University of Alberta

Identifying Agronomic Practices that Conserve and Enhance Natural Enemies of Root Maggots (*Delia* spp.) (Diptera: Anthomyiidae) in Canola

by

Ravindran Subramaniam

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of

Master of Science

in

Plant Science

Department of Agricultural, Food and Nutritional Sciences

Fall 2010

Edmonton, Alberta

Examining Committee

Dr. Lloyd M. Dosdall, Department of Agricultural, Food and Nutritional Science

Dr. B. Andrew Keddie, Department of Biological Science

Dr. Dean Spaner, Department of Agricultural, Food and Nutritional Science

Dr. John O'Donovan, Agri-Food Canada, Lacombe Research Station.

Abstract

Yield losses from infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) can be severe in canola crops in central Alberta. Studies were undertaken in central Alberta, Canada to manipulate agronomic practices that have potential to affect crop yield, root maggot infestations, and the survival and abundance of *Aleochara bilineata* (Coleoptera: Staphylinidae), which is an important natural enemy of root maggots. I investigated tillage regime (conventional versus zero tillage), row spacing, and seeding rate to assess effects on *Delia* spp. and *A. bilineata* populations. In general I observed greater root maggot incidence and damage, and greater activity density of *A. bilineata*, in plots subjected to a conventional tillage regime than in a zero tillage regime. I found relatively greater parasitism of root maggot puparia by *A. bilineata* in plots subjected to a zero tillage regime than a conventional tillage regime. No consistent effects were observed on *A. bilineata* activity in relation to seeding rate and row spacing. In this study, there is no evidence to conclude that tillage regime had a significant effect on canola seed yield. Seed yields in relation to seeding rate and row spacing were variable. In the context of integrated pest management in canola cropping systems, I suggest that canola growers utilize zero tillage in conjunction with adopting the currently recommended seeding rates of between 5.6 to 9.0 kg per ha and row spacing of 30 cm because this can bring advantages in terms of improved

management of root maggots and other important canola pests like flea beetles and weeds.

Acknowledgments

I would like to express my sincere gratitude to Dr. Lloyd Dosdall for offering me an opportunity to undertake my graduate programme under his supervision. I am greatly indebted to his valuable guidance, encouragement, patience and friendship throughout my study. Without his support I could not have completed my programme.

I would also like to sincerely thank other members of my supervisory committee; Drs. Dean Spaner, John O'Donovan, and Andrew Keddie, for their support and encouragement.

I am very grateful to the members of the Agriculture and Agri-Food Canada research team from Lacombe; Larry Michielson, Patty Reid, Jennifer Zuidhof, and Elizabeth Sroka as well as their many summer research assistants for their valuable support during field activities and post-harvest processing. I would also like to thank Rodney Werezuk of Alberta Research Council, Vegreville for his support during field activities and post-harvest processing.

I also gratefully acknowledge the services of Jessica Lynch, Brett Hoffmann, Kevin Hunt, Leanne Flahr, Mitch Tuckey and Sanjayan Ravindran for helping me with field work and sorting samples in the laboratory.

I am very grateful to Dr. Felix Sperling, Mr. Jason J. Dombroskie, Dr. Laki Goonewardene, and Dr. Ellen Macdonald for their support and encouragement during courses.

I sincerely thank my colleagues Dr. Jim Broatch, Dr. James Tansey, Dr. Jeremy Hummel, Ms. Meghan Vankosky, Mr. Adam Blake and Mr. Saba Naguleswaran for their support and encouragement throughout my study.

A special thanks to Ms. Jody Forslund for her support and guidance for the past three years of my stay in the Department of Agricultural, Food and Nutritional Science.

I really thank Dr. Thava Vasanthan and his research group for encouraging me to take up further studies while I was working with them upon my arrival in Canada.

A special thanks to Dr. Mohan Thiagarajah for his encouragement and support.

I am most grateful to Alberta Canola Producers Commission for funding my studies through which I have gained a valuable knowledge and experience in the field of canola entomology.

Finally I would like to thank my wife Yoga and children Krisanthini and Sanjayan for their support, patience, and understanding during my upgrading process.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

My thesis research project involves study of tritrophic interactions among canola crop plants, root maggots which are a species complex of anthomyiid flies that comprise the dominant herbivores of canola plants in central Alberta, and the staphylinid beetle *Aleochara bilineata* Gyllenhal which is the principal natural enemy of root maggots. My research attempts to bring these elements together in two studies: 1) an investigation of how several agronomic practices including tillage regime, seeding rate, and row spacing interact to influence various growth and yield parameters of canola and 2) a study of how root maggot and *A. bilineata* populations are influenced by these agronomic practices. In the Introduction to my two studies which follows below, I describe these three components of canola agrosystems separately: I begin with a discussion of canola, followed by information on the biology of root maggots, with a final section on the biology of *A. bilineata*. I conclude with statements describing my study objectives and hypothesis.

1.1 The Development and Economic Importance of Canola

Canola is the common name given to cultivars that are genetically modified from the standard or industrial oilseed rape plants, developed by Canadian plant scientists in the 1970s. Canola has become a very important cash crop for Canadian farmers with over five million ha planted every year and an estimated overall contribution of $13.8 billion in economic activity to the Canadian economy (Canola Council of Canada 2008). The seeds are harvested and used to extract the oil for human consumption; the by-product of the oil extraction is the meal which is used as animal feed.

Canola is a member of the highly diversified genus *Brassica* in the family Brassicaceae, and comprises *Brassica napus* L. and *Brassica rapa* L. Other commonly cultivated members of this economically important family include brown mustard (*Brassica juncea* (L.) Czern), white mustard (*Sinapis alba* L.), black mustard (*Brassica nigra* (L.) Koch), cabbage (*Brassica oleracea* L. var. capitata), broccoli (*B*rassica *oleracea* var. italica), Brussels sprouts (*Brassica oleracea* L. var. gemmifera), and rutabaga (*Brassica napus* var. napobrassica). History suggests that rapeseed plants were cultivated since the beginning of 20th century B.C in India, and were introduced into other Asian countries like China and Japan about 2000 years ago. In Europe rapeseed was cultivated as early as the 13th century. The earliest writings of European and Asian civilizations contain references regarding the use of rapeseed and of closely related plants (Downey 1983).

Rapeseed was one of the few oil sources that could be grown successfully in the cooler areas of the world's agricultural regions such as western Canada, northern Europe, and China (Canola Council of Canada 1982). Rapeseed plants have the ability to grow at relatively low temperatures with far fewer heat units required than for other oilseed crops (Thomas 2003). Therefore, the crop proved well adapted to areas of the Canadian prairies (Brandt et al. 2007). Rapeseed (*Brassica* spp.) was first grown extensively in Canada in the early 1940s to meet demand for marine engine oil (Brandt et al. 2007). Rapeseed use was not widespread until the development of steam engines in the eighteen century. Rapeseed oil was found to adhere to water or steam-washed metal surfaces better than other lubricants. It was this special physical property that led to the introduction of rapeseed production in Canada (Canola Council of Canada 1982). Rapeseed's successful entry as a prairie crop led to the construction of Prairie Vegetable Oils, a crushing facility at Moose Jaw in 1943 (Anonymous 1977).

Rapeseed plants contain glucosinolates, a group of approximately 70 sulfur-containing natural products. Glucosinolates are largely responsible for the sharp odor and bitter taste of many vegetables and field crops belonging the family Brassicaceae. Rapeseed meal is a good source of protein with a favorable balance of amino acids, but limited by its glucosinolate content because the glucosinolates in rapeseed are accompanied by certain anti-nutrient factors that led to palatability and nutritional problems when fed to livestock and poultry. Glucosinolates also break down into other detrimental chemical compounds during crushing and feed formulation, resulting in reduced efficiencies when fed to livestock and poultry at high levels in the ration (Downey 1983).

Rapeseed oil also contains erucic acid which is a monosaturated omega -9- fatty acid and is mildly toxic to humans in large doses. The canola cultivars grown in Canada contain low erucic acid and glucosinolate contents in seeds as compared to their parent rapeseed plants. Geneticists were able to convert rapeseed to canola by lowering glucosinolate and erucic acid levels so that the Canadian crop is now converted to the “double low” cultivars (Canola Council of Canada 1982).

Canola is grown throughout Canada, but the major growing areas are in the western prairie region. Canola is the third largest crop in terms of production in western Canada (Canola Council of Canada 2008). Canola is planted in spring, from May to June, and harvested from August to October. Canola accounted for about 77% of total oilseed production in Canada during the 2009 production year, with 48, 26, and 24% of this total produced in Saskatchewan, Alberta and Manitoba respectively (Canola Council of Canada 2009b). Small amounts of canola are grown in British Columbia, Ontario and Quebec.

Globally, Canada is the second biggest canola producer; behind China with India in third. Average annual production of canola in Canada in 2008 was approximately 10 million tonnes (Statistics Canada. 2009). Anticipated demand for biofuels is expected to result in increased canola production in the future. As far as gross farm receipts are concerned, canola is the number one generator of economic returns of all crops. In 2008 canola generated 21% of Canada's $23.1 billion in gross receipts from the sale of crops. In 2006, Canadian canola exports accounted for 18.2% of our total exports of agricultural products. In absolute numbers, exports of canola have quadrupled from a level of just under $705 million in 2000 to over $2.8 billion in 2006 (Canola Council of Canada 2009a).

1.2 Root Maggots and Canola Cropping Systems

The steady increase of canola production area on the Canadian prairies has resulted in a corresponding increase in the incidence and damage inflicted by insect pests (Lamb 1989). Soroka et al. (2004) reported that in 1996 and 1997 root maggots (*Delia* spp.) (Diptera: Anthomyiidae) occurred wherever canola was grown in western Canada. Approximately 96.0% of the fields surveyed in Manitoba and Saskatchewan and 99.8% of the fields in Alberta showed evidence of root maggot feeding. The greatest damage over the largest geographical area was found in western and northwestern Alberta (Soroka et al. 2004).

Root maggots are well known as serious pests of brassicaceous crops in Europe and North America. Larvae of *Delia radicum* (L.), *Delia planipalpis* (Stein) and *Delia floralis* (Fallén) are considered as primary pests (Griffiths 1991b). Plant damage occurs when larvae feed on taproots, forming feeding channels in the main rootstock of a number of host plant species, both wild and cultivated. Several other economically important species including *Delia platura* (Meigen) and *Delia florilega* (Zetterstedt) are considered as secondary pests, and contribute to damage after initial attack by the primary pests (Griffiths 1991b).

Studies conducted in north central Alberta determined that adult *Delia* spp. emerge continuously from their overwintered puparia from mid-May to mid-July, but are most abundant during the latter part of May to mid-June (Dosdall et al. 1996a). Oviposition on canola reaches its maximum at about the stem elongation stage (“bolting”) of the plant, usually around mid-June (Griffiths 1986a). Gravid female flies commence laying eggs within one week of emerging from their puparia and continue laying eggs for a five- to six-week period (Griffiths 1991b). Ovipositing females generally lay eggs in small clusters at the base of brassicaceous plants near the root collar or on the axils of lower leaves (McDonald 1985). Female flies are attracted towards plants with larger basal stems for oviposition (Dosdall et al. 1996b), and undergo a series of spiral flights before landing on a suitable host for oviposition (Finch and Kienegger 1997).

Root maggot eggs are small, white and elongate, 0.9 to 1.1 mm long and 0.3 to 0.4 mm broad (Hughes and Salter 1959). Each egg has several longitudinal grooves. On one side there is a deep groove through which the larva, when hatching, breaks the shell of the egg and emerges (Caesar 1922). Eggs hatch and larvae emerge generally within three to four days of oviposition (Harris and Svec 1966). Dryness of soil and direct sunlight will cause many eggs not to hatch successfully (Caesar 1922). Female flies are stimulated by the presence of glucosinolates during host selection and oviposition (Coaker 1970). It appears that the magnitude of the response of the laying female is determined by the interactions among various glucosinolates and their breakdown products during the host plant selection process (Nair and McEwen 1976).

Gravid females respond differently to various components of habitat such as plant and soil qualities during the selection of an oviposition site. Beirne (1971) stated that the nature of the soil has a major influence on the severity of *D. radicum* infestations. Infestations tend to be minimal on soils that have bigger particle size and severe on soils that have smaller particle size. The most favorable soil for oviposition comprised soil particles 1 mm in diameter which easily permits entry of the extended ovipositor (Traynier 1967a). The ovipositor is stimulated mainly by the interplay of many contact chemostimuli arising from undamaged host plants (Traynier 1967b).

Post-alighting behavioral studies of gravid females have been undertaken by Kostal and Finch (1994) and Hopkins et al. (1999) on *D. radicum* and *D. floralis* respectively. The authors reported that complex behavioral events precede host selection and oviposition. A wide range of behavioral sequences on potential host plants that include spiral flights around host plants (Kostal and Finch 1994), standing, walking and running on various plant parts and proboscis extension (Hopkins et al. 1999) all collectively determine whether or not flies will select the plant for oviposition. A study conducted by Ellis et al. (1982) also determined that microbial activity in and around host plants influenced the egg laying behavior of *D. radicum.* In their study, radish plants grown from untreated seeds stimulated gravid females to deposit up to three to four times as many eggs as compared to ones carrying few or no microorganisms (as the result of washing in antibiotics and sodium hypochlorite). Sampling or counting eggs has often been used as a means for assessing root maggot infestations. The method used most commonly in canola cropping system has been an *in situ* visual counting approach first developed by Dosdall et al. (1994).

Delia spp. larvae are whitish with two black hooks at the anterior end for scratching the tissues of the root. This feeding releases root fluids, which are then absorbed through the mouth near the hooks (Caesar 1922). The larvae possess a number of small tubercles at the posterior end, of which the two most prominent and central ones are notched at the apex. These notched tubercles are used to distinguish among larvae in taxonomic keys (Brooks 1951). There are three larval instars. The first, second and the third larval instars are approximately 1.5, 3.8, and 2.5 to 8.0 mm in length respectively (Schoene 1916).

First-instar larval development generally requires approximately four days and development of the second instar needs about six days (McDonald 1985). Duration of development of third-instar larvae is eight to twelve days (Schoene 1916). The pre-pupal stage of *Delia* spp. lasts for about three days (Harris and Svec 1966). Larval injury is confined mainly to a narrow band of tissue bordered on the outside of the taproot by a thin layer of periderm and phloem tissue, and on the inside by the parenchyma cells of secondary xylem (McDonald and Sears 1992). The puparium that encloses the pupa is formed by the exoskeleton of the third-instar larva when it is full-grown and has stopped feeding. The puparium is brownish and sub-elliptical (Miles 1952). The length of the puparium varies from 3.5 to 6.5 mm (Scheone 1916). The two notched posterior tubercles of the larvae can be seen on the surface of the puparium and help to differentiate among different species (Caesar 1922).

Pupariation occurs most commonly in the soil surrounding the root. The puparial stage is the only stage able to overwinter. The major environmental cues for root maggot diapause induction are temperature and photoperiod (Collier and Finch 1983b). Also, light intensity can be a contributing factor (Read 1969). Post-diapause development begins once temperatures become adequately warm in the spring (Collier and Finch 1983a). The temperatures necessary for post-diapause development and emergence are variable (Bracken 1988; Collier and Finch 1983a; Eckenrode and Chapman 1971; Wyman et al. 1977). Turnock et al. (1985)

determined that exposure to temperatures below –10^{o}C reduces survival and affects post-diapause development. Coaker and Wright (1963) reported a threshold temperature of 5.6^{o}C for post-diapause development of overwintering *D. radicum* puparia. However, subsequent studies found that the base temperature for post-diapause development in the soil is 4.0^{o}C for *D. radicum* (Collier and Finch 1985). The total time required for post-diapause development of *D. radicum* mainly depends on temperature and varies among populations (Collier and Finch 1983b).

The body color of the adult male of *D. radicum* is dark and has gray markings on the thorax and abdomen (Schoene 1916); the compound eyes are holoptic; the thorax is ash gray with three prominent longitudinal lines on the dorsum. Females are lighter in colour than males; the body and legs are gray with a tinge of brown, and the compound eyes are dichoptic (Schoene 1916). Adults feed on water and nectar of various kinds of flowers like dandelion, white clover, and marsh marigold. In addition they can feed on the juices of rotten apples on the ground and at times feed on sap exuding from trees (Caesar 1922).

Hawkes (1972) determined that adult dispersal of *D. radicum* within an agricultural field was about 8 to 20 m per day. Females tend to disperse more vigorously than males and were more evenly distributed through the crops (Finch and Skinner 1982). Gravid females entered crops without accompanying males, and Finch and Skinner (1982) inferred that they are migratory and mate near the site of emergence. Nair and McEwen (1976) determined that the adults have shown a higher capability to disperse, up to 915 m in seven days, and that the presence of a host crop influences dispersal rate.

The numbers of generations per year (voltinism) varies among *Delia* spp. depending on geographical regions. Studies conducted in England (Finch 1980) and in North America (Mukerji 1971) revealed that *D. radicum* can have up to three to four generations per year (Griffiths 1991b). Broatch et al. (2006) found a single generation of *D. radicum* in canola in Lacombe, AB in 2003, 2004, and 2005, but determined that *D. platura* was bivoltine in this crop during the same period. Studies by Broatch (1993) suggest that *D. floralis* and *D. planipalpis* may also be bivoltine in Alberta.

Economic impacts of root maggots have been well studied and reported for commercial vegetable crops, including cabbage (Getzin 1978; Vincent and Stewart 1980), and rutabaga (Read 1958). Most such reports relate secondary bacterial and fungal infections in crop plants with root maggot larval damage. Griffiths (1986a) reported that in canola, primary root damage is exacerbated when feeding channels are invaded secondarily by Fusarium root rot fungi and he further reported that root rot involving *Fusarium* spp. occurred in all plants he observed with root maggot damage.

Dosdall et al. (1998a) stated that root maggot damage throughout Alberta was positively and significantly correlated with soil moisture, with areas of high rainfall associated with more root damage than areas with low rainfall. Based on mapping studies of the relative abundance of *Delia* spp. conducted by Griffiths (1986b), *D. radicum* was dominant in areas with a mean June-August precipitation approaching or exceeding 250 mm, whereas *D. floralis* was dominant in areas where precipitation was lower.

Studies conducted in Manitoba determined that the level of damage from *D. radicum* increased with increased precipitation and temperature during June and July (Turnock et al. 1992). Turnock et al. (1992) speculated that an extended period of cool, moist conditions could result in increased damage and probably in considerable yield loss. Dosdall et al. (1998a) reported that root maggot damage ratings were associated with seed yield, with the greatest yields obtained where root damage values were low. Griffiths (1991a) reported that exclusion of root maggot adults, achieved through the use of screened cages, increased seed yield by 51.7%, seed weight by 37.6% and protein content of meal by 6.43% in *B. rapa*, and yield increases of 20.2% were observed in *B. napus* protected from damage by root maggots with insecticidal seed treatments. Using replicated field experimentation and multiple site-years, Dosdall et al. (2004) confirmed that yield losses to canola were reduced when fertility levels were high, even though canola subjected to increased levels of soil fertility had greater root maggot damage than canola with decreased fertility.

A wide range of control options for root maggots have been investigated in vegetable and canola cropping systems. Finch and Skinner (1976) determined that increasing mini-cauliflower plant density reduced the *D. radicum* eggs per individual plants remarkably, but increased the absolute population of the pest per unit area without affecting the yield of mini-cauliflower. A similar study with canola by Dosdall et al. (1996b) determined that increasing plant density reduced maggot infestations and yield loss. Increased canola plant densities resulted in plants with reduced basal stem diameters, and egg-laying females were less attracted to such plants (Dosdall et al. 1996b).

Altering of seeding dates to ensure that highly susceptible plants were not present at the time of peak egg laying activity is a widespread method of protecting vegetable crops from *D. radicum* (Coaker 1969). Dosdall et al. (1996b) determined that root maggot infestations in canola were reduced when seeding late, but seed yield also decreased with late seeding. It appears that even with higher root maggot infestations plants seeded early take advantage of the more suitable growing conditions early in the short growing season in Canada and resulted in increased seed yield (Dosdall et al. 1996b).

Dosdall et al. (1996a) determined that cultivation prior to seeding reduced survival of overwintering puparia and adult emergence in the range of 55 to 64% for *D. radicum* and 53 to 72% for *D. floralis.* Dosdall et al. (1998b) suggested that adapting zero tillage or reduced tillage to increase yield is an appropriate agronomic practice in areas infested by high populations of root maggots. Dosdall et al. (2002) also suggested that producers should employ adequate sulphur nutrition for optimum crop health to enable canola plants to better compensate for root maggot infestation.

No registered insecticides are available to control root maggots in canola cropping systems in Canada because the vulnerable maggot stage occurs in mid-July. Insecticidal seed treatments that would be active in July are too persistent to be used (Holliday.2003). Therefore, manipulations of agronomic practices to manage the habitat to reduce root maggot populations are an appropriate strategy for the integrated management of this pest.

1.3 Natural Enemies of Root Maggots

An important area of research that has been largely overlooked involves identifying different ways to manipulate canola agronomic practices to provide more suitable habitat for natural enemies of root maggots in canola production systems. In canola in the Canadian prairies, the principal natural enemies of root maggots are the staphylinid beetles *Aleochara bilineata* Gyllenhal and *Aleochara verna* Say (Coleoptera: Staphylinidae), the hymenopteran wasp *Trybliographa rapae* (Figitidae) and various species of carabid beetles (Coleoptera: Carabidae) (Hemachandra et al. 2007).

The predator-parasitoid rove beetle, *A. bilineata*, occurs commonly in canola crops, but we have very limited understanding of strategies that can enhance its effectiveness. *Aleochara bilineata* has a host range that includes several pest species of brassicaceous crops such as *D. radicum*, *D. platura*, *D. floralis*, and *D. planipalpis* (Read 1962; Klimaszewski 1984; Maus et al. 1998). *Aleochara bilineata* is of considerable interest in canola production because adults are predators, consuming large quantities of root maggot eggs and larvae. The beetle is also a parasitoid: Soon after hatching, the first-instar larva of *A. bilineata* locates a root maggot puparium, bores through the puparial wall, and attaches itself ectoparasitically to the developing fly within (Broatch et al. 2008).

Aleochara bilineata remains inactive during winter, but in spring it consumes tissues of its host, eventually killing it (Royer et al. 1998).

The adult beetle is 2 to 6 mm long (Klimaszewski 1984) and there is no size difference between sexes (Fuldner et al. 1960). The size difference of the adult beetles is attributed to the host puparium in which it developed (Langlet et al. 1998). The adult body of *A. bilineata* is black and the elytra are uniformly coloured (Klimaszewski 1984). Accurate identification of *A .bilineata* depends on structure of the aedeagus and spermatheca (Klimaszewski 1984; Maus 1998). In the laboratory, when beetles were placed in oviposition dishes, copulation occurred immediately. There was no apparent courtship period in laboratory experiments (Colhoun 1953; Fuldner 1960). Colhoun (1953) found that the preoviposition period of *A. bilineata* is approximately two days. *Aleochara bilineata* lays eggs in the soil near Diptera-infested brassicaceous plants (Fuldner 1960). Fournet et al. (2001) found that the maximum average fecundity (eggs/day) of *A. bilineata* is 15.5 and the mean daily fecundity is 8.5. The adult life span is about two months (Read 1962; Langlet et al. 1998). Eggs are usually shiny milky white, oval in shape and measure 0.45 by 0.36 mm in size (Fuldner 1960). The larvae emerge in approximately 3 to 7 days (Colhoun 1953; Fuldner 1960) and newly emerged larvae are extremely mobile and move freely in the soil in search of a host. After selecting the most suitable host puparium, the larva will chew a small hole into the puparial wall (Fournet et al. 2001). The *A. bilineata* larva then enters the puparium and eventually consumes the developing pupa within (Royer et al. 1998). Generally, only one larva enters a puparium. If two or three larvae enter a puparium, only one larva survives (Fuldner 1960; Read 1962).

Temperature and humidity influence the entry of the first-instar larva into the puparium (Brunel and Langlet 1994). Parasitoid penetration is facilitated when humidity softens the puparium wall (Brunel and Langlet 1994). After entering the puparium, the larvae closes the entry hole within 6 to 12 hours using a white anal secretion, which later turns brown or black (Fuldner 1960). Overwintering of *A. bilineata* occurs as a first instar within the puparium, and adults of the new generation emerge in the following spring (Colhoun 1953).

Second- and third-instar larvae are eruciform and approximately 2.8 and 7.6 mm long respectively (Fuldner 1960). Durations of the second- and third-instar larvae at 15.5°C are 5 and 10 days respectively (Fuldner 1960). *Aleochara bilineata* pupates within the host puparium and the total duration of the milky white pupa at 15.5°C is 34 days (Fuldner 1960).

In the laboratory, a single pair of beetles consumes approximately 1,210 eggs and 128 larvae in their lifetime and a single adult beetle can consume an average of 23.8 eggs or 2.6 larvae per day (Read 1962).

Acting as both a predator and parasitoid, *A. bilineata* is an important biological control agent of cabbage maggot populations (Mukerji 1971). Turnock et al. (1985) found that in western Canada, parasitism of cabbage maggot puparia by *A. bilineata* in cole crops can be as high as 94%. Hemachandra (2007) determined that average parasitism levels of cabbage maggot by *A. bilineata* in western Canada were 67%.

In addition, carabid beetles can consume large numbers of root maggot eggs, and can also prey upon root maggot larvae. Consequently, carabid beetles are considered to be very important natural enemies of root maggots. A number of species of Carabidae have been associated with root maggot predation in Canada. Gibson and Treherne (1916) noted that in British Columbia five species of carabid beetles were observed in the act of devouring root maggots in the field or were observed in close association with infested roots. These species included *Bembidion mutatum* Gemminger and Harold, *Bembidion trechiforme* LeConte, *Platynus cupreus* Dejean, *Pterostichus lucublandus* Say and *Amara farcta* LeConte. Among the above five species, *B. mutatum* was the most abundant species followed by *B. trechiforme*. Coaker and Williams (1963) reported that several carabid species captured from plots of brassicaceous vegetables in Britain had relatively high predatory value. Of the predatory carabids, *Bembidion lampros* (Herbst) was the most frequently occurring species, and together with five other species studied constituted over 90% of the total carabids trapped on the Brassica plots (Coaker and Williams 1963). Wishart et al. (1956) reported that carabids, in particular *Bembidion quadrimaculatum oppositum* Say, were the most abundant species they encountered in Canada that were predatory on root maggots. *Bembidion quadrimaculatum oppositum* Say was determined as the most abundant and effective predator of *D. radicum* eggs in Canada, and *Bembidion nitidum* Kirby, was also highly predatory on eggs (Wishart et al. 1956). Wright et al. (1960) demonstrated an inverse relationship between the numbers of carabid beetles trapped on plots of brassicaceous vegetable crops and subsequent survival of the cabbage root fly. In addition, Hughes et al. (1959) derived a relationship between the numbers of both *Bembidion* spp. and *Trechus* spp. and the loss of root maggot eggs, and concluded that these beetles were responsible for destroying more than 90% of the eggs laid. In a laboratory experiment, Coaker and Williams. (1963) demonstrated that *B. lampros* and *Trechus obtusus* Erichson were the most efficient predators of cabbage maggot eggs. *Bembidion quadrimaculatum* and *Harpalus aeneus* (Fabricius) were also comparatively good predators. The species with the highest predatory values were frequently observed to be the most active of the species compared (Coaker and Williams 1963). However, the seasonal abundances of the carabids trapped varied considerably from year to year (Coaker and Williams 1963).

Studies have demonstrated that manipulating agronomic practices like tillage regime, row spacing, and seeding rate can influence infestations of root maggots in canola (Dosdall et al. 1998b). However, the influence of these agronomic practices on populations of natural enemies of root maggots including Carabidae and the staphylinid beetle *A. bilineata* have never been studied previously in canola agroecosystems. Habitat management, through implementation of varying agronomic practices to produce a particular crop, could provide different microhabitats for insects that are associated with the crop. Hence, the population dynamics of a particular insect species could vary with different microhabitats within the same cropping system. Suitable ecological infrastructures can potentially be created by adopting appropriate agronomic practices to enhance natural enemy populations of root maggots.

The overall goal of my project is to identify agronomic practices that can be used by farmers to increase the effectiveness of natural enemies of root maggots in canola. It is anticipated that ultimately this research will enhance integrated crop management and make canola production more sustainable. Specifically, the objective is to determine the integrated effects of conventional versus zero tillage, seeding rate, and row spacing on root maggots and the natural enemies of root maggots, with emphasis on the rove beetle, *A. bilineata.*

My hypothesis is that by manipulating the agronomic factors of seeding rate, row spacing, and tillage regime, optimal conditions will be found for enhancing natural enemy populations.

The introduction of herbicide-tolerant canola technology and the rapid adoption by growers of hybrid canola varieties have changed important aspects of canola production systems in western North America. However, the high input costs associated with hybrid canola often tempts producers to cut back on various farm operating costs, including costs for maintaining recommended seeding rates and tillage regimes. Although several agronomic studies have been undertaken to evaluate effects of seeding rate, row spacing, and tillage regime on production of open-pollinated canola, to my knowledge, no previous research has been conducted to assess these factors with herbicide-tolerant hybrid canola. In this study, row spacing and seeding rate were altered under conventional versus zero tillage systems to determine effects on seed yield, seed weight, and seed protein and oil contents, on the herbicide-tolerant hybrid canola variety InVigor 5020.

Literature Cited

Anonymous. 1977. Principles and practices of commercial farming. Faculty of Agriculture, University of Manitoba. 520 pp.

Beirne, B.P. 1971. Pest insects of annual crop plants in Canada. I. Lepidoptera. II. Diptera. III. Coleoptera. Mem. Entomol. Soc. Can. 78: 53-59.

Bracken, G.K. 1988. Seasonal occurrence and infestation potential of cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), attacking rutabaga in Manitoba as determined by captures of females in water traps. Can. Ent. 120: 609-614.

Brandt, S. A., S. S. Malhi, D. Ulrich, G. P. Lafond, H. R. Kutcher, and A. M Johnston. 2007. Seeding rate, fertilizer and disease management effects on hybrid versus open pollinated canola (*Brassica napus* L.). Can. J. Plant Sci. 87: 255-266.

Broatch, J.S. 1993. A study of root maggots infesting canola in the Peace River region of Alberta. M.P.M. Thesis, Simon Fraser University, Burnaby, British Columbia. 109 pp.

Broatch, J.S., L.M. Dosdall, G.W. Clayton, K.N. Harker, and R.-C. Yang. 2006. Using degree-day and logistic models to predict emergence patterns and seasonal flights of the cabbage maggot and seed corn maggot (Diptera: Anthomyiidae) in canola. Environ. Ent. 35: 1166-1177.

Broatch, J. S., L. M. Dosdall, R.-C. Yang, K. N. Harker, G. W. Clayton. 2008**.** Emergence and seasonal activity of the entomophagous rove beetle

Aleochara bilineata (Coleoptera: Staphylinidae) in canola in western Canada. Environ. Entomol. 37: 1451-1460.

Brooks, A. 1951. Identification of the root maggots (Diptera: Anthomyiidae) attacking cruciferous garden crops in Canada with notes on biology and control. Can. Ent. 93: 109-120.

Brunel, E., and X. Langlet. 1994. Comparison of the rate of penetration of pupae of *Delia radicum* and *D. antiqua* by first–instar larvae of the parasitoid *Aleochara bilineata*. IOBC Bulletin 17: 141-147.

Caesar, L. 1922. The cabbage maggot. Ontario Department of Agriculture. Bulletin No. 289: 1-39.

Canola Council of Canada 1982. Canola Oil. Properties and performance. Publication No. 60. Published by: Canola Council of Canada.

Canola Council of Canada 2008. Canola in Canada. Socio-Economic Value Report. http://www.canola-council.org. Accessed on 11 August 2008.

Canola Council of Canada. 2009a. Canada's Canola Industry. Adding billions to the Economy. http://www.canola-council.org. Accessed on 3 January 2010.

Canola Council of Canada 2009b. Provincial Acreages and Yields. http://www.canola-council.org. Accessed 3 January 2010.

Coaker, T. H., and D. A. Williams. 1963. The importance of some Carabidae and Staphylinidae as predators of the cabbage root fly, *Erioischia brassicae* (Bouché). Entomol. Exp. Appl. 6: 156-164.

Coaker, T.H., and D.W. Wright. 1963. The influence of temperature on the emergence of the cabbage root fly *Erioisha brassicae* (Bouché) from overwintering pupae. Ann. Appl. Biol. 52: 337-343.

Coaker, T.H. 1969. New approaches to cabbage root fly control. Proc. Fifth British Insectic. Fungic. Conf. pp. 704-710.

Coaker, T.H. 1970. Host plant preference by the cabbage root fly. National Vegetable Research Station 20th Annual Report, pp. 97-98.

Colhoun, E. H. 1953. Notes on the stages and the biology of *Baryodma ontarionis* Casey (Coleoptera: Staphylinidae), a parasite of the cabbage maggot, *Hylemya brassicae* Bouché (Diptera: Anthomyiidae). Can. Entomol. 85: 1-8.

Collier, R.H., and S. Finch. 1983a. Completion of diapause in field populations of the cabbage root fly (*Delia radicum*). Ent. Exp. Appl. 34: 186-192.

Collier, R.H., and S. Finch. 1983b. Effects of intensity and duration of low temperatures in regulating diapause development of the cabbage root fly (*Delia radicum*). Ent. Exp. Appl. 34: 193-200.

Collier, R.H., and S. Finch. 1985. Accumulated temperatures for predicting the time of emergence in the spring of the cabbage root fly, *Delia radicum* (L.) (Diptera: Anthomyiidae). Bull. Entomol. Res. 75: 395-404.

Dosdall, L.M., M.J. Herbut and N.T. Cowle. 1994. Susceptibilities of species and cultivars of canola and mustard to infestation by root maggots (*Delia* spp.) (Diptera: Anthomyiidae). Can. Ent. 126: 251-260.

Dosdall, L.M., M.J. Herbut, N.T. Cowle, and T.M. Micklich. 1996a. The effect of tillage regime on emergence of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) from canola. Can. Ent. 128: 1157-1165.

Dosdall, L.M., M.J. Herbut, N.T. Cowle, and T.M. Micklich. 1996b. The effect of seeding date and plant density on infestations of root maggots, *Delia* spp. (Diptera: Anthomyiidae), in canola. Can. J. Plant Sci. 76: 169-177.

Dosdall, L.M., J. Soroka, and O.O. Olfert. 1998a. Incidence and yield impact of root maggots in canola. Technical Report, Alberta Agricultural Research Institute, Project Number 96M980.

Dosdall, L.M., L.Z. Florence, P.M. Conway, and N.T. Cowle. 1998b. Tillage regime, row spacing, and seedling rate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 78: 671-681.

Dosdall, L.M., R.C. Yang, and P.M. Conway. 2002. Do applications of sulfur or sulfate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 82: 599-610.

Dosdall, L.M., G.W. Clayton, K.N. Harker, J.T. O'Donovan, and F.C. Stevenson. 2004. The effects of soil fertility and other agronomic factors on infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Agron. J. 96: 1306-1313.

Downey, R.K. 1983. The origin and description of the Brassica oilseed crops. *In* Kramer, J.K.G. and W.J. Pigden (eds.), High and Low Erucic Acid Rapeseed Oils, pp. 1-20. Academic Press, New York.

Eckenrode, C.J., and R.K. Chapman. 1971. Effect of various temperatures upon rate of development of the cabbage maggot under artificial conditions. Ann. Ent. Soc. Amer. 64: 1079-1083.

Ellis, P.R., J.D. Taylor, and I.H. Littlejohn. 1982. The role of microorganisms colonizing radish seedlings in the oviposition behaviour of cabbage root fly, *Delia radicum*. Proc. Fifth Int. Symp. Insect-Plant relationships, Wageningen, pp. 131-137.

Finch, S. 1980. Pest assessment as it relates to *Hylemya brassicae* populations. I0BC-WPRS Bull. 3: 1-9.

Finch, S., and G. Skinner. 1976. The effect of plant density on populations of the cabbage root fly (*Eroischia brassicae* (Bouché)) and the cabbage stem weevil (*Ceutorhynchus quadridens* (Panz.)) on cauliflowers. Bull. Ent. Res 66: 113-123.

Finch, S., and G. Skinner. 1982. Trapping female cabbage root flies (*Delia radicum* (L.)) (Diptera: Anthomyiidae) with allyl isothiocyanate-baited traps in England. Bull. Entomol. Res. 72: 165-173.

Finch, S., and M. Kienegger. 1997. A behavioral study to help clarify how undersowing with clover affects host-plant selection by pest insects of brassica crops. Ent. Exp. Appl. 84: 165-172.

Finch, S., C. Hartfield, and E. Brunel. 1999. IOBC/WPRS Working group “Integrated control in vegetable field crops”. Proceedings of the Meeting. IOBC Bulletin 22, 240 pp.

Fournet, S., D. Poinsot, E. Brunel, J. P. Nénon, and A. M. Cortesero. 2001. Do female coleopteran parasitoids enhance their reproductive success by selecting high-quality oviposition sites? J. Anim. Ecol. 70: 1046-1052.

Fuldner, D.1960. Beitrage zur morphologie und biologie von *Aleochara bilineata* Gyll. und *A. bipustulata* L. (Coleoptera: Staphylinidae). Zeitchrift fur Morphologie und Okologie der Tiere 48: 312-386.

Getzin, L.W. 1978. Hybrid cabbage seed. J. Econ. Ent. 71: 528-530.

Gibson, A., and R.C. Treherne. 1916. The cabbage root maggot and its control in Canada with notes on the imported onion maggots and the seed-corn maggot. Dominion of Canada, Department of Agriculture, Entomological Branch, Bulletin No. 12.

Griffiths, G.C.D. 1986a. Phenology and dispersion of *Delia radicum* (L.) (Diptera: Anthomyiidae) in canola fields in Morinville Alberta. Quaest. Ent. 22: 29-50.

Griffiths, G.C.D. 1986b. Relative abundance of the root maggots *Delia radicum* (L.) and *D. floralis* (Fallén) (Diptera: Anthomyiidae) as pests of canola in Alberta. Quaest. Ent. 22: 253-260.

Griffiths, G.C.D. 1991a. Economic assessment of cabbage maggot damage in canola in Alberta. Proceedings of the GCIRC Congress, pp. 528-535.

Griffiths, G.C.D. 1991b. Flies of the Nearctic region. Volume VIII, Part 2, Number 7. Cyclorrhapha II (Schizophora: Calyptratae) Anthomyiidae. E. Schweizerbart'sche Veragsbuchhandlung (Nagele u. Obermiller), Stuttgart, Germany, pp. 953-1048.

Harris, C.R., and H.J. Svec. 1966. Mass rearing of the cabbage maggot under controlled environmental conditions with observations on the biology of cyclodiene-susceptible and resistant strains. J. Econ. Ent. 59: 569-573.

Hawkes, C. 1972. The estimation of the dispersal rate of the adult cabbage root fly (*Erioischia brassicae* (Bouché)) in the presence of a brassica crop. J. Appl. Ecol. 9: 617-632.

Hemachandra, K. S., N. J. Holliday, P. G. Mason, J. J. Soroka, and U. Kuhlmann. 2007. Comparative assessment of the parasitoid community of *Delia radicum* in the Canadian prairies and Europe: A search for classical biological control agents. Biol. Control 43: 85–94.

Holliday, N. J. 2003. Classical Biological Control of Root Maggots, *Delia* spp. on Canola. Manitoba Agriculture, Food and Rural Initiatives. http://www.gov.mb.ca. Accessed on 22 June 2010.

Hopkins, R.J., F. Wright, A.N.E. Birch, and R.G. Mckinlay. 1999. The decision to reject an oviposition site: Sequential analysis of the post-alighting behavior of *Delia floralis*. Physiol. Ent. 24: 41-50.

Hughes, R. D. 1959. The natural mortality of *Erioischia brassicae* (Bouché) (Diptera, Anthomyiidae) during the egg stage of the first generation. J. Anim. Ecol. 28: 343-357.

Hughes, R.D., and D. Salter. 1959. Natural mortality of *Erioischia brassicae* Bouché (Dipt., Anthomyiidae) during the immature stages of the first generation. J. Anim. Ecol. 28: 231-241.

Klimaszewski, J. 1984. A revision of the genus *Aleochara* Gravenhorst of America north of Mexico. (Coleoptera: Staphylinidae, Aleocharinae). Mem. Ent. Soc. Can. 129. 211 pp.

Kostal, V., and S. Finch. 1994. Influence of background on host-plant selection and subsequent oviposition by the cabbage root fly (*Delia radicum*). Ent. Exp. Appl. 70: 153-163.

Lamb, R. J. 1989. Entomology of oilseed Brassica crops. Ann. Rev. Ent. 34: 211-229.

Langlet, X., G. Boivin, E. Brunel, and J. P. Nénon. 1998. Variation in weight of *Aleochara bilineata* (Coleptera: Staphylinidae) in relation to host size and reproduction. Can. Entomol. 130: 257-265.

Maus, C., B. Mittmann, and K. Peschke. 1998. Host records of parasitoid *Aleochara* Gravenhorst species (Coleptera: Staphylinidae) attacking puparia of cyclorrhapheous Diptera. Dtsch. Entomol. Z. 45: 231-254.

McDonald, R.S. 1985. Impact of the cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), on canola, *Brassica campestris* L., in north central Alberta. M. Sc. thesis, University of Guelph, Guelph, Ontario. 98 pp.

McDonald, R.S., and M.K. Sears. 1992. Assessment of larval feeding damage of the cabbage maggot (Diptera: Anthomyiidae) in relation to oviposition preference in canola. J. Econ. Ent. 85: 957-962.

Miles, M. 1952. Studies of British anthomyiid flies. III. Immature stages of *Delia cilicrura* (Rond.), *D. trichodactyla* (Rond.), *Erioishia brassicae* (Bouché), *E. floralis* (Fall.) and *Pegohylemyia fugax* (Mg.). Bull. Entomol. Res. 43: 83-90.

Mukerji, M.K. 1971. Major factors in survival of the immature stages of *Hylemya brassicae* (Diptera: Anthomyiidae) on cabbage. Can. Ent. 103: 717-728.

Mukerji, M.K. 1971. Major factors in survival of the immature stages of *Hylemya brassicae* (Diptera: Anthomyiidae) on cabbage. Can. Ent. 103: 717-728.

Nair, K.S.S., and F.L. McEwen. 1976. Host selection by the adult cabbage maggot, *Hylemya brassicae* (Diptera: Anthomyiidae): Effect of glucosinolates and common nutrients on oviposition. Can. Ent. 108: 1021-0130.

Read, D. C. 1962. Notes on the life history of *Aleochara bilineata* (Gyll.) (Coleoptera: Staphylinidae), and on its potential value as a control agent for the cabbage maggot, *Hylemya brassicae* (Bouché) (Diptera: Anthomyiidae). Can. Ent. 94: 417-424.

Read, D.C. 1958. Factors influencing infestation and injury of rutabagas by root maggots (Diptera: Anthomyiidae) in Prince Edward Island. I. Field Studies. Can. J. Plant Sci. 38: 188-198.

Read, D.C. 1969. Rearing the cabbage maggot with and without diapause. Can. Ent. 101: 725-737.

Royer, L., J. LeLannic, J. P. Nenon, and G. Boivin. 1998. Response of first-instar *Aleochara bilineata* larvae to the puparium morphology of its dipteran host. Ent. Exp. Appl. 87: 217-220.

Schoene, W.J. 1916. The cabbage maggot, its biology and control. Bull. N.Y. State Agric. Exp. Station 419: 99-160.

Soroka, J.J., L.M. Dosdall, O.O. Olfert, and E. Seidle. 2004. Root maggots (*Delia* spp., Diptera: Anthomyiidae) in prairie canola (*Brassica napus* L. and *B. rapa* L.): Spatial and temporal surveys of root damage and prediction of damage levels. Can. J. Plant Sci. 84: 1171-1182.

Statistics Canada. 2009. Canola: a Canadian success story. Component of Statistics Canada Catalogue no. 96-325-X. http://www.statcan.gc.ca. Accessed on 3 January 2010.

Thomas, P. 2003. Canola Growers Manual. http://www.canolacouncil.org. Accessed on 3 January 2010.

Traynier, R.M.M. 1967a. Stimulation of oviposition by the cabbage root fly *Erioischia brassicae*. Ent. Exp. Appl. 10: 401-412.

Traynier, R.M.M. 1967b. Effect of host plant odour on the behaviour of the adult cabbage root fly, *Erioischia brassicae*. Ent. Exp. Appl. 10: 321-328.

Turnock, W.J., B. Timlick, B.E. Galka, and P. Palaniswamy. 1992. Root maggot damage to canola and the distribution of *Delia* spp. (Diptera: Anthomyiidae) in Manitoba. Can. Ent. 124: 49-58.

Turnock, W.J., T.H. Jones, and P.M. Reader. 1985. Effects of cold stress during diapause on the survival and development of *Delia radicum* (Diptera: Anthomyiidae) in England. Oecologia 67: 506-510.

Vincent, C. and R. K. Stewart. 1980. Niveau de dommage économique de la mouche du chou, *Hylemya (Delia) brassicae* (Wiedemann) (Diptera: Anthomyiidae). Attaquant le chou. Phytoprotection 61: 107-103.

Wishart, G., J.F. Doane and E.G. Maybee.1956. Notes on beetles as predators of eggs of *Hylemya brassicae* (Bouché) (Diptera: Anthomyiidae). Can. Ent. 88: 634-637.

WPRS Bull. 3: 1-9.

Wright, D.W., R.D. Hughes, and J. Worral. 1960. The effect of certain predators on the number of cabbage root fly (*Erioischia brassicae)* (Bouché) and on the subsequent damage caused by the pest. Ann. Appl. Ent. 48: 756-763.

Wyman, J.A., J.L. Libby, and R.K. Chapman. 1977. Cabbage maggot management aided by predictions of adult emergence. J. Econ. Ent. 70: 327-331.

Chapter 2

Effects of tillage regime, seeding rate, and row spacing on seedling emergence, yield, seed weight, and seed quality of canola (*Brassica napus*) in central Alberta.

2.1 Introduction

Canola (*Brassica napus* L. and *Brassica rapa* L.) is one of the major oilseed crops grown worldwide, and the crop has undergone significant expansion of its production area during the past two decades (Howlett et al. 2001). In the Canadian prairies, canola is an economically important crop produced on more than five million ha of Canada's 76 million ha of farm land (Statistics Canada 2009). Canola is grown for its food-grade oil for human consumption and for high-protein livestock feed. Canola seeded in the 2006 crop year yielded approximately 9.0 million tonnes, and by 2008 production surpassed 10.0 million tonnes. In 2006 Canadian canola/rapeseed production ranked second in the world behind China and ahead of India, Germany, and France (Statistics Canada 2009). More than one-half of the 9.0 million tonnes of canola produced in Canada were exported in 2006 in various forms (Statistics Canada 2009). By 2005, canola had surpassed wheat in terms of revenue to become the most valuable field crop in Canada (Statistics Canada 2009). Farm cash receipts for wheat totaled $2.2 billion in 2006, while those for canola totaled $2.5 billion (Statistics Canada 2009). Canola is often grown in rotation with Canada's traditional cereal crops of wheat, oats, and barley.

Low water availability is the greatest limitation to crop production in the Canadian semiarid prairie where most of Canada's canola is grown (Cutforth et al. 2006). Generally, in agricultural areas, 50 to 60 percent of annual precipitation occurs during the growing season, mostly as rain, but crop water use generally exceeds precipitation during the growing season in Alberta (Alberta Agriculture 2004). Therefore overwinter precipitation is important for building soil moisture reserves for crop production. In the interval between harvest and seeding of annual crops, 25 to 30 percent of the precipitation is rain, while the rest is snow (Alberta Agriculture 2004). From long-term weather data, daily precipitation begins to decline three to four weeks before average daily maximum temperatures have reached their highest values in late July (Angadi et al. 2003). Therefore, the moisture deficit for the semiarid prairie increases as the growing season progress (Cutforth et al. 2006). The transpirational component of evapotranspiration can be increased by increasing the water supply and /or by decreasing water losses (Cutforth et al. 2006). Low-disturbance direct seeding into standing stubble is a very effective practice for increasing the water supply and for reducing evaporation (Cutforth et al. 2006). Soil water regimes are a function of precipitation, transpiration, evaporation, run-off and drainage (Lafond and Derksen 1996).

There is growing interest among farmers worldwide to adopt conservation tillage to overcome various constraints to crop production. One of the most important benefits of conservation tillage, which maintains surface residues and standing stubble, is the ability to trap snow, improve infiltration, reduce run-off, and minimize evaporative losses (Smika and Unger 1986). A recent survey revealed that 25% of cropped land in the Canadian prairies is seeded with reduced tillage and 53% with zero-tillage production practices (Statistics Canada 2010). However, it appears that a considerable number of farmers in Canada still prefer to produce canola under conventional tillage. A wide range of tillage practices are adopted for a number of reasons in modern agriculture. Conventional tillage systems involve cultivating and harrowing of the topsoil, while the general term conservation tillage refers to tillage systems with less soil disturbance and higher coverage of the soil surface with crop residues (Tebrügge and Düring 1999). With conventional tillage, soil erosion by both water and wind are accelerated, often resulting in extensive soil degradation (Young et al. 1994). Conservation tillage includes techniques such as direct seeding which places seeds with minimal disturbance in the soil, zero tillage or no-till which leaves all crop residue on the soil surface, or minimal tillage which leaves varying amounts of residue on the soil surface by performing a varied number of tillage operations at different times in the year (Bailey and Duczek 1996). Reduced tillage creates increasing amounts of crop residue on the surface while crop rotation alters residue quality and quantity by introducing other crop species (Bailey and Duczek 1996). As a rule, reduced tillage systems improve water storage and availability of water for crop growth (Lafond and Derksen 1996).

Different seeding rates can be used to adjust plant densities in fields for a number of reasons (Neal 1981). Increased plant density can be associated with changes in the rate of development of canola plants and such developmental alterations can eventually cause changes in the magnitude of each yield component. A common expectation is that increasing seeding rates with a specific row spacing will result in increased plant density at harvest. However, the density of mature plants at harvest depends upon a series of factors and processes, including the initial seeding rate, germination rate, natural seedling mortality, and plant losses from environmental stresses, including insects and diseases (Robert and Walker 1994). For the past 30 years, many researchers involved in canola production have conducted research to attain improved grain yield and quality by adjusting seeding rates, in conjunction with other agronomic practices. A study on the influence of seeding date and seeding rate on seed yield and growth characters of five genotypes of *B. napus* was carried out by Degenhardt and Khondra (1981). This study revealed that Seeding rate did not influence yield performance. Brandt et al. (2007) compared hybrid versus open-pollinated canola in terms of seed yield and quality by combining various levels of seeding rates and fertilizer levels. This study also revealed that the two cultivars did not differ in their responses to seeding and fertilizer rates, nevertheless, overall, the HYB performed better than the OP. Harker et al. (2003) conducted research to identify the optimal combination of cultivar, seeding rate and weed removal timing with respect to weed management, canola yield and quality. Harker et el (2003) reported that combining the better cultivar with the highest seeding rate, and the earliest time of weed removal led to a 41% yield increase compared with the combination of the weaker cultivar, the lowest seeding rate and the latest time of weed removal. Tartary buckwheat (*Fagopyrum tataricum*) was effectively suppressed when canola (*B. rapa*) seeding rate was increased from 2 to 8 kg per ha (O’Donovan 1996).

The optimal row spacing for crops is often established through empirical observations, and once established, changes little over the years (Neal 1981). Leaf area, Net Assimilation Rate (NAR), leaf shape and angle are important considerations in managing some agronomic aspects such as plant density and row spacing. Yield ultimately depends on the rate of addition of dry matter per unit area of land and this depends on the efficiency of the photosynthetic process, and the extent of the photosynthetic surface. The relationship between canopy type and yield is highly management dependent (Robert and Walker 1994). In the era of hybrid canola production, various considerations are involved when selecting a specific row spacing. In practice, row spacing and plant density must be considered concurrently (Neal 1981). In the history of canola research trials in the past 20 years, various research studies have been conducted to realize improved grain yield and quality in canola by manipulating row spacings in conjunction with other agronomic practices. Johnson and Hanson (2003) conducted a study on row spacing interactions on spring canola performance in the Northern Great Plains and found that yield and seed oil content, the primary characters determining crop value were not affected by row spacing. The effect of planting pattern on morphology, yield and yield components of three spring canola varieties were compared by Pak et al. (2008) in Iranian climatic conditions. Dosdall et al. (1998) conducted a study on root maggot infestation and canola yield by manipulating tillage regime, row spacing and seeding rate. Dosdall et al (1998) reported that increased yield was associated with wider row spacings, but there was no apparent relationship between higher plant densities and seed yield.

Xie et al. (1998) conducted a study to manipulating row spacing and seed/fertilizer placement to compare agronomic performance of wheat and canola in a zero tillage system. Xie et al (1998) reported that in zero tillage and intensive management systems, the paired– row seed/fertilizer placement at the 25- or 38-cm row spacings resulted in the best performance for wheat, and the paired- row seed at the 38- cm row spacing resulted in the best performance for canola.

Canadian canola production history reveals that Canadian farmers adopted hybrid canola varieties rapidly as compared with farmers in the other parts of the world (Blackshaw et al. 2008). Adoption of hybrid canola increased from 15 to 70% during 2003 to 2008. Herbicide-tolerant technology has also received widespread adoption. The 2006 harvest comprised 95% non-conventional herbicide-tolerant canola varieties that included 50% Roundup Ready (resistant to glyphosate), 30% Liberty Link (resistant to glufosinate ammonium), 15% Clearfield (resistant to imidazoline), and 5% conventional canola (Broad 2005).

The introductions of herbicide-tolerant canola systems and hybrid canola varieties have changed the nature of canola production (Harker et al. 2003). However, the high cost of production involved for hybrid canola often tempts producers to cut back on various farm operating costs including, costs involved in seeding rate and tillage operations. Studies in different ecoclimatic regions in Alberta were conducted to determine the performance of canola varieties, in relation to different agronomic practices, to better inform the producers on various issues associated with canola production. The objective of this study was to investigate the impact of conventional versus zero tillage systems, used in conjunction with four seeding rates and three different row spacings on seedling emergence, seed yield, seed weight, and percent seed protein and oil contents of the herbicide tolerant hybrid canola variety InVigor 5020.

2.2 Materials and Methods

2.2.1 Study Sites and Experimental Design

The study was conducted at two sites in central Alberta in 2007 and 2008: Lacombe (113°44´W; 52°28´N) and Vegreville (112°03´W; 53°30´N). Soil type at both sites was black Chernozemic loam. At Lacombe soil composition was 34% sand, 39% silt, and 27% clay with a pH of 7.3 and 9.3% organic matter. At Vegreville the soil composition was 35% sand, 34% silt, and 31% clay with a pH of 6.3 and 7.2% organic matter.

Plots were seeded to a cereal crop (barley, *Hordeum vulgare* L.) in the years preceding the study. Plots subjected to zero tillage were seeded directly into the cereal stubble in a narrow slot opened by the planter with minimal disturbance of the surface crop residue. No additional tillage was done for seedbed preparation as compared to conventional tillage where the soil was worked with at least two cultivations to a depth of approximately 8 cm prior to seeding. Weeds were removed when canola was in the three-to four-leaf stage with Liberty Link (glufosinate ammonium) herbicide at the recommended rate of 500 g ai/ha along with clethodim (Select® /Centurion®) 15 g ai/ha and Amigo® (surfactant) at 0.5% v/v.

Plots of *B. napus* cv. InVigor 5020 were seeded at Lacombe on 10 May 2007 and 5 May 2008, and at Vegreville on 15 May in 2007 and 2008. The sites were fertilized according to the soil test recommendation for canola production. Plots at Lacombe were seeded with a Conserva Pak® no-till drill whereas plots at Vegreville were seeded with a double-disc no-till drill.

The field experiment was a randomized complete block, strip-plot design with four replicate plots per treatment. Tillage treatment (conventional- and zero-till) was assigned to 'vertical strips' and the 12 treatment combinations (4 by 3 full factorial: seeding rate had four levels and row spacing had three levels) were assigned randomly to 'horizontal strips' perpendicular to the tillage treatment strips. Row spacings used in the study were 22, 30, and 45 cm, and seeding rates were 2.5, 5.0, 7.5, and 10.0 kg per ha. Each sub-plot measured 4 by 15 m. Seed number was adjusted for each seeding rate and row spacings to achieve target canola densities of 60, 120, 180, and 240 plants per square meter. These seeding rates corresponded approximately to 0.5, 1.0, 1.5, and 2.0 times the recommended seeding rates for canola production (Thomas 2003).

2.2.2 Data Collection

Data collected included plant emergence counts, canola seed yield, 1,000 kernel weight, canola seed oil content and canola seed protein content. Plant emergence counts were taken when the rows of seedlings were easily visible. At Lacombe, plant emergence counts were performed on 3 June 2007 and 5 June 2008 whereas in Vegreville the counts were completed on 5 June 2007 and 9 June 2008. Two counts of seedlings were performed from each treatment sub plot. For each count the total number of plants from either side of a one-meter strip of a randomly selected row was used. To avoid edge effects, the two rows along the plot edges were not used for emergence counts.

At Lacombe canola plants were swathed on 21 August 2007 and 27 August 2008. Swathing was performed when 30 to 40% of seed on the main stem had undergone color change. The swathed canola was threshed approximately two weeks later when the seed moisture content dropped to approximately 10%. At Vegreville canola plants were directly combined on 28 August 2007 and 27 August 2008 after applying Reglone® (1,1'-ethylene-2,2'-bipyridinium di bromide) as a chemical desiccant.

During the fall of each production year the harvested canola from both sites was processed at the Lacombe Research Centre of Agriculture Agri-Food Canada to determine the dockage due to weed seed contamination and 1,000 kernel weight. After threshing, the grains were further analyzed to determine the oil and protein contents. Protein content was determined using Near-Infrared Reflectance Spectroscopy. Oil content was determined from 20 g of whole seeds from the clean sample with Nuclear Magnetic Resonance (NMR) utilizing a Newport Analyser

MklllA. Samples were dried in coin envelopes for 48 h at 35ºC, followed by cooling for 24 h at room temperature. Results of oil and protein analyses were reported as percentages of seed weight.

2.2.3 Data Analysis

Treatment effects were determined by analysis of variance (ANOVA) using the Proc Mixed procedure (SAS Institute Inc. 2003). Methods of Gomez and Gomez (1984) were used as a basis for comparing fixed treatment effects (seeding rate, row spacing, and tillage regime) having block (replication) as a random effect. The model used to fit the data at each site within the same year was:

$$\mathbf{Y_{ijkl} = \mu + p_i + a_j + (pa)_{ij} + b_k + (pb)_{ik} + c_l + (pc)_{il} + (ab)_{jk} + (ac)_{jl} + (bc)_{kl} + (abc)_{jkl} + (pab)_{ijk} + (pac)_{ijl} + (pbc)_{ikl} + (pabc)_{ijkl} + \varepsilon_{ijkl}}$$

Where,

Y_{ijkl} : response variable corresponding to j^{th} level of tillage regime, k^{th} level of seeding rate, l^{th} level of row spacing in the i^{th} block.

μ : overall expected population mean response.

p_i : effect of i^{th} block .

a_j : effect of j^{th} level of tillage regime.

b_k : effect of k^{th} level of seeding rate.

c_l : effect of l^{th} level of row spacing.

$(ab)_{jk}$: interaction between j^{th} level of tillage regime and k^{th} level of seeding rate.

$(ac)_{jl}$: interaction between j^{th} level of tillage regime and l^{th} level of row spacing.

$(bc)_{k\,l}$: interaction between k^{th} level of seeding rate and l^{th} level of row spacing.

$(abc)_{j\,k\,l}$: interaction between j^{th} level of tillage regime, k^{th} level of seeding rate and l^{th} level of row spacing.

The error components $(pa)_{i\,j}$, $(pb)_{i\,k}$, $(pc)_{i\,l}$, $(pab)_{i\,j\,k}$, $(pac)_{j\,l}$, $(pbc)_{i\,k\,l}$, $(pabc)_{i\,j\,k\,l}$ and $\varepsilon_{i\,j\,k\,l}$ are random effects in the model. Block refers to a complete set of replicates for treatment combinations, tillage refers to tillage regime (conventional- and zero-till), seed rate refers to four levels of seeding rates, row spacing refers to three levels of row spacings, and ε is the random, residual variance component of the model. Response variables were yield, 1000 kernel weight, and oil and protein contents of canola grains.

2.3 Results

2.3.1 Environmental Conditions

Precipitation at Lacombe during the growing season of 2007 from April to June exceeded long-term mean values (1971-2008), but in July precipitation was considerably lower than the long-term mean value (Table 2.1). Thereafter precipitation was similar to long-term mean values. In 2008, precipitation at Lacombe was lower than the long-term mean values throughout the growing period except for June when approximately 25 mm more precipitation was received than the mean. Mean air temperature at Lacombe during the 2007 growing season was consistent with the long–term average values although in April the mean temperature was lower than the long-term mean, and in July the temperature exceeded than the long-term average by nearly 4˚C. In 2008, temperatures were relatively consistent with long-term average values, except for slightly cooler than the normal conditions in April (Table 2.1).

At Vegreville, approximately two-fold more precipitation occurred than the long-term mean value (1971-2008) in the month of April in both years (Table 2.1). In 2007 precipitation was lower than long-term mean values from May through September for every month except August. In 2008 precipitation was similar to the long-term mean in May, less than the long-term normal in June, July, and September and greater than the normal value in August. Most of the time, in 2007, mean air temperatures exceeded the long-term mean values (1971-2008) except in the month of April. However, in 2008 the mean air temperature was similar to the long-term mean values every month except April (Table 2.1).

2.3.2 Canola Seedling Emergence – Plant Density

Tillage significantly affected canola plant density only at Lacombe in 2007 (highest under zero-tilled plots) and Vegreville in 2008 (highest under conventionally-tilled plots) (Table 2.2; Figure 2.1). As expected increasing the seeding rate always significantly increased canola plant density (Table 2.2; Figure 2.2). The effect of row spacing was variable depending on site-years. Row spacing significantly affected canola plant density only at Lacombe in 2007 and Vegreville in 2008 (Table 2.2; Figure 2.3). At Lacombe in 2007, mean canola plant density declined as row spacing increased from 30 to 45 cm (Figure 2.3). However, at Vegreville in 2008, plant density increased with an increase in row spacing (Figure 2.3). In all site-years, at the time of counting, mean canola plant density exceeded the targeted plant density of *B. napus* for optimum yield which is 70 to 120 plants per square meter (Alberta Agriculture 2009).

2.3.3 Canola Seed Yield

Seed yield was not affected by tillage (Table 2.2; Figure 2.4). Seeding rate affected yield only at Lacombe in 2007 (Table 2.2) where yield tended to increase with seeding rate up to an optimum (Figure 2.4). There were trends towards a decrease in yield above 7.5 kg/ha with zero tillage and above 5 kg/ha with conventional tillage. Row spacing significantly affected yield only at vegreville in 2008 where optimum yield occurred at 30 cm (Figure 2.6). At Lacombe in 2008, a three-way interaction suggests that yield was optimized at 5.0 kg/ha seed rate and 30 cm row spacing with zero tillage; and 7.5 kg/ha and 45 cm spacing with conventional tillage (Appendix 1, Table 4).

2.3.4 Thousand Kernel Weight (1,000 K)

The effect of tillage was significant at Lacombe in 2008 and Vegreville in 2007 and 2008 (Table 2.2) but effects were variable. 1,000 K weights were higher under conventional tillage at Lacombe and Vegreville in 2008 (Figure 2.7). The opposite occurred at Vegreville in 2007. 1,000 K weights were similar among different seeding rates and row spacings

(Figures 2.8, 2.9). At Vegreville in 2007, a three-way interaction suggests that 1, 000 K weights were optimized at 10 kg/ha seed rate and 30 cm row spacing with zero tillage; and 2.5 kg/ha and 35 cm spacing with conventional tillage (Appendix 1, Table 5, 6).

2.3.5 Canola Seed Protein Concentration

Seed protein content was unaffected by tillage treatment and seeding rate (Table 2.2, Figures 2.10, 2.11). At Lacombe in 2007 only row spacing produced statistically significant results for canola seed protein content ($P = 0.0048$) (Table 2.2). The highest mean protein content (23.3%) occurred at a row spacing of 30 cm and the lowest mean protein content (22.5%) occurred at a row spacing of 22 cm (Appendix 1, Table 8). In both zero- and conventionally-tilled plots, seed protein increased when row spacing increased from 22 to 30 cm and decreased when row spacing increased from 30 to 45 cm (Figure 2.12). In zero-tilled plots, mean differences for row spacings of 22 and 30 cm were statistically significant ($P = 0.0166$) (Appendix 1, Table 9). In conventionally-tilled plots, mean differences for 22 and 30 cm, and 30 and 45 cm were statistically significant ($P = 0.0043$ and $P = 0.0339$ respectively) (Appendix 1, Table 9). In 2008, at Lacombe, the two-way and the three-way interactions produced statistically significant results for canola seed protein content (Table 2.2). However, at Vegreville both in 2007 and 2008 none of the individual treatments or treatment combinations produced statistically significant results on canola seed protein content ($P > 0.05$). In 2008, at Lacombe in zero-tilled plots, the seeding rate of 7.5 kg per ha at a row spacing 30 cm produced highest protein content (22.6%) whereas the seeding rate 5.0 kg per ha at a row spacing of 22 cm produced the lowest protein content (19.7%) (Appendix 1, Table 10). Moreover among zero-tilled plots, 10 pairs of treatment combinations had mean differences that are statistically significant (Appendix 1, Table 10). In plots subjected to conventional tillage, the seeding rate of 10.0 kg per ha by row spacing of 30 cm produced the highest seed protein content (21.7%) and the seeding rate of 7.5 kg per ha at a row spacing of 22 cm produced the lowest seed protein content (19.6%). At the same time, among conventionally-tilled plots, nine pairs of treatment combinations had mean differences that are statistically significant (Appendix 1, Table 11).

2.3.6 Canola Seed Oil Concentration

Only two main effects, seeding rate and row spacing, had statistically significant effects on seed oil content in 2007 at Lacombe ($P = 0.0027$ for seeding rate and $P = 0.0043$ for row spacing) (Table 2.2) (Figs. 2.13, 2.14, 2.15). But in 2008, at Lacombe, the two-way interaction (seeding rate by row spacing) and the three-way interaction (tillage regime by seeding rate by row spacing) produced statistically significant results for seed oil content ($P = 0.0018$ for the two-way interaction and $P = 0.0046$ for the three-way interaction). At Vegreville, both in 2007 and

2008, none of the main treatment effects or treatment combinations produced statistically significant results for seed oil content (Table 2.2).

At Lacombe, in 2007, seeding rate of 10 kg per ha produced the highest oil content of 46.6% whereas seeding rate of 2.5 kg per ha produced the lowest oil content of 45.5% (Appendix 1, Table 12). Moreover, mean difference for seed oil content between 2.5 kg per ha and 5.0 kg per ha was statistically significant (*P* = 0.0025). Mean differences were not statistically significant between seeding rates of 5.0 and 7.5 kg per ha (*P* = 0.7977), 7.5 and 10.0 kg per ha (*P* = 0.2827), and 5.0 and 10.0 kg per ha (*P* = 0.1965). At the same time, mean differences were statistically significant between seeding rates of 2.5 and 7.5 kg per ha (*P* = 0.0039) and between 2.5 and 10.0 kg per ha (*P* = 0.0005) (Appendix 1, Table 13). Moreover, in zero-tilled plots only the 2.5 and 10 kg per ha combination resulted in statistically significant mean difference whereas in conventionally tilled plots three pairs resulted in a statistically significant mean differences (in zero-tilled plots *P* = 0.0116 for 2.5 and 10.0 kg per ha; in conventionally-tilled plots *P* = 0.0018 for 2.5 and 5.0 kg per ha; *P* = 0.0019 for 2.5 and 7.5 kg per ha; *P* = 0.0006 for 2.5 and 10.0 kg per ha) (Appendix 1, Table 13).

In terms of row spacings, mean differences between all three pairs of row spacings were statistically significant (*P* = 0.0015 for row spacings of 22 and 30 cm, *P* = 0.0203 for row spacings of 22 and 45 cm, and *P* =

0.0467 for row spacings of 30 and 45 cm) (Appendix 1, Table 14). At the same time, in both tillage treatments least square mean difference between 22 and 30 cm resulted in statistically significant results (P = 0.0169 for zero-tilled plots; P = 0.0037 for conventionally-tilled plots) (Appendix 1, Table 14).

At Lacombe in 2008, among all the zero-tilled plots, the 5.0 kg per ha by 22 cm combination produced the highest mean value of 49.5% and the 7.5 kg per ha by 30 cm combination produced the lowest mean value of 47.3% for canola seed oil content. Moreover, 11 pairs of treatment combinations produced mean differences that are statistically significant (Appendix 1, Table 14). At the same time, in conventionally-tilled plots, the 7.5 kg per ha by 22 cm combination produced the highest mean value of 49.6% and the 10.0 kg per ha by 30 cm combination produced the lowest mean value of 47.8% for canola seed oil content. Moreover, eight pairs of treatment combinations produced mean differences that are statistically significant. (Appendix 1, Table 16).

In general, an inverse relationship was observed between seed protein content and oil content. For example, in Lacombe 2008 the combination of agronomic practices that produced highest seed protein content always produced lowest seed oil content (in zero-tilled plots, the seeding rate of 7.5 kg per ha at a row spacing of 30 cm and in conventionally-tilled plots, the seeding rate of 10.0 kg per ha at a row spacing of 30 cm) and the combination of agronomic practices that produced lowest seed protein content always produced highest seed oil content (in zero-tilled plots, the seeding rate of 5.0 kg per ha at a row spacing of 22 cm and in conventionally-tilled plots, the seeding rate of 7.5 kg per ha at a row spacing of 22 cm) (Appendix 1, Tables 10, 11, 14 and 15).

2.4 Discussion

Environmental conditions during all four site-years were generally conducive to good seedling germination and emergence. However, at Vegreville in 2007, canola plants in one section of the experimental site were not as vigorous in their development as in the remainder of the site. Upon completion of thorough examinations of the seedlings at this site, and after considering its cropping history, it was concluded that herbicide carry-over from previous years likely affected plant development and yield. Data from the affected plots were therefore not included in my analysis.

Seed germination and seedling emergence result from a series of biological events initiated by water imbibitions followed by enzymatic metabolism of storage nutrients (Gusta et al. 2003). Seedling emergence is apparently more sensitive than germination to adverse environmental conditions and differences in seed quality (Clarke and Moore 1986). In this study, uniform emergence of canola seedlings was observed in all site-years except the herbicide-damaged area in Vegreville in 2007. Nevertheless canola seedling counts varied among site-years.

Following seed germination and seedling emergence, successful crop establishment depends on many factors which include soil moisture, soil temperature, seeding depth, pest issues and other abiotic and biotic factors. Canadian studies (Thomas 2003) have shown that under favourable conditions 60 to 80% of Canola seed planted produce viable plants, and this declines to 40 to 60% of germinated seeds under average conditions. Anticipated plant densities for different seeding rates used for this study were 60, 120, 180 and 240 plants per square meter for seeding rates of 2.5, 5.0, 7.5 and 10.0 kg per ha respectively. However, not all the treatment combinations achieved the expected plant densities. Nevertheless, in general, in all site-years at the time of counting, mean canola plant density for each treatment combination exceeded the desired plant density of *B. napus* for optimum yield, which is 70 to 120 plants per square meter (Alberta Agriculture 2009). Moreover, the achieved plant densities at the time of counting have surpassed the 50% emergence estimate, which is considered as a representative average of canola emergence under field conditions (Harker et al. 2003). Usually, in an experimental set-up like this, low soil temperature and lack of available moisture in the spring can delay and reduce seedling emergence (Gusta et al. 2003). Many canola crops have delayed and reduced emergence if precipitation does not occur within 10 to 14 days of sowing (Zheng et al.

1998). In addition to cool temperatures in the spring, most Canadian prairie soils are also exposed to rapid drying on the surface when disturbed by any form of cultivation (Zheng et al. 1998).

In general, zero-tilled plots had relatively greater plant density as compared to conventionally-tilled plots in all site-years except in Vegreville in 2008. This result was presumably attributed to improved utilization of water from spring snow melt facilitated by the surface-retained barley stubble. Stubble retention is widely promoted as a key component of conservation cropping systems designed to reduce erosion and soil degradation, increase water availability to crops and maintain soil organic matter (Bruce et al. 2006). However, at Vegreville in 2008, greater plant density was obtained in conventionally-tilled plots and this is likely due to increased soil temperatures during seed germination and seedling emergence in conventionally-tilled plots as compared to zero-tilled plots. This result agreed somewhat with the study performed in Australia by Bruce et al. (2006), although effects in this study were not as dramatic. Bruce et al. (2006) found that surface-retained wheat stubble caused poor canola germination and emergence and eventually reduced canola vegetative biomass by 46% and yield by 26%. Soils under zero-tilled management have been reported to exhibit lower daily maximum temperature than conventionally-tilled soils (Gauer et al. 1982; Grant et al. 2004).

As expected in all site-years, increasing seeding rates from 2.5 to 10.0 kg per ha increased plant densities significantly and this result is in conformity with previous studies conducted by Brandt et al. (2007) and Christensen and Drabble (1984). This trend was reported in both tillage regimes in this study (Figure 2.2). Current seeding rate recommendations for canola in North Dakota and western Canada are to seed between 5.6 and 9.0 kg per ha, depending on seed bed conditions at the time of seeding, with the aim of establishing a plant population of 40 to 200 plants per square meter (Berglund and McKay 2002; Thomas 2003). This study has documented the clear plant density differences that can occur with different seeding rates.

Row spacing resulted in statistically significant results for plant density at Lacombe in 2007 and at Vegreville in 2008. Most previous studies of interactions among plant densities and row spacings were conducted in situations where seed numbers were not adjusted for each row spacing and seeding rate as in this study. Sims (1976) reported a significant increase in plant populations (plant density) corresponding to reduced row spacing, and Christensen and Drabble (1984) stated that plant densities varied significantly between row spacings but there was no clear pattern. In this study, at Lacombe in 2007 in both tillage regimes, plant density increased with increasing row spacing from 22 to 30 cm and then plant density decreased with increasing row spacing from 30 to 45 cm. However, at Vegreville in 2008 plant density increased with increasing row spacing from 22 cm to 45 cm in both tillage regimes. Reasons for these variable results are not known.

Canola grain yield is the product of four major components including number of plants per unit area, number of pods per plant, number of seeds per pod and the seed weight (Thomas 2003; Clarke et al. 1978). Agronomic practices and the environment greatly influence each canola yield component (Thomas 2003). In this study tillage regime did not have a significant effect on yield. The results suggest that regardless of tillage regime, crops responded similarly in terms of photosynthesis and all the other crop physiological processes related to grain production. These results agree with the findings of Brandt et al. (1992).

Seeding rate had no significant effect on canola grain yield in all but one site-year. This finding is in agreement with the studies conducted by Kondra (1975) and Degenhardt and Kondra (1981) who found that seeding rates had no consistent effect on yield. Similarly Christensen and Drabble. (1984) determined that there were no significant yield differences due to seeding rates. However, several studies found important yield effects in relation to seeding rate. Clarke et al. (1978) determined that the effects of seeding rates on seed yield were more pronounced than those reported by Kondra (1975), and indicated that higher rates than those recommended may be beneficial. Seed yield was less with 4 kg per ha than with 8.0, 12.0 or 16.0 kg per ha (Brandt et al. 1992). Morrison et al. (1990)

achieved maximum yields with low seeding rates of 1.5 and 3.0 kg per ha. Clarke and Simpson (1978) achieved maximum yield with a seeding rate of 20.0 kg per ha under dryland conditions and 5.0 to 10.0 kg per ha under irrigated conditions. It is evident, therefore, that previous canola seeding rate studies have given variable results.

Like seeding rate, row spacing had no significant effect on grain yield in all but one site-year. Narrow row spacing generally produced higher yields than wider row spacing in oilseed crops (Kondra 1975). This pattern was generally observed in my studies even though the effect of row spacing on canola seed yield was not statistically significant in most site-years. The three-way interaction of tillage regime, seeding rate and row spacing and the two-way interaction of tillage regime and row spacing were statistically significant at Lacombe in 2008. Such interactions were not observed in other site-years. For logistical reasons, explanations were given only for the three-way interaction. From different tillage regimes, canola seed yield for Lacombe in 2008 produced variable results for similar seeding rate and row spacing combinations. These results indicate that each agronomic treatment combination at Lacombe in 2008 provided a unique production system for the crop. Kondra (1975) similarly determined that changes in row spacing affect the crop’s response to seeding rates. Since yield results are not consistent and differ from previous studies with *B. napus,* further research on agronomic combinations is warranted. It is recommended to consider two agronomic parameters at a time for more precise results.

The 1,000 kernel (1,000 K) weight is a measure of seed size. Seed size and the 1,000 K weight can vary from one crop to another, between varieties of the same crop and even from year to year or from field to field of the same variety. Because of this variation in seed size, the number of seeds and, consequently, the number of individuals in a given mass of seed is also highly variable (Alberta Agriculture 2009). 1,000 K weight is the most important component of yield (Clarke et al. 1978). In this study tillage regime had a significant effect on 1,000 K weight in most of the site-years except in Lacombe in 2007. Moreover, different tillage regime produced variable results for 1,000 K weight depending on site-year. However, tillage regime had no significant effect on seed yield in any site-year. The effect of tillage was variable. Therefore 1,000 K weight and seed yield do not have a specific correlated relationship for different agronomic practices tested in this study. At Vegreville in 2007, three-way interactions of tillage regime, row spacing and seeding rates produced significant results for 1,000 K weight. Hence, it appears that 1,000 K weight of a crop may be dependent on several environmental and agronomic factors. This study revealed that seeding rate resulted in no significant effect on 1,000 K weight. Previous studies conducted by Kondra (1975, 1977) and Degenhardt and Kondra (1981) found that seeding rate had no significant effect on 1,000 K weight. However, studies conducted by Clarke et al. (1978) determined that 1,000 K weight tended to increase with increasing seeding rate for different seeding methods. Clarke et al. (1978) further stated that high compensation was evident in 1,000 K weight relationships to pod and seed number. Yield improvement would only result if there were no compensatory reductions in the other components of yield. Clarke and Simpson (1978) determined that seeding rate and irrigation affected 1,000 K weight of rapeseed, probably because of a combination of their effects on assimilate supply and distribution in the plant.

In this study, single treatments and treatment combinations produced variable results for canola seed protein content. At Vegreville in 2007 and 2008, there were no significant effects on seed protein content for different treatments/or treatment combinations. The two main treatments, tillage regime and seeding rate, had no effects on seed protein concentration in any site-year. Harker et al. (2003) similarly found that seeding rate had no effect on primary seed constituent concentrations such as protein and oil. However, Kondra (1977) determined that seeding rate had a significant effect on protein content in one test. However, no trends were observed. McKenzie et al. (2006), in a study on mustard, discovered that seeding rate did not affect protein content. The results of the effect of row spacing on seed protein content at Lacombe 2007 may have agronomic significance that needs to be studied further. At the same time, the presence of three-way interaction of main effects at Lacombe 2008 on seed protein content revealed that seed quality is a result of compounding effects of many production factors. This requires further research.

Single treatments and treatment combinations produced variable results for canola seed oil content. However, similar to seed protein content, at Vegreville, both in 2007 and 2008, results indicated that there were no significant effects on seed oil content for different treatments/or treatment combinations. Grant et al. (2004), also found that tillage management did not influence seed oil concentration in any site-year. Kondra (1975) reported that row spacing and seeding rate had no significant effects on oil content. However, tests conducted by Kondra (1977) revealed that seeding rate had a significant effect on oil content. However, no trends were observed.

A wide range of mixed results were obtained for canola plant density, yield and seed weight for the different agronomic practices tested in this study. As far as final grain yield is concerned, there is no clear evidence that the two tillage regimes influenced the results. Therefore adopting zero or reduced tillage to produce canola should result in both short- and long-term benefits to the farming community. Nevertheless, the overwhelming evidence from many studies over a large number of ecoregions has found that reduced tillage is associated with many benefits for farmers that include reduced requirements of human labour, fuel and equipment (Lafond and Derksen 1996; Stinner and House 1990; Jensen and Timmermans 1991). The long-term benefits of adopting zero-till systems are many, including reduction of greenhouse gases, increasing soil organic matter content, and perhaps altering/enhancing the composition of beneficial soil fauna and flora in commercial farming systems. Evidence from previous studies also indicates that crop yields can be maintained or improved in zero-tillage for most crops grown in western Canada (Lafond et al. 1996).

In this study, adjusting seeding rate did not affect grain yield, and row spacing alone did not influence final grain yield. Moreover combinations of agronomic practices that produced highest seed yield in different site-years were different from each other. It appears that seed weight and final canola seed yield did not have a clear relationship. Evidently, other factors also play vital roles in determining the final seed yield and the seed weight by influencing the growth and development of canola yield components. However, the 30 cm row spacing produced favorable results in most cases. Therefore, adopting 30 cm rather than 22 cm would be favorable in the long run especially when seeding on standing stubble. In general the conclusions from this study are in agreement with a study conducted in Australia on row spacings and seeding rates of canola cultivars (Potter et al. 1999). It was concluded that in stubble retention systems growers can increase row spacing with little or no effect on yield or quality especially in medium to high rainfall environments. Therefore, it is recommended to adopt zero tillage in conjunction with 5.0 kg per ha to 9.0 kg per ha seeding rate and approximately 30 cm row spacings to produce canola in western Canada.

Table 2.1: Mean monthly temperature and precipitation data during the growing season at Lacombe and Vegreville, AB in 2007 and 2008 compared with long-term average values.

Lacombe

	Mean monthly precipitation (mm)			Mean monthly temperature (°C)		
			1971-2008			1971-2008
Month	2007	2008	Mean	2007	2008	Mean
April	51.5	-	21.0	2.4	1.3	4.3
May	117.9	46.4	55.6	9.8	10.3	10.1
June	174.0	100.6	75.7	14.9	13.5	13.9
July	48.8	50.6	89.4	19.1	15.3	15.4
August	69.2	56.2	70.8	13.2	15.5	14.7
September	46.0	10.4	47.3	9.4	10.3	9.8

Vegreville

	Mean monthly precipitation (mm)			Mean monthly temperature (°C)		
			1971-2008			1971-2008
Month	2007	2008	Mean	2007	2008	Mean
April	39.6	34.4	19.5	3.2	0.5	4.5
May	28.6	37.2	37.4	17.1	10.7	10.5
June	52.6	43.6	64.1	20.9	14.9	14.5
July	55.6	47.4	79.9	27.3	16.5	16.3
August	66.8	69.0	55.5	20.3	16.1	15.8
September	28.2	37.0	40.0	16.8	10.3	10.2

Source: National climate data and information archive. Environment Canada 2009.

Table 2.2: Analysis of variance results (***P*** values) for canola production data in 2007 and 2008 from Lacombe and Vegreville, Alberta. Statistically significant (*P* < 0.05) values are given in bold font.

Effect	Percent seedling emergence	Seed Yield	Seed weight (1000kwt)	Seed protein concentration	Seed oil concentration
2007 - Lacombe					
Tillage (T)	**0.0130**	0.1981	0.2513	0.2091	0.3835
Seeding rate (S)	**<0.0001**	**0.0043**	0.0799	0.1676	**0.0027**
Row spacing (R)	**0.0016**	0.2410	0.7032	**0.0048**	**0.0043**
T × S	0.0560	0.6564	0.6103	0.1442	0.2696
T × R	0.6062	0.4021	0.4030	0.6605	0.7162
S × R	0.1592	0.7611	0.4147	0.8093	0.2698
T × R × S	0.6297	0.0755	0.1884	0.8868	0.8576
2008 - Lacombe					
Tillage (T)	0.7294	0.2931	**0.0190**	0.0596	0.0640
Seeding rate (S)	**<0.0001**	0.2472	0.2044	0.4828	0.3728
Row spacing (R)	0.6510	0.3233	0.9723	0.2340	0.3908
T× S	0.2431	0.6473	0.7938	0.2249	0.1949
T×S	0.1598	**0.0374**	0.6753	0.7646	0.9915
S × R	0.1718	0.2033	0.2915	**0.0008**	**0.0018**
T × R × S	0.0566	**0.0317**	0.4222	**0.0420**	**0.0046**
2007 - Vegreville					
Tillage (T)	0.7945	0.9968	**0.0384**	0.1925	0.1276
Seeding rate (S)	**0.0081**	0.2931	0.9120	0.7562	0.6587
Row spacing (R)	0.0605	0.8062	0.2636	0.8928	0.6381
T × S	0.7197	0.1452	0.3210	0.1460	0.3461
T × R	0.3783	0.4750	0.3140	0.3749	0.1172
S × R	0.7464	0.7212	0.1487	0.8859	0.8322
T × R × S	0.5214	0.1274	**0.0256**	0.5278	0.4088
2008 - Vegreville					
Tillage (T)	**0.0310**	0.0960	**0.0478**	0.7485	0.6054
Seeding rate (S)	**0.0001**	0.8841	0.3651	0.3629	0.2753
Row spacing (R)	**0.0024**	**0.0308**	0.4970	0.3835	0.5283
T × S	0.5104	0.3502	0.1052	0.1096	0.1261
T × R	0.4341	0.3196	0.5454	0.2883	0.3348
S × R	0.5703	0.0671	0.9850	0.4410	0.3956
T × R × S	0.3679	0.8908	0.1648	0.9528	0.7978

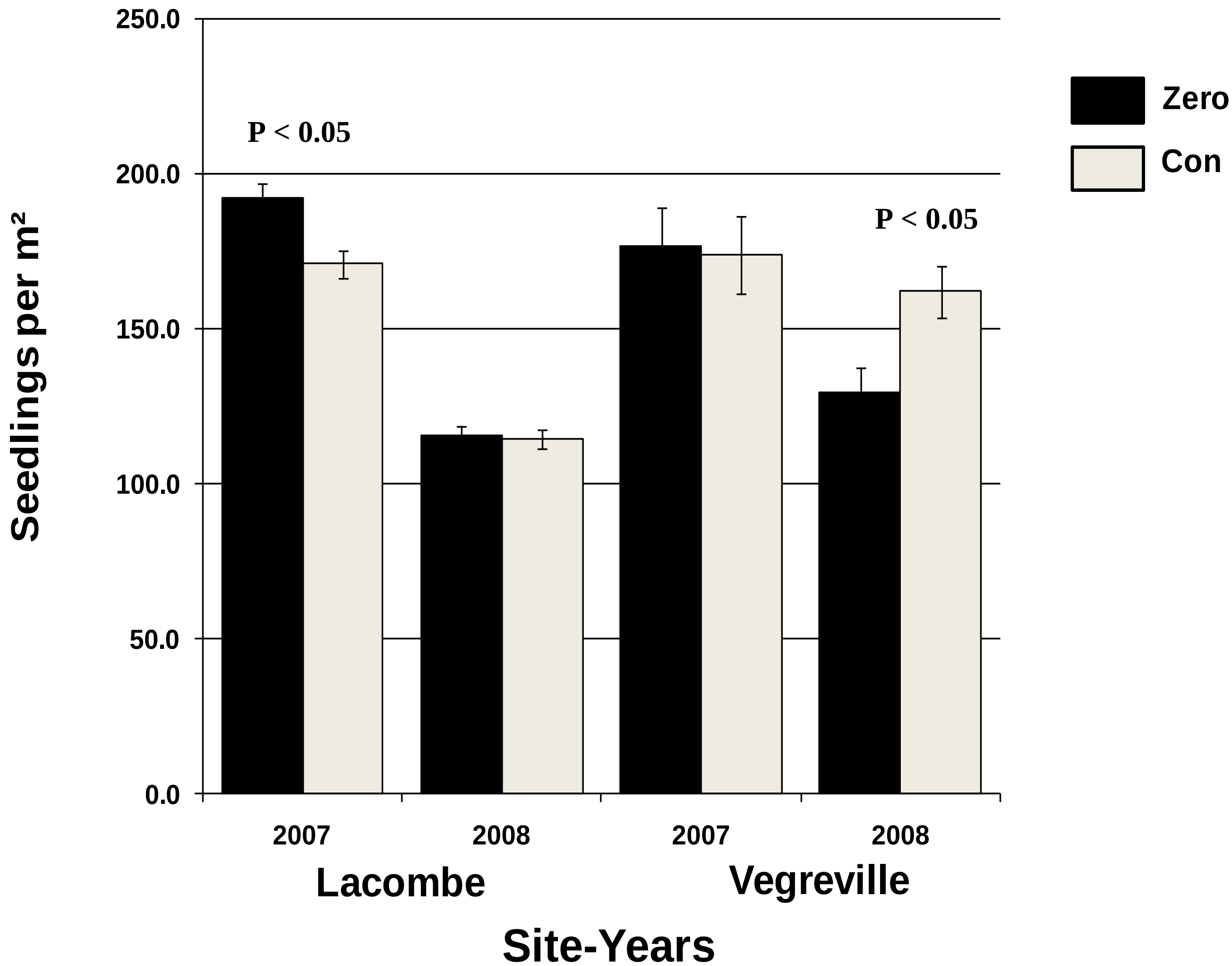


Figure 2.1. Mean plant density of *Brassica napus* seeded under zero (Zero) and conventional (Con) tillage regimes at Vegreville and Lacombe, AB in 2007 and 2008.

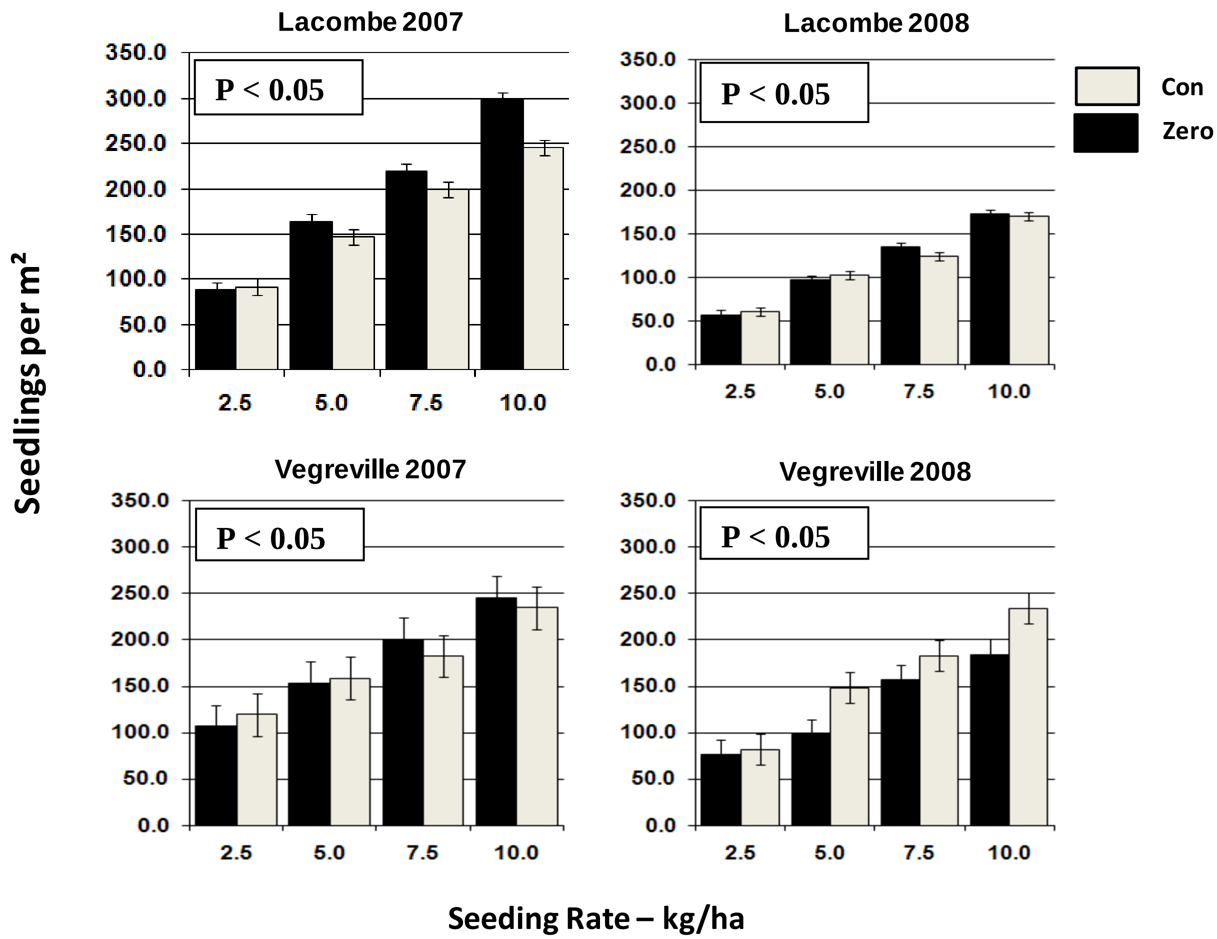


Figure 2.2. Mean plant density of *Brassica napus* seeded at various seeding rates (2.5, 5.0, 7.5, 10.0 kg/ha) under zero (Zero) and conventional (Con) tillage regimes at Vegreville and Lacombe, AB in 2007 and 2008.

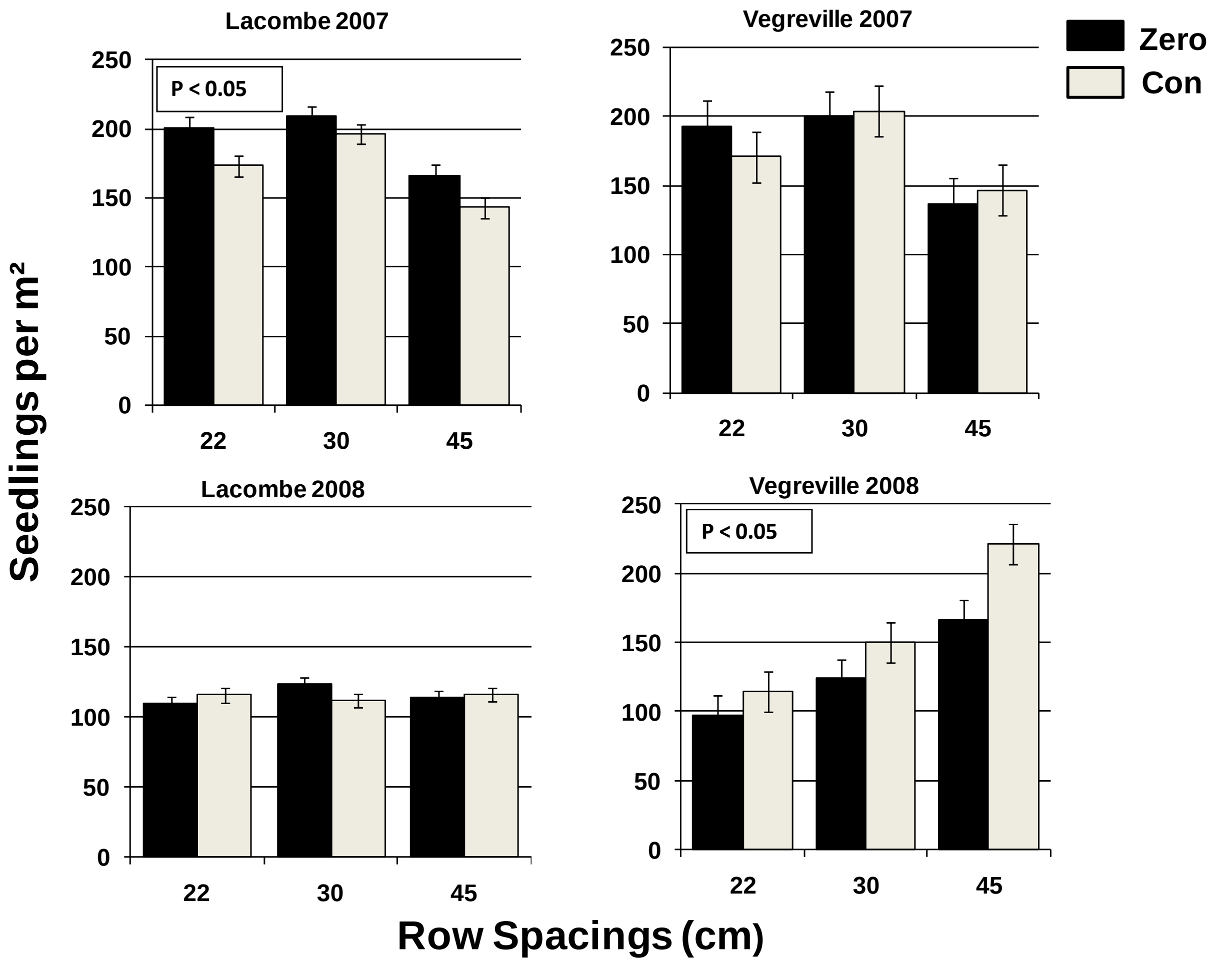


Figure 2.3. Mean plant density of *Brassica napus* seeded at various row spacings (22, 30, and 45 cm) under zero (Zero) and conventional (Con) tillage regimes at Vegreville and Lacombe, AB in 2007 and 2008.

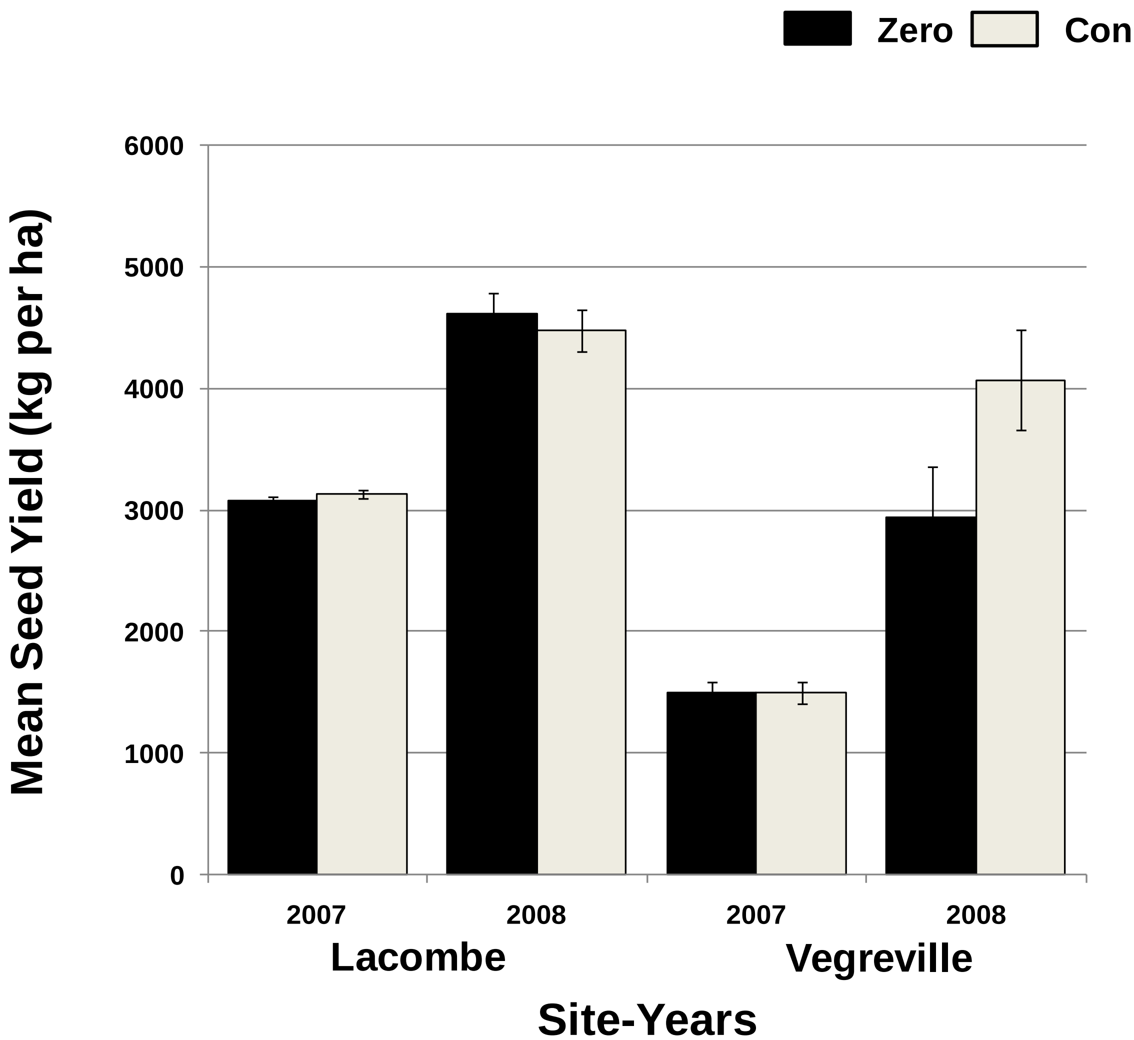


Figure 2.4. Mean seed yield of *Brassica napus* seeded under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

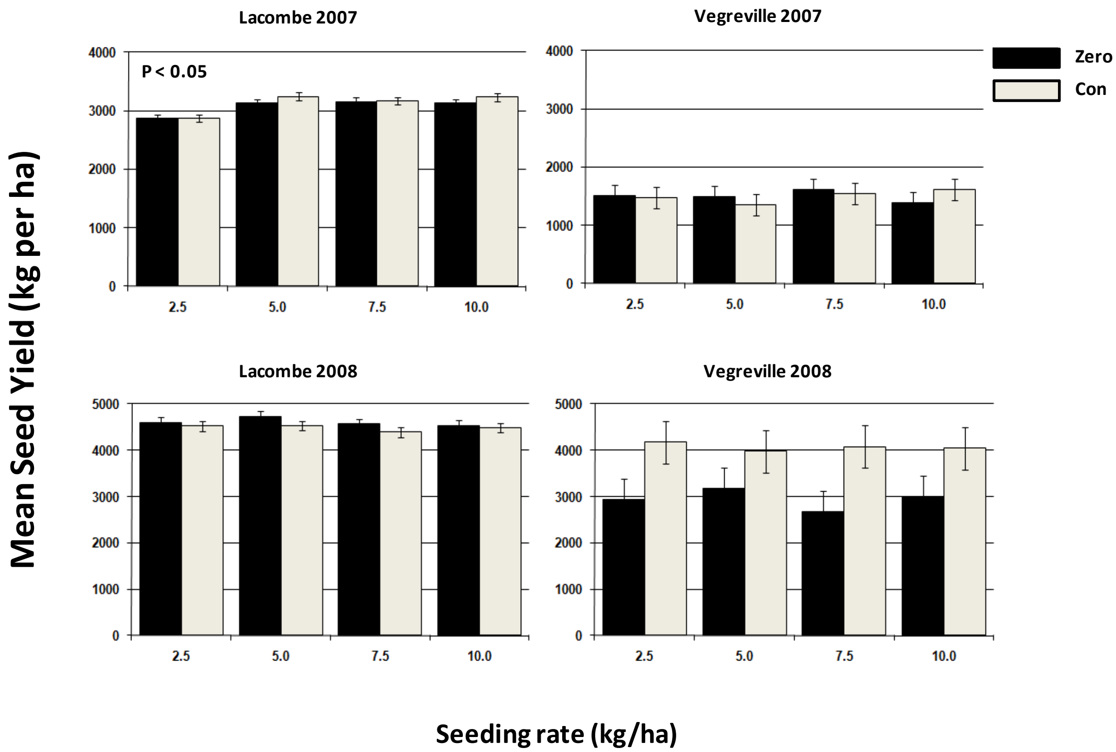


Figure 2.5. Mean seed yield of *Brassica napus* seeded at various seeding rates (2.5, 5.0, 7.5 and 10.0 kg/ha) under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

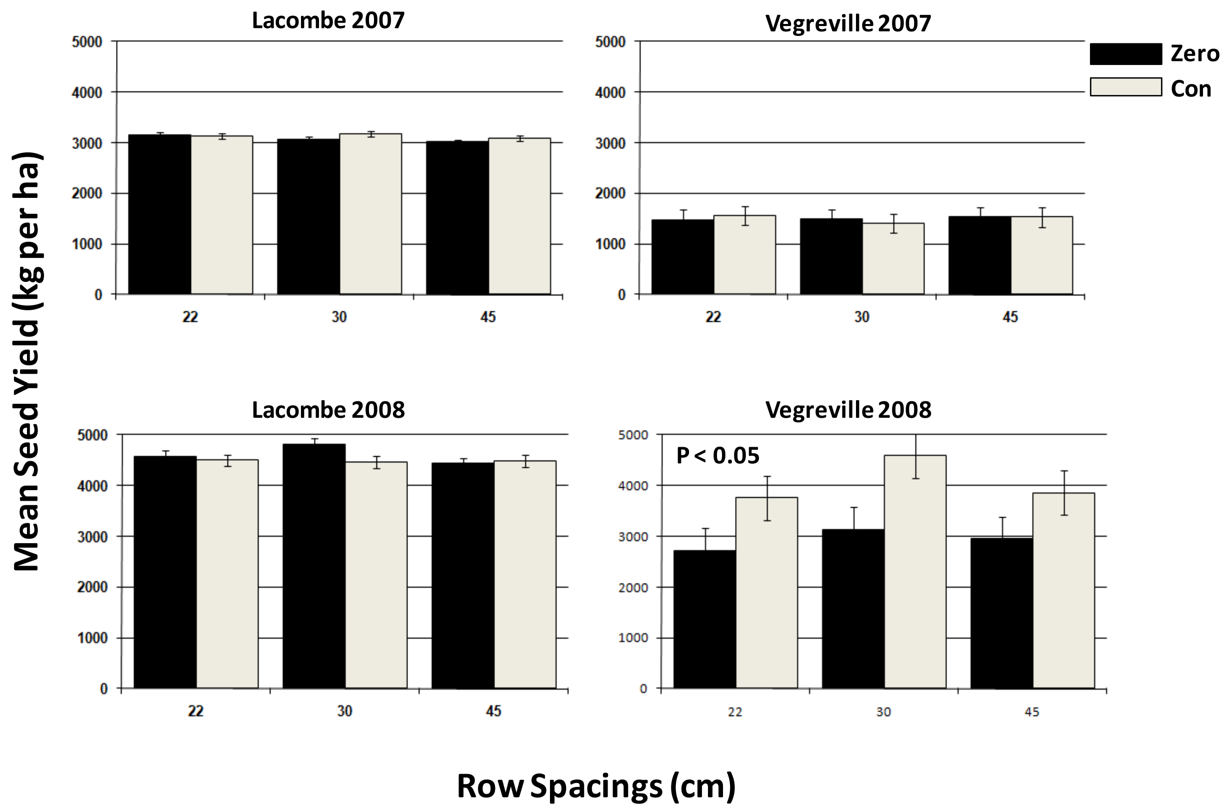


Figure 2.6. Mean seed yield of *Brassica napus* seeded at various row spacings (22, 30, 45 cm) under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

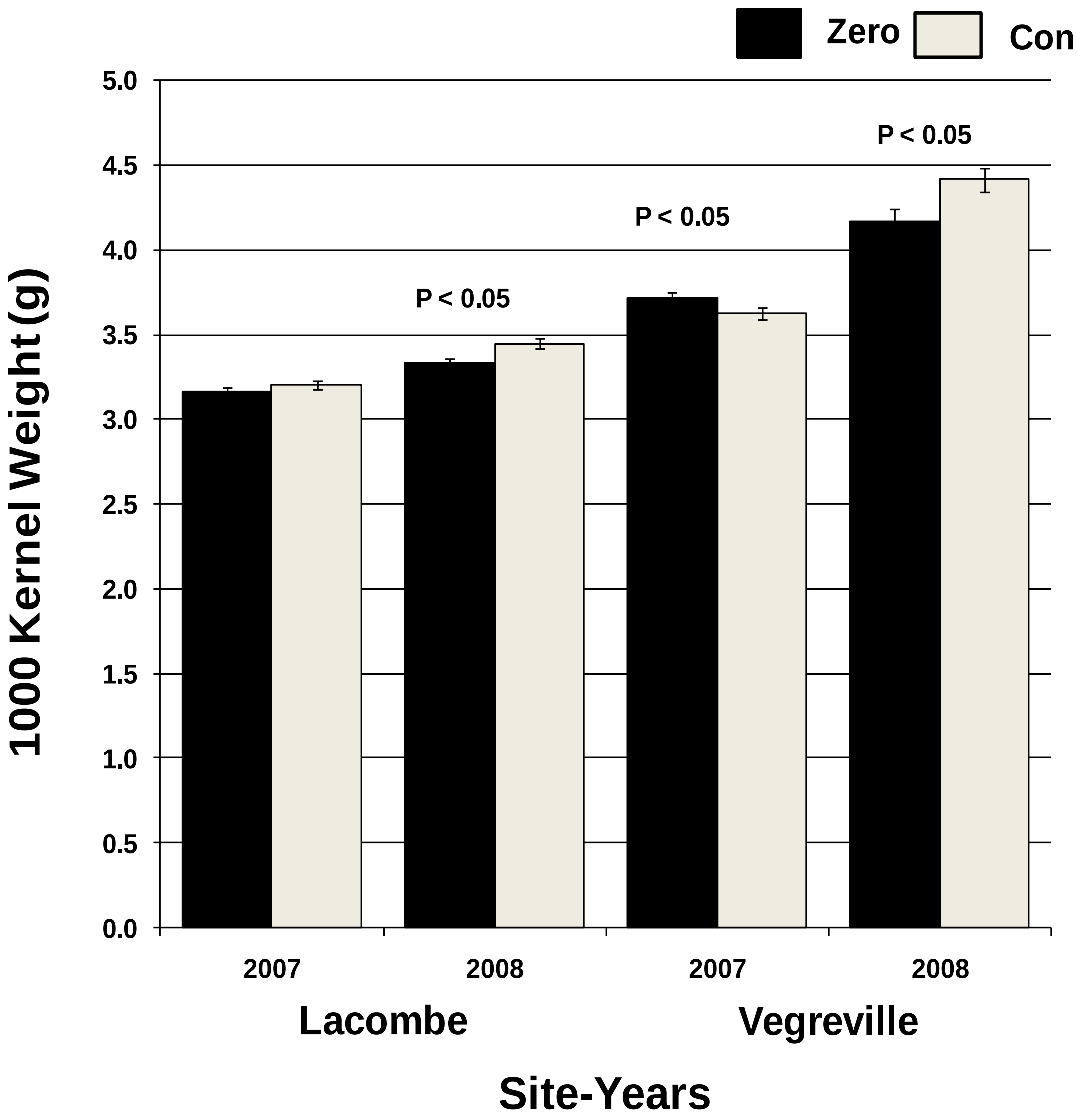


Figure 2.7. Mean 1,000 kernel weight in grams of *Brassica napus* seeded under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

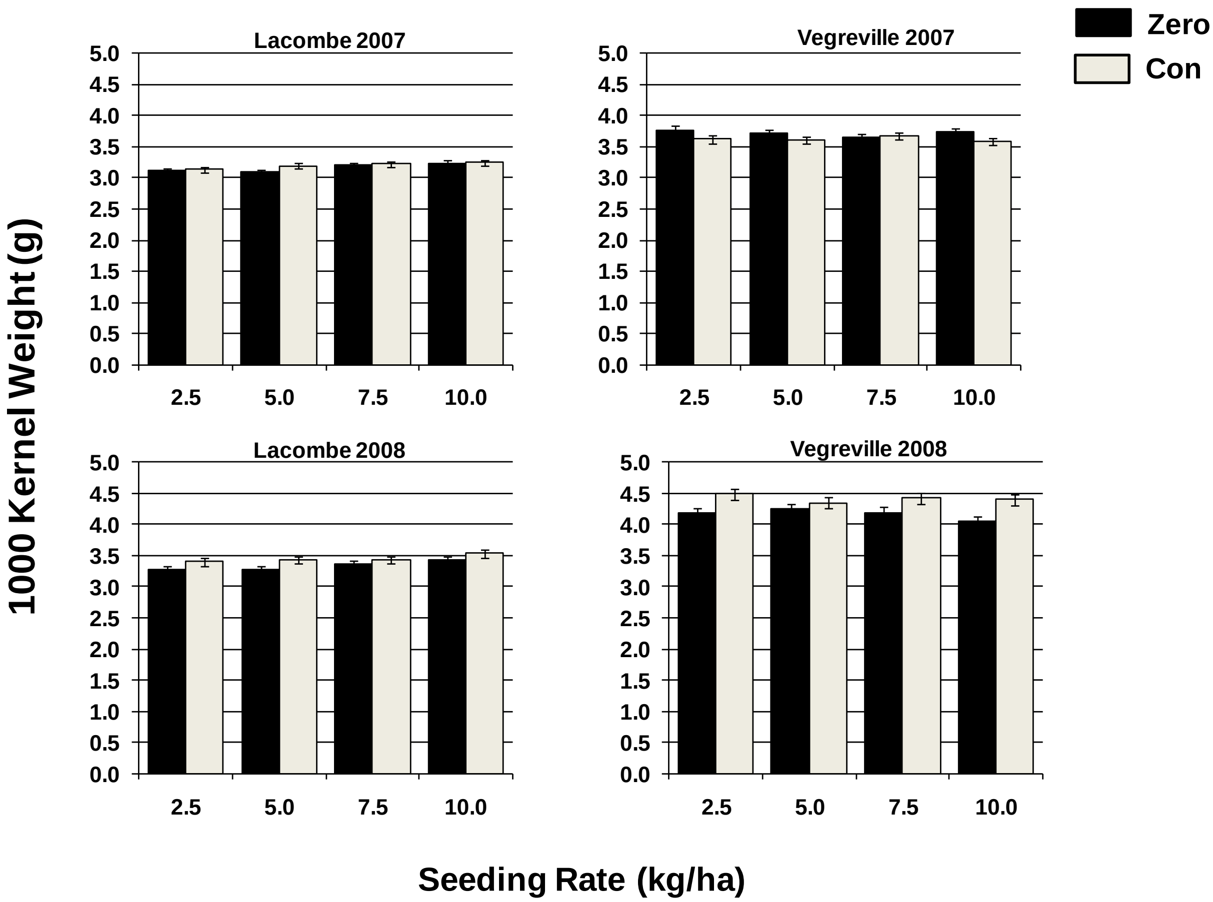


Figure 2.8. Mean 1,000 kernel weight in grams of *Brassica napus* seeded at various seeding rates (2.5, 5.0, 7.5 and 10.0 kg/ha) under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

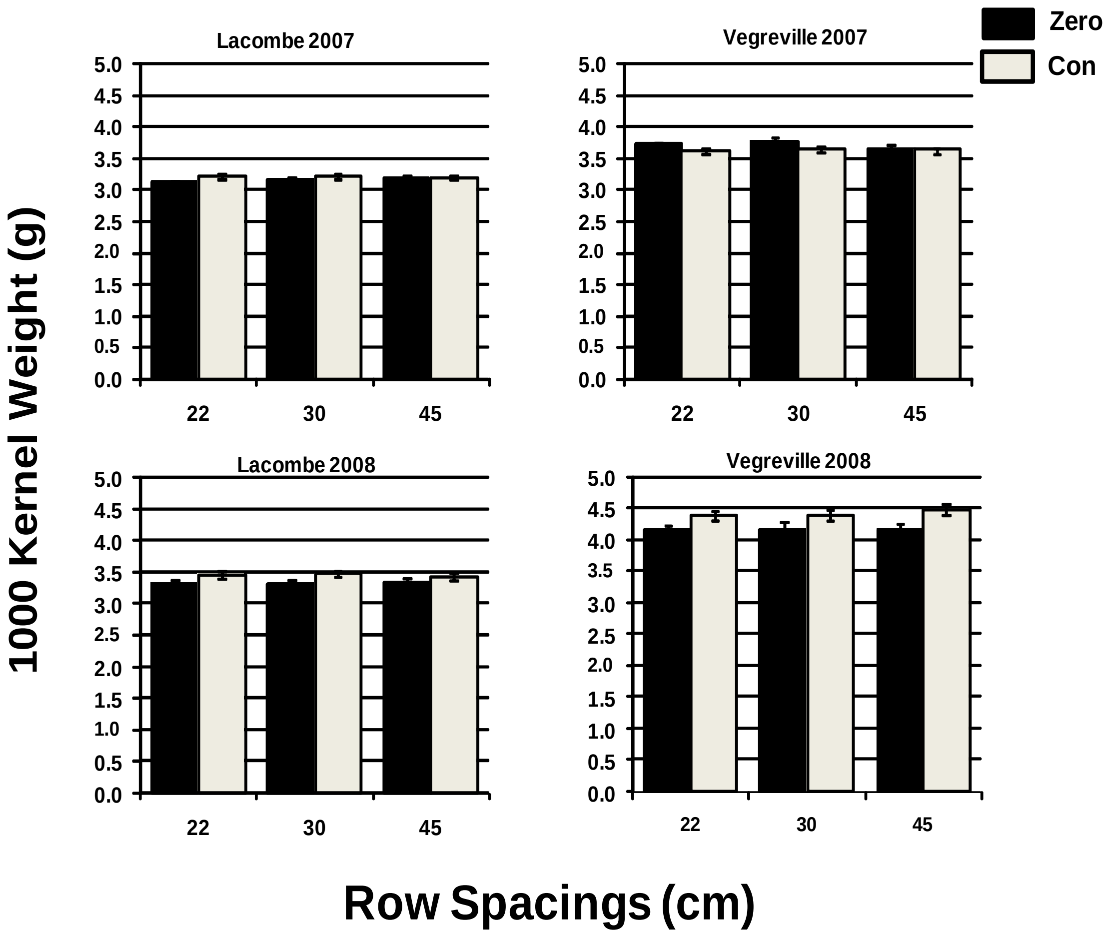


Figure 2.9. Mean 1000 kernel weight in grams of *Brassica napus* seeded at various row spacings (22, 30 and 45 cm) under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

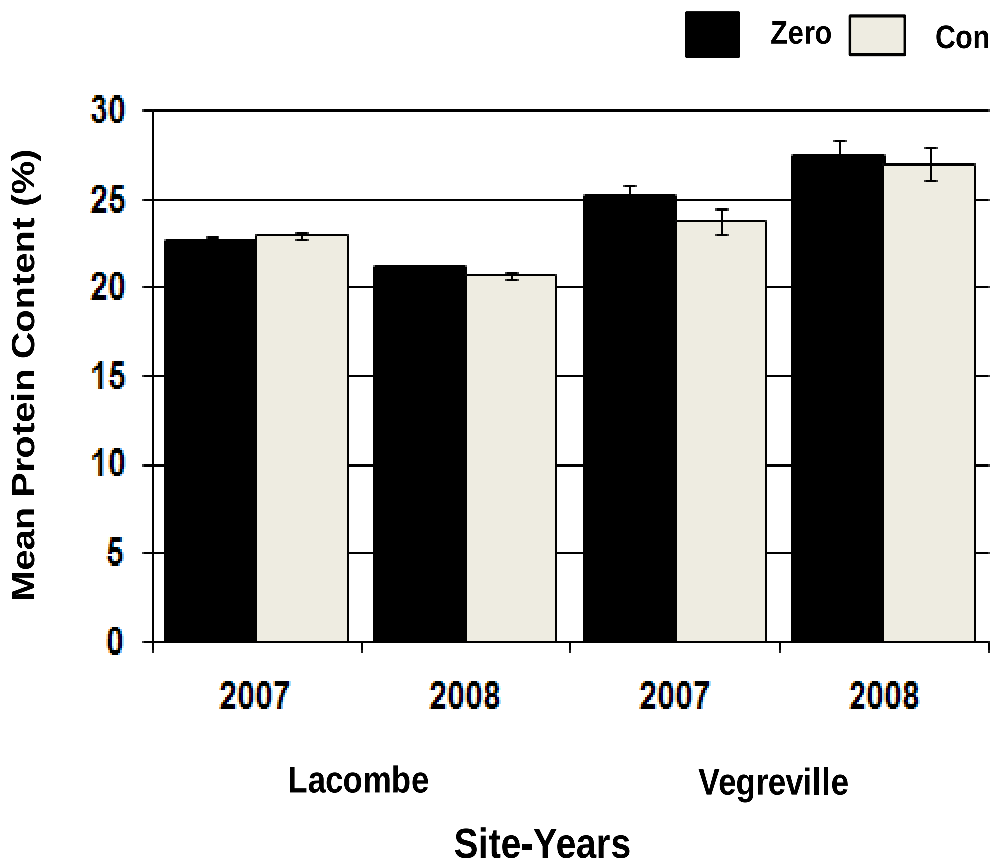


Figure 2.10. Mean protein percent of seeds of *Brassica napus* grown under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

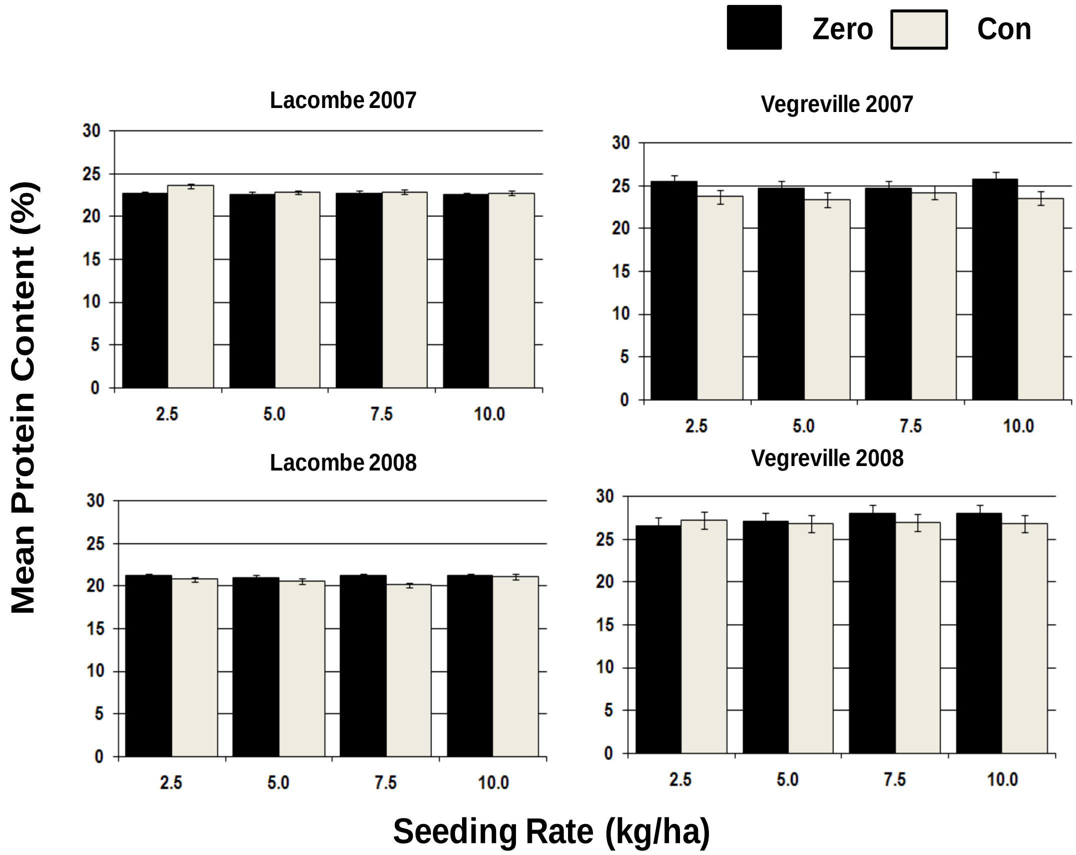


Figure 2.11. Mean protein percent of seeds of *Brassica napus* grown at different seeding rates (2.5, 5.0, 7.5, and 10.0 kg/ha) under zero (Zero) and conventional (Con) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

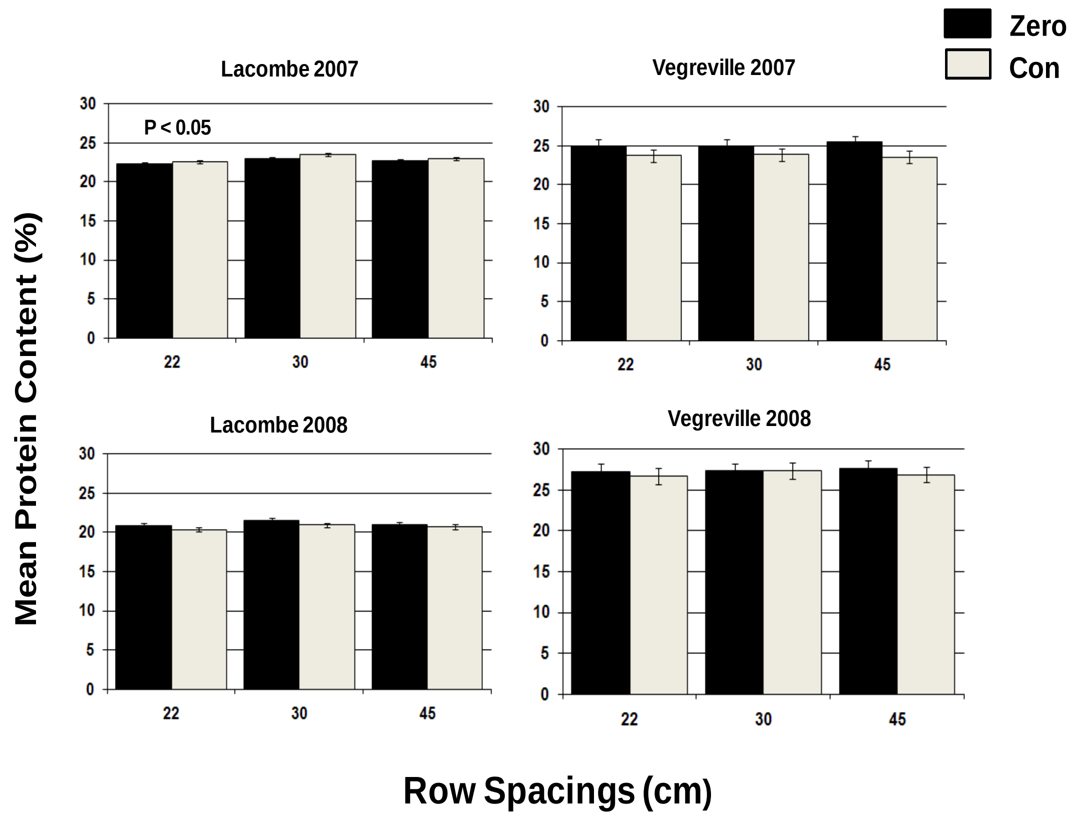


Figure 2.12. Mean protein percent of seeds of *Brassica napus* grown at different row spacings (22, 30 and 45 cm) under zero (Zero) and conventional (Con) tillage regime at Lacombe and Vegreville, AB in 2007 and 2008.

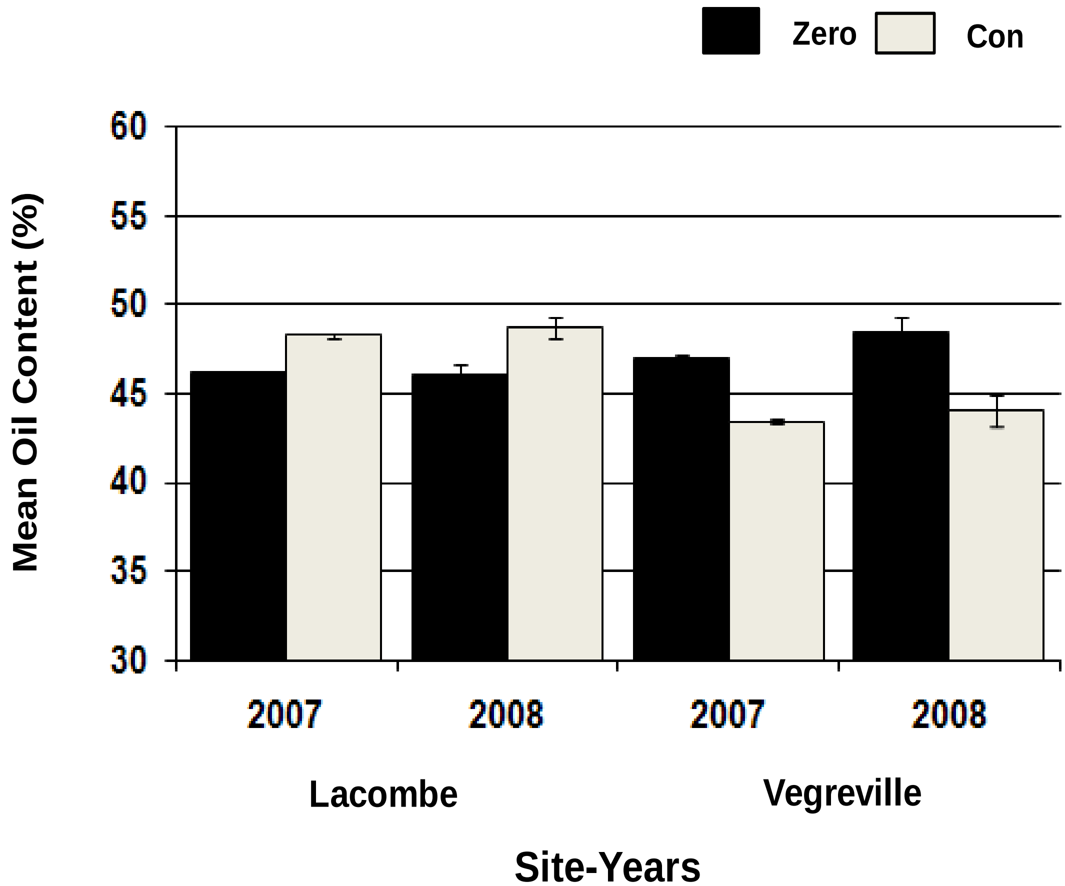


Figure 2.13. Mean oil percent of seeds of *Brassica napus* grown under zero (Zero) and conventional (Con) tillage regime at Lacombe and Vegreville, AB in 2007 and 2008.

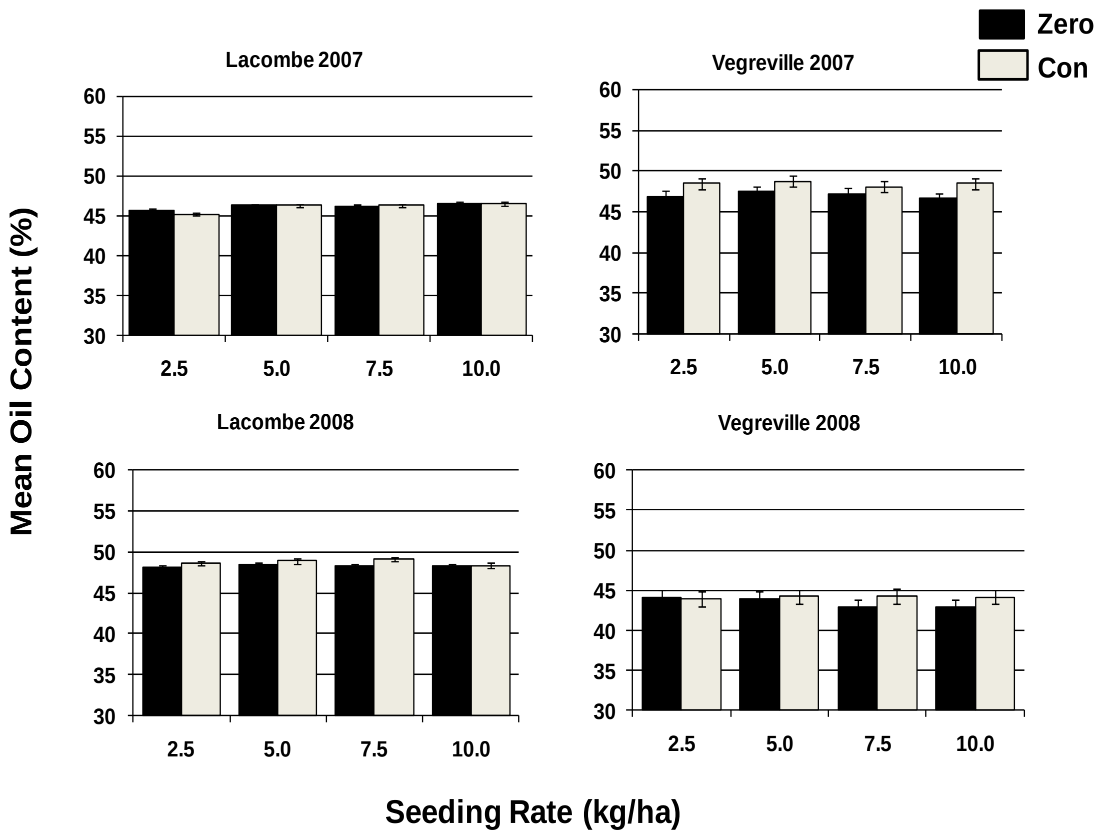


Figure 2.14. Mean oil percent of seeds of *Brassica napus* grown at different rates (2.5, 5.0, 7.5 and 10.0 kg/ha) under zero (Zero) and conventional (Con) tillage regime at Lacombe and Vegreville, AB in 2007 and 2008.

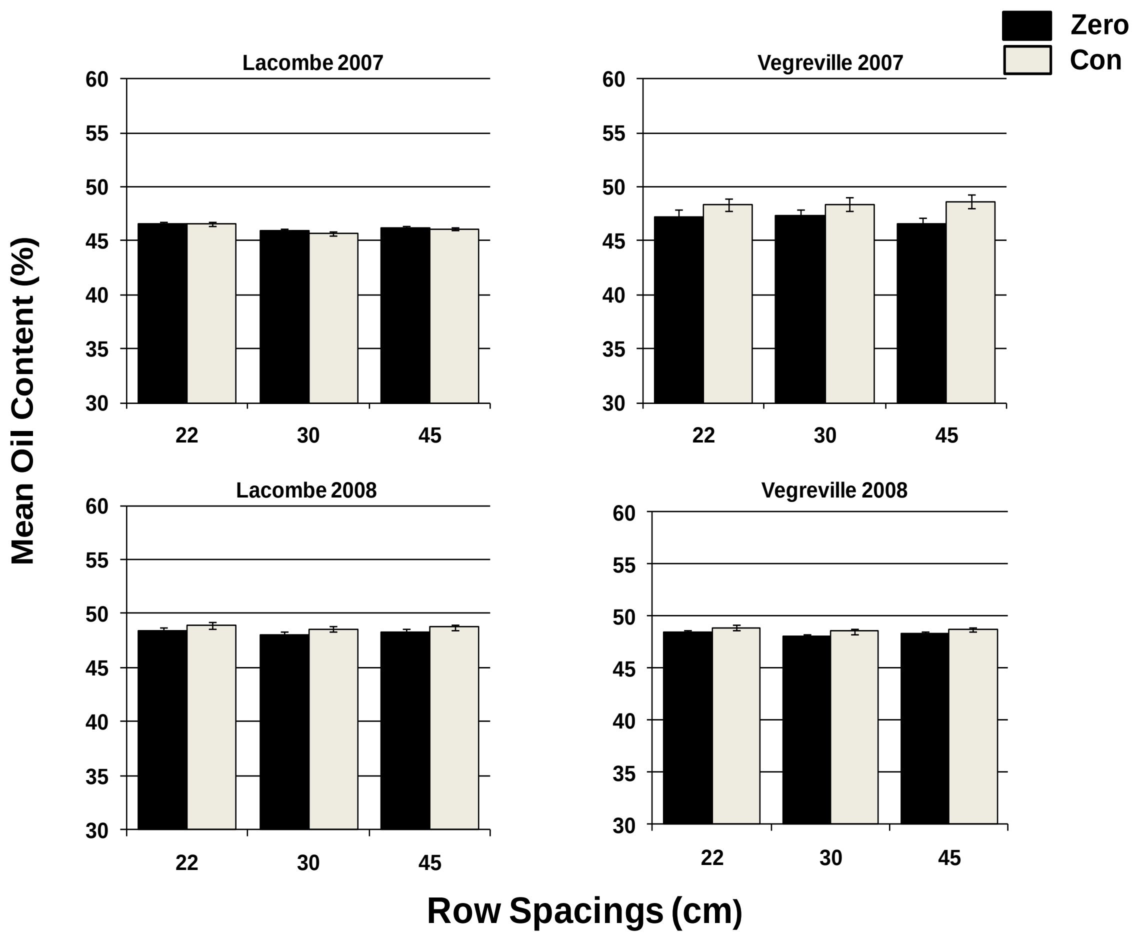


Figure 2.15. Mean oil percent of seeds of *Brassica napus* grown at different row spacings (22, 30 and 45 cm) under zero (Zero) and conventional (con) tillage regime at Lacombe and Vegreville, AB in 2007 and 2008.

Literature Cited

Alberta Agriculture. 2004. Agroclimatic Atlas of Alberta 1971-2000. Alberta Agriculture Food and Rural Development.

Alberta Agriculture. 2009. Using 1, 000 Kernel Weight for Calculating Seeding rates and Harvest Losses. http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex81. Accessed on 15 January 2009.

Angadi, S. V., H. W. Cutforth, B. G. McConkey, and Y. Gan. 2003. Yield adjustments by canola at different plant populations under semiarid conditions. Crop Sci. 43: 1358-1366.

Bailey, K. L., and L. J. Duczek. 1996. Managing cereal diseases under reduced tillage. Can. J. Plant Pathol. 18: 159-167.

Berglund, D. R., and K. McKay. 2002. Canola production. North Dakota Agric Ext. Serv. Bull. A-686. North Dakota State Univ. Ext. Serv., Fargo.

Blackshaw, R.E., K.N. Harker, J.T. O'Donovan, H.J. Beckie, and E.G. Smith. 2008. Ongoing development of integrated weed management systems on the Canadian prairies. Weed Science 56: 146-150.

Brandt, S. A. 1992. Zero vs. conventional tillage and their effects on crop yield and soil moisture. Can. J. Plant Sci. 72: 679-688.

Brandt, S. A., S. S. Malhi, D. Ulrich, H. R. Kutcher, and A. M. Johnston. 2007. Seeding rate, fertilizer and disease management effects on hybrid versus open pollinated canola (*Brassica napus* L.). Can. J. Plant Sci. 87: 255-266.

Broad, A. 2005. Best practice canola production. A report for Nuffield Australia Farming Scholars. Sponsored by Grains Research and Development Corporation, Australia.

Bruce, S. E., J. A. Kirkegaard, J. Pratley, and G. Howe. 2005. Impacts of retained wheat stubble on canola in southern New South Wales. Aust. J. Exp. Agric. 45: 421–433.

Bruce, S. E., J. A. Kirkegaard, J. Pratley, and G. Howe. 2006. Growth suppression of canola through wheat stubble. 1. Separating physical and biochemical causes in the field. Plant Soil 281: 203-218.

Christensen, J. V., and J. C. Drabble. 1984. Effect of row spacing and seeding rate on rape seed yield in northwest Alberta. Can. J. Plant Sci. 64: 1011-1013.

Clarke, C., and K. J. Moore. 1986. Effects of seed treatments on the emergence of oil seed rape seedlings from compacted soil. Ann. Botany 58: 363-369.

Clarke, J. M., and G. M Simpson. 1978. Influence of irrigation and seeding rates on yield and yield components of *Brassica napus* cv. Tower. Can. J. Plant Sci. 58: 731-737.

Clarke, J. M., F. R. Clarke, and G. M. Simpson. 1978. Effects of method and rate of seeding on yield of *Brassica napus*. Can. J. Plant Sci. 58: 549-550.

Cutforth, H. W., S. V. Angadi, and B. G. McConkey. 2006. Stubble management and microclimate, yield and water use efficiency of canola grown in the semiarid Canadian prairie. Can. J. Plant Sci. 86: 99-107.

Degenhardt, D. F., and Z. P. Kondra. 1981. The influence of seeding rate on seed yield and yield components of five genotypes of *Brassica napus.* Can. J. Plant Sci. 61: 175-183.

Dosdall, L. M., L. Z. Florence, P. M. Conway, and N. T. Cowle. 1998. Tillage regime, row spacing, and seeding rate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 78: 671-681

Dosdall, L. M., M. G. Dolinski, N. T. Cowle, and P. M. Conway. 1999. The effect of tillage regime, row spacing, and seeding rate on feeding damage by flea beetles, *Phyllotreta* spp. (Coleoptera: Chrysomelidae), in canola in central Alberta, Canada. Crop Prot. 18: 217-224.

Environment Canada. 2009. National climate data and information archive. Website at www.weatheroffice.ec.gc.ca. Accessed on 16 July 2009.

Gauer, E., C. F. Shaykewch, and E. H. Stobbe. 1982. Soil temperature and water under zero tillage in Manitoba. Can. J. Soil. Sci. 62: 311-325.

Gomez, K. A., and A. A. Gomez. 1984. Statistical procedure for agricultural research. 2nd ed. John Wiley and Sons, New York, NY.

Grant, C. A., A. M. Johnston, and G. W. Clayton. 2004. Sulphur fertilizer and tillage management of canola and wheat in western Canada. Can. J. Plant. Sci. 84: 453-462.

Gusta, L. V., E. N. Johnson, N. T. Nesbitt, and K. J. Kirkland. 2003. Effect of seeding date on canola seed quality and seed vigour. Can. J. Plant Sci. 84: 463-471.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, and F. C. Stevenson. 2003. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can. J. Plant Sci. 83: 433-440.

Howlett, B. J., A. Idnurm, and M. S. C. Pedras. 2001. *Leptosphaeria maculans,* the causal agent of blackleg disease of *Brassicas.* Fungal Genet. Biol. 33: 1-14.

Jensen, T., and J. Timmermans. 1991. Conservation tillage. Agdex 516-3, Alberta Agriculture, Edmonton, AB.

Johnson, B. L., and B. K. Hanson. 2003. Row spacing interactions on spring canola performance in the Northern Great Plains. Agron. J. 95: 703-708.

Kondra, Z.P. 1975. Effects of row spacing and seeding rate on rapeseed. Can. J. Plant. Sci. 55: 339-341.

Kondra, Z.P. 1977. Effects of planted seed size and seeding rate on rapeseed. Can. J. Plant. Sci. 57: 277-288.

Lafond, G. P., and D. A. Derksen. 1996. Long-term potential of conservation tillage on the Canadian prairies. Can. J. Plant Pathol. 18: 151-158.

McKenzie, R. H., A. B. Middleton, and E. Bremer. 2006. Response of mustard to fertilization, seeding date, and seeding rate in southern Alberta. Can. J. Plant Sci. 86: 353-362.

Morrison, M. J., P. B. E. McVetty, and R. Scarth. 1990. Effect of row spacing and seeding rates on summer rape in Southern Manitoba. Can. J. Plant Sci. 70: 127-137.

Neal, C. S. 1981. Understanding Crop Production. Reston Publishing Company, Inc., Reston, VA.

O'Donovan, J. T. 1994, Canola (*Brassica rapa*) plant density influences tartary buckwheat (*Fagopyrum tataricam*) interference, biomass, and seed yield. Weed Sci. 42: 385-389.

Pak, M. V., A. M. Meskarbashee, and R. Mamghani. 2008. Effect of planting pattern on morphology, yield and yield components of three spring canola varieties in Ahvaz climatic conditions. Res. Crops 9: 39-44.

Potter, T. D., J. R. Kay, and I. R. Ludwig. 1998. Effect of row spacing and sowing rate on canola cultivars with varying early vigour. Proceedings of the 10th International GCIRC Rapeseed Congress, Canberra, Australia, 26-29 September, 4 pp.

Robert, K. M. H., and A. J. Walker. 1994. An introduction to the physiology of crop yield. Longman Sci. Tech. 3: 159-174.

SAS Institute Inc. 2003. SAS/STAT User’s Guide, version 9.1 SAS Institute Inc. Cary, NC.

Sims, R. E. H. 1976. Effects of planting pattern and sowing method on the seed yield of safflower, oilseed rape and lupin. N. Z. J. Exp. Agric. 4: 185-189.

Smika, D. E., and P. W. Unger. 1986. Effects of surface residues on soil water storage. Adv. Soil. Sci. 5: 111-138.

Statistics Canada. 2009. Canola a Canadian success story. Website at www.statcanada.gc.ca/daily-quotidien. Accessed on 10 April 2009.

Statistics Canada. 2010. Tillage practices in Canada by ecozone. Website at http://www.statcan.gc.ca/pub/16-201-x/2009000/part-partie1-eng.htm . Accessed on 15 January 2010.

Stinner, B. R., and G.J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Ann. Rev. Entomol. 35: 299–318.

Tebrügge, F., and R. A. Düring. 1999. Reducing tillage intensity - a review of results from a long term study in Germany. Soil Till. Res. 53: 15-28.

Thomas, P. 2003. Canola Growers' Manual. http://www.canolacouncil.org. Accessed on 2 September 2009.

Xie, H. S., D. R. S. Rourke, and A. P. Hargrave. 1998. Effect of row spacing and seed/fertilizer placement on agronomic performance of wheat and canola in zero tillage system. Can. J. Plant Sci. 78: 389-394.

Young, F. L., A. G. Ogg Jr., R. I. Papendick, D. C. Thill, and J. R. Alldredge. 1994. Tillage and weed management affects winter wheat yield in an integrated pest management system. Agron. J. 86: 147-154.

Zheng, G. H., Y. P. Gao, R. W. Wilen, and L. V. Gusta. 1998. Canola seed germination and seedling emergence from pre-hydrated and re-directed seeds subjected to salt and water stresses at low temperatures. Ann. Appl. Biol 132: 339-348.

Appendix 1, Table 1: LS Means and standard errors (SEM) for seedling emergence (plant density) data for Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	192.40	4.34	115.64	2.97	176.87	12.55	129.19	8.26
Conventional	170.98	4.34	114.39	2.97	174.00	12.55	161.96	8.26
Seeding rate								
2.5 kg/ha	90.36	6.13	58.88	3.81	113.49	20.46	79.09	11.69
5.0 kg/ha	155.34	6.13	99.91	3.81	156.20	20.46	123.29	11.69
7.5 kg/ha	209.18	6.13	129.97	3.81	191.88	20.46	170.01	11.69
10 kg/ha	271.88	6.13	171.31	3.81	240.16	20.46	209.89	11.69
Row spacing								
22 cm	187.28	5.20	112.45	3.87	182.15	16.26	105.88	10.13
30 cm	202.93	5.20	117.50	3.87	202.15	16.26	136.96	10.13
45 cm	154.85	5.20	115.10	3.87	142.00	16.26	193.88	10.13
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	88.58	8.67	56.98	4.86	107.08	23.02	76.21	16.53
Zero × 5.0 kg/ha	163.45	8.67	97.31	4.86	153.79	23.02	97.90	16.53
Zero × 7.5 kg/ha	219.09	8.67	135.40	4.86	201.09	23.02	157.14	16.53
Zero × 10 kg/ha	298.47	8.67	172.88	4.86	245.52	23.02	185.50	16.53
Con × 2.5 kg/ha	92.14	8.67	60.79	4.86	119.89	23.02	81.98	16.53
Con × 5.0 kg/ha	147.23	8.67	102.50	4.86	158.62	23.02	148.69	16.53
Con × 7.5 kg/ha	199.27	8.67	124.54	4.86	182.68	23.02	182.88	16.53
Con × 10 kg/ha	245.29	8.67	169.74	4.86	234.81	23.02	234.28	16.53
Tillage × Row spacing								
Zero × 22 cm	201.22	7.36	109.67	4.82	193.30	18.29	97.40	14.31
Zero × 30 cm	209.46	7.36	123.19	4.82	200.13	18.29	123.82	14.31
Zero × 45 cm	166.50	7.36	114.08	4.82	137.18	18.29	166.35	14.31
Con × 22 cm	173.34	7.36	115.24	4.82	171.01	18.29	114.37	14.31
Con × 30 cm	196.41	7.36	111.80	4.82	204.16	18.29	150.10	14.31
Con × 45 cm	143.19	7.36	116.13	4.82	146.82	18.29	221.41	14.31

Appendix 1, Table 2: LS Means and standard errors (SEM) for canola seed yield data for Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	3077.10	32.00	4611.50	86.60	1501.30	171.10	2940.00	413.80
Conventional	3131.90	31.00	4483.80	86.60	1500.30	171.10	4072.00	413.80
Seeding rate								
2.5kg/ha	2877.20	50.40	4562.00	79.20	1497.10	133.70	3556.60	343.40
5.0kg/ha	3193.00	49.60	4630.10	79.20	1423.20	133.70	3575.30	344.80
7.5kg/ha	3163.80	50.40	4484.00	79.20	1580.60	133.70	3373.40	343.40
10kg/ha	3184.10	50.40	4514.60	79.20	1502.20	133.70	3518.40	343.40
Row spacing								
22 cm	3138.80	37.00	4542.40	91.50	1520.50	146.50	3242.00	315.20
30cm	3120.20	37.50	4640.20	91.50	1450.50	146.50	3867.50	315.20
45cm	3054.60	36.30	4460.30	91.50	1531.30	146.50	3408.40	315.20
Tillage ×Seeding rate								
Zero ×2.5kg/ha	2875.40	64.50	4599.70	105.80	1517.50	183.20	2932.50	458.10
Zero ×5.0kg/ha	3137.40	62.00	4730.60	105.80	1490.50	183.20	3166.10	462.30
Zero ×7.5kg/ha	3159.20	64.50	4575.10	105.80	1612.40	183.20	2666.50	458.10
Zero ×10kg/ha	3136.60	64.50	4540.40	105.80	1384.60	183.20	2992.80	458.10
Con×2.5kg/ha	2879.00	62.00	4524.20	105.80	1476.70	183.20	4180.80	458.10
Con×5.0kg/ha	3248.70	62.00	4529.50	105.80	1355.90	183.20	3982.50	458.10
Con×7.5kg/ha	3168.30	62.00	4392.80	105.80	1548.80	183.20	4080.40	458.10
Con×10kg/ha	3231.70	62.00	4488.70	105.80	1619.80	183.20	4044.00	458.10
Tillage ×RowSpacing								
Zero × 22 cm	3149.10	50.30	4583.50	112.60	1479.80	190.90	2727.70	437.60
Zero × 30cm	3065.30	52.10	4818.60	112.60	1494.80	190.90	3138.80	437.60
Zero × 45cm	3018.30	48.40	4432.30	112.60	1529.10	190.90	2953.50	437.60
Conv × 22 cm	3128.53	48.40	4501.30	112.60	1561.20	190.90	3756.20	437.60
Conv × 30cm	3176.20	48.40	4462.00	112.60	1406.20	190.90	4596.30	437.60
Conv × 45cm	3091.10	48.40	4488.20	112.60	1533.50	190.90	3863.30	437.60

Appendix 1, Table 3: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on canola seed yield at Lacombe in 2008 in zero-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Zero-tilled Plots			
Treatment combinations	**LSMeans**	**Standard Error (SEM)**	**Code for treatment Combinations**
Zero × 2.5 kg/ha × 22 cm	4754.97	154.11	1 1 1
Zero × 2.5 kg/ha × 30 cm	4636.27	154.11	1 1 2
Zero × 2.5 kg/ha × 45 cm	4407.81	154.11	1 1 3
Zero × 5.0 kg/ha × 22 cm	4451.45	154.11	1 2 1
Zero × 5.0 kg/ha × 30 cm	5020.80	154.11	1 2 2
Zero × 5.0 kg/ha × 45 cm	4719.72	154.11	1 2 3
Zero × 7.5 kg/ha × 22 cm	4508.36	154.11	1 3 1
Zero × 7.5 kg/ha × 30 cm	4918.09	154.11	1 3 2
Zero × 7.5 kg/ha × 45 cm	4299.00	154.11	1 3 3
Zero × 10.0 kg/ha × 22 cm	4619.10	154.11	1 4 1
Zero × 10.0 kg/ha × 30 cm	4699.22	154.11	1 4 2
Zero × 10.0 kg/ha × 45 cm	4302.84	154.11	1 4 3

Differences in least square Means, standard errors and probability values			
Treatment Combinations	**Differences in LS Means**	**Standard Error (SEM)**	**Probability Values**
Between 1 1 1 and 1 3 3	456.00	194.12	**0.0304**
Between 1 1 1 and 1 4 3	452.00	194.12	**0.0317**
Between 1 1 2 and 1 2 2	-384.49	171.86	**0.0382**
Between 1 1 3 and 1 2 2	-612.96	194.12	**0.0054**
Between 1 1 3 and 1 3 2	-510.28	194.12	**0.0170**
Between 1 2 1 and 1 2 2	-569.32	194.12	**0.0089**
Between 1 2 1 and 1 3 2	-466.64	194.12	**0.0272**
Between 1 2 2 and 1 3 1	512.40	194.12	**0.0166**
Between 1 2 2 and 1 3 3	721.80	194.12	**0.0166**

Appendix 1, Table 4: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on canola seed yield at Lacombe in 2008 in conventionally-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Conventionally-tilled Plots			
Treatment Combinations	**LSMeans**	**Standard Error (SEM)**	**Code-treatment Combinations**
Con × 2.5 kg/ha × 22 cm	4572.17	154.11	2 1 1
Con × 2.5 kg/ha × 30 cm	4418.52	154.11	2 1 2
Con × 2.5 kg/ha × 45 cm	4581.95	154.11	2 1 3
Con × 5.0 kg/ha × 22 cm	4701.44	154.11	2 2 1
Con × 5.0 kg/ha × 30 cm	4348.67	154.11	2 2 2
Con × 5.0 kg/ha × 45 cm	4538.23	154.11	2 2 3
Con × 7.5 kg/ha × 22 cm	4345.06	154.11	2 3 1
Con × 7.5 kg/ha × 30 cm	4326.58	154.11	2 3 2
Con × 7.5 kg/ha × 45 cm	4506.65	154.11	2 3 3
Con × 10.0 kg/ha × 22 cm	4386.66	154.11	2 4 1
Con × 10.0 kg/ha × 30 cm	4753.63	154.11	2 4 2
Con × 10.0 kg/ha × 45 cm	4325.90	154.11	2 4 3
Differences in least square Means, Standard Errors and probability values			
Treatment Combinations	**Differences in LS Means**	**Standard error (SEM)**	**Probability Values**
Between 2 2 2 and 2 4 2	-404.96	171.86	**0.0300**
Between 2 3 1 and 2 4 2	-408.57	194.12	**0.0496**
Between 2 3 2 and 2 4 2	-427.57	171.86	**0.0230**
Between 2 4 2 and 2 4 7	427.73	194.12	**0.0408**

Appendix 1, Table 5: LS Means and standard errors (SEM) for canola 1000 kernel weight at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	3.17	0.02	3.33	0.04	3.72	0.03	4.17	0.07
Conventional	3.20	0.02	3.45	0.04	3.62	0.03	4.42	0.07
Seeding rate								
2.5 kg/ha	3.13	0.03	3.33	0.05	3.70	0.05	4.34	0.07
5.0 kg/ha	3.15	0.31	3.35	0.05	3.66	0.05	4.30	0.07
7.5 kg/ha	3.21	0.03	3.40	0.05	3.66	0.05	4.31	0.07
10 kg/ha	3.24	0.03	3.48	0.05	3.66	0.05	4.22	0.07
Row spacing								
22 cm	3.17	0.03	3.39	0.05	3.66	0.03	4.26	0.06
30 cm	3.19	0.03	3.40	0.05	3.71	0.03	4.29	0.06
45 cm	3.19	0.03	3.39	0.05	3.64	0.03	4.32	0.06
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	3.12	0.04	3.27	0.06	3.78	0.06	4.18	0.09
Zero × 5.0 kg/ha	3.10	0.04	3.27	0.06	3.71	0.06	4.25	0.09
Zero × 7.5 kg/ha	3.20	0.04	3.37	0.06	3.65	0.06	4.19	0.09
Zero × 10 kg/ha	3.24	0.04	3.43	0.06	3.74	0.06	4.05	0.09
Con × 2.5 kg/ha	3.14	0.04	3.40	0.06	3.62	0.06	4.49	0.09
Con × 5.0 kg/ha	3.20	0.04	3.43	0.06	3.61	0.06	4.35	0.09
Con × 7.5 kg/ha	3.23	0.04	3.43	0.06	3.67	0.06	4.43	0.09
Con × 10 kg/ha	3.25	0.04	3.53	0.06	3.59	0.06	4.40	0.09
Tillage× Row spacing								
Zero × 22 cm	3.13	0.03	3.33	0.06	3.72	0.04	4.15	0.08
Zero × 30 cm	3.18	0.03	3.33	0.06	3.77	0.04	4.18	0.08
Zero × 45 cm	3.19	0.03	3.35	0.06	3.66	0.04	4.17	0.08
Con × 22 cm	3.20	0.03	3.45	0.06	3.61	0.04	4.37	0.08
Con × 30 cm	3.21	0.03	3.48	0.06	3.64	0.04	4.40	0.08
Con × 45 cm	3.19	0.03	3.43	0.06	3.62	0.04	4.48	0.08

Appendix 1, Table 6: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on canola 1000 kernel weight for zero-tilled plots at Vegreville in 2007. Values in bolt font indicate statistically significant ***P*** values.

Zero-tilled Plots			
Treatment combinations	**LS Means**	**Standard Error (SEM)**	**Code for treatment combinations**
Zero × 2.5 kg/ha × 22 cm	3.83	0.08	1 1 1
Zero × 2.5 kg/ha × 30 cm	3.75	0.08	1 1 2
Zero × 2.5 kg/ha × 45 cm	3.75	0.08	1 1 3
Zero × 5.0 kg/ha × 22 cm	3.65	0.08	1 2 1
Zero × 5.0 kg/ha × 30 cm	3.75	0.08	1 2 2
Zero × 5.0 kg/ha × 45 cm	3.74	0.08	1 2 3
Zero × 7.5 kg/ha × 22 cm	3.70	0.08	1 3 1
Zero × 7.5 kg/ha × 30 cm	3.74	0.08	1 3 2
Zero × 7.5 kg/ha × 45 cm	3.49	0.08	1 3 3
Zero × 10.0 kg/ha × 22 cm	3.70	0.08	1 4 1
Zero × 10.0 kg/ha × 30 cm	3.85	0.08	1 4 2
Zero × 10.0 kg/ha × 45 cm	3.67	0.08	1 4 3
Differences in least square Means, Standard Errors and probability values			
Treatment combinations	**Differences in LS Means**	**Standard Error (SEM)**	**Probability Values**
Between 1 1 1 and 1 3 3	0.34	0.11	**0.0057**
Between 1 1 2 and 1 3 3	0.26	0.11	**0.0293**
Between 1 1 3 and 1 3 3	0.25	0.11	**0.0267**
Between 1 2 2 and 1 3 3	0.25	0.11	**0.0309**
Between 1 2 3 and 1 3 3	0.25	0.11	**0.0306**
Between 1 3 1 and 1 3 3	0.21	0.08	**0.0251**
Between 1 3 2 and 1 3 3	0.25	0.85	**0.0082**
Between 1 3 3 and 1 4 2	-0.36	0.11	**0.0036**

Appendix 1, Table 7: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on canola 1000 kernel weight for conventionally-tilled plots at Vegreville in 2007. Values in bolt font indicate statistically significant ***P*** values.

Conventionally-tilled plots			
Treatment Combinations	**LSMeans**	**Standard Error (SEM)**	**Code for treatment Combinations**
Con × 2.5 kg/ha × 22 cm	3.58	0.08	2 1 1
Con × 2.5 kg/ha × 30 cm	3.77	0.08	2 1 2
Con × 2.5kg/ha × 45 cm	3.52	0.08	2 1 3
Con × 5.0 kg/ha × 22 cm	3.54	0.08	2 2 1
Con × 5.0 kg/ha × 30 cm	3.65	0.08	2 2 2
Con × 5.0 kg/ha × 45 cm	3.65	0.08	2 2 3
Con × 7.5 kg/ha × 22 cm	3.74	0.08	2 3 1
Con × 7.5 kg/ha × 30 cm	3.60	0.08	2 3 2
Con × 7.5 kg/ha × 45 cm	3.66	0.08	2 3 3
Con × 10.0 kg/ha × 22 cm	3.58	0.08	2 4 1
Con × 10.0 kg/ha × 30 cm	3.54	0.08	2 4 2
Con × 10.0 kg/ha × 45 cm	3.66	0.08	1 4 3
Differences in least square Means, Standard Errors and probability values			
Treatment Combinations	**Differences in LS Means**	**Standard Error (SEM)**	**Probability Values**
Between 2 1 2 and 2 4 2	0.23	0.11	**0.0453**
Between 2 1 2 and 2 1 3	0.25	0.08	**0.0094**
Between 2 1 2 and 2 2 1	0.23	0.11	**0.0438**
Between 2 1 1 and 2 1 3	-0.19	0.08	**0.0338**

Appendix 1, Table 8: LS Means and standard errors (SEM) for canola seed protein content at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	22.67	0.19	21.15	0.18	25.19	0.72	27.45	0.95
Conventional	23.04	0.19	20.68	0.18	23.74	0.72	27.00	0.95
Seeding rate								
2.5 kg/ha	23.16	0.19	21.01	0.26	24.60	0.64	26.93	0.70
5.0 kg/ha	22.75	0.18	20.80	0.26	24.07	0.64	27.04	0.70
7.5 kg/ha	22.82	0.19	20.68	0.26	24.50	0.64	27.47	0.70
10.0 kg/ha	22.69	0.19	21.17	0.26	24.68	0.64	27.46	0.70
Row spacing								
22 cm	22.45	0.16	20.65	0.23	24.39	0.56	27.01	0.68
30 cm	23.27	0.16	21.23	0.23	24.45	0.56	27.37	0.68
45 cm	22.85	0.16	20.86	0.23	24.54	0.56	27.30	0.68
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	22.70	0.25	21.21	0.31	25.47	0.84	26.60	1.00
Zero × 5.0 kg/ha	22.64	0.25	20.96	0.31	24.73	0.84	27.18	1.00
Zero × 7.5 kg/ha	22.76	0.25	21.20	0.31	24.76	0.84	27.99	1.00
Zero × 10.0 kg/ha	22.59	0.25	21.21	0.31	25.79	0.84	28.03	1.00
Con × 2.5 kg/ha	23.62	0.25	20.81	0.31	23.73	0.84	27.26	1.00
Con × 5.0 kg/ha	22.86	0.25	20.63	0.31	23.41	0.84	26.91	1.00
Con × 7.5 kg/ha	22.88	0.25	20.15	0.31	24.23	0.84	26.95	1.00
Con × 10.0 kg/ha	22.79	0.25	21.13	0.31	23.57	0.84	26.89	1.00
Tillage × Row spacing								
Zero × 22 cm	22.29	0.23	20.92	0.29	25.03	0.76	27.31	0.97
Zero × 30 cm	23.01	0.23	21.53	0.29	25.03	0.76	27.35	0.97
Zero × 45 cm	22.72	0.22	20.99	0.29	25.51	0.76	27.70	0.97
Con × 22 cm	22.62	0.22	20.39	0.29	23.75	0.76	26.72	0.97
Con × 30 cm	23.53	0.22	20.93	0.29	23.88	0.76	27.39	0.97
Con × 45 cm	22.97	0.22	20.73	0.29	23.58	0.76	26.90	0.97

Appendix 1, Table 9: LS Means, standard errors (SEM), and ***P*** values for effects of row spacing on canola seed protein content at Lacombe in 2007. Values in bolt font indicate statistically significant ***P*** values.

Treatment or Treatment Combination	LS Means / Differences of LS Means	Standard Error (SEM)	Probability value (*P*)
22 cm and 30 cm	-0.82	0.15	**0.0016**
22 cm and 45cm	-0.40	0.15	**0.0358**
30 cm and 45 cm	0.42	0.15	**0.0291**
Zero Tillage			
22 cm and 45 cm	-0.73	0.22	**0.0166**
Conventional Tillage			
22 cm and 30 cm	-0.92	0.21	**0.0043**
30 cm and 45 cm	0.56	0.21	**0.0339**

Appendix 1, Table 10: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on seed protein content at Lacombe in 2008 zero-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Zero-tilled Plots			
Treatment Combination	**LS Means or Differences in LS Means**	**Standard Error (SEM)**	**Code for Treatment combination**
Zero × 2.5 kg/ha × 22 cm	22.07	0.46	1 1 1
Zero × 2.5 kg/ha × 30 cm	20.77	0.46	1 1 2
Zero × 2.5 kg/ha × 45 cm	20.81	0.46	1 1 3
Zero × 5.0 kg/ha × 22 cm	19.73	0.46	1 2 1
Zero × 5.0 kg/ha× 30 cm	21.55	0.46	1 2 2
Zero × 5.0 kg/ha × 45 cm	21.61	0.46	1 2 3
Zero × 7.5 kg/ha × 22 cm	20.46	0.46	1 3 1
Zero × 7.5 kg/ha × 30 cm	22.57	0.46	1 3 2
Zero × 7.5 kg/ha × 45 cm	20.58	0.46	1 3 3
Zero × 10.0 kg/ha × 22 cm	21.42	0.46	1 4 1
Zero × 10.0 kg/ha × 30 cm	21.25	0.46	1 4 2
Zero × 10.0 kg/ha × 45 cm	20.97	0.46	1 4 3
Differences in LSMeans, Standard Errors and Probability values			
Treatment Combination	**LS Means or Differences in LS Means**	**Standard Error (SEM)**	**Probability values**
Between 1 1 1 and 1 1 2	1.30	0.59	**0.0396**
Between 1 1 1 and 1 1 3	1.26	0.59	**0.0457**
Between 1 1 1 and 1 2 1	2.34	0.58	**0.0008**
Between 1 1 1 and 1 3 1	1.61	0.58	**0.0124**
Between 1 1 1 and 1 3 3	1.49	0.65	**0.0336**
Between 1 1 2 and 1 3 2	-1.80	0.58	**0.0060**
Between 1 1 3 and 1 3 2	-1.76	0.65	**0.0140**
Between 1 3 2 and 1 3 3	1.99	0.59	**0.0033**
Between 1 3 2 and 1 4 2	1.32	0.58	**0.0353**
Between 1 3 2 and 1 4 3	1.60	0.65	**0.0237**

Appendix 1, Table 11: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on seed protein content at Lacombe in 2008 in conventionally-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Conventionally-tilled Plots			
Treatment combination	**LS Means or Differences in LS Means**	**Standard Error (SEM)**	**Code for Treatment combination**
Con × 2.5 kg/ha × 22 cm	21.44	0.46	2 1 1
Con × 2.5 kg/ha × 30 cm	20.58	0.46	2 1 2
Con × 2.5 kg/ha × 45 cm	20.42	0.46	2 1 3
Con × 5.0 kg/ha × 22 cm	20.27	0.46	2 2 1
Con × 5.0 kg/ha × 30 cm	20.83	0.46	2 2 2
Con × 5.0 kg/ha × 45 cm	20.79	0.46	2 2 3
Con × 7.5 kg/ha × 22 cm	19.64	0.46	2 3 1
Con × 7.5 kg/ha × 30 cm	20.57	0.46	2 3 2
Con × 7.5 kg/ha × 45 cm	20.23	0.46	2 3 3
Con × 10.0 kg/ha × 22 cm	20.00	0.46	2 4 1
Con × 10.0 kg/ha × 30 cm	21.73	0.46	2 4 2
Con × 10.0 kg/ha × 45 cm	21.47	0.46	2 4 3
Differences in LSMeans, Standard Errors and Probability values			
Treatment combination	**LS Means or Differences in LS Means**	**Standard Error (SEM)**	**Probability values**
Between 2 1 1 and 2 3 1	1.80	0.58	**0.0061**
Between 2 1 1 and 2 4 1	1.24	0.58	**0.0459**
Between 2 2 1 and 2 4 2	-1.46	0.58	**0.0363**
Between 2 3 1 and 2 4 2	-2.09	0.58	**0.0047**
Between 2 3 1 and 2 4 3	-1.83	0.58	**0.0112**
Between 2 3 3 and 2 4 2	-1.51	0.58	**0.0318**
Between 2 3 3 and 2 4 3	-1.24	0.58	**0.0456**
Between 2 4 1 and 2 4 2	-1.53	0.58	**0.0179**
Between 2 4 1 and 2 4 3	-1.27	0.58	**0.0444**

Appendix 1, Table 12: LS Means and standard errors (SEM) for canola seed oil content at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	46.24	0.10	48.27	0.17	47.05	0.58	43.46	0.95
Conventional	46.12	0.10	48.73	0.18	48.47	0.58	44.13	0.95
Seeding rate								
2.5 kg/ha	45.50	0.15	48.33	0.22	47.68	0.52	44.05	0.64
5.0 kg/ha	46.35	0.15	48.68	0.22	48.14	0.52	44.04	0.64
7.5 kg/ha	46.29	0.15	48.69	0.22	47.65	0.52	43.55	0.64
10.0 kg/ha	46.58	0.15	48.29	0.22	47.58	0.52	43.55	0.64
Row spacing								
22 cm	46.58	0.11	48.67	0.19	47.81	0.45	43.94	0.63
30 cm	46.82	0.11	48.30	0.19	47.85	0.45	43.67	0.63
45 cm	46.15	0.11	48.52	0.19	47.62	0.45	43.78	0.63
Tillage × Seeding rate								
Zero × 2.5 kg/ha	45.77	0.19	48.12	0.26	46.89	0.68	44.14	0.91
Zero × 5.0 kg/ha	46.34	0.18	48.50	0.26	47.48	0.68	43.89	0.91
Zero × 7.5 kg/ha	46.25	0.19	48.21	0.26	47.20	0.68	42.88	0.91
Zero × 10 .0 g/ha	46.60	0.19	48.24	0.26	46.63	0.68	42.94	0.91
Con × 2.5 kg/ha	45.24	0.18	48.54	0.26	48.47	0.68	43.96	0.91
Con × 5.0 kg/ha	46.35	0.18	48.86	0.26	48.79	0.68	44.19	0.91
Con × 7.5 kg/ha	46.34	0.18	48.17	0.26	48.09	0.68	44.22	0.91
Con × 10.0 kg/ha	46.56	0.18	48.35	0.26	48.52	0.68	44.15	0.91
Tillage × RowSpacing								
Zero × 22 cm	46.60	0.15	48.43	0.26	47.26	0.62	43.51	0.89
Zero × 30 cm	45.94	0.16	48.06	0.26	47.31	0.62	43.55	0.89
Zero × 45 cm	46.18	0.15	48.31	0.26	46.59	0.62	43.33	0.89
Con × 22 cm	46.55	0.15	48.90	0.26	48.36	0.62	44.38	0.89
Con × 30 cm	45.69	0.15	48.55	0.26	48.40	0.62	43.78	0.89
Con × 45 cm	46.13	0.15	48.74	0.26	48.65	0.62	44.23	0.89

Appendix 1, Table 13: LS Means, standard errors (SEM), and ***P*** values for effects of seeding rates on canola seed oil content at Lacombe in 2007. Values in bolt font indicate statistically significant ***P*** values.

Treatment or Treatment Combination	LS Means / Differences of LS Means	Standard Error (SEM)	Probability Value (P)
2.5 and 5.0 kg per ha	-0.8431	0.2033	**0.0025**
2.5 and 7.5 kg per ha	-0.7894	0.2051	**0.0039**
2.5 and 10.0 kg per ha	-1.0754	0.2051	**0.0005**
Zero Tillage			
2.5 and 10.0 kg per ha	-0.8339	0.2642	**0.0116**
Conventional Tillage			
2.5 and 5.0 kg per ha	-1.1103	0.2532	**0.0018**
2.5 and 7.5 kg per ha	-1.0954	0.2532	**0.0019**
2.5 and 10.0 kg per ha	-1.3169	0.2532	**0.0006**

Appendix 1, Table 14: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on seed oil content at Lacombe in 2008 in zero-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Zero-tilled Plots			
Treatment combinations	**LSMeans or Differences in LS Means**	**Standard error (SEM)**	**Code for Treatment combinations**
Zero × 2.5 kg/ha × 22 cm	47.41	0.38	1 1 1
Zero × 2.5 kg/ha × 30 cm	48.56	0.38	1 1 2
Zero × 2.5 kg/ha × 45 cm	48.38	0.38	1 1 3
Zero × 5.0 kg/ha × 22 cm	49.46	0.38	1 2 1
Zero × 5.0 kg/ha × 30 cm	48.10	0.38	1 2 2
Zero × 5.0 kg/ha × 45 cm	47.92	0.38	1 2 3
Zero × 7.5 kg/ha × 22 cm	48.80	0.38	1 3 1
Zero × 7.5 kg/ha × 30 cm	47.28	0.38	1 3 2
Zero × 7.5 kg/ha × 45 cm	48.56	0.38	1 3 3
Zero × 10.0 kg/ha × 22 cm	48.06	0.38	1 4 1
Zero × 10.0 kg/ha × 30 cm	48.29	0.38	1 4 2
Zero × 10.0 kg/ha × 45 cm	48.04	0.38	1 4 3
Treatment Combinations	**Differences in LS Means**	**Standard error (SEM)**	**Probability value**
Between 1 1 1 and 1 1 2	-1.15	0.47	**0.0257**
Between 1 1 1 and 1 2 1	-2.06	0.47	**0.0003**
Between 1 1 1 and 1 3 1	-1.39	0.47	**0.0070**
Between 1 1 1 and 1 3 3	-1.15	0.47	**0.0456**
Between 1 2 1 and 1 2 2	1.36	0.47	**0.0101**
Between 1 2 1 and 1 2 3	1.54	0.47	**0.0044**
Between 1 2 1 and 1 3 2	2.18	0.54	**0.0007**
Between 1 2 1 and 1 4 1	1.40	0.46	**0.0067**
Between 1 2 1 and 1 4 2	1.17	0.54	**0.0431**
Between 1 3 2 and 1 3 3	-1.28	0.47	**0.0145**
Between 1 3 2 and 1 4 2	-1.01	0.46	**0.0401**

Appendix 1, Table 15: LS Means, standard errors (SEM), and ***P*** values for the three-way interaction of tillage, seeding rate and row spacing on seed oil content at Lacombe in 2008 in conventionally-tilled plots. Values in bolt font indicate statistically significant ***P*** values.

Conventionaly-tilled Plots			
Treatment Combinations	**LS Means or Differences in LS Means**	**Standard error (SEM)**	**Code for treatment combinations**
Con × 2.5 kg /ha × 22 cm	48.04	0.38	2 1 1
Con × 2.5 kg /ha × 30 cm	48.64	0.38	2 1 2
Con × 2.5 kg /ha × 45 cm	48.94	0.38	2 1 3
Con × 5.0 kg /ha × 22 cm	48.91	0.38	2 2 1
Con × 5.0 kg /ha × 30 cm	48.78	0.38	2 2 2
Con × 5.0 kg /ha × 45 cm	48.90	0.38	2 2 3
Con × 7.5 kg /ha × 22 cm	49.56	0.38	2 3 1
Con × 7.5 kg /ha × 30 cm	48.97	0.38	2 3 2
Con × 7.5 kg /ha × 45 cm	48.98	0.38	2 3 3
Con × 10.0 kg /ha × 22 cm	49.11	0.38	2 4 1
Con × 10.0 kg /ha × 30 cm	47.81	0.38	2 4 2
Con × 10.0 kg /ha × 45 cm	48.13	0.38	2 4 3
Treatment Combinations	**Differences in LSMeans**	**Standard error (SEM)**	**Probability Value**
Between 2 1 1 and 2 3 1	-1.52	0.46	**0.0038**
Between 2 1 1 and 2 4 1	-1.07	0.46	**0.0312**
Between 2 2 2 and 2 4 2	0.97	0.46	**0.0492**
Between 2 3 1 and 2 4 2	1.75	0.54	**0.0044**
Between 2 3 1 and 2 4 3	1.43	0.54	**0.0162**
Between 2 3 2 and 2 4 2	1.16	0.46	**0.0206**
Between 2 3 3 and 2 4 2	1.17	0.54	**0.0430**
Between 2 4 1 and 2 4 2	1.30	0.47	**0.0135**

Zero Till	Con Till	Zero Till	Zero Till
1	5	1	11
2	7	2	8
3	12	7	12
4	1	8	9
5	6	10	1
6	9	3	3
7	2	11	10
8	8	12	6
9	3	4	4
10	4	9	5
11	11	5	2
12	10	6	7

Con Till	Zero Till	Con Till	Con Till
5	6	6	5
1	7	8	2
12	12	2	6
2	8	3	1
9	11	5	7
8	2	12	4
11	3	9	12
7	9	7	9
4	1	1	3
10	5	11	10
6	4	4	8
3	10	10	11
Block 1	**Block 2**	**Block 3**	**Block 4**

Treatments

1. Seeded at 2.5 kg per ha, 20 cm row spacing
2. Seeded at 2.5 kg per ha, 30 cm row spacing
2. Seeded at 2.5 kg per ha, 45 cm row spacing
4. Seeded at 5 kg per ha, 20 cm row spacing
5. Seeded at 5 kg per ha, 30 cm row spacing
6. Seeded at 5 kg per ha, 45 cm row spacing
7. Seeded at 7.5 kg per ha, 20 cm row spacing
8. Seeded at 7.5 kg per ha, 30 cm row spacing
9. Seeded at 7.5 kg per ha, 45 cm row spacing
10. Seeded at 10 kg per ha, 20 cm row spacing
11. Seeded at 10 kg per ha, 30 cm row spacing
12. Seeded at 10 kg per ha, 45 cm row spacing

Appendix 1, Table 16: Site map of the experimental design, treatments and randomization at Vegreville in 2007.

Chapter 3

Effects of tillage regime, seeding rate, and row spacing on infestations of *Delia* spp. (Diptera: Anthomyiidae) and activity density and parasitism of the predator-parasitoid *Aleochara bilineata* Gyllenhal (Coleoptera: Staphylinidae).

3.1 Introduction

Root maggots (*Delia* spp.) (Diptera: Anthomyiidae) are serious pests of canola in western Canada. Yield losses from root maggots have been reported as high as 20% in crops of *Brassica napus* L. and 50% in *Brassica rapa* L. (Griffiths 1991a), amounting to approximately $100 million annually in Alberta alone (Soroka et al. 2004). In Alberta, *Delia radicum* (L.), *Delia floralis* (Fallén), and *Delia platura* (Meigen) are the major root maggot species infesting canola (Griffiths 1986a, 1986b, 1991b; Broatch et al. 2006). *Delia radicum* and *D. floralis* are oligophagous on Brassicaceae and larvae attack fresh roots, but *D. platura* is polyphagous and typically feeds on root tissues already damaged by other root maggot larvae (Brooks 1951; Griffiths 1991b).

Delia radicum and *D. floralis* are univoltine whereas *D. platura* is bivoltine in canola in Alberta (Griffiths 1986a; Broatch et al. 2006). *Delia radicum* adults are most abundant in and around canola fields from mid May through the first three weeks of June (Griffiths 1986a). *Delia platura* adults are commonly observed in the spring before *D. radicum* adults, and maximum flight activity occurs in early June, approximately two weeks before that of *D. radicum* (Broatch et al. 2006). *Delia floralis* adults first appear in Alberta in the second week of June (over three weeks later than the first appearance of *D. radicum*), but numbers of both species peak about the same time around the third week of June (Griffiths 1986b). All three species deposit eggs at the basal region of canola stems, and newly hatched larvae burrow through the soil and begin feeding on canola taproots (Griffiths 1986a; McDonald and Sears 1992; Dosdall et al. 1994). Larval feeding can lead to reductions in root weight and root sugar content, stunted growth, premature lodging, decreased raceme numbers, and decreased seed yields (McDonald and Sears 1992; Griffiths 1991a; Soroka et al. 2004). Because chemical control with insecticide is not an option for managing root maggot infestations in canola (Soroka et al. 2004), manipulation of agronomic practices like altering plant density, row spacing, tillage regime, and crop fertility have been identified as important components in the integrated management of these pests (Dosdall et al. 1996a, 1996b, 1998, 2002, 2004).

An important area of research that has been inadequately studied involves identifying ways to manipulate canola agronomic practices to provide more suitable habitat for natural enemies of root maggots in canola production systems. In Canada, the natural enemies of root maggots comprise the staphylinid beetles *Aleochara bilineata* Gyllenhal and *Aleochara verna* Say (Coleoptera: Staphylinidae), the hymenopteran *Trybliographa rapae* (Fitigae), and various species of carabid beetles (Coleoptera: Carabidae) (Colhoun 1953; Read 1962; Turncock et al. 1995; Dixon et al. 2004; Hemachandra et al. 2007). Of these, the predator-parasitoid rove beetle, *A. bilineata*, was identified as the most common and effective natural enemy of *Delia* spp. in western Canada (Broatch et al. 2008;

Hemachandra et al. 2007). This insect is of considerable interest in canola production because adults are predators, consuming large quantities of root maggot eggs and larvae (Read 1962). The beetle is also a parasitoid. Soon after hatching, the first-instar larva of *A. bilineata* locates a root maggot puparium, bores through the puparial wall, and attaches itself ectoparasitically to the developing fly within (Broatch et al. 2008). The *A. bilineata* larva remains inactive during winter, but in spring it resumes development and consumes tissues of its host, eventually killing it (Royer et al. 1998).

Recent studies of Broatch et al. (2008) determined that emergence and seasonal activity periods of *A. bilineata* in canola were well synchronized with occurrence of pre-imaginal life stages of its principal hosts, *D. radicum* and *D. platura*, with beetle emergence beginning shortly after the onset of root maggot oviposition.

Manipulation of plant density, tillage regime, and row spacing were found to influence damage by *Delia* spp. on canola (Dosdall et al. 1998, 1996a), but no previous studies have been undertaken to investigate effects of such agronomic practices on the activity density or parasitism levels of *A. bilineata.* In this study I investigated the hypothesis that habitat management, through implementation of various agronomic practices, could alter microclimatic conditions and so influence predation and parasitism by *A. bilineata* on pre-imaginal life stages of root maggots. My objectives were to determine the effects of tillage regime, row spacing, and plant density on infestations of root maggots, and activity density and parasitism levels of *A. bilineata* on root maggots.

3.2 Materials and Methods

3.2.1 Field Operations

The study was conducted at two sites in central Alberta in 2007 and 2008: Lacombe (113°44´W; 52°28´N) and Vegreville (112°03´W; 53°30´N). The test sites are well known from previous studies to have consistently abundant root maggot populations. Soil type at both sites was black Chernozemic loam. At Lacombe, soil composition was 34% sand, 39% silt, and 27% clay with a pH of 7.3 and 9.3% organic matter. At Vegreville the soil composition was 35% sand, 34% silt, and 31% clay with a pH of 6.3 and 7.2% organic matter.

Each study site was seeded to a cereal crop (barley, *Hordeum vulgare* L.) in the year preceding each field season. Plots subjected to zero tillage were seeded directly into cereal stubble in a narrow slot opened by the planter with minimal disturbance of the surface crop residue. No additional tillage was performed for seedbed preparation as compared to conventional tillage where the soil was worked by two cultivations to a depth of approximately 8 cm each time. Weeds were removed when canola was in the three-to four-leaf stage with Liberty Link (glufosinate ammonium) herbicide at the recommended rate of 500 g ai/ha along with clethodim (Select® /Centurion®) 15 g ai/ha and Amigo® (surfactant) at 0.5% v/v.

Plots of *B. napus* cv. InVigor 5020 were seeded at Lacombe on 10 May 2007 and 5 May 2008, and at Vegreville on 15 May 2007 and 15 May 2008. The sites were fertilized according to the soil test recommendation for canola production. Plots at Lacombe were seeded with a Conserva Pak® no-till drill whereas plots at Vegreville were seeded with a double-disc press drill.

The field experiment was a randomized complete block, strip-plot design with four replicate plots per treatment. Tillage treatment (conventional- and zero-till) was assigned to 'vertical strips' and the 12 treatment combinations (4 by 3 full factorial: treatment seeding rate had four levels and treatment row spacing had three levels) were assigned randomly to 'horizontal strips' perpendicular to the tillage treatment strips. The 12 treatment combinations included row spacings of 22, 30, and 45 cm, and seeding rates of 2.5, 5.0, 7.5, and 10.0 kg per ha. Each sub-plot measured 4 by 15 m.

3.2.2 Data Collection

Data collected for this study from the treatment sub-plots included assessments of root maggot oviposition, root maggot damage ratings, rove beetle activity density, and rove beetle parasitism levels on root maggot puparia.

Root maggot oviposition was assessed once each week for a three-week period spanning the period of peak oviposition at each site. During sampling, 25 randomly selected canola plants were examined *in situ* and the numbers of *Delia* spp. eggs laid at the base of these plants and in the soil in a 1-cm radius and to a 1-cm depth around the plants were counted and recorded using the method of Dosdall et al. (1994). Examinations for eggs began when plants were at the three- to four-leaf stage of development.

At the end of the season, plots were combined to determine seed yields per plot. After harvest, roots of 100 plants per treatment (25 from each replicate sub-plot) were randomly selected, excavated, washed, and scored for degree of root maggot damage. Damage ratings were determined using the method of Dosdall et al. (1994), where 0 represented no damage, 1 represented superficial damage of up to 10% of the root surface, 2 represented damage of between 11 and 25% of the root surface with minor tunneling, 3 represented 26-50% surface damage with tunneling, 4 represented 51-75% damage to the root surface and extensive tunneling, and 5 represented complete severance of the root and 76-100% surface damage.

Each year, field populations of *A. bilineata* were investigated using pitfall trap captures. Pitfall traps were established in each replicate sub-plot in spring and samples were collected weekly during the entire cropping season. At Lacombe pitfall traps were established on 21 June 2007 and 3 June 2008, whereas at Vegreville the traps were established on 25 June 2007 and 18 June 2008.

Traps were maintained for a total of eight and 11 weekly collections from Lacombe in 2007 and 2008, respectively. At Vegreville, traps were maintained for a total of eight collections in both 2007 and 2008.

Each sub-plot contained two pitfall traps. The traps were positioned randomly within each plot with the requirement that the traps be at least 1.5 m in from the plot edges. Pitfall traps consisted of two GenPak® plastic cups placed one inside the other. Cups had a diameter of 11 cm, and a depth of 15 cm. For each trap, a hole slightly more than 15 cm deep and 11 cm in diameter was excavated in the soil. The bottom cup was placed into that hole, just below ground level. The second cup was placed within the first and the rim height was adjusted by adding top soil so it remained in line with the ground level. Each pitfall trap contained approximately 50 mL of fluid (50% solution of propylene glycol) for preserving insects. During trap collections, the inner sleeve component of each trap was removed from the sub-plot and the collected insect samples were carefully transferred to a labeled jar partially filled with 70% ethanol. In the laboratory, specimens were later sorted, identified, and data recorded.

Identifications of *A. bilineata* specimens were performed using Klimaszewski (1984), with verification of selected specimens confirmed by J.D. Hummel. Voucher specimens from the study have been deposited in the Strickland Museum of Entomology, University of Alberta, Edmonton, AB.

Sex was determined for each specimen through dissection, and comparison with line drawings of Klimaszewski (1984). Total population count was processed against individual treatment combinations using the PROC MIXED procedure of SAS statistical software (SAS Institute Inc. 2003), and sex was reported as percentages of the overall collection of males and females for that year, based on the dates when they were removed from the pitfall traps. When sex determination was not possible because abdominal structures were damaged (e.g., the genital structures), the specimens were not included in the totals.

In spring of each year following harvest of the plots, collections were made of root maggot puparia from each sub-plot. In this process, soil was carefully excavated around taproots of canola stubble to a depth of approximately

5 to 8 cm using a trowel. Soil was cleaned from the taproots and puparia found were removed and preserved in 70% ethanol. A total of 25 puparia was collected from each treatment sub-plot and returned to the laboratory where they were dissected and examined for the presence or absence of *A. bilineata* larvae. At Vegreville in 2007, plots were mistakenly tilled after harvest and as a consequence, no puparia collections were made for this site-year.

3.2.3 Data Analysis

Treatment effects were determined by analysis of variance (ANOVA) using the Proc Mixed procedure (SAS Institute Inc. 2003). Methods of Gomez and Gomez (1984) were used as a basis for comparing fixed treatment effects (seeding rate, row spacing, and tillage regime) having block (replication) as a random effect. The model used to fit the data at each site within the same year was:

$$\mathbf{Y_{ijkl} = \mu + p_i + a_j + (pa)_{ij} + b_k + (pb)_{ik} + c_l + (pc)_{il} + (ab)_{jk} + (ac)_{jl} + (bc)_{kl} + (abc)_{jkl} + (pab)_{ijk} + (pac)_{jl} + (pbc)_{ikl} + (pabc)_{ijkl} + \varepsilon_{ijkl}}$$

Where,

Y_{ijkl} : response variable corresponding to j^{th} level of tillage regime, k^{th} level of seeding rate, l^{th} level of row spacing in the i^{th} block.

μ : overall expected population mean response.

P_i : effect of i^{th} block .

a_j : effect of j^{th} level of tillage regime.

b_k : effect of k^{th} level of seeding rate.

c_l : effect of l^{th} level of row spacing.

$(ab)_{jk}$: interaction between j^{th} level of tillage regime and k^{th} level of seeding rate.

$(ac)_{jl}$: interaction between j^{th} level of tillage regime and l^{th} level of row spacing.

$(bc)_{k.l}$: interaction between k^{th} level of seeding rate and l^{th} level of row spacing.

$(abc)_{j.k.l}$: interaction between j^{th} level of tillage regime, k^{th} level of seeding rate and l^{th} level of row spacing.

The error components $(pa)_{ij}$, $(pb)_{ik}$, $(pc)_{il}$, $(pab)_{ijk}$, $(pac)_{jl}$, $(pbc)_{ikl}$, $(pabc)_{ijkl}$ and ε_{ijkl} are random effects in the model.

Block refers to a complete set of replicates for treatment combinations, tillage refers to tillage regime (conventional- and zero-till), seed rate refers to four levels of seeding rates, row spacing refers to three levels of row spacings, and ε is the random, residual variance component of the model. Y, the dependent or response variables, were root maggot oviposition counts, root maggot damage ratings, *A. bilineata* activity density, and parasitism of *Delia* spp. puparia by *A. bilineata*.

Because of occasional losses of pitfall trap samples from excessive rainfall or flooding, *A. bilineata* trap captures were standardized for trapping effort (beetles per trap per day) prior to analysis. On each sampling date the two trap captures for each sub plot were combined and divided by the sum of the total number of trapping days. In addition, the catch rates for all sampling dates were combined for each plot to obtain a total catch rate for the year.

3.3 Results

3.3.1 Environmental Conditions

Precipitation at Lacombe during the growing season of 2007 from April to June exceeded long-term mean values (1971-2008) (Anonymous 2009), but in July precipitation was considerably lower than the long-term mean value (Table 3.1). Thereafter precipitation was similar to long-term average values. In 2008, precipitation at Lacombe was less than the long term-mean values throughout the growing period except for June when approximately 25 mm more precipitation was received than the mean. Mean air temperature at Lacombe during the 2007 growing season was consistent with the long-term average although in the month of April the mean temperature was lower than the long-term mean, and in July the temperature exceeded the long-term average by nearly 4°C (Table 3.1). Mean air temperatures at Lacombe during the 2008 growing season were consistent with the long-term average values although in the month of April the mean temperature was lower than the long-term average by 3°C (Table 3.1).

At Vegreville, approximately two-fold more precipitation occurred than the long-term mean value (1971-2008) in the month of April in both years (Table 3.1). In 2007 precipitation was lower than long-term mean values from May through September except during August. In 2008 precipitation was similar to the long-term mean in May, less than the long-term normal in June, July and September, and greater than the normal value in August. In 2007, mean monthly air temperatures exceeded the long-term mean values (1971-2008) except in the month of April. However, in 2008 the mean air temperatures were similar to the long-term mean values during every month except April which was about 4°C cooler than normal (Table 3.1).

In general the environmental conditions at both sites and years were conducive to good seedling germination and the development of substantial root maggot infestations. However, at Vegreville in 2007, it became apparent approximately three weeks after seedling emergence that canola plants in one block of the site were not as vigorous in their development as in the remainder of the study area. Following extensive examinations of the seedlings at this site, and after considering the cropping history of the site, it was concluded that there was some herbicide carry-over from previous years that affected plant development, root maggot infestations, and yield. Data from these plots were not included in the analyses.

3.3.2 *Delia* spp. Oviposition

In 2007, oviposition at Lacombe increased gradually over the three-week sampling period, with peak egg-laying observed on 15 and 21 June. At Vegreville, however, egg numbers on all assessment dates were lower than those at Lacombe, with significantly more mean *Delia* spp. eggs per plant deposited on 18 June than later in the season. In 2008, oviposition at Lacombe was generally lower than in 2007 with similar numbers of eggs per plant recorded on all sampling dates. At Vegreville, oviposition decreased gradually over the sampling period with peak egg-laying observed on 25 June 2008 (Figure 3.1).

At Lacombe, in both 2007 and 2008, plants developing in plots tilled conventionally had significantly greater root maggot oviposition than plants grown under a zero tillage regime ($P < 0.05$) (Table 3.2; Figure 3.2). However at Vegreville in 2008, zero-tilled plots had greater root maggot oviposition than conventionally tilled plots. Root maggot oviposition was significantly affected by seeding rate for three of four site-years ($P < 0.05$) (Table 3.2). In both tillage regimes, greatest numbers of mean eggs per plant were observed for canola grown at the lowest plant density (approximately 60 plants per m^2 or 2.5 kg seeds per ha), and fewest were observed on plants grown at the highest density (240 plants per m^2 or 10 kg seeds per ha) (Figure 3.3). At Vegreville, no statistically significant effect was observed for oviposition at the different seeding rates in 2007 (Table 3.2). Row spacing had no significant effect on root maggot oviposition in three of four site-years ($P > 0.05$) (Table 3.2). However, at Lacombe in 2008, row spacing had a statistically significant effect on oviposition ($P < 0.05$) (Table 3.2), where mean eggs per plant decreased when row spacing increased from 22 to 45 cm in zero-tilled plots (Figure 3.4). Similarly, in conventionally-tilled plots root maggot oviposition declined as row spacing increased from 22 and 30 cm to 45 cm (Figure 3.4).

3.3.3 Root Maggot Damage Ratings

In 2007, at Lacombe, mean root maggot damage was significantly greater when canola was grown under conventional tillage than with zero tillage ($P <$ 0.05) (Table 3.2; Figure 3.5). However for all other site-years, mean root maggot damage ratings to canola were not affected significantly by tillage treatment (*P* > 0.05) (Table 3.2; Figure 3.5).

At Lacombe in both 2007 and 2008, a trend was observed whereby mean root maggot damage ratings to canola declined with an increase in seeding rate, especially under conventional tillage. However, this effect was not significant statistically (*P* > 0.05) (Table 3.2; Figure 3.6). At Vegreville in 2007 and 2008, mean root maggot damage per plant was similar as seeding rate increased from 2.5 kg per ha to 10 kg per ha (Table 3.2; Figure 3.6).

In all four site-years, under both tillage regimes, root maggot damage to canola taproots was not affected significantly by row spacing (*P* > 0.05) (Table 3.2; Figure 3.7).

3.3.4 Pitfall Trap Captures of *Aleochara bilineata*

In total, 1,620 adults of *A. bilineata* were captured in pitfall traps in 2007 at Lacombe. The total male and female adults of *A. bilineata* were 925 and 695 respectively (Figure 3.8). Trap captures were highest in second sampling week (2 July) followed by the fourth sampling week (16 June). In general male adult captures were high throughout the sampling period (Figure 3.8). At Vegreville in 2007, a total of 1,937 adults of *A. bilineata* were captured in pitfall traps, comprising 927 males and 1,010 females. Trap captures were high during the first week of sampling (2 July) and thereafter weekly captures declined. The final sampling week (20 August) experienced another peak in captures but the numbers were lower than during the first week of sampling (Figure 3.9). In general, female *A. bilineata* captures exceeded males during most sampling periods (Figure 3.9).

In 2008 at Lacombe captures of adults of *A. bilineata* were higher than the 2007 collections at the same site. A total of 3,144 adults were captured in pitfall traps, and this number comprised 1,831 males and 1,313 females. Again at Lacombe in general, male adult captures were more abundant throughout the sampling period than females (Figure 3.10). Trap captures were high during the second sampling week (16 June) and then captures gradually declined to the fifth sampling week (7 July). Thereafter a steady increase in trap captures was recorded until the final week of sampling (18 August). In 2008, Vegreville experienced the highest pitfall trap captures among all four site-years. In total, 5,439 adults of *A. bilineata* were captured comprising 2,667 males and 2,772 females. The first peak of adult trap captures was observed during the second sampling week (30 June) and then captures declined until the fourth sampling week (14 July). Then, a steady increase in trap captures was recorded until the seventh sampling week (4 August). Trap captures declined towards the final sampling week (11 August). For the first four weeks, male *A. bilineata* dominated trap collections but thereafter females were captured in greater numbers until the end of the season (Figure 3.11).

3.3.5 Activity Density of *Aleochara bilineata* in Relation to Agronomic Practices

In all four site-years, mean *A. bilineata* activity density (adults per trap per day) was greater in conventionally tilled plots as compared to plots subjected to zero tillage. However, this treatment effect was statistically significant only at Lacombe in 2008 (*P* = 0.0326) (Table 3.2) (Figure 3.12).

In all site-years, no significant effects of seeding rate were observed for mean *A. bilineata* activity density (*P* > 0.05) (Table 3.2; Figure 3.13). Mean *A. bilineata* activity density has shown a variable trend in all four site-years at various row spacings, but the effect of row spacing was not significant statistically (*P* > 0.05) (Table 3.2). The most frequently observed trend in the different site-years involved decreasing activity density of *A. bilineata* with an increase in row spacing, especially for canola grown in plots tilled conventionally (Figure 3.14). Overall seeding rate, row spacing and their interactions with tillage regimens were not statistically significant (*P* > 0.05) (Table 3.2).

3.3.6 Pitfall Trap Captures of *Aleochara verna*

Aleochara verna adult captures in pitfall traps were very low in all site-years compared with *A. bilineata*. In 2007 at Lacombe, a total of 29 adults were captured comprising 12 males and 17 females. In 2007 at Vegreville, 30 adults were captured comprising 18 males and 12 females. In 2008 at Lacombe, five adults were captured comprising two males and three females. In 2007 at Vegreville, 51 adults were captured and of this 29 were males and 22 were females. The captures of adult *Aleochara verna* from all site-years comprised only 0.93% of the total *Aleochara* spp. captured.

3.3.7 *Aleochara bilineata* Parasitism of *Delia* spp.

Mean percent of parasitized *Delia* spp. puparia for this entire study varied between 38 and 74%. At Vegreville in 2008, significantly greater mean percent of parasitized puparia occurred in zero-tilled plots than in conventionally-tilled plots (P = 0.0228) (Table 3.2) (Figure 3.15). However, this effect was not observed at Lacombe in 2007 and 2008 (P > 0.05) (Table 3.2). Mean percentages of parasitized puparia at Lacombe in 2007 in plots subjected to zero and conventional tillage were 38% and 42% respectively. Highest mean percentages of parasitized puparia for this study was found at Lacombe in 2008, where 72 and 70% of puparia were parasitized in plots subjected to zero and conventional tillage, respectively. At Vegreville in 2008, mean percentages of parasitized puparia were 57 and 43% in plots subjected to zero and conventional tillage respectively. Although interactions of any kind in this study were not statistically significant in any of the site-years, few agronomic treatment combinations resulted in greater percent of parasitized puparia. For example, at Lacombe in 2008, zero-tilled plots seeded at 7.5 kg per ha resulted in 74% parasitized puparia. Likewise at Vegreville in 2008, zero-tilled plots seeded at 10 kg per ha resulted in 70% parasitized puparia.

The effect of seeding rate (plant density) (Figure 3.16) or row spacing (Figure 3.17) of canola on mean percent of parasitized puparia was not significant statistically in any of the site-years (P > 0.05) (Table 3.2).

3.4 Discussion

Quantification of oviposition by *Delia* spp. on or near its host plants has long been utilized by researchers as a useful measure of susceptibility to infestation by these pests (e.g., Swailes 1959; Doane and Chapman 1962; Matthewman and Lyall 1966; Dosdall et al. 1994). Egg counts performed *in situ* around each plant represent an estimate of the numbers of eggs deposited less the number of eggs eaten by predators and destroyed by other biotic and abiotic factors (Hughes 1959b). In all four site-years of my study, *Delia* spp. oviposition followed a similar trend whereby peak egg-laying was observed between 18-25 June, when most plants were in the four to five true-leaf or rosette stages of development. This oviposition pattern was similar to that recorded previously in canola with egg populations increasing to a peak in mid to late June (Dosdall et al. 1994, 1996a).

In three of four site-years, *Delia* spp. oviposition was affected significantly by tillage treatment; more eggs were laid on plants grown in conventionally tilled plots at Lacombe in both 2007 and 2008, and more eggs were laid on plants grown in zero-tilled plots at Vegreville in 2008. Studies by Finch and Collier (2000) have shown that populations of herbivorous insects associated with a particular crop species are often reduced considerably when the background of the crop is allowed to become more heterogenous. Finch and Collier (2000) referred to heterogeneity as a result of increased plant biodiversity through greater weed populations, intercropping with another plant species, or when the crop is undersown with living mulch; however, it is conceivable that some herbivores could also respond to heterogeneity resulting from increased crop residue on the soil surface. Perhaps greater organic residue on the soil surface in a zero-till system interferes in some way with the complex behavioral sequence undertaken by female flies prior to oviposition, as described by Kostal and Finch (1994); if so, it could result in more egg laying in conventional-till systems. This hypothesis requires testing.

At Vegreville in 2008, zero-tilled plots had greater root maggot oviposition than conventionally-tilled plots. Greater *Delia* spp. oviposition in zero-tilled plots at Vegreville may reflect microclimatic differences between the two tillage regimes (Dosdall et al. 1998). Precipitation at Vegreville in June 2008 was lower than the long term average (Table 3.1), and root maggots are known to thrive in conditions of moist soil (Griffiths 1986b). Zero-till systems are characterized by higher soil moisture levels than occur in conventional systems (Lafond and Derksen 1996), and cooler soils tend to reduce evaporation (Larney et al. 2003; Bailey and Duczek 1996); consequently, the increased water holding capacity of the Vegreville plots likely facilitated high *Delia* spp. oviposition and root damage.

Increasing seeding rate was associated with reduced root maggot damage ratings for *B. napus* in three of four site-years. Increasing seeding rate increases plant density, and higher plant density promotes reduced basal stem diameter that is not favorable to ovipositing females of *Delia* spp. (Dosdall et al. 1996a). Reductions in oviposition are usually reflected in decreased taproot damage by larvae (Dosdall et al. 1996a, 1998). My observations agree with those of previous investigations of *Delia* spp. in canola (Dosdall et al. (1996a, 1998), and represents a relationship not uncommon in insect-host plant relations (A‘Brook 1968; Farrell 1976).

Canola plant row spacing did not influence *Delia* spp. oviposition in three of four site-years. However, at Vegreville in 2008 fewest eggs were generally laid on plants grown at the widest spacing in plots subjected to either tillage treatment. Results from the Vegreville site in 2008 are in agreement with previous results of Dosdall et al. (1998), but it is unclear why this effect was not observed consistently.

In all four site-years, mean root maggot damage ratings to *B. napus* plants were greater for plants grown in conventionally-tilled plots than for plants grown in zero tillage. At Lacombe in 2007 and 2008, this result concurs with observations on root maggot oviposition because significantly more eggs were also laid on plants grown in conventional tillage. But in contrast, at Vegreville in 2008, greater root maggot oviposition per plant was observed in zero-tillage plots than in plots tilled conventionally, but the root maggot damage ratings of plants were greater for plants grown in conventionally-tilled plots. This disagreement between root maggot oviposition and root maggot damage ratings of plants could perhaps be explained by the results of research by Hughes (1959a) who investigated natural mortality factors affecting *Delia* spp. populations during their immature stages. Hughes (1959a) found that the three pre-imaginal stages of *Delia* spp. (eggs, larvae, and pupae) have different levels of mortality in natural systems, with the highest occurring during the egg stage, followed by the pupal stage, with the larval stage having lowest mortality. Hughes (1959b) implicated a number of important egg predators including *Bembidion* spp. (Carabidae), and *Aleochara* spp. (Staphylinidae), as responsible for this mortality because they could consume large numbers of *Delia* spp. eggs. Broatch (2008) and Hummel (2009) studied carabid egg predators in Lacombe, and collected a considerable number of species, including *Bembidion* spp. However, to date, no similar studies of the coleopteran fauna have been undertaken at Vegreville. My results suggest that the diversity and/or abundance of beetle species at Vegreville differs from that found in Lacombe, and these differences may perhaps be responsible for the differences between sites in root maggot egg populations.

The life history of *A. bilineata* has been well studied, and it has been determined that first-instar larvae seek out host puparia, penetrate the puparial wall, and overwinter within the puparium; larvae complete their development and emerge from the puparia following diapause in the spring (Royer and Boivin 1999). The recommended production practice for canola in western Canada is to rotate crops, so canola is usually not seeded on land on which the same crop was grown in the preceding year (Thomas 2003). In this study, plots were seeded to a cereal crop in the years before the canola plots were established; hence adults of *A. bilineata* would have migrated into the plots from elsewhere.

The number of weekly adult beetle captures from the two pitfall traps established within a single treatment sub-plot varied considerably, and this may be explained by the phenology of this species. In *A. bilineata*, mating starts just after emergence and females begin to oviposit on the second day after adult eclosion (Colhoun 1953). Maximum egg-laying occurs four to seventeen days later, and thereafter oviposition rate declines (Langlet et al. 1998). In view of this phenology, it is probable that the behavior pattern of individual *A. bilineata* in a given population would be variable and rather unpredictable; individual adults in a given treatment plot would be nonsystematic in terms of foraging, mating, oviposition, and larval parasitism. In this context, there are predicted to be greater chances that pitfall trap captures at times do not correlate with the total number of adult beetles attracted to a particular canola plot. Dixon et al. (2004) noted that pitfall trap monitoring of predators usually measures relative abundance and activity rather than absolute population density.

Ggreater activity density of *A. bilineata* occurred in conventionally-tilled plots in all four site years. Moreover plots subjected to conventional tillage had plants with greater root maggot damage ratings, indicating that *A. bilineata* was concentrated in patches of greatest resource availability. Insect predators and parasitoids use vision, audition, and/or olfaction to locate a suitable habitat (Royer and Boivin 1999). Tomlin et al. (1992) suggested that *A. bilineata* may use infochemicals to locate the best sites for mating, foraging and oviposition, by aggregating where *Delia* spp. are abundant. In the process of host location, *A. bilineata* adults could disperse as far as 5 km from a release point to aggregate in sites with high *Delia* spp. larval density (Tomlin et al. 1992). Olfactory stimuli arising from host plants infested by *Delia* spp. were found to be highly attractive to *A. bilineata* adults (Royer and Boivin 1999). Royer and Boivin (1999) found that water-soluble infochemicals arising from larval integument and larval frass associated with damaged rutabaga were attractive to *A. bilineata* adults. Nonetheless, the most reliable cue to attract *A. bilineata* adults is the effluvia of prey(root maggot larvae) than the effluvia of damaged rutabagas containing frass, but not larvae (Royer and Boivin 1999). Therefore it appears that observations from Lacombe are in agreement with the concept of this predator-parasitoid responding to infochemical cues arising from higher *Delia* spp. populations in some treatment plots.

Dixon et al. (2004) captured greater numbers of *A. bilineata* in plantings of rutabaga grown surrounded by bare soil than in plots with rutabaga undersown to clover (*Trifolium repens* L.). In my study, activity density of *A. bilineata* was significantly greater in conventionally tilled plots at Lacombe in 2008, and in all other site-years the beetle showed a trend in this direction. Foraging strategies of predators and parasitoids involve trade-offs between the quality and quantity of resources/prey obtained and time spent and risk associated with foraging (Gullan and Cranston 2005). It is quite possible that crop residue on the soil surface in the zero-till plots hampered locomotory movements by *A. bilineata*, and the residues could have placed limitations on their ability to capture prey. If so, this would help explain greater pitfall trap captures in conventionally tilled plots.

In the context of locomotory movements of *A. bilineata* adults within the test sites, I suggest that the first peak of adult *A. bilineata* trap captures occurred after the arrival of *A. bilineata* adults from their overwintering sites, prior to beetle mating or egg-laying. The first peak of *A. bilineata* adult trap captures occurred approximately one week after peak *Delia* spp. oviposition dates in three of four site-years. But at Vegreville in 2008, the first *A. bilineata* peak occurred during the onset of peak *Delia* spp. oviposition. These results are in agreement with studies conducted on the population dynamics of *A. bilineata* in relation to its root maggot hosts in canola cropping systems in western Canada by Broatch et al. (2008). Hence, it appears that the peak of *A. bilineata* trap captures indicate the timing of active locomotory movements within the test plots and presumably during this time the beetles were actively searching for prey or mating partners. The second adult peak occurred at the time of *Delia* spp. completing pupation towards the end of July to early August. I suggest that the reason for this second peak of adult *A. bilineata* trap captures is due to infochemicals released from infestation caused by *Delia* spp. larvae to canola taproots, and subsequent locomotory movements to locate suitable sites for egg-laying.

Activity density data of *A. bilineata* tended to be somewhat variable in relation to different seeding rates and row spacings, but this is perhaps not unexpected. Even in a suitable habitat, resources are rarely evenly distributed, and occur in more or less discrete microhabitat clumps, termed patches, and insects show a gradient of responses to these patches (Gullan and Cranston 2005). Patch selection is vital to successful foraging (Gullan and Cranston 2005). Moreover different *A. bilineata* biotypes may vary in their abilities to locate prey. As well, the damage inflicted to canola taproots may vary due to different species compositions of root maggots in different sites and years, and among treatment plots. Hence, these reasons may help explain why we failed to establish a clear relationship between the behavioral parameters of host *Delia* spp. and the predator-parasitoid *A. bilineata* in field conditions.

Overall parasitism of *Delia* spp. by *A. bilineata* ranged from 38 to 74% in this cropping system. In the early 1950s a research study conducted by Wishart

(1957) in Newfoundland recorded parasitism of 34% by *A. bilineata* on *D. radicum* in cole crops. Turnock et al. (1995) recorded a wide range of parasitism of *Delia* spp. by *A. bilineata* collected from commercial plots of rutabaga in southern Manitoba, Canada; parasitism ranged from 10 to 94% at Winnipeg. Hemachandra et al. (2007) recorded 18 to 52% parasitism of *Delia* spp. by *A. bilineata* in the Canadian prairies. The high percent parasitism of *Delia* spp. by *A. bilineata* in the range of 38 to 74% in the current study would be sufficient to suppress the *Delia* spp. egg and larval populations from these sites.

As noted, the high rates of activity density of *A. bilineata* in conventional-tilled plots at Lacombe in 2008 were presumably due to a high root maggot density that attracted more beetle adults to those plots. In turn, more *A. bilineata* adults would have produced more first-instar larvae that could eventually parasitize more *Delia* spp. puparia in those plots. However, in 2008 at Vegreville, mean percent parasitism of *Delia* spp. puparia by *A. bilineata* was greater in zero-till plots that had plants with lower root maggot damage ratings than conventional-till plots. These observations seem contradictory to the concepts of infochemical attraction effects on adults, and density dependency with regard to movements of *A. bilineata* (Royer and Boivin 1999; Jones et al. 1993). It would have been expected that parasitism should also have been higher in conventionally tilled plots. This contradiction can perhaps be better understood through review of the biology of *A. bilineata*. Females oviposit near host plants infested by *Delia* spp. larvae (Fournet et al. 2001). Upon hatching, the first-instar larva of *A. bilineata* must locate a root maggot puparium, penetrate its wall, enter, and finally seal its entry hole all within an average life expectancy of only five to six days (Fournet et al. 2001; Royer et al. 1999). Moreover, *A. bilineata* first instars decrease their locomotory activity 36 h after eclosion, and they can spend 12 to 36 h in the process of chewing an opening through the puparial wall. When considering these life history characteristics, I suggest that the microenvironment of zero-till plots may have provided better conditions for parasitism than plots tilled conventionally. The cool, moist conditions provided by crop residues may have enhanced longevity of *A. bilineata* first-instars by delaying desiccation of the larvae and the residue may have provided some cover from carabid beetle predators during the vulnerable period prior to penetration of the root maggot puparial wall.

Conclusion

My studies have determined that the predator-parasitoid *A. bilineata* is important for reducing populations of root maggot pests in canola agroecosystems in central Alberta. I observed parasitism rates of 38 to 74% to *Delia* spp. puparia, and in addition, the large numbers of adults found in some site-years (e.g., > 5,400 adults at one study site in pitfall traps) indicate that large numbers of root maggot eggs were removed by these insects. The comparatively high percentage of parasitism of *Delia* spp. by *A. bilineata* observed in zero-till plots has important implications for agricultural production in central Alberta. Important advantages of utilizing zero-till systems for canola production are the reduced requirements of human labour, fuel and equipment (Lafond and Derksen 1996;

Stinner and House 1990; Jensen and Timmermans 1991). The long-term benefits of adopting zero-till systems are many, including reduction of greenhouse gases, increasing soil organic matter content, and perhaps altering/enhancing the composition of beneficial soil fauna and flora in commercial farming systems. In addition to these benefits, canola producers in areas infested annually with high population densities of root maggots should be encouraged to adopt, or continue to utilize, zero or reduced tillage systems because results of this study showed lower root maggot infestations and higher parasitism in zero-till plots relative to plots tilled conventionally.

When considering seeding rates, results of this study were in agreement with previous research that determined reduced root maggot infestations at higher seeding rates (e.g., Dosdall et al. 1996, 1998). In addition to enhancing cultural control of root maggots, higher seeding rates in canola can reduce infestations of other pests. For instance, Dosdall et al. (1999) found that increasing seeding rates in canola reduced seedling damage by flea beetles (*Phyllotreta* spp.), and O'Donovan (1994) proposed increasing canola seeding rate to 7 kg per ha to minimize infestations of tartary buckwheat, *Fagopyrum tataricum* (L.) Gaertn. Current seeding rate recommendations for canola in North Dakota and Canada are between 5.6 to 9.0 kg per ha, depending on seed bed conditions at the time of seeding, with the aim of establishing a plant population of 40 to 200 plants per square meter (Berglund and McKay 2002; Thomas 2003). Therefore adopting a seeding rate between 5.6 to 9.0 kg per ha should bring advantages in terms of improved management of root maggots and other important canola pests like flea beetles and weeds.

I did not observe consistent results for root maggot infestations or for *A. bilineata* activity for different row spacings from this study. Nevertheless, evidence from previous studies by Dosdall et al. (1996a and 1998) suggests that adopting wider row spacing resulted in reduced infestations of root maggots. In addition, Dosdall et al. (1998) found that widening row spacing in canola plantings tended to reduce seedling damage by flea beetles. In view of the above factors I suggest that adopting zero or reduced tillage in conjunction with a seeding rate of 5.6 to 9.0 kg per ha and row spacing of 30 cm will facilitate integrated management of *Delia* spp. infestations in canola while helping maintain reasonably good seed yields.

Table 3.1: Mean monthly temperature and precipitation data during the growing season at Lacombe and Vegreville, AB in 2007 and 2008 compared with long-term average values.

Lacombe

	Mean monthly precipitation (mm)			Mean monthly temperature (°C)		
			1971-2008			1971-2008
Month	2007	2008	Mean	2007	2008	Mean
April	51.5	-	21.0	2.4	1.3	4.3
May	117.9	46.4	55.6	9.8	10.3	10.1
June	174.0	100.6	75.7	14.9	13.5	13.9
July	48.8	50.6	89.4	19.1	15.3	15.4
August	69.2	56.2	70.8	13.2	15.5	14.7
September	46.0	10.4	47.3	9.4	10.3	9.8

Vegreville

	Mean monthly precipitation (mm)			Mean monthly temperature (°C)		
			1971-2008			1971-2008
Month	2007	2008	Mean	2007	2008	Mean
April	39.6	34.4	19.5	3.2	0.5	4.5
May	28.6	37.2	37.4	17.1	10.7	10.5
June	52.6	43.6	64.1	20.9	14.9	14.5
July	55.6	47.4	79.9	27.3	16.5	16.3
August	66.8	69.0	55.5	20.3	16.1	15.8
September	28.2	37.0	40.0	16.8	10.3	10.2

Source: National climate data and information archive. Environment Canada 2009.

Table 3.2: Analysis of variance results (*P* values) for insect activity data in plots of *Brassica napus* grown in zero and conventional tillage at various row spacings and seeding rates at Lacombe and Vegreville, Alberta in 2007 and 2008. Statistically significant ($P < 0.05$) values are given in bolt font.

Effect	***Delia* spp. oviposition**	**Canola root damage**	**Activity density of *A. bilineata***	**Parasitism of *A. bilineata* on *Delia* spp.**
2007- Lacombe				
Tillage (T)	**0.0406**	**0.0033**	0.1222	0.2722
Seeding rate (S)	**0.0001**	0.6117	0.4564	0.9610
Row spacing (R)	0.3305	0.5400	0.0628	0.7316
T × S	0.1362	0.0978	0.7291	0.1571
T × R	0.1120	0.6582	0.0871	0.7253
S × R	0.1567	0.5051	0.3238	0.3454
T × R × S	0.2789	0.3435	0.2531	0.1326
2008- Lacombe				
Tillage (T)	**0.0433**	0.2493	**0.0326**	0.3939
Seeding rate (S)	**0.0006**	0.061	0.1379	0.3319
Row spacing (R)	**0.0468**	0.1722	0.5386	0.3763
T × S	0.6412	0.0615	0.6584	0.6935
T × R	0.6529	0.2890	0.9850	0.4410
S × R	0.2129	0.2178	0.9065	0.6037
T × R × S	0.3263	0.0612	0.8214	0.2068
2007-Vegreville				
Tillage (T)	0.0660	0.6800	0.2223	N/A
Seeding rate (S)	0.5799	0.5990	0.5882	N/A
Row spacing (R)	0.5436	0.1750	0.5416	N/A
T × S	0.8929	0.4802	0.3611	N/A
T × R	0.1617	0.4805	0.4747	N/A
S × R	0.5050	0.5463	0.2410	N/A
T × R × S	0.5719	0.4943	0.7286	N/A
2008-Vegreville				
Tillage (T)	**0.0181**	0.0807	0.3939	**0.0228**
Seeding rate (S)	**0.0018**	0.0807	0.3319	0.2750
Row spacing (R)	0.1548	0.1584	0.3763	0.1198
T × S	0.3278	0.5611	0.6935	0.5587
T × S	0.4432	0.6452	0.441	0.5942
S × R	0.2426	0.3772	0.6037	0.6114
T × R × S	0.1342	0.9118	0.2068	0.1768

[1]N/A- In 2007, at Vegreville, the production site was mistakenly cultivated after harvesting the crop. Hence, puparia of *Delia* spp. were not collected in the following spring.

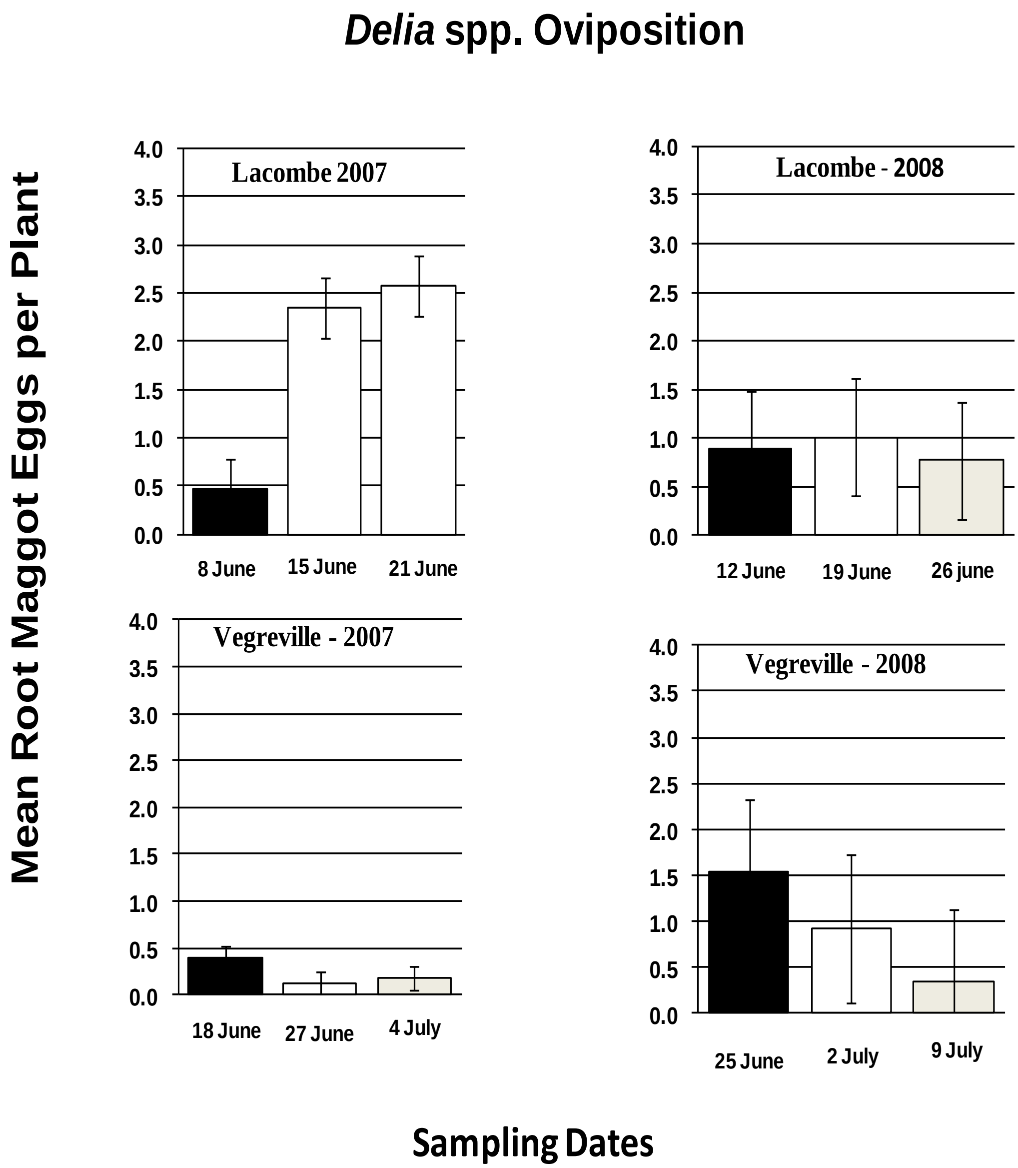


Figure 3.1. Mean root maggot eggs per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded at different plant densities and row spacings under conventional and zero tillage regimes.

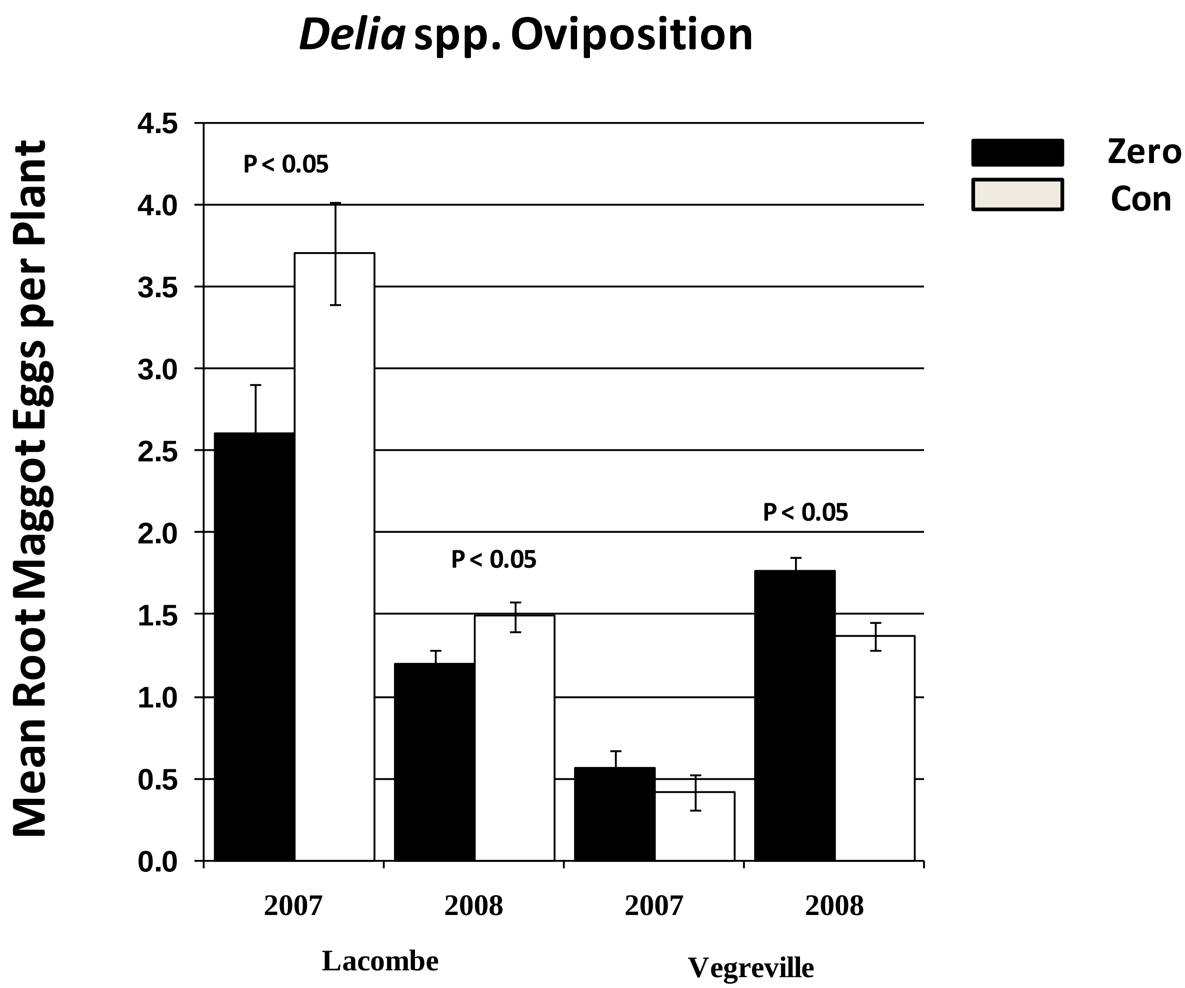


Figure 3.2. Mean root maggot eggs per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded under conventional (Con) and zero (Zero) tillage regimes.

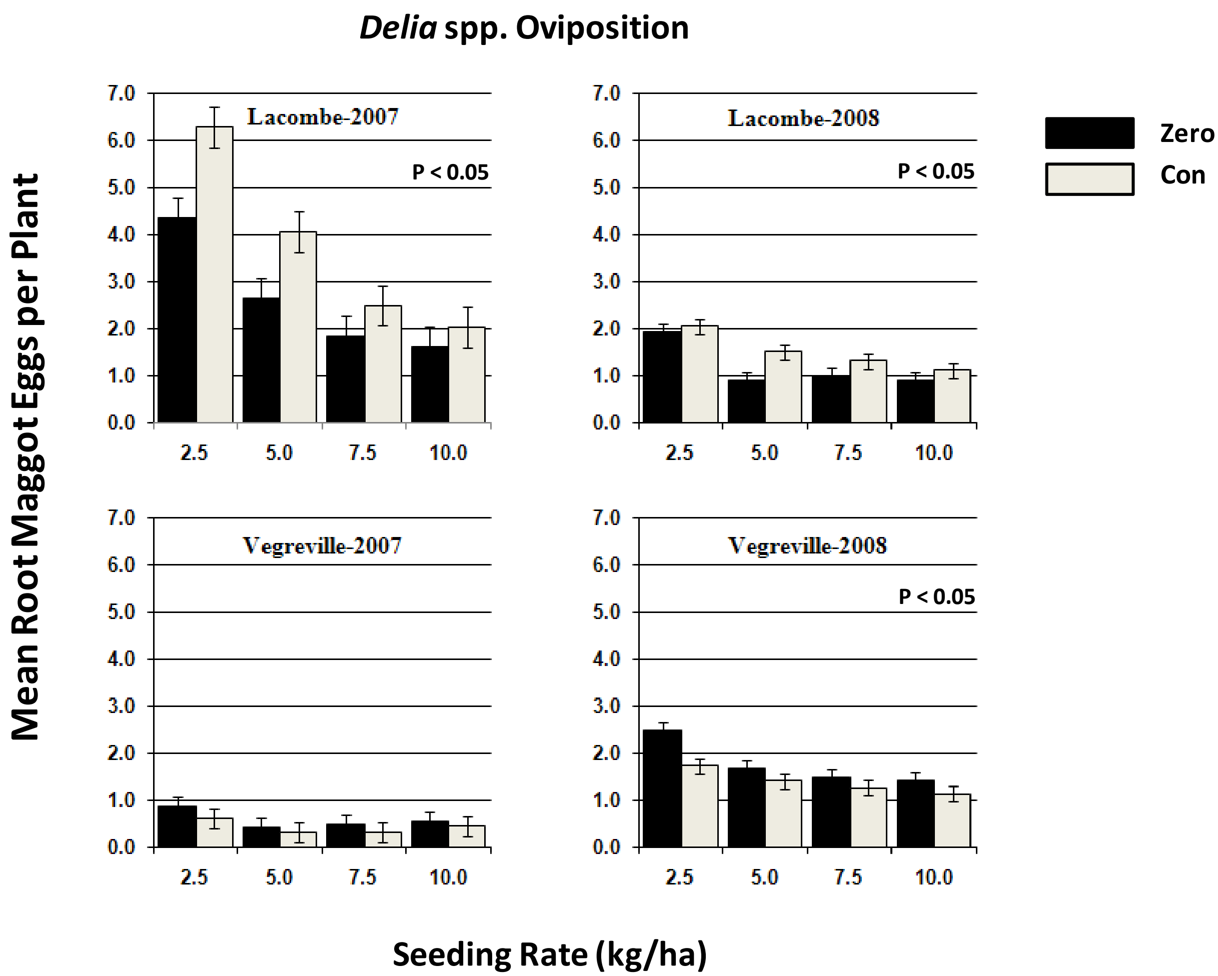


Figure 3.3. Mean root maggot eggs per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded at four rates (2.5, 5.0, 7.5 and 10.0 kg per ha) under conventional (Con) and zero (Zero) tillage regimes.

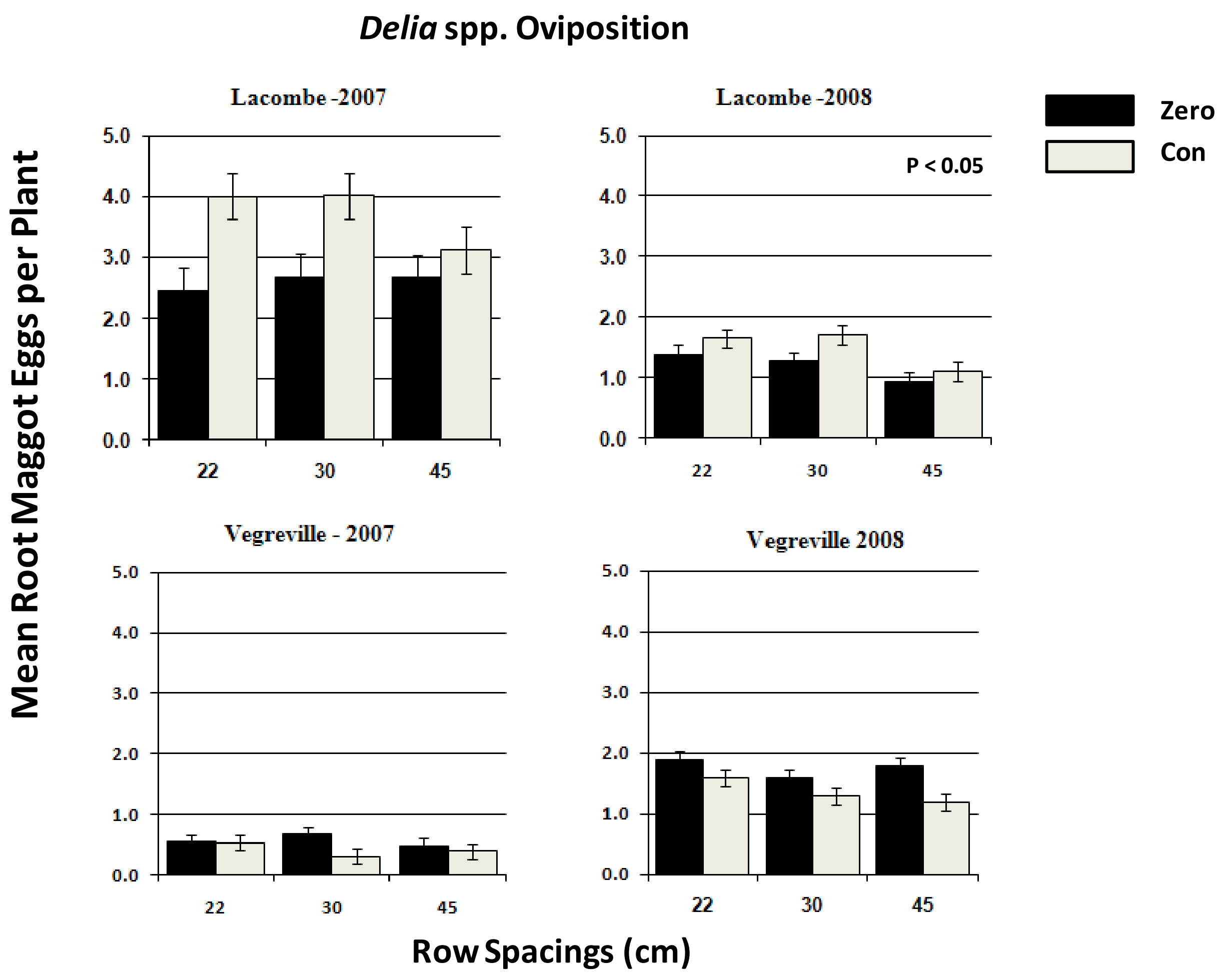


Figure 3.4. Mean root maggot eggs per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded at three row spacings (22, 30, and 45 cm) under conventional (Con) and zero (Zero) tillage regimes.

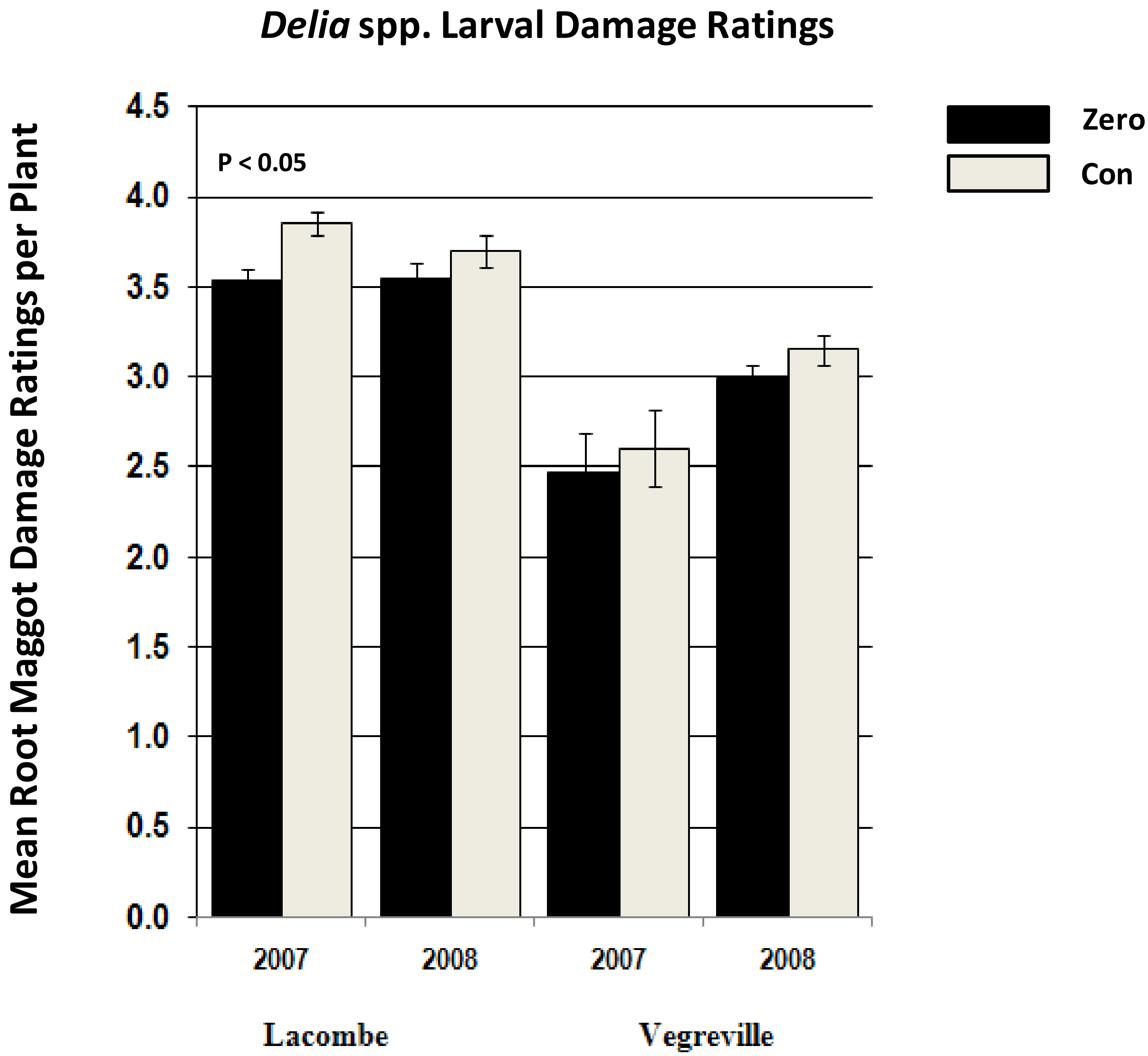


Figure 3.5. Mean root maggot damage ratings per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded under conventional (Con) and zero (Zero) tillage regimes.

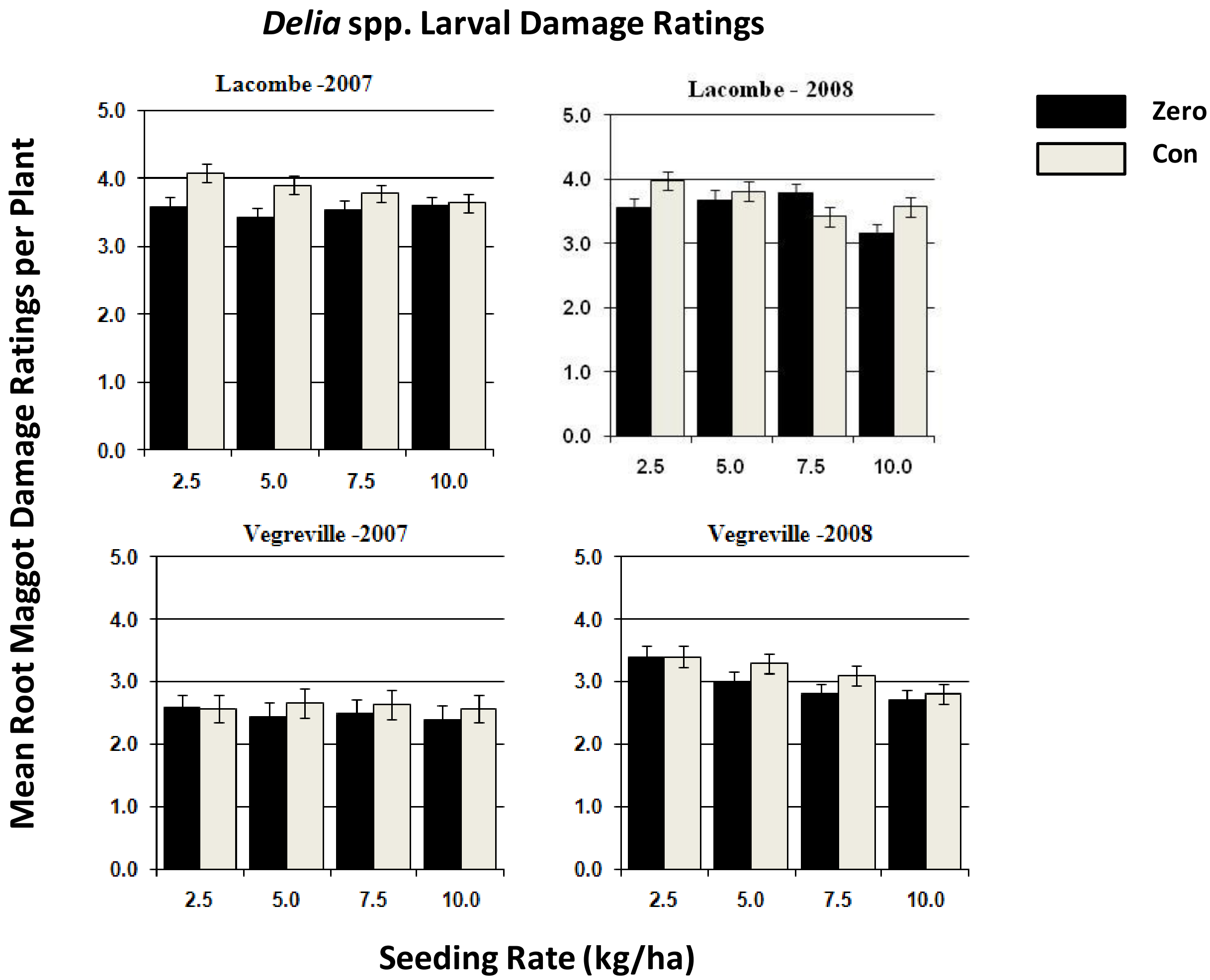


Figure 3.6. Mean root maggot (*Delia* spp.) damage ratings per plant of *Brassica napus* at Lacombe and Vegreville, AB in 2007 and 2008 seeded at various rates (2.5, 5.0, 7.5 and 10.0 kg per ha) under zero (Zero) and conventional (Con) tillage regimes.

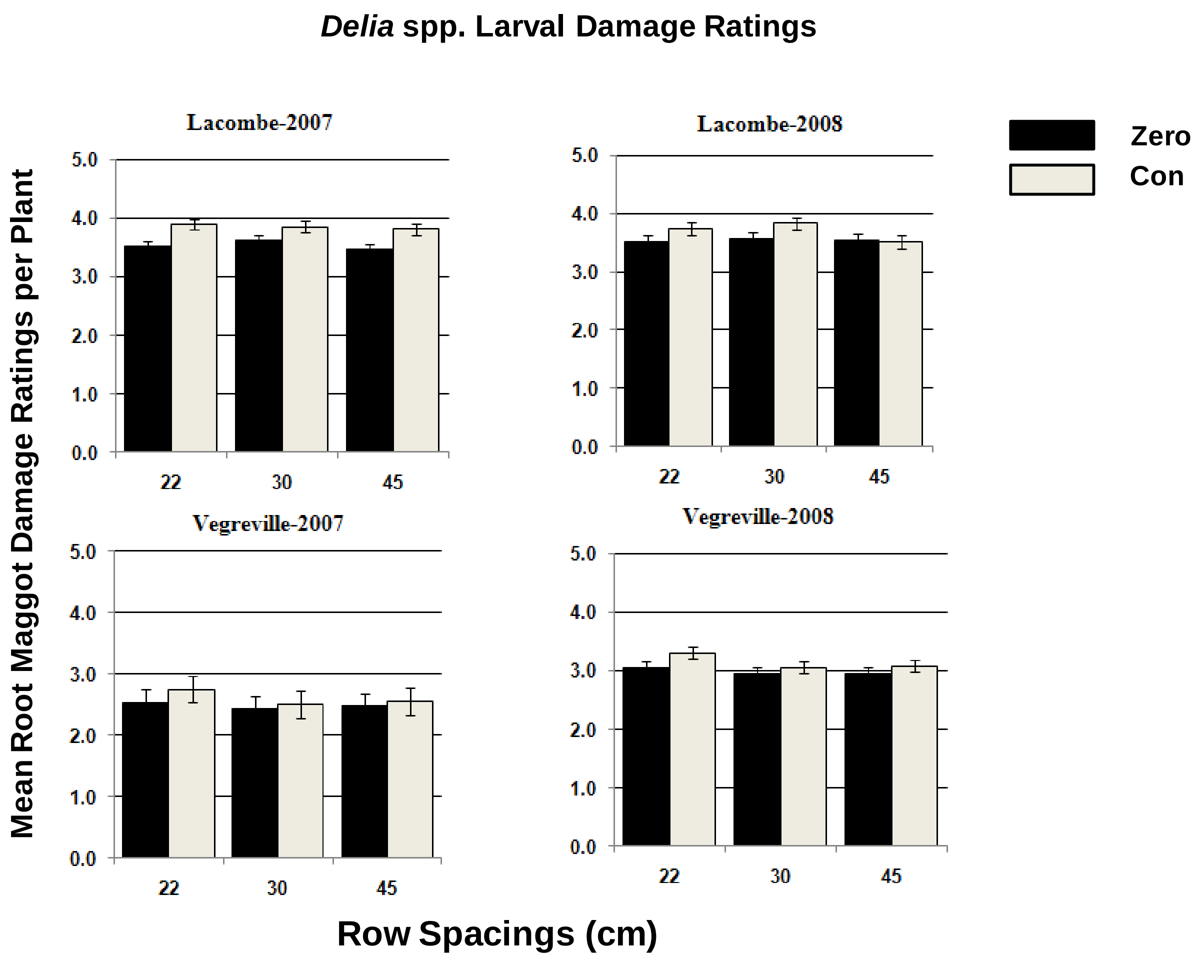


Figure 3.7. Mean root maggot (*Delia* spp.) damage ratings per plant of *Brassica napus* seeded at various row spacings (22, 30, and 45 cm) under conventional (Con) and zero (Zero) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

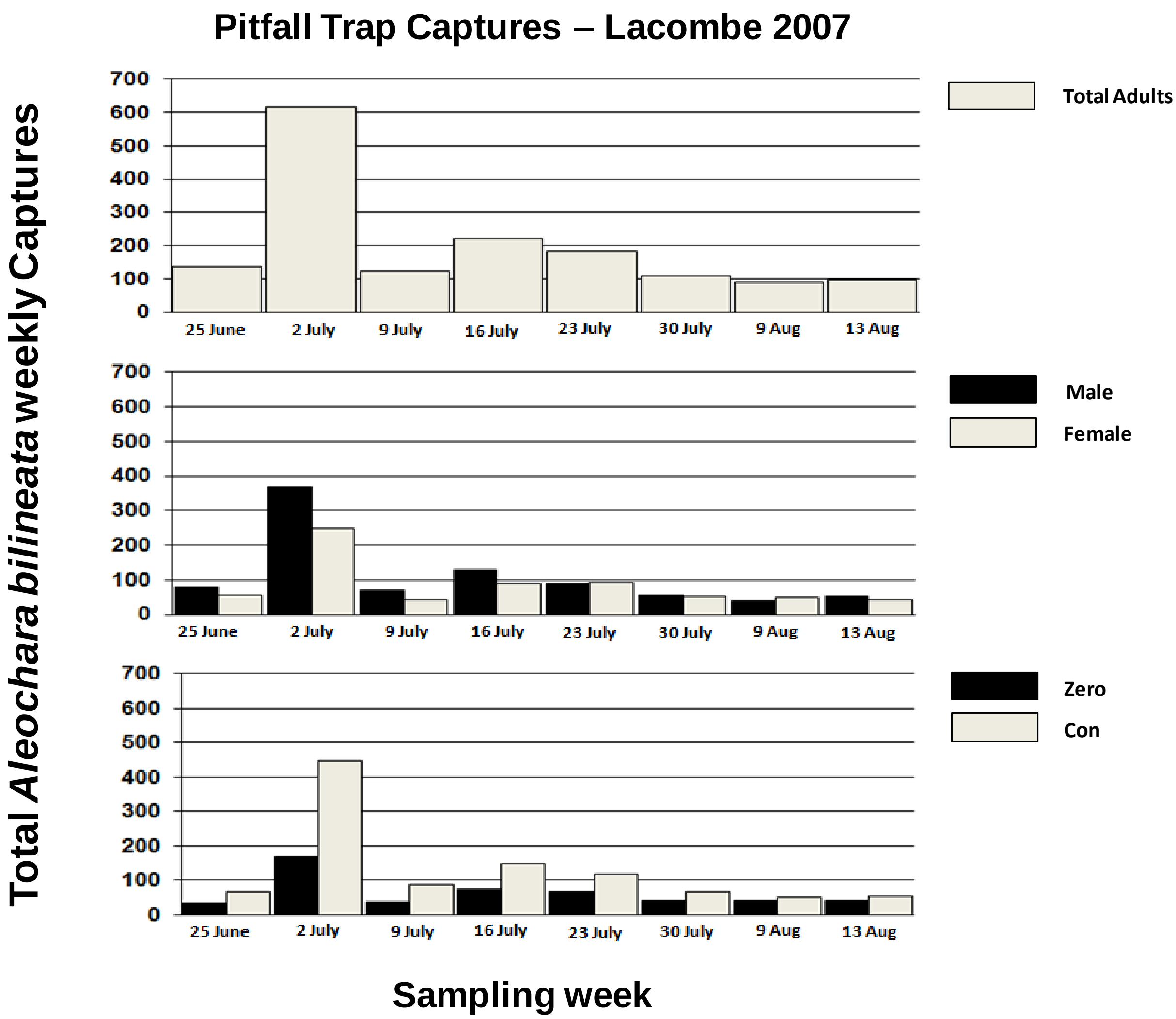


Figure 3.8. Weekly pitfall trap captures of *Aleochara bilineata* adults from plots subjected to conventional (Con) and zero (Zero) tillage treatments at Lacombe from 25 June to 13 August 2007.

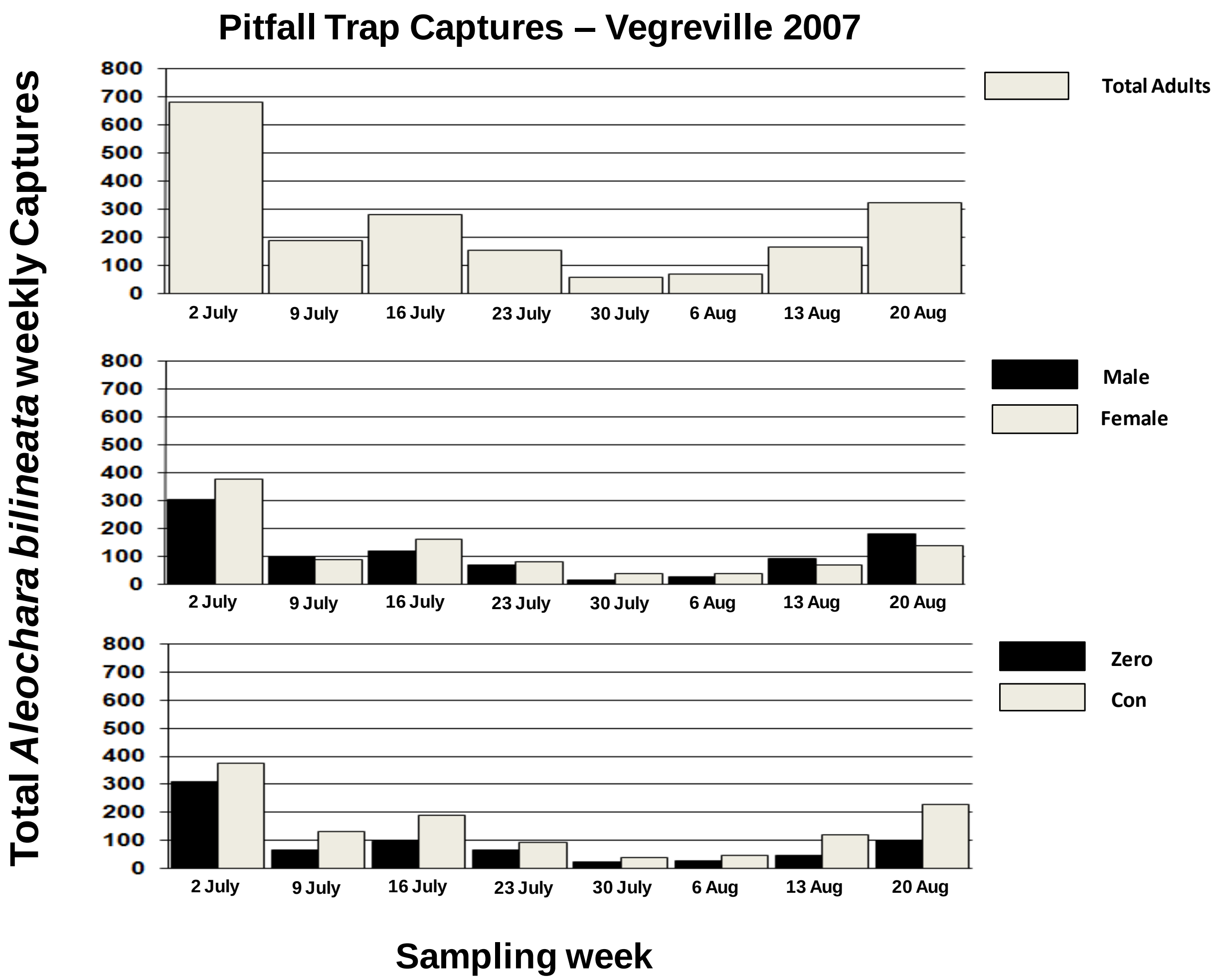


Figure 3.9. Weekly pitfall trap captures of *Aleochara bilineata* adults from plots subjected to conventional (Con) and zero (Zero) tillage treatments at Vegreville from 2 July to 20 August 2007.

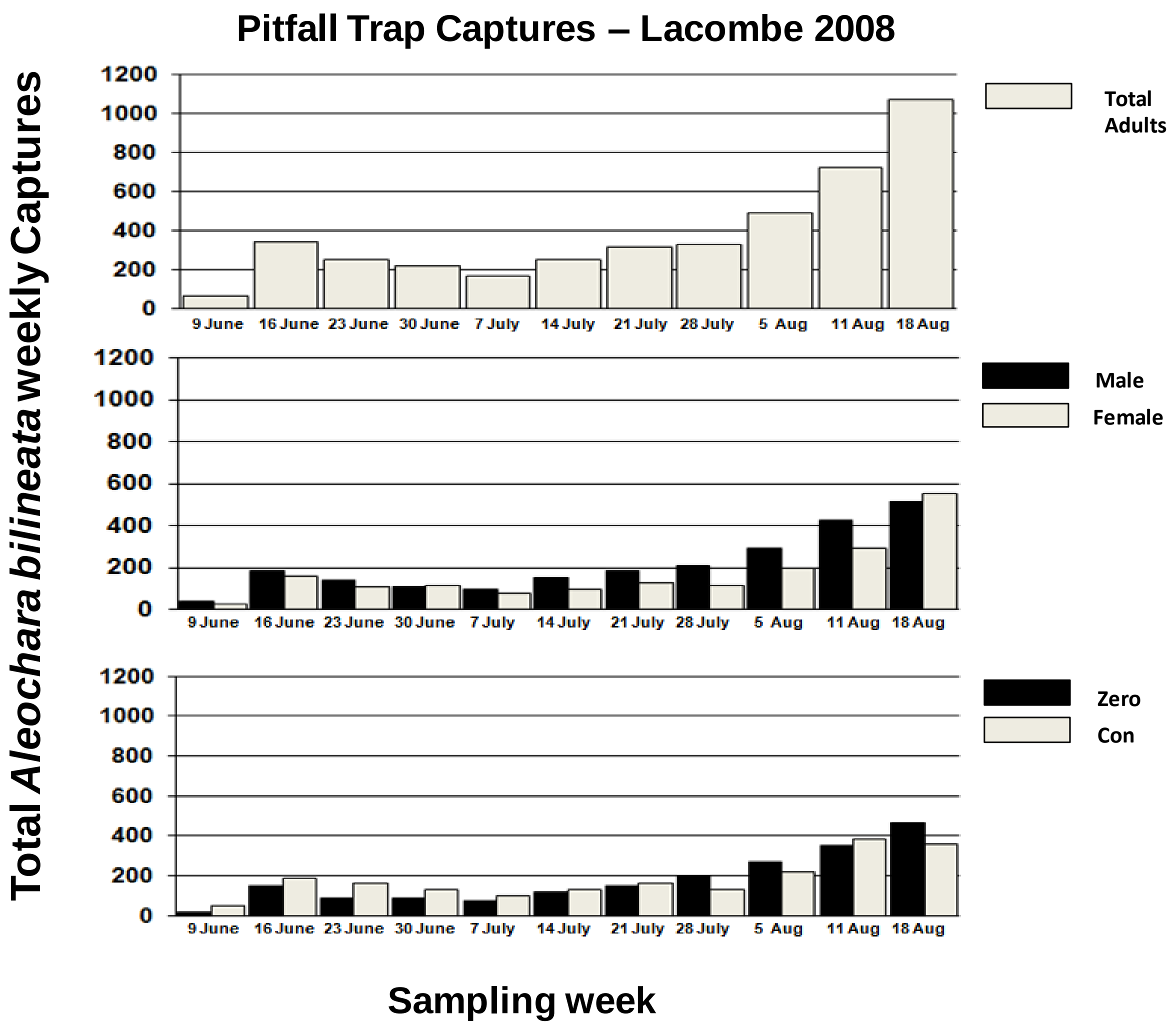


Figure 3.10. Weekly trap captures of *Aleochara bilineata* adults from plots subjected to conventional (Con) and zero (Zero) tillage treatments at Lacombe from 9 June to 11 August 2008.

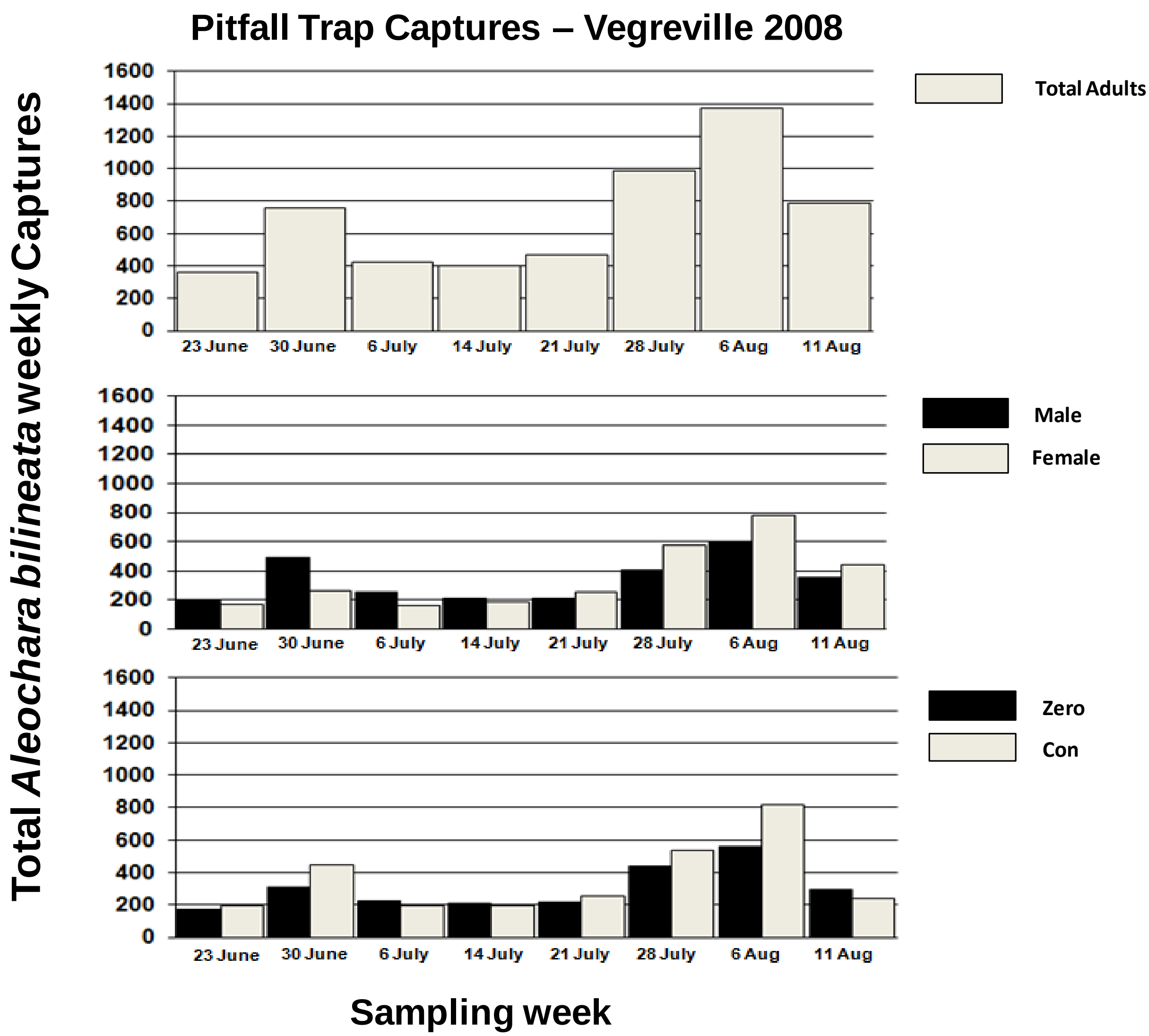


Figure 3.11 Weekly pitfall trap captures of *Aleochara bilineata* adults from plots subjected to conventional (Con) and zero (Zero) tillage treatments at Vegreville from 23 June to 11 August 2008.

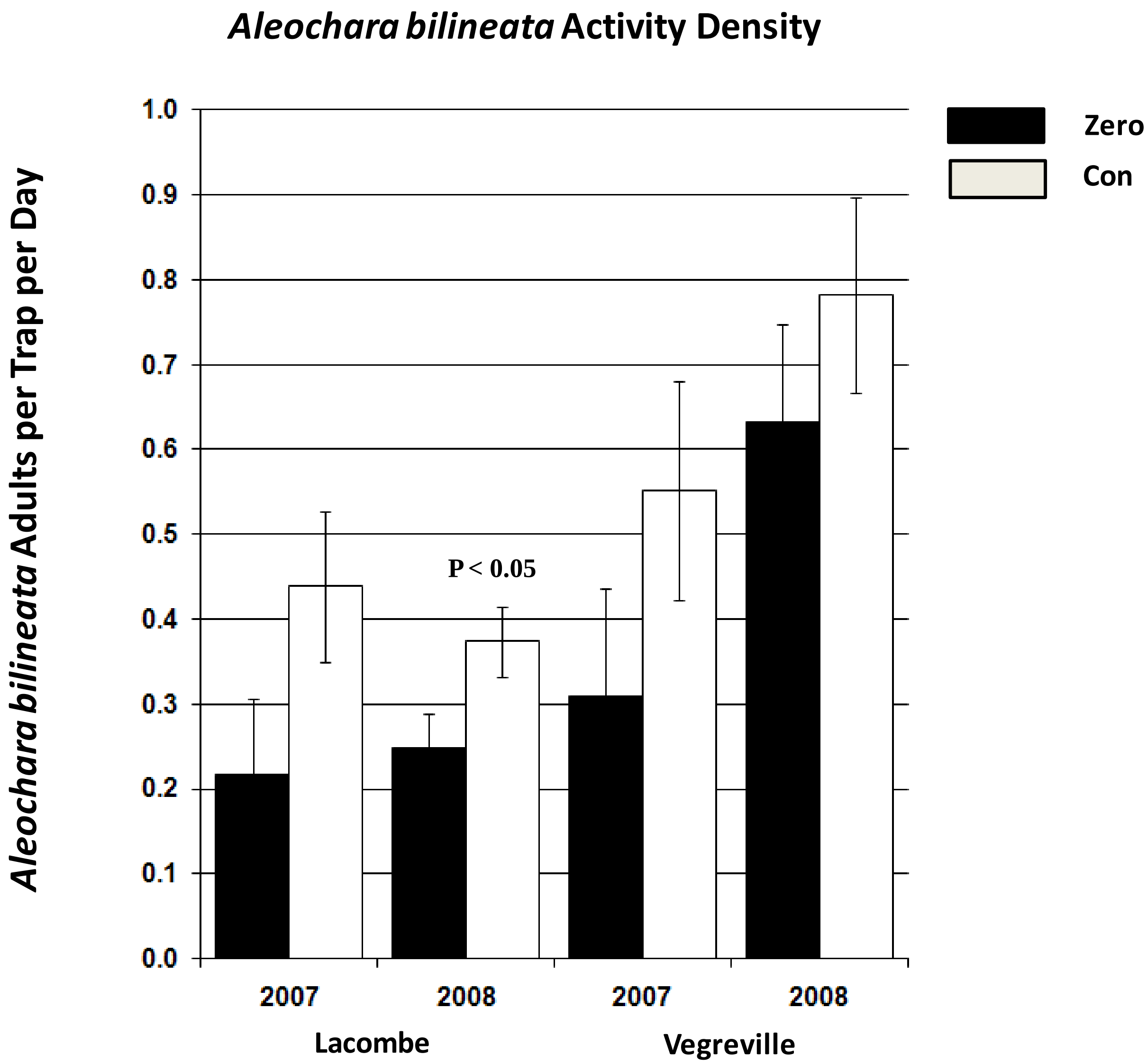


Figure 3.12. Mean *Aleochara bilineata* activity density in *Brassica napus* plots seeded at Lacombe and Vegreville, AB in 2007 and 2008 under conventional (Con) and zero (Zero) tillage regimes.

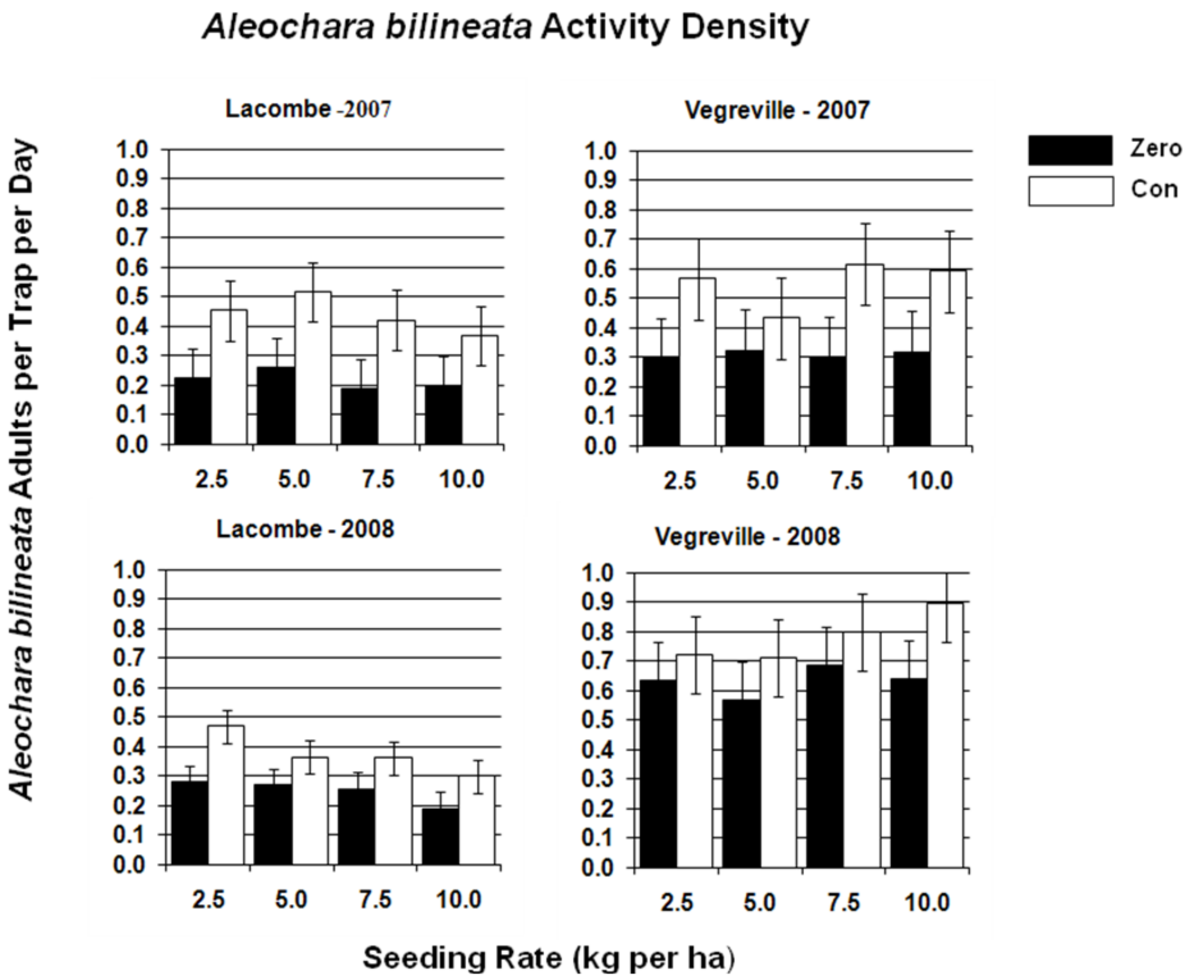


Figure 3.13. Mean *Aleochara bilineata* activity density in *Brassica napus* plots at Lacombe and Vegreville, AB in 2007 and 2008 seeded at different rates (2.5, 5.0, 7.5 and 10.0 kg per ha) under conventional (Con) and zero (Zero) tillage regimes.

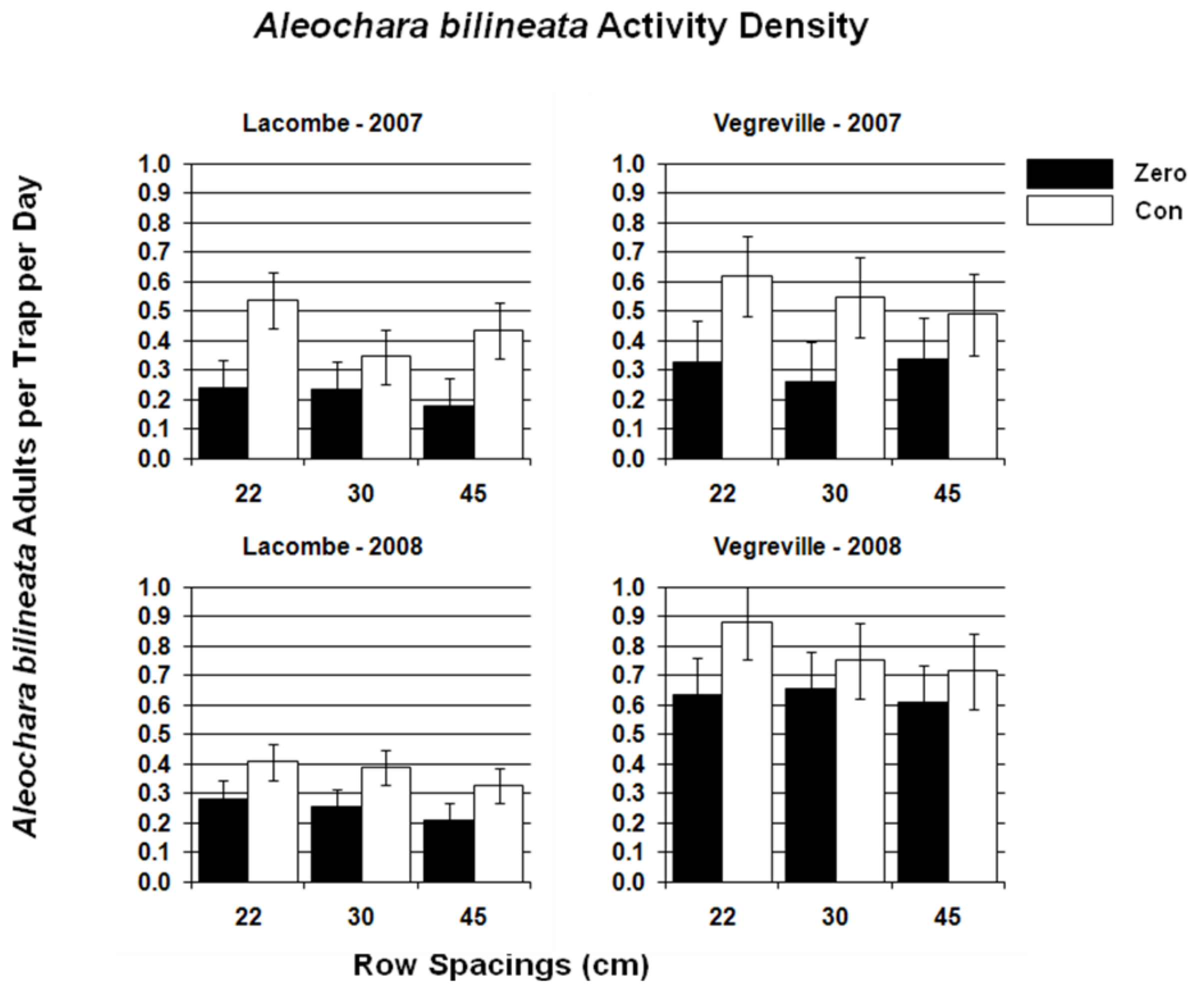


Figure 3.14. Mean *Aleochara bilineata* activity density in *Brassica napus* plots at Lacombe and Vegreville, AB in 2007 and 2008 seeded at different row spacings (22, 30, and 45 cm) under conventional (Con) and zero (Zero) tillage regimes.

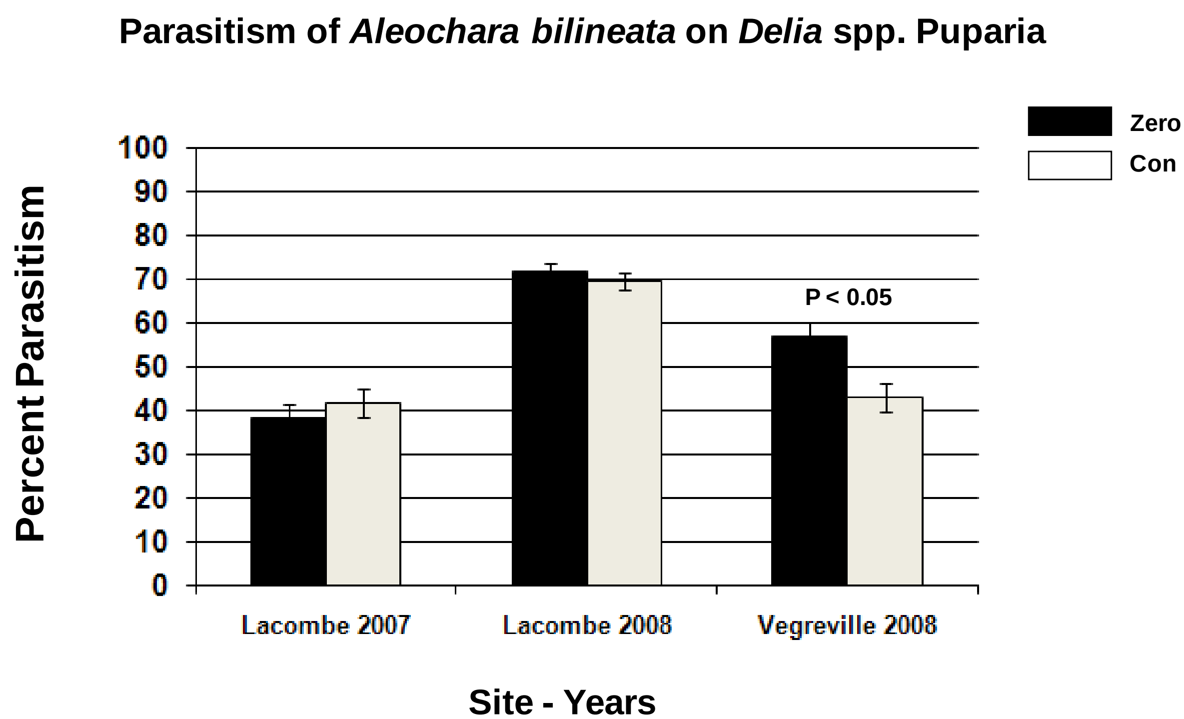


Figure 3.15. Mean percent parasitism of *Aleochara bilineata* on *Delia* spp. puparia in *Brassica napus* plots seeded under conventional (Con) and zero (Zero) tillage at Lacombe and Vegreville, AB in 2007 and 2008.

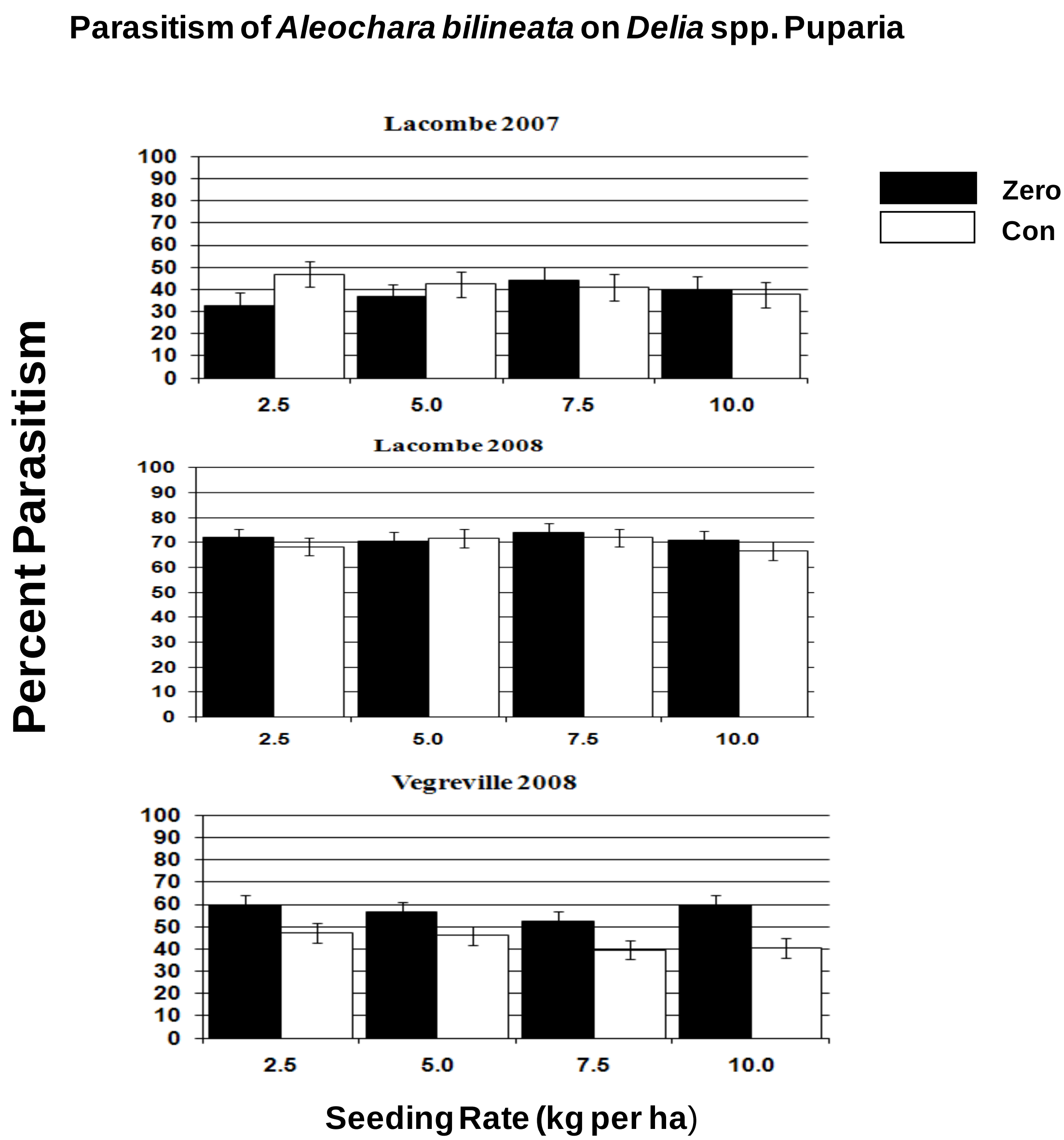


Figure 3.16. Mean percent parasitism of *Aleochara bilineata* on *Delia* spp. puparia in *Brassica napus* plots seeded at different rates (2.5, 5.0, 7.5 and 10 kg per ha) under conventional (Con) and zero (Zero) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

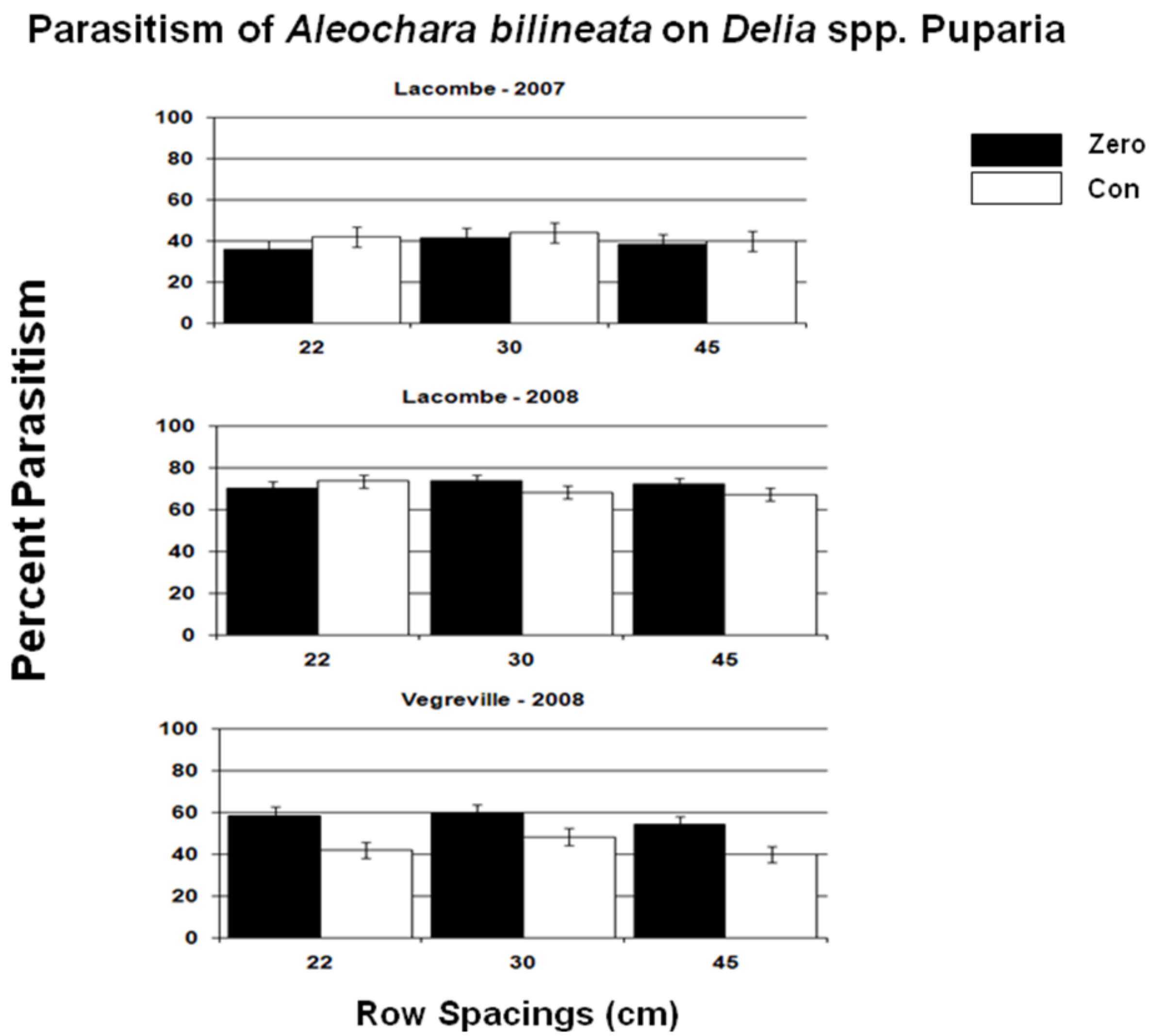


Figure 3.17. Mean percent parasitism of *Aleochara bilineata* on *Delia* spp. puparia in *Brassica napus* plots seeded at different row spacings (22, 30, and 45 cm) under conventional (Con) and zero (Zero) tillage regimes at Lacombe and Vegreville, AB in 2007 and 2008.

Literature Cited

A'Brook, J. 1968. The effect of plant spacing on the numbers of aphids trapped over a groundnut crop. Ann. Appl. Biol. 61: 289-294.

Anonymous. 2009. National climate data and information archive. Environment Canada. www.climate.weatheroffice.ec.gc.ca . Accessed May 3, 2009.

Bailey, K. L., and L. J. Duczek. 1996. Managing cereal diseases under reduced tillage. Can. J. Plant Pathol. 18: 159-167.

Berglund, D.R., and K. McKay. 2002. Canola production. North Dakota Agric. Ext. Serv. Bull. A-686. North Dakota State Univ. Ext. Serv., Fargo.

Broatch, J. S., L. M. Dosdall, G. W. Clayton, K. N. Harker, and R. C. Yang. 2006. Using degree-day and logistic models to predict emergence patterns and seasonal flights of the cabbage maggot and seed corn maggot (Diptera: Anthomyiidae) in canola. Environ. Entomol. 35: 1166-1177.

Broatch, J.S. 2008. Root Maggot and Beneficial Insect Dynamics in Response to Weed Populations in Canola. Ph.D. Thesis, University of Alberta, Edmonton, AB. 255 pp.

Broatch, J. S., L. M. Dosdall, R.-C. Yang, K. N. Harker, G. W. Clayton. 2008. Emergence and seasonal activity of the entomophagous rove beetle *Aleochara bilineata* (Coleoptera: Staphylinidae) in canola in western Canada. Environ. Entomol. 37: 1451-1460.

Brooks, A. R. 1951. Identification of root maggots (Diptera: Anthomyiidae) attacking cruciferous garden crops in Canada, with notes on biology and control. Can. Entomol. 83: 109-120.

Colhoun, E. H. 1953. Notes on the stages and the biology of *Baryodma ontarionis* Casey (Coleoptera: Staphylinidae), a parasite of the cabbage maggot, *Hylemya brassicae* Bouché (Diptera Anthomyiidae). Can. Entomol. 85: 1-8.

Dixon, P. L., J. R. Coady, D. J. Larson, and D. Spaner. 2004. Undersowing rutabaga with white clover: Impact on *Delia radicum* (Diptera: Anthomyiidae) and its natural enemies. Can. Entomol. 136: 427-442.

Doane, J. F., and R. K. Chapman. 1962. Oviposition preference of the cabbage maggot, *Hylemya brassicae* (Bouché). J. Econ. Entomol. 55: 137-138.

Dosdall, L. M., M. J. Herbut, and N. T. Cowle. 1994. Susceptibilities of species and cultivars of canola and mustard to infestation by root maggots (*Delia* spp.) (Diptera: Anthomyiidae). Can. Entomol. 126: 251-260.

Dosdall, L. M., M. J. Herbut, N. T. Cowle, and T. M. Micklich. 1996a. The effect of seeding date and plant density on infestations of root maggots, *Delia* spp. (Diptera: Anthomyiidae), in canola. Can. J. Plant Sci. 76: 169-177.

Dosdall, L. M., M. J. Herbut, N. T. Cowle, and T. M. Micklich. 1996b. The effect of tillage regime on emergence of root maggots (*Delia* spp.) (Diptera: Anthomyiidae), from canola. Can. Entomol. 128: 1157-1165.

Dosdall, L. M., L.Z. Florence, P. M. Conway and N. T. Cowle. 1998. The effect of tillage regime, row spacing, and seeding rate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 78: 671-681.

Dosdall, L. M., M. G. Dolinski, N. T. Cowle, and P. M. Conway. 1999. The effect of tillage regime, row spacing, and seeding rate on feeding damage by flea beetles, *Phyllotreta* spp. (Coleoptera: Chrysomelidae), in canola in central Alberta, Canada. Crop Prot. 18: 217-224.

Dosdall, L.M., R.C. Yang, and P.M. Conway. 2002. Do applications of sulfur or sulfate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola? Can. J. Plant Sci. 82: 599-610.

Dosdall, L.M., G.W. Clayton, K.N. Harker, J.T. O'Donovan, and F.C. Stevenson. 2004. The effects of soil fertility and other agronomic factors on infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Agron. J. 96: 1306-1313.

Farrell, J. A. K. 1976. Effects of groundnut crop density on the population dynamics of *Aphis craccivora* Koch (Hemiptera, Aphididae) in Malawi. Bull. Entomol. Res. 66: 317-329.

Finch, S., and R. H. Collier. 2000. Host-plant selection by insects – A theory based on 'appropriate/inappropriate landings' by pest insects of cruciferous plants. Entomol. Exp. Appl. 96: 91-102.

Fournet, S., D. Poinsot, E. Brunel, J. P. Nénon, and A. M. Cortesero. 2001. Do female coleopteran parasitoids enhance their reproductive success by selecting high-quality oviposition sites? J. Anim. Ecol. 70: 1046-1052.

Gomez, K. A., and A. A. Gomez. 1984. Statistical Procedures for Agricultural Research. 2nd ed. John Wiley and Sons, New York, NY.

Griffiths, G. C. D. 1986a. Phenology and dispersion of *Delia radicum* (L.) (Diptera: Anthomyiidae) in canola fields at Morinville, Alberta. Quaest. Entomol. 22: 29-50.

Griffiths, G. C. D. 1986b. Relative abundance of the root maggots *Delia radicum* (L.) and *D. floralis* (Fallén) (Diptera: Anthomyiidae) as pests of canola in Alberta. Quaest. Entomol. 22: 253-260.

Griffiths, G. C. D. 1991a. Economic assessment of cabbage maggot damage in canola in Alberta. *In*: Proc. GCIRC 8th Int. Rapeseed Congr. Saskatoon, SK. 9-11 July 1991, Vol. 2, pp. 528-535.

Griffiths, G. C. D. 1991b. Cyclorrhapha II (Schizophora: Calyptratae). Part 2, Anthomyiidae. *In* G. C. D. Griffiths (Ed.), Flies of the Nearctic Region. Volume VIII. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, Germany, pp. 953-1048.

Gullan, P.J., and P. S. Cranston. 2005. The Insects. An Outline of Entomology. Blackwell Publishing. Third edition. 505 pp.

Hemachandra, K. S., N. J. Holliday, P. G. Mason, J. J. Soroka, and U. Kuhlmann. 2007. Comparative assessment of the parasitoid community of *Delia radicum* in the Canadian prairies and Europe: A search for classical biological control agents. Biol. Control 43: 85–94.

Hughes, R. D. 1959a. The natural mortality of *Erioischia brassicae* (Bouché) (Diptera, Anthomyiidae) during the egg stage of the first generation. J. Anim. Ecol. 28: 343-357.

Hughes, R. D. 1959b. Natural mortality of *Erioischia brassicae* (Bouché) (Diptera, Anthomyiidae) during the immature stages of the first generation. J. Anim. Ecol. 28: 231-241.

Hummel, J.D. 2009. Insect and Agronomic Responses in Canola and Wheat Intercrops. Ph.D. Thesis, University of Alberta, Edmonton, AB. 177 pp.

Jensen, T., and J. Timmermans. 1991. Conservation tillage. Agdex 516-3, Alberta Agriculture, Edmonton, AB.

Jones, T. H., M. P. Hassel, and S. W. Pacala. 1993. Spatial heterogeneity and the population dynamics of a host-parasitoid system. J. Animal Ecol. 62: 251-262.

Klimaszewski, J. 1984. A revision of the genus *Aleochara* Gravenhorst of America north of Mexico (Coleoptera: Staphylinidae, Aleocharinae). Mem. Entomol. Soc. Can. 129: 1-211.

Kostal, V., and S. Finch. 1994. Influence of background on host-plant selection and subsequent oviposition by the cabbage root fly (*Delia radicum*). Entomol. Exp. Appl. 70: 153-163.

Lafond, G.P., and D.A. Derksen. 1996. Long-term potential of conservation tillage on the Canadian prairies. Can. J. Plant Pathol. 18: 151-158.

Langlet, X., G. Boivin, E. Brunel, and J. P. Nenon. 1998. Variation in weight of *Aleochara bilineata* (Coleoptera: Staphylinidae) in relation to host size and reproduction. Can. Entomol. 130: 257–265.

Larney, F.J., J. Ren, S. M. McGinn, C.W. Lindwall, R.C. Izaurralde. 2003. The influence of rotation, tillage and row spacing on near-surface soil temperature for winter wheat in southern Alberta. Can. J. Plant Sci. 83: 89-98.

Matthewmann, W. G., and L. H Lyall. 1966. Resistance in cabbage to the cabbage maggot, *Hylemya brassicae* (Bouché). Can. Entomol. 98: 59-69.

McDonald, R.S., and M.K. Sears. 1992. Assessment of larval feeding damage of the cabbage maggot (Diptera: Anthomyiidae) in relation to oviposition preference in canola. J. Econ. Ent. 85: 957-962.

O'Donovan, J. T. 1994. Canola (*Brassica rapa*) plant density influences tartary buckwheat (*Fagopyrum tataricum*) interference, biomass, and seed yield. Weed Sci. 42: 385-389.

Read, D. C. 1962. Notes on the life history of *Aleochara bilineata* (Gyll.) (Coleoptera: Staphylinidae), and on its potential value as a control agent for the cabbage maggot, *Hylemya brassicae* (Bouché) (Diptera: Anthomyiidae). Can. Entomol. 94: 417-424.

Royer, L., J. Le Lannic, J. P. Nénon, and G. Boivin. 1998. Response of first-instar *Aleochara bilineata* larvae to the puparium morphology of its dipteran host. Entomol. Exp. Appl. 87: 217-220.

Royer, L., and G. Boivin. 1999. Infochemicals mediating the foraging behaviour of *Aleochara bilineata* Gyllenhal adults: Sources of attractants. Entomol. Exp. Appl. 90: 199-205.

SAS Institute Inc. 2003. SAS/STAT User's Guide, version 9.1. SAS Institute, Inc. Cary, NC.

Soroka, J. J., L. M. Dosdall, O.O. Olfert, and E. Seidle. 2004. Root maggots (*Delia* spp., Diptera: Anthomyiidae) in prairie canola (*Brassica napus* L. and *B. rapa* L.): Spatial and temporal surveys of root damage and prediction of damage levels. Can. J. Plant Sci. 84: 1171-1182.

Stinner, B. R., and G.J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Annu. Rev. Entomol. 35: 299–318.

Swailes, C. E. 1959. Resistance in rutabagas to the cabbage maggot, *Hylemya brassicae* (Bouché) (Diptera: Anthomiidae). Can. Entomol. 91: 700-703.

Thomas, P. 2003. Canola growers manual. Canola Council of Canada, Website at www.council.org

Tomlin, A. D., D. G. R. McLeod, L. V. Moore, J. W. Whistlecraft, J. J. Miller, and J. H. Tolman. 1992. Dispersal of *Aleochara bilineata* [Col.: Staphylinidae] following inundative releases in urban gardens. Entomophaga 37: 55-63.

Turnock, W. J., G. Boivin, and J. W. Whistlecraft. 1995. Parasitism of overwintering puparia of the cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), in relation to host density and weather factors. Can. Entomol. 127: 535-542.

Wishart, G. 1957. Surveys of parasites of *Hylemya* spp. (Diptera: Anthomyiidae) that attack cruciferous crops in Canada. Can. Entomol. 89: 450-454.

Appendix 2, Table 1: LS Means and standard errors for *Delia* spp. oviposition data at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		**Lacombe 2008**		**Vegreville 2007**		**Vegreville 2008**	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	2.60	0.31	1.20	0.09	0.81	0.03	1.76	0.09
Conventional	3.71	0.31	1.49	0.09	0.80	0.03	1.37	0.09
Seeding rate								
2.5 kg/ha	5.32	0.32	1.99	0.12	0.84	0.22	2.10	0.11
5.0 kg/ha	3.35	0.32	1.24	0.12	0.78	0.22	1.53	0.11
7.5 kg/ha	2.15	0.32	1.14	0.12	0.80	0.22	1.37	0.11
10 kg/ha	1.81	0.32	1.01	0.12	0.79	0.22	1.27	0.11
Row spacing								
22 cm	2.05	0.19	1.52	0.12	0.82	0.02	1.74	0.10
30 cm	2.06	0.19	1.49	0.12	0.79	0.02	1.46	0.10
45 cm	2.03	0.19	1.02	0.12	0.80	0.02	1.50	0.10
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	2.02	0.03	1.93	0.17	0.86	0.03	2.48	0.16
Zero × 5.0 kg/ha	1.98	0.03	0.97	0.17	0.79	0.03	1.68	0.16
Zero × 7.5 kg/ha	2.01	0.03	0.98	0.17	0.81	0.03	1.48	0.16
Zero × 10 kg/ha	2.02	0.03	0.90	0.17	0.78	0.03	1.41	0.16
Con × 2.5 kg/ha	2.14	0.03	2.04	0.17	0.82	0.03	1.72	0.16
Con × 5.0 kg/ha	2.10	0.03	1.50	0.17	0.78	0.03	1.39	0.16
Con × 7.5 kg/ha	2.07	0.03	1.30	0.17	0.78	0.03	1.26	0.16
Con × 10 kg/ha	2.03	0.03	1.12	0.17	0.81	0.03	1.12	0.16
Tillage× Row Spacing								
Zero × 22 cm	2.00	0.02	1.38	0.16	0.82	0.03	1.89	0.14
Zero × 30 cm	2.03	0.02	1.27	0.16	0.81	0.03	1.59	0.14
Zero × 45 cm	1.99	0.02	0.94	0.16	0.81	0.03	1.80	0.14
Con × 22 cm	2.10	0.02	1.65	0.16	0.81	0.03	1.59	0.14
Con × 30 cm	2.08	0.02	1.71	0.16	0.78	0.03	1.33	0.14
Con × 45 cm	2.07	0.02	1.11	0.16	0.79	0.03	1.20	0.14

Appendix 2, Table 2: LS Means and standard errors for *Delia* spp. larval damage to canola tap roots at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	2.01	0.02	1.88	0.02	1.72	0.06	1.72	0.02
Conventional	2.08	0.02	1.92	0.02	1.75	0.06	1.77	0.02
Seeding rate								
2.5 kg/ha	2.08	0.03	1.94	0.03	1.75	0.05	1.83	0.04
5.0 kg/ha	2.04	0.03	1.93	0.03	1.74	0.05	1.76	0.04
7.5 kg/ha	2.04	0.03	1.89	0.03	1.74	0.05	1.72	0.04
10 kg/ha	2.03	0.03	1.83	0.03	1.72	0.05	1.67	0.04
Row spacing								
22 cm	2.05	0.02	1.90	0.02	1.77	0.05	1.78	0.02
30 cm	2.06	0.02	1.92	0.02	1.72	0.05	1.73	0.02
45 cm	2.03	0.02	1.87	0.02	1.73	0.05	1.74	0.02
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	2.02	0.03	1.88	0.04	1.75	0.07	1.83	0.05
Zero × 5.0 kg/ha	1.98	0.03	1.92	0.04	1.72	0.07	1.73	0.05
Zero × 7.5 kg/ha	2.01	0.03	1.94	0.04	1.73	0.07	1.68	0.05
Zero × 10 kg/ha	2.02	0.03	1.77	0.04	1.70	0.07	1.65	0.05
Con × 2.5 kg/ha	2.14	0.03	1.99	0.04	1.74	0.07	1.84	0.05
Con × 5.0 kg/ha	2.10	0.03	1.95	0.04	1.77	0.07	1.80	0.05
Con × 7.5 kg/ha	2.07	0.03	1.84	0.04	1.76	0.07	1.76	0.05
Con × 10 kg/ha	2.03	0.03	1.89	0.04	1.75	0.07	1.68	0.05
Tillage× Row Spacing								
Zero × 22 cm	2.00	0.02	1.87	0.03	1.74	0.07	1.74	0.03
Zero × 30 cm	2.03	0.02	1.89	0.03	1.71	0.07	1.71	0.03
Zero × 45 cm	1.99	0.02	1.87	0.03	1.72	0.07	1.72	0.03
Con × 22 cm	2.10	0.02	1.93	0.03	1.80	0.07	1.81	0.03
Con × 30 cm	2.08	0.02	1.96	0.03	1.73	0.07	1.74	0.03
Con × 45 cm	2.07	0.02	1.87	0.03	1.74	0.07	1.75	0.03

Appendix 2, Table 3: LS Means and standard errors for activity density of *A. bilineata* at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	0.22	0.09	0.25	0.04	0.31	0.13	0.63	0.12
Conventional	0.44	0.09	0.37	0.04	0.55	0.13	0.78	0.12
Seeding rate								
2.5 kg/ha	0.34	0.08	0.37	0.05	0.43	0.10	0.68	0.09
5.0 kg/ha	0.39	0.08	0.32	0.05	0.38	0.10	0.64	0.09
7.5 kg/ha	0.31	0.08	0.31	0.05	0.46	0.10	0.74	0.09
10 kg/ha	0.28	0.08	0.24	0.05	0.45	0.10	0.76	0.09
Row spacing								
22 cm	0.39	0.07	0.34	0.05	0.47	0.10	0.76	0.09
30 cm	0.29	0.07	0.32	0.05	0.40	0.10	0.70	0.09
45 cm	0.31	0.07	0.27	0.05	0.41	0.10	0.66	0.09
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	0.22	0.10	0.28	0.06	0.29	0.14	0.63	0.13
Zero × 5.0 kg/ha	0.26	0.10	0.27	0.06	0.32	0.14	0.57	0.13
Zero × 7.5 kg/ha	0.19	0.10	0.26	0.06	0.30	0.14	0.68	0.13
Zero × 10 kg/ha	0.20	0.10	0.19	0.06	0.32	0.14	0.64	0.13
Con × 2.5 kg/ha	0.45	0.10	0.47	0.06	0.57	0.14	0.72	0.13
Con × 5.0 kg/ha	0.52	0.10	0.36	0.06	0.43	0.14	0.71	0.13
Con × 7.5 kg/ha	0.42	0.10	0.36	0.06	0.62	0.14	0.80	0.13
Con × 10 kg/ha	0.37	0.10	0.30	0.06	0.59	0.14	0.89	0.13
Tillage× Row Spacing								
Zero × 22 cm	0.24	0.09	0.28	0.06	0.33	0.14	0.63	0.13
Zero × 30 cm	0.23	0.09	0.26	0.06	0.26	0.14	0.65	0.13
Zero × 45 cm	0.18	0.09	0.21	0.06	0.34	0.14	0.61	0.13
Con × 22 cm	0.54	0.09	0.41	0.06	0.62	0.14	0.88	0.13
Con × 30 cm	0.28	0.09	0.39	0.06	0.55	0.14	0.75	0.13
Con × 45 cm	0.43	0.09	0.33	0.06	0.49	0.14	0.71	0.13

Appendix 2, Table 4: LS Means and standard errors for percent parasitism of *A. bilineata* at Lacombe and Vegreville in 2007 and 2008.

	Lacombe 2007		Lacombe 2008		Vegreville 2007		Vegreville 2008	
Effect	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**	**LSMean**	**SEM**
Tillage regime								
Zero	38.43	3.23	71.92	1.92	N/A	N/A	57.17	3.27
Conventional	42.00	3.19	69.67	1.92	N/A	N/A	43.33	3.27
Seeding rate								
2.5 kg/ha	39.83	5.18	70.17	2.53	N/A	N/A	53.50	3.19
5.0 kg/ha	39.50	5.18	71.17	2.53	N/A	N/A	51.33	3.19
7.5 kg/ha	42.64	5.23	73.00	2.53	N/A	N/A	46.17	3.19
10 kg/ha	38.88	5.23	68.83	2.53	N/A	N/A	50.00	3.19
Row spacing								
22 cm	38.75	4.16	71.88	2.09	N/A	N/A	50.25	2.82
30 cm	42.64	4.23	70.88	2.09	N/A	N/A	53.63	2.82
45 cm	39.25	4.16	69.63	2.09	N/A	N/A	46.88	2.82
Tillage ×Seeding rate								
Zero × 2.5 kg/ha	32.67	5.87	72.00	3.58	N/A	N/A	50.00	4.36
Zero × 5.0 kg/ha	36.67	5.87	71.00	3.58	N/A	N/A	57.00	4.36
Zero × 7.5 kg/ha	44.27	6.05	74.00	3.58	N/A	N/A	53.00	4.36
Zero × 10 kg/ha	40.10	6.05	71.00	3.58	N/A	N/A	70.00	4.36
Con × 2.5 kg/ha	47.00	5.87	68.33	3.58	N/A	N/A	47.33	4.36
Con × 5.0 kg/ha	42.33	5.87	72.00	3.58	N/A	N/A	46.00	4.36
Con × 7.5 kg/ha	41.00	5.87	72.00	3.58	N/A	N/A	39.67	4.36
Con × 10 kg/ha	37.67	5.87	67.00	3.58	N/A	N/A	40.33	4.36
Tillage× Row Spacing								
Zero × 22 cm	35.50	4.79	70.25	2.95	N/A	N/A	58.50	3.95
Zero × 30 cm	41.28	5.05	73.50	2.95	N/A	N/A	59.00	3.95
Zero × 45 cm	38.50	4.79	72.00	2.95	N/A	N/A	54.00	3.95
Con × 22 cm	42.00	4.79	73.50	2.95	N/A	N/A	42.00	3.95
Con × 30 cm	44.00	4.79	68.25	2.95	N/A	N/A	48.25	3.95
Con × 45 cm	40.00	4.79	67.25	2.95	N/A	N/A	39.75	3.95

[1]N/A- In 2007, at Vegreville, the production site was mistakenly cultivated after harvesting the crop. Hence, puparia of *Delia* spp. were not collected in the following spring.

Zero Till	Con Till	Zero Till	Zero Till
1	5	1	11
2	7	2	8
3	12	7	12
4	1	8	9
5	6	10	1
6	9	3	3
7	2	11	10
8	8	12	6
9	3	4	4
10	4	9	5
11	11	5	2
12	10	6	7
Con Till	**Zero Till**	**Con Till**	**Con Till**
5	6	6	5
1	7	8	2
12	12	2	6
2	8	3	1
9	11	5	7
8	2	12	4
11	3	9	12
7	9	7	9
4	1	1	3
10	5	11	10
6	4	4	8
3	10	10	11
Block 1	**Block 2**	**Block 3**	**Block 4**

Treatments

1. Seeded at 2.5 kg per ha, 20 cm row spacing
2. Seeded at 2.5 kg per ha, 30 cm row spacing
2. Seeded at 2.5 kg per ha, 45 cm row spacing
4. Seeded at 5 kg per ha, 20 cm row spacing
5. Seeded at 5 kg per ha, 30 cm row spacing
6. Seeded at 5 kg per ha, 45 cm row spacing
7. Seeded at 7.5 kg per ha, 20 cm row spacing
8. Seeded at 7.5 kg per ha, 30 cm row spacing
9. Seeded at 7.5 kg per ha, 45 cm row spacing
10. Seeded at 10 kg per ha, 20 cm row spacing
11. Seeded at 10 kg per ha, 30 cm row spacing
12. Seeded at 10 kg per ha, 45 cm row spacing

Appendix 2, Table 5: Site map of the experimental design, treatments and randomization at Vegreville in 2007.

Life Stages of Root Maggots

Adult

Eggs

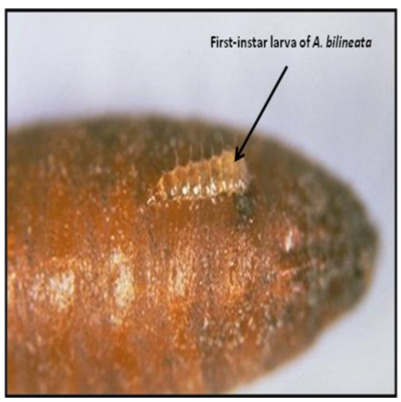
Larvae

Larvae and Puparia

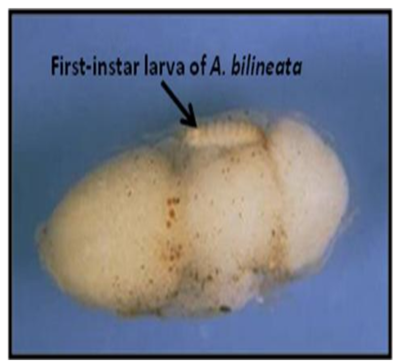
Photos: L. Dosdall

Life Stages of *Aleochara bilineata*

Adult



First Instar Larvae on Root Maggot Puparium



First Instar Larvae as an ecto parasite on Root Maggot Pupae

Photos: L. Dosdall and J. Hummel

Appendix 2, Figure 1.0: Life Stages of Root Maggots and the parasitoid *Aleochara bilineata*

Chapter 4: General Discussion

4.1 Introduction

This thesis describes results of a study of tritrophic interactions among canola crop plants, root maggots which are a species complex of anthomyiid flies and the dominant herbivores of canola plants in central Alberta, and the staphylinid beetle *Aleochara bilineata* Gyllenhal which is the principal natural enemy of root maggots. My study was conducted in four site-years in weed-free monocultures which are the common mode of growing canola in commercial farms worldwide and in particular in western North America. The herbicide tolerant hybrid canola (*Brassica napus* L.) variety InVigor 5020 was used for this study.

Over the past three decades, canola (*Brassica napus* L. and *Brassica rapa* L.) has attained the status of an important cash crop and has become a rotational option for commercial producers in western North America. Since it was first developed, plant breeders and researchers in canola have transformed the crop to an extent whereby the canola industry currently adds $13.8 billion in economic activity to the Canadian economy (Canola Council of Canada 2008). Moreover, there is a plan to take the canola industry to 15 million tonnes of sustained market demand and production by 2015 (Canola Council of Canada 2008). This ambitious plan will bring new challenges and opportunities to researchers and producers. Perhaps foremost among the challenges for researchers will arise in developing strategies for enhancing sustainable canola production by minimizing crop losses from insect pests, plant pathogens, and weeds.

For the past 30 years numerous research activities were undertaken in canola agroecosystems to promote sustainable canola production. In my research, I manipulated tillage regime, seeding rate and row spacings as treatments to study the tritrophic interactions noted above. More-or-less similar research studies have been undertaken in the past with open-pollinated canola varieties to study the agronomic and entomological aspects of the tritrophic interaction. However, to my knowledge, no previous research has been conducted to study these aspects with herbicide-tolerant hybrid canola varieties.

The introductions of herbicide-tolerant canola production systems and of hybrid canola varieties have changed the status of canola production in western North America (Harker et al. 2003). Adoption by Canadian producers of herbicide tolerant canola (HTC) varieties has been ongoing for several years and consequently the substantial acreage associated with HTC indicates the application, acceptance, and success of the technology (Johnson et al. 2001). The 2006 harvest comprised 95% non-conventional canola varieties that included 50% Roundup Ready® varieties resistant to glyphosate, 30% Liberty Link® varieties resistant to glufosinate ammonium, 15% Clearfield® varieties resistant to imidazoline, and 5% conventional canola varieties (Broad 2005). Hybrid canola varieties currently grown in the Northern Great Plains provide higher yield potential than open-pollinated varieties. However, the management strategies necessary to achieve optimum yield are not well understood (Brandt et al. 2005).

4.2 Agronomic practices of tillage regime, seeding rate, and row spacings and their effects on the herbicide tolerant hybrid canola variety, InVigor 5020

In Chapter Two I presented the results of a study investigating the effects of tillage regime, seeding rate and row spacings on seedling emergence, yield, seed weight, and seed quality of canola (*Brassica napus* L.) variety InVigor 5020 in central Alberta. InVigor 5020 is an herbicide tolerant hybrid canola variety which contains the Liberty Link® trait, and so is genetically tolerant of the herbicide, glufosinate ammonium.

Overall, the canola emergence data from my study were comparable to the desired plant density of *B. napus* for optimum yield, which is 70 to 120 plants per square meter (Alberta Agriculture 2009). Moreover, the achieved plant densities at the time of counting surpassed the 50% emergence estimate, which is considered as a representative average of canola emergence under field conditions (Harker et al. 2003). Variable results were obtained for canola yield in my studies depending on the site-year. Canola yield was not affected by tillage regime in any of the site-years ($P > 0.05$). Hybrid canola can therefore be grown successfully with either zero or conventional tillage regimes. The effects of seeding rate and row spacings on mean seed yield were inconsistent. Seeding rate in open-pollinated canola has been studied extensively in western Canada, providing a wide range of results (Brandt et al. 2005). A number of early studies with open-pollinated canola revealed that seeding rate did not influence yield performance (Degenhardt and Kondra 1981; Christensen and Drabble 1984). However, other studies conducted by Kondra (1975, 1977) indicated that greater yield was produced at a seeding rate of approximately 6.0 kg per ha. Harker et al. (2003) determined that the open-pollinated canola variety ‘Exceed’ produced greater yield at higher seeding rates than 3.5 kg per ha. Hanson et al. (2008) determined that open pollinated and hybrid canola generally produced increased yield with increasing seeding rates although differences among higher rates were not always significant. Harker et al. (2003) found that the hybrid canola variety InVigor 2153 produced greater yield at higher seeding rates than 5.5 kg per ha. I found that seed yield increases were not incremental at higher seeding rates, indicating effects of intraspecific plant competition at higher plant densities.

I also found that seed yield was not incremental at wider row spacings. In my study, seed numbers were adjusted for each seeding rate and row spacing to achieve target densities of 60, 120, 180, and 240 plants m^{-2}. Therefore plants were packed closely within each row at wider row spacings than for narrow row spacings for a specific seeding rate, and this can lead to decreased seed yield in much the same way that increased seeding rates correlate with decreased seed yields in my study.

The results for 1,000 kernel weight (K) were also variable in my studies depending on sites and years. Moreover 1,000 K and seed yield did not have a specific correlated relationship for different agronomic practices tested in this study. My findings on 1,000 K with InVigor 5020 for different agronomic practices tested in this study were in agreement with the findings of previous studies undertaken with open-pollinated canola varieties by Kondra (1975, 1977) and Degenhardt and Kondra (1981).

In my study, variable results were obtained for seed quality assessment (seed protein and oil content) for single treatments and treatment combinations depending on sites and years. These results were in agreement with most similar studies conducted with open-pollinated canola varieties. For example, Kondra (1975) found that row spacing and seeding rate had no significant effects on oil content. Harker et al. (2003) found that seeding rate had no effect on primary seed constituent concentrations such as protein and oil. Moreover, tillage regime had no significant effect on seed quality assessments in any site-year in this study. At the same time, the presence of a three-way interaction of main effects at Lacombe 2008 on seed protein and oil content revealed that seed quality is a result of compounding effects of many production factors depending mainly on sites and years.

Overall, the findings of my study with hybrid canola are more-or-less comparable to the findings of previous studies of this nature with open-pollinated canola varieties in terms of trend changes in seed yield and quality. The magnitude of yield advantages of InVigor 5020 over open-pollinated varieties was clearly evident from my study. All four site-years produced higher seed yields with hybrid canola than for seed yields using traditional canola varieties in Alberta two decades ago (Thomas 1984). Additionally, three site-years produced seed yields comparable to the yields obtained for InVigor varieties from the independent Prairie Canola Variety Trials (PCVT) (Canola Council of Canada 2009).

4.3 Infestations of *Delia* spp. (Diptera: Anthomyiidae) and activity density and parasitism of the predator-parasitoid *Aleochara bilineata* Gyllenhal (Coleoptera: Staphylinidae)

In Chapter Three I presented the results of a study designed to investigate the effects of tillage regime, seeding rate, and row spacing on infestations of *Delia* spp. (Diptera: Anthomyiidae), and activity density and parasitism of the predator-parasitoid *Aleochara bilineata* Gyllenhal (Coleoptera: Staphylinidae). Effects of agronomic parameters on *Delia* spp. populations and damage were in general agreement with similar studies previously undertaken by Dosdall et al. (1994, 1996, 1998) in canola in central Alberta. For example, in all four site-years of my study, *Delia* spp. oviposition followed a trend whereby peak egg-laying was observed between 18 to 25 June, when most plants were in the four to five true-leaf or rosette stages of development. This oviposition pattern was similar to that recorded previously in canola with egg populations increasing to a peak in mid to late June (Dosdall et al. 1994, 1996). Moreover, I found that *Delia* spp.

oviposition consistently and significantly ($P < 0.05$) decreased when seeding rate increased from 2.5 kg per ha to 10 kg per ha in plots subjected to both tillage treatments in all four site-years. Increasing seeding rate increases plant density, and higher plant density promotes reduced basal stem diameters in canola that reduce oviposition of *Delia* spp. (Dosdall et al. 1996). Reductions in oviposition are usually reflected in decreased taproot damage by larvae (Dosdall et al. 1996, 1998). I found that increasing seeding rate was associated with reduced root maggot damage ratings for *B. napus* in three of four site-years. Again, this trend also was in agreement with earlier work by Dosdall et al. (1996, 1998). In two site-years greater root maggot oviposition occurred in plots subjected to conventional tillage and the other site-year had greater root maggot oviposition in plots subjected to zero tillage. However, mean root maggot damage ratings were relatively greater in plots subjected to conventional tillage in all site-years.

I found that a relationship between the behavioral parameters of *Delia* spp. hosts and the predator-parasitoid *A. bilineata* existed in my test sites despite a few exceptions. *Aleochara bilineata* trap captures followed a similar trend in all four site-years with at least two peaks in beetle captures per site-year. The first peak of *A. bilineata* adult trap captures occurred approximately one week after peak *Delia* spp. oviposition dates in three of four site-years. But at Vegreville in 2008, the first *A. bilineata* peak occurred during the onset of peak *Delia* spp. oviposition. These results are in agreement with studies conducted on the population dynamics of *A. bilineata* in relation to root maggot hosts in canola cropping systems in western Canada by Broatch et al. (2008b). The recommended production practice for canola in western Canada is to rotate crops, so canola is usually not seeded on land on which the same crop was grown in the preceding year (Thomas 2003). In this study, plots were seeded to a cereal crop in the years before the canola plots were established; hence adults of *A. bilineata* would have migrated into the plots from elsewhere. I observed greater activity density of *A. bilineata* in conventionally-tilled plots in all four site years. Plots subjected to conventional tillage had plants with greater root maggot damage ratings, indicating that *A. bilineata* was concentrated in patches of greatest resource availability. Insect predators and parasitoids use vision, audition, and/or olfaction to locate a suitable habitat (Royer and Boivin 1999). Tomlin et al. (1992) suggested that *A. bilineata* may use infochemicals to locate the best sites for mating, foraging and oviposition, by aggregating where *Delia* spp. are abundant.

Overall parasitism of *Delia* spp. by *A. bilineata* ranged from 38 to 74% in this cropping system. Only at Vegreville in 2008, significantly greater mean percent of parasitized puparia occurred in zero-tilled plots than in conventionally-tilled plots ($P < 0.05$). However, these plots had plants with lower root maggot damage ratings and lower activity density of *A. bilineata*. These observations seem contradictory to the concepts of infochemical attraction effects on adults, and density dependency with regard to movements of *A. bilineata* (Royer and Boivin 1999; Jones et al. 1993). Nevertheless it appears that the microenvironment of zero-till plots may have provided better conditions for parasitism than in plots tilled conventionally.

The predator-parasitoid, *Aleochara verna* Say (Coleoptera: Staphylinidae), was captured in pitfall traps in all site-years, but comprised only 0.93% of the total *Aleochara* spp. captured. Therefore, it was not included in the statistical analyses for different agronomic practices tested in this study. This species is evidently of very minor importance in the biological control of root maggots in canola in central Alberta, an observation that agrees with previous research by Broatch (2008) and Hummel (2009).

4.4 Classical biological control of root maggots (*Delia* spp.; Diptera: Anthomyiidae) in canola in Canada.

Classical biological control of *Delia radicum* (L.) in vegetable crops in Canada has been attempted during mid-twentieth century, but failed because of erroneous records of *Aphaereta* and *Aleochara* species introduced at that time (Andreassen et al. 2007). Work is now underway to revive a classical biological control programme of *D. radicum* in canola by a group of researchers at the University of Manitoba. Hemachandra et al. (2007) identified *Aleochara bipustulata* (L.), a congeneric species of *A. bilineata* as a potential candidate for classical biological control of *D. radicum* in canola. However, it appears that, if introduced, the chances of permanent establishment of *A. bipustulata* in an ecological region where *A. bilineata* is already well established is very low. I observed *A. bilineata* parasitism rates of 38 to 74% to *Delia* spp. puparia, and in addition, the large numbers of adult beetles found in some site-years (e.g., > 5,400 adults at one study site in pitfall traps) indicate that a remarkable level of suppression of *Delia* spp. population could be achieved in canola cropping systems. In central Alberta, Broatch (2008) and Hummel (2008) also found large numbers of *A. bilineata* adults from their study sites that are more-or-less similar in area to my study sites (e.g., the area of my study site was approximately 5000 m^2). Moreover, Hummel (2009) determined that the parasitism rate of *Delia* spp. puparia by *A. bilineata* ranged from 46 to 81% in one site-year. Therefore, I consider that *A. bilineata* is very well established in central Alberta and most of the research findings summarised below from Fournet et al. (2000) suggest that *A. bipustulata* will not survive against *A. bilineata*.

- The reproductive potential of *A. bipustulata* females is higher than that of *A. bilineata.*

- Development time of *A. bilineata* (61.91 days) is more synchronised with the development time of *D. radicum* (50.37 days) than that of *A. bipustulata* (73.41 days).

- Host acceptance of *A. bilineata* is higher (86.5%) than that of *A. bipustulata* (68.3%).

- *A. bilineata* has high degree of host specificity by parasitising only species of the genus *Delia*, but *A. bipustulata* has a broader host range which could cause harmful non-target effects.

- *A. bilineata* larvae have a strong competitive advantage by parasitising host pupae already parasitised by *A. bipustulata.*

- *A. bilineata* can probably be mass-reared more efficiently and at lower cost than *A. bipustulata*.

Aleochara bipustulata may be considered a generalist with a wider host range, extending from phytophagous species such as *Delia* spp. to coprophagous and necrophagous species of the dipteran genera *Lucilia*, *Helicophagella*, *Lonchaea,* and *Ravinia* (Maus et al. 1998). Even though high reproductive potential may appear to enhance the prospects for *A. bipustulata* for biological control, a lack of host specificity in this species means that its offspring are not necessarily targeting root maggot hosts. However, the high reproductive potential may be a great advantage for *A. bipustulata* to have maximum chance to rapidly find and colonise decaying materials. This strategy may not be necessary for *A. bilineata* which only parasitises host pupae associated with living plants (Fournet et al. 2000). Riley et al. (2007) suggested that mustard seed meal can be an important tool in a biological control programme involving release of *A. bipustulata* to attract this species to a location where it can find mates and hosts. Andreassen et al. (2007) are of the opinion that mustard seed meal can be spread around the roots of canola plants to attract *A. bipustulata* to increase the success rate of establishment of this species in canola cropping system. However, such an additional task associated with the proposed classical biological control is practically not feasible in the context of large acreage of canola planted every year in the Canadian Prairies.

Moreover, based on a laboratory study conducted by Andreassen et al. (2009), three non-target species appear to be at risk from an introduction of *A. bipustulata* in Canada. Among the three non-target species, one includes *Lonchaea corticis* Taylor (Diptera: Lonchaeidae), whose larvae are predators of an important forest pest in Canada, *Pissodes strobi* Peck (Coleoptera: Curculionidae) (Hulme 1990; Andreassen et al. 2009). Although Andreassen et al. (2009) stated that the risk of disrupting natural control of *P. strobi* is low, a thorough pest risk analysis is required before making an attempt to introduce *A. bipustulata* from Europe in Canadian canola agroecosystems. Such a pest risk analysis should be carried out for each and every non-target species in the risk category. The pest risk analysis should be conducted using appropriate methodologies in accordance with ISPM No. 2 Guidelines for pest risk analysis (Anonymous 2005).

4.5 Key observations from this study and implications for sustainable canola cropping

Overall the key observations of my study are as follows:

1. No seed yield differences occurred for the hybrid *B. napus* variety InVigor 5020 subjected to either zero or conventional tillage treatments.

2. In general, seed yield did not increase incrementally at higher seeding rates and wider row spacings. Response was variable.

3. Relatively greater *Delia* spp. oviposition was observed in plots subjected to conventional tillage than zero tillage.

4. Relatively greater *Delia* spp. larval damage was observed in plots subjected to conventional tillage than zero tillage.

5. Reasonably large numbers of *A. bilineata* adults were found in my test sites (e.g., > 5,400 adults at one study site in pitfall traps).

6. Relatively greater *A. bilineata* activity density was observed in plots subjected to conventional tillage.

7. Relatively greater parasitism of *Delia* spp. by *A. bilineata* was observed in plots subjected to zero tillage.

8. Overall parasitism of *Delia* spp. puparia by *A. bilineata* ranged from 38 to 74%.

Based on the above observations some implications of my research are as follows:

1. Canola producers in areas infested annually with high population densities of root maggots should be encouraged to adopt, or continue to utilize, zero or reduced tillage systems. I found that in general *Delia* spp. oviposition and larval damage ratings for plants were relatively greater when canola was grown under conventional tillage than with the heterogeneous microenvironment associated with zero tillage. More-or-less similar observations were made by Dosdall et al. (2003), Broatch et al. (2008) and Hummel et al. (2009). Moreover, I observed a comparatively high percentage of parasitism of *Delia* spp. by *A. bilineata* in zero-till plots. Other advantages of utilizing zero-till systems for canola production are the reduced requirements of human labour, fuel and equipment (Lafond and Derksen 1996; Stinner and House 1990; Jensen and Timmermans 1991). The long-term benefits of adopting zero-till systems are many, including reduction of greenhouse gases, increasing soil

organic matter content, and perhaps altering/enhancing the composition of beneficial soil fauna and flora in commercial farming systems

2. The overall parasitism of *Delia* spp. by *A. bilineata* in the range of 38 to 74% and the occurrence of reasonably large numbers of *A. bilineata* adults in canola monocultures are promising in terms of suppressing *Delia* spp. populations in the long run. Nevertheless further research studies in the direction of understanding interactions among the different members of the root maggot natural enemy community, including pathogens of *Delia* spp., in canola monocultures across a series of ecoregions in western Canada would be appropriate for the following reasons.

    a. Such research activities may help researchers to sensitize the stakeholders of canola industry to develop a holistic idea of suppressing *Delia* spp. populations and other insect pests in canola using purely locally available natural enemies in a sustainable manner.

    b. Such research activities may help the stakeholders in the canola industry to review the rationale given for the proposed introduction of *A. bipustulata* to Canadian canola agroecosystems.

3. Undertaking further research activities to identify specific seeding rates for different hybrid canola varieties would help the producers to make wise decisions during farm budgeting.

4. Undertaking a similar research study with larger plot area may produce more refined results for entomological aspects of my study. For example, a

larger plot area may help to establish a comprehensive relationship between different seeding rates and beetle captures or different row spacings and beetle captures.

5. Establishment of beetle banks using *Brassica rapa* L. or any other brassicaceous crops susceptible to *Delia* spp. larval infestation may be helpful to conserve and enhance *A. bilineata* populations in the long run. Such beetle banks should be established close to fields identified for canola production for the following year. Producers should be encouraged to establish beetle banks or maintain other habitats with the focus of increasing insect species richness and abundance of natural enemies of insect pests in their farming environment.

6. In the context of sustainable development, regular contacts should be maintained with producers through agriculture extension workshops on crop/pest management techniques to sensitize the producers towards enhanced ecosystem sustainability.

Literature Cited

Alberta Agriculture 2009. Using 1,000 kernel weight for calculating seeding rates and harvest losses. www.agric.gov.ab.ca. Accessed on15 January 2010.

Andreassen, L. D., U. Kuhlmann, P. G. Mason, N. J. Holliday. 2007. Classical biological control of the cabbage root fly, *Delia radicum*, in Canadian canola: an analysis of research needs. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2,: 1-12.

Andreassen, L. D., U. Kuhlmann, P. G. Mason, N. J. Holliday. 2009. Host range testing of a prospective classical biological control agent against cabbage maggot, *Delia radicum*, in Canada. Biol. Control 48: 210-220.

Anonymous. 2005. ISPM No. 3. Guidelines for the export, shipment, import and release of biolgical control agents and other beneficial organisms. Produced by the Secretariat of the International Plant Protection Convention, FAO, Rome.

Brandt, S., D. Ulrich, G. Lafond, R. Kutcher, S. Malhi, and A. Johnston. 2005. Management of high yielding canola cultivars. Better Crops 89: 12-14.

Broad, A. 2005. Best practice canola production. A Report for Nuffield Australia Farming Scholars. Sponsored by Grains Research and Development Corporation, Canberra, Australia.

Broatch, J. S., L. M. Dosdall, J. T. O'Donovan, K. N. Harker, and G. W. Clayton. 2008a. Herbicide rate effects on weed and root maggot dynamics in canola. Weed Sci. 56: 477-483.

Broatch, J. S., L. M. Dosdall, R.-C. Yang, K. N. Harker, G. W. Clayton. 2008b. Emergence and seasonal activity of the entomophagous rove beetle *Aleochara bilineata* (Coleoptera: Staphylinidae) in canola in western Canada. Environ. Entomol. 37: 1451-1460.

Broatch, J.S. 2008. Root Maggot and Beneficial Insect Dynamics in Response to Weed Populations in Canola. Ph.D. Thesis, University of Alberta, Edmonton, AB. 255 pp.

Canola Council of Canada. 2008. Canola in Canada. Socio-Economic Value Report. Canola Council of Canada. http://www.canola-council.org. Accessed on 9 January 2010.

Canola Council of Canada. 2009. Prairie Canola Variety Trials. http://www.canola-council.org/pcvt.aspx. Accessed on 9 January 2010.

Christensen, J. V., and J. C. Drabble. 1984. Effect of row spacing and seeding rate on rapeseed yield in Northwest Alberta. Can. J. Plant Sci. 64: 1011-1013.

Degenhardt, D. F., and Z. P. Kondra. 1981. The influence of seeding rate on seed yield and yield components of five genotypes of *Brassica napus.* Can. J. Plant Sci. 61: 175-183.

Dosdall, L. M., M. J. Herbut, and N. T. Cowle. 1994. Susceptibilities of species and cultivars of canola and mustard to infestation by root maggots (*Delia* spp.) (Diptera: Anthomyiidae). Can. Entomol. 126: 251-260.

Dosdall, L. M., M. J. Herbut, N. T. Cowle, and T. M. Micklich. 1996. The effect of seeding date and plant density on infestations of root maggots, *Delia* spp. (Diptera: Anthomyiidae), in canola. Can. J. Plant Sci. 76: 169-177.

Dosdall, L. M., L.Z. Florence, P. M. Conway, and N. T. Cowle. 1998. The effect of tillage regime, row spacing, and seeding rate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 78: 671-681.

Dosdall, L. M., G. W. Clayton, K. N. Harker, J. T. O'Donovan, and F. C. Stevenson. 2003. Weed control and root maggots: Making canola pest management strategies compatible. Weed Sci. 51: 576-585.

Fournet, S., J. O. Stapel, N. Kacem, J. P. Nenon, and E. Brunel. 2000. Life history comparism between two competitive Aleochara species in the cabbage root fly, Delia radicum: implications for their use in biological control. Entomol. Exp. Appl 96: 205-211.

Hanson, B. K., B. L. Johnson, R. A. Henson, and N. R. Riveland. 2008. Seeding rate, seeding depth, and cultivar influence on spring canola performance in the northen great plains. Agron. J. 100: 1339-1346.

Harker, K. N., G. W. Clayton, R. E. Blackshaw, J. T. O'Donovan, and F. C. Stevenson. 2003. Seeding rate, herbicide timing and competitive hybrids contribute to integrated weed management in canola (*Brassica napus*). Can. J. Plant Sci. 83: 433-440.

Hemachandra, K. S., N. J. Holliday, P. G. Mason, J. J. Soroka, and U. Kuhlmann. 2007. Comparative assessment of the parasitoid community of *Delia radicum* in the Canadian prairies and Europe: A search for classical biological control agents. Biol. Control 43: 85–94.

Hulme, M. A. 1990. Field assessments of predation by *Lanchaea cortics* (Diptera: Lonchaeidae) on *Pissodes strobi* (Coleoptera: Curculionidae) in *Picea sitchensis*. Environ. Ent. 19: 54-58.

Hummel, J. D., L. M. Dosdall, G. W. Clayton, K. N. Harker, and J. T. O'Donovan 2009. Effects of canola-wheat intercrops on *Delia* spp. (Diptera: Anthomyiidae) oviposition, larval feeding damage and adult abundance. J. Econ. Entomol. 102: 219-228.

Hummel, J.D. 2009. Insect and Agronomic Responses in Canola and Wheat Intercrops. Ph.D. Thesis, University of Alberta, Edmonton, AB. 177 pp.

Jensen, T., and J. Timmermans. 1991. Conservation tillage. Agdex 516-3, Alberta Agriculture, Edmonton, AB.

Johnson B. L., P. M. Carr, E. D. Ericksmoen, B. K. Hanson, and N. Riveland. 2001. New canola production practices challenge researchers to provide defined techniques to producers. Annual Report. Agronomy Section. Dickinson Research Extension Centre. 1089 State Avenue, Dickinson, ND 58601.

Jones, T. H., M. P. Hassel, and S. W. Pacala. 1993. Spatial heterogeneity and the population dynamics of a host-parasitoid system. J. Animal Ecol. 62: 251-262.

Kondra, Z.P. 1975. Effects of row spacing and seeding rate on rapeseed. Can. J. Plant.Sci. 55: 339-341.

Kondra, Z.P. 1977. Effects of planted seed size and seeding rate on rapeseed. Can. J. Plant.Sci. 57: 277-288.

Lafond, G.P., and D.A. Derksen. 1996. Long-term potential of conservation tillage on the Canadian prairies. Can. J. Plant Pathol. 18: 151-158.

Maus, C., B. Mittmann, and K. Peschke. 1998. Host records of parasitoid *Aleochara* Gravenhorst species (Coleoptera: Staphylinidae) attacking puparia of cyclorrhapheous Diptera. Dtsch. Entomol. Z. 45: 231-254.

Riley, K. J., U. Kuhmann, P. G. Mason, J. Whistlecraft, L. J. Donald, and N. J. Holliday. 2007. Can mustard seed meal increase attacks by *Aleochara* spp. on *Delia radicum* in oilseed rape? Biocontrol Sci. and Technol. 17: 273-284.

Royer, L., and G. Boivin. 1999. Infochemicals mediating the foraging behaviour of *Aleochara bilineata* Gyllenhal adults: Sources of attractants. Entomol. Exp. Appl. 90: 199-205.

Stinner, B. R., and G.J. House. 1990. Arthropods and other invertebrates in conservation-tillage agriculture. Annu. Rev. Entomol. 35: 299–318.

Thomas, P. 1984. Canola Growers' Manual. Published by Canola Council of Canada. pp 1430.

Thomas, P. 2003. Canola Growers Manual. Canola Council of Canada, http://www.canola-council.org/canola_growers_manual.aspx

Tomlin, A. D., D. G. R. McLeod, L. V. Moore, J. W. Whistlecraft, J. J. Miller, and J. H. Tolman. 1992. Dispersal of *Aleochara bilineata* [Col.: Staphylinidae] following inundative releases in urban gardens. Entomophaga 37: 55-63.