Integrated Management of the Cabbage Seedpod Weevil, and Overwintering Biology of Canola Pests

Final Report: May 2004 [Final Report: Year 3 of a 3-year CARP Project]

Principal Investigator: Dr. Lloyd Dosdall
Department of Agricultural, Food and Nutritional Science
4-10 Agriculture/Forestry Centre
University of Alberta
Edmonton, Alberta T6G 2P5

Joint Applicant: Mr. Doug Moisey
Canola Council of Canada
P.O. Box 1427
St. Paul, Alberta T0A 3A0

Joint Applicant: Dr. Héctor Cárcamo
Agriculture and Agri-Food Canada
P.O. Box 3000
Lethbridge, Alberta T1J 4B1

Joint Applicant: Ms. Jennifer Otani
Agriculture and Agri-Food Canada
P.O. Box 29
Beaverlodge, Alberta T0H 0C0

Table of Contents

List of Tables

List of Figures

Abstract

Several field and laboratory experiments were undertaken during 2001 to 2003 to develop an integrated management strategy for cabbage seedpod weevil in canola, and to investigate aspects of the overwintering biology of lygus bugs and cabbage seedpod weevil. Research on integrated management of cabbage seedpod weevil focused on host plant resistance, cultural control, and biological control. In the host plant resistance component of the project, research was conducted to evaluate susceptibilities of different species and varieties of Brassicaceae to infestation by cabbage seedpod weevil, to assess *Sinapis alba* x *Brassica napus* intergeneric hybrids for resistance, and to assess *Brassica carinata* x *B. napus* interespecific hybrids for weevil resistance. Differences in susceptibility to infestation by cabbage seedpod weevil were observed among and within species of Brassicaceae. The order of susceptibility to infestation by *C. obstrictus* was *B. rapa* > *B. napus* = *B. napus* x *S. alba* ≥ *B. tournefortii* = *B. juncea* > *B. nigra* = *S. alba* = *C. abyssinica.* Among several genotypes of *S. alba* evaluated, all had equivalent levels of resistance. Considerable variation occurred in levels of susceptibility to cabbage seedpod weevil infestation among the 236 *S. alba* x *B. napus* intergeneric hybrids evaluated. One genotype had no weevil exit holes, and 17 genotypes had only one to five exit holes per 100 pods. Of the remaining intergeneric hybrid genotypes, the frequency of exit holes per 100 pods ranged from 6 to 72. During the 2002 field season, the most promising intergeneric hybrid genotypes were re-evaluated, and of these, 12 were found to have fewer than five weevil exit holes per 100 canola pods. Four interspecific hybrid species, derived from crosses between *B. carinata* and *B. napus*, also appear to have a degree of resistance to the weevil. Research conducted to investigate effects of canola crop canopy manipulation determined that increasing the seeding rate to 5 kg per ha, from 1 or 3 kg per ha, resulted in greater weevil infestation levels and damage; however, seed yields were still greatest at the highest seeding rate. Seeding in early May resulted in greater weevil infestation levels than seeding in mid-May. Insecticide applications were effective for reducing cabbage seedpod weevil infestations. Planting trap border strips of early-flowering canola surrounding fields of plants that flowered later

concentrated cabbage seedpod weevil adults on field edges. This facilitated edge spraying, which reduced input costs and damage to non-target beneficial insects. Trap cropping therefore holds promise for sustainable management of cabbage seedpod weevil. Biological control initiatives for cabbage seedpod weevil resulted in the discovery of at least 13 parasitoid species of weevil larvae. Studies on *Microctonus melanopus* Ruthe, a parasitoid that attacks adult weevils, determined that the species is now widespread in mixed weed patches near Lethbridge, AB. It appears to overwinter as a larva or embryo. Several species of hymenopteran parasitoids were reared from canola pods infested by cabbage seedpod weevil larvae. These species are ectoparasitic on weevil larvae within pods, but in spite of the high species diversity of the parasitoid fauna, the percentage of weevil parasitism still remained low. More lygus bug and cabbage seedpod weevil adults overwintered in tree shelters than in roadside ditches or alfalfa fields. Microcosm cages used to enclose weevils and lygus bugs and retrieved at varying intervals during winter indicated high levels of survival (ca. 70%) in both fields and treed areas. Although ambient air temperatures can vary widely, soil temperatures showed much less variance. At depths occupied by overwintering lygus bugs and cabbage seedpod weevil adults, mean minimum soil temperatures did not exceed -5 °C.

Substantial research progress was achieved during these three years of study. Brassicaceae species having high levels of resistance to infestation by cabbage seedpod weevil were identified, and include *Sinapis alba*, *Crambe abyssinica*, *Brassica nigra*, and *Brassica carinata*. Of 236 intergeneric hybrids developed from crosses of a resistant parent (*S. alba*) with a susceptible parent (*B. napus*), 12 were found to have high levels of resistance (< 5 weevil exit holes per 100 pods) in both field seasons. Manipulating canola plant stands by seeding early and increasing seeding rate resulted in higher levels of infestation by cabbage seedpod weevil. Trap borders of canola that flowered earlier than the main crop were effective for concentrating cabbage seedpod weevil adults, enabling growers to spray just the borders and not the entire crop. Even where two border sprays were required for adequate weevil control, growers could obtain an economic benefit from trap crops, and damage to non-target and beneficial insect species was minimized with this approach.

Several parasitic wasp species, previously unknown to canola agroecosystems, now attack larval weevils feeding within pods. Tree shelters, rather than other habitats, appear to hold the key role in sustaining overwintering populations of lygus bugs and cabbage seedpod weevil.

Introduction

The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham), was discovered infesting canola in Alberta in 1995, and by 1999 it had increased to outbreak levels in canola crops in southern Alberta (Dosdall and Dolinski 2001). Since then, its range has expanded from southern Alberta to encompass central Saskatchewan, and it has been dispersing northward and eastward at a rate of about 55 km per year (Dosdall et al. 2002). Dosdall et al. (2002) used CLIMEX® software to estimate the eventual range of cabbage seedpod weevil, and predicted that this pest will infest canola throughout its entire region of production in western Canada, with the most significant infestations occurring in southern Manitoba.

The cabbage seedpod weevil has a single generation per year and completes its larval development only in some host plants of the family Brassicaceae (Bonnemaison 1957; Dmoch 1965; Dosdall and Moisey 2004). In spring, overwintered adults emerge from shelterbelts and other overwintering sites and can be abundant in brassicaceous weeds (Dosdall et al. 2001). Later in the season, adult weevils feed on canola flower buds and females deposit eggs into immature pods. Larvae feed on developing seeds, consuming five to six seeds during three larval instars (Dmoch 1965). Mature larvae chew circular exit holes in pod walls, drop to the soil, burrow in, and pupate. New generation adults emerge about 10 days later, and feed on canola or other Brassicaceae until air temperatures decline late in the season and they migrate to overwintering sites (Dosdall and Dolinski 2001).

The cabbage seedpod weevil can inflict severe economic losses in canola, both in the larval and adult stages. When adults invade crops, primarily in the bud to early-flowering stages, feeding on flower buds can cause their destruction ("bud-blasting") (Dosdall and Dolinski 2001). Plants with severe bud-blasting produce racemes with few pods. Feeding by larvae within seedpods results in seed losses of approximately 18 to 20%. If environmental conditions are humid after larvae bore exit holes, the pods can be invaded by fungal spores that germinate and destroy additional seeds within the pods. Pods with exit holes shatter more readily than noninfested pods, further increasing crop damage by the weevil. When new generation adults emerge late in the season, they feed on seeds within

green pods to build up fat stores for overwintering (Dosdall and Dolinski 2001), resulting in reductions in yield and crop quality (Buntin et al. 1995).

At present, insecticide application is the only effective control strategy for cabbage seedpod weevil (Dosdall et al. 2001), and some producers in southern Alberta have already eliminated canola from their crop rotations given the need to factor insecticide applications into their production costs. This project was initiated with a view to developing an integrated management strategy for cabbage seedpod weevil in canola, to reduce reliance upon insecticide applications, and so enhance environmental sustainability. Our strategy was to attack the pest on several different fronts simultaneously. Consequently, we have undertaken research to develop crop cultivars resistant to attack by the weevil, studies to develop cultural control methods, and research to enhance biological control.

A key factor affecting the population dynamics of insect pests of field crops in western Canada relates to their ability to withstand winter conditions. Therefore, a further goal of this research was to investigate the overwintering biology of cabbage seedpod weevil and lygus bugs.

Objectives

The goals of this research were to investigate different control strategies for cabbage seedpod weevil in canola to identify the most promising practices or combinations for developing an integrated management strategy, and also to investigate the overwintering biology of both cabbage seedpod weevil and lygus bugs.

The specific project objectives were:

1) **to identify genetic sources of resistance to cabbage seedpod weevil with a view to developing weevil-resistant canola germplasm.** In this component of our project we evaluated several different species and varieties of Brassicaceae to identify potential sources of resistance. A resistant brassicaceous species (*Sinapis*

alba) was crossed with a susceptible one (*Brassica napus*) to produce several intergeneric hybrid accessions. The hybrids were evaluated for weevil resistance, and the most promising genotypes were selected for future research to produce resistant varieties of canola.

2) **to investigate integrated effects of seeding date and seeding rate on infestations of cabbage seedpod weevil.** Seeding date and rate can be readily manipulated by growers. Our project determined the integrated effects of seeding on two dates (an early seeding date in late April to early May versus a later seeding date in mid-May), and three seeding rates (1, 3, and 5 kg per ha) on infestations of cabbage seedpod weevil.

3) **to investigate trap cropping as a potential cultural control strategy for cabbage seedpod weevil.** Cabbage seedpod weevil adults are most attracted to crops in the bud and early flowering stages. This component of our research determined whether borders of early-flowering canola surrounding crops that flowered later concentrated cabbage seedpod weevil adults so that insecticidal control could be achieved by spraying only the borders, not the entire crop.

4) **to enhance biological control of cabbage seedpod weevil in canola in western Canada.** It is probable that the massive increases in weevil populations over the past few years occurred because weevil populations in southern Alberta escaped control by natural enemies. Biological control of this pest with parasitoids can enhance long-term control without environmental damage. In this component of our research we investigated the potential of the parasitic wasp of adult weevils, *Microctonus melanopus* (Ruthe) (Hymenoptera: Braconidae), for mass production and releases in areas infested by the weevil. We also investigated the distribution, taxonomy, and biology of ectoparasitoids attacking larvae of the cabbage seedpod weevil within canola pods.

5) **to investigate aspects of the overwintering biology of cabbage seedpod weevil and lygus bugs in order to provide canola growers with predictive information on the survivorship of these pests and their potential for damage in a given year.** This component of our research identified habitats utilized by lygus bugs and cabbage seedpod weevil for overwintering, as keys to understanding their cold-hardiness and overwintering survivorship under field conditions. The lethal and sublethal temperatures (supercooling points) for both cabbage seedpod weevil and lygus bugs were also investigated.

Methods and Materials

Objective 1: Development of Canola Germplasm Resistant to Weevil Attack

On 14 May 2001, plots were seeded with a coulter double disc no-till drill at a rate of 5.6 kg per ha on irrigated land at the Canola Council of Canada's Production Centre site near Coaldale. Experiment 1 comprised eight species of Brassicaceae, with several different cultivars, and intergeneric hybrids derived from crosses of *S. alba* x *B. napus*. The genotypes evaluated included: *Brassica rapa* (Accession Nos. 030, 005), *Brassica juncea* (Accession Nos. 077, 065), *Brassica napus* (Accession Nos. 084, 013, 087, 100, and 115),

Brassica nigra (Accession Nos. 008, 006), *Brassica tournefortii* (Accession No. 001), *Brassica carinata* (Accession No. 99-17001), *Crambe abyssinica* (Accession No. 001), and *Sinapis alba* (Accession Nos. 115, 027, 044). The *S. alba* x *B. napus* intergeneric hybrids evaluated included Accession Nos. 009, 001, 101, and 569. Plots were seeded in a randomized complete block design with four replications and four rows per treatment (genotype).

This experiment was repeated during the 2002 field season, except that seed of *B. carinata* was not available, so this species was not included in the trial. Seeding was performed on 16 May 2002 at the Canola Production Centre irrigated site near Coaldale.

At the end of the season after plants had matured and all larval development of the cabbage seedpod weevil had been completed, 20 randomly selected plants per genotype were hand-harvested. Plant samples were bagged and stored. For each plant, the numbers of pods per plant, and the numbers of pods with weevil exit holes were counted and recorded.

Egg and larval development were compared on selected representative genotypes, comprising *B. napus* (Accession 84), *B. napus* x *S. alba* (Accession 101), *S. alba* (Accession 97), *B. juncea* (Accession 77), *B. nigra* (Accession 8), *B. rapa* (Accession 30), and *B. tournefortii* (Accession 001). Pods were collected from the field plots weekly, as soon as they were large enough to excise, from 6 July to 10 August 2001. Twenty-five randomly selected pods from three replicate plots per genotype were collected and stored in 70% ethanol. Fifty pods per genotype were randomly selected for the composite sample, and these pods were dissected microscopically. For each pod, the number of eggs, first-, second- and third-instar larvae, and weevil exit holes were counted.

Selected Brassicaceae were examined for their susceptibilities to adult weevil feeding and oviposition by conducting controlled laboratory experiments in 2002. The germplasm evaluated comprised *B. rapa* (Accession 30), *B. napus* (Accession 84), an intergeneric hybrid of *S. alba* x *B. napus* (Accession 101), *B. tournefortii*, *B. juncea* (Accession 77), *B. nigra* (Accession 8), and *S. alba* (Accession 97). Brassicaceous plants were potted in vermiculite and maintained in a greenhouse chamber at approximately 20 °C, 14L:10D. Pods were excised unripe, when their length ranged from 40 to 60 mm, with the

exception of *B. nigra* and *S. alba*, which naturally develop smaller pods. *Brassica nigra* pods tended to be 15 to 20 mm in length and *S. alba* pods were 10 to 15 mm long.

Egg-producing female weevils were used to examine possible antixenotic (nonpreference) factors of the plant species. Weevils were collected as early as 12 July and then as needed by sweeping borders of commercial fields of *B. napus* near Lethbridge, AB. Weevils were maintained for no more than two days on a diet of 10% sucrose solution and wild mustard flowers at room temperature and light conditions. Female weevils were separated using a binocular microscope and *B. napus* (Accession 84) was used to confirm ovipositional status prior to experimental set-up (Harmon and McCaffrey 1997).

Cages for the laboratory screening trial were similar to those described by Harmon and McCaffrey (1997). Four replicate cages with a volume of 2,738 cm^3 (18.5 cm long x 18.5 cm wide x 8 cm high) were constructed to hold 8 by 8 evenly spaced pods. Brassicaceous species were tested in an 8 by 8 Latin square design using two pods from *B. napus* and a single pod from each of the other six species in each column of the screening cage. All replicate tests used a pod to weevil ratio of 4:1. Weevils were placed in the cages for 24 or 48 h and cages were maintained at the aforementioned temperature and light conditions in the greenhouse. After the allocated time period, pods were removed and microscopically dissected. The numbers of feeding punctures and weevil eggs in each pod were counted and recorded.

Selected Brassicaceae were examined for their susceptibilities to late summer (i.e., new generation) adult weevil feeding. Setup was identical to the spring weevil bioassays and included most of the same genotypes of Brassicaceae except that the additional *B. napus* genotype was replaced with *B. carinata*. Female weevils were also chosen for this assay, however, since late summer weevils are sexually immature (Fox and Dosdall 2003), no attempt was made to verify ovipositional status. Four replicate cages were maintained for 24 h in the greenhouse, and then the number of weevil feeding punctures in each pod were counted and recorded.

Experiment 2 evaluated susceptibilities to weevil infestation of 236 intergeneric hybrids, developed by crossing the resistant parent, *S. alba*, with the susceptible parent, *B.*

napus, and then backcrossing the progeny for several generations with *B. napus*. The hybrids were developed by research collaborator, Dr. Laima Kott of the University of Guelph, Guelph, ON. Due to limitations in quantities of seed available, each accession was seeded on 14 May 2001 in a single 6-m row, at a plant density of approximately 300 per row. The single-row plots were interspersed every fifth row with *B. napus* cv. Q2, a variety of *B. napus* determined by previous work to be comparatively susceptible to cabbage seedpod weevil infestation (Dosdall and Dolinski 2001).

At the end of the season, after all cabbage seedpod weevil development had occurred within infested pods, 35 plants were randomly selected from each plot, bagged, and labeled. The numbers of pods per plant and the numbers of pods with weevil exit holes were counted and recorded.

The intergeneric hybrid accessions that had low infestation levels of cabbage seedpod weevil in 2001 (< 5 weevil exit holes per 100 pods) were grown in greenhouse chambers during the winter of 2001 to 2002 to multiply seed quantities available. Seed of these 18 hybrids was again planted in single-row field plots on 16 May 2002 for re-testing. At the end of the season, 35 plants were randomly selected from each plot, and weevil exit holes were counted and recorded.

Seed from 10 genotypes having fewer than five exit holes per 100 pods in the 2002 field test was increased under greenhouse conditions during the winter of 2002 to 2003, and these accessions were used to further investigate their susceptibilities to weevil attack in 2003 using controlled laboratory conditions. The germplasm evaluated comprised *S. alba* x *B. napus* intergeneric hybrid Accession Nos. 22, 83, 128, 305, 329, 362, 374, 394, 408, and 428. Laboratory evaluations were conducted using these 10 genotypes using the laboratory screening method described above for Experiment 1.

Experimental plots established and maintained for Experiment 3 included a series of mustard lines, both brown mustard (*Brassica juncea*) and white mustard (*Sinapis alba*), in comparison with commercial canola varieties (*B. napus* and *B. rapa*). The genotypes evaluated comprised *B. juncea* cvs. Commercial Brown, J 904253, and AC Vulcan, the *B. rapa* cv. AC Sunbeam, the *B. napus* cv. AC Excel, and the *S. alba* cvs. Ochre, AC Base, AC

93-0860, Svalof, and SRS-2764. Experiment 3 was initiated in 2001 and repeated in 2002. Plots were seeded under irrigation at the Canola Council of Canada's Production Centre site near Lethbridge on 14 May 2001 and 16 May 2002 in a randomized complete block design with four replications. Each treatment plot comprised four rows spaced 20 cm apart, at a seeding rate of 5.6 kg per ha.

At the end of the season, 20 plants were selected randomly from each plot, bagged, and labeled; the numbers of pods per plant and the numbers of pods with weevil exit holes were counted and recorded.

Experiment 4 was initiated in 2002 to investigate the susceptibilities of *B. napus* cvs. Westar and Quantum, *B. juncea*, *B. carinata*, and 10 interspecific hybrid accessions resulting from crosses of *B. carinata* x *B. napus* followed by frequent backcrosses with the *B. napus* parent. The interspecific hybrid genotypes comprised Accession Numbers 01-R, 02-R, 03-R, 07-R, 08-R, 09-R, 02-MR, 01-MS, 03-MS, and 03-S. The germplasm was obtained from the laboratory of Dr. G. Stringam, University of Alberta, and the genotypes varied in their susceptibilities to infection by the blackleg pathogen (R = resistant to blackleg; MR = moderately resistant to blackleg; MS = moderately susceptible to blackleg; and S = susceptible to blackleg). Due to limitations in quantities of seed available, each accession was seeded in a single 6-m row on 16 May 2002 at a plant density of approximately 300 per row.

In 2003, plants from 19 genotypes comprising *B. carinata* x *B. napus* interspecific hybrid Accession Nos. 11, 13, 15, 18, 19, 21, 25, 26, 33, 35 36, 38, 39, 40, 41, 43, 46, 50, and 55 were grown under greenhouse conditions and investigated for their susceptibilities to weevil attack in 2003. Laboratory evaluations were conducted with these genotypes using the laboratory screening method described above for Experiment 1. The evaluation compared susceptibilities of these accessions with *B. napus* cvs. Quantum and Westar, as well as *B. carinata*.

Objective 2: Determining Integrated Effects of Seeding Date and Seeding Rate (Canola Plant Stand Manipulation) on Cabbage Seedpod Weevil Infestations

In May 2001, 2002, and 2003 research plots were established 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. Weevil control treatment (either insecticide or no control) 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 to mid May (3 May 2001, 15 May 2002, and 22 May 2003) and mid to late May (10 May 2001, 21 May 2002, and 28 May 2003); these correspond to "early" and "normal" planting dates, respectively, according to accepted agronomic practices for this agricultural region and local environmental conditions during the years when the studies were conducted. Plots measured 100 by 9 m, and were seeded into cereal stubble. Seeding with *B. napus* cv. InVigor 2153 was performed with a John Deere 9450 Hoe Press Drill using 18 cm row spacings. Prior to seeding, all seed was treated with Vitavax rs® 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.

In late June 2001 and 2002, sweep net samples in the research plots indicated that weevil populations exceeded the recommended economic threshold of 3 to 4 weevils per 180° sweep net sample (mean density = 6 weevils per sweep). Applications with insecticide were made with Matador® EC (cyhalothrin-lambda) at 10 g a.i. per ha. In 2003, weevil densities remained below economic threshold values throughout the season. However, for experimental consistency for all years of the study, the plots were sprayed with insecticide.

Insecticide applications were made on 5 July 2001, 15 July 2002, and 8 July 2003 from 12:45 h to 15:00 h. No rain was received in any year from the beginning to the end of the applications. A custom-built plot sprayer was used to apply the insecticide. The boom length was 4.5 m, so complete coverage of the 9.0 m plots was obtained by two passes of the sprayer. Other application parameters were: volume = 60 L per ha; 8001 TeeJet nozzles; 350 mL per min confirmed; speed 6.9 km per h; 4-L tank.

In early August when most final-instar larvae had emerged from canola pods, canola plants over a $1m^2$ area of each plot were cut off at the base, and an emergence trap was placed over the stubble. The emergence traps were pyramidal, and followed the design of Dosdall et al. (1996). All weevils within each trap were aspirated and counted three times weekly for three weeks using battery-powered aspirators.

At the end of the season, canola in the plots was swathed, and at that time, assessments were made of numbers of branches per plant on 25 randomly selected plants per plot. In addition, numbers of pods and exit holes per plant from cabbage seedpod weevil larvae were counted and recorded. In 2003, weevil densities were very low in all research plots. Exit hole counts were performed only for plants in plots seeded on the early date, not on the normal date since exit holes in pods seeded on the normal date were practically nonexistent. Each year, plots were harvested at the end of the season and yield data for each plot were recorded.

Objective 3: Investigating Trap Cropping as a Cultural Control Strategy for Cabbage Seedpod Weevil in Canola

In 2001, 2002, and 2003, research on trap cropping for the cultural control of cabbage seedpod weevil was undertaken to: 1) determine if earlier-flowering canola planted along the borders of the main canola crop, that would flower later, could concentrate weevil populations where they could be controlled with insecticide applications; 2) determine if a trap crop could provide increased yields and higher financial margins relative to conventionally grown canola; and 3) determine if other insects such as lygus bugs and beneficial insects were affected by the trap crop technique.

In 2001, five sites were selected throughout southern Alberta for studies on cultural control of cabbage seedpod weevil using trap crops. Site 1 was located near Skiff, about 50 km south of Taber on the farm of Mr. B. Hildebrand. The main crop was *B. napus* cv. InVigor 2663, planted on 250 ha on 28 to 31 March 2001 at a rate of 3.5 kg per ha. The trap strip was established by re-seeding the outside 24 ha with *B. rapa* cv. Hysin 111 at a rate of 2 kg per ha on 1 April 2001.

Site 2 was located about 5 km east of Stirling (about 25 km south of Lethbridge) on the New Rock Port Hutterite colony. The trap strip around the 101 ha field consisted of *B. napus* cv. LG 3235, a variety known to flower a few days earlier than standard varieties (e.g. Q2). The east, west, and north borders were seeded to the trap strip at a width of 30 m on 26 April 2001, at the rate of 4 kg per ha. The south border was lost to wind erosion and re-seeded to barley. The main crop was *B. napus* cv. Ryder, a glyphosate-tolerant variety, planted two days later (28 April 2001) at 4 kg per ha.

Site 3 was located about 10 km north east of Coaldale on irrigated land (Mr. E. Richards). The main crop of this 32-ha field was *B. napus* cv. InVigor 2573 planted at 5 kg per ha on 4 May 2001. The trap crop was established by planting a 1:1 mixture of InVigor 2573 and *B. rapa* cv. Hysin 111 at the rate of 6 kg per ha on 5 May 2001. The width of the trap crop was 10 m and surrounded the outside north, south, and east borders of the main crop for a total of about 1.6 ha.

Site 4 was located near Granum, about 60 km NW of Lethbridge. The producers here (Mr. L. Fjorbaten and Mr. D. Hubbard) planted two 28-ha fields with trap strips 20 m wide. *Brassica napus* cv. 45A55 was planted at 5 kg per ha on 27 April and 6 May 2001 on the trap and main crops, respectively.

Site 5 was located near Strathmore and consisted of a 122-ha field with the border planted to *B. rapa* and the main crop to *B. napus*, both planted on the same day.

Two control fields were selected to assess weevil distributions in the absence of a trap crop border. Control Field 1 was near Stirling, AB, about 100 m from Site 2, and consisted of a 53-ha field planted to an InVigor variety at the same time and following the same seeding rates as the main crop of the trap field. Control Field 2 was about 5 km north of Coaldale, AB and about 5 km east of Site 3. This field consisted of 32 ha under irrigation planted to Nexera™ on 27 April 2001 at 5 kg per ha.

In 2002, four canola fields had trap crops established along the outside perimeters. Field 1 was 73 ha under irrigation located approximately 8 km north of Coaldale (49°49′N; 113°00′W) and was farmed by Mr. Lyle Fletcher. The trap strip was 27 m wide and was planted on 23 November 2001 with *B. napus* cv. InVigor 2573 treated with Foundation® at 5.5 kg per ha. The main crop was planted in mid May to the same variety at 5 kg per ha. Field 2 was 130 ha of dryland (49°53′N; 113°09′W) near Nobleford, and farmed by Mr. Doug Wright. The trap crop ranged from 28 to 42 m in width and was planted on 18 November 2002 with InVigor 2573 only on the east perimeter. The main crop was planted on 1 May 2002 to the same variety at 5 kg per ha. Field 3 was 122 ha under irrigation (49°41′N; 112°30′W) about 10 km SE of Coaldale farmed by Mr. Cam Campbell. The trap strip, 20 m wide, was planted to *B. napus* cv. RR45A55 at 5 kg per ha on 2 May 2002. The main crop was planted on 16 May 2002 to the same variety and rate. Field 4 was 65 ha of dryland located about 5 km east of Stirling (about 25 km south of Lethbridge) on the New Rock Port Hutterite colony (49°31′N; 112°25′W). The trap crop consisted of 30 to 42 m of the outside perimeter of RR45A55 planted on 17 April 2002 at 6 kg per ha. The main crop was planted to *B. napus* 45H21 at 5 kg per ha on 29 April 2002.

Three check fields without trap crops were selected to monitor weevil distributions in 2002. The west side of Field 2 above was used as one of the checks. The second check field was immediately north and west and was planted to a Nexera variety on the same date as the first check. The third check was 4 km south of the trap crop field at New Rock Port and was planted on 29 April 2002 to an unregistered hybrid seed variety.

In 2003, there were five fields with trap borders. Field 1 was located near Stirling at the New Rock Port Hutterite Colony managed by Mr. Dave Waldner. This field was 77 ha with the two outside passes (27 m) planted on 11 April 2003 to LL2573 (Helix-treated) at a rate of 4 kg per ha. The mail crop was planted to LL2733 (Helix-treated) on 25 April at 4 kg per ha. The variety LL2733 was selected for the main crop because varietal testing determined that it flowered about three days later than the trap strip (LL2573). Fields 2 to 5 were all located in the Skiff area, about 100 km SE from Lethbridge. Field 2, farmed by Mr. Brian Hildebrand, was 260 ha of Hysin 111, *B. rapa* canola with the outside border (27 m) planted on 3 May 2003 and the rest on 16 May; both at 5 kg per ha (this was an unplanned trap caused by a snow storm that prevented seeding the entire field on 3 May). Field 3 (farmed by Mr. Lorne Hazell) was a half section (1600 m x 800 m) (49°37'N; 111°45'W), about 4 km NE of Field 2 with a trap border of 33 m of *B. rapa* (Hysin 111) on the outside and *B. napus* InVigor as the main crop; both were planted on 26 May 2003. The remaining Fields 4 (49°35'N; 111°37'W) and 5 (49°38'N; 111°35'W; 194 ha) were in the same area (farmed by Mr. Hildebrand) and consisted of 26 m borders of LL2733 and main crops of LL2663 planted at 5.5 kg per ha and within one day or less of each other. Helix Xtra® was used in the trap borders of all these fields because of a mistake made by the seed dealer but Helix® on the main crop variety since flea beetle infestations were known to be minimal in these fields.

Two check fields were monitored in 2003. Check 1 was about 3 km N of Field 1 in the Stirling area and was a quarter section (1600 x 400 m) planted to an Invigor variety. Check 2 was in the Skiff area and it was a full section of LL2663 planted in mid May similar to the main crops of the trap crop fields mentioned above.

Sampling was always conducted with a standard 38-cm sweep net. Four transects were established at each field by collecting 10, 180° sweeps at the field edge or trap crop border and at 50, 100 and if feasible 200 m into the field; the midpoint of large fields was sampled in 2001 only. Each trap crop field was sampled when the trap crop reached the bolting stage and weekly until the main crop reached the flower stage. The control fields were sampled at the early flowering stage and a second time at an advanced flowering stage if not sprayed (Control Field 2). Insects were transferred from the sweep net to a plastic bag and stored in a freezer until counted in the laboratory. One set of 10 sweeps was counted in the field to make chemical control decisions.

Objective 4: Developing a Biological Control Strategy for Cabbage Seedpod Weevil

In 2000, a population of cabbage seedpod weevil adults was found to be parasitized by a small wasp species in a mixed patch (ca. 50 m^2) of brassicaceous weeds (primarily wild mustard, *Sinapis arvense* L.) near Lethbridge, AB. These specimens were identified as *Microctonus melanopus* Ruthe (Hymenoptera: Braconidae) by Dr. H. Goulet, Eastern Cereal and Oilseed Research Centre, Agriculture and Agri-Food Canada, Ottawa, ON. This wasp is an important natural enemy of cabbage seedpod weevil in Europe and the Pacific Northwest of the United States (Bonnemaison 1957; Harmon and McCaffrey 1997b). Research in 2001 concentrated on identifying sites harboring weevils parasitized by *M. melanopus*, with a view to establishing laboratory colonies of the parasitoid for possible releases throughout western Canada.

In 2001, surveys were conducted in Alberta to find further evidence of parasitism by *M. melanopus*. In addition, surveillance was begun outside of Alberta, and surveys for the weevil larval ectoparasites *Trichomalus perfectus* (Walker) and *Mesopolobus morys* L. (Hymenoptera: Pteromalidae) were initiated. *Trichomalus perfectus* and *M. morys* are important parasitoids of *C. obstrictus* in Europe, and may account for parasitism of 90% or more of their weevil hosts in European crops of oilseed rape (Lerin 1987). Both ectoparasitoids were introduced to British Columbia in 1949 for biological control of the

cabbage seedpod weevil (McLeod 1953), although their establishment success has not been documented.

Extensive sampling of adult weevils was conducted at sites near Lethbridge during May, June, and July 2001, and weevils were dissected to determine whether they harbored larval endoparasitoids. The monitoring sites were stands of wild mustard, flixweed (*Descurainia sophia* [L.] Webb), hoary cress (*Cardaria* spp.), and volunteer canola (*B. napus* and *B. rapa*). Weevils from 31 samples, with up to 100 specimens per sample, were dissected. Sweep net samples were also taken to monitor adult *M. melanopus* and other parasitic wasp species at these sites. Only five sweeps per site were taken to minimize the impact of sampling on insect populations at the study sites.

Many additional samples were collected for this study in 2001. Twenty-five canola and cruciferous weed sites were sampled in southern Alberta from 17 to 30 June 2001. Dissection results leading up to the 2001 survey, and studies conducted in 2000, indicated that this time period was an important surveillance window in southern Alberta, representing the time when most *M. melanopus* were in their final larval instar. Samples of 100 adult weevils per site were preserved in fixative and stored in ethanol for later dissection to determine the incidence of parasitism, and five sweep net samples per site were collected and stored in alcohol for adult parasitoid surveillance.

Sweep net collections of adult weevils were made from study sites that had a significant number of parasitized weevils with parasitoids approaching their final stage of larval development. Weevils were maintained in screened cages, and when adult wasps emerged we added newly collected weevils in an attempt to amplify wasp numbers and establish a colony. A total of seven wasps emerged from 30 June to 7 July 2001 with one additional wasp emerging later.

A colony of rice weevil (*Sitophilus oryzae* (L.): Coleoptera, Curculionidae), a common pest of stored products, was established from specimens provided by Dr. Paul Fields, Agriculture and Agri-Food Canada, Winnipeg, MB. Because the rice weevil is in the same insect family as cabbage seedpod weevil and can easily be maintained in laboratory

colonies, it was plausible that rice weevil could be used as a host for rearing large numbers of parasitoids.

Rice weevils were exposed to the newly emerged adults of *M. melanopus* until the wasps died. The weevils were maintained for an extended period in the hope of collecting newly emerged specimens of *M. melanopus*.

Populations of cabbage seedpod weevil have occurred in the Creston Valley of British Columbia for many years. Creston Valley is only a few kilometers from the Idaho, U.S.A. border where weevil parasitoids have also been long established. In 2001, our collecting efforts expanded to include the Creston Valley in the hope of finding an abundant source of parasitoids for possible releases throughout western Canada.

On 20 June 2001, a collection of approximately 500 adult weevils was made in canola at Creston Valley, and specimens were dissected for the presence of adult endoparasitoids. On 17 July 2001, extensive collections of weevil adults and infested pods were made throughout the Creston Valley, both in commercial canola fields and in patches of cruciferous weeds.

From 18 to 31 July 2001, collections of immature canola pods were made from 17 commercial canola fields throughout southern Alberta, and from two fields near Creston, BC. From each field, approximately 150 pods were collected, preserved in ethanol, and dissected for the presence of larval parasitoids of cabbage seedpod weevil. *Trichomalus perfectus*, one of the primary ectoparasitoids of cabbage seedpod weevil larvae in Europe and northwestern United States, has potential for enhancing biological control of cabbage seedpod weevil in Alberta (Kuhlmann et al. 1999), so finding this species in western Canada was a primary objective of the 2001 surveillance program. McLeod (1953) reported six parasitoids of cabbage seedpod weevil in British Columbia, so the surveys were intended to document species currently responsible for parasitism of the cabbage seedpod weevil in the Creston Valley.

In early September, a large collection of volunteer canola pods was made from a site in Lethbridge, AB where evidence was found to indicate the possible presence of larval

parasitoids of cabbage seedpod weevil. Many racemes were placed in a screened pail in an attempt to rear adult parasitoid specimens.

In 2002, field surveys were conducted in southern Alberta and near Creston, BC to investigate the incidence of parasitism of cabbage seedpod weevil by *M. melanopus*. Sweep samples from each site were deposited into a cage and weevils were maintained on a diet of their host plants – primarily those plant pieces that were collected while sweeping. Live dissections of the weevils were initiated as expediently as possible to determine if any of the weevils in the collection had been parasitized. Live dissections were conducted under a dissecting microscope using a petri dish filled with physiological saline (6 to 8% sodium chloride). The head of the weevil was removed. Layers of the weevil abdomen were then pulled apart, beginning on the dorsal side of the weevil with the elytra. Parasitism was confirmed by the presence of teratocytes (spherical, white masses of cellular material within the weevil abdominal cavity) or a parasitoid larva that tended to occupy a large portion of the abdominal cavity. For each site, we attempted to dissect at least 50 weevils, although the sweeps from some of the sites did not yield enough adults. If evidence of parasitoids was found, efforts were made to return to the site and vigorously sweep the site to establish a colony of weevils for mass rearing *M. melanopus*.

Colonies were set up with weevils from sites that showed evidence of parasitism. For colony set-up, weevils were aspirated from sweep collections and placed in a cage – care was taken to ensure that only weevils (i.e., no flea beetles) were collected for the colony set-up. Although there was evidence of parasitism from one site south of Lethbridge, we were unable to find enough weevils there to start a colony. Some of the sites yielded small numbers of weevils to start colonies so we returned to sweep those sites periodically to increase our numbers of captive weevils. Each colony was fed three times weekly with a vial of 10% sucrose solution and a vial with a wild mustard raceme in water. Colonies were maintained at ambient room temperature and light conditions. The colonies were checked daily for the emergence of any parasitoids.

Field surveys were also conducted in 2002 to determine the distribution and abundance of ectoparastoids of cabbage seedpod weevil larvae. In mid-August when canola

crops were maturing and most cabbage seedpod weevil larvae inhabiting canola pods were in their third larval instar, approximately 500 pods were collected from each of 44 fields throughout southern Alberta. The area surveyed encompassed 42 fields from Calgary south to the U.S. border, and two fields north of Calgary. Pods were placed in sealed cardboard containers, with a collecting vial attached (Figs. 1A, 1B). For a one-month period after collection, any newly emerged parasitoids were collected from the containers and preserved for later identification.

In 2003, 49 emergence traps were placed at nine different locations within a 20-km-radius of Lethbridge, AB in an attempt to determine the overwintering habitat of ectoparasitoids of cabbage seedpod weevil larvae. Emergence traps were placed in non-cultivated sites in either open, intermediately sheltered, or fully sheltered habitats. Emergence traps in open habitats were not shaded from any direction and were in an exposed grassy area, generally comprising smooth brome (*Bromus inermis* Leyss.) (Poaceae) or crested wheat grass (*Agropyron cristatum* L.) (Poaceae). Traps in sheltered habitats, shelter belts or treed yard sites, were shaded on at least three sides and from above by vegetation higher than the cages. The predominant tree species were caragana (*Caragana arborescens* Lam.) (Fabaceae) and poplar (*Populus* spp.) (Salicaceae) but American elm (*Ulmus americana* L.) (Ulmaceae), Siberian elm (*Ulmus pulmila* L.) (Ulmaceae), ash (*Fraximus americana* L.) (Olceaceae), and willow (*Salix* spp.) (Salicaceae) were also present at some sites. Traps that were slightly shaded or sheltered on only one or two sides were categorized as intermediate. Emergence traps were set out on 9 April 2003. Trap collections were first made on 15 April and weekly thereafter (weather permitting) until 24 July. The emergence traps were pyramidal, 1 m^2 at the base, and followed the design of Dosdall et al. (1996). All insects were collected from the emergence traps with battery-powered aspirators (Hausherr's Machine Works, Toms River, NJ) inserted through openings in the trap sides. Trap openings were sealed except at sampling times. Contents of the traps were frozen and examined later under a stereomicroscope for the presence of adult ectoparasitoids of cabbage seedpod weevil larvae.

Sites harboring brassicaceous weeds (flixweed, hoary cress, wild mustard, pennycress, and volunteer canola) were monitored for the presence of adult ectoparasitoids of cabbage seedpod weevil larvae. Monitoring was conducted using 6-inch-diameter bowl traps attached to metal brackets that were anchored to metal stakes (Figs. 2A, 2B). The containers were half filled with a 50% solution of propylene glycol, and were emptied weekly until weeds in each patch became senescent. Sample collections commenced 20 May 2003 for flixweed, pennycress, and hoary cress and on 5 June 2003 for wild mustard and volunteer canola. The brackets holding the bowl traps could be raised along the metal stakes as the weed canopy height increased. Bowl trap samples were examined under a stereomicroscope for the presence of parasitoids of cabbage seedpod weevil. Two bowl traps per site were set out in four stands of hoary cress, four mixed stands of flixweed and pennycress (*Thlaspi arvense* L.), four stands of wild mustard, and four stands of caragana.

A survey encompassing approximately 120 canola fields (primarily *B. napus*) was conducted from late July to late August of 2003 to determine the distribution and abundance of larval ectoparasitoids of cabbage seedpod weevil. Approximately 1000 pods were collected from each field in an area extending from Lacombe, AB south to the U.S. border and east to the Saskatchewan border. A similar survey was conducted in Saskatchewan by research collaborator Dr. O. Olfert of Agriculture and Agri-Food Canada, Saskatoon, SK. Pods were placed in sealed cardboard containers as described above, and for a one-month period after collection, any newly emerged parasitoids were collected from the containers and preserved for later identification.

In 2003 studies were set up in commercial canola crops in an effort to monitor parasitoid migrations and establishment within the crops. One field of *B. rapa* and one field of *B. napus* that were in a similar developmental stage (early bud) were chosen. Along one edge of each field, rectangular grids were established each consisting of 256, 5 by 10 m plots. Within each grid an adjustable bowl trap (as described above) was placed in every other plot (i.e., 128 bowls per field). All insects were removed from the bowls weekly from 25-26 June 2003 until harvest. Samples were preserved in 70% ethanol and returned to the laboratory for analysis. In the laboratory, bowl trap samples were examined under a

stereomicroscope for the presence of ectoparasitoids of cabbage seedpod weevil. Immature pods were also collected from each site (17 July 2003 for *B. rapa*, 21 July 2003 for *B. napus*) and placed in emergence boxes (as described above). Approximately 250 pods were collected from every other plot in each grid (i.e., 128 emergence boxes per grid). Adult parasitoids collected from the sample vials on the emergence boxes were counted and identified. Upon completion of parasitoid emergence, all pods within each box were examined for weevil and parasitoid infestation to determine rates of parasitism.

The susceptibilities of six species of Brassicaceae to cabbage seedpod weevil larval ectoparasitism were compared in field plots established near Lethbridge in 2003. On 7 May 2003, plots were seeded with a coulter double disc no-till drill at a rate of 5.6 kg per ha at a study site approximately 5 km south of Lethbridge. The species evaluated included *B. rapa*, *B. juncea*, *B. napus*, *B. nigra*, *B. tournefortii*, and a *S. alba* x *B. napus* intergeneric hybrid. Plots were seeded in a randomized complete block design with four replications and four rows per treatment (species). Beginning on 29 July 2003 and continuing until 27 August 2003, weekly collections of approximately 100 randomly selected pods were made from the plots of each host plant species and placed into emergence boxes. Adult parasitoids were collected from the sample vials on the emergence boxes, counted, and identified. Upon completion of parasitoid emergence, all pods within each box were examined for weevil and parasitoid infestation to determine rates of parasitism.

Objective 5. Determining the Overwintering Biology of Lygus Bugs and Cabbage Seedpod Weevil

In 2001, 2002, and 2003 studies were undertaken to: 1) determine habitats utilized by lygus bugs and cabbage seedpod weevil for overwintering sites; 2) determine lygus bug and cabbage seedpod weevil overwintering survivorship under field conditions; 3) evaluate the cold-hardiness of cabbage seedpod weevil and lygus bugs; and 4) provide predictive information, based on overwintering success, on the likelihood of outbreaks of cabbage seedpod weevil and lygus bugs.

The first study was performed at Lethbridge and Beaverlodge and examined three sites (considered replicates) of each of four potential overwintering habitats utilized by cabbage seedpod weevils and lygus bugs: 1) tree shelters, mostly caragana and other broadleaf shrubs around farm buildings in the vicinity of canola stubble; 2) ditches, with grass and other weedy vegetation alongside canola stubble; 3) alfalfa fields; and 4) poplar stands. Three sampling methods were used to determine the relative abundance of the two insects in the above habitats. Three emergence cages, each enclosing a 1 m x 1 m area of overwintering substrate, were deployed at each site to capture and measure densities of insects as they emerged in the spring. Emergence cages were spaced a minimum of three metres apart at each site. Six pitfall traps were also deployed at each site; two traps, each within five metres of an emergence cage, were buried flush with the soil surface to monitor ground activity of the two insects. Pitfall traps were made from 500 mL plastic tubs buried within 1 L ice cream tubs that provided a permanent structure; plumbing-grade propylene glycol was used as the killing and preserving fluid.

Manual sorting of soil litter collected in the fall was performed in Beaverlodge in 2001. Five distinct and intact 25 x 25 cm squares of litter plus associated soil (5 cm deep) were removed from a treed area and the same number and size of litter plus soil squares were removed from the adjacent field area. These squares of litter were stored individually in paper bags and refrigerated at 5°C until moved to the laboratory for manual sorting. When sorted at room temperature, the number of lygus bugs per 25 x 25 cm litter sample was recorded. In 2002 and 2003 manual sorting of soil litter was replaced with pitfall trapping methods used in Lethbridge. Pitfall trapping replaced soil litter sampling since obtaining and processing the litter required considerable time while no lygus bugs were recovered.

At Lethbridge, pitfall trapping was used to sample insects instead of hand-searching soil cores. This was done to minimize sample processing time because hand searching cores recovered very few insects compared to pitfall traps which caught more insects compared to the emergence cages. In 2003 only pitfall traps were used to sample insects in tree shelters, weeds and alfalfa from mid April till the end of June.

Although collection and manual sorting of soil cores was performed in 2001, this sampling method proved to yield few, if any, weevils and lygus bugs in both Lethbridge and Beaverlodge and was abandoned in favor of pitfall trapping which proved more effective at Lethbridge. Emergence cages and pitfall traps were deployed in the third week of April and monitored until the middle of June; the only exception was the tree shelter near the Lethbridge Research Centre where nine traps (instead of six) were deployed on 26 March 2002 and monitored weekly. Other sites were monitored every second week.

The second study investigated overwintering survivorship in the field and cold-hardiness of cabbage seedpod weevils and lygus bugs. Cylindrical microcosm cages measuring 30 cm tall by 13 cm in diameter were constructed of nylon (1 mm gauge). Poplar leaf litter collected from the field was placed inside the cages above a 5 cm deep layer of soil and was intended to reproduce a microcosm that approximated an insect overwintering habitat in the field. Sweep-net collections for weevils and lygus bugs were performed in late fall. An equal number of adult males and females of the same species of insect were isolated from sweep-net collections then placed inside each microcosm cage ($n = 10$ adults per cage). A total of 40 microcosm cages housing one species of insect were buried outside in late fall. Ten cages were buried in each of two habitats: 1) shelter belts located near agricultural land or a field margin near agricultural land, and 2) the adjacent field. Lygus bugs were caged and monitored throughout the winter at Beaverlodge, while cabbage seedpod weevils were caged and monitored at Lethbridge. At Lethbridge, in the last two years of the study, the surface leaf litter of half of the microcosm cages were sprayed with *Beauvaria bassiana* spores (a fungal pathogen), to test the impact of the pathogen on overwintering survivorship of the weevils. This was done because of a field observation of dead weevils in microcosms with fungal mycelia of this species and subsequent laboratory studies compared this strain with commercial isolates (Carcamo and Goettel, unpubl. data).

The overwintering survivorship of lygus bugs and weevils was determined by retrieving the buried microcosm cages at three dates from each of the two habitats as the winter progressed. Microcosm cages were retrieved from the field in December ($n = 3$ cages per site), February ($n = 3$ cages per site) and mid-April ($n = 4$ cages per site). Each

microcosm cage was gently removed from the field, placed inside a cooler, then transported into the laboratory and allowed to sit at room temperature. The contents of each microcosm cage was sorted immediately with all retrieved insects transferred to a 90 mm Petri dish provided daily with three to four frozen green beans. The overwintering survival of the insects was recorded as the number of dead, moribund (i.e., at the point of death), or live insects per microcosm cage when held at room temperature 4, 24, and 48 h following retrieval from the field.

In addition to the outlined studies, a parallel experiment consisting of a laboratory overwintering study was conducted at Lethbridge during the past three years. Overwintering survival of five adult weevils placed in a vial partially filled with soil was examined using four treatments consisting of duration of exposure to different cold temperatures: (i) -5°C for eight weeks, (ii) +5°C for eight weeks, (iii) alternate treatment where vials were moved from +5 to -5°C after a week and vice versa for a total of eight weeks, and (iv) 18.5 weeks at +5°C. At the end of the experimental overwintering period, all the weevils in each of the four replicate vials were examined to determine overwintering survivorship. In 2002-2003, only treatments (i) and (iv) were conducted because of weevil scarcity.

The third study evaluated the cold-hardiness of cabbage seedpod weevils and lygus bugs. Temporal variation in cold-hardiness was measured using supercooling temperatures, the point at which tissue freezes and liberates heat, for individual weevils and lygus bugs. Supercooling temperatures for overwintering lygus bugs surviving within retrieved microcosm cages at Beaverlodge on 10 March 2003 and 9 February 2004 were determined at Lethbridge. Any lygus bugs surviving 48 h following retrieval from the field were shipped to Lethbridge. Upon arrival, the lygus bugs were held at 5°C until supercooling temperatures (i.e., point at which tissue freezes and its heat is liberated) were determined for each individual. Studies on overwintering habitat and cold-hardiness will be used to attempt to predict the magnitude of infestations of these pests from year to year.

The fourth study involved collection of environmental data during the winter in Beaverlodge and Lethbridge, Alberta to: 1) provide a better understanding of insect overwintering conditions in the Peace River and Lethbridge regions; 2) provide baseline

information for comparing overwintering survivorship of cabbage seedpod weevil and lygus bugs; and 3) to predict distributions and potential infestation levels for lygus bugs or cabbage seedpod weevil in northern and southern Alberta.

Weather data were collected from microclimates assumed to be suitable overwintering habitats for lygus bugs and cabbage seedpod weevils. Temperature, relative humidity, precipitation, and snow cover were monitored through the winter from two sites located in the Peace River Region near Beaverlodge and one site near Lethbridge. Weather data collected will be compared to supercooling temperatures observed in the laboratory for cabbage seedpod weevils collected in southern Alberta and field data to determine if the weevil's distribution will be limited by Peace River Region winters.

Results and Discussion

Objective 1: Development of Canola Germplasm Resistant to Weevil Attack

Under field conditions, the various species of Brassicaceae matured at different rates. Pods formed first on *B. rapa*, *B. juncea*, and *S. alba* approximately 40 to 50 days after seeding. By about 50 to 60 days after seeding, pods had developed on *B. napus*, *B. napus* x *S. alba* hybrids, *B. tournefortii*, and *B. nigra*.

In Experiment 1, differences in susceptibilities to infestation by cabbage seedpod weevil occurred among and within species of Brassicaceae. Differences between genotypes were greater in 2001 than in 2002, presumably because weevil densities in the field were much greater in 2001 than in 2002 (Dosdall, unpublished data). In both years, Accession 115 of *B. napus* had significantly fewer weevil exit holes per pod than Accessions 84 and 87 ($P < 0.05$), and the *S. alba* x *B. napus* hybrid Accession 9 had significantly less weevil damage than hybrid Accessions 1 and 101 ($P < 0.05$) (Fig. 3). No differences were observed in infestation levels among the genotypes of *S. alba* and *B. nigra* in either 2001 or 2002.

When field infestation data for the different cultivars were pooled within each species, data from both 2001 and 2002 determined that *B. rapa* was significantly more susceptible to attack by cabbage seedpod weevil (in terms on weevil exit holes per pod) than

all other species evaluated ($P < 0.05$) (Fig. 4). Infestation levels of *B. tournefortii*, *B. napus*, *B. juncea*, and the *S. alba* x *B. napus* intergeneric hybrids were intermediate in their susceptibilities. In 2001, the field evaluation found no statistically significant differences in susceptibilities among these species ($P > 0.05$), but in 2002 *B. tournefortii* and *B. juncea* had significantly fewer exit holes per pod than the hybrids and *B. napus* ($P < 0.05$). In both years, mean exit holes per pod of plants of *B. nigra*, *S. alba*, and *C. abyssinica* were significantly lower than those of the other species evaluated ($P < 0.05$) (Fig. 4).

Greatest numbers of *C. obstrictus* eggs were found in *B. rapa* pods (Fig. 5). In contrast, no eggs were found in pods of *B. nigra* or *S. alba*. Egg laying tended to last about two weeks in most species and eggs were most abundant in the early-formed pods (Fig. 5). In plant species where *C. obstrictus* eggs were found, approximately 20 to 30% of the pods had egg(s). Of those pods with eggs, the likelihood of finding more than one egg per pod was greater than 40% and some pods harboured up to five or six eggs.

Larvae were found in pods of the hybrid and in most of the species except for *B. nigra* and *S. alba* (Fig. 5). First-instar larvae were present for about two weeks, approximately 50 to 70 days after seeding (Fig. 5). Second-instar larvae also tended to be present for two weeks and third-instar larvae were recovered over three to five weeks. Third-instar larvae were found as early as 60 days after seeding and the greatest numbers of third-instar larvae were found about 65 to 80 days after seeding. Usually only one larva was found in a pod.

Exit holes were found in all species, although the few holes that were found in *S. alba* and *B. nigra* pods were morphologically distinctive from those in other species and may not have been caused by *C. obstrictus*. *Brassica rapa* had the greatest frequency of exit holes per pod, followed by *B. napus*, the hybrid, *B. tournefortii*, and *B. juncea* (Fig. 5). Exit holes were found beginning about nine weeks after seeding (Fig. 3). The number of exit holes (h) for a species was related to the number of deposited eggs (e) ($n = 5$, $P < 0.05$, $r^2 = 0.92$, $h = 1.263\ (e) - 89.193$). Besides having the greatest number of exit holes, *B. rapa* also had the greatest mean number of exit holes per pod at 0.39. Most infested pods of *B. rapa* had a single exit hole. In contrast, *B. napus* pods were almost as likely to have multiple exit

holes as a single exit hole. The majority of the exit holes in pods of the hybrid, *B. tournefortii*, and *B. juncea* were single with approximately 10 to 20% of the pods having an exit hole.

Data from the laboratory arena studies validated the field infestation data, which indicated that *S. alba* and *B. nigra* were less susceptible to oviposition by cabbage seedpod weevil than the other Brassicaceae evaluated. After 24 h, mean eggs per pod deposited in *B. rapa* and *B. napus* x *S. alba* exceeded those in *B. tournefortii*, *B. juncea*, *B. nigra*, and *S. alba* ($P < 0.05$) (Table 1). Mean eggs per pod deposited in *B. napus* and *B. tournefortii* exceeded those in *B. nigra* and *S. alba* ($P < 0.05$). After 48 h, mean eggs per pod deposited in *B. rapa* exceeded those in *B. juncea*, *B. nigra*, and *S. alba* ($P < 0.05$), and mean eggs deposited in *B. napus*, *B. napus* x *S. alba* and *B. tournefortii* exceeded those in *B. nigra* and *S. alba* ($P < 0.05$) (Table 1).

After 24 h, mean feeding punctures on *B. rapa* exceeded those on *B. napus*, *B. tournefortii*, *B. juncea*, *B. nigra* and *S. alba* ($P < 0.05$) (Table 1). Feeding punctures on *B. napus*, *B. tournefortii*, *B. juncea*, and *B. nigra* also exceeded those on *S. alba* ($P < 0.05$). After 48 h, mean feeding punctures on *B. juncea* exceeded those on *B. rapa*, *B. napus*, *B. napus* x *S. alba* and *S. alba* ($P < 0.05$). Further, mean feeding punctures on *B. rapa* and *B. napus* exceeded those on *S. alba* ($P < 0.05$).

Feeding punctures by late summer weevils ranged from 0 on *S. alba* pods to a mean of 1.5 ± 0.7 (S.E.) per pod of *B. napus*. However, there were no significant differences in mean feeding punctures per pod among the brassicaceous species ($P = 0.17$).

For Experiment 2, the 2001 field evaluation determined that considerable variation occurred in levels of susceptibility to cabbage seedpod weevil infestation among the *S. alba* x *B. napus* intergeneric hybrids evaluated. One genotype had no weevil exit holes, and 17 genotypes had only 1 to 5 exit holes per 100 pods (Fig. 6). Of the remaining hybrid genotypes, the frequency of exit holes per 100 pods ranged from 6 to 72. The *B. napus* cultivar, Q2, had a mean of 24 exit holes per 100 pods (Fig. 6).

The 2002 field evaluation of *S. alba* x *B. napus* intergeneric hybrids selected for low susceptibility in 2001 determined that mean exit holes per plant of *B. napus* cv. Q2 were

approximately twice as abundant as those of any other genotype (Fig. 7). The genotypes were arbitrarily divided in two groups: accessions with greater than an average of five exit holes per 100 pods, and accessions with less than or equal to five exit holes per 100 pods. Fourteen genotypes were then found in the latter category; these comprised Accessions 428, 571, 305, 22, 329, 537, 408, 362, 394, 83, 128, 374, 578, and 23. Of these, Accession 428 had the greatest number of exit holes (mean = 0.037 per pod) and Accession 23 had the fewest (mean = 0.007 per pod) (Fig. 7).

Laboratory screening experiments conducted in 2003 with *S. alba* x *B. napus* intergeneric hybrids determined that Accessions 394, 329, 83, and 22 had significantly fewer cabbage seedpod weevil eggs deposited per pod than Accessions 408 and 374 (Fig. 7). Accessions 408, 305, 362, 128, and 428 had intermediate numbers of weevil eggs deposited per pod.

In Experiment 3, mean weevil exit holes per pod of *B. rapa* cv. AC Sunbeam significantly exceeded those of all other species and varieties in evaluations conducted in both 2001 and 2002 ($P < 0.05$) (Fig. 8). Susceptibility of plants of *B. napus* cv. AC Excel was intermediate, and approximately 30% less than that of *B. rapa* cv. AC Sunbeam. Mean exit holes per pod of *B. juncea* cv. AC Vulcan significantly exceeded those of *B. juncea* cvs. J90 4253 and Commercial Brown in the 2001 evaluation ($P < 0.05$), but not in 2002 ($P > 0.05$). In both years, no statistically significant differences in mean weevil exit holes per pod were observed among the five cultivars of *S. alba* tested ($P > 0.05$), and their susceptibilities were significantly lower than those of other Brassicaceae ($P < 0.05$). Among the species of Brassicaceae evaluated in Experiment 3, the order of susceptibility to infestation by *C. obstrictus* was *B. rapa* > *B. napus* ≥ *B. juncea* > *S. alba* (Fig. 8).

In Experiment 4 comparing susceptibilities of *B. napus* (cvs. Westar and Quantum), *B. juncea*, and *B. carinata* with susceptibilities of intergeneric hybrid accessions derived from crosses of *B. carinata* x *B. napus*, susceptibility of *B. carinata* was substantially lower than that of *B. napus* and *B. juncea* (Fig. 9). Considerable variation in susceptibilities occurred among the intergeneric hybrid accessions evaluated, with Accession 03-S as most susceptible, and Accession 07-R as least susceptible. Among the 10 hybrid accessions

evaluated, four had less than or equal to a mean of five exit holes per 100 pods (Accessions 02-R, 07-R, 02-MR, and 01-MS) (Fig. 9).

The 2003 laboratory assessments of the *B. carinata* x *B. napus* intergeneric hybrids determined that fewest cabbage seedpod weevil eggs were deposited in pods of the *B. carinata* parent (Fig. 10). Accession Numbers 35, 41, 15, and 36 had fewer eggs deposited per pod compared with pods of the other hybrids. Eggs in pods of Accessions 15 and 36 were less than 0.5 per pod, and eggs in Accessions 35 and 41 were approximately 1.0 per pod. Other genotypes had more than 1.0 eggs per pod, and *B. napus* cvs. Westar and Quantum had approximately 2.3 and 1.8 eggs per pod, respectively (Fig. 10).

This is the first study to document pod exit hole frequency distributions among species of Brassicaceae. Frequencies of exit holes varied among species; for example, infested pods of *B. rapa* and *B. juncea* usually had single exit holes but *B. napus* pods frequently had multiple ones. The synergistic effects of *C. obstrictus* and other pests occurring concomitantly have already been recognized (Free et al. 1983; Cárcamo et al. 2001). Our results indicate that consideration of exit hole frequencies among brassicaceous species should be taken into account in areas where opportunistic pests utilize *C. obstrictus* exit holes to gain access to otherwise inaccessible resources. For example, yield loss to *B. rapa* could be higher than predicted based on mean exit hole counts alone because a single exit hole makes all of the seed in a pod available to opportunistic pests, but damage to *B. napus* could be less than predicted from exit hole counts because multiple exit holes per pod reduce the total amount of seed exposed to opportunistic pests.

In the field trials of 2001 and 2002, the order of susceptibility of host plant species was *B. rapa* > *B. napus* = *B. napus* x *S. alba* ≥ *B. tournefortii* = *B. juncea* > *B. nigra* = *S. alba* = *C. abyssinica*. Similarly, in the laboratory bioassays, *C. obstrictus* oviposited less frequently in pods of *B. juncea*, and not at all in pods of *B. nigra* and *S. alba*. In contrast, no differences were observed among Brassicaceae species in the feeding preferences of new generation weevils. This generation of weevils can cause extensive late-season damage to canola, particularly in years when weevil densities are high (Dosdall et al. 2001). Thus, all

Brassicaceae species are susceptible to feeding damage and potential yield loss in years of weevil outbreaks.

Data from this study on common North American crop species concur with previous studies conducted in Europe and the U.S.A. *Brassica rapa* and *B. napus* were highly susceptible whereas *B. juncea* was moderately susceptibility to attack by the cabbage seedpod weevil (McLeod 1953; Doucette 1947; Dmoch 1965). Brown et al. (1999) found the order of susceptibility for four Brassicaceae species as *B. rapa* > *B. napus* > *B. juncea* > *S. alba*, a ranking which was confirmed in our study.

This study also clarified the susceptibilities of *S. alba* and *B. nigra* to the weevil. Dmoch (1965) listed both *B. nigra* and *S. alba* var. *genuina* as hosts that sustained weevil reproduction. However, our findings support Doucette's (1947) studies that *S. alba* and *B. nigra* are resistant to *C. obstrictus*. Other no-choice laboratory studies have also confirmed that *C. obstrictus* do not oviposit in *S. alba* pods (Harmon and McCaffrey 1997). McCaffrey et al. (1999) attributed lower feeding and ovipositing rates on *S. alba* pods to high concentrations of *p*-hydroxybenzyl glucosinolate in the pods and seeds.

The apparent immunity of *B. nigra* to attack by *C. obstrictus* is perhaps complicated by its pod morphology. *Brassica nigra* pods are only a few mm wide and Doucette (1947) found that weevils did not oviposit in pods less than 2 mm diameter. In this study, no eggs or larvae were found in pods of *B. nigra* but a few exit holes were observed. Some of the holes may not have been caused by *C. obstrictus*, but in at least one instance, frass and hole morphology indicated the hole was formed by a weevil. Doucette (1947) also found evidence of possible larval presence in pods. *Brassica nigra* has possible antixenotic resistance to *C. obstrictus*, but further investigations should be conducted to clarify host status of this species prior to considering it as a source for resistant germplasm.

Our study confirmed that *Crambe abyssinica* does not sustain weevil reproduction (Dmoch 1965). Although not discussed by Dmoch (1965), *C. abyssinica* pods cannot support weevil development as the spherical pods, measuring 1 to 3 mm diameter, would not provide enough nutrition for a developing larva which requires an average of 5 to 6 canola

seeds (Dosdall and Dolinski 2001). Furthermore, the size of final-instar *C. obstrictus* larvae is larger than the size of *C. abyssinica* pods.

For the first time in literature, we present data on the susceptibility of *B. tournefortii* to *C. obstrictus*. *Brassica tournefortii* is a weed, native to the Mediterranean region (Prakash 1974). Although *B. tournefortii* is moderately susceptible to the weevil, in years like 2002 when weevil densities are low to moderate, *B. tournefortii* may be less susceptible to *C. obstrictus* than the more common canola cultivars. Such resistance may make *B. tournefortii* a good candidate for consideration in genetical engineering. Other desirable qualities of *B. tournefortii* include its tolerance to the mustard aphid, *Lipaphis erysimi* Kalt (Singh et al. 1965), and its drought tolerance (Salisbury 1991).

Additional resistant species may be found by considering the taxonomic relatedness of the Brassicaceae species. *Brassica* can be divided into two phylogenetic pathways: the "*rapa/oleracea*" lineage and the "*nigra*" lineage (Ripley and Arnison 1990; Yang et al. 1998). Our study evaluated a narrow sampling of Brassicaceae, but because *B. rapa* and *B. nigra* varied so dramatically in their susceptibilities to *C. obstrictus*, we predict that there may be other resistant species within the "*nigra*" lineage. *Sinapis alba*, considered closely related to *B. nigra* (Yang et al. 1998), fits this hypothesis.

Besides confirming Brassicaceae species susceptibilities to the cabbage seedpod weevil, this study examined susceptibilities among genotypes of species. Although susceptibilities of genotypes varied somewhat between years, differences were consistently observed among genotypes of *B. rapa*, *B. napus*, *B. napus* x *S. alba*, and *B. juncea*. Choices of genotypes for this study were not based on agronomic performance and thus, no specific recommendations on variety choices can be made. Nonetheless, this observation may have important ramifications for seed selection, particularly if these differences affect overall crop yield. More work should be conducted to test registered genotypes of the agricultural crops. Furthermore, careful examinations of susceptibility differences among genotypes of a species may contribute of our overall understanding of crop resistance to the cabbage seedpod weevil.

This study focused on determining susceptibilities of selected genotypes and species of Brassicaceae to infestation by the cabbage seedpod weevil and consequently, the findings may have important implications for oilseed growers in regions of high population densities of *C. obstrictus*. Producers in these regions should first consider planting the resistant *S. alba* and then consider planting less susceptible crops like *B. juncea* or *B. napus*.

Three field seasons of research have enabled us to select accessions resulting from *S. alba* x *B. napus* intergeneric crosses that appear to harbor genes for resistance to the cabbage seedpod weevil. These genes for resistance would have been derived from the resistant parent (*S. alba*). Furthermore, some genotypes derived from *B. carinata* x *B. napus* intergeneric crosses also show promise in serving as parents for eventually developing cultivars of canola resistant to the weevil. We determined that species of Brassicaceae most resistant to attack by the cabbage seedpod weevil include *S. alba*, *B. nigra*, *B. carinata*, and *C. abyssinica*. It is not possible to perform crosses between *C. abyssinica* and *B. napus*, so the usefulness of this species in resistance development programs will be negligible. Nevertheless, the resistance found in *B. nigra*, *S. alba* and *B. carinata* may hold the key to developing canola germplasm resistant to this pest if their genes for resistance can be successfully incorporated in elite canola cultivars.

Objective 2: Determining Integrated Effects of Seeding Date and Seeding Rate (Canola Canopy Manipulation) on Cabbage Seedpod Weevil Infestations

Data on plant densities and percent ground cover for the two seeding dates were similar for the different years of study; representative data are presented in Table 2 for 2002. Altering canola seeding rate was effective for manipulating mean numbers of canola plants per m^2 in the research plots. For canola seeded at 1 kg per ha, approximately 18 and 28 mean plants per m^2 occurred in plots seeded on early and normal seeding dates, respectively, but plant populations increased to approximately 132 and 109 plants per m^2 for canola seeded at 5 kg per ha on early and normal seeding dates. In early July, the canopy was nearly closed for plots seeded early at 3 and 5 kg per ha, as indicated by percent ground cover in Table 2. However, canopy closure was less extensive for plots seeded early at 1 kg per ha, and for plots seeded on the normal date.

In all years of study and for both early and normal seeding dates, mean numbers of primary, secondary, and total branches per plant were significantly greater for plants seeded at 1 kg per ha than for plants seeded at 3 to 5 kg per ha ($P < 0.05$) (Fig. 11). Data on branching (primary vs. secondary) and pod distribution (pod numbers on different branches) for the two seeding dates were similar for the different years of study; representative data are presented in Table 3 for 2002. Mean primary branches were relatively similar for plants seeded at 3 and 5 kg per ha, but mean numbers of secondary branches of plants seeded at 3 kg per ha usually significantly exceeded those of plants grown at 5 kg per ha ($P < 0.05$) (Fig. 11).

Mean numbers of pods on the main stem declined with an increase in seeding rate. At a seeding rate of 1 kg per ha, plants produced approximately 44 and 41 pods on the main stem at early (early May) and normal (mid May) seeding dates, respectively (Table 3). As seeding rate increased to 5 kg per ha, plants seeded on early and normal dates produced approximately 31 and 30 pods on the main stem. Similarly, pods on primary branches declined as seeding rate increased. At 1 kg per ha, plants produced approximately 228 and 186 mean pods per primary branch on early and normal planting dates, but only

approximately 53 and 62 mean pods per primary branch on early and normal seeding dates when seeded at 5 kg per ha. Mean pods on secondary branches also declined with an increase in seeding rate. At 1 kg per ha, plants produced approximately 244 and 163 mean pods per secondary branch on early and normal planting dates, respectively, but only approximately 4 and 10 pods per secondary branch on early and normal seeding dates when seeded at 5 kg per ha (Table 3).

Mean numbers of cabbage seedpod weevil adults collected per pan trap sample tended to increase with seeding rate in 2001 and 2002; however, there were no statistically significant differences observed among the seeding rates evaluated ($P > 0.05$) (Fig. 12A). In 2003, mean adult weevils captured per pan trap were significantly lower in plots seeded at 1 kg per ha than for plots seeded at 3 or 5 kg per ha ($P < 0.05$). Mean adult weevil numbers per pan trap sample did not differ significantly for early versus normal seeding in either 2001 or 2002 ($P > 0.05$); however, in 2003 significantly fewer adults were collected per sample for plots seeded on the normal date than plots seeded early ($P < 0.05$) (Fig. 12A).

Mean numbers of cabbage seedpod weevil larvae collected per pan trap sample increased with seeding rate in 2001 ($P < 0.05$), but not in 2002 or 2003 ($P > 0.05$) (Fig. 12B). In 2001, mean numbers of larvae per trap for plots seeded at 5 kg per ha significantly exceeded larvae per trap from plots seeded at 1 kg per ha. In all years of study, significantly more weevil larvae were collected from plots seeded early than from plots seeded later ($P < 0.05$) (Fig. 12B).

Although no significant differences in mean exit hole numbers per pod were observed among plots seeded at 1 kg per ha versus 3 kg per ha in either 2001, 2002, or 2003 ($P > 0.05$), cabbage seedpod weevil exit hole numbers were significantly greater on plots seeded at 5 kg per ha than on plots seeded at 1 kg per ha ($P < 0.05$) (Fig. 13). Plants seeded early had significantly more exit holes per pod than plants seeded later ($P < 0.05$), and plants sprayed with Matador® 120 EC had significantly fewer exit holes per pod than those not sprayed ($P < 0.05$) (Fig. 13).

In both 2001 and 2002, emergence of new generation adults of *C. obstrictus* was significantly greater in plots seeded 5 kg per ha than for plots seeded at 1 kg per ha ($P <$

0.05) (Fig. 14). In 2003, weevil emergence was very low in all plots, and no significant differences were observed among the different seeding rates ($P > 0.05$) (Fig. 14).

In 2001 and 2002, weevil emergence from early-seeded canola significantly exceeded emergence from plots seeded later ($P < 0.05$) (Fig. 14). In 2003, however, emergence of new generation adults was greater in normal-seeded plots than in plots seeded early ($P < 0.05$) (Fig. 14).

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 and produced greater seed yields (Canola Council of Canada 2001) (see representative data in Table 4). Increasing canola seeding rate appears to predispose plants to greater attack by *C. obstrictus*, 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. However, seed yields were similar between seeding dates in 2001 (Canola Council of Canada 2001), but in 2002 yields were slightly higher for the normal planting date for all seeding rates (Table 4). In 2001, spraying appeared to have a negligible impact on yield (Canola Council of Canada 2001), but in 2002 and 2003, plots sprayed with insecticide yielded more than non-sprayed plots. In 2002, mean yields for the three seeding rates on the early seeding date were 48.5 bu per acre for plots sprayed with insecticide compared with 46.1 bu per acre for non-sprayed plots. Mean yields for the three seeding rates on the normal seeding date were 51.7 bu per acre for plots sprayed with insecticide versus 48.2 bu per acre for non-sprayed plots. As expected, days to maturity were greater at lower seeding rates than at higher rates. Seed oil content was similar regardless of seeding rate (Table 4).

Ceutorhynchus obstrictus responded to variations in canola plant stand manipulation. Pan trap collections early in the season indicated that migrations to plots seeded early and at higher densities exceeded migrations to plots seeded later and at lower densities. However,

canola seeded at higher densities produced greater seed yields, indicating a greater compensatory ability of those crops. Results of this study indicate that growers should maintain normal 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 improved yields. Canola growers in regions infested with high numbers of cabbage seedpod weevil should therefore avoid early seeding, but maintain normal seeding rates.

Objective 3: Investigating Trap Cropping as a Cultural Control Strategy for Cabbage Seedpod Weevil

In 2001, trap crop Sites 4 and 5 were lost due to a severe windstorm on 19 May and were re-seeded to cereal crops. At Site 1, the trap crop border began to flower on 28 May and cabbage seedpod weevils reached four per sweep (the economic threshold level) on 31 May 2001. The trap border was sprayed with Matador® 120 EC (0.34 L per acre) on 2 June 2001 (Fig. 15). By 11 June, weevils re-invaded the field and mean densities were approximately six per sweep; the trap strip was therefore re-sprayed. On 16 June, the grower re-sprayed the trap border based on his own sampling results and also sprayed the inside edge of the main crop including the 50 m sampling points. Mean weevil densities were less than two per sweep on all sampling dates at various distances from the trap border (ca. 50, 100, 200 m and near the middle) (Fig. 15). Lygus bugs (Fig.16A) were less than 0.25 per sweep at the end of June at the early pod stage and were highest 50 m from the trap crop and lowest at the centre of the field. A similar pattern was observed for flea beetles (Fig.16B) and overall numbers of beneficial insects (Fig. 16D: wasps, bees, predator beetles, spiders, etc.). In contrast, diamondback moth larvae were more abundant at unsprayed areas toward the middle of the field (Fig.16C).

At the Skiff site in 2001, less than 2% of the pods were infested by cabbage seedpod weevil in the trap crop and about 6 to 7 % in the main crop (Fig. 17A). Seed yields and overall dry plant biomass (Fig. 17B and 17C) estimated from 1 m quadrat samples were slightly higher at the trap border than at the edge and toward the middle (200 m from trap) of

the main crop. There was no significant relationship between percent of infested pods and seed yield (Fig. 17D).

At the Coaldale site in 2002, weevils reached 16 per sweep along the south and west trap borders on 19 June and were sprayed the next day (Fig. 18A). By 4 July, weevils reached about five per sweep near the middle of the field (ca. 400 m from trap border) and the farmer was advised to spray. Weevil densities were considerably lower 50 and 150 m from the south trap border than at comparable distances from the patchy northern trap border (Figs. 18B and 18C). Weevil damage was not estimated at this field.

At the New Rock Port trap crop, weevil densities reached about 10 per sweep on 18 June and two days later the trap border was sprayed (Fig. 19A). By 25 June (Fig. 19B), the average number of weevils at the main crop was just under four per sweep but at some sampling points near the middle they reached five per sweep; therefore, the grower opted to spray the field. Less than 3% of the pods were infested by cabbage seedpod weevil at the trap border and main crop.

All control fields sampled in 2002 had a distinct pattern of higher weevil abundance near the edge and decreasing abundance towards the middle of the fields (Figs. 19C, 20, and 21). At Stirling, AB there were high weevil numbers (ca. five per sweep) throughout several middle points of the field and the farmer was advised to spray (Fig. 19C). However, the second control field near Coaldale, AB was below the economic threshold, except along one of the edges where weevils were four per sweep on 29 June but lower on 10 July (Fig. 20). The farmer opted not to spray this field until mid-July for lygus bugs and other late season pests (e.g., diamondback moth). Pods infested by the weevil ranged from 9 (middle) to 16% (edges), but there was no indication that yields (based on 50 plants per sampling point) were affected negatively (Fig. 22). The third control field also near Coaldale, AB had extremely high weevil densities, probably because it was planted earlier. On average, the middle of the field had approximately five weevils per sweep. This field was sprayed on 29 June 2002.

In 2003, cabbage seedpod weevil average abundances per field were below economic threshold levels in all trap crop and check fields. However, at Stirling, AB (Figs. 23, 24) a few of the sampling points along the west and northwest trap crop had close to 30

weevils per 10 sweeps based on counts done in the field or from field samples processed in the laboratory. Weevils also reached the economic threshold along a few spots of the edge of the check field nearby. Therefore, the farmer had the trap crop site and check fields sprayed along the borders as a preventative measure. Such spraying was unnecessary as suggested by very low levels of damage at the *B. rapa* field in Skiff, AB where similar weevil abundance was observed (Figs. 25, 26). Mr. Hildebrand's *B. rapa* trap crop (Field 2) was the earliest planted (3 May) within the known flying distance of the weevil (6 km) and presumably received the majority of the weevils in the area but only a few spots along the north end and northwest of the trap border reached the economic threshold and the farmer opted not to spray. In all other trap crop or check fields in the Skiff area, planted around or after the middle of May in 2003, cabbage seedpod weevils had less than five weevils in 10 sweeps.

There was no correlation between seed yield and weevil damage (% pods with exit holes) at Skiff, AB (r^2 <0.00). At Stirling there was a weak but significant correlation (r^2 = 0.34, $P < 0.05$). However, with such low damage levels (means approximately 1.5 and 2 to 3% in the trap and main crops, respectively) it is unlikely that this relationship is meaningful and more likely that there were other insects such as flea beetles that may have reduced yields in the unsprayed areas that had slightly higher weevil damage. Flea beetle infestations were damaging at the seedling stage, and the west border of the trap field was sprayed twice prior to the 25 June 2003 spray for weevils.

Lygus bugs were generally low, as expected, during the early flower stages in all fields with or without trap crop borders. At the Stirling fields, lygus remained low also at the critical early pod stage, approximately one per 10 sweeps, in the middle or field borders. At Skiff, the *B. rapa* trap crop Field 2 (Figs. 27, 28) had approximately 11 and 7 lygus bugs per sample along the trap border or 200 m distance, respectively but the variation was high as seen by overlapping standard errors. Beneficial insects, mainly potentially parasitic wasps were very low at both Stirling and Skiff; however, there was a trend towards concentration of beneficials along the trap crop border or edges at the Stirling site. Planting the trap strip in the middle of the field to concentrate mobile weevils but not less dispersive parasitoids is a

strategy that warrants further research particularly if there is legislation in the future preventing spraying pesticides near buffer zones such as margins adjacent to tree shelters.

After three years of data collection it can be concluded that in large fields of 259 ha, weevils can be controlled along trap strips and it can be possible to avoid having to spray entire fields even when populations are far above the economic thresholds. We cannot exclude the possibility that because of the large field size, weevils would not reach four per sweep in the middle even without a trap crop if a farmer simply sprayed only the borders. Until further studies are completed, planting a trap strip along the borders, either a mixture of *B. rapa* with *B. napus*, or *B. napus* planted a week earlier than the main crop, may be considered a sound management strategy. Under low weevil abundances, approximately four per sweep, spraying the borders of fields with no trap crops may be sufficient to prevent damage.

Farmers that plant very early (e.g., early April) and with no other canola nearby may need to spray the trap border twice. This strategy can result in considerable savings over spraying entire fields. Assuming a cost of $4.00 for chemical and $4.00 in labor and ground equipment costs, it would total $960.00 to spray the trap strip twice. Blanket-spraying a field of 259 ha once by plane would cost at least $6400.00 at $10 per acre. This would translate into a $5,440.00 savings for the Skiff site or $8.50 per acre (20.99 per ha).

In 2001, fields at Stirling and Coaldale were sprayed despite having trap crop strips. Both trap strips were not ideal systems compared to the Skiff site. At Stirling the trap crop was a cultivar of *B. napus* planted only two days before the main crop and there were only a few days difference between the appearance of flowers in the main and trap crop. At Coaldale, weevils invaded the field from all edges including the west side at the cereal-canola interface where there was no trap crop. We assumed that the trap border would be needed only on the outside of the irrigation pivot. Also the trap strip was only about 7 m wide, perhaps not wide enough to retain large densities of weevils. Furthermore, the northern trap strip was extremely patchy because of windy conditions during irrigation after planting.

Our control fields ranged from 32 to 53 ha and weevils surpassed economic thresholds in the middle of the dryland and irrigated fields that were planted early. It remains to be investigated if border spraying, with no trap border, would be enough to keep weevils from reaching economic thresholds in the middle of small, early-planted fields or large dryland fields (e.g. 260 ha) when populations approximate economic threshold densities. Weevils remained below economic threshold values at the irrigated (32 ha) field, planted at the end of April. Clearly, field size and seeding date in relation to other fields are important determinants of weevil population dynamics in canola and their potential pest status.

In 2002, cabbage seedpod weevil adults reached the economic threshold of three to four per sweep at many sampling points of the trap crop strip in fields near Coalhurst (Fig. 29), Coaldale, and New Rock Port and were sprayed with insecticide. The trap crop near Nobleford was near the economic threshold, so spraying was not recommended. However, the farmer sprayed the trap and all checks at mid flower because of grasshopper infestations. None of the check fields elsewhere had weevil densities to justify spraying but the farmer at New Rock Port sprayed his hybrid seed canola field because of the high value of the crop. A few irrigated fields without trap crops were sprayed in the area to prevent damage from weevils but none of these were sampled.

Damage by cabbage seedpod weevils at the trap crop fields ranged from four to 13 exit holes per 100 pods in the trap crop border and two to eight holes per 100 pods in the main crop areas (Fig. 30). These values are considered low damage levels and are unlikely to have an impact on crop yield since there are reports from the literature suggesting that until damage levels reach over 25% there is no yield loss (Buntin 1999; Lerin 1984).

Seed yields were similar in the main crop and trap strips in all sites and in the check field edges and middle areas (Figs. 31, 32). Coalhurst and Nobleford had the lowest yields, around 50 g per quadrat in both the trap crop and main crop areas. At Stirling there were slightly higher yields (no statistics were performed since the error bars clearly overlap) in the main crop than in the trap crop but the same trend was observed in the check field (hybrid canola) that was sprayed for weevils and had less than 1% of pods with exit holes. The lower yields along the edges are likely explained by high grasshopper pressure at some sites.

Research on trap cropping for the cultural control of cabbage seedpod weevil in canola indicates that in some situations this can be an appropriate management strategy for this pest. When the approach is effective, it often results in improved economic and environmental sustainability. Future research should include integrating the trap crop concept with biological control options such as protection of native beneficials by planting the trap strip in the middle of fields and also research the possibility of applications of biopesticides such as *Beaveria bassiana* fungal spores or even mass releases of parasitoids in the trap strips where the weevils are concentrated.

Objective 4: Developing a Biological Control Strategy for Cabbage Seedpod Weevil

In 2001, parasitism by the braconid wasp, *M. melanopus*, was documented at four different host plant sites as determined by dissections of living adults of *C. obstrictus* (Table 5). Weevils captured in sweep net samples were pooled to obtain more adult parasitoids but emergence was low. It was apparent from dissections of adult weevils that mid to late June were times when *M. melanopus* was most readily found in its late larval stages within weevil hosts. A survey of 25 sites across southern Alberta, conducted from 17 to 30 June 2001, resulted in finding the parasitoid at 10 sites in the region near the city of Lethbridge, but not as far north as Calgary or as far east as Medicine Hat (Fig. 33). The most productive site outside of Lethbridge was at Fort MacLeod, AB with 9.2% parasitism.

The presence of spherical, white pellets in the abdomens of parasitized weevils could be used as an indicator of the presence of mid- to late-instar larvae of *M. melanopus*. The pellets are teratocytes, or masses of cells that develop from the interaction of the weevil immune system with cells sloughed off from the wasp embryo as hatching occurs. This phenomenon is documented for other species of parasitic wasps in the hymenopteran family Braconidae (Vinson 1970).

Attempts to establish a laboratory colony of cabbage seedpod weevil using rice weevils as alternate hosts were unsuccessful. Other possible host candidates for establishing a laboratory colony of wasps still need to be identified and tested.

In 2002, evidence of parasitism of cabbage seedpod weevil by *M. melanopus* was found at 32% of the sites examined (Table 6). There was no evidence of parasitism in the 302 weevils dissected from Creston, BC. Parasitized weevils were collected from 17 June to 27 June 2002 and all weevils were from the Lethbridge, AB region. Parasitized weevils were found on host plants comprising wild mustard, volunteer canola, flixweed, and stinkweed. A general observation was made that there tended to be woody debris, such as deciduous forests, shelterbelts, or old abandoned wood buildings near sites where parasitoids were found.

Eleven weevil colonies were established from seven different sites (Table 7). We successfully reared two wasps in the colonies, one from Creston, BC and the other from Lethbridge, AB. On 28 June 2002, the Creston cage had what appeared to be a female *M. melanopus* in it. The cage had been checked frequently for emergence, so it most likely emerged from a weevil. When found, this wasp was placed in a cage with 20 weevils (12 males, 8 females), a vial of 10% sucrose solution, and a vial filled with wild mustard. When the wasp was placed into the container, it chased the weevils, curving its abdomen towards them, and touching them with its antennae. The wasp was removed from the cage on 1 July 2002 after 72 h. It was still alive, although not very active. As the weevils died, they were dissected until the colony was terminated. Signs of parasitism were found in two of the dead weevils (both females). The male wasp that emerged from the Lethbridge site was kept, in the hope that another female wasp would emerge and they could mate. Unfortunately, however, no additional wasps emerged.

The discovery of *M. melanopus* in southern Alberta in 2000 and its distribution in 2001 indicate that this European species has become established in the mixed grassland ecoregion of the Canadian prairies. The highest rate of parasitism that we found in southern Alberta was 9%, compared with 71% in northwestern U.S.A. (Harmon and McCaffrey 1993) and 60% in Europe (Bonnemaison 1957).

In the fall-seeded canola cropping system of the northwestern U.S.A., parasitized weevils that emerge from overwintering sites have the opportunity to disperse directly to crops. In southern Alberta canola crops are spring-seeded, and weevils utilize brassicaceous

weeds and volunteer canola for sustenance before dispersing to crops (Fox and Dosdall 2003).

Although parasitized weevils were active at the time of capture, late stages of parasitism could negatively affect the ability of parasitized weevils to disperse from weed sites to crops. Adult parasitoids that emerge from weevils that failed to disperse would miss the opportunity to parasitize weevils that already dispersed. The overwintered generation of parasitoids, unless they are able to disperse as adults, would then be isolated in weed habitat with few weevils. This would limit opportunities to amplify numbers of second-generation parasitoids, and limit opportunities for second-generation parasitoids to parasitize new generation weevils.

The absence of parasitized weevils in *B. napus* crops, and the presence of parasitized weevils in volunteer *B. napus* and other weed sites in the current study, suggests that *M. melanopus* is not effectively dispersing from weed sites to crops. Therefore, *M. melanopus* may not be able to provide substantial control of *C. obstrictus* in the mixed grassland ecoregion of its new range.

Protecting stands of volunteer *B. napus* to maintain populations of *M. melanopus* would be unacceptable as stands of volunteer *B. napus* are generally considered to be undesirable from a weed management perspective, especially if they are herbicide-resistant strains. Also, their destruction is recommended to reduce weevil populations (Fox and Dosdall 2003). Furthermore, protecting low populations of parasitoids in volunteer canola may not result in a benefit to weevil control in crops.

The occurrence of parasitized weevils in *S. alba* is possibly linked to a slightly earlier development of this crop compared to *B. napus*. Also, annual fluctuations in spring seeding conditions may have played a role. However, the population of new generation weevils needed to complete the seasonal life cycle of the parasitoid would be exceedingly low, because *S. alba* pods are poor hosts for weevil reproduction (Doucette 1947; Brown et al. 1999; Kalischuk and Dosdall 2004).

The first parasitoids we encountered in the spring were probably the overwintering generation. However, if the parasitoid overwinters as a first-instar larva, which is generally

established in the literature, then the occurrence of embryos on 8 June indicates an encounter with the second generation. This would only occur if overwintering parasitoids emerge from their weevil host at overwintering sites and parasitize the overwintering generation before weevils disperse to weed sites. This is unlikely in southern Alberta's variable spring climate. A more likely explanation is that the life history of *M. melanopus* is more elastic than generally documented. Jourdheuil (1960) found embryos as well as first-instar larvae in *C. obstrictus* in October, and Speyer (1925) found parasitoids overwintering as eggs and larvae in *C. quadridens*.

The occurrence of weevils containing embryos on 9 July, and results of laboratory parasitism, provide some insight into the time frame of parasitoid activity and readiness to oviposit. Jourdheuil (1960) reported that the adult male to female parasitoid ratio was close to one, and males lived for up to 2, and females for 8 to10, days. Harmon and McCaffrey (1997) found few adult male parasitoids in the field relative to females (3:287 in 1992) but found 60% male emergence in the laboratory. In 2000 of the current study, there was 55% male emergence in the laboratory ($n = 29$). We documented only females in the field and the incidence was low.

Kuhlmann et al. (2002) listed *M. melanopus* as a potential candidate for release to control cabbage seedpod weevil, but cautioned that potential negative effects of this parasitoid on non-endemic Ceutorhynchinae released for weed control, and other endemic Ceutorhynchinae, must first be established. Bousquet (1991) listed 35 species of Ceutorhynchinae in Alberta. Now that *M. melanopus* is documented in southern Alberta it may be best to monitor its natural expansion and performance, and further investigate its life history, prior to considering mass releases for biological control of *C. obstrictus*.

Surveys undertaken in 2001 to determine the incidence of ectoparasitoids of cabbage seedpod weevil larvae in Alberta and British Columbia determined that ectoparasitoids occurred in Creston, BC. Parasitism rates ranged from 3.0 to 14.0%, depending on the field site (Table 8).

Surveys for ectoparasites near Lethbridge, AB from samples collected on 4 and 26 July 2001 in volunteer and commercial canola stands did not show evidence of

ectoparasitoids (Table 8). However, dissection of wild mustard pods from Lethbridge revealed a low incidence of ectoparasitoids (Table 8). In addition, 5 of 2,053 wild mustard pods dissected from the same site revealed evidence of wasp exuviae around exit holes. One other pod had a fully eclosed wasp trapped at the exit hole; this was not an adult invader as the wings were partly unexpanded. This wasp was not *T. perfectus* based on a comparison with *T. perfectus* specimens provided by Mr. Brad Harmon, University of Idaho, Moscow, ID.

Dr. H. Cárcamo, Agriculture and Agri-Food Canada, Lethbridge, AB reported finding a single ectoparasitoid pupa and a single ectoparasitoid larva in canola pods from his experimental plots in Lethbridge in 2001. Insect activity had ceased at this site when we sampled, revealing only a low proportion of pods with an exit hole (Canola Control, Table 8). Pods from an adjacent plot of volunteer canola (Lethbridge Volunteer Canola, Table 8) were taken too early to document abundant third-instar weevil larvae, the primary host developmental stage for ovipositing pteromalid ectoparasitoids. However, weevil infestation was high, indicating a potentially ideal habitat for ectoparasitoids. An analysis of sweep net samples for the reproduction study from this site produced two pteromalids captured on 4 July and one pteromalid captured on 9 July that are similar morphologically to confirmed, voucher specimens of *T. perfectus*.

Sweep net samples taken at Creston, BC contained many pteromalids, which are potential ectoparasites of cabbage seedpod weevil larvae. One of the two most robust sweep net samples from the stand of volunteer canola, documented in Table 8, contained 330 weevils and 72 pteromalids. Fifty of these pteromalids are similar to voucher specimens of *T. perfectus* and 19 others were clearly a single species.

In 2002, 19 of 44 sampling sites in southern and central Alberta were found to harbor larval ectoparasitoids (Fig. 34). The ectoparasitic Hymenoptera fauna represented the families Pteromalidae (7 species), Eulophidae (2 species), Eurytomidae (1 species), Mymaridae (1 species), and Chalcididae (2 species) (Table 9). The mymarid species may be an egg parasitoid of lygus bugs, not eggs of cabbage seedpod weevil; however, its status remains to be resolved.

Although considerable effort was made to determine the overwintering sites and spring emergence patterns of ectoparasitoids of the cabbage seedpod weevil, the study yielded few specimens. Only three known cabbage seedpod weevil ectoparasitoid species were collected in emergence traps throughout the summer and none of the three species responsible for most weevil parasitism were found. One female specimen of *Euderus albitarsis* Zetterstedt emerged from an emergence trap in a sheltered site on 1 May 2003, one female specimen of *Pteromalus* sp. emerged from a sheltered site on 5 June 2003, and three male specimens of *Mesopolobus bruchophagi* emerged from intermediately sheltered sites between 26 June and 3 July 2003.

Adult ectoparasitoids of cabbage seedpod weevil larvae were not abundant in bowl trap samples at the weed monitoring sites. Only one female of *N. duplicatus* (Hymenoptera: Eulophidae) was collected on 5 June 2003 in a patch of hoary cress.

In 2003, ectoparasitoids of the cabbage seedpod weevil were found at 40 of 121 survey sampling sites in southern and central Alberta (Fig. 35). All species of ectoparasitoids reared in 2002 were found again in 2003 except *Lycrus maculatus* Gahan which had been found in relatively low numbers in 2002. The predominant species found in southern Alberta, where the weevil is well established were *Necremnus duplicatus* Gahan, *Trichomalus* sp. and *Chlorocytus* sp. (Figs. 36, 37, and 38). The most widespread ectoparasitoid species of weevil larvae in Alberta were *Pteromalus* sp. and the two *Conura* species (Figs. 39, 40, and 41).

In the study designed to examine the spatio-temporal dynamics of weevil larval ectoparasitoids in relation to those of their host and the crop, weevil infestations were similar in the *B. rapa* and *B. napus* crops. In the *B. napus* crop, the weevil infestation level was 0.16 weevils per pod, and the ectoparasitism rate was 3.5%. In the *B. rapa* crop, the weevil infestation rate was 0.15 weevils per pod and the ectoparasitism rate was 1.9%.

In the *B. napus* crop, weevil adults collected in bowl trap samplers were concentrated along one edge of the crop in the 2 July 2003 collection when plants were in the early flowering stage (Fig. 42). On 9 July, when plants were in full flower, no weevils were found in the bowl trap samplers. However, weevils were very abundant on 17 and 23 July, and

commonly reached densities of more than 50 weevils per trap. In the *B. rapa* crop, weevil adults were very abundant (mostly greater than or equal to 25 adults per trap) on the 26 June and 2 July sampling dates when the crop was in early flower (Fig. 42). Weevil numbers declined dramatically when plants were in full flower, but by 24 July weevil abundance was again quite high with most traps having more than 25 adults per sample. For both crop species, weevil densities were initially higher along edges of the fields than further inward, but over time densities became more evenly distributed and homogeneous (Fig. 42).

Weevil larval exit holes in the field of *B. napus* were concentrated more densely along one edge of the field, corresponding to the edge where adult weevils were concentrated on 2 July 2003 when the crop was in early flower (Fig. 43). Greatest densities of ectoparasitoids corresponded generally, but not precisely, to those areas of greatest larval density. In the field of *B. rapa*, weevil larval exit holes were concentrated along one edge and in the central region of our grid. Ectoparasitoid numbers were lower in this field than in the *B. napus* field, and comprised primarily the eulophid, *N. duplicatus*. Greatest ectoparasitoid density corresponded to an area that also had a high density of weevil larvae (Fig. 43).

In the study conducted to compare ectoparasitoid activity on six different *Brassica* species (*B. napus*, *B. nigra*, *B. juncea*, *B. rapa*, *B. tournefortii*, *B. napus* x *S. alba*), parasitism was found to occur on all species and the number of individual parasitoids found emerging from each plant species was related to the level of weevil infestation. For example, *B. nigra* which was most resistant to the weevil, also yielded the fewest parasitoids. Within this study parasitoid emergence was also examined. Peak parasitoid emergence occurred approximately 10 days earlier (end of July) in *B. rapa* than in the longer maturing *B. napus*. There was insufficient parasitism on the other plant species to speculate on the relationship between crop phenology and parasitoid activity for those species at this time. *Necremnus duplicatus* appears to be active slightly earlier than the other most significant cabbage seedpod weevil larval ectoparasitoids. First parasitoid collections were made on 29 July 2002 and both *N. duplicatus* and *Trichomalus* sp. were found to be emerging. *Chlorocytus* sp. was first found emerging on 5 August 2003. The last *N. duplicatus* emerged from pods collected on 12 August. The last *Trichomalus* sp. emerged from pods collected

on 27 August and the last *Chlorocytus* emerged from pods collected on 19 August. There were insufficient numbers of the other parasitoid species to speculate on relative emergence times. It also appears that *N. duplicatus* may be relatively more important on *B. rapa* than on the other *Brassica* species; however, it is unclear if this is a product of crop phenology or other plant characteristics. *Trichomalus* sp. was the most dominant parasitoid species on all *Brassica* species tested at this site.

Results of our field surveys and other research studies indicate that larval ectoparasitoids of the cabbage seedpod weevil are relatively common in the mixed grassland ecoregion of southern Alberta. However, it is unclear which, if any, of the species attacking the weevil have been introduced and become established and which species are native to the region and have switched hosts to take advantage of the new resource that cabbage seedpod weevil larvae have provided.

Trichomalus perfectus and *Mesopolobus morys*, the two most important biological control agents of the cabbage seedpod weevil in Europe, were introduced to British Columbia in 1949 (McLeod 1953). Although it was originally thought that these two species were part of the ectoparasitoid complex of southern Alberta (and northwestern North America), it now appears that these species may not have established outside the original release areas, if at all. It is presently unclear which ectoparasitoid species attacking the weevil are native to North America and which species may have been intentionally or accidentally introduced from Europe. Of particular interest are the most abundant parasitoids (*N. duplicatus*, *Trichomalus* sp., *Chlorocytus* sp., and *Pteromalus* sp.); however, almost certainly several of the species found attacking the weevil in low numbers are native to North America and have become opportunistic on the cabbage seedpod weevil.

A concerted effort was made in 2003 to collect biological information concerning the overwintering and spring emergence biology of the ectoparasitoids of the cabbage seedpod weevil; however, few specimens were collected. Although a few specimens were collected for three of the parasitoids (*E. albitarsis*, *M. bruchophagi* and *Pteromalus* sp.) no specimens of the species that most frequently attack larvae of *C. obstrictus* were collected (*Trichomalus* sp., *N. duplicatus*, *Chlorocytus* sp.). The specimens that were collected emerged from early

May (*E. albitarsis*) until early July (*M. bruchophagi*) from intermediately sheltered to fully sheltered sites in shelterbelts and farm yards. Based on these collections, and the collection of many closely related species (but not relevant to this project), it is likely that the species attacking the cabbage seedpod weevil overwinter as adults and emerge from sheltered areas starting in May. This is supported by sweep net collections and limited collections from bowl traps in weedy patches early in the season. Several collections of *N. duplicatus* were made in early June from brassicaceous weed patches. Based on ectoparasitoid collections in brassicaceous weed patches it appears that these parasitoids, especially the ones which seem to be specializing on the cabbage seedpod weevil, are attracted to cruciferous plants early in the season, perhaps as a host-finding cue or perhaps as sources of nectar. Brassicaceous weed patches may therefore be important resources for these beneficial insects.

Results of the 2003 ectoparasitoid survey concurred with those of 2002, which determined that the most important ectoparasitoids in regions where the weevil is established are *Trichomalus* sp., *N. duplicatus* and *Chlorocytus* sp. These findings were also supported by several other studies conducted in southern Alberta where these three species were consistently the most abundant weevil larval ectoparasitoids, although they occurred in different proportions at different sites. However, these species only appear to be present where the weevil is well established and do not appear to have migrated to the northern portion of the range of *C. obstrictus* in Alberta. Three species were widespread throughout the range of the weevil: *Conura albifrons* (Walsh), *Conura torvina* (Cresson), and *Pteromalus* sp. It is likely that these species existed in these areas before the arrival of the weevil and have switched hosts to become opportunistic on *C. obstrictus*. For example, *C. albifrons* and *C. torvina* have been previously reared from diamondback moth, *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) in Alberta (Braun et al. 2003). All of the 12 ectoparasitoid species that were collected in 2002 were again found in 2003 with the exception of *L. maculatus*. However, this species was not very abundant in 2002 and it is likely that it still exists in low numbers but was not collected in 2003.

In the study designed to investigate the relative susceptibilities of six *Brassica* species to the incidence of ectoparasitism of weevil larvae, weevil larvae on all six host plant species

were parasitized. Although fewer parasitoids were found on the more resistant host plants, rates of parasitism were similar on all species. Weekly collections of pods during this study also showed that different ectoparasitoid species may be attacking the weevil at different times. Of the three most abundant parasitoids, *N. duplicatus* attacked weevil larvae earlier in the season than did *Trichomalus* sp. and *Chlorocytus* sp., and emergence by *N. duplicatus* ended up to two weeks earlier than for *Trichomalus* sp. Although *Trichomalus* sp. was the most abundant parasitoid on all plant species in this study, there appeared to be some discrimination between host plant species and the associated parasitoid complex. *Necremnus duplicatus* was relatively more abundant on *B. rapa* than on *B. napus*, but *Trichomalus* sp. and *Chlorocytus* sp. were equally abundant on both host plant species. This may be a result of the relatively early maturity of *B. rapa* combined with the apparent earlier activity of *N. duplicatus*.

Ectoparasitoids of *C. obstrictus*, whether they are introduced or native, appear to be well established and occur throughout the range of the weevil in Alberta. In areas where the weevil has been established for several years (southern Alberta), the rate of parasitism was approximately 5% (range = 1 to 8.3% in 2003). These rates are not sufficiently high to control the weevil but are significant and comparable to the rates of 7 to 14% reported in Idaho in the early 1990's (Harmon and McCaffrey 1991).

In Europe, ectoparasitism rates of 80% and greater have been reported on larvae of the cabbage seedpod weevil (Alford 2003). It is unclear whether the ectoparasitoid species currently inhabiting cropland in western Canada are capable of attaining such levels of control, or whether the climatic conditions here will facilitate or hamper their effectiveness. Nevertheless, it is evident that ectoparasitoids hold much promise for the biological control *C. obstrictus* in western Canada. At the extremities of the range of the cabbage seedpod weevil, parasitism rates are low and appear to be predominantly a result of generalist and opportunistic species. It is probable that over time migrations of the most effective species of weevil larval ectoparasitoids will continue to follow the range expansion of *C. obstrictus*, resulting in improved biological control of this important pest of canola.

Studies on natural enemies of cabbage seedpod weevil indicate that the braconid, *M. melanopus*, is not likely to have an extensive role in the biological control of cabbage seedpod weevil since its populations appear to be quite variable from year to year, and the species has not yet become abundant at any site. On the other hand, species of larval ectoparasitoids, primarily in the hymenopteran families Pteromalidae and Eulophidae, appear to hold good potential for biological control of the weevil. These individuals are relatively abundant, widespread, and appear to be effective in attacking weevil hosts.

Objective 5. Determining the Overwintering Biology of Lygus Bugs and Cabbage Seedpod Weevil

The first study examining habitats utilized by overwintering lygus bugs and cabbage seedpod involved a variety of insect collecting methods employed in late fall and early spring. Collection methods used to determine location and relative abundances of overwintering weevils and lygus bugs were changed to provide more economical and relevant insect data in 2002. Preliminary results from Lethbridge in 2001 indicated manual sorting of soil cores collected from overwintering habitat sites required large amounts of time but yielded few specimens. No lygus bugs were collected in litter and soil samples (25 cm x 25 cm) collected from the field on 15 November 2001, 26 February 2002, or 15 May 2002. The pitfall traps proved to be more economical and yielded more suitable sample sizes of insect specimens. In 2002 and 2003, manual sorting of soil cores was replaced by pitfall trapping of weevils and lygus bugs in Lethbridge and lygus bugs in Beaverlodge.

Very few lygus bugs were retrieved from emergence cages set in the various habitats late in the fall and monitored the following spring. Very low numbers of lygus bugs were collected with either emergence cage or pitfall trap collection methods at Lethbridge in 2001 and 2002 (Fig. 44A) while zero lygus bugs were collected at Beaverlodge using both emergence cage and pitfall trap methods over the same years. At Lethbridge, only five lygus bugs were collected in emergence cages and 12 in the pitfall traps. All five bugs collected from emergence cages were found in the tree shelter habitats. However, six of the 12

specimens from pitfall traps came from alfalfa habitats, four from shelters and two from ditches.

For lygus bugs, data from emergence cages should be considered more definitive than pitfalls because of the possibility of dispersal in search of early spring hosts and subsequent falling into pitfall traps. Only one of the six lygus bugs found in pitfall traps was found in the first two weeks of trapping from mid-April to early May. In 2003 considerably more lygus bugs were collected in pitfall traps than in previous years with 6 to 8 bugs collected in weeds and alfalfa (Fig. 45). Pan traps were more effective for monitoring early spring activity of lygus bugs than pitfall traps. Although pitfall trap catches suggested higher activity of lygus bugs in weeds and alfalfa than in shelters, these results likely reflect availability of feeding hosts rather than a preference for a specific overwintering habitat.

Both emergence cage and pitfall trapping data suggest that cabbage seedpod weevils were more likely to overwinter in tree shelters than in any of the other three habitats studied in Lethbridge (Fig. 44B). Twenty of the 24 weevils collected came from emergence cages positioned within tree shelters, three from ditches, and one from alfalfa. The distribution of weevils collected from pitfall traps also favored the tree shelters: 58 weevils were collected in pitfall traps positioned in caragana shelters, five from alfalfa, three from cottonwood forests, and two from ditches. In 2002 weevils were found only in the tree shelters but at less than 0.2 individuals per trap (Fig. 46). In 2003, weevil abundance per trap was too low to draw any conclusions about overwintering habitats.

In Lethbridge, insect abundance in 2002 from both pitfall traps and emergence cages confirmed data obtained in 2001 which indicated that cabbage seedpod weevil adults are more abundant in tree shelters than in ditches, alfalfa, or forest patches in the river valley (Fig. 46). Lygus bug numbers were very low in 2002 from both cages and pitfall traps. Only cages in the tree shelters caught bugs, suggesting that this is their preferred overwintering site. The absence of lygus bugs in overwintering habitats at Beaverlodge was not expected given that identical trapping methods employed at Lethbridge yielded bugs. All traps were in good condition, caught spider and fly species, yet no lygus bugs were retrieved in the spring of 2001 or 2002 at Beaverlodge.

The second study determined overwintering survivorship under field conditions and employed nylon microcosm cages stocked with field-collected adult lygus bugs at Beaverlodge and cabbage seedpod weevils at Lethbridge. Nylon microcosm cages stocked with adult lygus bugs were buried in the field from late fall to early spring between 2001 and 2004. At Beaverlodge, microcosm cages were buried in a field plus adjacent margin habitat at two sites between 2001 and 2004. Refer to Table 10 for vegetative description of habitats. In the late fall of 2001 a total of six microcosm cages prepared with field-collected *Lygus keltoni* were buried in the field and margin at Site 1 while a total of three microcosm cages similarly prepared were buried at Site 2. In the fall of 2002 and 2003, 10 microcosm cages prepared as above were buried in the field plus adjacent margin at both Sites 1 and 2.

The overwintering survivorship of lygus bugs placed within microcosm cages in the field and retrieved throughout the winter varied by year and by site at Beaverlodge. In 2001-2002, overwintering survivorship of lygus bugs within microcosms in the field was relatively high with average survivorship of 78% at Site 1 and 80% at Site 2. All 10 bugs were retrieved in only three cages, however, the apparent disappearance of individuals is believed to be attributable to death and decomposition rather than escape of individuals from cages. With the exception of two microcosm cages, no less than seven out of 10 lygus bugs per cage were alive 24 h at room temperature following retrieval from the field (Fig. 47) and corresponds to a winter of continuous snow cover in the field and margin habitats at both sites throughout the winter (Fig. 48). The high survivorship of bugs indicated microcosm cages were suitable overwintering sites for lygus bugs since live individuals were recovered. More importantly, the relatively high survivorship in the field and adjacent margin at both sites suggests either overwintering habitats at both sites were equally favorable for lygus bug overwintering in the first winter studied.

In the late fall of 2002 and 2003, it was possible to prepare a greater number of microcosm cages for burying in the two sites and respective field and margin habitats. Data collected from the first winter confirmed microcosm cages were suitable to study lygus bug overwintering since an average 83% of bugs caged were recovered and high proportions of those caged bugs survived the winter. Therefore, retrieval of microcosm cages was delayed

in the second and third winter studied and cages were left in the field from late-October until February, March, and April of 2003 and again in 2004. Unlike the winter of 2001-2002, lygus bug overwintering survivorship was generally lower in cages for the successive two winters (Figs. 49, 50); greater numbers of caged lygus bugs were dead following retrieval from the field and exposure to room temperature for 24 h. More specifically, low survivorship (mean of 21% survivorship per cage) was observed in cages retrieved from Site 1 in February, March, and April of 2003 at Beaverlodge (Fig. 49A). Similarly, low survivorship (mean of 42% survivorship of adults per cage) was observed in microcosm cages positioned in Site 2 through February, March, and April of 2003 (Fig. 49B). Assuming unaccounted for or missing adults were dead and decomposed, lygus bug mortality was very high during the second winter.

High mortality of lygus bugs in microcosm cages in the winter of 2002-2003 corresponded with a winter commencing with a wet fall combined with repeated freeze-thaw events which resulted in cages being frozen solidly to the ground in February and March 2003. Additionally, there was little snow cover until January 2003 (Fig. 51). The absence of snow on the ground left microcosm cages exposed to cold temperatures, wind and desiccation. Interestingly, lygus bug mortality did not correspond to the number of days individuals were overwintering and exposed to the cold. Rather, lygus bug survivorship was highest in microcosm cages overwintering until 22 April 2003 compared to those retrieved earlier during the winter (Fig. 49A). Poor overwintering survivorship of lygus bugs within microcosm cages in the second winter corresponded with low levels of snow on the ground from October 2002 to mid-January 2003. The absence of an insulative snow layer resulted in colder temperatures in the soil profile within the leaf litter (0 cm) and soil (-4 cm) (Fig. 52), but is also expected to have contributed to desiccation of overwintering bugs since the microcosms would be more exposed to wind during the winter months studied in the second winter at Beaverlodge.

Survivorship of overwintering *L. keltoni* decreased as the 2003-2004 winter progressed at Beaverlodge yet mortality again corresponded to low snow cover, as occurred in the previous winter. Results from microcosm cages placed in overwintering habitats in

late-October 2003 and retrieved on 9 February 2004 revealed that *L. keltoni* overwintering within the field, as opposed to the margin, experienced higher survivorship during the third winter at Beaverlodge (Fig. 53). Of the cages retrieved on 9 February 2004, a mean 75% of *L. keltoni* overwintering within microcosm cages positioned in the field survived after 24 h at room temperature compared to a mean 58% of *L. keltoni* overwintering within the margin of both Sites 1 and 2. The comparatively high survivorship of overwintering bugs within the field versus margin corresponds with the discrepancy between snow depth wherein snow depth was higher in the field compared to margin at both Sites 1 and 2 throughout the winter (Fig. 54). However, by 21 April 2004 overwintering survivorship of *L. keltoni* was lower compared to that observed earlier in the winter on 9 February 2004 (Fig. 50). By late into the winter, the survivorship of caged *L. keltoni* dropped to a mean of 34% for individuals overwintering within the field and to 40% for those overwintering within the margin. The reduction in survivorship late in the winter corresponds with only trace amounts of snow on the ground by the thirteenth week of 2004 (22-26 March) (Fig. 54) and cool soil temperatures (Fig. 53) which was quickly followed by warmer temperatures observed from the fourteenth (29 March to 2 April) to sixteenth week of 2004 (12 to 16 April). The warming trend may have stressed the caged *L. keltoni* or the inability of caged individuals to commence foraging to sustain themselves during the warm days may have contributed to the low survivorship observed by 21 April 2004 at Beaverlodge.

At Lethbridge, four microcosm cages containing weevils and four containing lygus bugs were retrieved from the tree shelter near the Lethbridge Research Centre on 9-10 January 2002. The average survivorship was 77% for weevils (Fig. 55A) and 80% for lygus bugs (Fig. 55B). Gravimetric determination of soil moisture, included in these figures, showed a water content of about 25 to 30% inside and outside the microcosms. A few dead cabbage seedpod weevils had evidence of fungal mycelia growing on them despite autoclaving the soil prior to starting the experiment. This observation prompted an attempt to quantify the impact of a fungal pathogen, *Beauvaria bassiana*, on weevil survivorship. However, the results were inconclusive as only the 2003 data suggested that this pathogen was able to reduce weevil survivorship but only to those individuals overwintering under a

tree shelter. In the alfalfa, a more open site, weevil survivorship was low in 2003, regardless of fungal sport treatment (Fig. 56 A). In 2004, weevil survivorship was less than 20% in both habitats and was not affected by the application of the fungal pathogen (Fig. 56B). Overall, overwintering survivorship decreased dramatically from 52% in 2002 to less than 25% in 2003 and 2004 (Figs. 55, 56).

In the parallel laboratory overwintering study, survivorship of weevils at -5°C was near zero following eight weeks of incubation during 2003 and 2004, in contrast to 2002 when 50% or more survived this treatment. It is noteworthy that 70 to 100% of the weevils survived the +5°C treatment for eight or 18.5 weeks (Fig. 57). Alternating temperatures every week had little (Fig. 57 A) or no impact (Fig. 57 C) on weevil survivorship. These results reveal why the weevils overwinter well near Lethbridge despite the Chinook conditions that fluctuate between cooler and warmer temperatures during the winters in southern Alberta.

The third study examined cold-hardiness of cabbage seedpod weevils and lygus bugs. Many insects behaviorally adapt or physiologically to accommodate cold temperatures occurring in temperate climates. Supercooling temperatures indicate the temperature at which the insect freezes causing death. Results from field-overwintering weevils and lygus bugs revealed that laboratory temperatures of -6 to -7°C and ranging between -10 to -18°C, respectively, were lethal to these canola pests. Lygus bug and weevil survivors from the overwintering survivorship study conducted in the field described above were used to determine their supercooling temperature, a measure of their cold-hardiness (Fig. 58). Overwintering weevils and *Lygus* species were retrieved from the field in January 2002 then supercooling temperatures were determined for individuals. The cabbage seedpod weevils died at temperatures of –6 to –7 °C (n = 10 for each sex). The retrieved lygus bugs exhibited supercooling temperatures ranging between –10 to –18 °C, depending on the species; however, sample sizes were only one to two bugs for each sex. Additional samples could not be processed because of equipment breakdown. These measurements are in agreement with those taken in previous years and were supported by additional supercooling point data collected from lygus bugs surviving the 2002-2003 winter within microcosm

cages at Beaverlodge. Any lygus bug surviving from the 10 March 2003 retrieval was shipped to Lethbridge where the supercooling temperatures of individuals were determined. With the exception of one individual, male and female *Lygus borealis*, *L. keltoni*, and *L. elisus* individuals did not freeze and die until -11°C and many failed to freeze and die until -15°C (Fig. 59). Results from supercooling temperatures indicate that the three species of *Lygus* present in the Peace River region are capable of physiologically accommodating or tolerating temperatures well below 0°C to -11 or even -14°C. Microclimate data collected in 2001 from Beaverlodge indicate that, under cover of snow, temperatures dropped to -14°C at the soil/litter interface and down to -12°C at 4 cm below the soil surface. These microclimatic measurements correspond to the supercooling temperatures observed for lygus bugs and suggest that, while these bugs cannot physiologically survive temperatures at or below -16°C, temperatures at or just below the soil level under snow cover are likely tolerable and survivable.

Preliminary data collection was initiated during the winter of 1999 and 2000 in Beaverlodge for the fourth study involving collections of environmental data at suspected lygus bug and cabbage seedpod weevil overwintering sites. These data are being organized for comparison with data collected during the winters of 2001-2002, 2002-2003, and 2003-2004. In November 1999, temperature probes were placed in a headland or margin area which was suspected to fit lygus bug overwintering habitat. Individual temperature probes were positioned at five heights in this poplar-dominated margin (150 cm, 4 cm, 0 cm, -4 cm, and -8 cm from the soil/litter interface). Temperature data were recorded hourly from 10 November 1999 until 8 May 2000 (Fig. 60). Similarly, in November 2000, temperature data were collected from two sites within field and adjacent margin areas. Temperature probes were positioned at Site 1 at two heights (-4 cm and 0 cm from the soil/litter interface) in both the field (refer to Table 10 for vegetation details) and adjacent margin area. Temperature probes were positioned similarly at Site 2. Temperature data were collected from Sites 1 and 2 at hourly intervals from 2 November 2000 until 21 May 2001 (refer to Fig. 61 for mean daily temperature data).

In October 2001, 2002, and 2003, temperature data were collected from two sites within field and adjacent margin areas. Temperature probes were positioned at Site 1 at two heights (-4 cm and 0 cm from the soil/litter interface) in both the field and adjacent field margin area. Temperature probes were positioned similarly at Site 2. Results from three winters of temperature data collection at the microhabitat level suggest that insects that overwintering within the leaf litter or slightly below the soil surface level are insulated against the cold and are likely to tolerate and survive based comparison of supercooling temperatures observed for field-overwintering lygus bugs and weevils to microhabitat temperatures recorded at Beaverlodge hourly and expressed as daily mean temperatures by each week of the year sampled starting in fall of 2001 and ending in spring 2004 (Figs. 62, 52, 53). Maximum and minimum temperatures observed within microhabitats at or slightly below the soil level at Beaverlodge for the winters of 2001-2002, 2002-2003, and 2003-2004 are noteworthy (Figs. 62, 52, 53) since minimum temperatures are within the -10 to -18°C range of supercooling values observed for lygus bugs. During the three winters studied at Beaverlodge it is particularly noteworthy that minimum temperatures in either the leaf litter or four centimeters deep in the soil profile failed to consistently reach -5°C for prolonged periods and that temperatures varied between sites at Beaverlodge. These results suggest that overwintering habitats do exist for weevils currently present in Lethbridge, Alberta, and certainly native species of lygus bugs in the Peace River region.

At Lethbridge, a weather station was placed at the tree shelter where the survivorship study was undertaken (2001-2004), and at an alfalfa field about 2 km east of the shelter (2002-2004). Hourly temperature readings were recorded from the air, litter, and soil. Figs. 63 and 64 indicate that, despite air temperatures below –20°C, the soil temperature seldom reached –6°C and the leaf litter was also quite mild at the tree shelter. Snow depths were measured weekly and varied from 0 to 17 cm, depending on microcosm position. Survivorship of insects was not related to snow cover during this period but it may be more important if the winter gets colder. In 2002-2003 a second weather station was added to compare microclimatic temperatures to that of the tree shelter. Because of equipment malfunction at the alfalfa field in the middle of winter, limited data are available.

Nevertheless, the more open alfalfa field appears less capable of buffering very low air temperatures. During the cold periods in late November and December 2002, temperatures dropped only to -2°C in the tree shelter yet reached -4°C at the alfalfa field (Fig. 63). In early January 2004 temperatures dipped below -9°C at the alfalfa but were over -7°C at the tree shelter (Fig. 64). This temperature, however, is below the average supercooling temperature observed for weevils and may explain the poor survivorship at both sites. Although, in years of milder winter temperatures, the more buffered microclimate available within tree shelters in southern Alberta may increase weevil survivorship as noted in 2002 and 2003.

Conclusions and Research Impact

Three years of study have been completed toward developing an integrated management strategy of cabbage seedpod weevil, and to determine aspects of the overwintering biology of lygus bugs and cabbage seedpod weevil. The study has important implications for the canola industry in western Canada; these are summarized below.

- Host plant resistance research has determined that genetic sources of resistance to infestation by cabbage seedpod weevil exist within Brassicaceae. Of the species evaluated, *Crambe abyssinica*, *Sinapis alba*, *Brassica nigra*, and *Brassica carinata* are most resistant to attack by this pest. Resistance in *C. abyssinica* to attack by the weevil is of academic rather than practical interest because this species cannot be crossed with *B. napus*. However, resistance in *S. alba*, *B. carinata,* and *B. nigra* are of considerable interest because these species can now be used as sources of resistance in breeding programs to develop weevil-resistant canola. Germplasm development research has been initiated to incorporate resistance genes from these species into elite genotypes of *B. napus*.

- Intergeneric hybrid accessions, developed by performing crosses of *S. alba* x *B. napus*, and then backcrossing the progeny for several generations, had variable levels of resistance to cabbage seedpod weevil. Fourteen accessions had superior resistance, with less than 5 of 100 pods infested by weevil, confirmed in two consecutive years of field evaluations, and these will now be used to develop gene mapping populations which can then eventually facilitate movement of resistance genes into *B. napus*.

- Interspecific hybrid accessions, developed by performing crosses of *B. carinata* x *B. napus*, and then backcrossing the progeny for several generations, also had varying levels of resistance to infestation by cabbage seedpod weevil. Four genotypes appeared to have satisfactory resistance to the weevil, and have been selected for further research. The resistance will be confirmed in an additional year of testing, and if appropriate, the germplasm will be used to develop gene mapping populations for facilitating transfer of resistance genes to commercial canola varieties.

- Manipulation of canola seeding rates and seeding dates affected infestations of cabbage seedpod weevil. Infestations were greatest at high seeding rates (5 kg per ha) and when seeding occurred in early May compared with later in May. Because seed yields were still greater for plots seeded at higher rates, growers should be advised to maintain relatively dense canola plant stands. Yields of plots seeded earlier vs. later were variable: although we sometimes obtained similar or higher yield when seeding early compared with later, in other years yields of plots seeded on the later date had improved yield over early-seeded plots. It appears that growers in regions infested annually with high populations of cabbage seedpod weevil should avoid seeding crops quite early in season because they are highly attractive to these pests.

- Planting borders of early-flowering canola around crops that flower later was successful in concentrating weevils on field edges. This then facilitated applications of insecticide on the trap crops, without requiring treatment of entire canola fields. Trap cropping can enable growers to reduce their costs, limit insecticide use, and can therefore enhance environmental sustainability.

- Hymenopteran wasp parasitoids have been found in southern Alberta that attack both the adult and larval stages of cabbage seedpod weevil. The adult weevil endoparasite, *M. melanopus*, has been found at several sites throughout southern Alberta, and approximately 13 species of weevil larval ectoparasites have also been discovered. Currently the weevil parasitoid fauna is not sufficiently abundant to cause substantial reductions in cabbage seedpod weevil infestations; however, our research suggests that numbers have been increasing over the past three years and eventually they may represent important limiting factors on cabbage seedpod weevil populations. The weevil larval ectoparasitoid fauna is currently comprised of species endemic to North America, and until the potential impact of this fauna on cabbage seedpod weevil populations is determined, it is premature to consider parasitoid introductions from Europe.

- Tree shelters were more suitable overwintering habitats for cabbage seedpod weevils than other sites evaluated. Lygus bugs survived equally well in both field and adjacent headland or margin areas that were dominated by shelterbelt or poplar tree species. Lower temperatures in the soil in open fields can explain the higher survivorship of insects in the treed habitats and the corresponding observed pattern of higher abundances in those habitats. The survivorship of cabbage seedpod weevils for extended overwintering periods (18 weeks) suggests these insects are capable of surviving in more northern latitudes. Even though air temperatures can fluctuate widely, temperatures at or beneath the soil surface do not appear to exceed -5°C, the approximate supercooling temperature for cabbage seedpod weevil. The

approximate supercooling temperature for *L. keltoni*, *L. borealis*, and *L. elisus* ranges between -10 to -18°C. Temperature data from overwintering microclimates will be used to refine models to assist in predicting potential pest infestation potential and range expansion.

Acknowledgements

We express our sincere gratitude to all agencies that provided funding for this research, including the Canola Council of Canada, the Alberta Canola Producers Commission, the Saskatchewan Canola Development Commission and the Manitoba Canola Growers Association. We also thank Agriculture and Agri-Food Canada, the University of Alberta, and Alberta Agriculture, Food and Rural Development for providing senior scientist support. For technical assistance in Lethbridge we thank Carolyn Herle, Andy Fox, Pete Conway, Nancy Cowle, Alissa Reynolds, Andrea Kalischuk, Kyle Peake, Brett Peake, Jesse Dunn, and Colin McKenzie. Gratitude is also extended to Amie Nemecz, MaryAnn Oliver, Cheryl Fletcher, Wendy Walter, and Erna Villiger for their technical support with the insect overwintering studies situated at Beaverlodge. We are grateful to Peter Mills for sharing his skills in agricultural meteorology and monitoring the lygus bug overwintering microhabitats at Beaverlodge. Special thanks are extended to B.J. Ulmer, G. Gibson, H. Goulet, and S. Shaw for assistance with identifying the weevil parasitoids. Finally, we are very grateful to Bryan Ulmer, Andy Fox, Andrea Kalischuk, and Joan Seath for their organizational assistance and help in innumerable aspects of this project.

References

Alford, D.V. 2003. Biocontrol of Oilseed Rape Pests. Blackwell Science Ltd. Malden, MA, U.S.A.

Bonnemaison, L. 1957. Le charançon des siliques (*Ceutorhynchus assimilis* Payk.) biologie et méthode de lutte. *Annales des Épiphytes* 4: 387-543.

Bousquet, Y. 1991. Checklist of beetles of Canada and Alaska. Agriculture Canada Publication 1861/E.

Brown, J., J.P. McCaffrey, B.L. Harmon, J.B. Davis, A.P. Brown, and D.A. Erickson. 1999. Effect of late season insect infestation on yield, yield components and oil quality of *Brassica napus*, *B. rapa*, *B. juncea* and *Sinapis alba* in the Pacific Northwest region of the United States. *Journal of Agricultural Science* 132: 281-288.

Buntin, G.D., J.P. McCaffrey, P.L. Raymer, and J. Romero. 1995. Quality and germination of rapeseed and canola seed damaged by adult cabbage seedpod weevil, *Ceutorhynchus assimilis* (Paykull) [Coleoptera: Curculionidae]. *Canadian Journal of Plant Science* 75: 539-541.

Buntin, G.D. 1999. Damage loss assessment and control of the cabbage seedpod weevil (Coleoptera: Curculionidae) in winter canola using insecticides. *Journal of Economic Entomology* 92: 220-227.

Canola Council of Canada. 2002. Canola Production Centres, 2001 Report. Canola Council of Canada Technical Report, Winnipeg, MB, 196 pp.

Cárcamo, H.A., L. Dosdall, M. Dolinski, O. Olfert, and J.R. Byers. 2001. The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae) – a review. *Journal of the Entomological Society of British Columbia* 98: 201-210.

Dmoch, J. 1965. The dynamics of a population of the cabbage seedpod weevil (*Ceutorhynchus assimilis* Payk.) and the development of winter rape. Part I. *Ekologia Polska Seria A* 13: 249-287.

Dosdall, L.M., and D.W.A. Moisey. 2004. Developmental biology of the cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae), in spring canola, *Brassica napus*, in western Canada. *Annals of the Entomological Society of America* 97: 458-465.

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

Dosdall, L.M., and M. G. Dolinski. 2001. Biology and control of the cabbage seedpod weevil, a new pest of canola in Alberta. Alberta Agriculture, Food and Rural Development Technical Report, 65 pp.

Dosdall, L.M., D. Moisey, H. Cárcamo, and R. Dunn. 2001. Cabbage seedpod weevil factsheet. Alberta Agriculture, Food and Rural Development Agdex 622-21, 4 pp.

Dosdall, L.M., R.W. Weiss, O. Olfert, and H.A. Cárcamo. 2002. Temporal and geographical distribution patterns of the cabbage seedpod weevil (Coleoptera: Curculionidae), a new pest of canola in western Canada. *The Canadian Entomologist* 134: 403-418.

Doucette, C.F. 1947. Host plants of the cabbage seedpod weevil. *Journal of Economic Entomology* 40: 838-840.

Fox, A. S., and L. M. Dosdall. 2003. Reproductive biology of *Ceutorhynchus obstrictus* (Coleoptera: Curculionidae) on wild and cultivated Brassicaceae in southern Alberta. *Journal of Entomological Science* 38: 533-544.

Free, J.B., A.W. Ferguson, and S. Winfield. 1983. Effect of various levels of infestation by the seed weevil (*Ceutorhynchus assimilis* Payk.) on the seed yield of oil-seed rape (*Brassica napus* L.). *Journal of Agricultural Science* 101: 589-596.

Harmon, B.L., and J.P. McCaffrey. 1991. Research Report. 50th Annual Northwest Insect Management Conference, pp.36-37.

Harmon, B.L., and J.P. McCaffrey. 1997a. Laboratory bioassay to assess *Brassica* spp. germplasm for resistance to the cabbage seedpod weevil (Coleoptera: Curculionidae). *Journal of Economic Entomology* 90: 1392-1399.

Harmon, B. L. and J. P. McCaffrey. 1997b. Parasitism of adult *Ceutorhynchus assimilis* (Coleoptera: Curculionidae) by *Microctonus melanopus* (Hymenoptera: Braconidae) in northern Idaho and eastern Washington. *Journal of Agricultural Entomology* 14: 55-59.

Jourdheuil, P. 1960. Influence de quelques facteurs écologiques sur les fluctuations de population d'une biocénose parasitaire: Étude relative à quelques Hyménoptères (Ophioninae, Diospilinae, Euphorinae) parasites de divers Coléoptères inféodés aux Crucifères. *Annales des Épiphytes* 11: 445-658.

Kalischuk, A.R., and L.M. Dosdall. 2004. Susceptibilities of seven Brassicaceae species to infestation by the cabbage seedpod weevil (Coleoptera: Curculionidae). The Canadian Entomologist 136: 265-276.

Kuhlmann, K.U., B. Klander, and T. Bauer. 1999. Cabbage seedpod weevil *Ceutorhynchus obstrictus* Colonnelli) Summary Report 1999. Technical Report CABI Bioscience Centre, Switzerland, Agriculture Section, 3 pp.

Kuhlmann, U., L. M. Dosdall, and P. G. Mason. 2002. *Ceutorhynchus assimilis* Paykull, cabbage seedpod weevil (Coleoptera: Curculionidae). *In* P. G. Mason and J. T. Huber (Eds.) Biological Control Programmes in Canada 1981-2000, pp. 52-58. CABI Publishing, Wallingford, UK.

Lerin, J. 1984. Assessment of yield loss in winter rape due to seedpod weevil (*Ceutorhynchus assimilis* Payk.) II. Yield loss in a cage experiment. *Agronomie* 4: 147-154.

Lerin, J. 1987. A short bibliographical review of *Trichomalus perfectus* Walk., a parasite of seedpod weevil *Ceutorhynchus assimilis* Payk. IOBC/WPRS Bulletin 10: 74-78.

McCaffrey, J.P., B.L. Harmon, J. Brown, A.P. Brown, and J.B. Davis. 1999. Assessment of *Sinapis alba*, *Brassica napus* and *S. alba* x *B. napus* hybrids for resistance to cabbage seedpod weevil, *Ceutorhynchus assimilis* (Coleoptera: Curculionidae). *Journal of Agricultural Science* 132: 289-295.

McLeod, J.H. 1953. Notes on the cabbage seedpod weevil, *Ceutorhynchus assimilis* Payk. (Coleoptera, Curculionidae) and its parasites. *Proceeding of the Entomological Society of British Columbia* 49: 11-18.

Prakash, S. 1974. Haploid meiosis and origin of *Brassica tournefortii* Gouan. *Euphytica* 23: 591-595.

Ripley, V.L., and P.G. Arnison. 1990. Hybridization of *Sinapis alba* L. and *Brassica napus* L. via embryo rescue. *Plant Breeding* 104: 26-33.

Salisbury, P.A. 1991. Genetic variability in Australian wild crucifers and potential utilisation in oilseed *Brassica* species. Ph.D. thesis, La Trobe University.

Singh, S.R., A. Narain, K.P. Srivastava, and J.A. Siddiqui. 1965. Fecundity of mustard aphid on different rapes and mustard species. *Indian Oilseeds Journal* 9: 215-219.

Speyer, W. 1925. *Perilitus melanopus* Ruthe (Hym. Braconidae) als imaginalparasit von *Ceutorrhynchus quadridens* Panz. *Zeitschrift für Angewandte Entomologie* 11: 132-146.

Vinson, S.B. 1970. Development and possible functions of teratocytes in the host-parasite association. *Journal of Invertebrate Pathology* 16: 93-101.

Yang, Y.W., P.F. Tseng, P. Tai, and C.J. Chang. 1998. Phylogentic position of *Raphanus* in relation to *Brassica* species based on 5S rRNA spacer sequence data. *Botanical Bulletin of Academia Sinica* 39: 153-160.

Table 1. Feeding and oviposition of cabbage seedpod weevil on various Brassicaceous species after 24 and 48 hours (n = 32 pods/species).

	After 24 h		After 48 h	
Species	**Feeding Punctures (mean ± SE)**	**Eggs (mean ± SE)**	**Feeding Punctures (mean ± SE)**	**Eggs (mean ± SE)**
B. rapa Genotype 30	5.9 ± 0.8 *a*	3.4 ± 0.6 *a*	3.1 ± 0.7 *b*	5.9 + 0.8 *a*
B. napus Genotype 84	3.7 ± 0.6 *b*	2.4 ± 0.3 *ab*	2.7 ± 0.6 *b*	3.3 ± 0.8 *ab*
B. napus x *S. alba* Genotype 101	4.3 ± 0.6 *ab*	3.1 ± 0.6 *a*	2.6 ± 0.4 *bc*	4.2 ± 1.0 *ab*
B. tournefortii	3.6 ± 0.4 *b*	1.6 ± 0.3 *b*	4.3 ± 0.6 *ab*	3.4 ± 0.4 *ab*
B. juncea Genotype 77	3.4 ± 0.3 *b*	1.4 ± 0.3 *bc*	5.8 ± 0.7*a*	2.5 ± 0.6 *bc*
B. nigra Genotype 8	3.3 ± 0.5 *b*	0.0 *c*	3.7 ± 0.5 *ab*	0.0 *c*
S. alba Genotype 97	0.1 ± 0.1 *c*	0.0 *c*	0.4 ± 0.2 *c*	0.0 *c*

ANOVA after 24 h, feeding punctures $F_{6,215}$=11.31, $P < 0.0001$; eggs $F_{6,215}$=14.36, $P < 0.0001$.
ANOVA after 48 h, feeding punctures $F_{6,217}$=9.89, $P < 0.0001$; eggs $F_{6,217}$=12.15, $P < 0.0001$.
Means in a column followed by the same letter are not significantly different (P = 0.05) using Tukey's (HSD) multiple comparisons.

Table 2. Mean canola plants per m^2 determined when plants were seedlings (first true-leaf stage) and mature (pod ripening completed), in addition to percent ground cover measured on 2 July, of plants seeded on early (early May) and normal (mid May) dates and at different rates (1, 3, and 5 kg per ha) in 2002.

Treatment	Emergence (plants per m^2)	Harvest (plants per m^2)	Ground Cover, 2 July 2002 (%)
Early Planting Date			
1 kg per ha, sprayed	19	18	85
1 kg per ha, not sprayed	16	16	85
3 kg per ha, sprayed	49	45	98
3 kg per ha, not sprayed	57	57	97
5 kg per ha, sprayed	130	110	100
5 kg per ha, not sprayed	134	121	98
Normal Planting Date			
1 kg per ha, sprayed	26	25	82
1 kg per ha, not sprayed	29	29	81
3 kg per ha, sprayed	63	60	87
3 kg per ha, not sprayed	66	65	84
5 kg per ha, sprayed	112	102	90
5 kg per ha, not sprayed	106	100	90

Table 3. Mean primary and secondary branches per plant, and pods on various branches for plants seeded on early (early May) and normal (mid May) dates and at different rates (1, 3, and 5 kg per ha) in 2002.

	Branches		Pod Distribution		
Treatment	**Primary**	**Secondary**	**Pods on Main Stem**	**Pods on Primary Branches**	**Pods on Secondary Branches**
Early Planting Date					
1 kg per ha, sprayed	9	16	43	220	218
1 kg per ha, not sprayed	9	18	45	235	270
3 kg per ha, sprayed	7	6	45	131	35
3 kg per ha, not sprayed	6	5	39	144	35
5 kg per ha, sprayed	5	1	32	56	5
5 kg per ha, not sprayed	5	1	30	50	3
Normal Planting Date					
1 kg per ha, sprayed	8	12	42	193	142
1 kg per ha, not sprayed	7	12	40	179	183
3 kg per ha, sprayed	4	3	30	67	22
3 kg per ha, not sprayed	5	4	34	78	33
5 kg per ha, sprayed	4	2	29	59	10
5 kg per ha, not sprayed	5	2	30	65	9

Table 4. Mean seed yields, contribution margins, seed oil contents, 1000-kernel weights, and growing degree days for plants seeded on early (early May) and normal (mid May) dates and at different rates (1, 3, and 5 kg per ha) in 2002.

Treatment	Yield (bu/acre)	Contribution Margin ($/acre)	Oil (%)	1000 Kernel Weight (g)	Growing Degree Days to Maturity
Early Planting Date					
1 kg per ha, sprayed	42.4	234.50	44.3	4.5	1252
1 kg per ha, not sprayed	39.5	213.60	44.3	4.6	1252
3 kg per ha, sprayed	51.4	320.15	44.3	4.4	1135
3 kg per ha, not sprayed	49.0	303.75	44.4	4.4	1135
5 kg per ha, sprayed	51.6	314.11	45.1	4.0	1135
5 kg per ha, not sprayed	49.7	302.21	44.9	4.6	1135
Normal Planting Date					
1 kg per ha, sprayed	45.5	262.40	45.0	4.1	1223
1 kg per ha, not sprayed	41.2	228.90	45.0	3.9	1223
3 kg per ha, sprayed	52.3	328.25	45.0	4.3	1196
3 kg per ha, not sprayed	47.8	292.95	44.9	4.3	1196
5 kg per ha, sprayed	57.2	364.51	45.5	4.4	1216
5 kg per ha, not sprayed	55.5	354.41	45.5	4.5	1216

Table 5. Percentages of cabbage seedpod weevil adults parasitized by *Microctonus melanopus* in stands of hoary cress (*Cardaria* sp.), flixweed (*Descurainia sophia*), wild mustard (*Sinapis arvensis*), and volunteer canola (*Brassica napus* and *B. rapa*) at Lethbridge, AB in 2001.

Host Plant	Date	% Parasitism (n = 100)
Hoary Cress, *Cardaria* spp.	22 May	0
	28 May	0
	04 June	1
	11 June	1
	18 June	6
Flixweed, *Descurainia sophia*	23 May	0
	30 May	0
	06 June	0
	14 June	4
	19 June	9
Wild Mustard, *Sinapis arvensis*	31 May	0
	08 June	2
	18 June	7
	24 June	4
	25 June	3
Volunteer Canola, *Brassica rapa* and *Brassica napus*	15 June	1
	20 June	0
	25 June	1
	04 July	0
	09 July	4

Table 6. Collection sites and parasitism of the wasp, *Microctonus melanopus*, on adults of cabbage seedpod weevil in 2002. M=male, F=female

Site	Location (°N, °W)	Host Plant	Collection Date, 2002	# of weevils dissected (% female)	# weevils with parasitoids
Lethbridge, AB	49° 41.79; 112° 46.91 (Brown Road)	wild mustard	7-Jun	59 (25)	0
			17-Jun	78 (27)	1 M with tertatocytes
			25-Jun	31 (77)	1 F with tertatocytes and larva
			12-Jul	34 (50)	0
Lethbridge, AB	Goal Rd A	wild mustard	27-Jun	50 (54)	1 F with teratocytes and larva 1 M with teratocytes and larva
Lethbridge, AB	off hwy 4	volunteer canola	20-Jun	50 (26)	1 M with teratocytes 1 F with teratocytes and larva
Lethbridge, AB	Pavan Park	flixweed/stinkweed	23-Jun	50 (40)	1 M with teratocytes
Lethbridge, AB	Hardyville	flixweed	23-Jun	50 (36)	1 M with teratocytes 1 M with teratocytes and larva
Lethbridge, AB	south of CEB	flixweed	24-Jun	29 (62)	1 F with teratocytes and larva
Lethbridge, AB	Goal Rd B	wild mustard	27-Jun	50 (38)	0
Lethbridge, AB	49° 41.21; 112° 46.86 (43rd St)	flixweed	7-Jun	100 (19)	0
			17-Jun	74 (50)	0
			20-Jun	44 (32)	0
Lethbridge, AB	26 and 43rd	flixweed	23-Jun	50 (42)	0
Lethbridge, AB	north of CEB	flixweed	25-Jun	31 (77)	0
Lethbridge, AB	49° 41.33; 112° 46.86 (43rd St)	hoary cress	7-Jun	100 (26)	0
			17-Jun	54 (41)	0
Lethbridge, AB	by Walmart	volunteer canola	20-Jun	50 (18)	0
Lethbridge, AB	49° 24.85; 112° 55.13		9-Jul	50 (50)	0
Coaldale, AB	49° 41.95; 112° 45.88	wild mustard	24-Jun	50 (42)	0
Coaldale, AB		flixweed	20-Jun	50 (36)	0
Coaldale, AB	by water pump	volunteer canola	12-Jul	50 (42)	0
Coaldale, AB	hwy 845 south	volunteer canola	12-Jul	31 (45)	0
Creston, BC	49° 06.94; 116° 34.44	canola	4-Jun	2	0
Creston, BC	49° 07.06; 116° 35.07	stinkweed	4-Jun	100 (24)	0
Creston, BC	49° 05.65; 116° 35.36	wild mustard	4-Jun	100 (35)	0
			11-Jun	100 (28)	0

Table 7. Rearing success of adults of *Microctonus melanopus* from various sites in southern Alberta and British Columbia from cabbage seedpod weevil hosts in 2002.

Site	Location	Host Plant	Collection date, 2002	Colony start date, 2002	Approximate # of weevils in colony	# wasps emerged	Date of wasp emergence, 2002
Lethbridge, AB	Pavan Park	Flixweed/ stinkweed	23-Jun	28-Jun	106	0	
Lethbridge, AB	off hwy 4	Volunteer canola	25-Jun	28-Jun	194	0	
			2-Jul	3-Jul	149	0	
Lethbridge, AB	49° 41.79; 112° 46.91	wild mustard	25-Jun	28-Jun	222	0	
			2-Jul	2-Jul	242	1 M	2-Jul
Lethbridge, AB	Hardyville	Flixweed	27-Jun	28-Jun	43	0	
Lethbridge, AB	Gaol Rd A	wild mustard	27-Jun	28-Jun	21	0	
			3-Jul	3-Jul	217	0	
Creston, BC	49° 05.65;116° 35.36	wild mustard	4-Jun	5-Jun	423	1 F	28-Jun
			5-Jul	6-Jul	100	0	
Creston, BC	49° 03.86; 116° 34.70	wild mustard	5-Jul	6-Jul	105	0	

Table 8. Percentages of pods with different life stages of cabbage seedpod weevil and its larval ectoparasites at Lethbridge, AB in 2001.

Location / Date Host Plant[†]	% Pods with weevil egg to exit hole	% Pods with weevil 3rd Instar	% Pods with parasitoid larva/pupa	% Pods with parasitoid egg
Creston, BC / 17 July Volunteer Canola	57.0	40.0	14.0	7.0
Creston, BC / 17 July Volunteer Canola	68.0	40.0	3.0	1.0
Lethbridge, AB/ 4 July Volunteer Canola	77.0	2.0	0.0	0.0
Lethbridge, AB/ 5 September Canola Control	4.0	0.0	0.0	0.0
Alberta Survey[‡] / 26 July Canola Crop	25.0	14.0	0.0	0.0
Lethbridge, AB/ 1 August Wild Mustard	13.5	3.3	0.4	0.2

[†] Samples of $n = 100$ pods except wild mustard $n = 891$

[‡] Sample with highest weevil infestation from $n = 5$ of 13 samples processed. Samples were taken from across southern Alberta.

Table 9. Larval ectoparasitoids of cabbage seedpod weevil reared from pods of *Brassica napus* and *B. rapa* collected in commercial fields at various locations in southern Alberta in 2002 and 2003.

Family Pteromalidae
- Genus *Trichomalus*
  - *Trichomalus* sp.
- Genus *Pteromalus*
  - *Pteromalus* sp.
- Genus *Lycrus*
  - *Lycrus maculatus*
- Genus *Chlorocytus*
  - *Chlorocytus* sp. 1
  - *Chlorocytus* sp. 2
- Genus *Mesopolobus*
  - *Mesopolobus morys*
  - *Mesopolobus bruchophagi*

Family Eulophidae
- Genus *Necremnus*
  - *Necremnus duplicatus*
- Genus *Euderus*
  - *Euderus albitarsis*

Family Eurytomidae
- Genus *Eurytoma*
  - *Eurytoma* sp.

Family Mymaridae
- Genus *Anaphes*
  - *Anaphes* sp. (see note below)

Family Chalcididae
- Genus *Conura*
  - *Conura torvina*
  - *Conura albifrons*

TOTAL: Approximately 13 species of ectoparasitic Hymenoptera

* Note: *Anaphes* sp. may be a parasitoid of lygus bug eggs, not cabbage seedpod weevil.

Table 10. Description of dominant vegetation within the field and adjacent margin habitats at Sites 1 and 2 utilized in overwintering studies and to collect microhabitat temperature data at Beaverlodge, Alberta from 2000-2004.

Site	Habitat	General Description	Vegetation
1	Field	Meadow	Various grass species. Not cultivated.
	Margin	Treed area	Volunteer poplar, various grass species (gone to seed). Field located to Southeast of headland or margin.
2	Field	Annual cropping area	Cereal stubble (9" row spacing). Cultivated.
	Margin	Treed area (Windbreak)	Evergreen species, elm organized into N-S transect. Field located to East of headland or margin.

Site 1: East of bee laboratory; G.P.S. values: N55° 12.170' W119° 23.467'.
Site 2: Northwest of canola building; G.P.S. values: N55° 12.261' W119° 24.044'.

Appendix 1. Minimum and maximum temperatures recorded in overwintering microhabitats at Beaverlodge, Alberta between late fall of 2001 until spring of 2002.

Site	Week of Year	Dates	Range of air temperature measured (+150 cm from soil level)	Range of FIELD temperatures measured below soil level (-4cm in soil profile)	Range of FIELD temperatures measured at soil/litter interface level (0cm in soil profile)	Range of MARGIN temperatures measured below soil level (-4cm in soil profile)	Range of MARGIN temperatures measured at soil/litter interface level (0cm in soil profile)
Site 1	44*	Oct28-Nov03	1.21 to 4.73	-0.20 to 1.77	0.40 to 2.10	-6.83 to -3.92	1.17 to 2.53
	45	Nov04-10	-3.02 to 3.45	-2.43 to 2.01	-1.23 to 1.73	-12.56 to 1.02	-0.36 to 2.39
	46	Nov11-17	-1.11 to 6.09	-2.09 to 2.20	-0.29 to 2.18	-8.46 to -0.37	0.26 to 2.71
	47	Nov18-24	-8.14 to 0.37	-2.22 to -0.65	-1.51 to -0.65	-11.06 to -4.64	-0.36 to -0.23
	48	Nov26-30	-23.22 to -13.56	-2.52 to -0.98	-1.88 to -0.68	-5.55 to -2.68	-1.63 to -0.31
	49	Dec03-08	-20.93 to 3.10	-3.28 to -1.15	-2.54 to -1.37	-6.85 to -2.72	-2.27 to -1.13
	50	Dec10-14	-15.43 to -3.35	-1.79 to -1.44	-1.45 to -1.22	-3.28 to -2.17	-1.29 to -1.13
	51	Dec17-21	-13.61 to -7.16	-3.49 to -1.61	-2.55 to -1.23	-6.05 to -2.66	-2.22 to -1.21
	52	Dec24-28	-17.85 to -2.69	-4.72 to -2.37	-3.01 to -2.17	-6.00 to -3.67	-2.88 to -1.82
	1	Dec31-Jan01	-21.98 to 1.50	-5.45 to -2.50	-3.73 to -2.16	-7.55 to -2.75	-3.68 to -2.13
	2	Jan07-11	-2.91 to 4.43	-2.39 to -0.91	-2.38 to -1.26	-5.04 to -1.83	-2.15 to -1.08
	3	Jan14-18	-9.84 to -1.85	-3.43 to -2.25	-2.38 to -1.19	-5.47 to -1.79	-2.65 to -1.49
	4	Jan21-25	-27.89 to -8.84	-5.24 to -3.46	-3.58 to -2.43	-6.57 to -4.49	-4.11 to -2.61
	5	Jan28-Feb01	-27.29 to -5.27	-5.55 to -3.51	-3.88 to -3.05	-7.04 to -4.41	-4.36 to -3.07
	6	Feb04-08	-6.61 to -0.84	-2.85 to -2.42	-2.57 to -2.21	-4.27 to -3.20	-2.51 to -2.26
	7	Feb11-15	-3.50 to 5.61	-2.45 to -0.91	-2.13 to -1.21	-4.02 to -1.51	-2.18 to -1.15
	8	Feb18-22	-15.29 to -0.18	-3.26 to -1.55	-2.09 to -1.35	-3.85 to -1.95	-2.52 to -1.37
	9	Feb25-Mar01	-17.78 to -2.66	-4.07 to -2.96	-2.63 to -2.02	-4.94 to -3.13	-3.20 to -2.53
	10	Mar04-08	-25.01 to 3.20	-4.83 to -1.69	-2.48 to -1.67	-4.49 to -1.78	-3.60 to -1.41
	11	Mar11-15	-18.64 to -12.22	-4.42 to -3.39	-2.63 to -2.24	-4.32 to -3.14	-3.60 to -2.96
	12	Mar18-22	-23.12 to -3.55	-4.75 to -3.36	-2.87 to -2.43	-4.79 to -3.76	-3.81 to -3.19
	13	Mar25-29	-7.81 to 1.41	-2.53 to -1.45	-2.20 to -1.34	-3.30 to -1.31	-2.09 to -1.67

	14	Apr01-05	-14.93 to -5.57	-2.74 to -2.02	-1.62 to -1.41	-2.44 to -1.92	-2.30 to -1.89
	15	Apr08-12	-5.70 to 6.23	-2.20 to -0.18	-1.47 to -0.21	-2.00 to -0.28	-2.05 to -0.47
	16	Apr15-19	-1.52 to 7.19	-0.35 to -0.10	-0.34 to -0.10	-0.38 to -0.17	-0.42 to -0.12
	17	Apr22-26	-3.98 to 6.15	-0.70 to -0.13	-0.39 to -0.12	-0.88 to -0.16	-0.37 to -0.12
	18	Apr29-May03	-4.56 to 12.15	-0.47 to 7.15	0.15 to 5.67	-7.48 to 1.83	0.76 to 5.05
	19	May06-10	-4.28 to 9.42	-0.15 to 4.36	0.66 to 3.88	-4.28 to 0.10	0.28 to 4.52
	20	May13-17	7.71 to 15.65	3.67 to 8.83	4.67 to 8.10	-3.40 to 3.37	4.81 to 8.02
	21	May20-24	5.45 to 12.63	3.75 to 6.50	5.19 to 7.43	0.07 to 5.72	4.98 to 7.96
	22	May27-31	11.31 to 16.21	7.15 to 10.07	8.18 to 9.76	-2.46 to 4.43	8.73 to 9.90
	23‡	Jun02-08	12.50 to 16.99	8.18 to 10.65	9.58 to 10.49	-0.35 to 6.00	9.80 to 10.72
Site 2	44*	Oct28-Nov03	1.33 to 4.36	-0.46 to 1.64	-0.30 to 0.42	-2.77 to -1.13	1.49 to 2.59
	45	Nov04-10	-2.53 to 3.50	-4.82 to 2.11	-2.37 to -0.18	-5.15 to -0.08	-0.29 to 2.46
	46	Nov11-17	-1.53 to 5.87	-4.26 to 2.24	-1.89 to 0.86	-4.67 to -0.04	0.29 to 2.66
	47	Nov18-24	-3.85 to 1.49	-4.01 to 5.50	-2.68 to 5.61	-5.46 to -1.27	-0.43 to 7.67
	48†	Nov26-30	-14.92 to -1.97	No data	No data	No data	No data
	49†	Dec03-08	-10.82 to 11.31	No data	No data	No data	No data
	50†	Dec10-14	-0.49 to 11.08	-1.54 to 6.76	-0.40 to 8.42	No data	-0.42 to 8.54
	51†	Dec17-21	2.48 to 11.10	-6.10 to 7.89	-5.01 to 11.32	No data	-4.46 to 10.91
	52†	Dec24-28	-6.05 to 7.45	-2.61 to 7.81	-2.05 to 14.08	No data	-2.18 to 12.46
	1†	Dec31-Jan01	-13.12 to 6.28	No data	No data	No data	No data
	2†	Jan07-11	-2.01 to 9.34	-2.48 to -1.00	-2.18 to -1.56	No data	-2.61 to -1.42
	3	Jan14-18	0.38 to 0.38	1.52 to 1.52	4.01 to 4.01	-1.78 to -1.78	3.91 to 3.91
	9	Jan21-25	-17.14 to -5.05	-4.02 to -3.43	-1.83 to -1.81	-2.12 to -2.12	-3.09 to -2.98
	10	Jan28-Feb01	-23.51 to 2.01	-5.85 to -2.08	-2.39 to -1.65	-2.79 to -1.84	-4.64 to -2.19
	11	Feb04-08	-18.72 to -12.89	-5.23 to -4.07	-2.36 to -1.94	-2.68 to -1.99	-4.34 to -3.55
	12	Feb11-15	-21.62 to -3.43	-5.74 to -3.83	-2.32 to -2.09	-2.63 to -2.17	-4.76 to -3.79
	13	Feb18-22	-7.56 to 1.08	-2.97 to -1.86	-1.89 to -1.26	-2.18 to -1.28	-3.12 to -2.10
	14	Feb25-Mar01	-14.82 to -7.01	-3.59 to -2.50	-1.46 to -1.33	-1.57 to -1.31	-3.02 to -2.30
	15	Mar04-08	-5.97 to 6.07	-2.73 to -0.12	-1.33 to -0.18	-1.39 to -0.19	-2.57 to -0.10
	16	Mar11-15	-2.49 to 7.79	-0.23 to -0.08	-0.30 to -0.12	-0.29 to -0.15	-0.21 to -0.06
	17	Mar18-22	-4.86 to 5.47	-1.86 to 0.30	-0.35 to -0.10	-0.32 to -0.17	-0.25 to -0.03

18	Mar25-29	-5.56 to 11.79	-2.96 to 7.32	-0.16 to 5.76	-2.18 to 0.35	-0.10 to 4.02
19	Apr01-05	-5.12 to 8.69	-0.28 to 3.24	-0.23 to 5.53	-1.67 to 1.20	-0.11 to 3.22
20	Apr08-12	7.13 to 15.72	1.96 to 9.09	5.01 to 10.90	-0.02 to 4.21	3.96 to 6.47
21	Apr15-19	4.98 to 12.06	2.29 to 6.66	4.90 to 9.09	2.36 to 7.07	4.30 to 7.17
22	Apr22-26	11.27 to 15.94	6.08 to 10.26	9.76 to 12.75	2.96 to 7.59	7.79 to 9.41
23‡	Apr29-May03	11.83 to 16.93	6.85 to 11.84	10.42 to 15.00	5.37 to 9.26	9.13 to 10.08

* n = 5 days.

† Inaccurate data collected due to technical problems with datalogger from Week 48 to Week 2 inclusive.

‡ n = 4 days.

Appendix 2. Minimum and maximum temperatures recorded in overwintering microhabitats at Beaverlodge, Alberta between late fall of 2002 until spring of 2003.

Site	Week of Year	Dates	Range of air temperature measured (+150 cm from soil level)	Range of FIELD temperatures measured below soil level (-4cm in soil profile)	Range of FIELD temperatures measured at soil/litter interface level (0cm in soil profile)	Range of MARGIN temperatures measured below soil level (-4cm in soil profile)	Range of MARGIN temperatures measured at soil/litter interface level (0cm in soil profile)
Site 1	44*	Oct27-Nov02	-2.02 to 13.20	-0.55 to -0.39	-2.15 to -1.79	0.02 to 0.43	-1.77 to -0.69
	45	Nov03-09	-11.42 to 4.97	-0.69 to 0.53	-1.71 to 0.24	-0.10 to 0.93	-1.26 to 0.48
	46	Nov10-16	-11.06 to -0.03	-0.21 to -0.03	-0.75 to -0.25	0.24 to 0.44	-0.62 to -0.07
	47	Nov 17-23	-5.79 to 6.09	-0.40 to 1.07	-1.79 to 1.09	0.07 to 2.10	-1.84 to 1.98
	48	Nov24-30	-2.77 to 9.98	-0.82 to 0.34	-2.68 to 1.91	-0.16 to 1.28	-2.12 to 2.78
	49	Dec01-07	-9.25 to 5.68	-2.61 to -0.01	-4.63 to -0.22	-1.20 to 1.48	-3.70 to 0.31
	50	Dec08-14	-1.87 to 2.71	-1.74 to -0.69	-2.82 to -0.55	-0.79 to -0.34	-2.09 to -0.35
	51	Dec15-21	-13.47 to -1.20	-5.16 to -1.29	-7.29 to -1.52	-3.20 to -0.73	-6.12 to -1.14
	52	Dec22-28	-11.04 to -2.34	-6.85 to -3.87	-9.23 to -4.31	-4.50 to -2.59	-7.47 to -3.19
	1	Dec29-Jan04	-14.85 to -0.84	-7.93 to -3.23	-10.43 to -3.62	-5.32 to -2.24	-8.52 to -2.71
	2	Jan05-11	-18.18 to 10.45	-8.40 to -0.87	-10.84 to -0.34	-6.32 to -0.64	-9.69 to 0.17
	3	Jan12-18	-19.47 to 0.70	-6.79 to -3.12	-8.71 to -3.29	-5.50 to -2.37	-6.61 to -2.46
	4	Jan19-25	-28.12 to -7.10	-4.20 to -3.46	-4.69 to -3.77	-3.72 to -2.77	-4.51 to -3.21
	5	Jan26-Feb01	-18.57 to 1.28	-3.34 to -2.40	-3.60 to -2.47	-3.17 to -2.17	-3.60 to -2.26
	6	Feb02-08	-6.91 to -0.59	-2.39 to -1.99	-2.59 to -2.12	-2.16 to -1.71	-2.42 to -1.85
	7	Feb09-15	-12.32 to 0.23	-2.31 to -1.83	-2.60 to -1.89	-2.07 to -1.54	-2.47 to -1.60
	8	Feb16-22	-20.35 to -8.92	-2.81 to -2.11	-3.18 to -2.43	-2.73 to -1.99	-3.27 to -2.34
	9	Feb23-Mar01	-22.19 to -1.41	-2.82 to -1.81	-3.26 to -2.10	-2.72 to -1.82	-3.36 to -2.07
	10	Mar02-08	-30.68 to -3.67	-3.42 to -2.13	-3.98 to -2.27	-3.42 to -2.05	-4.26 to -2.22
	11	Mar09-15	-27.60 to -7.83	-3.54 to -2.70	-4.04 to -2.97	-3.61 to -3.07	-4.32 to -3.41
	12	Mar16-22	-5.29 to 3.46	-2.53 to -0.76	-2.73 to -0.90	-2.89 to -1.04	-3.12 to -0.56

	13	Mar23-29	-3.89 to 2.33	-0.86 to -0.33	-1.14 to -0.27	-1.00 to -0.40	-0.79 to -0.11
	14	Mar30-Apr05	-7.23 to 5.94	-0.44 to -0.21	-0.40 to -0.18	-0.40 to -0.16	-0.44 to -0.19
	15	Apr06-12	-3.31 to 5.45	-0.31 to -0.18	-0.28 to -0.17	-0.25 to -0.14	-0.28 to -0.17
	16	Apr13-19	0.80 to 5.70	-0.33 to -0.19	-0.28 to -0.18	-0.25 to -0.15	-0.32 to -0.16
	17	Apr20-26	2.25 to 9.59	0.07 to 3.78	0.24 to 4.26	0.31 to 3.29	-0.13 to 4.43
	18	Apr27-May03	-2.94 to 9.93	1.84 to 5.18	0.24 to 3.58	1.54 to 4.94	0.08 to 3.85
	19	May04-10	-1.59 to 9.74	2.32 to 6.00	0.45 to 3.86	1.60 to 5.66	0.26 to 4.50
	20	May11-17	3.37 to 13.10	4.04 to 6.96	1.15 to 5.53	4.35 to 6.73	1.29 to 6.48
	21	May18-24	8.11 to 18.73	5.84 to 11.42	2.60 to 12.33	5.39 to 10.45	3.18 to 12.84
	22‡	May24-31	11.91 to 16.45	8.95 to 10.78	6.08 to 10.02	8.92 to 9.99	7.46 to 10.20
Site 2	44*	Oct27-Nov02	-0.47 to 0.69	-2.89 to -2.34	-3.16 to -2.75	-0.41 to -0.31	-1.85 to -1.56
	45	Nov03-09	-11.86 to 4.96	-2.26 to -0.01	-2.43 to -0.07	-0.70 to 2.05	-2.23 to 2.07
	46	Nov10-16	-11.25 to 0.58	-0.96 to -0.20	-1.70 to -0.31	-0.56 to 0.28	-2.60 to -0.08
	47	Nov 17-23	-5.20 to 6.35	-2.82 to 0.01	-4.55 to 0.64	-0.49 to 2.66	-3.54 to 3.82
	48	Nov24-30	-2.62 to 9.62	-4.38 to 0.00	-6.07 to 2.01	-0.76 to 2.21	-2.94 to 5.12
	49	Dec01-07	-8.61 to 5.51	-8.11 to -0.39	-9.00 to -0.65	-2.60 to 1.64	-5.40 to -0.39
	50	Dec08-14	-1.05 to 3.59	-4.62 to -2.09	-4.86 to -1.41	-0.75 to -0.30	-2.58 to 0.70
	51	Dec15-21	-12.50 to -1.02	-12.01 to -2.94	-13.21 to -2.86	-4.67 to -0.65	-9.78 to -1.06
	52	Dec22-28	-9.96 to -0.84	-12.98 to -7.15	-14.25 to -6.80	-5.95 to -3.16	-10.36 to -3.76
	1	Dec29-Jan04	-13.89 to -0.01	-14.14 to -5.22	-15.27 to -5.23	-7.06 to -2.32	-11.86 to -2.54
	2	Jan05-11	-17.97 to 11.39	-14.74 to -2.33	-16.55 to -1.83	-8.46 to -0.14	-14.98 to 3.36
	3	Jan12-18	-19.59 to 1.16	-11.83 to -5.47	-12.11 to -5.57	-7.69 to -0.28	-12.25 to -2.10
	4	Jan19-25	-26.25 to -6.84	-6.17 to -5.24	-6.39 to -5.35	-5.42 to -3.54	-8.01 to -5.38
	5	Jan26-Feb01	-18.62 to 0.95	-4.90 to -3.68	-4.97 to -3.70	-4.05 to -0.60	-5.17 to -2.58
	6	Feb02-08	-5.19 to 0.13	-3.69 to -3.11	-3.74 to -3.13	-2.58 to -0.24	-2.99 to -2.01
	7	Feb09-15	-12.52 to 0.02	-3.59 to -2.87	-3.41 to -2.88	-2.71 to -0.06	-3.63 to -1.80
	8	Feb16-22	-20.49 to -8.77	-3.75 to -3.18	-3.73 to -3.09	-3.93 to -0.81	-5.41 to -3.63
	9	Feb23-Mar01	-20.30 to -0.97	-3.98 to -2.72	-3.95 to -2.74	-4.08 to -2.49	-5.64 to -2.83
	10	Mar02-08	-29.23 to -3.97	-4.35 to -2.97	-4.54 to -2.97	-4.56 to -2.60	-6.38 to -2.98
	11	Mar09-15	-25.77 to -7.02	-4.41 to -3.59	-4.54 to -3.67	-4.55 to -3.30	-6.34 to -3.76
	12	Mar16-22	-4.98 to 3.80	-3.45 to -1.37	-3.50 to -1.48	-3.10 to -0.52	-3.38 to -0.21

13	Mar23-29	-3.04 to 2.45	-1.47 to -0.31	-1.19 to -0.11	-0.63 to -0.17	-0.47 to -0.02
14	Mar30-Apr05	-7.35 to 5.81	-0.52 to -0.33	-0.42 to -0.18	-0.32 to -0.21	-0.31 to -0.10
15	Apr06-12	-2.51 to 6.31	-0.47 to -0.19	-0.32 to -0.12	-0.22 to -0.07	-0.15 to 0.36
16	Apr13-19	0.82 to 6.14	-0.30 to -0.08	-0.28 to -0.04	-0.11 to 4.11	-0.10 to 3.34
17	Apr20-26	2.15 to 10.29	0.15 to 5.81	0.08 to 6.49	2.71 to 7.03	0.68 to 7.11
18	Apr27-May03	-3.29 to 10.29	0.27 to 4.62	-2.23 to 2.07	1.55 to 7.09	-1.22 to 5.88
19	May04-10	-1.69 to 10.20	0.81 to 5.43	-2.00 to 3.49	0.17 to 7.13	-0.63 to 6.24
20	May11-17	3.47 to 13.57	2.90 to 7.29	-1.99 to 5.70	3.55 to 7.99	0.69 to 7.51
21	May18-24	7.96 to 19.44	4.46 to 14.08	0.73 to 14.00	6.11 to 11.95	3.82 to 15.45
22‡	May24-31	12.29 to 16.49	9.76 to 12.69	5.42 to 9.81	9.34 to 10.79	7.26 to 10.84

* n = 3 days.
‡ n = 5 days.

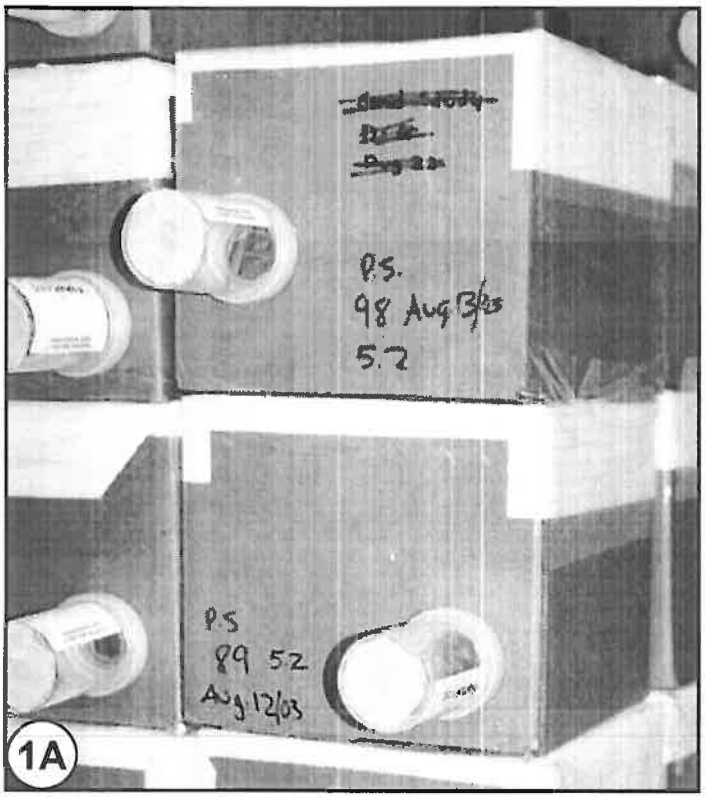
Appendix 3. Minimum and maximum temperatures recorded in overwintering microhabitats at Beaverlodge, Alberta between late fall of 2003 until spring of 2004 (in progress).

Site	Week of Year	Dates	Range of air temperature measured (+150 cm from soil level)	Range of FIELD temperatures measured below soil level (-4cm in soil profile)	Range of FIELD temperatures measured at soil/litter interface level (0cm in soil profile)	Range of MARGIN temperatures measured below soil level (-4cm in soil profile)	Range of MARGIN temperatures measured at soil/litter interface level (0cm in soil profile)
Site 1	41*	Oct05-11	4.82 to 8.40	5.07 to 7.91	6.19 to 10.21	5.07 to 7.40	5.18 to 9.03
	42	Oct13-17	-0.75 to 6.49	2.80 to 6.31	1.16 to 7.84	3.02 to 6.07	1.79 to 7.10
	43	Oct20-24	4.69 to 8.98	3.70 to 6.32	3.46 to 10.44	3.56 to 5.84	4.10 to 7.48
	44	Oct27-31	-14.12 to 13.30	2.59 to 6.93	1.65 to 10.73	2.19 to 6.90	1.07 to 7.51
	45	Nov03-07	-13.02 to -3.75	1.19 to 2.45	0.11 to 1.59	0.65 to 2.28	-0.39 to 1.58
	46	Nov10-14	-4.57 to 5.30	0.93 to 1.46	-0.36 to 0.85	0.50 to 1.10	-0.47 to 0.71
	47	Nov17-21	-17.73 to -0.94	-0.52 to 0.82	-1.95 to -0.21	-1.03 to 0.40	-2.36 to -0.18
	48	Nov24-28	-12.54 to -4.14	-0.69 to -0.46	-1.67 to -1.07	-1.11 to -0.74	-2.00 to -1.22
	49	Dec01-05	-9.09 to -1.86	-1.85 to -0.65	-2.87 to -1.26	-1.39 to -0.80	-2.34 to -1.27
	50	Dec08-12	-16.49 to -4.96	-4.01 to -2.23	-5.06 to -3.16	-2.66 to -1.70	-3.69 to -2.57
	51	Dec15-19	-7.73 to 0.48	-3.19 to -1.62	-3.72 to -1.79	-2.24 to -1.01	-2.76 to -1.18
	52	Dec22-26	-8.55 to 2.00	-3.70 to -1.49	-4.55 to -1.84	-2.45 to -1.00	-3.38 to -1.36
	1	Dec29-Jan02	-25.56 to -13.74	-6.08 to -4.39	-7.18 to -5.24	-4.92 to -2.97	-6.33 to -4.05
	2	Jan05-09	-18.74 to -8.91	-5.80 to -4.25	-6.76 to -4.57	-4.60 to -3.29	-5.67 to -3.64
	3	Jan12-16	-11.43 to -0.37	-3.89 to -3.01	-4.29 to -3.12	-2.94 to -2.25	-3.47 to -2.35
	4	Jan19-23	-17.65 to 0.18	-3.76 to -2.83	-4.33 to -3.31	-2.99 to -1.39	-3.67 to -1.42
	5	Jan26-30	-36.66 to -22.39	-5.36 to -3.48	-6.32 to -4.06	-4.47 to -2.63	-5.25 to -3.20
	6	Feb 01-07	-23.14 to -1.70	-4.89 to -3.67	-5.43 to -3.86	-4.19 to -2.90	-4.63 to -3.01
	7	Feb 08-14	-10.36 to 3.41	-3.27 to -2.56	-3.40 to -2.57	-2.59 to -1.64	-2.66 to -1.60
	8	Feb 15-21	-10.02 to 3.95	-2.93 to -1.56	-3.29 to -1.37	-2.48 to -0.92	-2.71 to -0.78
	9	Feb 22-28	-5.98 to 0.42	-2.35 to -1.69	-2.75 to -1.66	-1.98 to -0.94	-2.29 to -0.88

	10	Feb 29-Mar 06	-14.35 to -1.81	-2.64 to -2.14	-3.05 to -2.38	-2.63 to -1.87	-2.87 to -2.04
	11	Mar07-13	-3.41 to 7.29	-1.89 to -0.15	-2.06 to -0.09	-1.76 to -0.17	-1.76 to -0.07
	12	Mar 14-20	-9.21 to 1.92	-0.35 to -0.19	-0.41 to -0.19	-0.45 to -0.22	-0.46 to -0.17
	13	Mar 21-27	-8.56 to 4.00	-0.66 to -0.15	-1.57 to -0.06	-1.08 to -0.22	-1.04 to -0.09
	14	Mar 28- Apr 03	1.48 to 10.86	-0.13 to 0.65	-0.03 to 6.43	-0.20 to 0.15	-0.10 to 3.30
	15	Apr 04-10	6.13 to 10.51	1.42 to 4.40	5.22 to 10.64	0.06 to 1.69	0.92 to 7.73
	16	Apr 11-17	-5.82 to 13.16	0.66 to 6.36	-0.10 to 13.09	0.30 to 4.37	-0.04 to 10.76
	17‡	Apr 18-24	1.92 to 7.74	0.56 to 6.01	0.01 to 12.14	0.39 to 4.14	0.14 to 10.36
Site 2	41*	Oct05-11	4.63 to 7.82	4.86 to 7.64	6.02 to 10.04	4.55 to 7.18	3.82 to 8.69
	42	Oct13-17	-1.29 to 5.53	2.66 to 6.45	1.02 to 8.70	2.31 to 6.09	0.66 to 7.40
	43	Oct20-24	3.86 to 8.69	2.28 to 6.35	1.94 to 8.65	2.69 to 5.84	2.63 to 6.71
	44	Oct27-31	-13.93 to 12.58	1.78 to 6.63	1.01 to 7.29	0.58 to 7.34	-0.70 to 7.98
	45	Nov03-07	-12.97 to -4.24	0.44 to 1.63	-0.19 to 1.14	-0.61 to 1.03	-1.72 to 0.04
	46	Nov10-14	-4.33 to 5.11	0.20 to 0.62	-0.40 to 0.30	-0.63 to 0.18	-1.41 to 0.02
	47	Nov17-21	-17.98 to -1.09	-0.81 to 0.25	-1.53 to -0.19	-4.37 to -0.30	-5.43 to -0.64
	48	Nov24-28	-12.21 to -4.21	-0.89 to -0.59	-1.39 to -0.89	-3.21 to -2.24	-4.12 to -2.65
	49	Dec01-05	-9.16 to -2.22	-1.22 to -0.69	-1.74 to -0.94	-3.97 to -2.43	-4.85 to -2.94
	50	Dec08-12	-16.53 to -4.25	-2.69 to -1.48	-3.26 to -1.92	-5.31 to -3.71	-6.04 to -4.15
	51	Dec15-19	-7.07 to 0.23	-2.28 to -1.16	-2.54 to -1.27	-3.73 to -1.66	-4.04 to -1.64
	52	Dec22-26	-7.77 to 1.12	-2.32 to -1.18	-2.76 to -1.37	-4.19 to -1.85	-4.94 to -1.97
	1	Dec29-Jan02	-26.10 to -13.18	-4.47 to -2.80	-5.14 to -3.31	-9.82 to -5.49	-12.24 to -6.39
	2	Jan05-09	-19.12 to -9.08	-4.18 to -3.11	-4.70 to -3.24	-8.39 to -5.67	-9.77 to -6.25
	3	Jan12-16	-12.05 to -1.56	-2.96 to -2.26	-3.19 to -2.33	-5.45 to -3.47	-6.43 to -3.64
	4	Jan19-23	-18.49 to 0.60	-2.89 to -1.99	-3.20 to -2.40	-5.79 to -3.10	-6.68 to -2.48
	5	Jan26-30	-37.01 to -22.70	-4.23 to -2.73	-4.68 to -3.06	-9.04 to -6.29	-10.27 to -7.54
	6	Feb 01-07	-22.46 to -2.47	-3.70 to -2.86	-3.93 to -2.96	-7.31 to -4.33	-7.99 to -4.46
	7	Feb 08-14	-11.25 to 2.99	-2.61 to -2.17	-2.67 to -2.26	-4.09 to -2.81	-4.95 to -2.73
	8	Feb 15-21	-10.01 to 2.83	-2.33 to -1.57	-2.44 to -1.52	-4.25 to -1.31	-4.88 to -1.05
	9	Feb 22-28	-6.62 to 0.54	-2.08 to -1.75	-2.23 to -1.83	-3.46 to -2.14	-4.25 to -2.65
	10	Feb 29-Mar 06	-15.28 to -2.11	-2.19 to -1.85	-2.32 to -1.96	-4.96 to -3.17	-5.98 to -3.74
	11	Mar07-13	-3.29 to 7.00	-1.56 to -0.18	-1.62 to -0.01	-2.92 to -0.18	-2.63 to 0.08

12	Mar 14-20	-10.46 to 1.04	-0.35 to -0.17	-0.26 to -0.05	-2.63 to -0.44	-3.09 to -0.31
13	Mar 21-27	-8.91 to 3.91	-0.71 to -0.10	-0.74 to -0.01	-4.44 to -0.31	-5.04 to -0.02
14	Mar 28- Apr 03	0.80 to 10.84	-0.07 to 1.68	-0.11 to 6.27	-0.52 to 1.44	-0.38 to 5.12
15	Apr 04-10	5.47 to 9.12	3.38 to 5.87	7.36 to 12.99	0.33 to 1.96	0.29 to 4.21
16	Apr 11-17	-6.36 to 12.38	0.41 to 8.25	-0.01 to 15.07	-0.13 to 5.17	-0.79 to 8.95
17‡	Apr 18-24	1.51 to 7.00	0.33 to 7.58	1.45 to 14.25	0.03 to 3.16	0.34 to 5.11

* n = 2 days.
‡ n = 4 days.



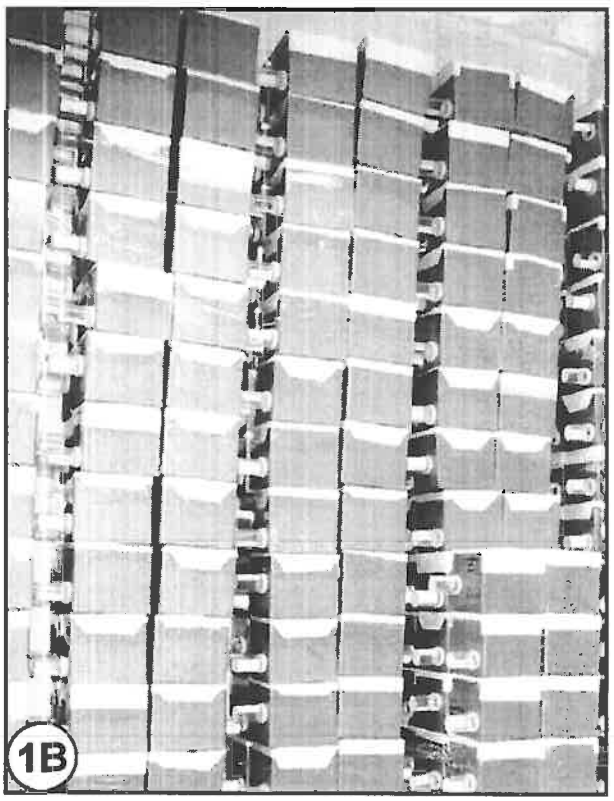


Figure 1. Cardboard rearing containers used to hold samples of canola pods infested with larvae of cabbage seedpod weevil and its ectoparasitoids. Newly emerged parasitoids could be collected in the vials attached to the containers (Fig. 1A). Field surveys required use of hundreds of emergence boxes (Fig. 1B).

Figure 2. Bowl traps used to monitor adult weevil ectoparasitoids were partially filled with an insect preservative (Fig. 2A), and could be raised or lowered depending on the height of the crop canopy (Fig. 2B).

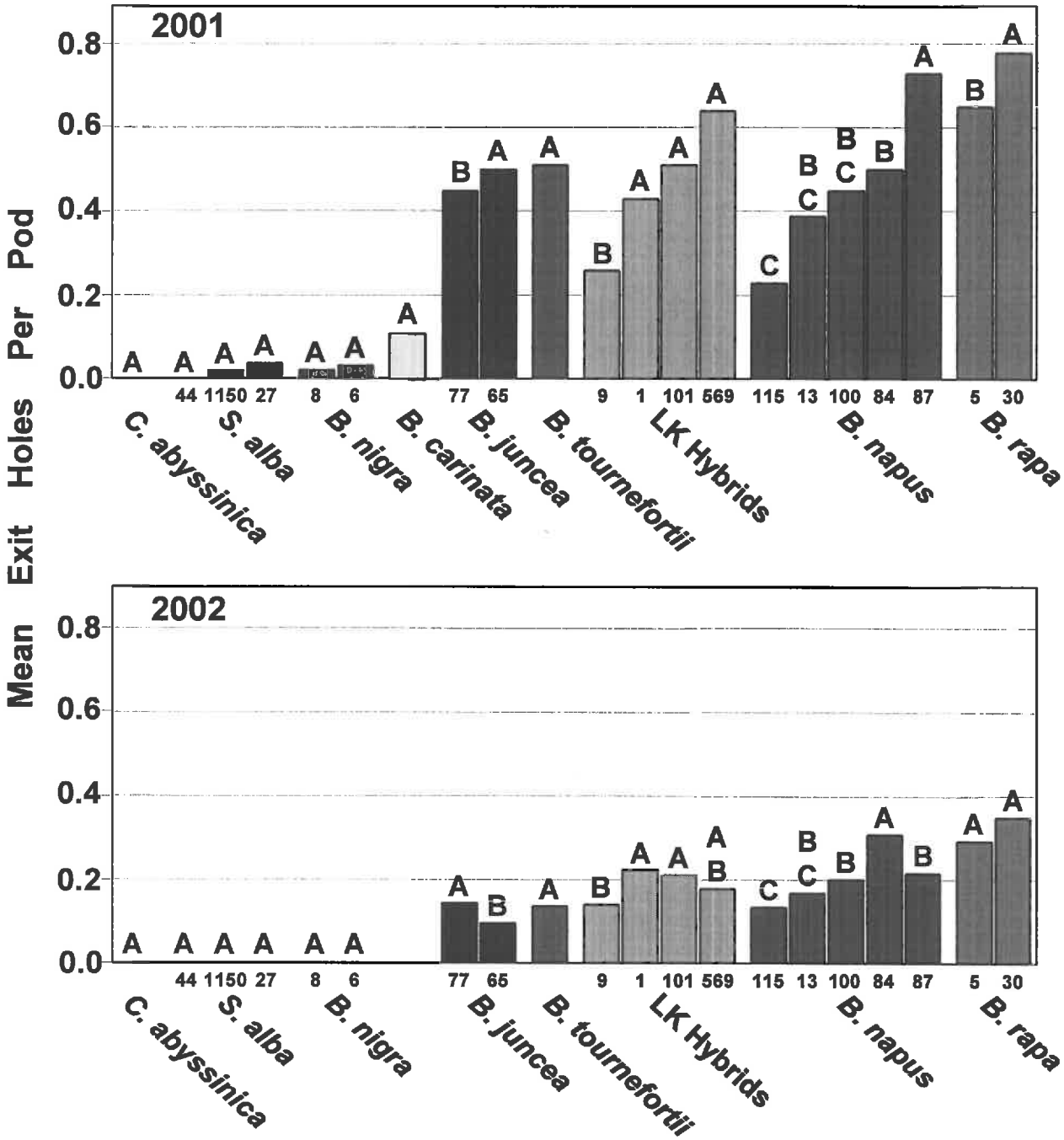


Figure 3. Mean cabbage seedpod weevil larval exit holes per pod for species and varieties of *Brassica rapa*, *Brassica napus*, *Brassica tournefortii*, *Brassica juncea*, *Brassica carinata*, *Brassica nigra*, *Sinapis alba*, *Crambe abyssinica*, and intergeneric hybrid accessions produced by crosses of *S. alba* x *B. napus* ("LK Hybrids"). Field evaluations were conducted in 2001 (upper graph) and 2002 (lower graph). Letters on histograms indicate significance of differences among genotypes within species: means having the same letter indicate no significant differences according to analysis of variance and Tukey's test.

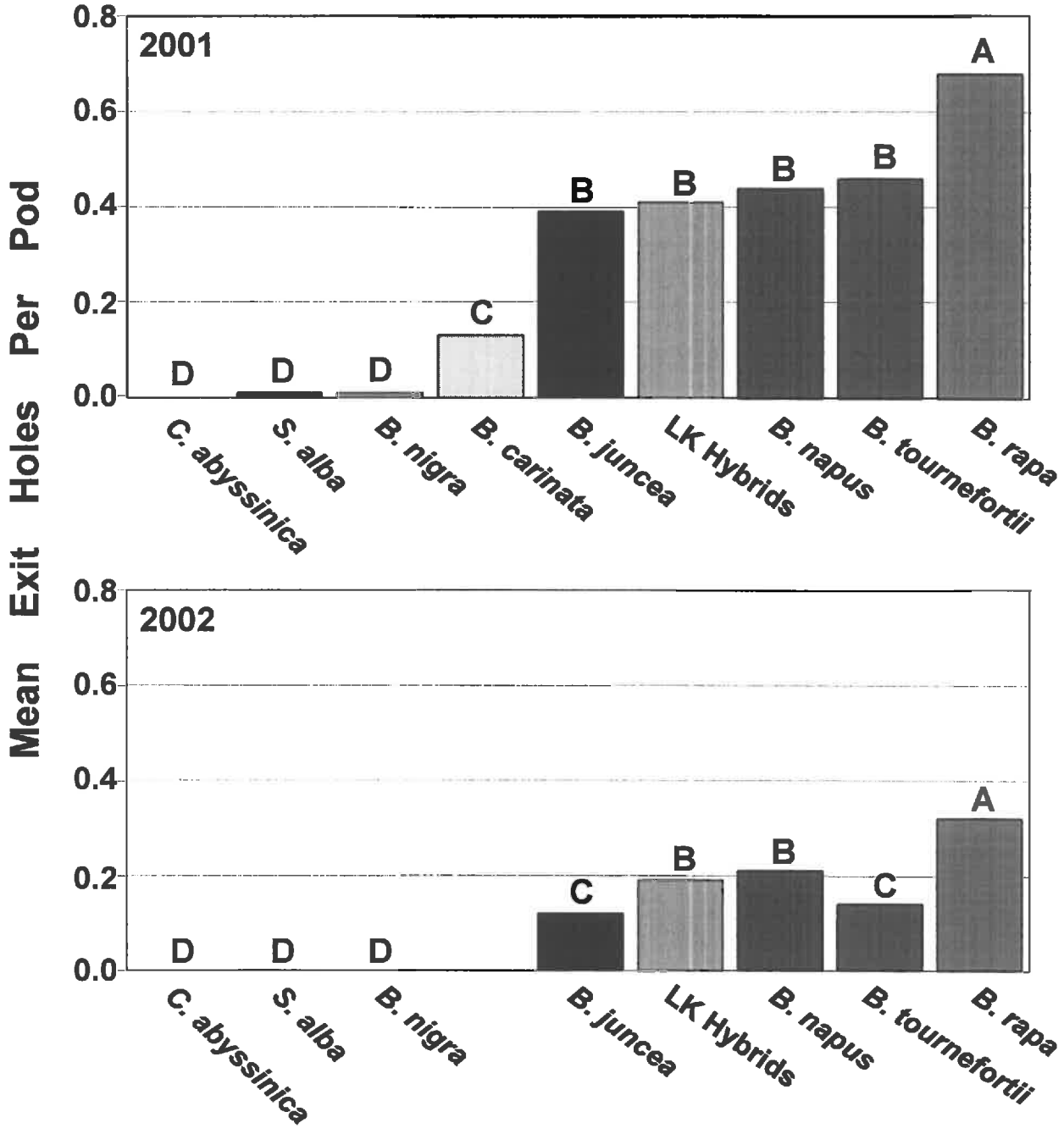


Figure 4. Mean cabbage seedpod weevil larval exit holes per pod for species of Brassicaceae, including *Brassica rapa*, *Brassica tournefortii*, *Brassica napus*, *Brassica juncea*, *Brassica carinata*, *Brassica nigra*, *Sinapis alba*, *Crambe abyssinica*, and intergeneric hybrid accessions produced by crosses of *S. alba* x *B. napus* ("LK Hybrids"). Field evaluations were conducted in 2001 (upper graph) and 2002 (lower graph). Letters on histograms indicate significance of differences between species: means having the same letter indicate no significant differences according to analysis of variance and Tukey's test.

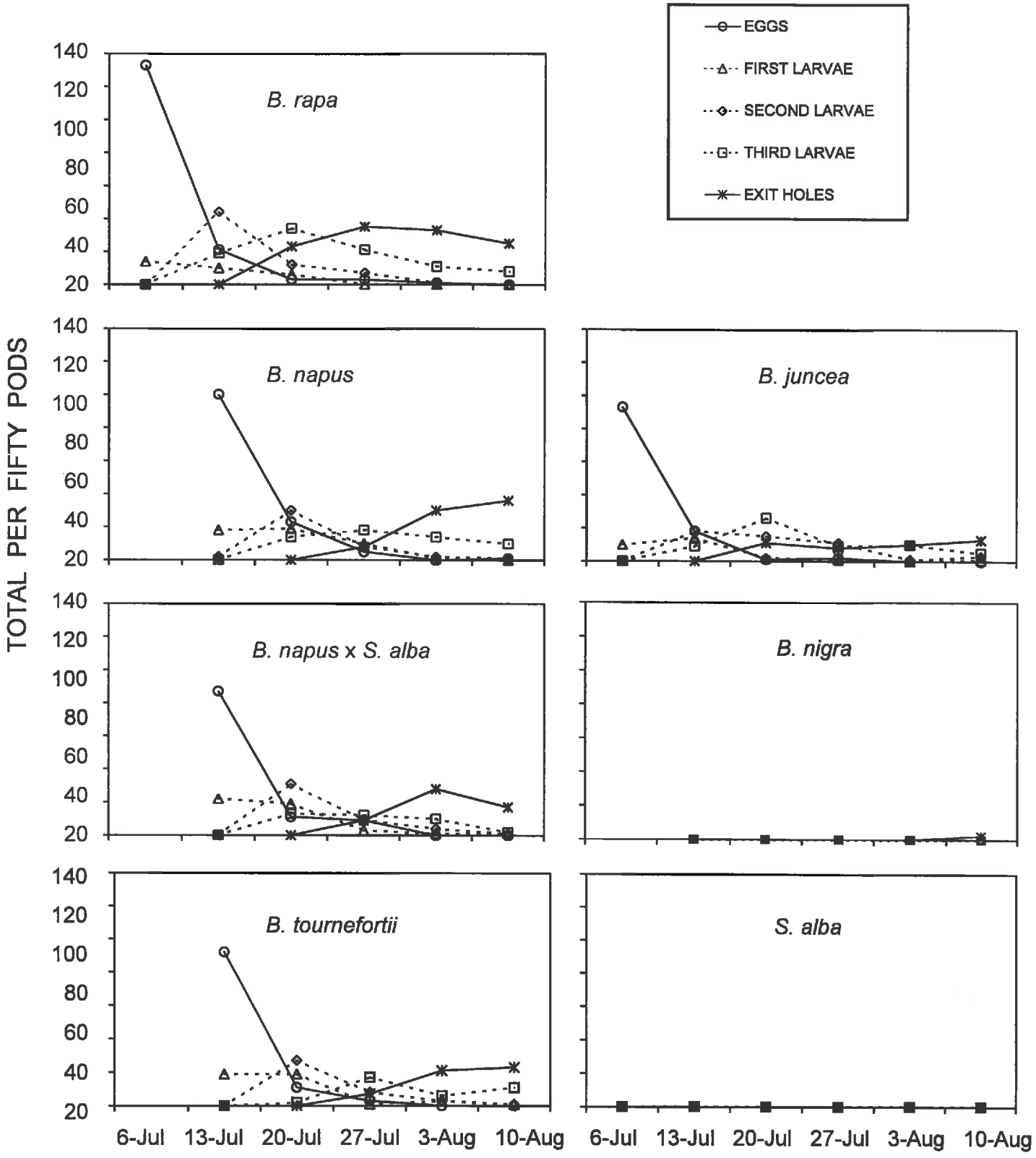


Figure 5. Total numbers of *Ceutorhynchus obstrictus* eggs, larvae, and exit holes found in dissected pods of *Brassica rapa*, *B. napus*, *B. napus* x *Sinapis alba*, *B. tournefortii*, *B. juncea*, *B. nigra*, and *S. alba*.

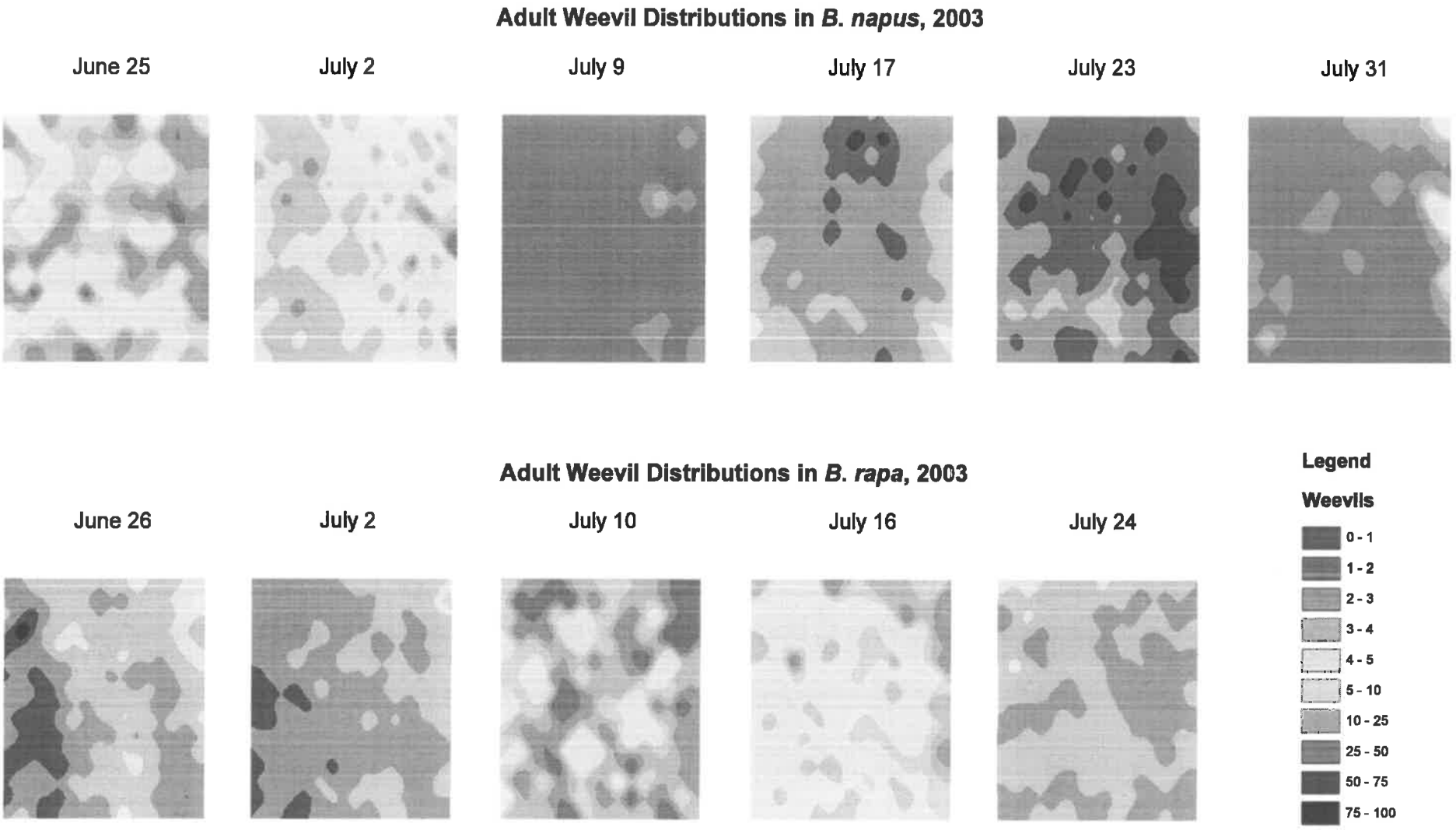


Figure 42. Distributions of cabbage seedpod weevil adults from bowl trap collections in a portion of fields of *Brassica napus* and *Brassica rapa* near Lethbridge, AB on different sampling dates in 2003.

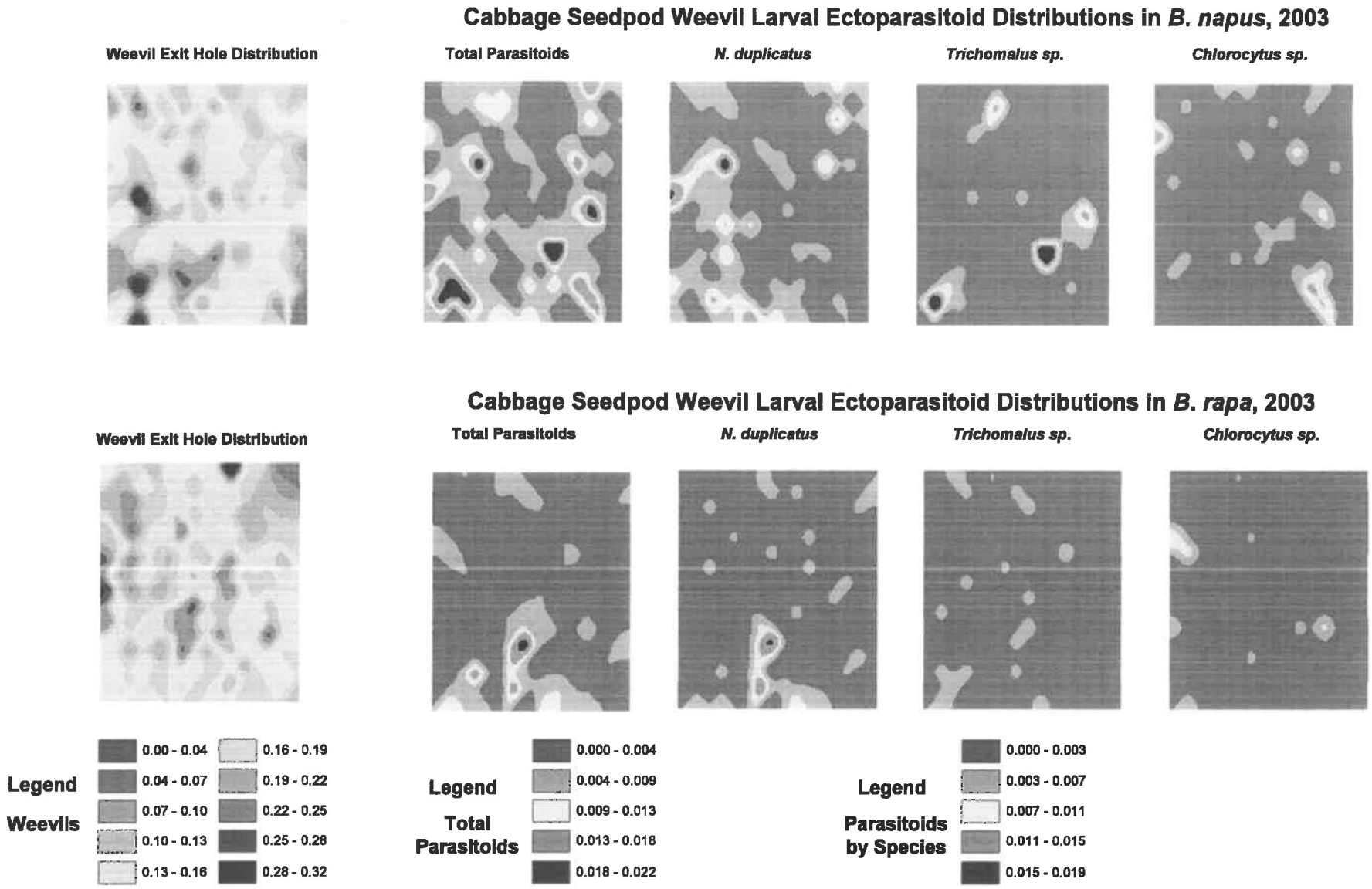


Figure 43. Distributions of cabbage seedpod weevil larval exit holes, and distributions of weevil larval ectoparasitoids from emergence box samples in portions of fields of *Brassica napus* and *Brassica rapa* near Lethbridge, AB in 2003.

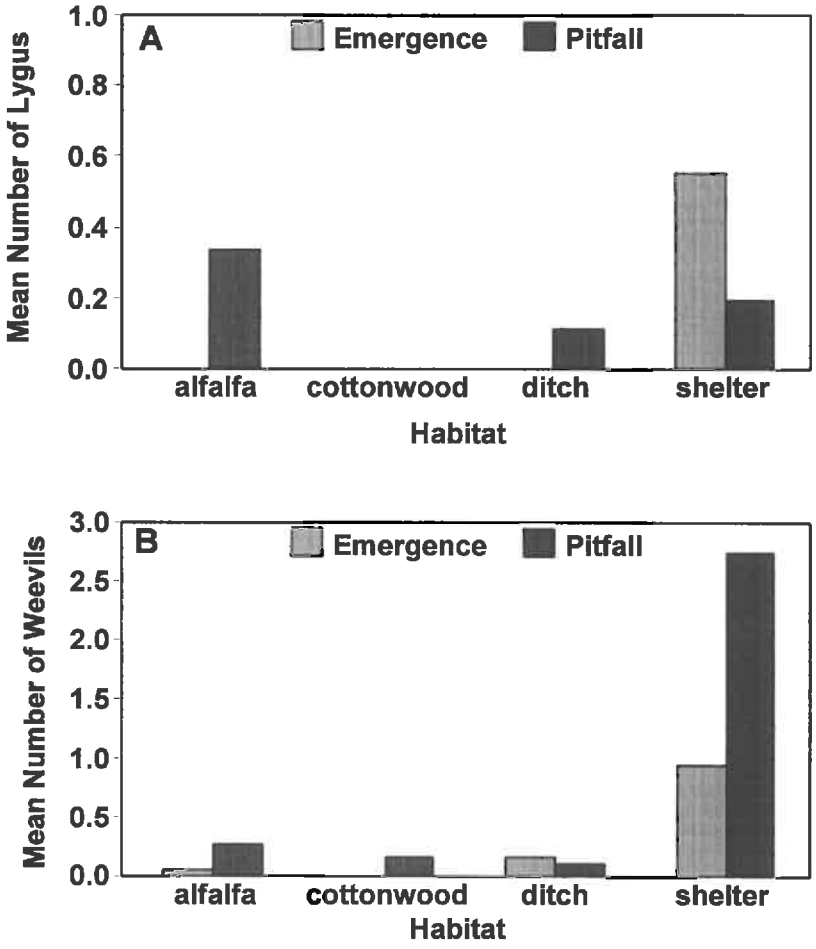
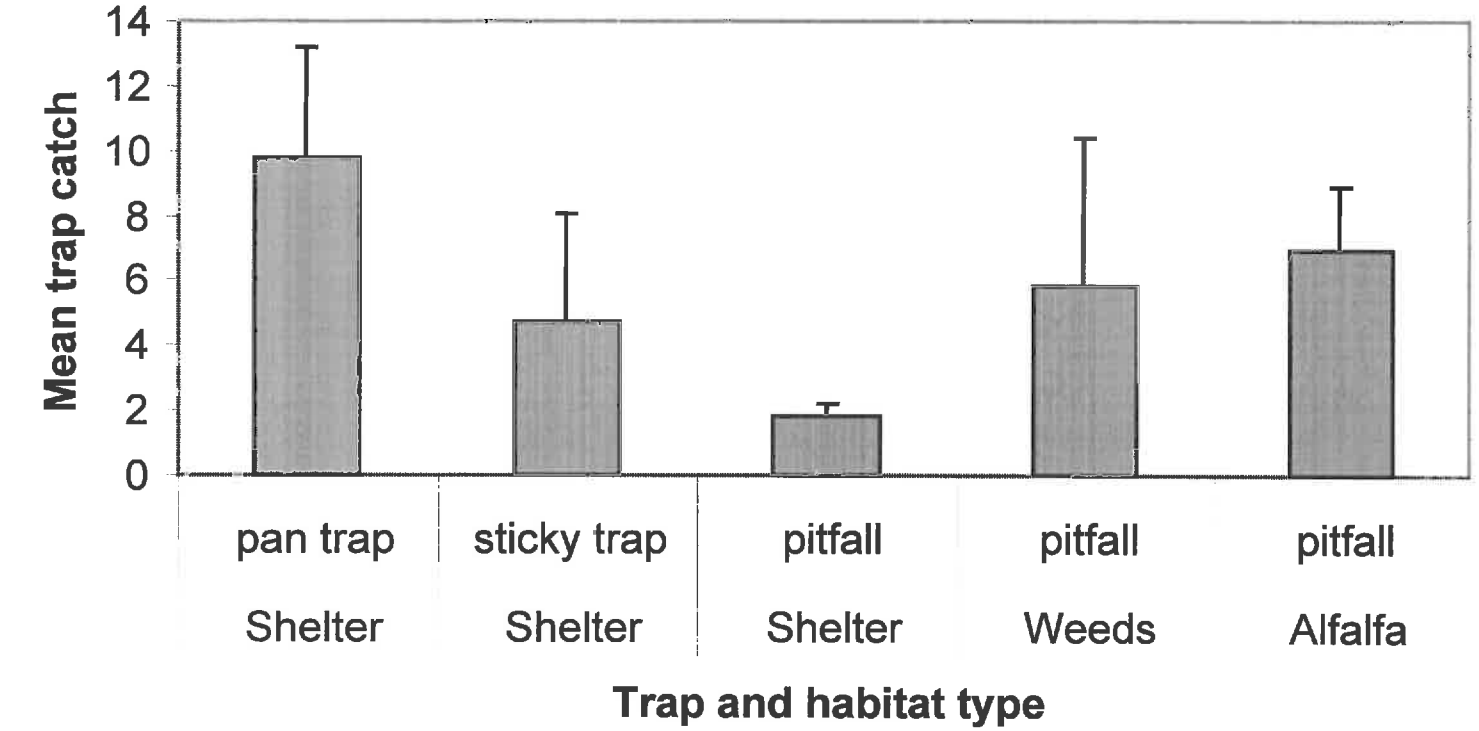


Figure 44. Mean numbers of lygus bugs (A), and cabbage seedpod weevil (B) adults collected in southern Alberta in emergence and pitfall traps deployed in various overwintering habitats in the spring of 2001.



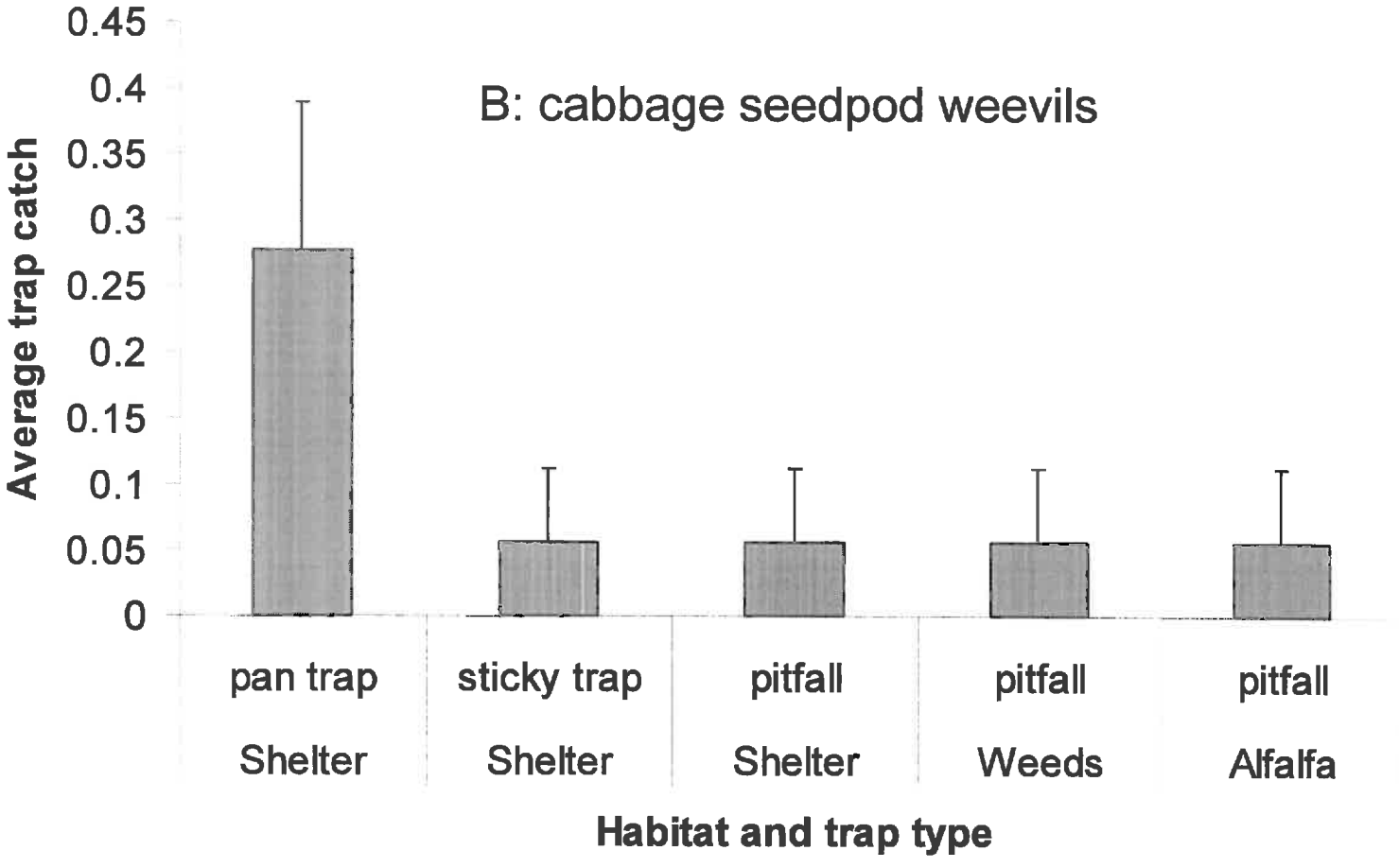


Figure 45. Trap catches of cabbage seedpod weevils near Lethbrige from 8 April to 30 June 2003 using three methods in a tree shelter and pitfall traps in three habitats. Entries are means of three sites with 1 standard error.

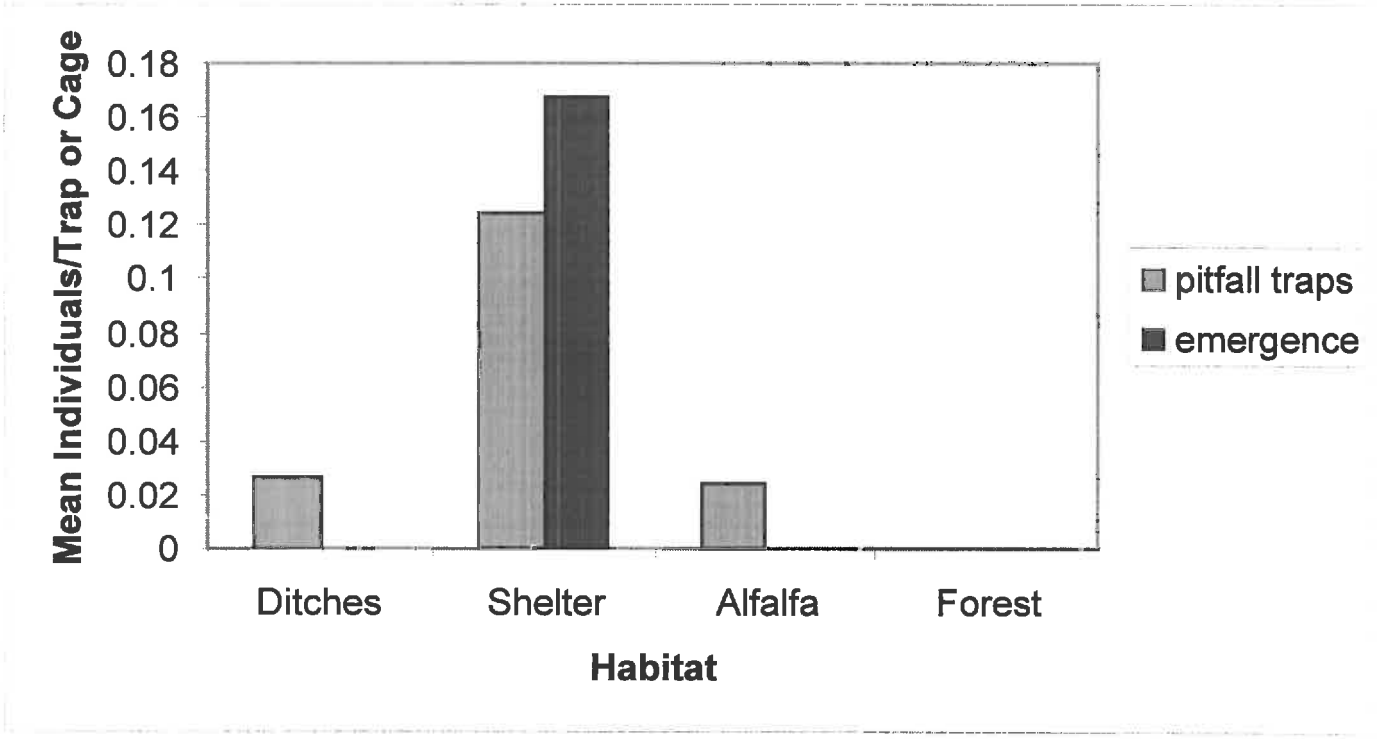


Figure 46. Mean numbers of cabbage seedpod weevil adults collected in various overwintering habitats near Lethbridge, AB from mid April 2002 to 22 July 2002.

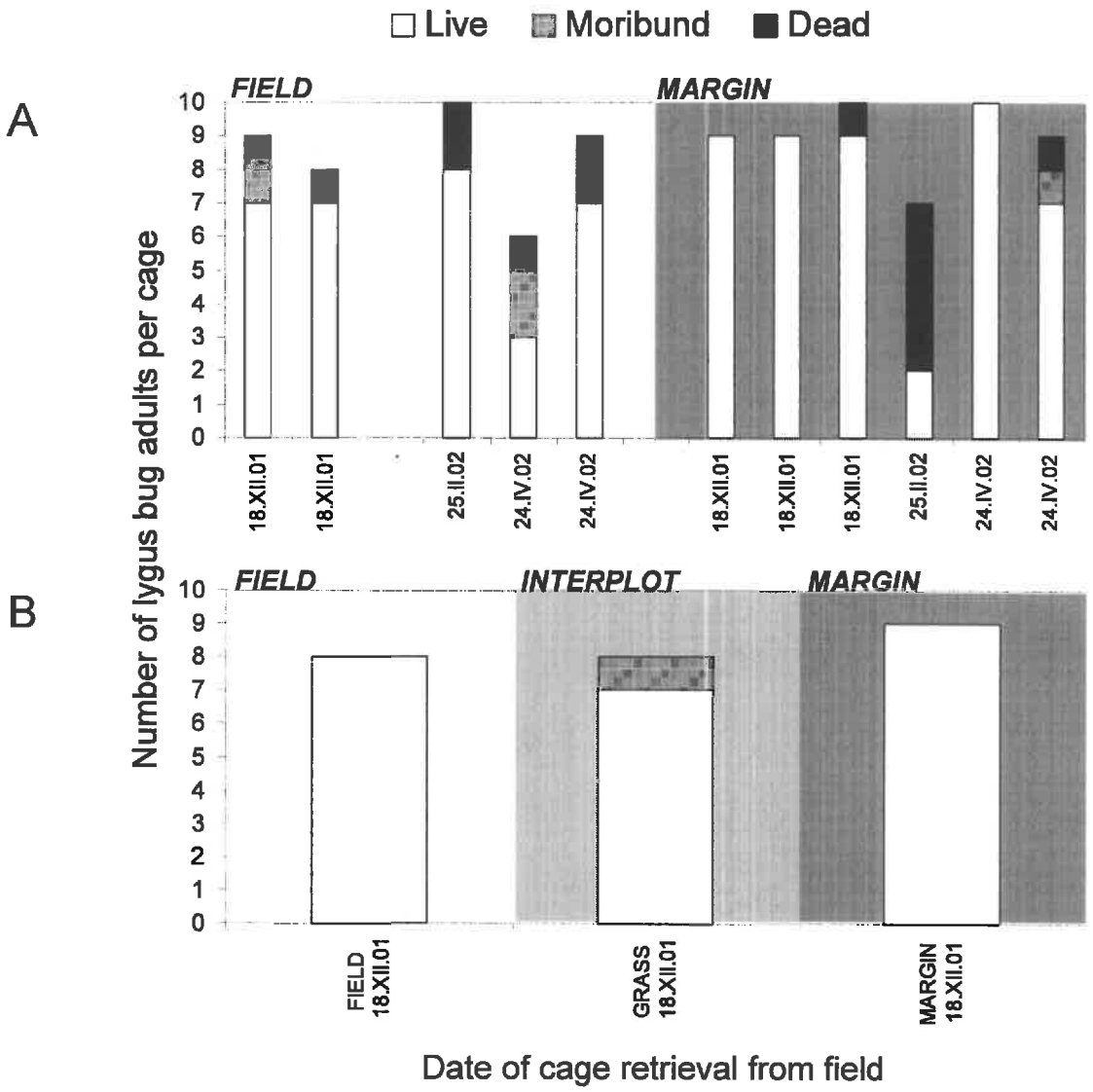


Figure 47. Overwintering survivorship of lygus bug adults (n = 10 per cage) retrieved from field and margin habitats at (A) Site 1, and (B) Site 2 during the 2001-2002 winter at Beaverlodge, Alberta. Survivorship was measured 24 hours at room temperature following retrieval from the field (each bar represents results from an individual microcosm cage).

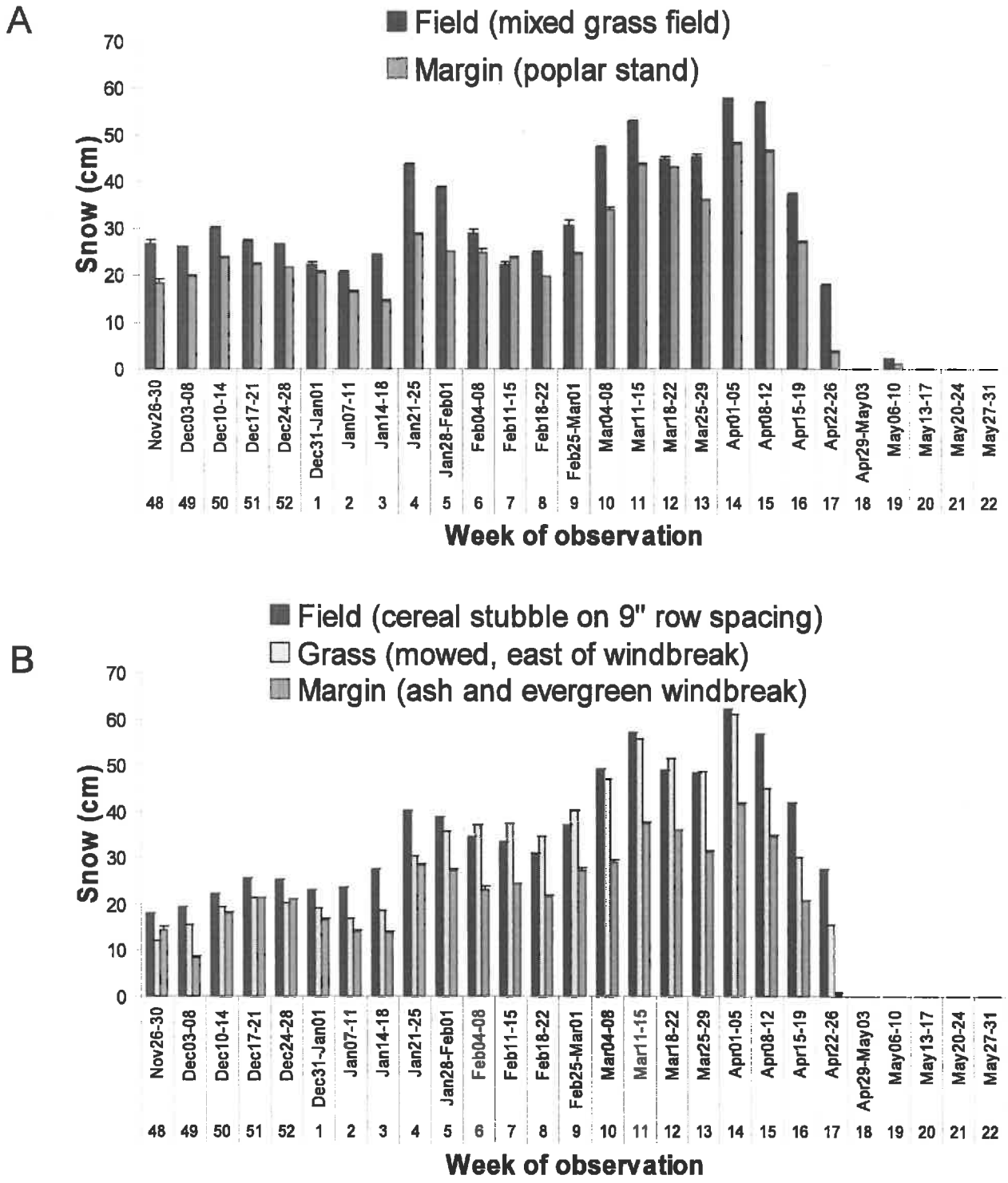


Figure 48. Mean weekly depth of snow (cm) on ground ($n = 3$ measurements per habitat per week) in overwintering (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the winter of 2001-2002.

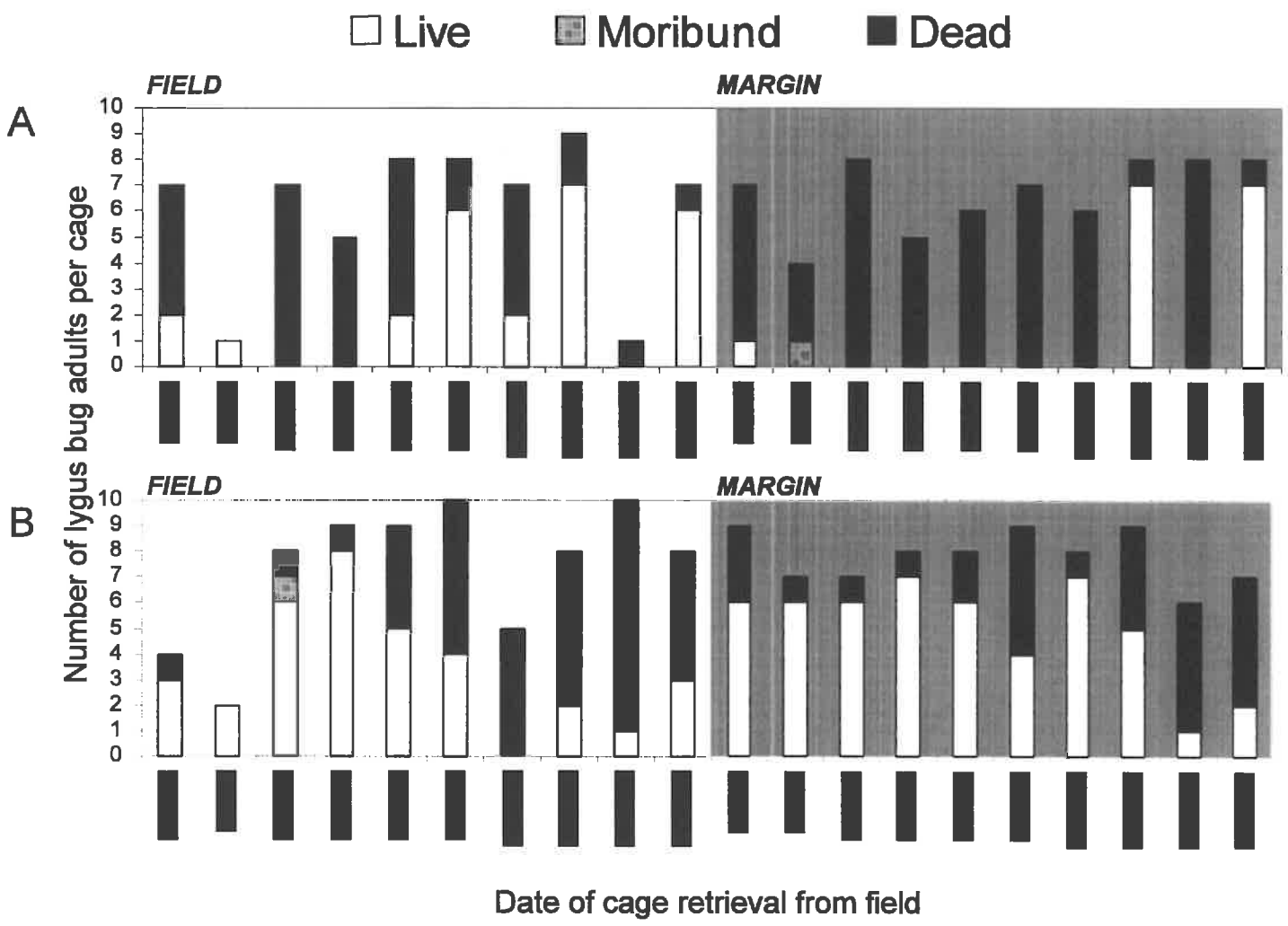


Figure 49. Overwintering survivorship of lygus bug adults (n = 10 per cage) retrieved from field and margin habitats at (A) Site 1, and (B) Site 2 during the 2002-2003 winter at Beaverlodge, Alberta. Survivorship was measured 24 hours at room temperature following retrieval from the field (each bar represents results from an individual microcosm cage).

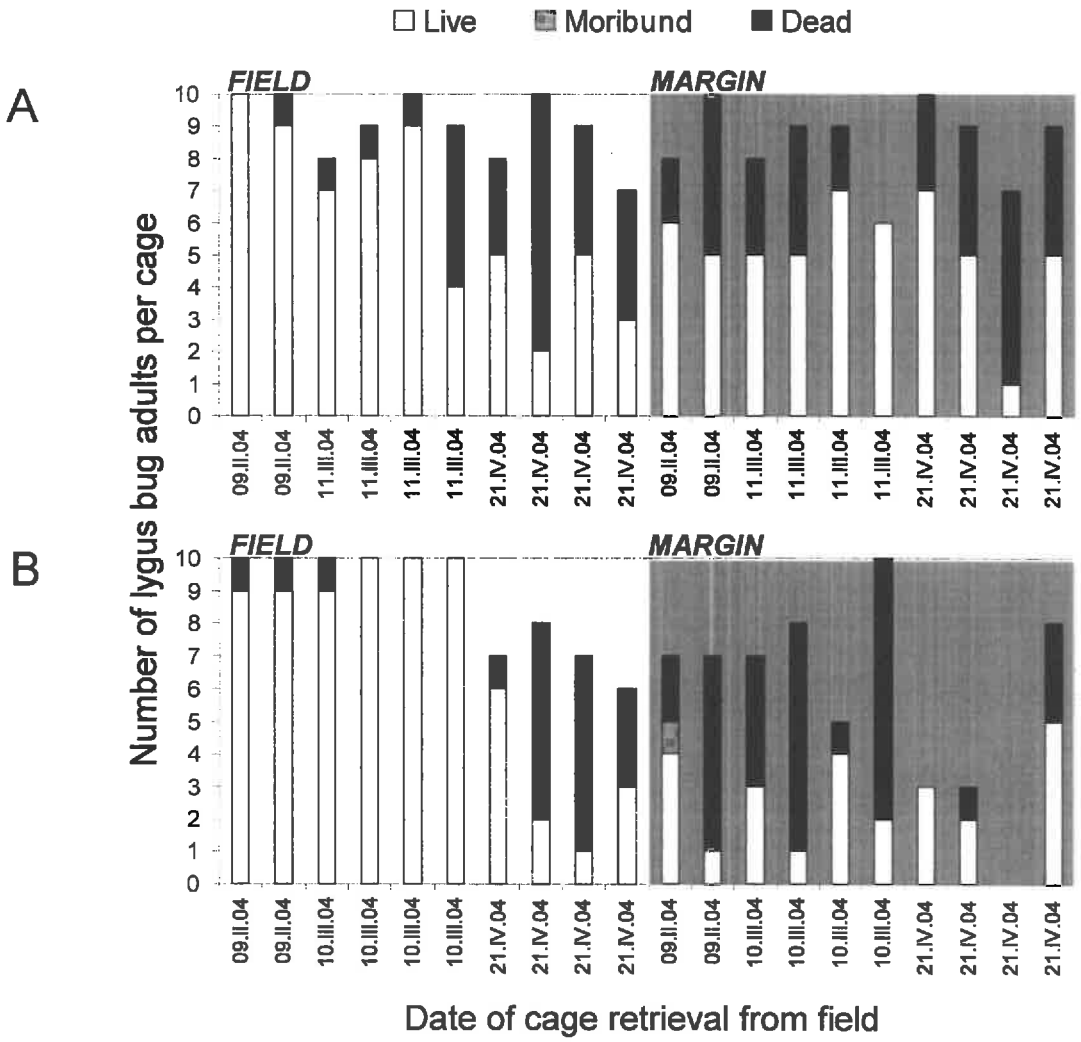


Figure 50. Overwintering survivorship of lygus bug adults (n = 10 per cage) retrieved from field and margin habitats at (A) Site 1, and (B) Site 2 during the 2003-2004 winter at Beaverlodge, Alberta. Survivorship was measured 24 hours at room temperature following retrieval from the field (each bar represents results from an individual microcosm cage).

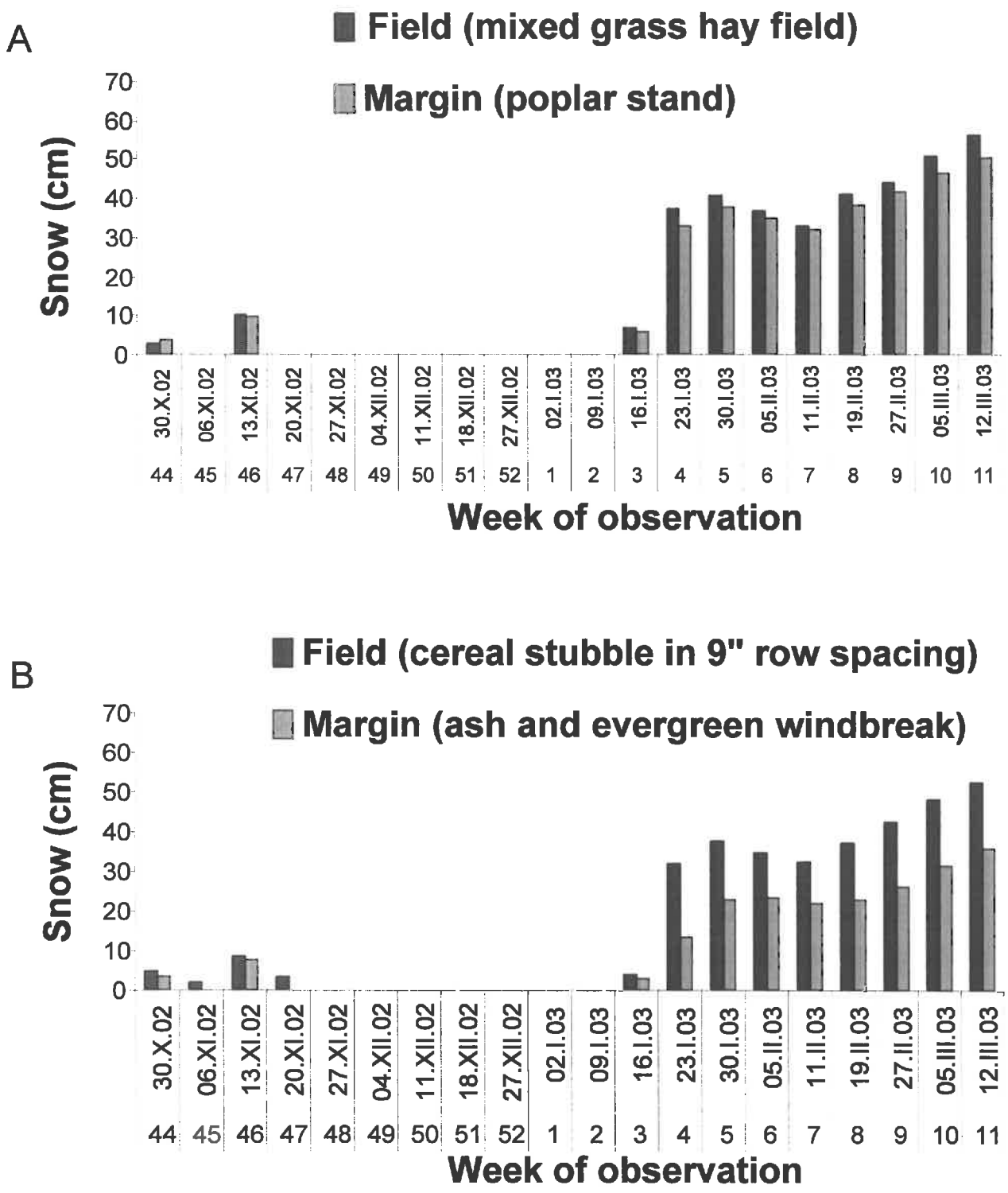


Figure 51. Mean weekly depth of snow (cm) on ground ($n = 3$ measurements per habitat per week) in overwintering (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the winter of 2002-2003.

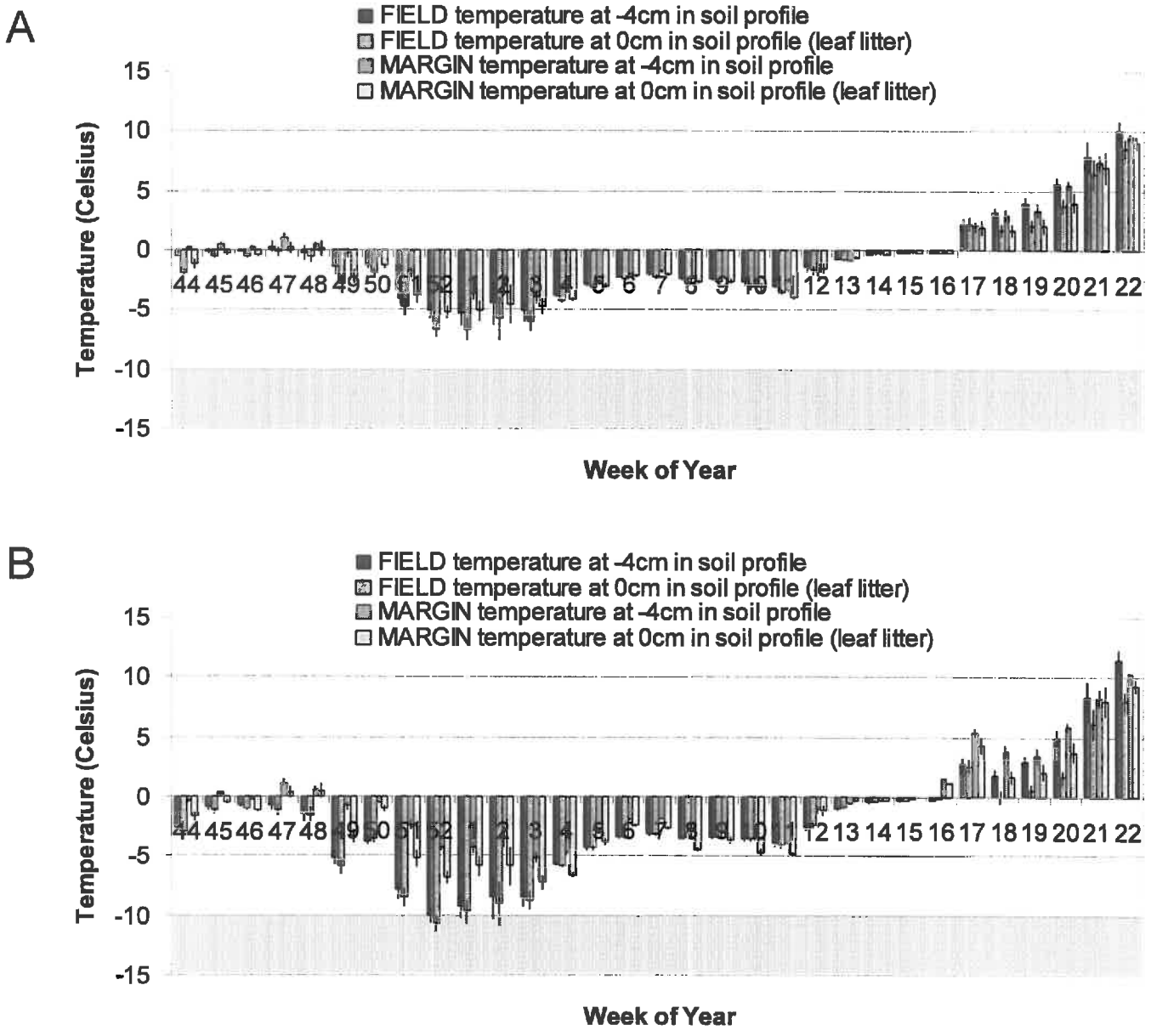


Figure 52. Mean weekly temperatures of soil profile at 0 cm (leaf litter) and -4 cm (below soil surface) levels measured hourly at (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the wintering of 2002-2003. (Notes: Error bars represent standard error of the mean; approximate supercooling values for cabbage seedpod weevil ☐ and lygus bugs ☐ observed in the cold-hardiness study.)

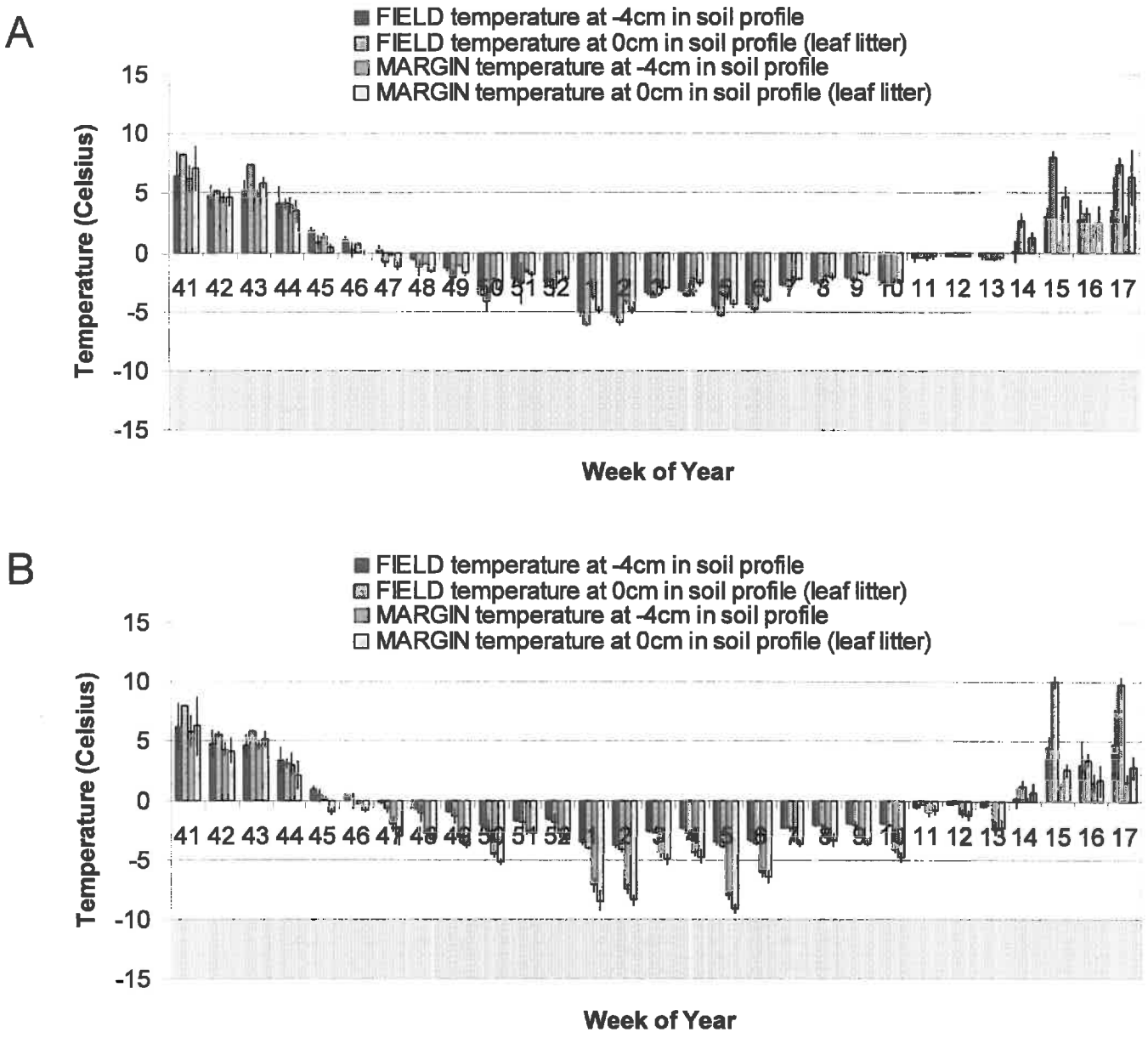


Figure 53. Mean weekly temperatures of soil profile at 0 cm (leaf litter) and -4 cm (below soil surface) levels measured hourly at (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the wintering of 2003-2004. (Notes: Error bars represent standard error of the mean; approximate supercooling values for cabbage seedpod weevil□ and lygus bugs▨ observed in the cold-hardiness study.)

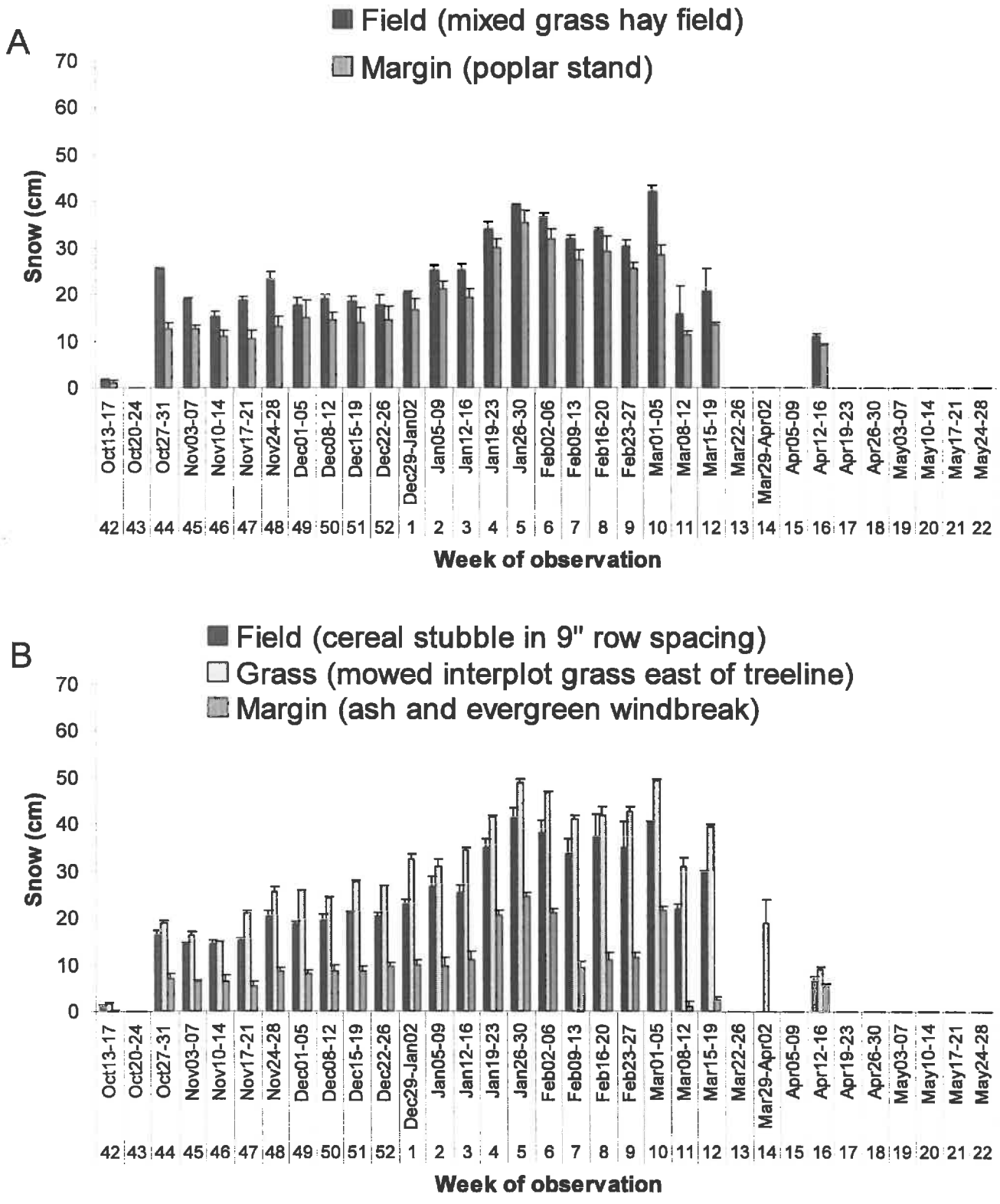


Figure 54. Mean weekly depth of snow (cm) on ground ($n = 3$ measurements per habitat per week) in overwintering (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the winter of 2003-2004.

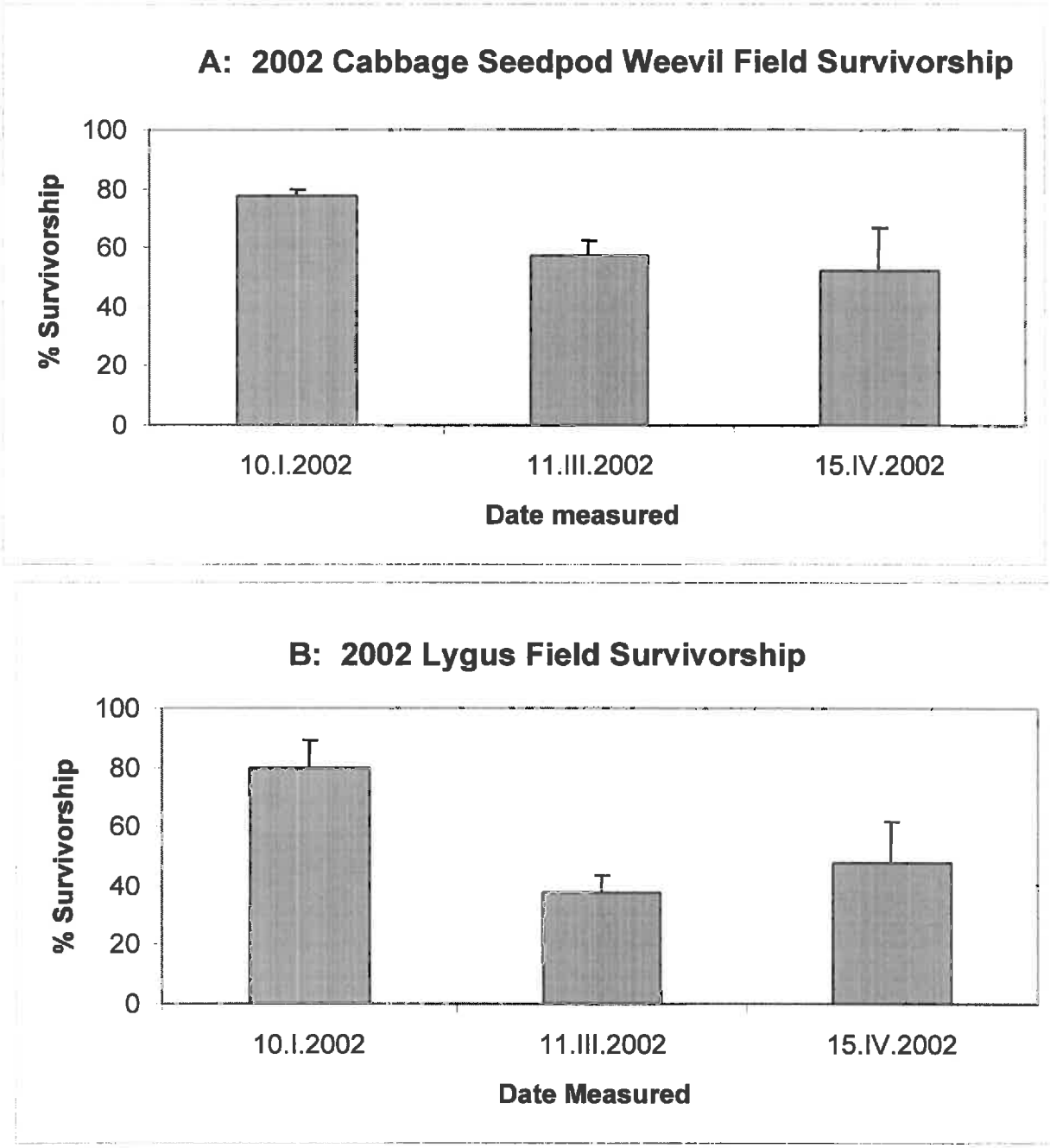


Figure 55. Percent survivorship of cabbage seedpod weevils (A) and lygus bugs (B) placed in microcosms in November 2001and retrieved in January, March, and April 2002 near Lethbridge, Alberta.

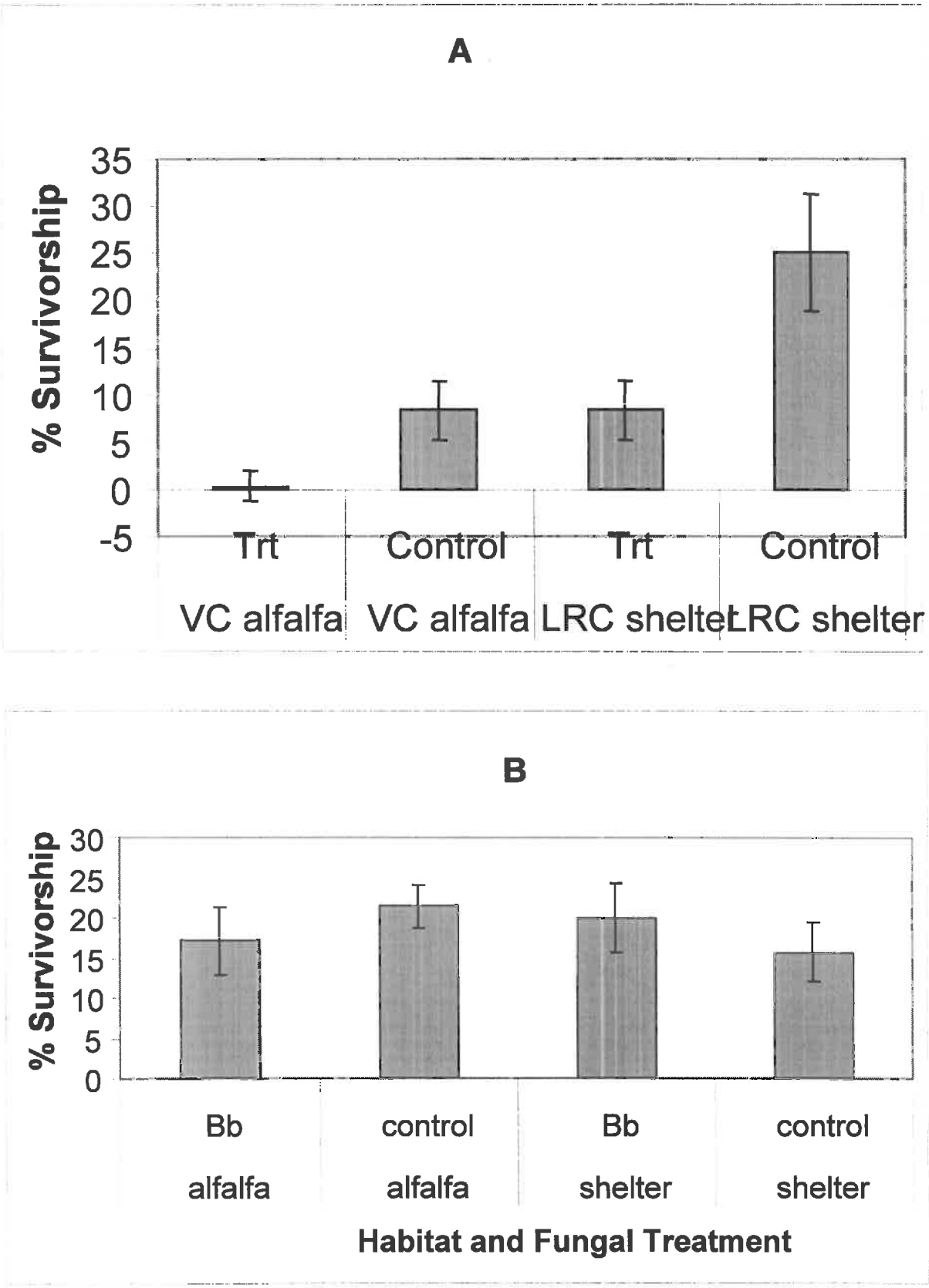


Figure 56. Comparison of cabbage seedpod weevil overwintering survivorship (A: Nov 02-April 03; B: Nov 2003-April 2004) in a tree shelter and alfalfa field and impact of treatment (Trt or Bb) of leaf litter with *Beaveria basssiana* fungal spores in the fall prior to adding the weevils.

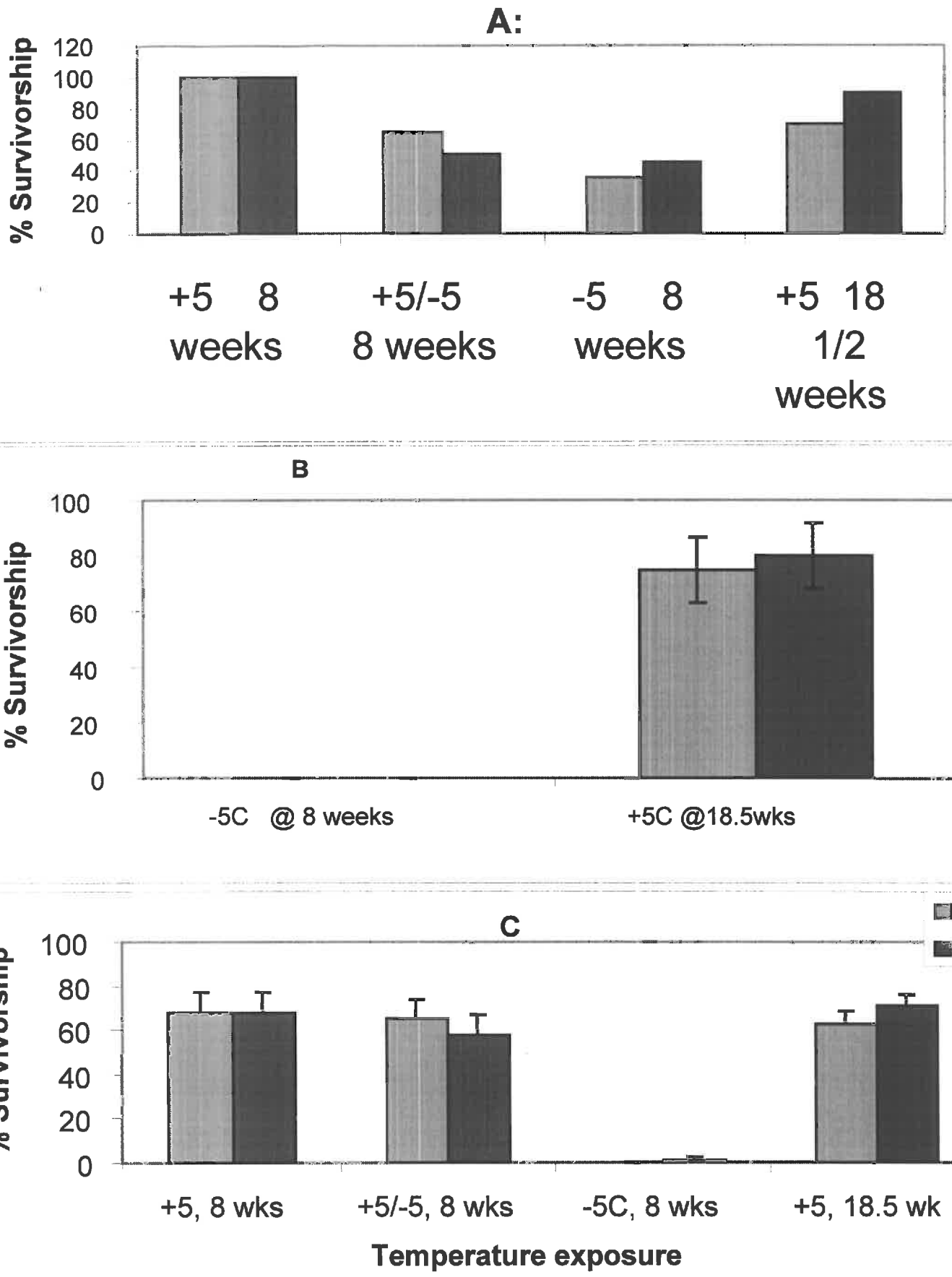


Figure 57. Survivorship of cabbage seedpod weevils at various cold temperatures and two exposure times under laboratory controlled conditions at the Lethbridge Research Centre in 2001-2002 (A), 2002-2003 (B), and 2003-2004 (C).

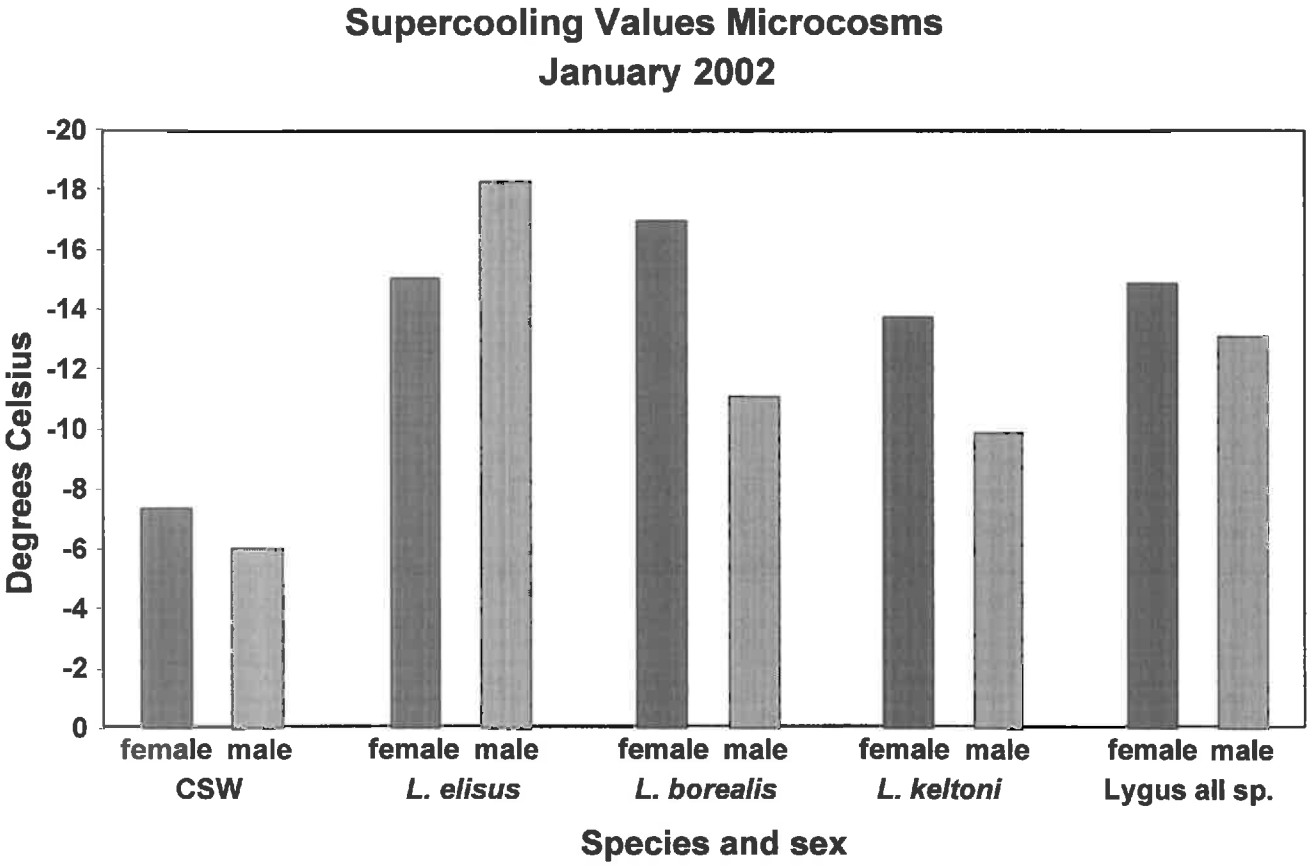


Figure 58. Supercooling temperatures for microcosm survivors retrieved from cages at Lethbridge, AB in January 2002 for various lygus bug species and cabbage seedpod weevils.

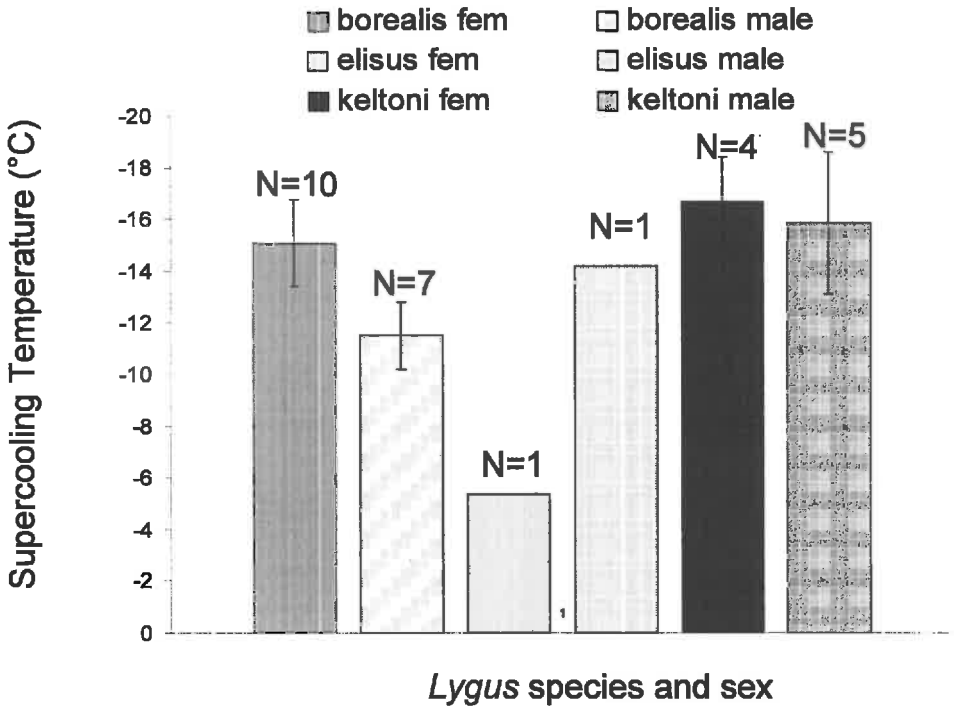


Figure 59. Supercooling temperatures for individual *Lygus* species placed in the field on 20 or 28 November 2002 and retrieved on 10 March 2003 from Sites 1 and 2 at Beaverlodge, Alberta.

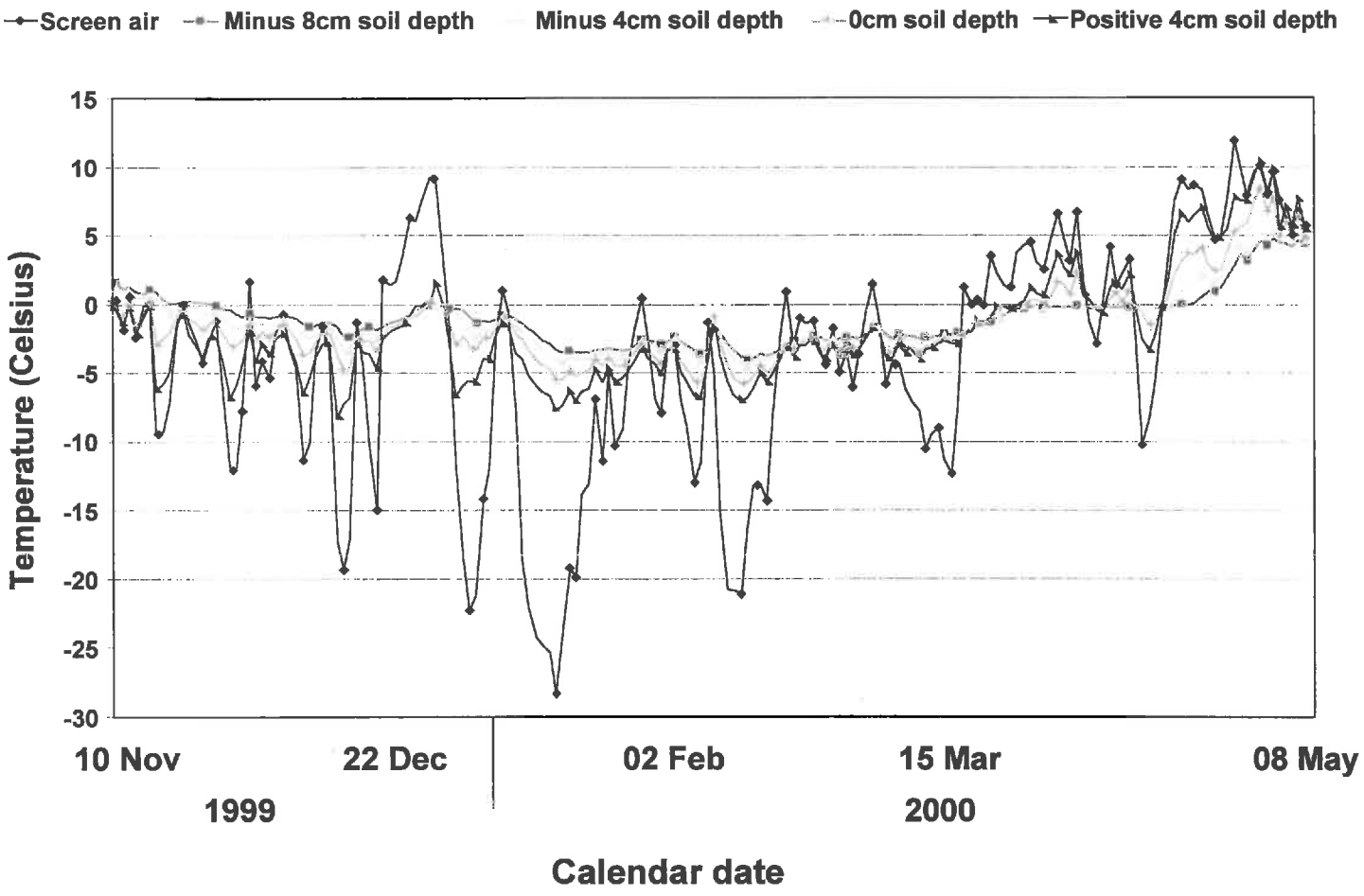


Figure 60. Mean daily overwintering temperature data from probes positioned at +150 cm (from soil/litter interface), -8 cm, -4 cm, 0 cm and +4 cm in a headland between 10 November 1999 and 8 May 2000 in Beaverlodge, AB at Site 1.

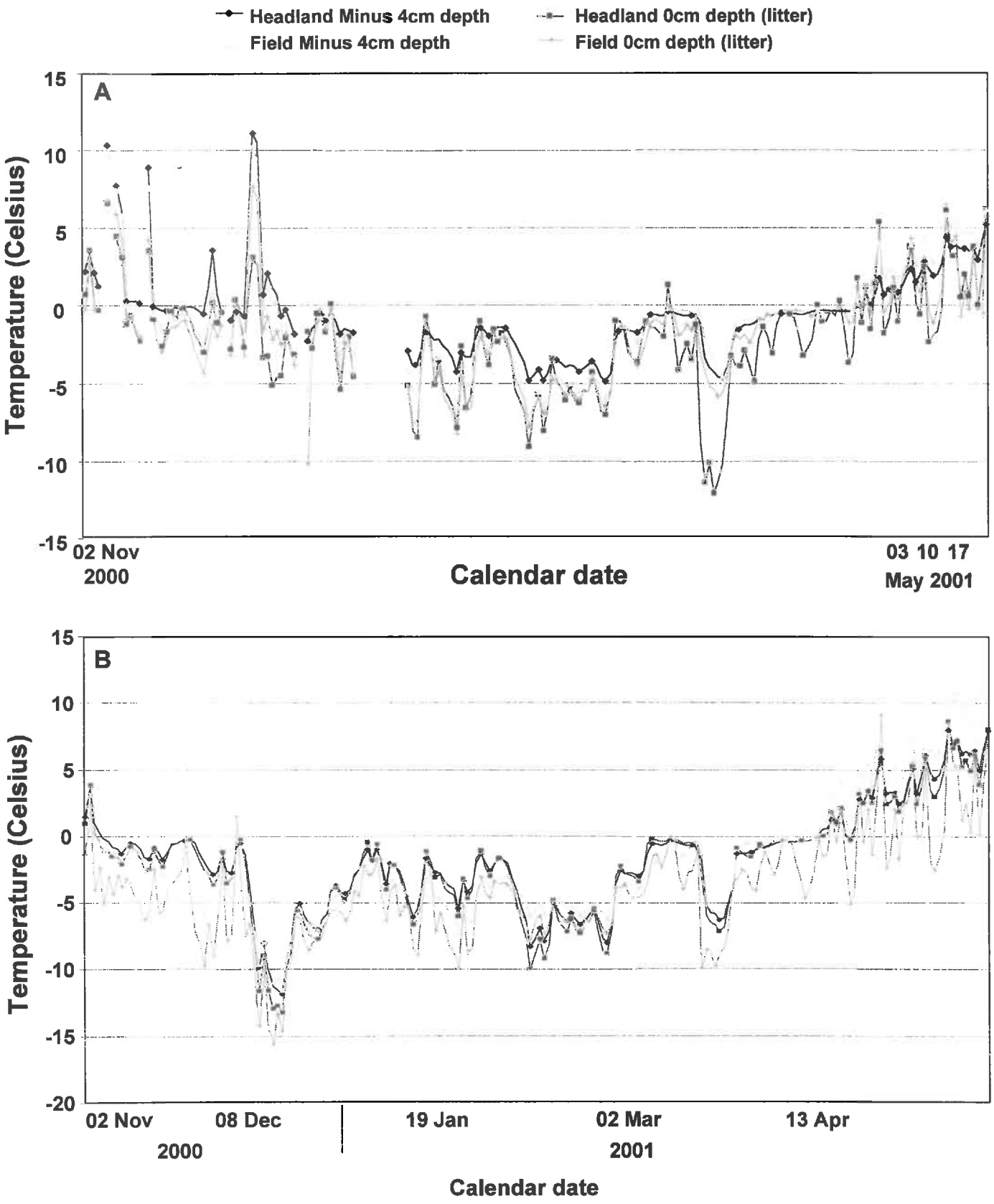


Figure 61. Mean daily overwintering temperature data from probes positioned at 0 cm (from soil/litter interface) and –4 cm depths in a headland and adjacent field between 2 November 2000 and 17 May 2001 in Beaverlodge, AB at (A) Site 1 and (B) Site 2.

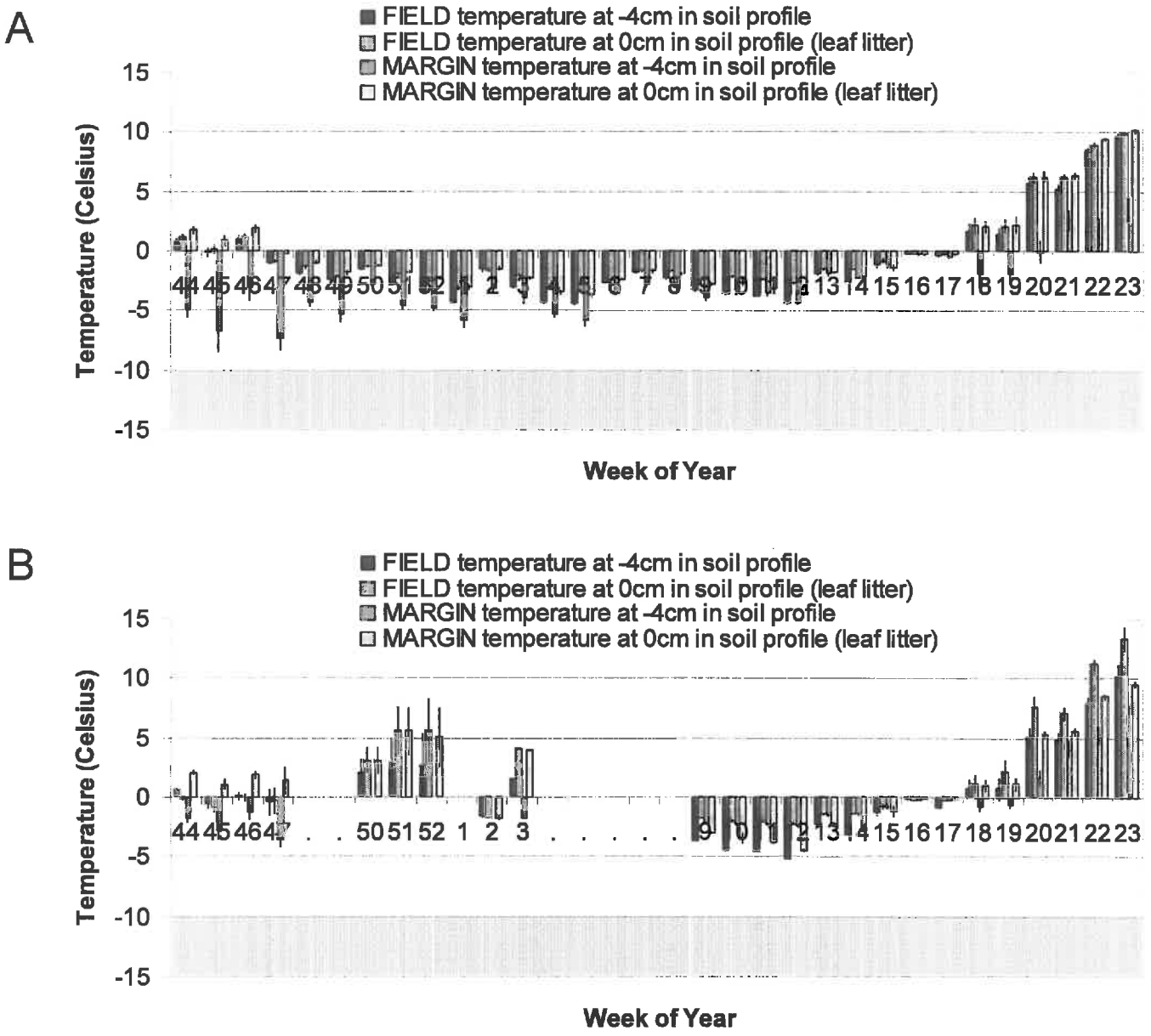
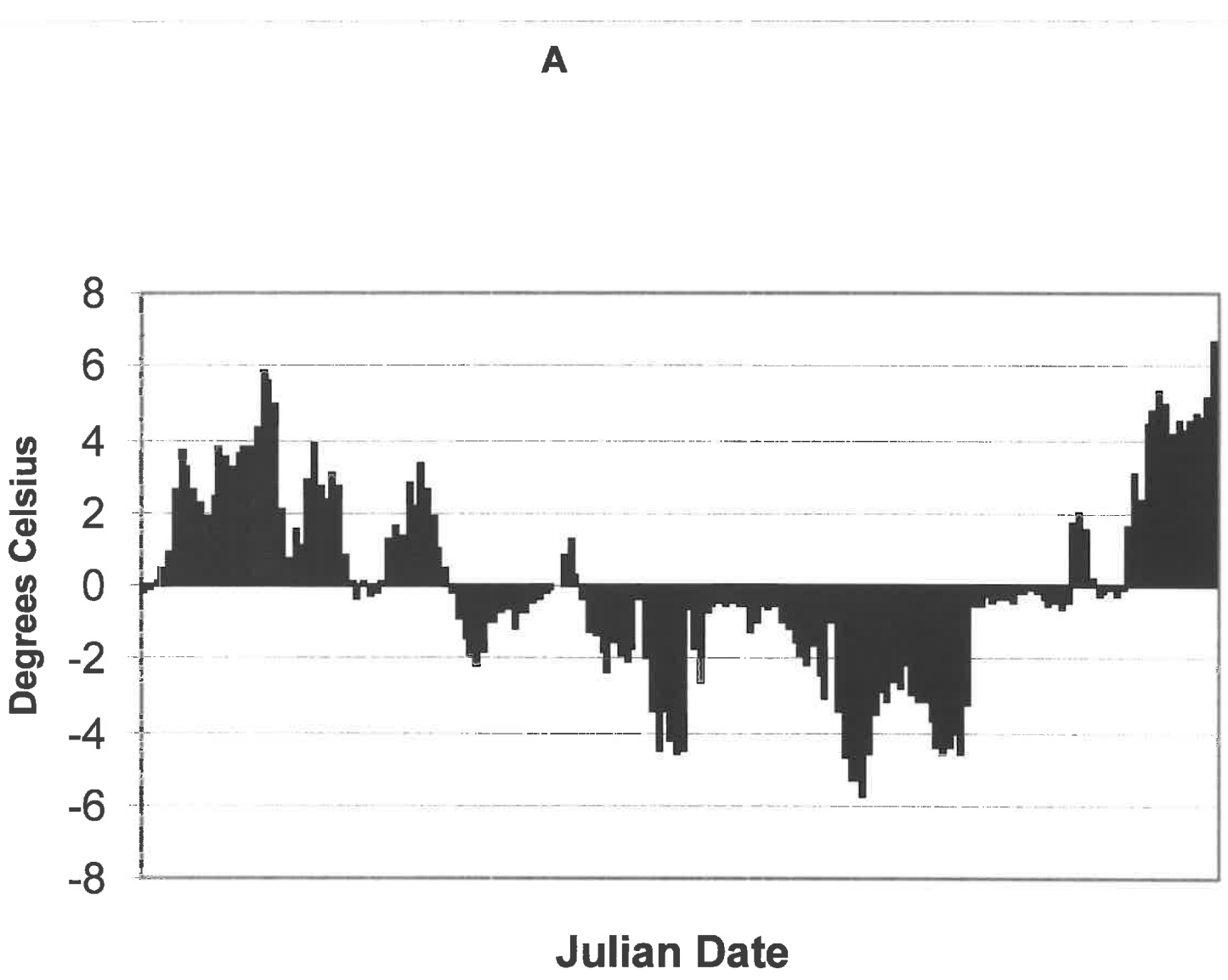


Figure 62. Mean weekly temperatures of soil profile at 0 cm (leaf litter) and -4 cm (below soil surface) levels measured hourly at (A) Site 1, and (B) Site 2 at Beaverlodge, Alberta during the wintering of 2001-2002. (Notes: Error bars represent standard error of the mean; approximate supercooling values for cabbage seedpod weevil ☐ and lygus bugs ☐ observed in the cold-hardiness study.)



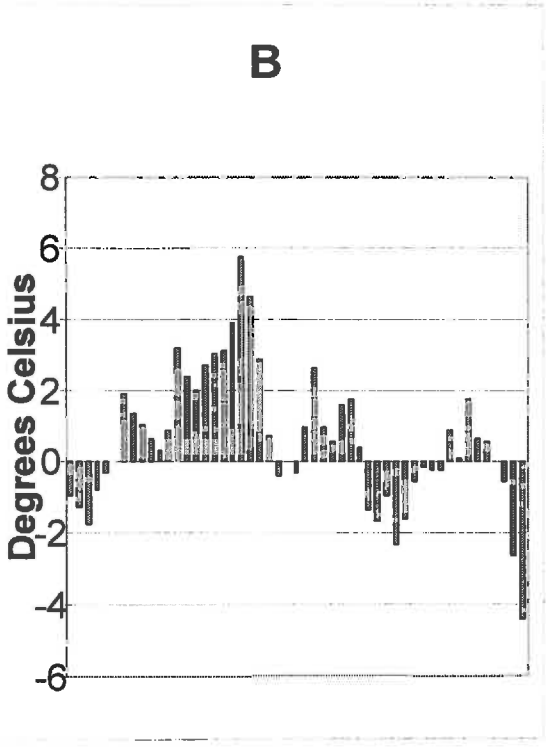


Fig. 63. Minimum daily soil temperatures near Lethbridge, AB at a tree shelter (LRC south Nov. 1, 2002-April 22, 2003) and an alfalfa field (Victory, Nov. 1, 2002 to Dec. 21, 2002).

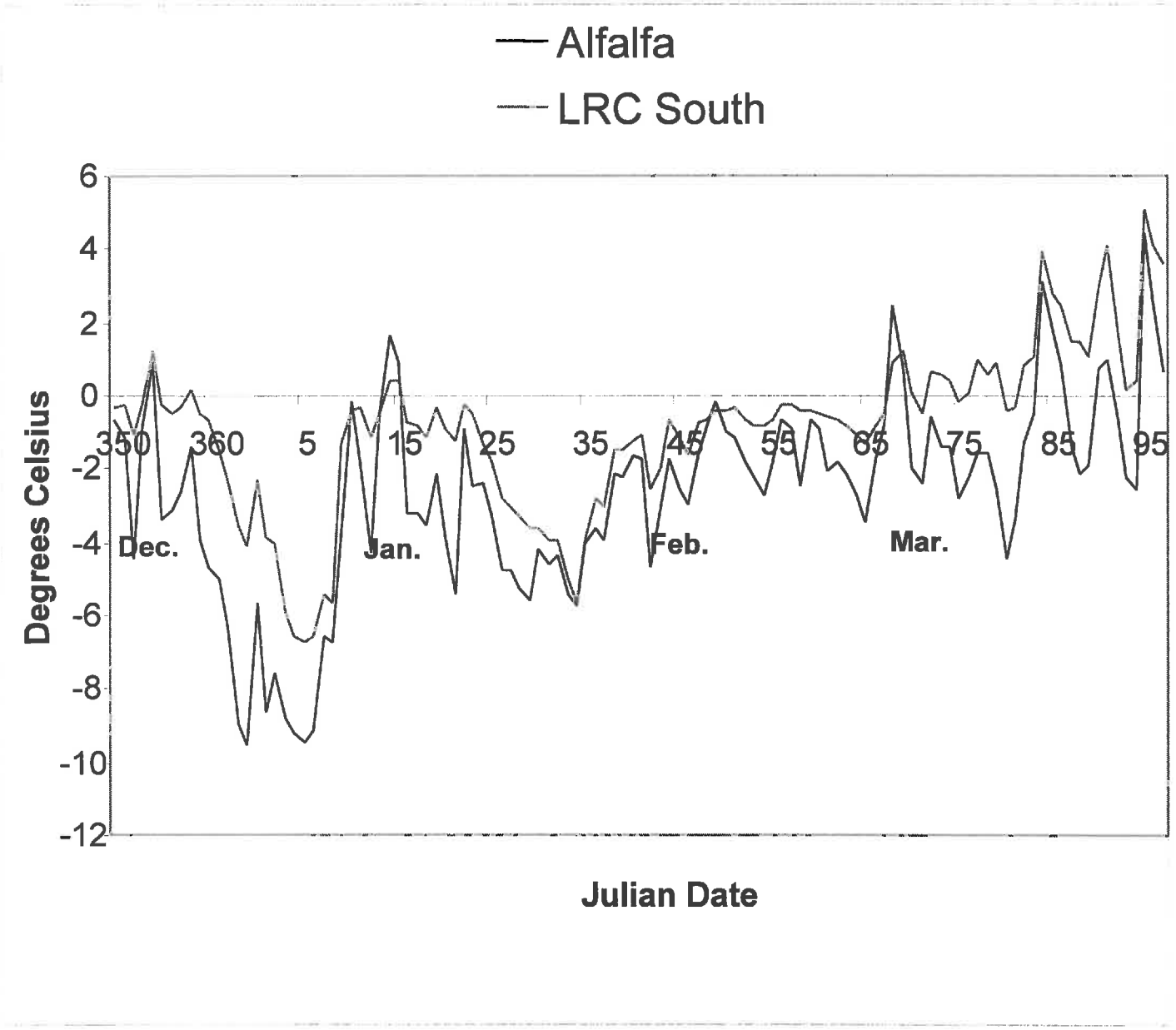


Figure 64. Minimum daily litter temperatures near Lethbridge from 16 December 2003 to 6 April 2004 at a tree shelter (LRC south) and an alfalfa field.