Improving Integrated Crop Management

by Conserving Natural Enemies of Insect Pests

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1. Abstract and Relevance of the Study

Field studies were undertaken in southern Alberta and Saskatchewan during the 2006 field season to investigate aspects of improved integrated crop management by conserving natural enemies of two major pests of canola, the cabbage seedpod weevil (*Ceutorhynchus obstrictus* [Marsham]), and the diamondback moth (*Plutella xylostella* [L.]). Surveys of ripening canola pods were used to determine the species composition and relative abundances of cabbage seedpod weevil parasitoids. From research in previous years, pod surveys were found to be the most effective means for determining parasitoid species composition and relative abundance. Twelve ectoparasitoid species were found attacking cabbage seedpod weevil larvae during 2006. The species composition of parasitoids in western Canadian canola differed from previous parasitoid surveys in Europe. Levels of parasitism were considerably lower than those commonly recorded in Europe; however, the situation in western Canada appears to reflect parasitoid populations that are building over time. The dominant parasitoid species found in Alberta and Saskatchewan were *Necremnus tidius* (Walker), *Trichomalus lucidus* (Walker), *Chlorocytus* sp., and *Pteromalus* sp. The only parasitoid reared from diamondback moth was the hymenopteran, *Diadegma insulare* (Cresson). Analysis and mapping of *P. xylostella* populations that were sampled from sites in a grid pattern over portions of commercial crops indicated that diamondback moth larvae were somewhat aggregated in their distributions. Parasitoid distributions were often spatially associated with high densities of their hosts. However, highest densities of the parasitoid were not always coincident with high densities of diamondback moth larvae. The cabbage

seedpod weevil responded to variations in canola plant stand manipulation. Weevil infestations were greatest to canola seeded at higher densities of 3 or 5 kg per ha, and in plants seeded in early May rather than in mid May. Pods on the main stems produced seed with higher kernel weights than pods on the primary or secondary branches; however, weevil infestation levels were also greatest to pods on main racemes. Greatest numbers of seeds per pod were found on plants seeded at 5 kg per ha rather than 1 or 3 kg per ha.

This study resulted in several research discoveries that have relevance to canola producers in western Canada:

- the level of parasitism of the cabbage seedpod weevil has increased dramatically in recent years, due to attack by native species like *T. lucidus*, *N. tidius*, *Chlorocytus* sp., and *Pteromalus* sp.; therefore, possible introductions of parasitoids from Europe should only be made if it is evident that native populations are not capable of causing acceptable levels of weevil population reduction;
- diamondback moth larvae are clustered in their distributions within canola fields, rather than randomly dispersed; therefore, monitoring/sampling of field populations of these pests should incorporate several samples so that more accurate density estimates can be obtained;
- the principal parasitoid of diamondback moth larvae in western Canada is the hymenopteran wasp, *D. insulare*, which is capable of causing significant reductions in populations of its host; in years of diamondback moth outbreaks, *D. insulare* populations should be monitored carefully and insecticidal spraying should be avoided where densities of the wasp are high; and

- canola growers in regions infested with damaging infestations of cabbage seedpod weevil should maintain recommended seeding rates (3 to 5 kg per ha) for optimal yields and consistent times to crop maturity; however, early seeding (late April) predisposes the crop to greater attack by the cabbage seedpod weevil and should be avoided.

2. Introduction

Canola insect pests are subject to attack by a wide range of natural enemies, comprising parasitoids, predators, and pathogens, many of which help limit or reduce pest populations (Alford 2003). However, in spite of their economic importance, comparatively little is known of their biology and the factors that can enhance their effectiveness. The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham) and the diamondback moth, *Plutella xylostella* (L.) are two important insect pests of canola in western Canada that can be subject to considerable population mortality by natural enemies.

The cabbage seedpod weevil was first discovered in Alberta in 1995 (Butts and Byers 1996), and since then its distribution and abundance have increased. Dosdall et al. (2002) found that its range was expanding north and east from southern Alberta at a rate of approximately 55 km per year, and it has the capability of eventually infesting the entire region of canola production in western Canada. Recent surveys have determined that the weevil has now invaded the Aspen Parkland Ecoregion of both Alberta and Saskatchewan where the majority of canola production occurs in Canada. The pest range presently extends east to North Battleford, SK, south to the U.S.A. border, west to the Rocky Mountains, and north to Red Deer, AB.

North American populations of the cabbage seedpod weevil originated in Europe, and there the pest is attacked by a number of parasitoids which can prevent the need for its control with insecticides (Murchie and Williams 1998). In southern Alberta, several parasitoid species have recently been found to attack cabbage seedpod weevil, but there is virtually no published information available on their biologies. The North American parasitoids are different species than those in Europe (Gibson et al. 2005), so European information cannot be applied here. A necessary first step for increasing the effectiveness of these parasitoids is to develop an understanding of their life history strategies and the factors that increase their population densities.

Diamondback moth routinely infests canola in western Canada. In the 1990's, diamondback moth was usually associated with minor crop damage, but in recent years population outbreaks have become more frequent. For example, in 2001 approximately 1.8 million ha were treated with insecticide for diamondback moth control in western Canada, at an estimated cost to producers of $72 million (WCCP 2001). Major outbreaks of the pest developed in 2003 and 2005. Although infestations in western Canada were generally believed to develop from adults blown in from southern U.S.A. (Philip and Mengersen 1989), a growing body of evidence indicates that our populations originate in part from overwintered moths (Dosdall 1994). The implications of this trend are very significant, because diamondback moth would get an earlier start in attacking Canadian canola crops in spring, and could therefore cause much greater damage. In 2001, 2003, and 2005 the diamondback moth parasitoid, *Diadegma insulare* (Cresson) (Hymenoptera: Ichneumonidae), was instrumental in ending the outbreaks.

In spite of the importance of natural enemies for reducing infestations of insect pests like cabbage seedpod weevil and diamondback moth, very little is known of the ecological requirements of these predators and parasitoids, and how different cropping practices can affect their numbers. In this project, we investigated aspects of the biology of these natural enemies in order to identify factors that can increase their impact. Our research seeks to enhance the sustainability of canola production in western Canada, and should increase its profitability to growers by enabling them to rely more on control by natural enemies and less on applications of chemical pesticides.

3. Objectives

The overall goal of this research was to investigate different management strategies for enhancing the effectiveness of natural enemies of cabbage seedpod weevil and diamondback moth in canola. The specific objectives of the project were:

1. to determine the key parasitoids responsible for causing greatest damage to the canola pests, cabbage seedpod weevil and diamondback moth;
2. to determine aspects of the life histories of these natural enemies;
3. to use geographical information systems (GIS) technology to determine the timing of pest movements into the crop, and subsequent invasions of their natural enemies; and
4. to determine the effects of canopy manipulation of canola on cabbage seedpod weevil through altered seeding dates and seeding rates.

4. Research Progress, 2006 Field Season

4.1 Objective 1. *Determining the Key Parasitoid Species of Cabbage Seedpod Weevil and Diamondback Moth*

The parasitoids of the cabbage seedpod weevil deposit eggs into pods inhabited by weevil larvae. The wasp eggs hatch and the larval wasps devour weevil larvae as they grow and develop. A parasitoid of adult weevils, *Microctonus melanopus* (Ruthe) (Hymenoptera: Braconidae) is rare in southern Alberta, and has only a minor impact on weevil populations (Fox et al. 2004). However, a diverse fauna of parasitoids in the hymenopteran superfamily Chalcidoidea has been found to attack larvae of the cabbage seedpod weevil in Alberta and Saskatchewan (Gibson et al. 2005; Dosdall et al. 2006). In western Canada, the principal agents responsible for biocontrol of diamondback moth include the parasitoids *D. insulare* (Cresson) (Ichneumonidae), *Microplitis plutellae* Muesebeck (Braconidae), and *Diadromus subtilicornis* (Gravenhorst) (Ichneumonidae) (Dosdall et al. 2004), and epizootics of fungal pathogens (Keddie and Dosdall, unpublished data).

4.1.1 Methods and Materials

Surveys of cabbage seedpod weevil parasitoids were conducted in late July to early August. Samples of approximately 500 to 1,000 canola pods were gathered from each of approximately 120 fields, in an area extending from Stettler, AB south to the U.S. border and east to the Saskatchewan border. The geographical coordinates of each collection site were determined with a Geographical Positioning System unit. Pod samples from each field were placed initially in labeled plastic bags and transported to the laboratory in coolers with ice. In the laboratory, pods were placed in sealed cardboard containers, each with a collecting vial attached. For a one-month period after collection, all newly emerged parasitoids were collected from the containers and preserved for later identification.

Parasitism levels of Chalcidoidea at each site were used to generate surface maps of abundance using ArcMap® Geographical Information Systems software with Spatial Analyst Extension (ESRI Services, Redlands, CA). The process examines point (site) data in relation to values from its nearest neighbor to estimate how values decline (decay) with distance from the point in question. The “interpolate to raster function” was used with the “inverse distance weighted option”. A fixed search radius of 500 km and an output cell size of 1 km were set. The spatial distribution of Chalcidoidea adults was presented as a contour map of parasitism level of *C. obstrictus* larvae.

A survey for diamondback moth parasitoids was conducted in August. Approximately 25 commercial fields of canola were sampled in southern Alberta in an area extending from Lethbridge south to the U.S. border and east to the Saskatchewan border. From each field, an attempt was made to collect a sample of 25 pupae. Each pupa was placed in a glass vial, labeled with the geographical coordinates of the field and the crop species, and returned to the laboratory for rearing of the host or parasitoids. Because diamondback moth infestations were quite rare in 2006, it was often not possible to locate larvae within fields selected for sampling, and to collect a suitable sample size.

Parasitoids were identified using published taxonomic keys and by comparison with type material or other authoritatively identified specimens. Voucher specimens of parasitoids were deposited in the Canadian National Collection of Insects and Arachnids, Ottawa, Ontario, Canada.

4.1.2 Results and Discussion

In total, 12 species of Chalcidoidea representing four families were reared from canola pods infested with *C. obstrictus*. The species reared were *Necremnus tidius* (Walker) and *Euderus albitarsus* (Zetterstedt) (Eulophidae), *Trichomalus lucidus* (Walker), *Chlorocytus* sp., *Pteromalus* sp., *Mesopolobus moryoides* Gibson, *Lyrcus maculatus* (Gahan), *Lyrcus incertus* (Ashmead), and *Catolaccus aeneoviridis* (Girault) (Pteromalidae), *Conura torvina* (Cresson) and *Conura albifrons* (Walsh) (Chalcididae), and *Eurytoma tylodermatis* Ashmead (Eurytomidae). Of these, *N. tidius*, *T. lucidus*, *Chlorocytus* sp., and *Pteromalus* sp. were the species most frequently reared.

The adult parasitoids of the species we collected deposit eggs into pods inhabited by cabbage seedpod weevil larvae. The wasp eggs hatch and their larvae devour weevil larvae as they grow and develop.

In 2006, *N. tidius* was collected from 32 sites throughout southern Alberta and southwestern Saskatchewan (Figure 1). In both provinces, levels of parasitism were approximately 10 to 12% in the most densely populated collection sites south of Medicine Hat and Swift Current. *Trichomalus lucidus* was reared from 14 sites throughout southern Alberta and from six fields in southwestern Saskatchewan (Figure 1). Its range in Alberta extended from the foothills of the Rocky Mountains, east to Medicine Hat and south to the U.S.A. border. In Saskatchewan, the species was collected most commonly in fields north of Swift Current. Its maximum parasitism level reached 2 to 3%. *Chlorocytus* sp. was reared from 16 sites throughout southern Alberta and from 18 fields in southwestern Saskatchewan (Figure 2). Its range extended from the foothills of the Rocky Mountains, east to Swift Current, and south to the U.S.A. border. Its maximum parasitism level reached 10%. In 2006, the abundance and range of *Pteromalus* sp. increased in Saskatchewan, but not in Alberta (Figure 2). Specimens were reared from eight fields in Alberta and from 17 fields in southern Saskatchewan. Maximum parasitism levels were 9% in Saskatchewan and 2% in Alberta.

The species composition of parasitoids in western Canadian canola differs from previous parasitoid surveys in western U.S.A. in which *T. lucidus* and *M. moryoides* were the dominant species (Gibson et al. 2005). These levels of parasitism are considerably lower than those commonly recorded in Europe where parasitism rates typically reach about 50% (Alford et al. 1996; Ulber and Vidal 1998), but can reach 90% and can be high even when larval densities are low (Murchie and Williams 1998). The situation in western Canada appears to reflect parasitoid populations that are building over time, because no parasitism of weevil larvae was found in southern Alberta from 1998 to 2001 (Dosdall and Dolinski 2001), and the incidence of parasitism in southern Alberta has increased approximately 50-fold from 2002 to 2004 (Dosdall et al. 2006).

The only parasitoid of diamondback moth recovered in the surveys were specimens of the ichneumonid wasp, *Diadegma insulare* (Cresson). *Diadegma insulare* is considered to be the major parasitoid of diamondback moth in the United States and Canada with parasitism levels exceeding 90% under some circumstances (Harcourt 1960; Lasota and Kok 1986; Idris and Grafius 1996; Mitchell et al. 1997). It is a solitary larval endoparasitoid that occurs throughout the range of diamondback moth in North America from southern Canada to Florida (Harcourt 1960; Mitchell et al. 1997). Like the diamondback moth, *D. insulare* is not able to tolerate low temperatures and is thought not to overwinter in Canada (Putnam 1973; Okine et al. 1996). *Diadegma insulare* attacks late-instar diamondback moth larvae. The diamondback moth larva remains alive long enough to spin a cocoon and pupate, after which *D. insulare* completes development and pupates within the diamondback moth cocoon. Development time is 10 to 20 days depending on the temperature and condition of the host (Harcourt 1960; Idris and Grafius 1996).

4.2 Objective 2. *Determining Life History Features of Parasitoids of Cabbage Seedpod Weevil and Diamondback Moth*

4.2.1 Biology of *Trichomalus lucidus* (Walker), *Chlorocytus* sp., *Eurytoma* sp., and *Pteromalus* sp., Parasitoids of the Cabbage Seedpod Weevil

Studies were conducted in the field to determine aspects of the life history and development of major parasitoids of cabbage seedpod weevil, including the wasps *T. lucidus*, *Chlorocytus* sp., *Eurytoma* sp., and *Pteromalus* sp.

4.2.1.1 Methods and Materials

A portion of a commercial canola field near Lethbridge, AB of approximately 1,250 m^2 was seeded to *B. rapa* cv. Reward on 28 April. From 19 July to 11 August, weekly collections were made of approximately 500 randomly selected pods. Emergence phenologies of parasitoid adults were determined by placing the pod samples in cardboard rearing containers measuring 18 by 18 cm and 16 cm tall, each with a small cylindrical plastic vial attached over a 4-cm diameter opening in the side of the box for collecting parasitoids (Dosdall et al. 2006). Newly eclosed parasitoid adults were removed every few days, and their numbers counted and recorded.

4.2.1.2 Results and Discussion

First emergence of *T. lucidus* was observed on 6 August (Figure 3). In the first 10 d of emergence, 77% of the population had emerged (*n* = 129). A gradual increase in emergence occurred from 6 August to a peak on 13 August, and this was followed by several days of comparatively low emergence levels until early September.

Few specimens of *Chlorocytus* sp. emerged from late July to 6 August, but thereafter emergence increased to peak levels from 13-16 August. By 16 August, 58% of the population had emerged. Emergence then declined nearly to zero by the end of the season (Figure 3).

No emergence of *Eurytoma* sp. was observed until 13 August (Figure 3). Small numbers of insects emerged over the next 10 days, with peak emergence occurring on 16 August. By 2 September, all specimens had emerged.

Emergence of *Pteromalus* was first observed on 3 August, with emergence gradually increasing to a peak on 9 August (Figure 3). By 16 August, 81% of the population had emerged (*n* = 54). Emergence declined to low levels from 20 August to the end of the season.

4.2.2 Biology of *Diadegma insulare* (Cresson), a Parasitoid of Diamondback Moth

The biology of the diamondback moth parasitoid, *D. insulare*, was studied in the field and laboratory. The objective of the field study was to determine the seasonal population dynamics in the relationship between the host and its parasitoid. The objective of the laboratory study was to investigate different developmental parameters of this parasitoid, in relation to the plant species or cultivar on which its host, the diamondback moth, had developed and fed.

4.2.2.1 Methods and Materials

Field investigations of the relationship between *D. insulare* and its host, *P. xylostella*, involved establishing a series of 80 yellow bowl traps in a commercial fields of *B. napus* and *B. rapa* near Lethbridge. The bowl traps were placed at regular intervals within the field, in a rectangular grid comprised of uniform plots of 10 m by 10 m with a bowl trap sampler in the centre. The bowls were half-filled with a 50% solution of propylene glycol, and all captured insect specimens were removed on weekly sampling dates.

The laboratory colonies of *D. insulare* and *P. xylostella* were maintained on potted *B. napus* cv. Q2 plants at 22 ± 0.5^{o}C with 16h L: 8h D. The moth and wasp colonies were developed from specimens collected from different commercial fields of canola in southern Alberta.

Eight Brassicaceae, namely *B. napus* cv. Q2 (susceptible to both glufosinate ammonium and glyphosate herbicides), *B. napus* cv. Liberty (resistant to glufosinate ammonium), *B. napus* cv. Conquest (resistant to glyphosate), *B. rapa* L. cv. Reward, *B.*

juncea (L.) Czern. cv. Cutlass, *B. carinata* L. (BCA-003), *B. oleracea* L. cv. Red Acre, and *Sinapis alba* L. (SAL-004) were grown under greenhouse conditions. Plants were grown individually in 15.2-cm-diameter pots using Metromix-220 (W. R. Grace and Co., Ajax, Ontario, Canada) as a potting medium and fertilized with 20: 20: 20 (N: P: K) at 0.5 g per pot when plants were two to three weeks old. Four-week-old plants were used for all experiments.

This study was conducted in controlled environmental conditions in a growth chamber (22 ± 0.5^{o}C with 16h L: 8h D). Excised leaves were placed on moist filter papers (9-cm diameter) in plastic containers; four holes were made in each transparent lid to ensure ventilation and to avoid condensation. For each plant genotype, 100 second-instar larvae (≤ 1 day old) taken from the laboratory colony were parasitized and introduced into individual plastic containers; a total of 800 larvae were used (one larva per container). Larvae were provided with fresh leaf tissue every 24 h until pupation. Developmental times from second-instar larva to pre-pupa and from pre-pupa to pupa were recorded. Pupae were harvested, weighed within 24 h of pupation, returned to their respective containers and developmental times from pupa to adult emergence were recorded. After adult eclosion, the silk cocoons were also weighed using a Sartorius Supermicro® balance (Sartorius Inc., Edgewood, NY, USA). Adults were sexed and used in the longevity (without food), body weight, and forewing area experiments.

To quantify levels of larval feeding, all leaves damaged by parasitized *P. xylostella* larvae were scanned daily into a digital format using a desktop scanner (Umax Powerlook 2100XL Flatbed Scanner, UMAX Technologies Inc., Dallas, TX, USA) and the final version (250 dpi) was saved as a TIFF file without LZW compression. Image J

(National Institutes of Health, Bethesda, MD, USA) was used to quantify the amount of leaf area removed due to larval herbivory.

Twenty females and 20 males reared from each plant taxon were used to determine their longevities without food. Wasps were weighed within 24 h of their death. Their forewings were carefully removed, scanned using a desktop scanner (Umax Powerlook 2100XL Flatbed Scanner, UMAX Technologies Inc., Dallas, TX, USA), and their areas were measured using Image J software.

4.2.2.2 Results and Discussion

In the field of *B. napus*, diamondback moth populations were high early in the season, with approximately 2000 specimens collected in the bowl trap samplers on 2 July (Figure 4). By late July, numbers of diamondback moth adults had declined dramatically to only approximately 250 specimens per sample. Populations of *D. insulare* remained low from late June to a peak of approximately 500 adults captured on 23 July. *Diadegma insulare* adults remained at this level until sampling was discontinued in late July (Figure 4).

In the *B. rapa* field, diamondback moth adults were high when the first samples were collected in late June, with approximately 1000 specimens collected (Figure 4). Thereafter, numbers of *P. xylostella* declined dramatically in the traps, with fewer than 200 adults collected on the 16 July sampling date. A second population peak was recorded on 24 July with more than 500 adults collected, but thereafter adult diamondback moth numbers declined. Numbers of *D. insulare* remained nearly at zero from late June until mid July; however, populations increased after the16 July sampling date and reached a maximum on the 24 July sampling date with approximately 350 specimens collected (Figure 4).

Survival and parasitism of *D. insulare* varied considerably among the tested plant genotypes on which host larvae were reared with most on *Sinapis alba* L. and least on *Brassica napus* L. cv. Q2 (Table 1). Egg to pre-pupal development was fastest on *B. juncea* (L.) Czern. and slowest on *B. oleracea* L., whereas pupae developed most rapidly on *B. napus* cv. Liberty (Table 2). *Plutella xylostella* larvae parasitized with female *D. insulare* consumed the largest and smallest leaf areas when reared on *B. napus* cv. Liberty and *B. carinata* L. respectively (Table 3). Parasitized *P. xylostella* larvae that consumed more food subsequently produced heavier *D. insulare* pupae with heavier silk cocoons than wasp larvae on hosts that consumed less foliage (Table 4). Heaviest *D. insulare* males were produced on *B. rapa* L. whereas females were heaviest on *B. carinata* (Table 5). Female and male specimens reared on *B. napus* cv. Q2 lived for the shortest time in the absence of food. Female wasps reared on *B. carinata* and *B. rapa* had the largest forewings whereas wasps reared on *B. napus* cv. Q2 had the smallest forewings (Table 5). Females reared on *B. napus* cv. Liberty and *B. rapa* developed the largest hindwings whereas male wasps reared on *B. napus* cv. Q2 had the smallest hindwings. *Plutella xylostella* larvae parasitized by *D. insulare* consumed significantly less foliage than their non-parasitized counterparts, suggesting that this parasitoid could provide a direct benefit to the plants.

Results of this study have facilitated an improved understanding of both effects of diamondback moth herbivory on different host plant species and cultivars, and effects of the host plants on parasitoids. Some host plants respond to herbivory by compensatory development of greater quantities of root tissue (e.g., *B. napus*, *B. rapa*, *S. alba*), but others lack this capability (e.g., *B. oleracea*, *B. juncea*). The plant genotype on which its diamondback moth hosts were reared is linked with several fitness correlates of the parasitoid, *D. insulare*. Such thorough analysis of tritrophic relationships is rarely incorporated in the integrated management of pests, yet our study has shown that without understanding the complexities and interactions that occur in these systems, important management aspects can be missed. For example, survival of *P. xylostella* larvae and pupae is high when reared on *B. napus* cv. Q2, new generation adult body weights are relatively high, and plants of Q2 can respond to this herbivory by compensatory increases in root mass (Sarfraz et al. 2007); however, parasitoids that develop on diamondback moth larvae reared on this host have low survival and new generation adults of *D. insulare* have poor longevities when held without food. To optimize integrated crop management, canola growers should then consider an alternate variety like *B. napus* cv. Conquest that also responds to herbivory by increasing its root mass, but leads to better survival of *D. insulare*, higher body weights of new generation parasitoids and greater longevity without food.

4.3 Objective 3. *Using Geographical Information System Technology to Determine Migration Patterns of Pests and Parasitoids*

This component of the project aimed to determine the dispersal and distribution patterns of the diamondback moth and its parasitoids. Geographical Information Systems technology can enable determination of factors associated with high, moderate, and low population densities of the pest and its natural enemies. This component of the project has the potential to provide essential foundation information for developing a system for pesticide application which targets areas of the crop or stages of the crop development where the pest is most abundant, but natural enemies are not.

4.3.1 Methods and Materials

In 2006, the distribution patterns of cabbage seedpod weevil, diamondback moth, and their parasitoids were studied in a commercial field of *B. napus* in southern Alberta approximately 15 km south of Lethbridge. A rectangular grid was established in one corner of each field; each grid comprised uniform plots of 10 m by 10 m with a bowl trap sampler in the centre. Each rectangular grid comprised 80 bowl trap samplers.

Monitoring of diamondback moth and its parasitoid, *D. insulare*, was conducted using the bowl traps as described above. The traps were placed in the field when plants were in the rosette stage of development, and collections were made weekly until the crop was mature.

Numbers of adults of diamondback moth or *D. insulare* were restructured to create separate ascii grid matrices by date using SAS statistical software (SAS Institute 1999). The ascii files were then imported into ArcInfo Geographical Information Systems software (ESRI Services, Redlands, CA) to create GRIDS using the ASCIIGRID function. Grid size was set to 100 units, and the grid data were then converted to point functions using the GRIDPOINT function of ArcInfo. The point coverages were then interpolated back to GRIDS using the POINTINTERP command. Interpolation was done by resampling the grid size to 10 units and interpolating to a radius of 200 units using exponential distance weighted interpolation with a smoothing factor applied to the point values. The process examines point data in relation to values from its nearest neighbor to estimate how values decline (decay) with distance from the point in question.

4.3.2 Results and Discussion

Geographical Information Systems (GIS) analysis showed an aggregated *P. xylostella* distribution within the crop, with some areas in the field having 10 to 20 adults per sampling period and others having none (Figure 5). *Diadegma insulare* also showed an aggregated distribution pattern within *B. napus*. In general, its areas of highest density were aligned with those of its host, the regions of the grid containing the highest densities of *P. xylostella* also having the highest *D. insulare* densities.

The aggregated pattern of distribution observed for diamondback moth not only affects *D. insulare* but also has important implications for producers. Diamondback moth infestations are often assessed in the field by trapping adults or counting the number of larvae on a plant or in a given area. Our data show that there can be substantial differences in diamondback moth numbers over relatively short distances within a crop, emphasizing the importance of sampling at several locations to achieve an accurate estimate of infestation levels.

4.4 Objective 4. *The Effects of Canopy Manipulation of Canola on Cabbage Seedpod Weevil*

4.4.1 Methods and Materials

In an agronomic study that spanned several years of research, plots were established near Lethbridge, AB in a randomized split-plot experimental design with four replications to assess the effect of canola plant stand manipulation on infestations of cabbage seedpod weevil and its natural enemies. Weevil control treatment (either insecticide or no insecticide) was assigned to main plots and seeding date and seeding rate were assigned randomly to treatment plots perpendicular to the main plots. The six treatment combinations were comprised of seeding rate (1.0, 3.0, and 5.0 kg per ha) and seeding date ("early" and "normal"). Plots were seeded on two dates in spring: early May and mid May; these correspond to "early" and "normal" planting dates, respectively, according to accepted agronomic practices for this agricultural region and local environmental conditions. Plots measured 100 by 9 m, and were seeded into cereal stubble. Seeding with *B. napus* cv. InVigor 5070 was performed with a John Deere 9450 Hoe Press Drill using 18 cm row spacings. Prior to seeding, all seed was treated with Helix® to reduce seedling mortality from phytopathogens and herbivory by flea beetles.

In mid-May, following seeding of plots on the 'normal' date, three pan traps were set within each replicate plot at approximate distances of 25, 50, and 75 m in from the plot edges. The yellow plastic pan traps measured 30.0 x 23.5 x 6.5 cm, were anchored to the soil with wire rods inserted through two opposite sides of each trap, and were filled with a 50% solution of propylene glycol. Each week, all insects collected in the pan traps were removed with an aquarium net and stored in sample jars containing 70% ethanol until cabbage seedpod weevil specimens could be removed, counted, and recorded.

When canola reached the rosette to bud stages of development, sweep net samples were also collected from each plot. The sweep net diameter was 38 cm, and once per week one set of 15, 180° sweep net samples was collected from each plot. Each sample was placed into a plastic bag, labeled, and frozen until weevil specimens could be sorted, counted, and recorded.

4.4.2 Results and Discussion

Seeding date had a highly significant effect on infestation levels of the cabbage seedpod weevil (Table 6). In each of the four years of study, mean numbers of cabbage seedpod weevil exit holes per pod on plants seeded early significantly exceeded those on plants seeded later ($P < 0.05$). Seeding rate also had a significant effect on infestation levels by the weevil (Table 6). Mean exit holes per pod for plants seeded at 3 and 5 kg per ha significantly exceeded exit holes on plants seeded at 1 kg per ha ($P < 0.05$). In addition, a significant interaction was observed between date of seeding and plant density (Table 6). This interaction appears to reflect that plots seeded on the early date, at 5 kg per ha, were particularly susceptible to attack by the cabbage seedpod weevil.

Thousand kernel weights of seeds produced on *B. napus* main stems significantly exceeded thousand kernel weights of seeds produced on the primary branches, and thousand kernel weights of seeds produced on primary branches significantly exceeded mean weights of seeds produced on secondary branches ($P < 0.05$). This relationship was consistent for each of the three seeding rates, and for early and normal seeding.

Mean numbers of seeds produced per canola pod on main stems for plants seeded at 5 kg per ha significantly exceeded seed number for plants seeded at 1 and 3 kg per ha ($P < 0.05$). However, this relationship was not found on pods from primary or secondary branches, where mean seeds per pod were similar and not significantly different among the three seeding rates ($P > 0.05$).

Mean numbers of seeds per pod tended to be highest at the 5 kg per ha seeding rate only for early-seeded plants, not for plants seeded later. For pods developing on the main stem, primary branches, and secondary branches, mean seeds per pod for plants seeded early at 5 kg per ha were usually significantly higher than those on plants seeded at 1 kg per ha ($P < 0.05$).

Manipulating canola plant stand canopies by altering seeding dates and seeding rates determined that increasing seeding rate of canola produced plant stands with fewer primary and secondary branches, but infestation levels in terms of exit holes per pod increased at higher seeding rates compared with lower seeding rates. However, plots seeded at higher rates (3 and 5 kg per ha) matured sooner. Increasing canola seeding rate appears to predispose plants to greater attack by cabbage seedpod weevil, but lowering seeding rate to 1 kg per ha is not an appropriate cultural control strategy for these pests because of the higher yields that can be obtained at high seeding rates. Seeding in early May, rather than in mid-May, resulted in greater infestations of cabbage seedpod weevil on canola, but early seeding did not result in more seeds per pod.

Results of this study indicate that growers should maintain recommended seeding rates (3 to 5 kg per ha) for optimal yields and consistent times to crop maturity. Seeding in mid May, rather than in early May, resulted in lower infestation levels of cabbage seedpod weevil and did not compromise yields. We therefore recommend that canola growers in regions infested with high numbers of cabbage seedpod weevil adults should therefore avoid early seeding, but maintain normal seeding rates.

5. Summary

Field studies were conducted during the 2006 field season for the project focusing on improving integrated crop management by conserving natural enemies of insect pests. Substantial progress was achieved toward meeting all project objectives. Surveys were undertaken to identify the parasitoid complexes of cabbage seedpod weevil and diamondback moth. Bowl trap samplers, raised to the height of the crop canopy, were used to investigate the alternate hosts of the natural enemies of these pests. Seasonal emergence phenologies of four major parasitoids of cabbage seedpod weevil, including *T. lucidus*, *Chlorocytus* sp., *Eurytoma* sp., and *Pteromalus* sp. were described for the first time. The seasonal population dynamics of the diamondback moth and its principal parasitoid, *D. insulare*, were described in commercial fields of *B. napus* and *B. rapa*. Many samplers were used in a commercial canola field in southern Alberta to develop geographical information systems technology for determining the timing of movements into the crop both by pests and their natural enemies. In general, high densities of the pest (diamondback moth) were aligned with high densities of the parasitoid. Cabbage seedpod weevil infestations in canola were significantly affected by date of seeding and seeding rate. Seeding canola early and at recommended rates predisposed canola plants to greater damage by these pests than seeding later at lower rates.

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Table 1. Mean percent survival (± S.E.) of the diamondback moth parasitoid, *Diadegma insulare*, from egg to pupa and from pupa to adult, when the parasitized host larvae were reared on intact plants of different Brassicaceae.

Host Plant Genotype	*Plutella xylostella**		*Diadegma insulare*	
	Larva to Pupa (%)	Pupa to Adult (%)	Egg to Pupa (%)	Pupa to Adult (%)
Brassica napus cv. Q2	72.00 [a]	97.5 [a]	42.67 [c]	88.00 [ab]
	(3.74)	(2.50)	(6.24)	(8.00)
Brassica napus cv. Liberty	80.00 [a]	96.00 [a]	45.61 [bc]	77.00 [ab]
	(8.37)	(2.45)	(6.48)	(9.17)
Brassica napus cv. Conquest	80.00 [a]	94.28 [a]	54.00 [abc]	68.76 [ab]
	(4.47)	(3.50)	(3.45)	(6.87)
Brassica juncea	86.00 [a]	92.70 [a]	62.06 [abc]	81.02 [ab]
	(4.00)	(4.64)	(3.80)	(4.17)
Brassica rapa	86.00 [a]	95.78 [a]	53.33 [abc]	65.67 [ab]
	(6.78)	(2.59)	(5.16)	(5.82)
Brassica carinata	78.00 [a]	90.92 [a]	48.44 [abc]	55.26 [b]
	(7.35)	(3.97)	(4.02)	(3.66)
Brassica oleracea	69.00 [a]	91.58 [a]	66.33 [ab]	88.45 [a]
	(6.78)	(3.55)	(2.66)	(2.71)
Sinapis alba	82.00 [a]	100.00 [a]	70.89 [a]	85.12 [ab]
	(4.90)	(0.00)	(3.07)	(2.90)

Table 2. Mean (± S.E.) developmental times of *Diadegma insulare* female and male specimens when parasitized host *Plutella xylostella* larvae were reared on leaf tissue of various Brassicaceae.

Host Plant Genotype	Egg to Pre-pupa (days)		Pre-pupa to Pupa (days)		Pupa to adult (days)	
	Female	Male	Female	Male	Female	Male
Brassica napus cv. Q2	6.40 [c]	6.00 [c]	1.20 [d]	1.50 [b]	8.80 [abc]	9.20 [a]
	(0.18)	(0.10)	(0.09)	(0.11)	(0.22)	(0.17)
Brassica napus cv. Liberty	5.60 [d]	5.80 [cd]	1.60 [bcd]	1.50 [b]	8.20 [c]	8.30 [b]
	(0.15)	(0.20)	(0.11)	(0.11)	(0.09)	(0.11)
Brassica napus cv. Conquest	5.80 [d]	5.80 [cd]	1.20 [d]	1.20 [b]	8.50 [bc]	8.70 [ab]
	(0.09)	(0.09)	(0.09)	(0.09)	(0.18)	(0.18)
Brassica juncea	5.40 [d]	5.30 [d]	1.70 [bc]	1.70 [ab]	9.00 [ab]	9.00 [a]
	(0.15)	(0.18)	(0.15)	(0.18)	(0.07)	(0.07)
Brassica rapa	7.00 [b]	7.60 [ab]	2.40 [a]	1.60 [ab]	8.90 [abc]	8.90 [ab]
	(0.10)	(0.18)	(0.15)	(0.11)	(0.07)	(0.16)
Brassica carinata	7.00 [b]	7.00 [b]	2.00 [ab]	2.05 [a]	9.40 [a]	9.20 [a]
	(0.07)	(0.15)	(0.10)	(0.09)	(0.26)	(0.09)
Brassica oleracea	8.05 [a]	8.10 [a]	1.20 [d]	1.30 [b]	8.70 [abc]	8.90 [ab]
	(0.11)	(0.16)	(0.09)	(0.11)	(0.23)	(0.22)
Sinapis alba	5.60 [d]	5.70 [cd]	1.40 [cd]	1.30 [b]	9.20 [ab]	9.00 [a]
	(0.11)	(0.11)	(0.11)	(0.11)	(0.14)	(0.07)

Table 3. Mean (± S.E.) foliage consumption by *Plutella xylostella* larvae when reared on leaf tissue of various Brassicaceae and either parasitized or non-parasitized by *Diadegma insulare*.

Host Plant Genotype	Non-parasitized*		Parasitized		Non-parasitized vs. Parasitized (*t*-test)	
	Foliage consumed (cm^2)		Foliage consumed (cm^2)			
	Female	Male	Female	Male	*t*	*P*
Brassica napus cv. Q2	3.02 [b]	2.13 [ab]	2.41 [ab]	1.82 [ab]	3.49	0.0012
	(0.13)	(0.16)	(0.19)	(0.19)		
Brassica napus cv. Liberty	2.96 [b]	1.95 [b]	2.81 [a]	2.23 [a]	-0.42	0.6798
	(0.16)	(0.01)	(0.25)	(0.19)		
Brassica napus cv. Conquest	2.65 [b]	2.45 [ab]	1.89 [bc]	1.84 [ab]	4.89	<0.0001
	(0.19)	(0.10)	(0.07)	(0.08)		
Brassica juncea	2.54 [b]	2.24 [ab]	1.96 [bc]	1.49 [b]	5.01	<0.0001
	(0.16)	(0.18)	(0.14)	(0.09)		
Brassica rapa	3.75 [a]	2.56 [a]	1.79 [bc]	1.64 [b]	7.35	<0.0001
	(0.24)	(0.14)	(0.21)	(0.12)		
Brassica oleracea	3.03 [b]	2.20 [ab]	2.19 [abc]	1.85 [ab]	7.23	<0.0001
	(0.09)	(0.07)	(0.05)	(0.14)		
Sinapis alba	2.37 [b]	1.97 [b]	1.80 [bc]	2.01 [ab]	2.37	0.0232
	(0.11)	(0.16)	(0.12)	(0.11)		

Table 4. Mean (± S.E.) pupal weights and silk weights of *Diadegma insulare* female and male specimens when parasitized *Plutella xylostella* host larvae were reared on leaf tissue of various Brassicaceae.

Host Plant Genotype	Pupal weight (mg)		Silk weight (mg)	
	Female	Male	Female	Male
Brassica napus cv. Q2	4.08 [ab]	3.94 [ab]	0.543 [c]	0.719 [a]
	(0.12)	(0.15)	(0.025)	(0.039)
Brassica napus cv. Liberty	4.24 [ab]	3.99 [ab]	0.679 [ab]	0.600 [a]
	(0.20)	(0.13)	(0.044)	(0.028)
Brassica napus cv. Conquest	3.91 [ab]	3.89 [b]	0.646 [abc]	0.610 [a]
	(0.10)	(0.09)	(0.015)	(0.020)
Brassica juncea	3.99 [ab]	3.86 [b]	0.628 [abc]	0.619 [a]
	(0.06)	(0.07)	(0.023)	(0.028)
Brassica rapa	4.36 [a]	4.40 [a]	0.711 [a]	0.612 [a]
	(0.06)	(0.12)	(0.010)	(0.046)
Brassica carinata	4.22 [ab]	4.10 [ab]	0.636 [abc]	0.694 [a]
	(0.10)	(0.10)	(0.028)	(0.027)
Brassica oleracea	3.82 [b]	4.03 [ab]	0.600 [bc]	0.625 [a]
	(0.06)	(0.07)	(0.009)	(0.015)
Sinapis alba	4.12 [ab]	3.81 [b]	0.713 [a]	0.622 [a]
	(0.05)	(0.10)	(0.020)	(0.020)

Table 5. Mean (± S.E.) adult body weights, longevities, and forewing and hindwing areas of female and male *Diadegma insulare* when parasitized diamondback moth hosts were reared as larvae on different hosts.

Host Plant Genotype	Adult body weight (mg)		Longevity without food (days)		Forewing area (cm^2)		Hindwing area (cm^2)	
	Female	Male	Female	Male	Female	Male	Female	Male
Brassica napus cv. Q2	1.26 ^{abc}	0.93 ^{c}	2.00 ^{c}	1.40 ^{d}	0.048 ^{c}	0.044 ^{e}	0.020 ^{de}	0.017 ^{e}
	(0.09)	(0.02)	(0.21)	(0.11)	(0.002)	(0.001)	(0.000)	(0.001)
Brassica napus cv. Liberty	1.35 ^{abc}	1.03 ^{bc}	2.40 ^{bc}	2.30 ^{c}	0.054 ^{b}	0.048 ^{cde}	0.029 ^{a}	0.023 ^{bcd}
	(0.11)	(0.01)	(0.11)	(0.11)	(0.002)	(0.001)	(0.001)	(0.000)
Brassica napus cv. Conquest	1.49 ^{a}	1.39 ^{a}	2.70 ^{ab}	2.30 ^{c}	0.053 ^{b}	0.047 ^{de}	0.022 ^{cd}	0.024 ^{bc}
	(0.08)	(0.06)	(0.11)	(0.11)	(0.001)	(0.001)	(0.001)	(0.001)
Brassica juncea	1.03 ^{c}	1.33 ^{ab}	2.80 ^{ab}	2.80 ^{ab}	0.053 ^{b}	0.052 ^{bc}	0.019 ^{e}	0.021 ^{cd}
	(0.09)	(0.05)	(0.09)	(0.09)	(0.001)	(0.000)	(0.001)	(0.000)
Brassica rapa	1.45 ^{ab}	1.61 ^{a}	3.10 ^{a}	3.20 ^{a}	0.063 ^{a}	0.058 ^{a}	0.029 ^{a}	0.028 ^{a}
	(0.10)	(0.10)	(0.07)	(0.09)	(0.000)	(0.001)	(0.001)	(0.001)
Brassica carinata	1.53 ^{a}	1.58 ^{a}	2.60 ^{ab}	2.80 ^{ab}	0.063 ^{a}	0.057 ^{ab}	0.027 ^{ab}	0.024 ^{bc}
	(0.03)	(0.05)	(0.11)	(0.09)	(0.001)	(0.002)	(0.001)	(0.001)
Brassica oleracea	1.07 ^{bc}	1.58 ^{a}	2.90 ^{ab}	2.90 ^{ab}	0.061 ^{a}	0.060 ^{a}	0.025 ^{bc}	0.026 ^{ab}
	(0.13)	(0.11)	(0.07)	(0.09)	(0.000)	(0.001)	(0.000)	(0.001)
Sinapis alba	1.04 ^{bc}	0.98 ^{c}	2.80 ^{ab}	2.60 ^{bc}	0.056 ^{b}	0.050 ^{cd}	0.022 ^{cd}	0.020 ^{de}
	(0.12)	(0.09)	(0.14)	(0.11)	(0.000)	(0.001)	(0.001)	(0.001)

Table 6. Analysis of variance of effects of seeding date, seeding rate, and interactions between seeding date and seeding rate for the study conducted to investigate effects of manipulating time of seeding and plant density on infestation levels of the cabbage seedpod weevil for 2001, 2002, 2004, and 2005.

Year	Effect	*P* value
2001	Date (D)	0.007
	Rate (R)	0.004
	D x R	< 0.001
2002	D	< 0.001
	R	< 0.001
	D x R	0.017
2004	D	0.002
	R	< 0.001
	D x R	0.025
2005	D	< 0.001
	R	< 0.001
	D x R	0.011

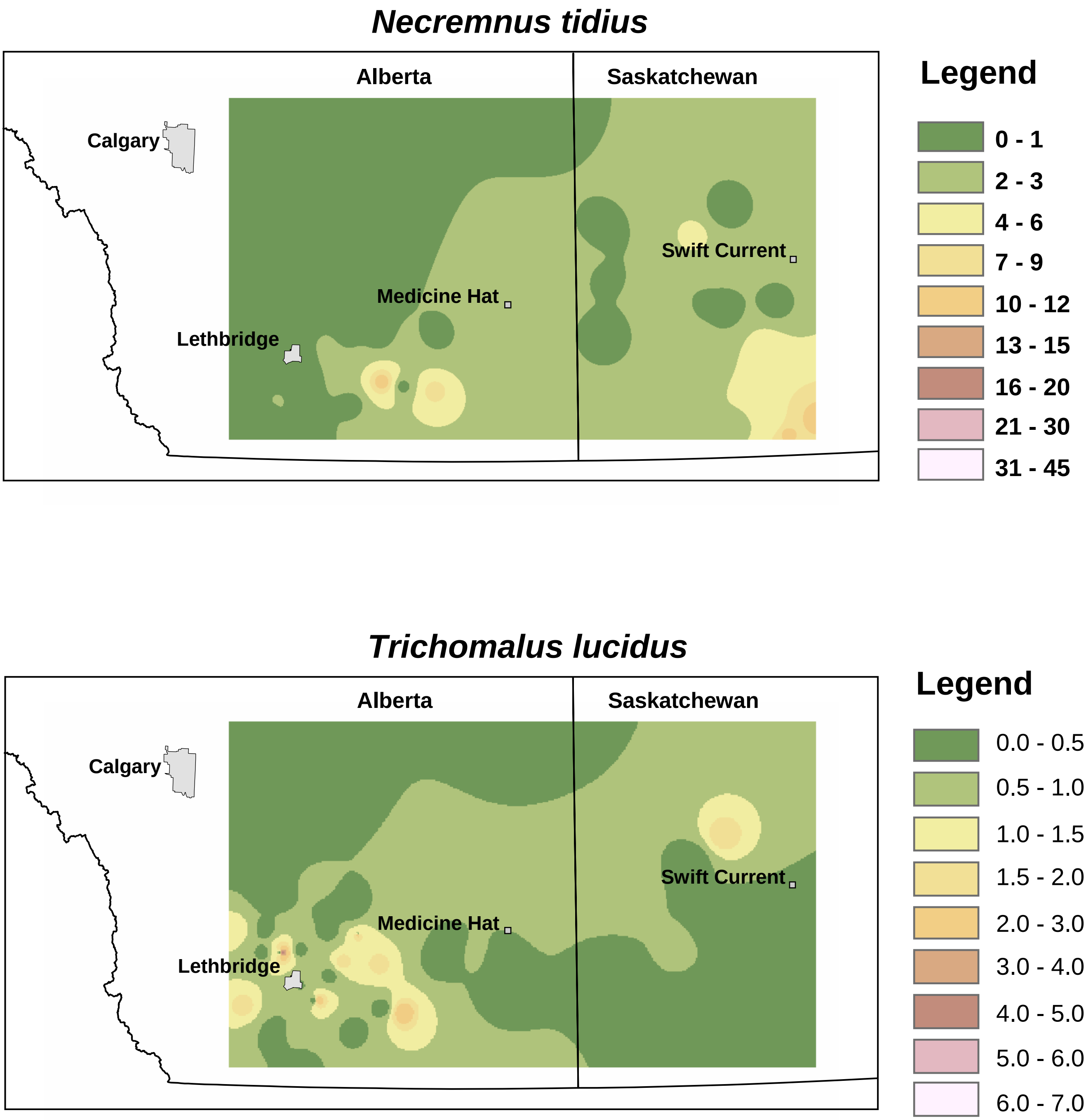

Figure 1. The distribution and level of parasitism of *Necremnus tidius* and *Trichomalus lucidus* on larvae of the cabbage seedpod weevil. The legend indicates the percentages of weevil-infested canola pods parasitized by *N. tidius* and *T. lucidus* in southern Alberta and Saskatchewan.

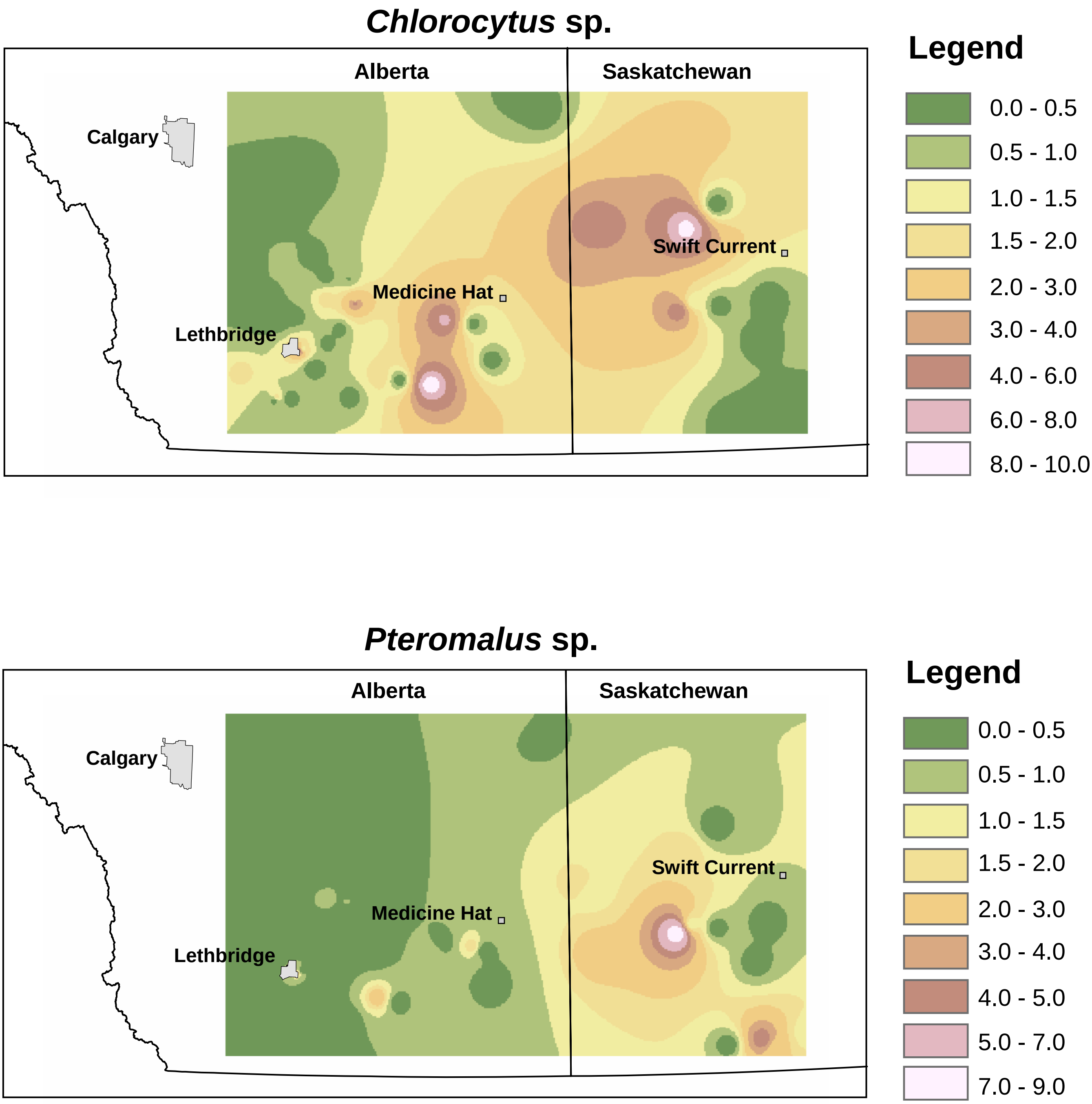

Figure 2. The distribution and level of parasitism of *Chlorocytus* sp. and *Pteromalus* sp. on larvae of the cabbage seedpod weevil. The legend indicates the percentages of weevil-infested canola pods parasitized by *Chlorocytus* sp. and *Pteromalus* sp. in southern Alberta and Saskatchewan.

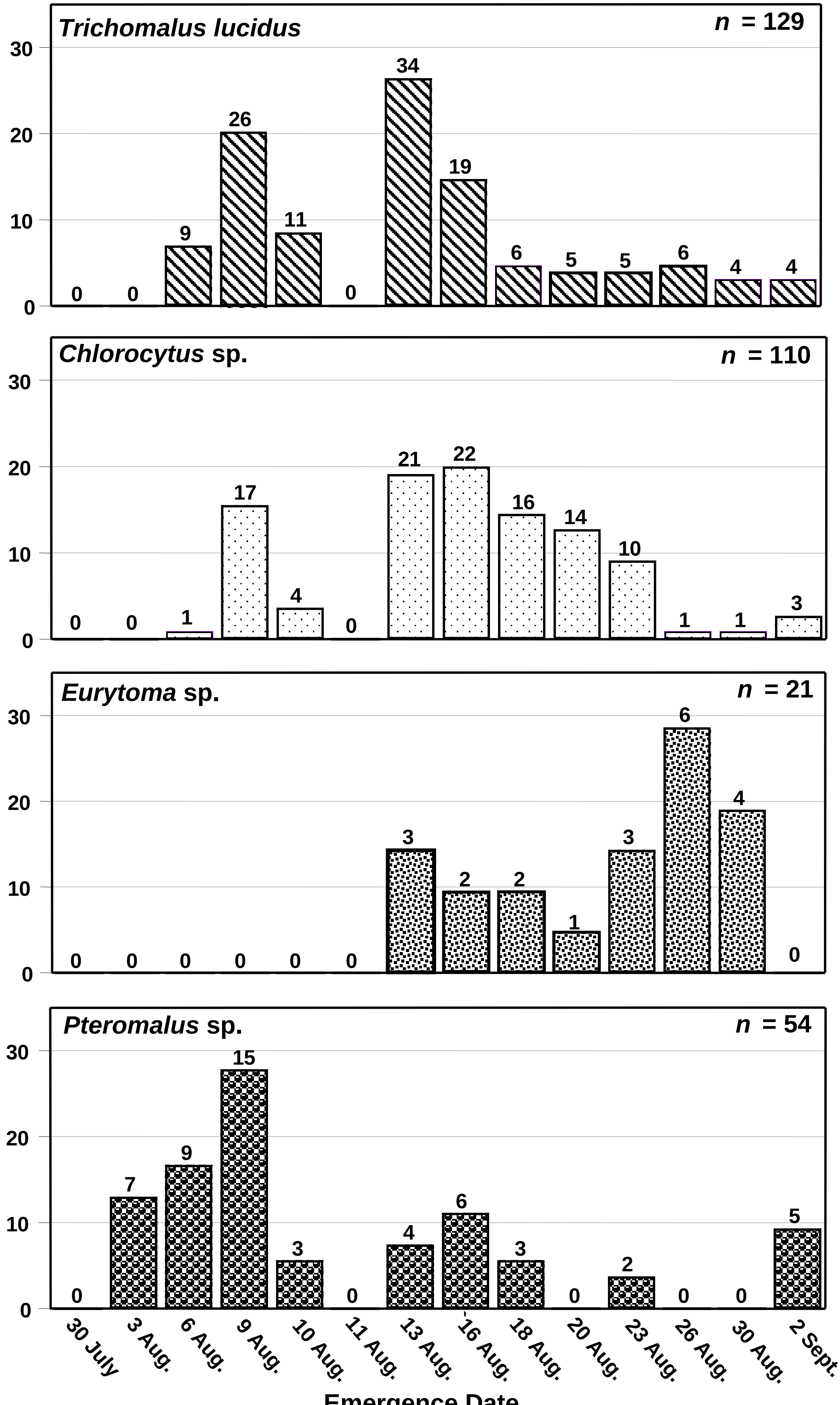

Figure 3. Emergence phenologies of *Trichomalus lucidus*, *Chlorocytus* sp., *Eurytoma* sp., and *Pteromalus* sp. from hosts of the cabbage seedpod weevil in southern Alberta, Canada.

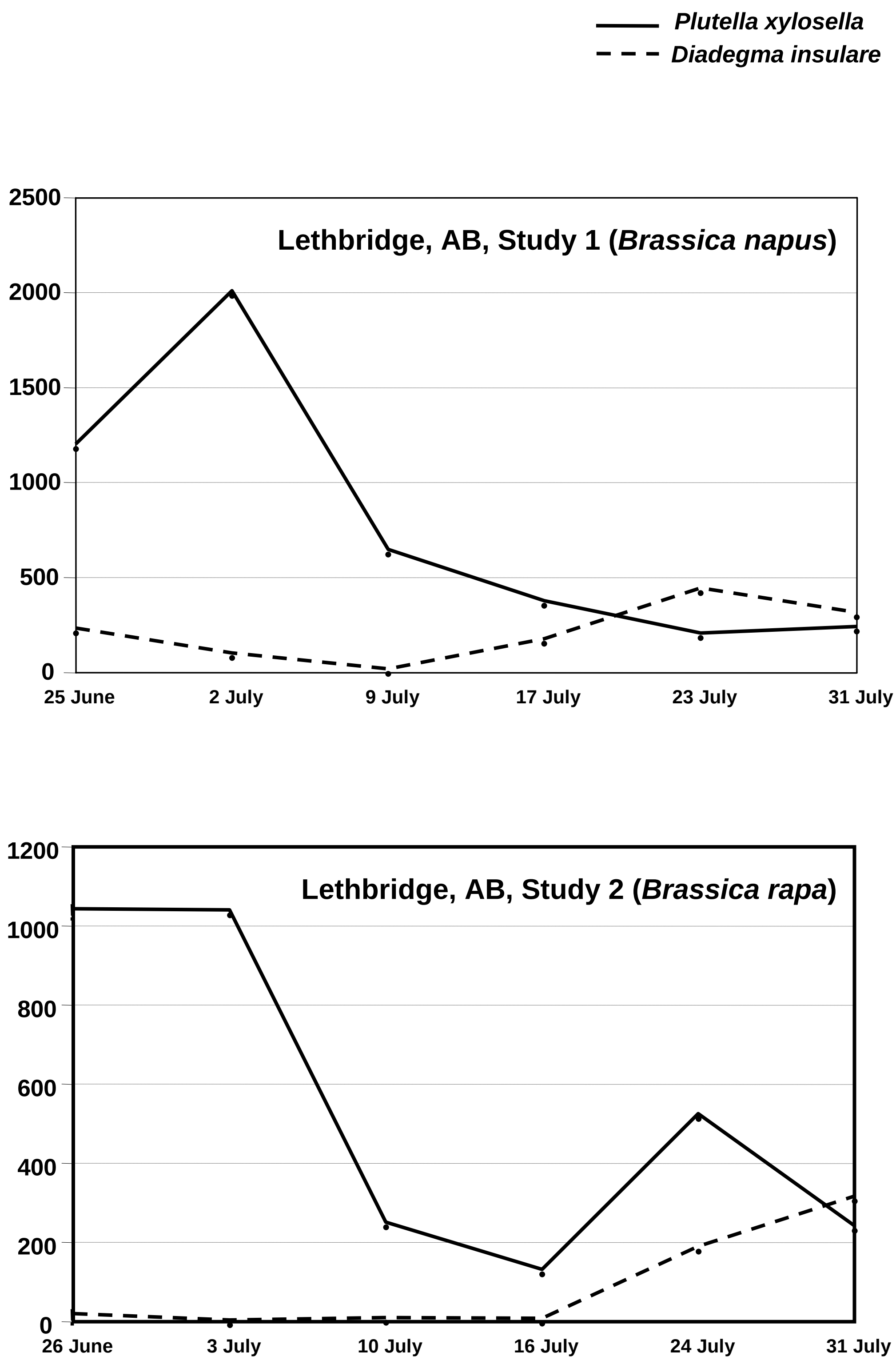

Figure 4. Seasonal population dynamics of adults of the diamondback moth, *Plutella xylostella*, and its parasitoid, *Diadegma insulare*, in commercial fields of *Brassica napus* and *B. rapa* in southern Alberta, Canada.

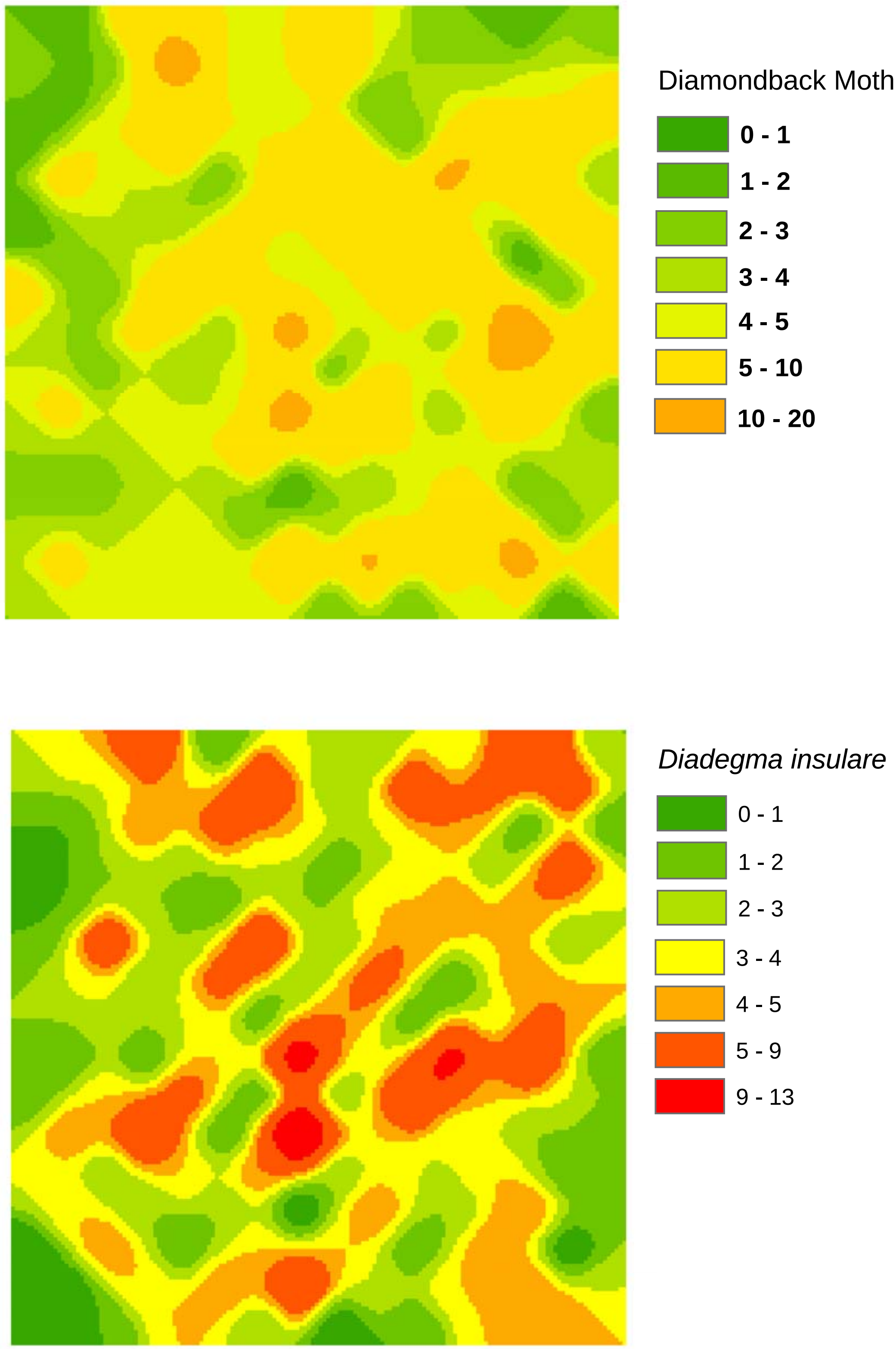

Figure 5. Densities of diamondback moth and *Diadegma insulare* interpolated from samples collected in a commercial field of *Brassica napus* L. near Lethbridge, AB.