gutierrez 1997). Pupae developing from these larvae were then held at 17°C and 16:8 h L:D until adult emergence. The number of individual pupae entering diapause was higher at shorter photoperiods across all temperatures and at low temperatures across all photoperiods. Diapause developmental time, the time required from diapause induction until adult emergence, increases with increasing temperature and decreases with increasing photoperiod. Johnsen and Gutierrez (1997) concluded that the effect of temperature on diapause induction is greater than the effect of photoperiod.

Diapause development requires lower winter temperatures. When the low temperatures begin in relation to photoperiod determines when adults will emerge in the spring (Collier and Finch 1983). Proximity of overwintering puparia to the soil surface does not affect mortality, during winters in the United Kingdom; however, if puparia are greater than 4 cm deep the emerging flies fail to reach the surface (Finch and Skinner 1980). Thermal unit requirements have been used to predict cabbage root maggot emergence and peak larval periods to develop better control programs (Eckenrode and Chapman 1971 & 1972).

In North America, *D. radicum* is found in gardens and cultivated lands (Griffiths 1991a). While feeding on the taproot of brassica plants, larvae construct tunnels; these tunnels may cause uncomplicated physical damage, or plants may suffer from subsequent invasions by pathogenic organisms (Turnock *et al.* 1992; Whistlecraft *et al.* 1985; Liu and Butts 1982). Death of the plant is not always the result of attacks by this pest. *Delia radicum* may cause direct loss to producer yields of broccoli, cauliflower, rutabaga, turnip, radish, or indirect loss to yields of canola. Direct losses occur when the maggot tunnels throughout the harvestable portion of a root crop, such as rutabaga, turnip, and radish (Bracken 1988; Brooks 1951; Doane and Chapman 1962; Eckenrode and Chapman 1971; Libby *et al.* 1974; Nair and McEwen 1975). Indirect losses result when the maggot feeds on roots of crops where the harvestable portion is above ground, such as cauliflower, broccoli, cabbage, and canola, causing a reduction in total yield (Bligaard *et al.* 1999; Finch *et al.* 1976; Goble *et al.* 1972; Brooks 1951; Miles 1950). The cabbage root maggot may cause damage to the heads of

cauliflower and broccoli, which is direct damage to harvestable portion of the plant.

The crops where indirect yield damage is a concern are most vulnerable in the first 5-7 weeks after germination (Matthews-Gehringer and Hough-Goldstein 1988). This is when it is essential for plants to establish a good root system to ensure the growth of the crop and adequate yields. If these crops are not protected from *D. radicum* in the first 5-7 weeks of growth, the injury caused by this pest may be enough to kill the plant (Matthews-Gehringer and Hough-Goldstein 1988). Where the damage to the crop is directly to the harvestable root portion, tunnelling may reduce yields at any point during the crop's growth (Doane and Chapman 1962).

Natural Enemies

Parasitoids

The first extensive records of parasitoids of *Delia radicum* were published in 1957 (Wishart 1957; Wishart *et al.* 1957). The two primary species parasitizing *D. radicum* in Europe and Canada are *Aleochara bilineata* (Gyllenhal) (Coleoptera: Staphylinidae) and *Trybliographa rapae* (Westw.) (Hymenoptera: Cynipidae). *Aleochara bilineata* is the most important parasitoid of *D. radicum* in Canada (Soroka *et al.* 2002). In Europe, *Aleochara bipustulata* (L.) is another significant parasitoid of the cabbage root maggot (Fournet *et al.* 2000); however, recent literature has established that this staphylinid is not present in North America (Hemachandra *et al.* 2005). In France, females of *A. bipustulata* have significantly longer reproductive potential and life spans than *A.*

bilineata (Fournet *et al.* 2000). While *A. bipustulata* has useful biological control characteristics making it a candidate as a biological control agent, *A. bilineata* has higher rates of increase, higher host specificity and host acceptance, and its developmental time is better synchronized with *D. radicum* (Fournet *et al.* 2000). This means that *A. bilineata* is the better choice for further studies of biological control of *D. radicum* (Fournet *et al.* 2000). *Aleochara bipustulata* should be evaluated for introduction in to North America as a biological control agent (Soroka *et al.* 2002).

Adults of *A. bilineata* feed on host eggs and first instar larvae. Immature *A. bilineata* drill a small hole in the external puparium of *D. radicum*, enter the puparial case and develop through three larval instars as ectoparasitoids of the pupa. To gain entrance into the host puparium, larvae gnaw holes in the dorsal surface of puparia, but may also gnaw holes in the lateral or ventral surfaces (Royer *et al.* 1998). The locations chosen for these holes is not random, but are in areas of the puparium with fewest ridges (Royer *et al.* 1998). At the completion of larval development, third instars pupate within the host puparia and emerge as adults, several weeks after the first generation of *D. radicum* has emerged (Soroka *et al.* 2002). The rate of parasitism by *A. bilineata* increases with an increase in temperature, but at low temperatures the parasitoid is unable to respond to changes in host density (Turnock *et al.* 1995). Parasitism rates in *D. radicum* puparia vary depending on locations from 5-23% (Hemachandra 2004). In the 1990's, parasitism rates from this same parasitoid in the London, ON. area was 0-38% (Turnock *et al.* 1995). Mass rearing and release of *A.*

bilineata adults to coincide with emergence of *D. radicum* larvae could provide better control than relying on natural populations of this parasitoid (Soroka *et al.* 2002). In the United Kingdom, in order to achieve control of *D. radicum* in cauliflower crops two staphylinid beetles per plant would need to be released (Finch and Collier 2000).

Trybliographa rapae is a larval parasitoid; eggs are laid in first, second or third instar larvae (Fournet *et al.* 2000). Generally, rates of parasitism by *T. rapae* are 11% in *D. radicum* larvae. Parasitism rates of pupae vary and are related to locality (Hemachandra 2004).

Multiparasitism, the condition when an insect is parasitised by two or more parasites of different species (Torre-Bueno 1978) does occur with *A. bilineata* and *T. rapae* (Reader and Jones 1990). *Aleochara bilineata* does not always differentiate between puparia that have been previously parasitized by *T. rapae* and those that have not. Once the larva has drilled through the puparial casing it can then determine whether it has been previously parasitized. If an *A. bilineata* larva does parasitize a puparia containing *T. rapae*, the staphylinid larva does not develop at a sufficient rate to destroy the *T. rapae* larva and does not complete development itself (Reader and Jones 1990). This can result in neither parasitoid developing to the reproductive stage and ultimately may lower the total level of parasitism of *D. radicum* (Reader and Jones 1990). In Manitoba, parasitism rates of *T. rapae* were affected by multiparasitism with *A. bilineata* (Hemachandra 2004).

Predators

Coleoptera are the most important predators of *D. radicum* eggs and larvae (Finch 1996). Carabidae is the most important predator family while staphylinids are somewhat less important predators (Wishart *et al.* 1956). There is a linear relationship between the numbers of eggs eaten and the length of individual carabid beetles, for every 1 mm increase in beetle length above 2.7 mm an additional 18 eggs were eaten per beetle per day (Finch 1996). In the United Kingdom four species of small carabid beetles, indigenous to Europe, can destroy approximately 90% of the first generation of cabbage root maggot eggs: *Bembidion lampros* (Hbst.), *Trechus obtusus* (Er.), *B. quadrimaculatum oppositum* (Say), *T. quadristriatus* (Schrank) (Finlayson 1976). Of these four species two are commonly found in the Prairie Provinces: *B. lampros* and *B. quadrimaculatum* (Melnychuck *et al.* 2003). In Saskatchewan, there were four other species of Carabidae that dominated pitfall trap collections: *B. obscurellum* (Motschulsky), *Agonum placidum* (Say), *Amara littoralis* (Mannerheim), and *B. nitidum* (Kirby) (Melnychuck *et al.* 2003). In Ontario, *B. quadrimaculatum oppositum* (Say) were the most abundant and most important predators of *D. radicum* eggs in cabbage (Wishart *et al.* 1956). While *B. nitidum* (Kirby) were not common in the Belleville, ON. area, they are fairly common in the Prairie Provinces and are considered an important egg predator in these areas (Wishart *et al.* 1956). *Pterostichus melanarius* (Ill.) are known to feed on cabbage root maggot eggs in the United Kingdom (Finlayson 1976); however, a recent study in Washington, U.S.A. found that these large carabid beetles might actually prefer

to prey on smaller beetles (e.g. *B. quadrimaculatum*). The large size of this beetle may restrict the number of cabbage root maggot eggs it consumes, larger mandibles make very small eggs difficult to handle (Prasad and Snyder 2004). Because *Agonum dorsale* (Pontoppidan) was rarely eaten by *P. melanarius* it is likely to be the most successful predator of *Delia* spp. eggs where the larger predator is present (Prasad and Snyder 2004).

Aleochara bilineata (Gyll.) is an important staphylinid predator of eggs and larva as well as the most important parasitoid (Colhoun 1953). As an adult *A. bilineata* feeds on eggs and larvae of *D. radicum* (Read 1962). In laboratory and greenhouse trials, *A. bilineata* adults consumed an average of 23.8 eggs or 1 to 2 day old larvae per day throughout their life. The number killed dropped to an average of 2.6 per day when *A. bilineata* were fed only third instar larvae or pupae with a portion of the puparial case removed (Read 1962).

The abundance and species diversity of Coleoptera can be affected by the nature of the soil surface. Beetles are more abundant and effective as predators in crop habitats than in forest habitats (Wishart *et al.* 1956). Within cropping systems, more carabids are generally caught in reduced tillage plots when compared to conventionally tilled plots (Andersen 2003). Predator patchiness exists within crop fields, and is associated with crop density; however, predator patchiness may be a common response to abiotic factors (Thomas *et al.* 2001). The effect of abiotic and biotic factors on species distribution needs to be better clarified to make the best management decisions possible (Thomas *et al.* 2001). Conditions must be good for juvenile development in some Carabidae species

(Petersen 1998). Cropping systems may affect the diversity of carabid species; however, total abundance may not be affected (Melnychuk *et al.* 2003). There has been some evidence to suggest that carabid assemblages may be affected by regional factors (isolation, glaciation, etc.) or by zonal factors (climatic conditions) (Penev 1996). Obviously, different predators will react differently and to varying degrees to changes in cropping systems (Andersen 2003).

One dipteran has been reported as being a significant predator of *D. radicum*: *Scathophaga stercoraria* (L.) (Scathophagidae) (Griffiths 1991a). The adult of this fly attacks the adult cabbage root maggot and feeds directly on the fly (Griffiths 1991a)

Pathogens

Bracken (1990) studied seven strains of entomogenous nematodes as control agents for *D. radicum* (Bracken 1990): *Steinernema feltiae* (Filipjev) Mexican, *S. feltiae* (Filipjev) Breton, *Heterorhabditis heliothidis* (Khan, Brooks and Hirschmann), *S. bibionis* (Bovien), *S. feltiae* (Filipjev) All, *S. feltiae* (Filipjev) DD136, and *H. bacteriophora* (Poinar). With the exception of *S. feltiae* DD136 and *H. bacteriophora*, the LD₅₀ for *D. radicum* ranged from 98 to 341 infective juveniles per host larva. The DD136 strain of *S. feltiae* and the *H. bacteriophora* strain were much less lethal than the other strains of nematodes (Bracken 1990). Other strains of nematodes have been discussed as natural enemies of *D. radicum*; these include *Steinernema carpocapsae* (Weiser) all strains and *Heterorhabditis bacteriophora* (Poinar) HP88 strain and Oswego strain (Schroeder *et al.* 1996; Simser 1992; Georgis *et al.* 1991).

Mycotic *D. radicum* adults were collected from Wisconsin off the flower stalks of radish, *Raphanus sativus* (L.), and cultured in a sterile environment. *Entomophthora virulenta* (Hall and Dunn) and *Conidibolus coronatus* (Costantin) were isolated from the flies (Matanmi *et al.* 1974). In northern Alberta, *Strongwellsea castrans* (Batko) and *Entomophthora muscae* (Cohn) have both been found to sporulate in living flies (Griffiths 1985, 1991a). There are currently no commercially available pathogens being applied to canola fields.

DELIA RADICUM IN CANOLA

In Manitoba, the first record of *Delia radicum* damage on oil seed rape was in 1958, at the University of Manitoba (Winnipeg, MB.) in field trials by B.R. Stefansson (Allen 1964). Canola quality cultivars are rapeseed cultivars (hereafter called canola) of *Brassica rapa* L. or *B. napus* L. that produces an oil that must contain less than 2% erucic acid, with the solid component of the seed containing less than 30 micromoles of any one or any mixture of 3-butenyl glucosinolate, 4-pentenyl glucosinolate, 2-hydroxy-3 butenyl glucosinolate, and 2-hydroxy- 4-pentenyl glucosinolate per gram of air-dry, oil-free solid (Canola Council of Canada 2005).

Canola is widely grown in Manitoba, Saskatchewan, and Alberta as an oilseed crop (Thomas 1984; Melnychuk *et al.* 2003). *Delia radicum*, as well as three other *Delia* species, have been reported and studied on canola crops in these three provinces (Allen 1964; Liu and Butts 1982; Griffiths 1986b, Soroka *et al.* 2002). *Delia radicum* (L.) and *D. planipalpis* (Stein) are primary invaders of canola roots while *D. platura* (Meig.) and *D. florilega* (Zett.) are secondary

invaders (Liu and Butts 1982). In Manitoba, *D. radicum* is the only *Delia* species that attacks the undamaged roots of canola in commercial fields and is found throughout the agricultural region (Turnock *et al.* 1992). *Delia radicum* can cause significant yield losses for canola in Alberta (Griffiths 1986a), in 1995 (a year of severe outbreak) there was an estimated loss of over \$100 million (Soroka *et al.* 2004). In Manitoba, yield losses have not been significant (Turnock *et al.* 1992); however, in the past 10-15 years there has been a marked increase in cabbage root maggot infestations across the Prairie Provinces. In the 1980s, 12% of the fields surveyed were infested with cabbage root maggots. In the late 1990s, in Manitoba and Saskatchewan, 96% of the fields surveyed had infestations while in Alberta 99.8% of those fields surveyed had infestations (Soroka *et al.* 2004).

Under laboratory conditions *D. radicum* can cause significant root damage and reduced overall yield in canola. When more than 50% of the surface area of the root is injured, canola plants produce fewer racemes, have lower biomass, reduced productive seedpods on auxiliary racemes, and reduced total yields (McDonald and Sears 1991).

Mapping of the relative abundance of *D. radicum* in Manitoba, Saskatchewan, and Alberta has made it possible to assess the degree of infestations (Griffiths 1986b, Soroka *et al.* 2004). With this and climate records it has been determined that, while air temperatures have little effect on patterns of abundance, the amount of summer precipitation is positively correlated with abundance patterns of *D. radicum* (Griffiths 1986b). Turnock *et al.* (1992) found that between the regions neither precipitation, temperature, nor soil texture

seemed to affect damage ratings. However, this has not been duplicated in further studies (Soroka *et al.* 2004). The relationship between cabbage root maggot feeding and physiological processes of canola are not linear and so models that examine actual infestation and damage to canola roots over large areas are needed (Soroka *et al.* 2004). It is important to look at the previous year's temperatures and precipitation if a model is used to determine a current year's potential for cabbage root maggot infestations (Soroka *et al.* 2004).

CONTROL MEASURES

Chemical Control Methods

Aldrin and heptachlor, cyclodiene insecticides, were two of the first insecticides to be studied for the control of *D. radicum* in rutabaga (King *et al.* 1955). These were highly effective and gave excellent results when applied using in-furrow, spray, and band application methods (Forbes and King 1956). Many cyclodiene insecticides were banned from use in Canada by the middle of the 1960s (McDonald and Swailes 1975), specifically heptachlor was deregistered for use in cabbage root maggots and deregistration of other cyclodiene insecticides followed (Allen 1964).

In Manitoba, many organophosphate insecticides proved to be ineffective (Allen 1964). Chlorfenvinphos, applied in laboratory studies to adult flies, was equal in effectiveness to dieldrin, a persistent cyclodiene insecticide (McDonald and Swailes 1975). Varying rates of application, timing, and methods of application have been studied to determine degree of control (Mowat 1975;

Dapsis and Ferro 1982). Single applications of carbofuran are not sufficient to control the maggots in rutabaga, but supplementary applications provide adequate control (Goble *et al.* 1972). Multiple applications of carbofuran also reduced maggot damage on broccoli, Brussels sprouts, cabbage and cauliflower (Finlayson 1979). In greenhouse trials propoxur was also a fast acting adulticide of the cabbage root maggot flies (Read 1981).

Insect growth regulators (IGRs), chemosterilization, and chemical deterrents have been studied for control of *D. radicum* (Van de Veire and de Loof 1974; Hawkes and Coaker 1977; Jones and Finch 1987). Insect growth regulators are a wide range of chemicals that disrupt metamorphosis (Young *et al.* 1987). Some IGRs slow the development of *D. radicum* eggs if treated at 3-7 hours old (Young *et al.* 1987); while other IGRs suppress eclosion to the adult stage (Young and Gordon 1987). A model was developed to combine information from observed egg sterility with other mating and reproductive parameters. The relative contributions of dispersal and loss of competitiveness were then modelled for *D. radicum* to understand previous failures in open field experiments for chemosterilization (Hawkes and Coaker 1977).

Oviposition deterrents may provide new control options; however, use of some of these chemicals, unless synthetically produced, may not be feasible; e.g. caterpillar frass (Jones and Finch 1987). Application of oviposition deterrents in canola needs to be addressed by further research.

A recent study investigated the application of sulfur and/or sulfate to canola and how this may influence infestations of cabbage root maggot

populations (Dosdall *et al.* 2002). It was concluded that while different applications of sulfur may affect cabbage root maggot egg deposition and root damage in some areas and years, the reduction was not substantial. However, adequate sulfur application is recommended for crop health and is essential for optimum yields (Dosdall *et al.* 2002).

Rutabaga in Manitoba is treated with diazinon, using timed drench treatments (Bracken 1988; Jeffrey Pers. Com. 1999). Commercial fields of rutabaga in Manitoba are between 6 and 10 hectares (Bracken 1988). Individuals or groups of producers usually grow canola in areas of 100s of hectares. Across Canada, 4.6 million hectares of canola is grown annually (10 year average) (Canola Council of Canada 2005). With no insecticidal control for *D. radicum* in canola, other agronomic practices are the key to controlling yield loss associated with this pest.

Cultural Control Methods

Cultural control methods are those agronomic practices that involve the manipulation of growing conditions, plant characteristics, and the growing environment. Such things as tillage practices, seeding rates, weed control, and host plant resistance are considered cultural control and will be discussed in the following section.

Host Plant Resistance

One of the cultural methods that may be applicable to both vegetable and canola crops, because it is plant species specific, is host plant resistance. This is the selection and growing of plants which have attributes that are not preferred in

a host plant (antixenosis) (Jyoti *et al.* 2001), or those that can withstand some degree of pest attack (tolerance), or those that reduce the survival, growth or reproduction of insects that feed on that plant (antibiosis) (Painter 1943). Some cultivars of canola are more sensitive to *D. radicum* damage than others. Of the two species of canola grown in Canada, *B. napus* is not affected by cabbage root maggot infestations to the same degree as *B. rapa* (Dosdall *et al.* 1994).

Antixenosis resistance seems to be involved in this resistance because fewer eggs are deposited on or near *B. napus* plants (Dosdall *et al.* 1994), but this has only been observed in Alberta (Soroka *et al.* 2004).

Host plant resistance can reduce the damage caused by *D. radicum* (Jyoti *et al.* 2001). This may be accomplished by selecting plants through breeding programs that have antixenosis or antibiosis or have a higher tolerance for damage from *D. radicum*. Antixenosis might be achieved by the further reduction of glucosinolate levels or other chemical substances found in canola plants that attract *D. radicum*. Cultivars of canola have already been selectively bred for low glucosinolate levels; however, this has not had the desired effect on crucifer insect specialists (Bodnaryk 1997).

Plant Density, Seeding Rate, and Row Spacing

Manipulation of plant density, seed and row spacing is another cultural practice that can be applied to most cruciferous crops (Finch *et al.* 1976; Dosdall *et al.* 1996b). Vegetable crops are generally planted at much greater spacing than canola giving lower plant densities: individual plants may be 16-46 cm apart within rows and rows may be 60-90 cm apart. When cabbage, cauliflower,

Brussels sprout and swede are planted at higher densities the infestations of *D. radicum* and the damage to the individual plants are reduced (Finch *et al.* 1976). If these crops are seeded at higher plant densities the use of insecticide may be unnecessary; however, if plant densities are low, applications of effective insecticide may be required (Finch *et al.* 1976).

Canola crops tend to be seeded at much greater density than vegetable crops. Plants emerge approximately 10-30 cm apart within rows; this depends on seeding rates, the higher the seeding rate the closer the seedlings emerge and the greater the plant density. Row spacing is set by the equipment operator and can be 10-30 cm apart. In canola the effects of seeding rates are essentially the same as in vegetable brassicas. Higher plant densities (higher seeding rates), are associated with reduced cabbage root maggot damage to individual canola plants (Dosdall *et al.* 1998).

Tillage and Cover Crops

Tillage regimes and cover crops are important management practices that can help to reduce *D. radicum* populations and the damage associated with this pest. Research on tillage as a cultural control method has been largely confined to canola (Dosdall 1999; Soroka 1997). For studies in canola, tillage treatment can be applied at different times (Dosdall *et al.* 1996a). Tillage treatment may be applied after canola harvest and in the spring or only in the spring. When the previous year's stubble is a Brassica crop, emergence of *D. radicum* adults is reduced by tillage at any time; however, untilled fields may also contain larger populations of parasites and predators (Dosdall *et al.* 1996a). When tillage is

applied in the spring, there is a significant decrease of *D. radicum* adults emerging: decreases range from 55-65% relative to emergence in zero-tilled areas. Tillage applied in the fall only, compared to fall and spring tillage or spring only tillage, tends to reduce *D. radicum* emergence the most (Dosdall *et al.* 1996a). Male and non-gravid female adults emerging from the previous years canola stubble may travel 10 to 20 m/day, while a gravid female may travel 40 to 80 m/day. Emerging adults from the previous years canola stubble would not be in a host crop field; however, if a host crop field is within the above distances they may disperse to find those fields (Hawkes 1974).

In a zero tillage system, tilling does not occur in the fall or spring and the crop (canola) is seeded directly into the previous year's stubble. When the previous years crop is not canola, there are benefits to canola yields to apply a zero tillage regime (Dosdall *et al.* 1998). While there are benefits to yield when growing canola in a zero tillage system, there is a greater amount of *D. radicum* oviposition on *B. rapa* in zero tillage in Alberta (Dosdall *et al.* 1998). The number of eggs laid at the base of *B. napus* is not affected by tillage regime (Dosdall *et al.* 1998).

Research on undersowing as a control measure has mainly focussed on vegetable brassicas (Kostal and Finch 1994). Cauliflower grown on bare soil had greater *D. radicum* oviposition, than when grown with clover, grass, peas or non-living ground covers (Kostal and Finch 1994). This could be attributed to the loss of contact and re-contact with the host plant, which prevents the gravid female from accumulating sufficient contacts to stimulate oviposition (Kostal and Finch

1994). Undersowing Brassica crops with clover can create reductions of *D. radicum* oviposition per plant of 69-85%; however, until the undersown crop is established there is no effect. Seeding of the cover crop must be timed to coincide with crop establishment (Finch and Kienegger 1997). If a cover crop is too competitive with the cash crop then the cover crop must be cut. It is those times when the cash crop is vulnerable to damage from the cabbage root maggot (Finch and Kienegger 1997). In Newfoundland, undersowing rutabaga with white clover reduced the number of cabbage maggot eggs, however, by the end of the growing season there were similar numbers of pupae in bare soil fields and undersown plots (Dixon *et al.* 2004). Competition was also a major concern for rutabaga in Newfoundland, where the damage in the bare soil fields was somewhat higher, but the average size of individual rutabagas was smaller in the undersown fields (Dixon *et al.* 2004). Undersowing a cash crop may provide some protection from the cabbage root maggot, providing that the competition with the cash crop is not too great.

Trap crops are another area of research that has recently been investigated for the control of *D. radicum* populations in France (Rousse *et al.* 2003). Planting a crop that is expected to be more attractive to cabbage root maggot females and will attract and sustain natural enemies along side the cash crop, will keep *D. radicum* populations low in the desired cash crop. Turnip, *Brassica rapa* (L.) was selected as a trap crop with broccoli as the cash crop. In this study fewer broccoli plants were attacked and those that were attacked were

less severely damaged. Pupae of *D. radicum* were parasitized more frequently in the trap crop than in the cash crop (Rousse *et al.* 2003).

Clean Fields

Reduction of early weeds can give crops a competitive advantage, how weed reduction is implemented will affect that advantage (Dosdall *et al.* 2003). While removal of weeds at the two-leaf stage resulted in higher root damage ratings (3.00), removal of weeds at the six-leaf stage resulted in significantly lower root damage ratings (2.85). Allowing weeds to persist until canola is at the six-leaf stage reduces the degree of root damage from cabbage root maggot, possibly by interfering with female cabbage root maggot oviposition (Dosdall *et al.* 2003). Reduction of wild host plants (i.e. cruciferous weeds) may reduce infestations of *D. radicum* in cultivated crops such as Brussels sprouts, cabbage, cauliflower, and swede (Finch and Ackley 1977). However this may not be the case in areas where canola is the dominant crop. While maintaining a diverse ecosystem may provide reservoirs of natural enemies for a pest it may also provide a haven for individuals of *D. radicum*. It may not be practical or even advantageous to eliminate all weeds from large areas (Dosdall *et al.* 2003); although, it may be feasible on a smaller scale where brassica crops are routinely grown (Finch and Ackley 1977). Heterogeneity in canola fields (resulting from more weeds, crucifers or others) has the effect of reducing *Delia* infestations and damage associated with *Delia* (Finch and Collier 2000). Several hypotheses have been suggested for why fewer specialist insects are found on host plants grown in diverse backgrounds, however none of these have been

supported by host plant selection theory (Finch and Collier 2000). Finch and Collier (2000) developed a theory based on observations of host plant selection, using this knowledge they developed the theory of 'appropriate/inappropriate landings'. Cabbage root maggot are said to require a specific number of appropriate landings (i.e. landing on stimulating host plants) in a specific time period to elicit oviposition (Finch and Collier 2000). An interruption caused by the presence of weed plants reduces oviposition (Finch and Collier 2000). In Alberta, there is a decrease in damage from the cabbage root maggot in weedy sites; however, the increase in yield achieved by early weed removal outweighs the benefit from lowered cabbage root maggot damage achieved through later or no weed removal (Dosdall *et al.* 2003).

MONITORING AND PREDICTION OF PEST POPULATIONS

Using degree-day accumulations, peak adult activity can be predicted for the cabbage root maggot (Finch 1977). Using pest population predictions allows producers to better apply control measures, applying insecticide treatments at the time when there will be a maximum impact on the pest populations (Finch and Collier 2000). While degree-day accumulations can help predict peak activity, monitoring requires trapping cabbage root maggot flies. Water traps baited with allyl isothiocyanate are common methods of trapping adult *D. radicum* (Eckenrode and Arn 1972; Finch and Skinner 1974, 1982b, 1982c). Colour is also an important characteristic of traps, *D. radicum* adults are more attracted to bright yellow traps. Different trapping methods may also affect total trap catches:

yellow water traps are more effective than yellow sticky traps (Finch and Skinner 1982c).

DISCUSSION: *DELIA* MANAGEMENT IN CANOLA IN THE CANADIAN PRAIRIES

One of the problems associated with insecticide use is the effect on non-target organisms (Read 1960). Carbofuran, chlorfenvinphos, and isofenphos reduce the number of predators (Finlayson *et al.* 1980). Severe pest outbreaks following pesticide application are a common problem suggesting that pesticide applications should be used with discretion and care (Coaker 1976). The use of pathogens to control *D. radicum* may also have negative effects on non-target insects (Georgis *et al.* 1991); however, proper timing may help to reduce these effects. There are numerous publications discussing the impact of insecticides and insect growth regulators on parasitoids and predators of *D. radicum* (Hassan 1969, 1973; Finlayson *et al.* 1980; Andersen 1982; Gordon and Cornect 1986).

In the 2005 Guide to Crop Protection (Manitoba Agriculture, Food and Rural Initiatives 2005) there are no insecticides registered for use in canola for the control of *D. radicum*. Application of insecticides for soil-dwelling pest insects in canola, must be made during seeding because once the crop is established it is difficult to apply insecticides to the soil. An insecticide to control *D. radicum* larva, if applied during seeding, would need to be very persistent and because of the required persistence would have undesirable environmental impacts.

Differences in geographic locations, methodology, and the evolving pest situation make it difficult to make generalisations about the *D. radicum* populations in canola (McDonald and Sears 1991; Turnock *et al.* 1992; Soroka 1997). The lack of reactive control measures for *D. radicum* in canola makes it impossible to define economic injury levels, because costs associated with reactive control measures are unknown (Stern 1973).

With no insecticides registered for use on cabbage root maggot in canola it is important to explore alternatives for control. The best methods for controlling this pest in canola in western Canada are likely to incorporate cultural and physical treatments (Dosdall *et al.* 1998). Using these practices, it may be possible to develop a long-term integrated pest management program to prevent large outbreaks from infesting canola. In this thesis, I will examine the effects and possible mechanisms of two cultural control methods: manipulation of tillage regime, and adjustment of plant density through changes in seeding rate.

Chapter III: Materials and Methods

EXPERIMENTAL DESIGN

To assess the effect of agronomic practices on cabbage root maggot infestations in canola, field research was conducted at the University of Manitoba Carman Research Station, located 62 kilometres southwest of Winnipeg. Tillage and seeding rate treatments were arranged factorially within a randomised complete block design (Figure 2). Two tillage treatments, conventional and zero tillage were used. For the purposes of this study conventional tillage was intended to follow normal Manitoba agricultural practice of two tillage operations: fall tillage shortly after the previous crop's harvest, and spring tillage shortly before seeding of the experimental crop. Zero tillage was defined as the complete lack of soil turnover (tillage) between the previous crop's harvest and seeding of the experimental crop. The two seeding rate treatments were used: 4 kg/ha and 8 kg/ha; based on industry standards these are considered low and high rates of seeding.

TREATMENTS

In each year, an experimental field measuring 60 x 240 metres was divided into two replicate blocks each containing four 30 x 60 m plots. Two adjacent plots at one randomly-selected end of each block were designated zero tillage and the two plots at the other end of the block were designated for conventional tillage. One randomly selected plot of each pair of tillage treatments plots was designated for high seeding rate and the other for low seeding rate.

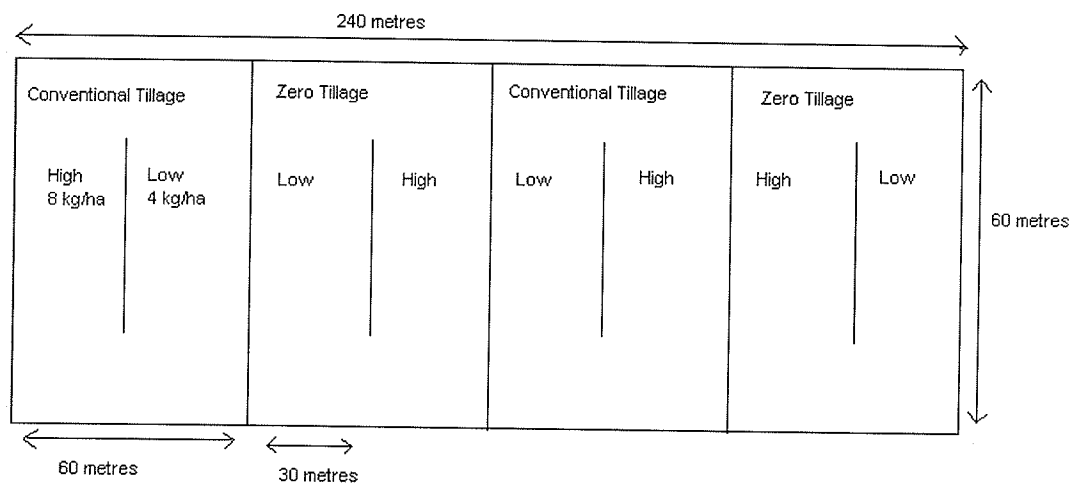


Figure 1: Map of randomized complete block design.

1999

In winter 1998-1999, the entire area used in the 1999 field experiment remained untilled after the previous crop, which was barley. This deviation from the intended conventional treatment was a result of uncertainty in fall 1998 about whether funding would allow the project to go ahead. The conventional tillage plots were treated with a shallow cultivation and then harrowed and packed 24 hours before seeding. For the zero tillage plots no cultivation or harrowing occurred before seeding. A pre-seeding burn-off with Roundup™ original, 356 g/l of glyphosate, at a rate of 3.7 litres per hectare was applied for weeds three days before seeding; a high rate of application was used because of the large number of dandelions present in the zero till plots. Seeding of all plots was done on 28 May 1999, using an Amazon® zero till drill 3 m wide with row spacing of 17.75 cm, set to a seeding depth of 1 cm. Plots were seeded with *Brassica napus* L. (Argentine Canola) cv. LG 3235 Roundup Ready Canola. Seed was pre-treated with Foundation Lite™ fungicide containing 123 g/l of iprodione and 88 g/L thiram. There is no insecticide present in Foundation Lite™. Fertilizer (12-51-0) was applied with the seed at a rate of 18 kg/ha of actual product, or 35.3 kg of phosphate/ha and 150 kg of nitrogen/ha of actual product.

A Versatile 400® self-propelled swather and swath roller was used to swath the crop on 20 August 1999. Combining occurred 10 days later using a Wintersteiger Nursery Master Elite® combine on the test swaths, selected for

yield assessment. Selected swaths were 3 m by 60 m. The remainder of the experimental field was harvested using a Gleaner Model G combine.

2000

The plots for 2000 were established on an area in which the previous crop was barley. In preparation for the 2000 field season, conventional till plots were deep tilled on 4 October 1999 and then tine harrowed twice before winter. On 16 May 2000, conventional till plots were cultivated, tine harrowed and coil packed. In the zero tillage plots three days before seeding, RoundupTM original, 356 g/l of glyphosate was applied at a rate of 1.25 l/ha to control dandelions and other weeds.

Prior to seeding, all plots were broadcast with 96 kg/ha of actual nitrogen (34-0-0) on 10 May 2000. Fertilization rates were changed based on soil samples taken on 26 April 2000. Soil samples were analysed at the Norwest Labs in Winnipeg. Results from these tests and the expertise of A. Iverson, farm manager of the Carman Research Station, indicated a need to change fertilization rates. Seeding took place on 16 May and seeding procedures including cultivar, seeder, seed treatment and fertilizer were identical to those in 1999.

The crop was sprayed with the fungicide RovralTM at a rate of 3.1 l/ha of formulation (744 g/ha of the active ingredient iprodione) on 19 July 2000 to reduce Sclerotinia stem rot damage. Swathing took place on 17 August 2000 using a Versatile 400TM self-propelled swather and swath roller. Some yield was lost due to shattering of seedpods. Test swaths were harvested using a Massey

Ferguson Plot combine on 30 August 2000; the remainder of the crop was harvested using a Gleaner Model G combine. Seed was weighed and cleaned on the day of combining.

INSECT SAMPLING

During the study, the effect of treatments on insects was assessed in three ways; yellow pail traps were used to assess the occurrence of adult *Delia* spp., soil samples were taken to assess abundance of immature *Delia*, and pitfall traps were used to assess occurrence of carabid beetles.

Yellow pail traps were bright yellow, plastic pails with a diameter of 15 cm, 17 cm depth, and 2.25 litre volume. The pails were initially placed on the ground, but as the crop grew, pails were raised on a moveable platform to keep them approximately level with the top of the crop. Each pail was filled 3/4 full with tap water to which a few drops of detergent was added. Twice per week, approximately 1 ml allyl isothiocyanate, was added to the water using a glass bulb pipette. Samples were collected once a week. Collection was done by sweeping a small cloth mesh net through the liquid to remove all the insects present. Water was added to return the level of solution to previous depth and 1 ml of allyl isothiocyanate was again added. Liquid was periodically replaced throughout the field season.

Insects from the yellow pail traps were placed in 70% ethanol and stored at 5°C until processing. Specimens were sorted and insect species of primary concern were recorded; only Anthomyiidae were kept for further identification. Anthomyiids were identified using (Griffiths 1991a, 1991b, 1992, 1993).

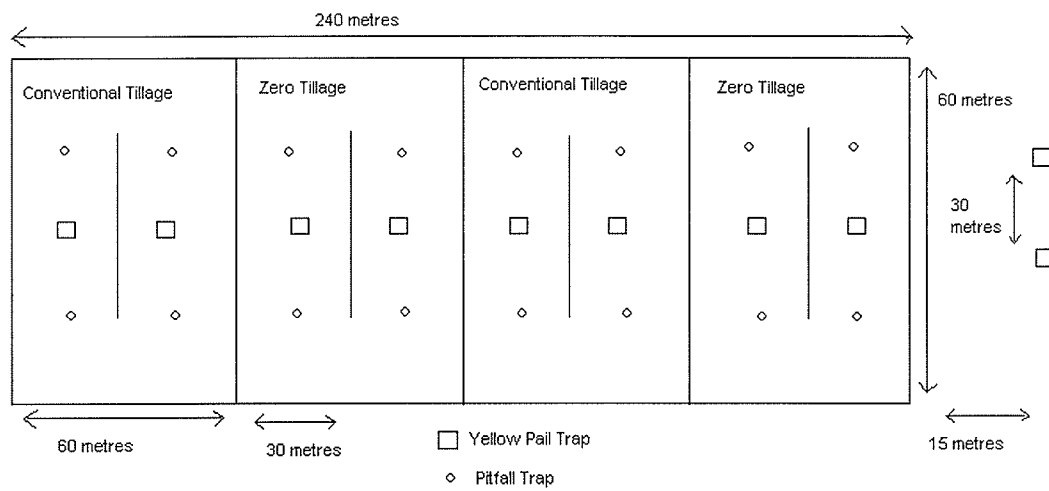


Figure 2: Trap placement for experimental fields in 1999 and 2000.

Either all the specimens or a subsample of no less than 10 flies per sample were identified. Voucher specimens were verified by L. Dosdall, J. Broatch in J. Sorokas's laboratory and G. Griffiths and were deposited in the J.B. Wallis Museum of Entomology at the University of Manitoba.

In 1999, the first four yellow pail traps were placed outside the experimental field on 21 May. Two traps were placed at the south end of the field within a row of windbreak bushes and two placed at the north end of the field also within a row of windbreak bushes. Each pair of traps was 15 m from the experimental field and members of the pair were 30 m apart (Figure 2). After canola seedlings had emerged, more traps were deployed on 8 June. One trap was placed in the centre of each 30 x 60 m plot. All traps were removed on 17 August 1999.

In 2000, the same procedures were followed. The first four yellow pail traps were placed outside the experimental field on 26 April, and the remaining eight traps were deployed on 23 May, after canola seedlings had emerged. All traps were removed on 10 August.

Sampling for immature *Delia* was carried out by taking core samples centred on randomly selected plants from each plot. Core samples were 10 cm diameter x 15 cm deep and centred on a plant so that the sample contained the root of the plant and the surrounding soil.

In 1999, three core samples were taken from each plot in each week from 15 June to 17 August. Core samples were individually placed in plastic bags, labelled and stored at 5°C until processing the next day. Processing was

conducted in the laboratory, by sorting through the soil by hand to find eggs, larvae or pupae. All larvae and pupae were placed alive in labelled containers for further identification using Brooks (1951). Brooks (1951) was also used for any eggs found in the samples.

In 2000, core samples were taken at weekly intervals from 16 June until 1 September. The procedure was the same as in 1999 except that six samples per plot were taken each week, and visual inspections for eggs on the surface of the core were conducted in the field prior to core sample removal.

Pitfall traps were used for the collection of epigeic predators. These traps consisted of two plastic cups nested one inside the other. Each cup was 9 cm diameter at the opening, tapering to 6.2 cm at the base and with a depth of 11.5 cm, the outside cup was sunk below the soil surface so that the rim of the inside cup was level with the soil surface. The inside cup was filled 3/4 full with saturated salt solution containing a few drops of detergent. A 14.7 cm x 14.7 cm wooden cover was suspended on nails approximately 2-3 cm above the trap to reduce evaporation, flooding, and vertebrate predation. At weekly intervals, traps were emptied by pouring the contents through a metal sieve, and collecting the salt solution in a spare cup for continued use. The salt solution was replenished if necessary. Samples from pitfall traps were stored in 70% ethanol at 5°C until sorting. Invertebrates in samples were sorted; Carabidae were later identified using Lindroth (1961-69). Staphylinidae and other arthropods were kept for future studies.

In 1999, pitfall traps were established in the field on 8 June, just after emergence of canola seedlings, and were operated until 17 August. Two traps were placed in each plot, one in the eastern half and one in the western half (Figure 2). In 2000, the same pitfall trapping procedures were used. Traps were placed in the field on 19 April and the last samples were collected on 10 August.

MEASURES OF PLANT RESPONSE

Plant responses were measured using three different approaches: degree of damage to the root, total yield per plot, and dry matter analysis.

The degree of damage to roots was assessed using Dosdall's (Dosdall *et al.* 1994) root damage rating system:

- 0 = no root injury
- 1 = less than 10% surface injury
- 2 = 11-25% surface injury
- 3 = 26-50% surface injury
- 4 = 51-75% surface injury
- 5 = 76-100% surface injury

Each root was examined in the laboratory and assigned a root damage rating.

Excess soil was shaken off, or when very heavy, washed off, and the root was examined by the naked eye for damage.

In 1999, after swathing and combining, 50 roots were removed from each plot on 31 August. In this year, root damage rating was done only at the end of the season. In 2000, root damage ratings were conducted throughout the growing season, beginning as soon as the roots were large enough to assess, on 6 July when plants had bolted and begun flowering. Root damage ratings were

done in the laboratory after removal of the soil and immature *Delia*. In 2000, roots were rated every week until 8 September.

Canola yield was assessed separately for each plot. In 1999, approximately 3 m x 60 m swaths were taken from each plot on 17 August for the determination of yield. Combining took place 10 days after swathing. All the seed from a swath was collected in labelled cotton bags (usually 2-4 bags per swath). Cleaning took place at the field station in the cleaning room, using a Clipper™ seed cleaner. Weights were measured to the nearest milligram. Total weights were then converted into kg/ha using the following equation for each swath:

$$\frac{10 \times \text{grams/ swath}}{\text{area of swath (m}^2\text{)}} = \text{kg/ha}$$

In 2000, yield assessment procedures were the same except the number of sample swaths was doubled to 2 swaths per plot. Swath size and cleaning procedures were the same as 1999, and weights were measured on the day of combining.

Quality parameters of canola seed were measured for seed harvested in 2000. Samples of approximately 2 g were taken from a larger sample of seeds, approximately 1 kg, that had been stored in the freezer. Samples were analysed by P. Kenyon of R. Scarth's laboratory at the University of Manitoba using the FOSS® near-infrared spectroscopic (NIR) systems 6500 full scanning spectrophotometer. Calibrations for all components were done using equations supplied by FOSS® for whole seed.

DATA ANALYSIS

All data was analysed using SYSTAT (Systat 2004). Statistical significance was assigned when P values ≤ 0.05 . Log transformation was performed when t values for studentized residuals > 2.00 and the plotting of residuals from the analysis of variance estimates created a kite scatterplot, or when the transformation improved model fit.

Yellow pail trap catch data did not require transformation before analysis; for these data, hypothesis testing was done after analysis of variance. Hypothesis testing was done to determine whether a difference in the catch existed between traps within the experimental field and traps outside the field.

Soil sample catch data, in 1999, were transformed for all immature stages of *D. radicum* at the peak sampling date and average catch over the season. In 2000, larval data were log transformed for the average number of larvae over the entire season, and for peak date data. Other data for immature stages in 2000 did not require transformation. Pitfall trap catch data were log transformed for both years.

The relationship between root damage rating and treatments was analysed using analysis of variance. Log transformation was not required. Similar analytical procedures were applied to the relationship between yield and treatments. The relationship between yield and root damage rating was explored graphically and trend lines fitted using the least squares, locally weighted smoothing algorithm, LOWESS (Systat 2004). The relationships between root damage rating and yield, glucosinolate content, moisture content, protein

content, and oil content were analysed using Pearson correlations and the relationships between root damage rating and these seed quality components were then depicted graphically by fitting confidence ellipses for the standard deviation of the bivariate normal distribution (Systat 2004). The relationships between seed quality components and treatments were also analysed using analysis of variance of untransformed data.

Chapter IV: Results

INSECT SAMPLING

Adult *Delia radicum*

In 1999, yellow pail traps caught 265 female and 318 male adult *Delia radicum*. There was no significant effect of tillage treatment or seeding rate on either male or females flies for that year (Tables 1 and 2). Hypothesis testing was used to determine any differences between number of individuals collected within the field and outside the field. More male *D. radicum* were caught within the field than outside the field (Table 2); for females, a similar, but non-significant pattern was seen (Table1).

In 2000, 806 female and 388 male *D. radicum* flies were caught. Again no significant effects of treatments were found. Significantly higher catches of both female and male flies were found outside of the field when compared to within the field (Tables 1 and 2).

Immature *Delia radicum*

Tables 3, 4, and 5 show the average number of eggs, larvae, and puparia collected from single soil core samples (three per plot) over twelve weeks (June-August) in 1999 and 13 weeks in 2000. Few eggs were collected in 1999, because of lack of egg recognition and collection in the field. Larval and puparial numbers were relatively low, even though collection procedures for larvae and pupae were relatively efficient. Analysis revealed no significant effect of

treatments on immature *D. radicum* for the average over the entire season (Table 3, 4, and 5), or the average number on the peak sampling date (Table 6 and 7).

In 2000, the numbers of *D. radicum* collected were considerably higher. Analysis showed that larvae were significantly affected by tillage treatment (Table 4 and 6). At the peak of larval abundance and for the average over thirteen weeks (June – Sept) there were significantly higher numbers of *D. radicum* larvae in the conventionally tilled plots (Tables 4 and 6). There was an almost significant effect of seeding rate on larvae over the thirteen weeks (Table 4 and 6).

Table 1: Catches of female adult *Delia radicum* in yellow pail traps in relation to trap position and to seeding rate and tillage treatments.
Significant treatments are in bold.

Year	Treatment	Levels	Mean (\pm SEM) catch per trap	F; d.f.; P
1999	Seeding rate	High	23.00 \pm 0.80	0.07; 1, 3; P=0.81
		Low	23.80 \pm 3.50	
	Tillage	Zero	21.00 \pm 1.80	2.64; 1, 3; P=0.20
		Conventional	25.80 \pm 2.50	
	Interaction	High, Zero	22.00 \pm 0.82	0.88; 1, 3; P=0.42
		High, Conventional	24.00 \pm 1.00	
		Low, Zero	20.00 \pm 4.00	
		Low, Conventional	27.50 \pm 5.50	
	Trap position	Outside plot	19.50 \pm 5.20	0.82; 1, 9; P=0.39
		Inside plot	23.38 \pm 1.68	
2000	Seeding rate	High	60.00 \pm 0.91	0.07; 1,3; P=0.81
		Low	61.75 \pm 6.50	
	Tillage	Zero	63.75 \pm 3.45	0.72; 1, 3; P=0.46
		Conventional	58.00 \pm 5.12	
	Interaction	High, Zero	58.50 \pm 0.50	1.66; 1, 3; P=0.29
		High, Conventional	61.50 \pm 0.50	
		Low, Zero	69.00 \pm 4.00	
		Low, Conventional	54.50 \pm 11.50	
	Trap position	Outside plot	79.80 \pm 6.00	9.13; 1, 9; P=0.01
		Inside plot	60.88 \pm 3.06	

Table 2: Catches of male adult *Delia radicum* in yellow pail traps in relation to trap position and to seeding rate and tillage treatments.
Significant treatments are in bold.

Year	Treatment	Levels	Mean (\pm SEM) catch per trap	F; d.f.; P
1999	Seeding rate	High	27.50 \pm 1.89	2.69; 1, 3; P=0.20
		Low	31.00 \pm 1.96	
	Tillage	Zero	30.50 \pm 2.22	1.45; 1, 3; P=0.32
		Conventional	27.75 \pm 1.89	
	Interaction	High, Zero	27.00 \pm 1.00	2.02; 1, 3; P=0.25
		High, Conventional	27.50 \pm 4.50	
		Low, Zero	34.00 \pm 2.00	
		Low, Conventional	28.00 \pm 1.00	
	Trap position	Outside plot	21.30 \pm 3.30	6.63; 1, 9; P=0.03
		Inside plot	29.13 \pm 1.45	
2000	Seeding rate	High	27.30 \pm 2.29	0.24; 1, 3; P=0.66
		Low	30.25 \pm 3.82	
	Tillage	Zero	29.25 \pm 3.01	0.03; 1, 3; P=0.88
		Conventional	28.25 \pm 3.47	
	Interaction	High, Zero	26.50 \pm 5.50	0.17; 1, 3; P=0.71
		High, Conventional	28.00 \pm 0.00	
		Low, Zero	32.00 \pm 3.00	
		Low, Conventional	28.50 \pm 8.50	
	Trap position	Outside plot	39.50 \pm 2.30	8.65; 1, 9; P=0.02
		Inside plot	28.75 \pm 2.14	

Table 3: Catches of eggs of *Delia radicum* collected from twelve and thirteen (1999 and 2000 respectively) weeks of sampling three core samples per plot in 1999 and six core samples per plot in 2000, averaged over the season (June-September).

Year	Treatment	Levels	Mean (\pm SEM) Numbers per core sample	F; d.f.; P
1999	Seeding rate	High	0.01 \pm 0.01	0.86; 1, 3; P=0.42
		Low	0.04 \pm 0.02	
	Tillage	Zero	0.02 \pm 0.02	0.00; 1, 3; P=1.00
		Conventional	0.02 \pm 0.01	
	Interaction	High, Zero	0.00 \pm 0.00	0.21; 1, 3; P=0.68
		High, Conventional	0.01 \pm 0.01	
		Low, Zero	0.04 \pm 0.04	
		Low, Conventional	0.03 \pm 0.03	
2000	Seeding rate	High	1.04 \pm 0.27	1.00; 1, 3; P=0.39
		Low	1.53 \pm 0.38	
	Tillage	Zero	1.27 \pm 0.27	0.01; 1, 3; P=0.94
		Conventional	1.30 \pm 0.11	
	Interaction	High, Zero	0.77 \pm 0.53	1.07; 1, 3; P=0.38
		High, Conventional	1.31 \pm 0.08	
		Low, Zero	1.76 \pm 0.83	
		Low, Conventional	1.30 \pm 0.27	

Table 4: Catches of larvae of *Delia radicum* collected from twelve and thirteen (1999 and 2000 respectively) weeks of sampling three core samples per plot in 1999 and six core samples per plot in 2000, averaged over the season (June-September). Significant treatments are in bold.

Year	Treatment	Levels	Mean (\pm SEM) Number per core sample	F; d.f.; P
1999	Seeding rate	High	0.73 \pm 0.15	2.21; 1, 3; P=0.23
		Low	0.52 \pm 0.14	
	Tillage	Zero	0.36 \pm 0.14	0.79; 1, 3; P=0.44
		Conventional	0.69 \pm 0.16	
	Interaction	High, Zero	0.79 \pm 0.13	3.18; 1, 3; P=0.17
		High, Conventional	0.67 \pm 0.33	
		Low, Zero	0.33 \pm 0.00	
		Low, Conventional	0.71 \pm 0.21	
2000	Seeding rate	High	1.12 \pm 0.31	9.37; 1, 3; P=0.06
		Low	1.68 \pm 0.23	
	Tillage	Zero	1.06 \pm 0.34	13.93; 1, 3; P=0.03
		Conventional	1.74 \pm 0.09	
	Interaction	High, Zero	0.62 \pm 0.24	3.45; 1, 3; P=0.16
		High, Conventional	1.63 \pm 0.06	
		Low, Zero	1.51 \pm 0.48	
		Low, Conventional	1.85 \pm 0.14	

Table 5: Catches of pupae of *Delia radicum* collected from twelve and thirteen (1999 and 2000 respectively) weeks of sampling three core samples per plot in 1999 and six core samples per plot in 2000, averaged over the season (June-September).

Year	Treatment	Levels	Mean (\pm SEM) Number per core sample	F; d.f.; P
1999	Seeding rate	High	0.42 \pm 0.14	0.18; 1, 3; P=0.70
		Low	0.46 \pm 0.14	
	Tillage	Zero	0.56 \pm 0.06	0.00; 1, 3; P=1.00
		Conventional	0.31 \pm 0.16	
	Interaction	High, Zero	0.58 \pm 0.08	0.71; 1, 3; P=0.46
		High, Conventional	0.25 \pm 0.25	
		Low, Zero	0.54 \pm 0.13	
		Low, Conventional	0.34 \pm 0.29	
2000	Seeding rate	High	1.92 \pm 0.56	1.30; 1, 3; P=0.34
		Low	2.47 \pm 0.42	
	Tillage	Zero	1.71 \pm 0.53	4.17; 1, 3; P=0.13
		Conventional	2.69 \pm 0.32	
	Interaction	High, Zero	1.17 \pm 0.43	1.19; 1, 3; P=0.35
		High, Conventional	2.67 \pm 0.76	
		Low, Zero	2.24 \pm 0.96	
		Low, Conventional	2.69 \pm 0.14	

Table 6: Catches of larvae of *Delia radicum* collected at the peak sampling date from three core samples per plot in 1999 and six core samples per plot in 2000. Significant treatments are in bold.

Year	Treatment	Levels	Mean (\pm SEM) Number per core sample	F; d.f.; P
1999	Seeding rate	High	3.00 \pm 1.08	0.22; 1, 3; P=0.67
		Low	2.00 \pm 1.68	
	Tillage	Zero	1.25 \pm 0.63	1.39; 1, 3; P=0.32
		Conventional	3.75 \pm 1.65	
	Interaction	High, Zero	2.00 \pm 1.00	0.06; 1, 3; P=0.83
		High, Conventional	4.00 \pm 2.00	
		Low, Zero	0.50 \pm 0.50	
		Low, Conventional	3.50 \pm 3.50	
2000	Seeding rate	High	4.71 \pm 1.75	2.30; 1, 3; P=0.23
		Low	6.79 \pm 1.93	
	Tillage	Zero	3.13 \pm 1.00	14.63; 1, 3; P=0.02
		Conventional	8.38 \pm 1.39	
	Interaction	High, Zero	1.75 \pm 0.92	0.24; 1, 3; P=0.66
		High, Conventional	7.67 \pm 0.00	
		Low, Zero	4.50 \pm 1.17	
		Low, Conventional	9.08 \pm 3.25	

Table 7: Catches of pupae of *Delia radicum* collected at the peak sampling date from three core samples per plot for each year.

Year	Treatment	Levels	Mean (\pm SEM) Number per core sample	F; d.f.; P
1999	Seeding rate	High	0.58 \pm 0.26	3.95; 1, 3; P=0.14
		Low	0.18 \pm 0.11	
	Tillage	Zero	0.42 \pm 0.23	0.16; 1, 3; P=0.72
		Conventional	0.33 \pm 0.19	
	Interaction	High, Zero	0.67 \pm 0.42	0.16; 1, 3; P=0.72
		High, Conventional	0.50 \pm 0.34	
		Low, Zero	0.17 \pm 0.17	
		Low, Conventional	0.17 \pm 0.17	
2000	Seeding rate	High	3.92 \pm 1.60	0.62; 1, 3; P=0.49
		Low	5.13 \pm 1.18	
	Tillage	Zero	3.58 \pm 1.56	1.49; 1, 3; P=0.31
		Conventional	5.46 \pm 1.08	
	Interaction	High, Zero	1.83 \pm 0.67	2.22; 1, 3; P=0.23
		High, Conventional	6.00 \pm 2.50	
		Low, Zero	5.33 \pm 2.83	
		Low, Conventional	4.92 \pm 0.42	

Pitfall traps

In 1999, twenty-one species of Carabidae were collected. There were a total of 2,495 individuals including unidentified larvae. The most frequently caught species are listed in Table 8. Only one of the six species was significantly affected by tillage treatments or seeding rates (Table 8). *Agonum placidum* was the only species significantly affected by tillage treatment, as well as total catch was significantly affected (Table 8).

In 2000, the same twenty-one species of Carabidae were caught; the total catch was 3,817 individuals including larvae. Of these species, tillage significantly affected catches of *A. placidum* and *Pterostichus corvus*. For both species, catch numbers were higher in the conventionally tilled plots (Table 8). *Bembidion quadrimaculatum* catches, while not significant, also tended to be higher in the conventionally tilled treatment (Table 8). None of the twenty-one species identified from trap catches exhibited any significant effect related to seeding rate (Table 8).

Table 8: Effect of tillage and seeding rate on most frequently caught carabid species in 1999 and 2000. Significant treatments are in bold.

Taxon		Treatments					
		Zero Average per trap Mean (\pm SEM)	Tillage Conventional Average per trap Mean (\pm SEM)	F; df; P	Low Average per trap Mean (\pm SEM)	Seeding rate High Average per trap Mean (\pm SEM)	F; df; P
<i>A. placidum</i>	1999	1.60 \pm 0.45	11.36 \pm 1.56	26.85; 1, 3; 0.01	6.90 \pm 2.83	6.10 \pm 3.22	0.17; 1, 3; 0.34
	2000	2.15 \pm 1.00	18.19 \pm 5.83	12.79; 1, 3; 0.04	11.40 \pm 6.36	8.94 \pm 6.03	1.58; 1, 3; 0.30
<i>B. quadrimaculatum</i>	1999	0.31 \pm 0.09	0.82 \pm 0.23	4.65; 1, 3; 0.12	0.60 \pm 0.31	0.53 \pm 0.07	0.11; 1, 3; 0.77
	2000	0.37 \pm 0.10	0.80 \pm 0.15	6.85; 1, 3; 0.08	0.69 \pm 0.21	0.48 \pm 0.12	1.51; 1, 3; 0.31
<i>C. granulatus</i>	1999	1.01 \pm 0.33	1.33 \pm 0.37	0.43; 1, 3; 0.56	1.60 \pm 0.35	0.80 \pm 0.15	3.11; 1, 3; 0.18
	2000	2.19 \pm 0.34	1.19 \pm 0.15	4.29; 1, 3; 0.13	1.79 \pm 0.41	1.59 \pm 0.35	0.17; 1, 3; 0.71
<i>P. corvus</i>	1999	0.05 \pm 0.02	0.11 \pm 0.11	0.34; 1, 3; 0.60	0.14 \pm 0.11	0.03 \pm 0.01	1.11; 1, 3; 0.37
	2000	0.07 \pm 0.06	0.34 \pm 0.10	14.06; 1, 3; 0.03	0.27 \pm 4.10	0.14 \pm 0.05	3.06; 1, 3; 0.18
<i>P. lucublandus</i>	1999	0.91 \pm 0.28	0.84 \pm 0.20	0.03; 1, 3; 0.87	1.05 \pm 0.29	0.70 \pm 0.14	0.65; 1, 3; 0.48
	2000	0.26 \pm 0.07	0.84 \pm 0.29	4.29; 1, 3; 0.13	0.79 \pm 0.31	0.31 \pm 0.11	0.17; 1, 3; 0.71
<i>P. melanarius</i>	1999	4.30 \pm 1.20	5.40 \pm 1.66	0.23; 1, 3; 0.66	6.30 \pm 0.88	3.40 \pm 1.49	1.62; 1, 3; 0.23
	2000	2.66 \pm 0.47	2.89 \pm 0.56	0.08; 1, 3; 0.79	2.76 \pm 0.49	2.80 \pm 0.55	0.00; 1, 3; 0.97
Larvae	1999	0.30 \pm 0.09	0.31 \pm 0.15	0.01; 1, 3; 0.93	0.31 \pm 0.15	0.30 \pm 0.09	0.01; 1, 3; 0.93
	2000	0.24 \pm 0.11	0.20 \pm 0.06	0.12; 1, 3; 0.75	0.23 \pm 0.11	0.21 \pm 0.06	0.04; 1, 3; 0.85

PLANT RESPONSE

Root Rating

Root rating as a measure of injury to the plant was analysed for treatment effect. In 1999, tillage treatment had a significant effect on root rating (Table 9). In 2000, tillage treatment, seeding rate and the interaction between the two treatments significantly affected root rating (Table 9).

Yield Quantity

Yields in 2000 were substantially higher than in 1999. Yield was not significantly affected by either treatment in 1999 or 2000 (Table 10). There was no significant correlation between yield and root rating, however, as root rating increased toward 4 the percent yield (standardized by maximum yield of the year to remove between year variation) tended to decrease (Figure 3).

Seed Quality

Four components of seed quality were measured in 2000: glucosinolate; moisture; protein; and oil (Tables 12-15). Glucosinolate content was significantly correlated with seeding rate (Table 12). Higher levels of glucosinolate were found in the high seeding rate plots (Table 12). There was a significant correlation between root rating and glucosinolate content; as root rating increased glucosinolate content decreased (Table 11 and Figure 4).

Protein content showed a trend toward higher levels in the plots with higher seeding rates, although this was not quite statistically significant. Protein

content was significantly affected by tillage treatment (Table 14), showing higher levels of protein in the zero tillage plots. As root rating increased protein content decreased (Figure 6), and this correlation was significant (Table 11).

There was no significant effect of treatment on oil content (Table 15). Oil content was significantly correlated with root rating (Table 11 and Figure 7); as root rating increased so did oil content.

Table 9: Root damage rating (Dosdall *et al.* 1994) (mean \pm SEM) for each treatment in 1999 and 2000.

Year	Treatment	Levels	Mean (\pm SEM) Root rating	F; d.f.; P
1999	Seeding rate	High	1.00 \pm 0.30	1.00; 1, 3; 0.39
		Low	1.30 \pm 0.30	
	Tillage	Zero	0.60 \pm 0.20	16.00; 1, 3; 0.03*
		Conventional	1.60 \pm 0.20	
	Interaction	High, Zero	0.50 \pm 0.30	0.00; 1, 3; 1.00
		High, Conventional	1.50 \pm 0.30	
		Low, Zero	0.80 \pm 0.30	
		Low, Conventional	1.80 \pm 0.30	
2000	Seeding rate	High	2.90 \pm 0.20	181.50; 1, 3; 0.00**
		Low	3.80 \pm 0.00	
	Tillage	Zero	3.20 \pm 0.40	13.50; 1, 3; 0.04*
		Conventional	3.50 \pm 0.20	
	Interaction	High, Zero	2.60 \pm 0.10	24.00; 1, 3; 0.02*
		High, Conventional	3.20 \pm 0.00	
		Low, Zero	3.80 \pm 0.00	
		Low, Conventional	3.80 \pm 0.10	

Table 10: Yield of canola seed in field plots in relation to treatments in 1999 and 2000.

Year	Treatment	Levels	Yield (kg/ha) Mean \pm SEM	F; d.f.; P
1999	Seeding rate	High	1695.16 \pm 76.24	2.19; 1, 3; 0.24
		Low	1605.45 \pm 76.39	
	Tillage	Zero	1693.36 \pm 61.31	0.011; 1, 3; 0.92
		Conventional	1607.25 \pm 89.41	
	Interaction	High, Zero	1679.45 \pm 88.83	0.015; 1, 3; 0.72
		High, Conventional	1710.88 \pm 162.76	
		Low, Zero	1707.28 \pm 119.47	
		Low, Conventional	1503.63 \pm 0.121	
2000	Seeding rate	High	1975.40 \pm 104.66	1.22; 1, 3; 0.35
		Low	1799.54 \pm 126.74	
	Tillage	Zero	1899.28 \pm 119.16	0.02; 1, 3; 0.89
		Conventional	1875.65 \pm 133.71	
	Interaction	High, Zero	2010.78 \pm 242.50	0.09; 1, 3; 0.79
		High, Conventional	1940.01 \pm 66.37	
		Low, Zero	1787.78 \pm 38.96	
		Low, Conventional	1811.29 \pm 307.54	

Table 11: Pearson correlations with root ratings in plots (d.f. = 6) and uncorrected probabilities for yield and seed quality components in 2000.

Measurement	Pearson Correlation	Probability (Uncorrected)
Yield kg/ha	-0.423	0.297
Glucosinolate $\mu\text{mol/g}$	-0.715	0.046
Protein $\mu\text{mol/g}$	-0.715	0.046
Oil $\mu\text{mol/g}$	0.749	0.032

Table 12: Glucosinolate content of canola seed from the field plot trial in each treatment in 2000.

Treatment	Levels	Glucosinolate content $\mu\text{mol/g}$ Mean ($\pm\text{SEM}$)	F; d.f.; P
Seeding rate	High	8.40 ± 0.50	15.06; 1, 3; 0.03*
	Low	5.50 ± 0.40	
Tillage	Zero	6.90 ± 0.60	0.00; 1, 3; 1.00
	Conventional	6.90 ± 1.20	
Interaction	High, Zero	7.90 ± 0.50	1.33; 1, 3; 0.33
	High, Conventional	8.80 ± 0.90	
	Low, Zero	5.90 ± 0.30	
	Low, Conventional	5.10 ± 0.80	

Table 13: Protein content of canola seed from field plots in each treatment in 2000.

Treatment	Levels	Protein content $\mu\text{mol/g}$ Mean ($\pm\text{SEM}$)	F; d.f.; P
Seeding rate	High	25.90 ± 0.20	8.30; 1, 3; 0.06
	Low	25.40 ± 0.20	
Tillage	Zero	26.00 ± 0.20	12.66; 1, 3; 0.04*
	Conventional	25.40 ± 0.20	
Interaction	High, Zero	26.30 ± 0.10	0.00; 1, 3; 1.00
	High, Conventional	25.60 ± 0.20	
	Low, Zero	25.70 ± 0.20	
	Low, Conventional	25.10 ± 0.30	

Table 14: Oil content of canola seed from field plots in each treatment in 2000.

Treatment	Levels	Oil content $\mu\text{mol/g}$ Mean (\pm SEM)	F; d.f.; P
Seeding rate	High	44.20 \pm 0.30	5.74; 1, 3; 0.10
	Low	45.20 \pm 0.20	
Tillage	Zero	44.50 \pm 0.30	0.69; 1, 3; 0.47
	Conventional	44.90 \pm 0.40	
Interaction	High, Zero	44.10 \pm 0.30	0.12; 1, 3; 0.75
	High, Conventional	44.30 \pm 0.50	
	Low, Zero	45.00 \pm 0.40	
	Low, Conventional	45.40 \pm 0.10	

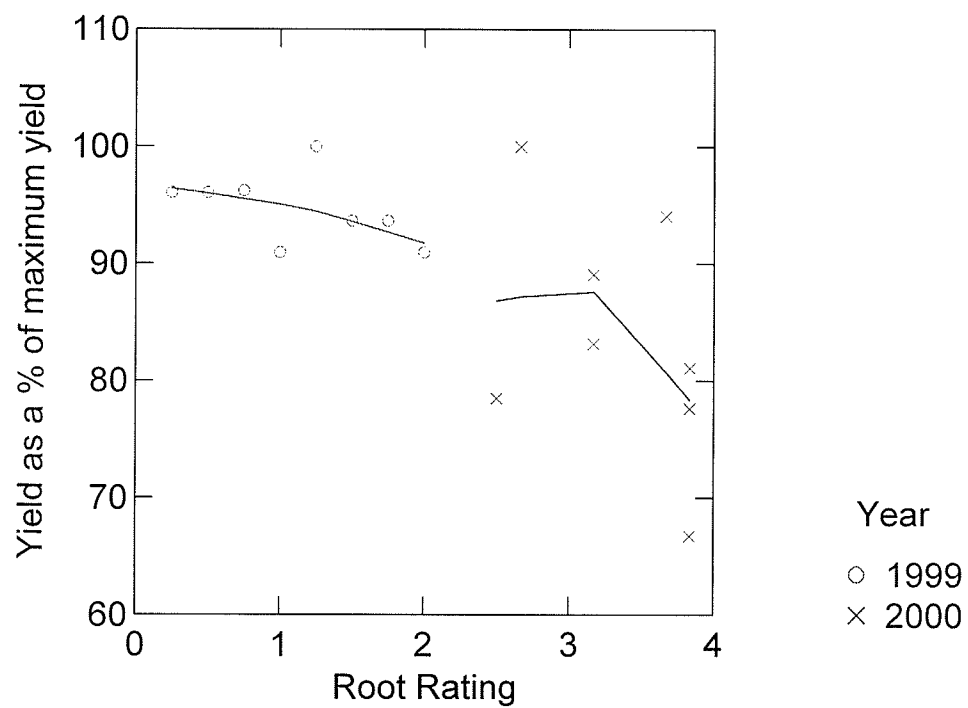


Figure 3: Yield as a percent of annual maximum yield in relation to root damage rating (Dosdall *et al.* 1994).

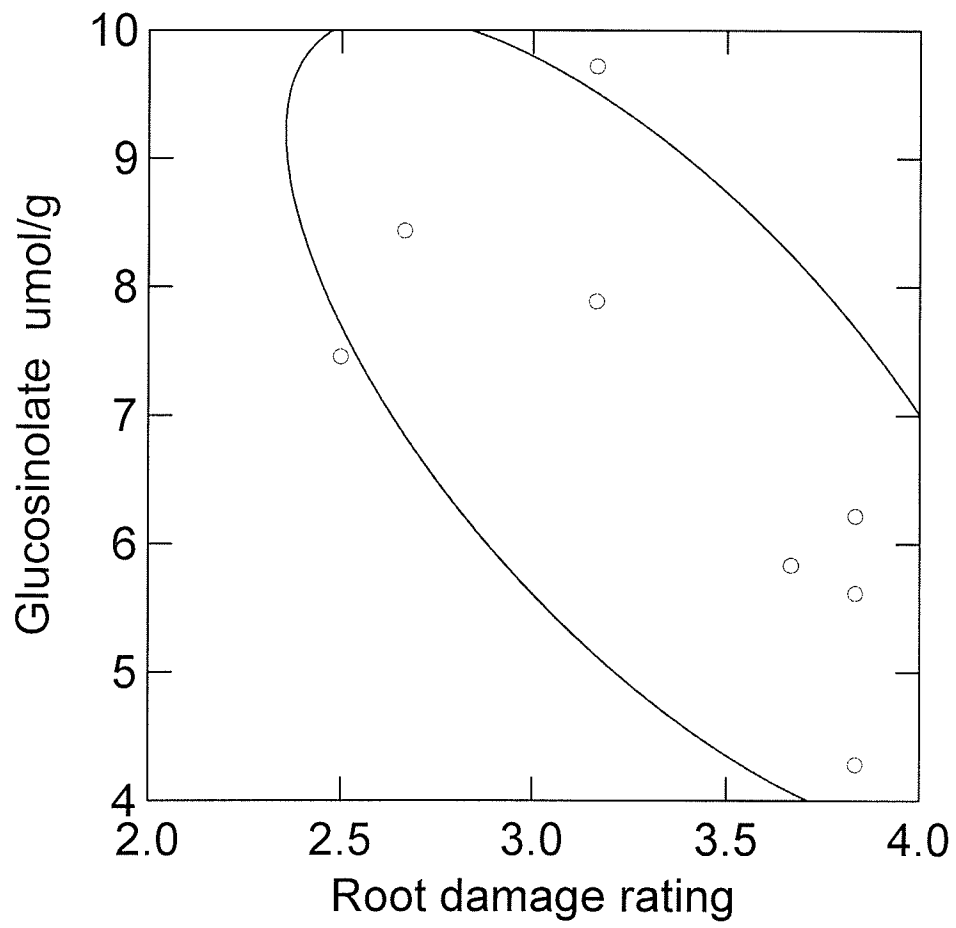


Figure 4: Relationship of glucosinolate content of seed with root damage rating (Dosdall *et al.* 1994) for 2000, and confidence ellipse for standard deviation of bivariate normal distribution.

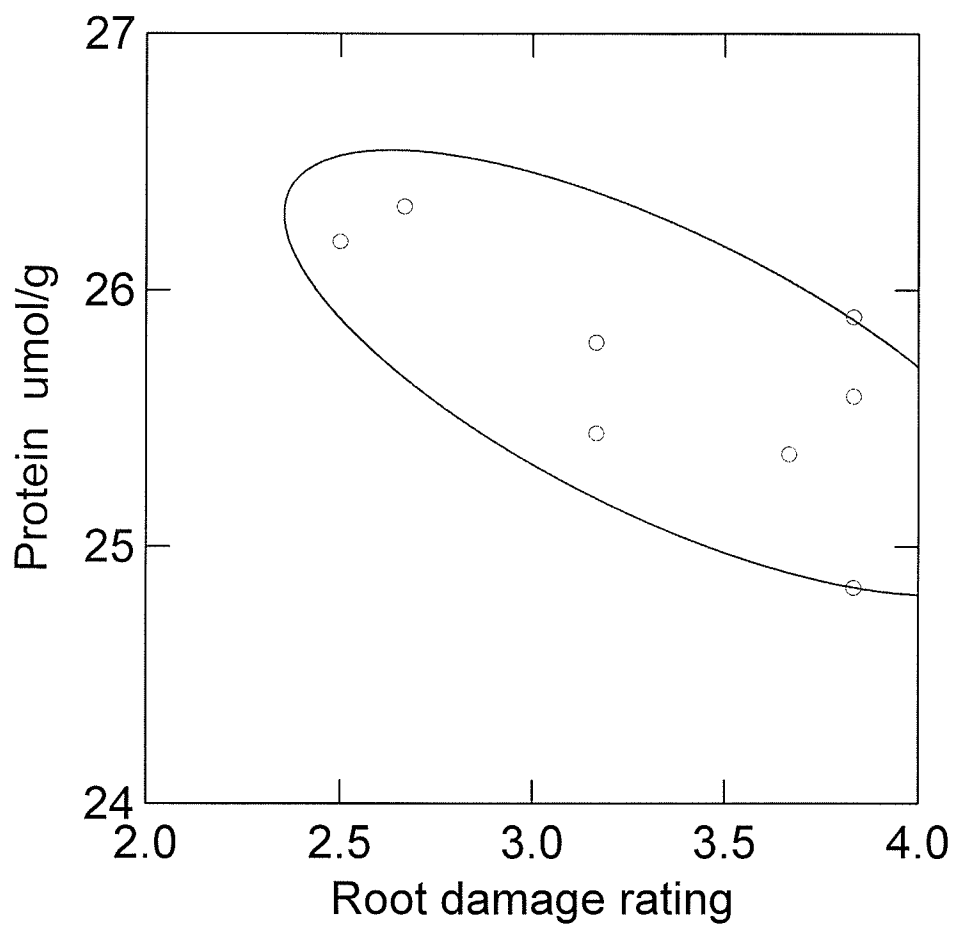


Figure 5: Relationship of protein content of canola seed with root damage rating (Dosdall *et al.* 1994) for 2000, and confidence ellipse for standard deviation of bivariate normal distribution.

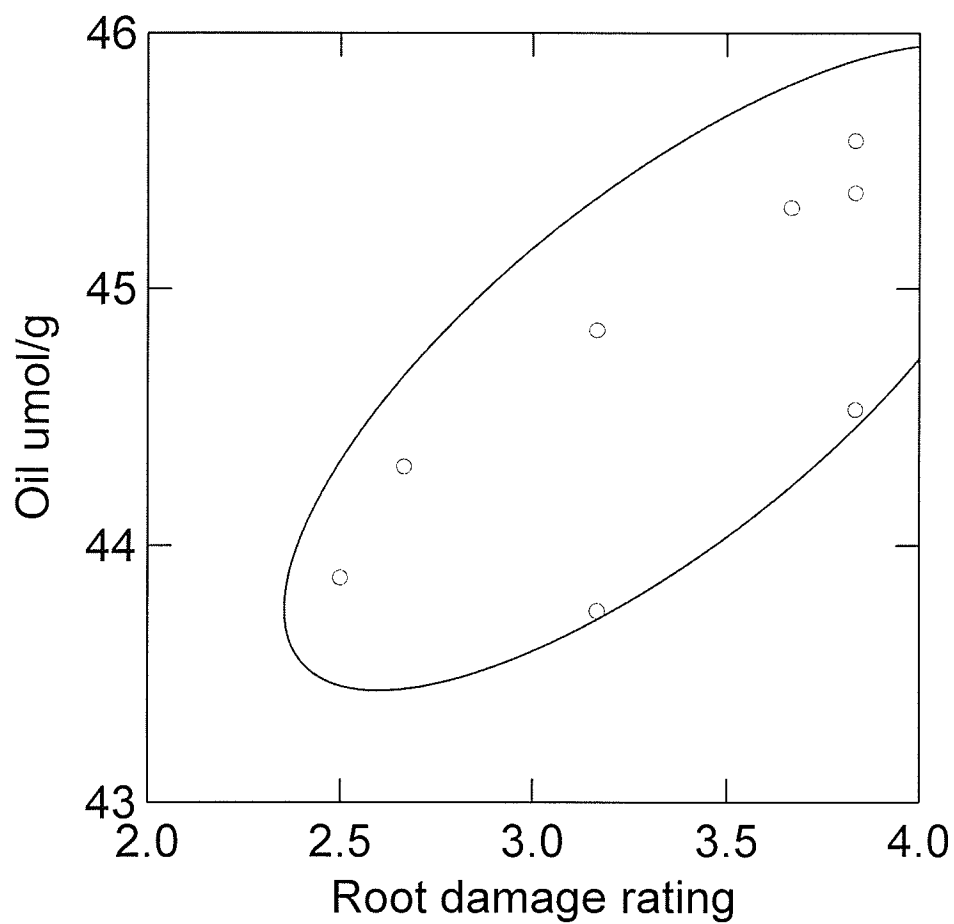


Figure 6: Relationship of oil content of canola seed with root damage rating (Dosdall *et al.* 1994) for 2000, and confidence ellipse for standard deviation of bivariate normal distribution.

Chapter V: Discussion

EFFECTS OF CULTURAL TREATMENTS

Tillage Treatment

Tillage treatment in 2000 was the only treatment applied that had a significant effect on immature *D. radicum*. Conventional tillage treatments resulted in higher larval populations over the entire season (Table 4) and on the date of peak larval abundance (Table 6). The same patterns were evident, although not significant in 1999. There was a correspondingly greater amount of root damage in conventional tillage plots (Table 9); root damage ratings were higher in conventionally tilled plots in both years. In Vegreville and Westlock, AB. a pattern was observed, where zero tillage treatment resulted in greater numbers of *D. radicum* eggs and greater levels of root damage (Dosdall *et al.* 1998); however, this was not supported by statistical analysis. This study was very similar to my study, with a few minor exceptions. In Alberta, testing was conducted on both *B. rapa* and *B. napus* species, while for my research, only *B. napus* was used throughout the experiment (Dosdall *et al.* 1998). Eggs were the only insect stage collected in Alberta (Dosdall *et al.* 1996a), while in my study I collected all 4 life stages. This should not impact results in any way. The greatest egg populations were found on *B. rapa* at the Vegreville site and there was no statistically significant effect on oviposition of tillage treatment on *B. napus* (Dosdall *et al.* 1996a). Because *B. napus* was only used for my research this may have affected my overall results. Root damage ratings were conducted

at the end of the season on 100 plants at the Vegreville site. Root damage ratings were conducted weekly through out the field season for my research. The larger number of samples surveyed in my study would affect the overall results. Using only final root ratings may have inflated ratings (particularly in the *B. rapa* plots) if *Fusarium* or other fungal diseases had damaged the roots (Soroka *et al.* 2004). It is most important to note that although patterns were observed in *D. radicum* abundance and degree of damage in Alberta, there were no supporting statistical analysis for these patterns (Dosdall *et al.* 1998). The relationship between the greater degrees of damage and larger larval infestations in conventionally tilled plots were statistically supported in my study (Tables 4, 6, 9). Differences in soils between the Vegreville and Westlock, Alberta study and this study conducted at Carman, Manitoba could also have changed the results. Black, chernozemic soils in Alberta received the greatest degree of root damage (Dosdall *et al.* 1998); however, soil texture has not been found to make a difference in root damage ratings in Manitoba (Turnock *et al.* 1992). While the first year (1999) of my study paralleled Dosdall's 1998 study, my second year's tillage treatment followed convention tillage practices for Manitoba and thus was not the same as those applied to the Alberta sites. Ultimately, this is the biggest reason for difference in my study results and those of Dosdall *et al.* (1998).

Adults were collected using emergence traps, from May until July (Dosdall *et al.* 1996a). I collected adults, larvae, pupae and eggs to determine the effect of tillage on this pest. Dosdall's 1996 study, answered questions regarding emergence of the *D. radicum* adults from the previous year's pupae and how

conventional and zero tillage practices affect these adults from a starting point of a zero tilled system. My study answered questions about how conventional and zero tillage affect the four stages of development from a starting point of a conventionally tilled system. I was hoping to answer questions based on how that year's agronomic practices might affect that year's population of *D. radicum*. Obviously, the differences between my study and Dosdall's 1996 study are the result of asking different questions at the start of the projects.

Adult populations of *D. radicum* were not affected by tillage treatment in either 1999 or 2000. The total numbers of *D. radicum*, adult and immature, were greater in 2000 than in 1999. This is likely the result of weather conditions. Higher damage levels and larger *D. radicum* populations have been correlated with lower fall temperatures in the previous year and low spring temperatures for that year (Soroka *et al.* 2004). Weather details were not considered during my study; however, from anecdotal observations weather could be the reason for smaller populations.

There is an inherent problem with pitfall trapping as a method of accurately estimating density and movement of carabid beetles; large-bodied carabids are generally over represented and small-bodied carabids are under-represented (Kromp 1999). Evidence also suggested that even if the populations are the same on bare and vegetated sites, carabid activity is greater on the bare soil, leading to higher catches in these sites (Kromp 1999). In my study, tillage treatment did result in differences in the carabid catches as determined using pitfall trap sampling. *Agonum placidum* catches were significantly larger in the

conventional tillage plots in 1999 and 2000 (Table 8). This is contrary to the findings of Kromp (1999), in which deep tilling/ ploughing had a negative effect on carabids. Reduced tillage systems generally seem to favour most carabid species (Kromp 1999; Andersen 2003). The contrary findings in my study may be the result of the timing of tillage applications. If cultivation is applied during carabid egg or early instar larva, little or no population reduction is evident; however if cultivation is applied during late instar larval stages or pupal instars then a reduction in carabid populations may become evident (Purvis and Fadl 2002).

There may have been a reduction of carabid populations in the zero tillage treatment because of the herbicide application. There has been research showing negative impacts on carabid populations from the application of chemical fertilizers and herbicides (Carcamo *et al.* 1995). The most important factor influencing abundance of carabid populations is canopy cover (Melnychuk *et al.* 2003), with the application of herbicide the early canopy would have been reduced, while in the conventional tillage plots there may have been some canopy remaining. Carabid species that prey on cabbage maggots may prefer ground cover that is more uniform with less debris than is present in the zero tillage plots. If there is more debris on the soil surface it may be more difficult to find *D. radicum* eggs and larvae, as well it may be more difficult for locomotion. In the zero tillage plots habitat resistance may be higher because of standing stubble, this would create higher habitat resistance making it unfavourable for carabid movement. High habitat resistance is generally associated with reduced

pitfall trap catches because of reduced movement; however, carabid numbers are enhanced by reduced tillage that would increase habitat resistance (Kromp 1999). Finding higher catch numbers where there is high habitat resistance may be the result of varying amounts of standing stubble present on the zero tillage plots. It is also possible that the key carabid species were indirectly affected by the herbicide application (Kromp 1999).

Seeding Rate Treatment

Seeding rate treatment had no significant effect on *D. radicum* flies, larvae, pupae or eggs. In 2000, there was a significantly higher degree of damage in the low seeding rate treatments. In 1999, the effect was not statistically significant, but the trend was the same; a higher degree of damage occurred in the low seeding rate treatments. Finch and Skinner (1976) had similar results in Wellesbourne, England using cauliflower as the test crop. They found that the greatest number of eggs per plant were in areas of the lowest plant density. In my canola stand, the low seeding rate treatments had fewer plants per square metre, but when measured the individual plants had thicker stems (Data not shown), likely making them more attractive for oviposition and for larval feeding (Dosdall *et al.* 1998; Dosdall *et al.* 1995). Thicker stemmed plants generally exhibit a greater degree of damage than those plants with thinner stems (Dosdall *et al.* 1995; Dosdall *et al.* 1996b). With the exception of larvae in 1999, the total number of eggs, larvae, and pupae tended to be higher in the low seeding rate treatments for both years, although this was not statistically significant. There was also a non-significant trend for there to be

more male and female *D. radicum* flies in the low seeding rate treatments than in the high seeding rate treatments in both years.

In some vegetable Brassica crops, it has been suggested that oviposition is interrupted by cover crops that result in less bare soil around the crop plants (Kostal and Finch 1994). When the soil is bare under the crop plant canopies there can be an increase oviposition (Finch and Skinner 1976). The thicker plant canopies in the higher seeding rates in my study, did not affect oviposition, supporting the hypothesis that canopy thickness does not influence oviposition choice of *D. radicum* females. The theory that has been hypothesised to be at work during host plant selection is that of appropriate/inappropriate landings (Finch and Collier 2000; Finch 1996). This theory has three inextricably bound links: volatile chemicals emanate from a host plant to stimulate landing; host plant finding is then initiated; and finally host plant acceptance (Finch and Collier 2000). In the case of *D. radicum* flies, a series of spiral flights are performed before the female deposits eggs alongside a plant. If during those spiral flights, the female fly only contacts a Brassica (acceptable) host once and the remainder of the time contacts non-host vegetation, then oviposition will not be stimulated (Finch and Collier 2000). Cover crops under a host crop is not a chemical or mechanical barrier, but a behavioural barrier disrupting oviposition (Finch and Collier 2000). However in my study, the plant canopy was very thick with canola; there were not a substantial weed population in any of the plots. So while observations about appropriate/inappropriate contact is of interest when studying *D. radicum* there is little evidence to support this theory from my study.

Seeding rate had no significant effect on individual carabid species in 1999 (Table 8).

Yield and Seed Quality

Generally it is considered to be beneficial to adopt zero tillage or reduced tillage for long term crop production; with reductions in energy consumption for the production of crops, less soil erosion, and greater water retention (for canola) (Borstlap and Entz 1994; Lafond *et al.* 1992). Under normal climatic conditions crop yields are not greatly affected by production in zero or reduced tillage systems (Borstlap and Entz 1994). In some cases, however, canola yield can be reduced under zero tillage systems (Wright 1989). In my study, there was no significant difference in yield for zero tillage compared to conventional tillage in either 1999 or 2000. Wright's (1989) field studies were conducted in Saskatchewan while Borstlap and Entz (1994) worked in Manitoba. The difference between results from my study and the Wright study could be attributed to differences in locations (Saskatchewan versus Manitoba).

Canola grown at a narrow row spacing produces higher yield while seeding rate seems to have variable effects on yield (Kondra 1975; Christensen and Drabble 1984). Seeding rates of 7 and 14 kg/ha grown in northwest Alberta did not affect yield (Christensen and Drabble 1984). While growing canola at seeding rates of 2, 4, and 8 kg/ha grown at Edmonton, Alberta showed variable effects. Seeding rate of 6 kg/ha increased yield compared to other seeding rates; however, higher seeding rates also resulted in greater amounts of lodging (Kondra 1975). Comparing my study with the above results, it is not surprising

that seeding rate had no significant affect on yield. Row spacing was not evaluated in my study; however this is something that would benefit from further research in Manitoba.

In my study, yield decreased when root damage rating was greater than 3.00 (Figure 7). In laboratory studies as damage (root rating) increased yield decreased (McDonald and Sears 1991). In field studies similar results have been found (Dosdall 1999; Dosdall *et al.* 1995). At low root damage ratings, yield was not affected. Future studies should investigate the effect of direct and indirect damage on yield. Another agronomic factor that may affect seed yield is seeding date (Gusta *et al.* 2004), although my study did not look at this component it is worth mentioning as something for future studies to incorporate. Seeding date can greatly affect emergence and total seed yield depending on climatic conditions in any given region (Gusta *et al.* 2004).

Seed quality is comprised of glucosinolate content, moisture content, protein content, and oil content. Glucosinolate is naturally found in most Brassica seeds and is an antinutritional compound which reduces the use of brassicas seed meal as a protein supplements in livestock feed (Daun 1986). The introduction of low glucosinolate rapeseed (canola) allowed this seed meal to replace soybean meal in feed supplements (Daun 1986). Rapeseed generally must contain less than 30 $\mu\text{mol/g}$ glucosinolate to be classified as canola (Daun 1986). In my study all glucosinolate contents were below this amount; however, there was a statistically significant reduction of glucosinolate content in the low seeding rate treatments (Table 2). Generally the primary factor in levels of

glucosinolate is variety of canola, not agronomic practice (Daun 1986). Findings from my study may suggest that agronomic factors can influence glucosinolate levels sufficiently to warrant further investigation. Of more interest is the relationship between stress and glucosinolate content. Glucosinolate and root rating were significantly correlated.

Canola is used as a high-protein feed supplement for many different livestock animals (Grant *et al.* 2003); for this reason protein content is an important component of seed quality. Protein was significantly affected by tillage treatment in my study; higher protein content was found in zero tillage treatment plots (Table 14). Although this was statistically significant, the actual total changes in protein content may not be sufficiently high to warrant further studies. The greatest differences in protein contents are typically the result of environmental factors such as available sulphur and nitrogen, not agronomic practices (Morrison *et al.* 1990).

Cabbage root maggot damage associated with cabbage root maggot feeding can induce changes in seed quality components, such as protein, oil, or glucosinolate (Bartlett *et al.* 1999). Larval tunnelling, by the turnip root fly (*Delia floralis* Fallén), has been found to increase glucosinolate content in roots and stems of rapeseed (Griffiths *et al.* 1994). When canola is damaged (by herbivory or mechanically) there are increases in indole glucosinolate and decreases in aliphatic glucosinolate concentrations in the plant (Barlett *et al.* 1999). Because my study only tested glucosinolate content of the seeds, it is not known how the action of herbivory affected the glucosinolate concentrations in the vegetative

plant material or whether they may be the same or not. Based on seed analysis, as root rating increased, glucosinolate content decreased. This was also the case for protein. Oil content showed the reverse correlation; as root rating increased oil content increased. Further research is needed to investigate how herbivory effects the glucosinolate, oil, and protein concentrations of seeds. It would be beneficial to have higher levels of root damage if protein consistently increased, that is the opposite of the correlation I saw or if oil contents always increased; however, if glucosinolate contents increased with root damage that would cause serious problems for producers trying to market their crop as 'canola'. Depending on the glucosinolate profile and class, and which component of the plant is used for testing, the trend is for concentrations to both increase and decrease as a result of damage (Barlett *et al.* 1999).

Chapter VI: Conclusion

In Manitoba, yield does not appear to be affected directly by *D. radicum* infestations or by the treatments imposed during this study. Weather, appropriate crop rotation, and adequate nutrients are much more important for maximum canola yield potential (Dosdall *et al.* 1998). The zero tillage treatment in this study did not result in greater numbers of cabbage root maggot or a greater degree of damage associated with this pest. Dosdall *et al.* (1998) found that zero tillage systems usually had greater degrees of damage from cabbage root maggot; however, the authors still recommended zero tillage systems in areas of high infestations. My study did find that zero tillage had the effect of reducing cabbage root maggot populations. There are several reasons why differences would have been seen between my study and those conducted in Alberta (Dosdall *et al.* 1998). The benefits of zero tillage for soil and water conservation are significant and the results from this study would support the use of zero tillage for canola production in Manitoba. There may be reasons for not implementing zero tillage in areas with shorter growing seasons, where seeding into stubble may delay emergence of canola (Wright 1989). In these areas minimum tillage should be adopted to capture some of the benefits associated with reduced tillage (Borstlap and Entz 1994). Tillage treatments can be applied to reduce emergence of *D. radicum* in plots in which canola was grown on the previous year (Dosdall 1996a). Proper crop rotation and tillage applied to canola stubble before seeding the next crop may reduce populations of cabbage root maggot in some areas where this pest affects yield.

In areas that have severe root maggot infestations, higher seeding rates will help reduce overall damage from *D. radicum* (Dosdall *et al.* 1998). Seeding date, while not assessed in this study, should be considered when growing canola in areas of high infestations (Gusta *et al.* 2004). The results of this study support other studies, which showed that seeding rate is one of the most important factors affecting yield (Dosdall 1999). When root maggot damage exceeds 50% of the root (root rating > 3) then yield reduction becomes evident (Figure 3) (McDonald and Sears 1991). Another important consideration when seeding canola in areas of high infestations is row spacing (Morrison *et al.* 1990; Dosdall *et al.* 1995; Dosdall *et al.* 1996b) although this study did not investigate this portion of canola production.

This study focused on abundance of predators or parasites of the cabbage root maggot under different seeding rates, plant densities, or tillage treatments. An important future study should incorporate these treatments and their effects on movement and efficacy of predators of cabbage root maggot. Carabid beetle abundance may not be directly affected by seeding rate or generally by tillage treatment. However the ability of these beetles to prey on cabbage root maggot eggs, larvae, or pupae may be affected by these treatments (Purvis and Fadl 2002; Andersen 2003). Adequate nutrient availability is essential for optimum yield in canola (Grant *et al.* 2003) as well as for seed quality components (Ahmad and Abdin 2000). Further studies should take all these factors into consideration in order to determine the optimum growing conditions for canola. Each region will have its own set of environmental factors that will influence canola yield and

seed quality. The ideal set of management practices can be developed for each set of conditions in order to obtain the greatest amount of yield and best seed quality possible. The findings of this study support the following recommendations for optimum canola production in Manitoba: higher seeding rates in a zero tillage system or reduced tillage system, a supply of adequate nutrients and use of appropriate crop rotations to protect against yield losses from *D. radicum*.

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