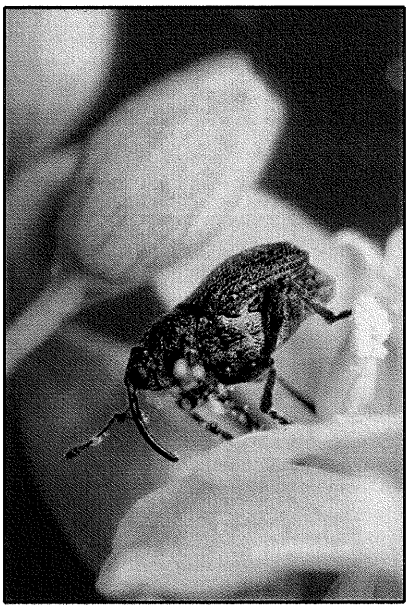
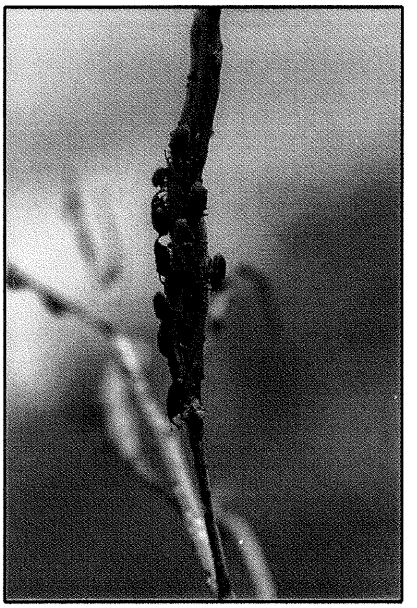
CARP 9908

Biology and Control of the Cabbage Seedpod Weevil,

A New Pest of Canola in Alberta





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Abstract

The cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham), was first observed infesting canola fields in Alberta only in 1995, but already it has dispersed extensively throughout southern and central Alberta. In 1999 and 2000, outbreaks of the cabbage seedpod weevil occurred in Alberta, with population densities as high as 15 to 80 adults per sweep net sample. These infestation levels were well in excess of the economic threshold of 2 to 3 adults per sweep net sample that is used in the U.S.A., and the threshold of 3 to 4 adults per sweep that has been used in Alberta.

Most research results reported here were obtained during the 1998 and 1999 field seasons because data from several studies conducted near Lethbridge in 2000 were compromised by frost and severe drought. In the 2000 studies, it was often difficult to separate, with confidence, effects of weevil feeding versus effects of the drought.

Adult weevils emerged from their overwintering sites over an extended period in early spring. Mating occurred for several weeks, and in spring adults initially occurred in high densities in volunteer canola and in cruciferous weeds. Wild mustard was a true host of cabbage seedpod weevil because larval development occurred within pods of this plant. Before canola crops were susceptible to invasion of the cabbage seedpod weevil in the bud to flowering stages, adult weevils fed upon flixweed, stinkweed, and hoary cress but no larval development occurred in pods of these species.

Although greater numbers of weevils tended to occur in early-seeded plots of canola than in plots seeded later, these differences were not significant statistically. Altering seeding date in spring plantings does not appear to hold great promise, therefore, as a cultural control strategy for this pest. However, the *Brassica napus* cultivar, Option 500, was found to be significantly less susceptible to attack by the weevil than the Hylite 201 and Hyola 401 cultivars. Canola growers should therefore be encouraged to plant less susceptible varieties like Option 500.

Species of Brassicaceae differed in their susceptibilities to infestation by cabbage seedpod weevil. For the species and cultivars we evaluated under field conditions, *Brassica napus* cv. Q2 was most susceptible, *Brassica juncea* cvs. Forge and Commercial Brown

were intermediate in susceptibilities, and *Sinapis alba* cv. AC Pennant was resistant to infestation. *Sinapis alba* can therefore serve as a genetic source of resistance to cabbage seedpod weevil for use in germplasm development programs to eventually develop canola resistant to attack by this pest.

In 1998 and 1999, no evidence of parasitism was observed in either larvae or adults of Alberta populations of *C. obstrictus*. In 2000, however, parasitoids infesting cabbage seedpod weevil adults were found at three sites near Lethbridge. At one site, hundreds of weevils were collected and placed into screened cages to capture emerged parasitoid adults; parasitism levels of approximately 18% were then recorded from this site. The identity of this parasitoid has not yet been verified, but it is a member of the Hymenoptera family Braconidae, subfamily Euphorinae. It is probable that this is the European parasitoid *Microctonus melanopus* Ruthe, a species previously found to be significant in reducing survival of adult weevils in Idaho and Washington.

Pan trap sampling was effective for monitoring adult weevil populations in the seedling and rosette stages of canola development, but as crop development proceeded, sweep net sampling was a more effective monitoring strategy. Because adults of *C. obstrictus* are most attracted to canola in the bud to flowering stages, it is recommended that canola growers use sweep net sampling to monitor cabbage seedpod weevil populations in their crops.

The distribution and abundance of the cabbage seedpod weevil increased extensively in 1999 and 2000 relative to 1998 and 1997. In 2000, the range of the species extended as far north as Innisfail, Olds, Oyen, and Hanna, and as far east as southwestern Saskatchewan. Population densities of the cabbage seedpod weevil were much greater than those observed in previous years. Pan trap sampling was conducted in canola research plots at sites in close proximity to each other from 1998 to 2000. Mean numbers of adult weevils per pan trap sample recorded during the first week of June in each year increased 232-fold between 1998 and 2000, and 14-fold between 1999 and 2000.

Insecticides now used to control other important insect pests of canola are also effective for controlling infestations of cabbage seedpod weevil. In particular, synthetic pyrethroid products are very effective, providing rapid mortality of cabbage seedpod weevil

adults. Synthetic pyrethroid insecticides are advantageous for weevil control compared with some organophosphate insecticides because they have little residual activity – an important consideration because it is necessary to spray crops in flower to attain maximum weevil mortality in canola.

It is evident that further research is needed to meet the challenges posed by this serious pest of canola. Research should be undertaken to evaluate various cultural control strategies like trap cropping, fall seeding, altering seeding rates, fertility regimes, and row spacings to identify those practices most effective in increasing the competitiveness of the crop relative to the pest. Biological control of the cabbage seedpod weevil should be enhanced. In the United States and Europe, biocontrol agents cause major reductions in cabbage seedpod weevil populations, but in Alberta, only small populations of parasitoids were found. Research should be undertaken to identify and evaluate different biological control agents of cabbage seedpod weevil, to obtain any necessary regulatory approvals for their release in western Canada, and to eventually release biocontrol agents at different sites throughout western Canada. Finally, a germplasm development program should be initiated to evaluate species and cultivars of Brassicaceae to identify sources of resistance, to use biotechnological approaches to locate the genes for resistance in the genome, and to then transfer resistance genes to commercial cultivars of canola. By using such a multi-faceted approach to pest management that involves attacking cabbage seedpod weevil infestations from several different angles at the same time, it should be possible to limit crop losses from this pest and improve the profitability of canola production in western Canada.

Introduction

In 1995, an unusual insect larva was found feeding on seeds in canola pods in research plots near Lethbridge, Alberta. Adult specimens collected in 1996 were identified as *Ceutorhynchus obstrictus* (Marsham) (= *C. assimilis* Paykull), the cabbage seedpod weevil. The discovery immediately raised concern among members of the canola industry because this species is a very serious pest of canola and rapeseed throughout Europe and the United States (McCaffrey 1992; Buntin et al. 1995; Dmoch 1965). At present, weevil populations in northwestern United States are regulated to some degree by natural enemies, primarily the parasitic braconid wasp, *Microctonus melanopus* Ruthe; however, application of broad-spectrum chemical insecticide (methyl parathion) for control of *C. obstrictus* is necessary in the U.S. for the economical production of canola. Yields in the U.S. can be reduced by as much as 35% without one or two insecticide applications per season (McCaffrey et al. 1986; Harmon and McCaffrey 1997).

The cabbage seedpod weevil has a single generation per year. Adults are ash-grey and 3 to 4 mm long with a prominent curved snout that is typical of most weevils. Cabbage seedpod weevil overwinters as sexually immature adults (Carlson et al. 1951) in protected areas such as beneath leaf litter in shelterbelts and roadside ditches (Dmoch 1965; Cárcamo, pers. comm.). When air temperatures reach approximately 12°C in spring, they fly from these sites to cruciferous host plants in the family Brassicaceae (Dmoch 1965). Adults are attracted to canola crops as they begin to flower. As soon as pods develop on canola, females form feeding punctures in the pods, and may then deposit a white, cylindrical egg into a puncture. Eggs hatch in approximately one week. Larvae are white with light brown head capsules, and feed on developing seeds within the seedpods. Each larva consumes about five seeds in its lifetime (Dmoch 1965). Mature larvae chew small, circular exit holes in the walls of the seedpods, drop to the soil surface, burrow into the soil, and pupate. Adults emerge approximately ten days later, and feed on canola or other cruciferous plants until late in the season when temperatures decline and they then remain in diapause throughout winter.

No published information exists on the biology and control of the cabbage seedpod weevil in canola in Canada, and there are currently no insecticides registered in Canada for its control. The focus of this project was to determine important aspects of the phenology, distribution, and control of *C. obstrictus* in spring canola in Alberta. This information will be essential to the development of an integrated management strategy for this pest. The specific objectives of the project were:

1) to determine aspects of the biology of the cabbage seedpod weevil in spring canola in Alberta;
2) to determine the natural enemy complex of *C. obstrictus* in Alberta;
3) to determine appropriate monitoring strategies for *C. obstrictus* in canola;
4) to monitor changes in the distribution and abundance of *C. obstrictus* in Alberta; and
5) to evaluate chemical insecticides for control of *C. obstrictus*.

Methods and Materials

Biology of Cabbage Seedpod Weevil in Canola in Alberta. Most studies on the biology of *C. obstrictus* were conducted at the Canola Council of Canada's Production Centre sites near Lethbridge (112°39′ W; 49°37′ N). The sites were in the mixed grassland ecoregion which is characterized by moisture deficits in late summer due to low precipitation (mean average = 250 to 350 mm) and high evapotranspiration. The soil type is brown chernozemic, and was fertilized prior to seeding with nitrogen, phosphorus, potassium, and sulfur according to the soil test recommendations for canola production.

a) 1998 Studies on Seeding Date Effects on Weevil Infestations. In 1998, research plots were established in a randomized complete block design with four replications to assess the effect of seeding date of *Brassica napus* L. on infestations of cabbage seedpod weevil. Plots were seeded on three dates in spring: 21 April, 1 May, and 13 May; these correspond to 'early', 'normal', and 'late' planting dates, respectively, according to accepted agronomic practices for this agricultural region. Plot dimensions were 6 by 100 m. Plots were seeded into wheat stubble with a John Deere 9450 Hoe Press

Drill using 18 cm row spacings at a rate of 6.6 kg per ha. All seed was treated with Vitavax rs® to reduce seedling mortality from phytopathogens and herbivory by flea beetles.

On 13 May 1998, following seeding of plots on the 'late' date, three pan traps were set in random locations within each replicate plot. The aluminum foil pan traps measured 30.0 by 23.5 by 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 and counted.

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 at –20°C until weevil specimens could be sorted and counted.

b) 1999 Studies on Effects of Variety and Seeding Date on Weevil Infestations. In 1999, research plots were established in a randomized complete block design with four replications to assess effects of variety and seeding date on infestations of cabbage seedpod weevil. Three varieties of *Brassica napus* (cvs. Hylite 201, Hyola 401, and Option 500) were seeded into barley stubble on 22 April and 4 May 1999 with a John Deere 9450 Hoe Press Drill at a rate of 6.6 kg per ha with 18 cm row spacings. Plot dimensions were 6 by 100 m. All seed was treated with Vitavax rs® to reduce seedling mortality from phytopathogens and herbivory by flea beetles.

On 5 May 1999 three pan traps were set in random locations within each replicate plot. The aluminum foil pan traps measured 30.0 by 23.5 by 6.5 cm, were anchored to the soil with wire rods inserted through two opposite sides of each trap, and were filled with a 35% 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 and counted.

When canola reached the rosette to bud stages of development, sweep net samples were 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 at –20°C until weevil specimens could be sorted and counted.

When cabbage seedpod weevil larval exit holes were abundant in canola pods on the research plots (approximately one week after the first weevil exit holes appeared), a 1 m^2 area of canola was cut down within each replicate plot and an emergence trap was placed onto the stubble. The emergence traps were pyramidal and followed the design of Dosdall et al. (1996). Twice weekly for four weeks, all newly emerged weevil adults 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.

At the end of the season, collections were made of 25 to 30 canola plants from each replicate plot, and numbers of pods per plant and numbers of cabbage seedpod weevil exit holes per plant were counted and recorded. Infestation levels were assessed as the percentages of pods with exit holes from the total number of pods per plant, and were determined by their positions on canola racemes. Each raceme was measured, divided into thirds, and the cabbage seedpod weevil exit holes from the lower, middle, and upper regions of the racemes were counted and recorded.

Data from pan trap samples, sweep net samples, and emergence trap samples were transformed logarithmically, $\log_{10}(x + 1)$, and subjected to analysis of variance using the General Linear Models procedure (SAS Institute, Inc. 1990). Tukey's studentized test was used to determine significance of differences in weevil infestation levels among the different varieties and seeding dates.

c) Studies on Alternate Host Plants of Cabbage Seedpod Weevil. From late April to late May of 1998, 1999, and 2000, several species of native and introduced flowering plants were examined visually and with sweep net sampling to determine whether they served as feeding hosts for cabbage seedpod weevil adults. Twelve plant species representing five families were examined, including Canada anemone (*Anemone canadensis* L.) and prairie buttercup (*Ranunculus rhomboideus* Goldie) (Ranunculaceae), pennycress (*Thlaspi arvense* L.), flixweed (*Descurainia sophia* (L.) Webb, volunteer canola (*B. napus*

and *Brassica rapa* L.), wild mustard (*Sinapis arvensis* L.), hoary cress (*Cardaria pubescens* (Meyer) Rollins), and shepherd's-purse (*Capsella bursa-pastoris*) (L.) Medic. (Brassicaceae), saskatoon (*Amelanchier alnifolia* Nutt.) (Rosaceae), dandelion (*Taraxacum officinale* Weber) (Compositae), and golden bean (*Thermopsis rhombifolia* (Nutt.) Richardson) (Leguminosae).

On 10 June 1999, a mixed stand of cruciferous weeds comprising flixweed (*D. sophia*), stinkweed (*T. arvense*), and wild mustard (*S. arvensis*) in approximately equal densities was examined to determine the relative susceptibilities of these Brassicaceae as hosts for cabbage seedpod weevil adults. The stand was located approximately 6 km south of Lethbridge along Highway 4. Weevil specimens on each of 50 plants of each species were counted, and their positions on each plant recorded as either on stems, leaves, or buds/flowers. On 10 August 1999, 50 plant specimens of each species were examined for the presence of larval exit holes in mature pods.

d) Field Evaluations of Susceptibilities of Canola and Mustard Varieties to Infestation by Cabbage Seedpod Weevil. Field trials were conducted in 1999 at Bow Island (111°37′W; 49°87′N) and Stirling (112°52′W; 49°50′N) to evaluate the susceptibilities of *B. napus* cv. Q2, *B. juncea* cvs. Forge and Commercial Brown, and *S. alba* cv. AC Pennant to infestation by cabbage seedpod weevil. In the year preceding the study, the Bow Island site was fallow and the Stirling site was seeded to a cereal crop. Plots were seeded on 14 June 1999 (Bow Island) and 15 June 1999 (Stirling) in a randomized complete block design with four replications. Each plot was 6 m in length, comprised of eight rows spaced 18 cm apart.

At maturity, 10 plants from each research plot were cut at the base, bagged, and labelled. Counts were made of the total numbers of pods per plant and numbers of infested pods per plant (i.e., pods with exit holes made by final-instar larvae when they emerged from pods to pupate). Seed from the plant specimens was then threshed, cleaned, and weighed to determine seed yield per sample.

Data on exit hole counts and seed yields were transformed logarithmically, $\log_{10}(x + 1)$, and subjected to analysis of variance using the General Linear Models procedure (SAS

Institute, Inc. 1990). Tukey's studentized test was used to determine significance of differences in weevil infestation levels and seed yield among the different cultivars.

e) Studies on Pre-imaginal Developmental Biology of Cabbage Seedpod Weevil in Relation to Development of Canola Host Plants. In 1999, collections of 100 randomly selected pods of *B. napus* cv. Option 500 were made each week for four weeks from the canola research site near Lethbridge. The first collection was made on 14 July when most plants were in Growth Stages 4.3 to 4.4 of Harper and Berkenkamp (1975). In Growth Stage 4.3, lower pods are starting to fill, and in Growth Stage 4.4 flowering is complete and seeds are enlarging in the lower pods. The final collection was made on 10 August when most plants were in Growth Stages 5.3 to 5.4 of Harper and Berkenkamp (1975). In Growth Stage 5.3, seeds in lower pods are a green-brown in color, indicating the advent of pod ripening; in Growth Stage 5.4, seeds in the lower pods are brown.

Pods were dissected under a stereomicroscope and all pre-imaginal weevil specimens were removed and their developmental stages were recorded. Each pod was measured to determine its length, width, and depth (height). Length measurements were made with a caliper from the distal tip to the 'collar' or receptacle between the pedicel and the pod. Width and depth (height) measurements were made with a caliper at three points: medial, or at the longitudinal midpoint between the distal tip and the collar; proximal, or at the longitudinal midpoint between the proximal tips of the valves and the medial point; and distal, or at the longitudinal midpoint between the distal tips of the valves and the medial point. Width measurements were made across the suture of the septum, and depth (height) measurements were made across one valve.

f) Crop Damage Caused by Cabbage Seedpod Weevil Infestations. In all years of the study, canola crops in southern Alberta were observed to determine the type of crop damage caused by these pests, both in the adult and larval developmental stages. This involved making behavioral observations of adult feeding on buds and pods, and assessments of damage by larvae feeding within canola pods.

In 2000, three fields were found in southern Alberta that experienced rainfall after exit holes developed on seedpods from emergence of final-instar larvae. Approximately 100 pods with weevil exit holes were collected from each field, and counts were made of

the number of seeds per pod consumed by cabbage seedpod weevil larvae, the number of seeds per pod damaged by secondary fungal infection, and the number of undamaged seeds per pod.

g) Morphological Studies of Cabbage Seedpod Weevil Life Stages. No detailed descriptions exist of the morphology of cabbage seedpod weevil life stages; consequently, studies were undertaken to determine morphological characteristics of different life stages using both phase contrast and scanning electron microscopy. Specimens of each life stage were collected by dissecting canola pods in varying stages of development, and pre-imaginal stages were preserved in 95% ethanol.

For phase contrast microscopy, soft tissues of final-instar larvae were dissolved by placing them in a 1.5 mL polypropylene microcentrifuge tube filled with a saturated solution of potassium hydroxide. An incision was made along the ventral body surface of each specimen from the penultimate abdominal segment to the head capsule to aid the penetration of the potassium hydroxide solution. The specimens were removed from the solution after one hour and excess soft tissue was cleared using a stream of 70% ethanol. The larvae were then returned to the potassium hydroxide solution until fully cleared. Cleared specimens were transferred through a series of ethanol solutions (70% to 95% to 100%) for dehydration. Specimens were held in each solution for at least 30 min. The head capsules were detached from the bodies for examination and dissection of the mouthparts; the labrum, mandibles, maxillae, and labium were removed from the head capsules with fine dissecting probes. Entire head capsules, dissected mouthparts, and body cuticles were placed in xylene for 1 h to complete the dehydration procedure before being mounted on slides with Permount® mounting medium. Slides were examined under a phase contrast microscope equipped with a camera lucida for description of morphological characters.

For morphological studies with scanning electron microscopy, eggs and larvae were immersed in formaldehyde and placed into a vacuum chamber to aid in penetration of the fixative. Larvae were punctured using a minuten pin to facilitate movement of the fixative through their bodies. After approximately 16 h, the specimens were removed from the vacuum chamber and dehydrated through a series of ethanol solutions (70% to 95% to 100%). Specimens were held in each solution for at least 1 h, critical point dried, mounted

on SEM pegs, and coated with gold for examination under the scanning electron microscope.

Measurements were made of cabbage seedpod weevil eggs, head capsule widths of the different larval instars, and body lengths of final-instar larvae using an ocular micrometer mounted in a dissecting microscope. Eggs were obtained from dissections of mature females. All eggs examined were entire and chorionated. It was assumed that they had descended into the oviducts because the ovary tissue was stretched and weakened, and eggs dispersed freely during dissection. Egg measurements were made on their longest and widest axes. Head capsules were measured dorsally along the widest axis, and body length measurements were made dorsally from the base of the head capsule to the tip of the abdomen.

Natural Enemies of Cabbage Seedpod Weevil in Alberta.

a) Parasitoid Studies. In 1998, adults of *C. obstrictus* were collected by sweep net in May (302 specimens), June (211 specimens), July (273 specimens), and August (35 specimens) from commercial canola fields near Lethbridge. Beetles were transferred from sweep nets to sterile glass containers and transported in coolers to a laboratory at the University of Alberta (Edmonton). Adults were maintained individually in sterile petri-plates with plastic tubes containing 30% honey water and a cotton stopper. Specimens were examined daily for 21 d for evidence of parasitoid emergence.

In 1999, adult weevils were collected for evidence of parasitoid infestation in May (125 specimens), June (304 specimens), July (260 specimens), and August (80 specimens) and were held in the same manner as described above. In addition, four weekly collections of 300 canola pods per week were made from a canola field near Lethbridge beginning on 14 July with the final collection on 10 August when plants had dried down and were ready for swathing. Pods were dissected under a stereomicroscope and examined for evidence of parasitism to weevil larvae.

In 2000, 100 adult weevils were collected each week from commercial canola fields near Lethbridge, AB from 23 May to 4 August inclusive, dissected under a stereomicroscope, and examined for evidence of parasitism (total = 1100 weevils over 11

weeks). In addition, weekly collections of 250 pods per week were made from 21 July to 4 August (total = 750 pods over 3 weeks), dissected and examined for evidence of parasitism of weevil larvae.

On 27 June 2000, a small collection of adult weevils (n = 25) was made from a roadside ditch populated with a mixed stand of cruciferous weeds (primarily wild mustard, *S. arvensis*, and pennycress, *T. arvense*). Specimens were dissected to examine their reproductive state, and in the process it was evident that two of the weevils were parasitized. One weevil contained an egg with a visible embryo, and the other contained a larva. Consequently, a thorough sweep net collection was undertaken at the site, and all adult weevil specimens collected (n = 508) were transferred with soft forceps to a screened cage (40.5 cm by 40.5 cm at the base and 80.5 cm high, lined on the sides with 500 μm Nitex® mesh screening). The cage contained a bottle filled with 50% sucrose solution with a cotton wick protruding through the mouth of the bottle. The cage was held at 25°C, 16 h L : 8 h D, for 13 d and then examined for evidence of parasitoids. Emerged parasitoids and living and killed adult weevils were transferred to vials containing 70% ethanol. Preserved weevil specimens were then examined for evidence of exit holes by the parasitoids, and specimens not bearing parasitoid exit holes were dissected for evidence of parasitoids that did not emerge from their hosts.

Additional collections of cabbage seedpod weevil adults were made in 2000, and specimens were dissected to determine evidence of parasitism. These included 75 and 74 adults collected in a commercial field of *B. napus* near Nobleford, AB (113°03′ W; 49°53′ N) on 29 June and 11 July, respectively, and 123 adults from a commercial field of *B. rapa* also near Nobleford, AB and adjacent to the *B. napus* field. On 12 June and 23 June, 117 adults were collected on each date from a stand of flixweed (*D. sophia*) near the Lethbridge Research Centre of Agriculture and Agri-Food Canada, and 140 specimens were collected from a stand of *B. rapa* approximately 4 km south of Lethbridge, AB. Specimens were held in glass jars (volume ≅ 1 L) until dissections were performed.

b) Pathogen Studies. On 7 June 1998, 50 adult specimens of *C. obstrictus* were collected from a commercial canola field near Lethbridge and maintained in a screened cage as described above in a growth chamber at 21°C, 16 h L : 8 h D. The weevils were divided

into two groups of 25 each and transferred to 2 L glass containers with paper towel bedding and a cotton wick attached to a container of honey water (10% w/v). Prior to their use, containers, honey water, and cotton were autoclaved, and drinking tubes were washed in sodium hydrochloride (10%) and sterile water. Spores of *Beauvaria bassiana* FTC-1 strain were harvested from the culture maintained on the artificial medium, PDA (potato dextrose agar) plates, and dispensed in 1 mL of potassium phosphate buffer (30 mM) to make the final concentration of 1.93×10^6 spores per mL. Twenty-five weevil adults from one experimental colony were transferred to individual sterile plastic petri dishes containing filter paper, where each weevil was surface contaminated with 30 µL of *B. bassiana* inoculum per specimen and kept in the petri dish for 30 min. All treated weevils were then transferred back to the glass container. The control specimens were treated the same way, except that potassium phosphate buffer was applied instead of *B. bassiana* inoculum. Both colonies were observed for mortality every day for 21 days.

Ten specimens of *C. obstrictus* were selected randomly from rearing colonies and examined for the presence of external and internal microbes that may be pathogenic to their hosts. To identify external symbionts, five adults were allowed to walk on PCA (plate count agar) and PDA plates for two minutes. To detect internal symbionts, five adults were surface sterilized, homogenized in 100 µL of potassium phosphate buffer, and plated on PCA and PDA plates. In both experiments, plates were incubated aerobically at room temperature (22 ± 2°C).

Monitoring Changes in the Distribution and Abundance of *C. obstrictus*. From 25 June to 7 July of 1998, 1999, and 2000, when most canola crops in southern and central Alberta were in the flowering stage, 102 to 127 fields were sampled for adults of *C. obstrictus* in an area extending from Red Deer south to the U.S. border, east to the Saskatchewan border, and west to the limits of canola production near the Rocky Mountains. In 1998, fields were sampled in Alberta only, but in 1999 and 2000 researchers from Agriculture and Agri-Food Canada in Saskatoon participated in the survey by sampling canola fields in western Saskatchewan. For each field, data were collected on the crop stage, crop species, geographical location, and collection date. Weevil populations were estimated as numbers

per 25, 180° sweep net samples. Sampling of each field commenced at the edge and progressed inward over a distance of about 25 to 30 metres.

Maps of cabbage seedpod weevil infestations for western Canada were developed using Tydac's SPANS (Spatial Analysis System) software. The program divided the area into a fine grid of "quadtree" cells, and a value was estimated for each cell by averaging data from samples collected from nearby locations. The number of observations used for each average was specified, as well as the way in which their influence decayed with distance.

Monitoring Methods for Cabbage Seedpod Weevil. Three methods were assessed for their effectiveness for monitoring populations of *C. obstrictus*: sticky card sampling, pan trap sampling, and sweep net sampling. Sticky cards were evaluated during the 1998 field season. On 30 May 1998, 50 yellow cards, coated with Tanglefoot® spray adhesive were placed at 10 m intervals along the edge of a commercial field of *B. napus* in the bud stage of development (Growth Stage 3.1 of Harper and Berkenkamp 1975). An additional 50 cards were placed in a row approximately 50 m in from the crop edge and spaced 10 m apart, and 50 cards were placed approximately 100 m from the crop edge and spaced about 10 m apart. The cards were mounted on small sticks, at the level of the crop canopy. Cabbage seedpod weevil adults were present in the crop, at a density of approximately 1 per 180° sweep net sample.

Pan trap and sweep net sampling methods are described above in the section on the biology of the cabbage seedpod weevil and were evaluated in both 1998 and 1999.

Evaluation of Insecticides for Control of Cabbage Seedpod Weevil.

i. Insecticide evaluations conducted in 1998. Two approaches were used to assess insecticide efficacy for the control of cabbage seedpod weevil in canola: 1) small-scale replicated tests with caged adults, and 2) larger-scale replicated studies conducted in commercial canola fields. The tests with caged weevils were conducted to determine appropriate dosages for field trials, and field trials were needed to validate efficacy under ambient environmental conditions.

The tests with caged weevils used 10 adult specimens per cage, and four replicate cages per treatment. The cages were aluminum foil pans (30 cm by 20 cm at the base, and 5 cm high), covered with coarse mesh screen. Spraying of the insecticides was performed outdoors with a Roger's shrouded sprayer, calibrated to deliver the correct volumes and droplet sizes into the cages. The products and application rates evaluated were Admire® (imidacloprid) at 50 and 100 g a.i. per ha, Di-Syston® (disulfoton) at 200 and 400 g a.i. per ha, Dylox® (trichlorfon) at 200 and 400 g a.i. per ha, Furadan® 480F (carbofuran) at 65 and 130 g a.i. per ha, Metasystox-R® (oxydemeton-methyl) at 150 and 300 g a.i. per ha, Decis EC® and Decis FLO® at 5 g a.i. per ha, Lorsban® 4E (chlorpyrifos) at 180 and 360 g a.i. per ha, and Spinosad® (spinosyn) at 60 g a.i. per ha. Insecticide application rates were selected based on registrations for other insect pests, or a best judgement; one-half this rate was then used for the next treatment. Wettable paper was placed inside the pans in addition to a flowering raceme of *B. napus*, and the sprayer speed was assessed with a speedometer. A quad was used to pull the sprayer, and accurate velocities and spray volumes were maintained over the pans. Numbers of living and dead weevils were recorded 1, 12, and 48 h after application of the insecticides.

Two trials to assess the efficacy of selected insecticides were conducted in commercial fields near the Canola Council of Canada's Production Centre site at Lethbridge (ca. 4 km south of Lethbridge). The experiments were randomized complete block designs with four replications; each replicate plot measured 9 m by 9 m. The crop at both sites was *B. napus*, and at the time of the studies, approximately 70% of flowering had been completed. Treatments were applied on 8 July 1998 (Trial 1) from 11:15 h to 16:15 h, and on 9 July 1998 (Trial 2) from 12:45 h to 16:05 h. The insecticides tested were Admire® (imidacloprid) at 200 g a.i. per ha, Dylox® (trichlorfon) at 1120 g a.i. per ha, Metasystox-R® (oxydemeton-methyl) at 150 g a.i. per ha, Decis EC® at 7.5 g a.i. per ha, Lorsban® 4E at 350 and 420 g a.i. per ha, and Spinosad® at 100 g a.i. per ha. No rain was received at either site from the beginning to the end of the studies. A custom-built plot sprayer was used to apply the insecticides. 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.

Air temperatures at times of insecticide application for Trial 1 were: Dylox®, 27°C; Metasystox®, 28°C; Admire®, 27°C; Decis®, 28°C; Lorsban® 4E at 350 g a.i. per ha, 28°C; Lorsban® 4E at 420 g a.i. per ha, 30°C; and Spinosad®, 26°C. Wind speed during the applications ranged from 1.0 to 11.0 km per h, and cloud cover was 30 to 60%. For Trial 2, air temperatures at times of application were: Dylox®, 24°C; Metasystox®, 26°C; Admire®, 27°C; Decis®, 26°C; Lorsban® 4E at 350 g a.i. per ha, 26°C; Lorsban® 4E at 420 g a.i. per ha, 26°C; and Spinosad®, 28°C. Wind speed during the applications ranged from 0 to 2.0 km per h, and cloud cover ranged from 5 to 30%.

Plots were sampled approximately 2 h before treatment, and 24 and 48 h after the treatments were applied. At each sampling time, 10 - 180° sweep net samples were taken from the west side of each replicate plot and an additional 10 - 180° sweep net samples were collected from the east side of each plot. Because two passes of the 4.5 m boom were required to completely spray each 9.0 m plot, the centre line of each plot may have been subjected to some underspray or overspray. Consequently, no sweep net collections were made along the centre of the plots. Sweep net samples were labelled and placed in sample jars containing 70% ethanol, and returned to the laboratory where counts were made of the number of adult weevils per sample.

Percent reductions of individuals in treated plots were calculated using pre- and post-treatment sample numbers, corrected for changes in weevil numbers in the control plots using Abbott's formula (Mulla et al. 1971). Data were subjected to analysis of variance (ANOVA) using a General Linear Models procedure and Tukey's studentized range test (SAS Institute Inc. 1990), after performing $\log_{10}(x + 1)$ transformations on counts of adults in each sample.

i. Insecticide evaluations conducted in 1999. Three trials were conducted in commercial canola fields approximately 4 km south of Lethbridge to assess the efficacy of selected insecticides for reducing adult populations of cabbage seedpod weevil. The experiments were randomized complete block designs with three replications; each replicate plot measured 4.5 m by 15.0 m. The crop was *B. napus*, and at the time of the studies, approximately 25% of flowering had been initiated. Treatments were applied on 29 June 1999 from 09:00 to 14:20 h. The insecticidal products tested were Lorsban® 4E

(chlorpyrifos) at 360, 480, and 576 g a.i. per ha, Decis® EC (deltamethrin) at 7.5 g a.i. per ha, and Matador® EC (cyhalothrin-lambda) at 10 g a.i. per ha. A custom-built plot sprayer was used to apply the insecticides. The boom extended 4.5 m, so complete coverage of the plots was achieved by one pass of the sprayer. Other application parameters were: volume = 60 L per ha; 8001 TeeJet nozzles; 320 mL per min confirmed; speed 6.4 km per h; 4-L tank.

Air temperatures at times of insecticide application were: Matador® EC, 21°C; Decis® EC, 24°C; Lorsban® 4E at 360 g a.i. per ha, 23°C; Lorsban® 4E at 480 g a.i. per ha, 24°C; and Lorsban® 4E at 576 g a.i. per ha, 25°C. Wind speed during the applications ranged from 1.0 to 7.0 km per h. Relative humidity ranged from 35 to 60%, and cloud cover was 20 to 50%.

Plots were sampled approximately 2 h before treatment, and 24 and 48 h after the treatments were applied. At each sampling time, 10 - 180° sweep net samples were taken from each replicate plot. The sweep net samples were placed into plastic bags, labeled, and stored at -20°C until they could be processed. At the end of the season when canola plants were mature, 25 plants from each replicate plot were cut off at their basal stems, bagged and labeled, and the numbers of pods per plant and numbers of weevil exit holes per plant were counted. All seed from the plant specimens was then threshed, cleaned, and weighed.

Percent reductions of individuals in treated plots were calculated using pre- and post-treatment sample numbers, corrected for changes in weevil numbers in the control plots using Abbott's formula (Mulla et al. 1971). Data were subjected to analysis of variance (ANOVA) using a General Linear Models procedure and Tukey's studentized range test (SAS Institute Inc. 1990), after performing $\log_{10}(x + 1)$ transformations on counts of adults and weights of seed yield from each sample.

Results

The 1998, 1999, and 2000 Field Seasons. In 1998, relatively high levels of residual soil moisture resulted in even emergence of canola crops in southern Alberta near Lethbridge, but cool temperatures and a frost in early June subsequently slowed crop development.

Very hot, dry weather in July and August resulted in rapid maturity of canola crops. In total, 25.3 cm of rainfall were received at the primary research site during the growing season (Canola Council of Canada 1998).

The 1999 field season was characterized by somewhat cool and dry environmental conditions until late June. In total, 22.7 cm of rainfall were received at the Canola Production Centre site during the growing season. Residual soil moisture levels were reasonably high and permitted uniform plant establishment and growth. Frost on 7 June caused some crop damage: plants growing in areas with heavy crop residue had more visible damage than plants surrounded by little residue. Recovery from the frost was slow but few plants were killed (Canola Council of Canada 1999).

In 2000, little residual soil moisture was available at the Canola Council of Canada's Production Centre site at the time of seeding, and strong winds further dried out the seedbed. Emergence was therefore very variable, and occurred over an extended time period. A severe frost on 10 June produced many killed plants, and slow recovery of plants where apical meristems were not damaged. Drought severely stressed the plants: only 3.1 cm of precipitation were received in the Lethbridge, AB region from May though August, resulting in low plant biomass and virtually no seed yield (Canola Council of Canada 2000).

Biology of Cabbage Seedpod Weevil.

a) 1998 Studies on Seeding Date Effects on Weevil Infestations. In 1998, pan trap samples indicated that adults of *C. obstrictus* gradually increased in abundance on canola from early May to a peak in mid-June; thereafter populations declined to relatively low numbers by mid-July. Movement of adults into the crop appeared to be strongly associated with developmental stage of canola. Populations were low in the cotyledon and rosette stages, with a mean of less than 0.4 weevils collected per pan trap sample. However, mean weevils per trap increased dramatically in the bud stage (ca. 1.5 weevils per trap) to a peak at flowering (ca. 2.0 weevils per trap). Thereafter weevil populations in pan trap samples declined to low levels, similar to those observed in the cotyledon and bud stages. Mean weevils per trap in bud and flowering canola significantly exceeded those in the cotyledon, rosette, and pod stages of development ($P < 0.05$).

Cabbage seedpod weevil infestation levels, determined by pan trap collections, indicated that adult populations were greater on early-seeded canola than on plots seeded on the two later dates; however differences between planting dates were not significant statistically ($P > 0.05$) (Table 1).

b) 1999 Studies on Effects of Variety and Seeding Date on Weevil Infestations. Pan trap collections determined that although numbers of cabbage seedpod weevil adults collected from plots seeded early exceeded those collected from plots seeded on normal dates, these differences were not significant statistically ($P > 0.05$) (Fig. 1). Similarly, weevil numbers from sweep net collections were greater, but not significantly so, in early-seeded plots than in plots seeded later ($P > 0.05$) (Fig. 2). Emergence trap samples also followed this trend: greater numbers of weevil adults emerged from canola stubble in early-seeded plots than from plots seeded later (Fig. 3), and differences between early- and normal-seeded plots were not significantly different ($P > 0.05$).

Pan trap collections of cabbage seedpod weevil adults from plots of the *B. napus* cvs. Hylite 201 (apetalous canola) and Hyola 401 were similar and not significantly different ($P > 0.05$) (Fig. 4). However, collections from plots seeded to the cultivar Option 500 were significantly lower than those from plots of the other varieties ($P < 0.05$). Similar results were obtained from emergence trap collections: mean numbers of adult weevils emerging from plots seeded to Option 500 were significantly lower than from Hylite and Hyola 401 ($P < 0.05$) (Fig. 5).

For all three cultivars of *B. napus*, mean numbers of exit holes formed by larvae of *C. obstrictus* on the lower pods significantly exceeded those on pods on the upper regions of the racemes ($P < 0.05$) (Fig. 6). This relationship was observed for both early- and late-seeded plots.

c) Studies on Alternate Host Plants of Cabbage Seedpod Weevil. Studies of alternate host plant species of *C. obstrictus* determined that weevils were not found on plant species that were not members of the Brassicaceae, even if the non-cruciferous species had yellow flowers (e.g., dandelion [*T. officinale*], buttercup [*R. rhomboideus*], and golden bean [*T. rhombifolia*]). However, depending on the site, weevils were very abundant on specimens of volunteer canola (*B. napus* and *B. rapa*), wild mustard (*S. arvensis*), flixweed

(*D. sophia*), shepherd's purse (C. *bursa-pastoris*), hoary cress (*C. pubescens*), and stinkweed (*T. arvense*). Sweep net collections of as many as 80 specimens per sweep were common in areas of volunteer canola or cruciferous weeds early in the season (mid-May to early June), before canola crops came into bud and flower.

Studies comparing susceptibilities of *D. sophia*, *T. arvense*, and *S. arvensis* in mixed stands of these species determined that *S. arvensis* was preferred to a significantly greater degree than the others ($P < 0.05$) (Fig. 7). Regardless of host plant species, adult weevils occurred most frequently on buds and flowers than on stems and leaves ($P < 0.05$) (Fig. 7). Wild mustard proved to be a true host plant: weevil larval development occurred successfully within pods of this species but no evidence of larval development (i.e., exit holes) was found in pods of flixweed or pennycress.

d) Susceptibilities of Species and Cultivars of Canola and Mustard to Infestations of Cabbage Seedpod Weevil. Differences in susceptibility to infestation by cabbage seedpod weevil were observed among the different cultivars of Brassicaceae. At both study sites, plants of *B. napus* cv. Q2 had significantly greater numbers of exit holes per plant than those of any other cultivar studied ($P < 0.05$) (Fig. 8). Plants of *B. juncea* cvs. Commercial Brown and Forge were intermediate in susceptibilities to infestation, but plants of *S. alba* cv. AC Pennant were resistant to attack by this pest. Mean numbers of exit holes on plants of *S. alba* cv. AC Pennant were significantly lower than those on any of the other species evaluated ($P < 0.05$).

Site differences were also evident. Mean numbers of weevil exit holes per plant at the Bow Island site significantly exceeded those at Stirling ($P < 0.05$). At both sites, yields per plant of *B. napus* cv. Q2 were lowest among the cultivars evaluated (Fig. 9). At Bow Island, yield of *B. napus* cv. Q2 was significantly lower than yields of *B. juncea* cvs. Forge and Commercial Brown ($P < 0.05$). At Stirling, seed yield of *B. napus* cv. Q2 was significantly lower than that of *B. juncea* cv. Commercial Brown and *S. alba* cv. AC Pennant.

e) Studies on Pre-imaginal Developmental Biology of Cabbage Seedpod Weevil in Relation to Maturity of Canola Host Plants. In 1999, weevil mating was observed in the field from 2 June to 15 July. Oviposition was first observed on 25 June, and second-

instar larvae were abundant in canola pods on 13 July. Peak emergence of final-instar larvae from canola pods occurred from 12 to 19 August 1999. Emergence of new-generation adults occurred in research plots from 24 August to 7 September 1999.

Mean numbers of cabbage seedpod weevil eggs per pod were highest, at nearly 0.8 eggs per pod, in canola at Growth Stages 4.2 to 4.3 when plants were still flowering but the lower pods were elongating and beginning to fill (Fig. 10). Egg deposition then declined rapidly to approximately 0.2 eggs per pod from Growth Stage 4.3 to 4.4 as flowering ended and seed enlargement occurred in lower pods. Thereafter egg numbers declined gradually to zero as canola pod ripening was completed in Growth Stages 5.3 to 5.4.

Mean numbers of first-instar larvae increased gradually to a peak of approximately 0.3 per pod in Growth Stage 4.4, and then declined to very low values from Growth Stages 5.2 to 5.4 (Fig. 11).

Second-instar larvae were not found in canola pods in Growth Stages 4.2 and 4.3, but their numbers then increased within seedpods to a maximum of approximately 0.3 larvae per pod at Growth Stage 5.1 (Fig. 12). Populations of second-instar larvae subsequently declined rapidly nearly to zero as pod development progressed.

Populations of third-instar larvae were absent from canola pods until Growth Stage 5.1, when seeds in lower pods on the racemes reached full size, and then increased to a peak of nearly 0.2 larvae per pod in Growth Stage 5.2 (Fig. 13). Thereafter mean numbers of third-instar larvae per pod declined to low values (< 0.1 per pod) as pod ripening was completed.

Mean numbers of cabbage seedpod weevil exit holes per pod remained at zero until Growth Stage 5.2 when approximately 0.2 exit holes per pod were recorded (Fig. 14). Thereafter, mean exit holes per pod increased to more than 0.2 per pod at Growth Stage 5.4.

f) Crop Damage Caused by Cabbage Seedpod Weevil Infestations. Crop losses from cabbage seedpod weevil attack occured in several ways. When adults invaded crops, primarily in the bud to early-flowering stages, they fed upon flower buds causing their destruction ("bud-blasting") (Figs. 15, 16). Plants with severe bud-blasting produced racemes with few pods (Fig. 17). Feeding by larvae on developing seeds within pods caused seed losses of approximately 18 to 20% to individual canola pods (Fig. 18). Pods bearing

weevil exit holes often appeared to shatter more readily than non-infested canola pods even after the crop had been swathed. If environmental conditions were humid after larvae bored exit holes, the pods were invaded by fungal spores that germinated and destroyed additional seeds within the pods. When new generation adults emerged late in the season, they fed upon seeds within green pods to build up fat stores for overwintering (Figs. 19, 20). This was often very destructive, especially in 1999, and resulted in severe damage to late-seeded canola. Feeding by new generation adults produced canola with punctured seeds and reduced oil content (Figs. 21, 22).

Crop losses in southern Alberta from cabbage seedpod weevil attack varied considerably. In 1999, severe damage was caused late in the season by new generation adults, and yield losses in some fields were 35 to 50% (P. Thomas, pers. comm.). In 1999, yield losses from cabbage seedpod weevil infestations were estimated at 20% from the Canola Council of Canada's Production Centre site near Lethbridge (Canola Council of Canada 1999).

The percentages of undamaged seeds in canola pods with weevil exit holes collected in 2000 from three fields in southern Alberta ranged from 71.8% to 74.5% (Fig. 23). Of the remaining seeds, 18.8 to 21.2% were consumed by cabbage seedpod weevil larvae, and damage to seeds by fungal invasion ranged from 6.6 to 7.3%.

g) Morphological Studies of Cabbage Seedpod Weevil Life Stages. All stages in the life history of cabbage seedpod weevil are described below. Descriptions of different life stages follow the terminology and format of Lee and Morimoto (1996), and Stehr (1991). Descriptions of sensilla follow Bloom et al. (1981), Zacharuk (1980), and Zacharuk et al. (1976).

Egg (Fig. 24). Smooth, opaque white, and spheroidal, measuring approximately 0.5 mm long (mean = 0.518 mm; S.D. = 0.028; range = 0.4503 to 0.5688 mm; n = 99) and 0.3 mm wide (mean = 0.260 mm; S.D. = 0.022; range = 0.2212 to 0.3160 mm; n = 99). Surface without apparent sculpture.

Final-instar larva (Figs. 26 to 37). Body moderately stout, slightly curved. Head free, dark brown as long as wide. Stemmata present. Antennae not

prominent, evenly convex. Antenna with two segments. Basal segment bearing six sensillae; two peg sensillae, two round flat sensillae, and two round sunken sensillae. Apical segment covered by a multiporous sensillum with round sunken sensillae scattered over its surface. Epicranial suture visible throughout entire length, frontal sutures U-shaped, complete anteriorly. Catapophyses in same plane as frons. Frons with one pair of setae, two pairs of dorsal epicranial setae, one pair of lateral epicranial setae, two pairs of ventral epicranial setae, and three pairs of minute posterior epicranial setae. Clypeus bears two pairs of setae, anterior margin of labrum trilobed. Labrum with three pairs of setae, median sensillum indistinguishable. Labral rods short, subparallel. Epipharynx with three anterolateral setae, four anteromedian setae, and four median spines. Mandible with two apical teeth and one subapical tooth. Mandibular Seta One shorter than and in front of Seta Two. Labial palpus with two segments, apical segment with seven uniporous peg sensillae at apex. Uniporous peg sensillae with both simple pit pores and sculpted pit pores. Premental sclerite complete, bearing three pairs of setae. Posterior margin of labium distinctly trilobed. Postmentum bearing three pairs of setae. Stipes bearing four setae. Maxillary palpus with two segments, basal segment with one short lateral seta, apical segment bearing twelve uniporous peg sensillae at apex and one lateral digitiform peg sensilla. Uniporous peg sensillae with both simple pit pores and sculpted pit pores. Mala with four ventral and five dorsal setae. Abdomen with eight pairs of bicameral spiracles, marginal air tubes directed posteriorly. Abdominal segments with three dorsal folds, anus terminal with four folds. Mean head capsule width = 0.5430 mm (S.D. = 0.019; range = 0.5056 to 0.5925 mm; n = 87); mean body length = 0.6030 mm (S.D. = 0.180; range = 0.3792 to 1.0270 mm; n = 38).

First- and second-instar larvae (Fig. 25). Morphological characters described above for third-instar larvae are consistent with those of first- and second-instar larvae except that the labium and maxillae of first-instar larvae are not as developed as those on later instars. Sensilla on labial and maxillary

palps of first-instar larvae are also not well developed. For second-instar larvae, mean head capsule width = 0.3710 mm (S.D. = 0.015; range = 0.3318 to 0.4108 mm; n = 110); mean body length = 0.5190 mm (S.D. = 0.137; range = 0.3081 to 0.8295 mm; n = 58). For first-instar larvae, mean head capsule width = 0.2310 mm (S.D. = 0.007; range = 0.2054 to 0.2449 mm; n = 96); mean body length = 0.2290 mm (S.D. = 0.051; range = 0.1264 to 0.3476 mm; n = 76).

Pupa. Pupation occurred approximately 1 to 2 cm beneath the soil surface in earthen cells measuring approximately 5 mm in length. Newly formed pupae are approximately 4 mm long, and white in color with pigmentation apparent on the compound eyes. Pupae have sparse dark setae spread uniformly across the body.

Natural Enemies of *C. obstrictus* in Alberta. Of the 821 adult specimens of *C. obstrictus* that were collected in the field and maintained in the laboratory for examination of their parasitism levels in 1998, only one specimen was found to be parasitized. One adult Chloropidae (Diptera) was reared from a cabbage seedpod weevil adult. The parasitoid was determined to be opportunistic: parasitoid eggs are laid into hosts that are injured or wounded, but this parasitoid does not normally attack healthy hosts.

In 1999, none of the 769 adult specimens of cabbage seedpod weevil collected in the field and maintained in the laboratory demonstrated evidence of parasitism. Similarly, none of the 1,200 canola pods dissected showed evidence of parasitism of weevil larvae.

In 2000, none of the 1100 adult weevils collected from commercial canola fields indicated evidence of parasitism, and none of the 750 pods dissected indicated the presence of parasitoids.

However, several parasitoid specimens were found infesting adult weevils in a mixed stand of cruciferous weeds near Lethbridge. In addition to the two parasitoids found in dissections of the initial collection of 25 weevil specimens (one egg and one larva), additional parasitoid specimens emerged over a period of 13 days from the 508 weevils placed in rearing cages, including 6 prepupae, 12 pupae, 16 males, and 13 females. Adult wasps were keyed to the family Braconidae, subfamily Euphorinae (Hymenoptera). The

parasitism rate based on emergence from hosts was 9.25%; parasitism rate based on emergence and dissection was 17.7%.

None of the 149 cabbage seedpod weevil adults collected from the *B. napus* field near Nobleford, AB were parasitized, but one of the 123 weevils collected from the adjacent *B. rapa* field was found to have a parasitic larva. Dissections of the weevil specimens collected at the flixweed site in Lethbridge determined that 4 of 234 specimens contained larval parasitoids (parasitism rate = 1.71%). Two of the 140 weevils collected from the *B. rapa* stand south of Lethbridge, and dissected for evidence of parasitism, were found to be parasitized.

No differences in mortality were found between control colonies of cabbage seedpod weevil and those treated with *B. bassiana*. Dead weevils were homogenized in 50 µL of potassium phosphate buffer and examined for the presence of *B. bassiana*. Ten µL of homogenate was used for microscopy; 40 µL was spread on PDA plates. No hyphae or spores were observed under the microscope, and *B. bassiana* was not recovered on PDA plates from any of the dead specimens from either colony.

Several isolates of bacteria and fungi (yeast) were obtained from external surfaces of the weevils and from their digestive tracts; however, none of the isolates appeared to be pathogenic to their hosts.

Monitoring Changes in the Distribution and Abundance of Cabbage Seedpod Weevil. Survey results indicated that in 1998, *C. obstrictus* was relatively common throughout southern Alberta, but not particularly abundant (Fig. 38). Infestations were common in canola fields near Lethbridge, Macgrath, Taber, and Claresholm, but densities were generally less than or equal to one specimen per sweep net sample. Cabbage seedpod weevil was not found as far east as Medicine Hat, and no specimens were found in Saskatchewan.

In 1999, surveys determined that the distribution of *C. obstrictus* extended further northward (to Olds) and eastward (to Medicine Hat) than in 1998 (Fig. 38). Infestations were observed along the Alberta-Saskatchewan border at several locations, but the species range did not extend into Saskatchewan. Enormous population densities occurred in fields

in southern Alberta; densities of 10 to 15 weevils per sweep were relatively common in fields near Lethbridge, Taber, and Coaldale. These densities exceeded the economic threshold of two weevils per sweep sample that is used in the U.S.A. Greatest weevil infestations occurred in the region extending from Lethbridge to the U.S. border.

In 2000, the range and abundance of cabbage seedpod weevil increased further (Fig. 38). In eastcentral Alberta, the species was found in fields near Hanna and Oyen, and for the first time, specimens were collected in southwestern Saskatchewan. Populations of 50 to 80 weevils per sweep net sample occurred in some fields near Grassy Lake, Lethbridge, and Raymond. Although cabbage seedpod weevil was first reported in fields near Medicine Hat only in 1999, by 2000 its populations had increased to densities of approximately 20 per sweep sample in some fields.

Monitoring Methods for Cabbage Seedpod Weevil. Attempts to monitor populations of cabbage seedpod weevil with sticky cards placed at the level of the crop canopy were unsuccessful. The sticky cards captured very few specimens, and several samplers were lost because they were blown away from their anchoring stakes by strong winds. A further major difficulty with the sticky traps was that they quickly became covered in drifting soil. Sticky trap sampling was therefore abandoned in favor of pan trap sampling and sweep net sampling. Pan trap sampling proved to be effective while the crop was in the cotyledon, rosette, and bolting stages of development, but was less effective when crops progressed to the flowering and pod developmental stages because the traps were no longer visible within the crop canopy. Sweep net sampling was effective from the time crops reached the rosette and early flowering stages until the late pod stages.

Evaluation of Insecticides for Control of Cabbage Seedpod Weevil.

i. Insecticide evaluations conducted in 1998. Spray cards used to monitor the insecticide droplet density and application uniformity indicated that the insecticides in both the small cage and the field studies were applied evenly, and a relatively dense pattern of insecticide spray was obtained.

One hour after application of insecticides to weevils in the small cages, no mortality was observed for control specimens, or for adults of *C. obstrictus* exposed to applications of 150 and 300 g a.i. per ha of Metasystox-R®, 200 and 400 g a.i. per ha of Dylox®, 200 and 400 g a.i. per ha of Di-Syston®, and 60 g a.i. per ha of Spinosad® (Table 2). However, mortality levels of 10 and 33% were observed for specimens exposed to 65 and 130 g a.i. per ha of Furadan® 480F, respectively, and 33 and 55% mortality levels were observed for weevils exposed to 50 and 100 g a.i. per ha of Admire®. Mortality levels of 55 and 23% were recorded following exposure to Decis EC® and Decis FLO®. Mortality levels of 100% mortality were observed for specimens exposed to both 180 and 360 g a.i. per ha of Lorsban® 4E.

By 12 h after treatment, some recovery was observed for specimens treated with Admire® because mortality declined from 55% to 38% for specimens exposed to 100 g a.i. per ha (Table 2). Mortality of weevils treated with 50 g a.i. per ha of Admire® increased to 48% from 33%. At 12 h after treatment, all specimens exposed to Di-Syston® (at both application rates) were dead, but mortality levels for weevils treated with Dylox® were only 3 and 33% for application rates of 200 and 400 g a.i. per ha, respectively. Mortality levels 12 after treatment for adults of *C. obstrictus* treated with Furadan® 480F were 93 and 95% for application rates of 65 and 130 g a.i. per ha, and mortality levels from Metasystox-R® were 98 and 100% for application rates of 150 and 300 g a.i. per ha, respectively. Mortality 12 h after treatment with Decis EC® and Decis FLO® was 100 and 88%, respectively, but no mortality occurred to specimens treated with Spinosad®.

By 48 h after treatment with insecticide, complete mortality was observed for adults of *C. obstrictus* exposed all application rates of Metasystox-R®, Furadan® 480F, Decis EC®, Decis FLO®, and Di-Syston® (Table 2). Mortality levels for weevils treated with 50 and 100 g a.i. per ha of Admire® were 80 and 95%, respectively, and mortality levels for specimens exposed to Dylox® were 10 and 67.5% for the application rates of 200 and 400 g a.i. per ha, respectively. Mortality to specimens treated with Spinosad® was 2.5%. By the end of the experiment, control mortality was 2.5%.

Weevil populations in the plots prior to application of the insecticides in Trial 1 ranged from 0.40 weevils per sweep in plots treated with Spinosad® to 0.56 weevils per sweep in plots treated with Metasystox-R® at 150 g a.i. per ha (Table 3). In Trial 2, weevil populations ranged from 0.24 per sweep in plots treated with Metasystox-R® to 0.64 for the untreated control plots.

In the first field trial, weevil populations 24 h after application of the insecticides were reduced significantly for plots treated with Lorsban® 4E at 420 g a.i. per ha, Dylox®, and Decis EC® compared with the untreated controls ($P < 0.05$) (Table 3). By 48 h after treatment, populations of *C. obstrictus* were significantly reduced, relative to those of control plots, for plots treated with both application rates of Lorsban® 4E, Decis®, and Admire® ($P < 0.05$). In the second field trial, weevil numbers in plots treated with both application rates of Lorsban® 4E, Dylox®, Decis®, and with Spinosad® were significantly reduced on both the 24 and 48 h post-treatment sampling dates compared with populations in the control plots ($P < 0.05$) (Table 3).

In the first field trial, mortality levels 48 h after treatment, adjusted for changes in weevil populations in the control plots using Abbott's formula (Mulla et al. 1971), ranged from 51% with Spinosad® to 100% with Decis® (Table 3). In Trial 2, adjusted mortality levels 48 h after treatment ranged from 31% with Spinosad to 75% with Lorsban at 350 g a.i. per ha (Table 3).

i. Insecticide evaluations conducted in 1999. Spray cards used to monitor insecticide droplet density and application uniformity indicated that the insecticides were applied evenly, and a relatively dense pattern of insecticide droplets was obtained. No rainfall was received for several days prior to beginning the studies and no rain occurred from the time when pre-treatment sampling was begun until after the final post-treatment samples were collected.

Weevil populations in the plots prior to application of the insecticides were approximately 6 to 10 adults per sweep net sample. In Trial 1, adjusted mortality levels 48 h after applications of Decis® EC and Matador® EC were 86 and 92%, respectively (Table 4). A clear dose response was evident following application of Lorsban® 4E, with mortality

levels of 48, 73, and 82% following applications of 360, 480, and 576 g a.i. per ha, respectively. In Trial 2, adjusted mortality levels of 100 and 98% occurred 48 h after treatment with Decis® EC and Matador® EC, respectively, and applications of 360, 480, and 576 g a.i. per ha of Lorsban® 4E resulted in mortality to adult weevils of 36, 69, and 83%, respectively. In Trial 3, adjusted mortality levels 48 h after applications of Decis® EC and Matador® EC were 97 and 96%. Application of Lorsban® 4E at 360, 480, and 576 g a.i. per ha resulted in weevil population reductions of 39, 77, and 84% (Table 4).

When data from the three field trials were combined and analysed as a single experiment, adjusted weevil mortality levels 48 h after treatment were 95 and 96% for Decis® EC and Matador® EC, respectively, and 54, 79, and 87% for Lorsban® 4E at 360, 480, and 576 g a.i. per ha (Table 5).

In Trial 1, mean seed yields of 25 plants from plots treated with Decis® EC and Matador® EC were 97 and 111 g, respectively (Table 6). The mean yield for both pyrethroid products was approximately 27% greater than that of the control plots (76 g). Yields from plants treated with Lorsban 4E ranged from 75 g at the lowest application rate (360 g a.i. per ha) to 119 g at the highest application rate (576 g a.i. per ha). Mean yield of Lorsban® 4E at the highest rate of application was approximately 36% higher than that of the untreated controls. In Trial 2, mean seed yields of Decis® EC and Matador® EC were 127 and 130 g, respectively, representing an increase of 31% compared with the controls when mean yields for both products were averaged. Seed yields for plants treated with Lorsban® 4E at 360, 480, and 576 g a.i. per ha were 99, 107, and 118 g, respectively; at the highest rate of application, this was an increase of 24% over yields of the controls. In Trial 3, mean seed yields of Decis® EC and Matador® EC were 84 and 67 g, respectively, or an increase of 2% relative to the untreated controls for the average yield for both pyrethroid compounds. Yields with Lorsban® 4E were 66, 89, and 95 g per plot at application rates of 360, 480, and 576 g a.i. per ha, respectively. At the highest rate of application, this yield was 23% higher than that of the untreated controls (Table 6).

When seed yields for all three trials were averaged, mean yields for plants treated with Decis® EC and Matador® EC were 102 and 103 g, respectively, representing an

increase of approximately 23% relative to yields from plants in the untreated control plots (Table 7). Mean yields for plants treated with Lorsban® 4E at 360, 480, and 576 g a.i. per ha were 80, 98, and 111 g respectively; at the highest rate of application, this was a yield increase of 28% over that of the untreated controls (Table 7).

In Trial 1, mean percentages of canola pods with exit holes from final-instar larvae of cabbage seedpod weevil were 33 and 42% for Decis® EC and Matador® EC, respectively; approximately 40% of pods in the untreated control plots had weevil exit holes (Table 8). Following application with Lorsban® 4E at 360, 480, and 576 g a.i. per ha, mean percentages of pods with weevil exit holes were 37, 38, and 28%, respectively. A reduction in exit holes of approximately 31% occurred following treatment with Lorsban® 4E at 576 g a.i. per ha. In Trial 2, plants treated with Decis® EC and Matador® EC had 31 and 28% of pods with larval exit holes, compared with 54% of pods in the untreated control plots. Following treatment with Lorsban® 4E at 360, 480, and 576 g a.i. per ha, mean percentages of pods with weevil exit holes were 39, 35, and 29%, respectively. At the highest rate of application of Lorsban® 4E, this represented a reduction in pods with larval exit holes of 46%. In Trial 3, mean percentages of canola pods with exit holes from final-instar larvae of cabbage seedpod weevil were 24 and 12% for Decis® EC and Matador® EC, respectively; approximately 28% of pods in the untreated control plots had weevil exit holes. Plants treated with Lorsban® 4E at 360, 480, and 576 g a.i. per ha had exit holes in 31, 23, and 22% of their pods; at the highest rate of application this was a reduction of pods with exit holes of 22% (Table 8).

When all three trials were averaged, plants treated with Decis® EC and Matador® EC had 29 and 28% of their pods with weevil exit holes, compared with 41% in the untreated controls (Table 9). For plants treated with Lorsban® 4E at 360, 480, and 576 g a.i. per ha, 36, 32, and 26% of pods had weevil exit holes. Application of Lorsban® 4E at 576 g a.i. per ha caused reductions in pods with larval exit holes of 36% compared with the untreated controls.

Discussion

Most research results presented here were generated during the 1998 and 1999 field seasons which were very favorable for development of cabbage seedpod weevil in canola. Several studies that were initiated during 1998 and 1999 were also seeded in 2000, but for various reasons, meaningful research data were not obtained in 2000. The study to evaluate seeding date effects on weevil infestation levels was established and maintained at the Canola Council of Canada's Production Centre site near Lethbridge; however, severe frost and drought at that site produced very uneven plant stands, stunted canola plant development, and virtually no seed yield from any of the study plots. The study to evaluate canola and mustard species for susceptibilities to cabbage seedpod weevil was also seeded in 2000 (as well as in 1999). Unfortunately feeding pressure from cabbage seedpod weevil was so intense in 2000 that plants would not even come into flower, so it was necessary to abandon the study.

Prior to our research, the life cycle of cabbage seedpod weevil was studied in France (Bonnemaison 1957), Poland (Dmoch 1965), and the UK (Williams 1978). European researchers found that the cabbage seedpod weevil completes one generation per year. Adults diapause in winter, usually away from crops, in dry soil, leaf litter, or underneath scrub. In April or May, when the air temperature exceeds 15°C (Bonnemaison 1957; Kjaerpedersen 1992), they fly to flowers and feed on plant tissue, which the females need to mature their ovaries (Ni et al. 1990). Before crop infestation, wild crucifers or volunteer oilseed rape can be important food sources. The adults migrate to oilseed rape or other brassicaceous seed crops as they start to flower, with numbers peaking during flowering and declining as the pods develop. Crop edges are usually more infested at the start of crop invasion, but this effect declines during the season (Free and Williams 1978). The life cycle is better synchronised with winter crops than spring crops. Adults feed for three to four weeks on buds, flowers, pods, and stem tips before mating (Free and Williams 1978), so there is a delay before laying eggs on winter rape, but they start laying at once on spring rape. Females bore a hole through the pod wall with their rostrum and then use the ovipositor to insert a single egg into the pod, which is then marked with an oviposition

deterring pheromone, by brushing the abdomen along the pod (Kozlowski et al. 1983; Mudd et al. 1997). Pods of medium length, about 20 to 40 mm, are preferred for oviposition. Adults lay a total of 25 to 240 eggs during their lifetime. The larvae hatch after six to 10 days, but embryonic development can take as long as 30 days if temperatures are low. Larvae are found mainly during June and feed within the pods for 14 to 21 days, but development can take as long as 40 days if the weather is cold. Most infested pods contain only one larva, although two or three can occur. Each larva consumes about five seeds. When fully grown, larvae bore an exit hole through the pod wall and drop to the soil where they pupate within a cocoon. Pupation usually occurs before a crop is swathed or harvested. The old adults die off during June. The new generation adults emerge after 15 to 19 days and feed on any remaining crop pods or on wild hosts during July and August before finding a site to overwinter.

Results obtained by the European researchers are in general agreement with our studies on the biology of cabbage seedpod weevil in spring canola in Alberta. We found that adult weevils emerged from their overwintering sites from mid- to late April, and fed on brassicaceous host plants like flixweed, stinkweed, hoary cress, and volunteer canola until canola crops entered the bud to early flowering stages. Adults then fed on canola, especially pollen in buds and in open flowers, and began to deposit eggs during flowering when the first small pods developed on the lower regions of canola racemes. By the time that pods were mature and nearly completely ripe, larval development was complete and the majority of the population was in the pupal stage. Pupation occurred within earthen cells beneath the soil surface.

Larvae emerged from canola pods through exit holes, created by chewing openings through the pod walls. Under moist conditions, the exit holes could be invaded by fungal spores that germinated and destroyed additional seeds within the pods.

Besides canola (*B. napus* and *B. rapa*), wild mustard (*Sinapis arvensis*) is the most important host plant of cabbage seedpod weevil in Alberta. We observed feeding damage on this introduced weed at several sites in southern Alberta, especially on buds and flowers. Exit holes were observed on pods of wild mustard, indicating that larvae of cabbage

seedpod weevil can complete their development on this species. By contrast, feeding but not weevil reproduction, was observed on flixweed, stinkweed, and hoary cress.

Fewer weevil adults were generally collected on canola seeded on a "normal" date in spring (i.e., early to mid-May) compared with canola seeded earlier (i.e., mid- to late April); however, we found no statistically significant differences in weevil populations between these seeding dates. Altering seeding date in spring, therefore, may slightly reduce infestations of the cabbage seedpod weevil in canola, but will probably be of little importance as a cultural control strategy. However, fall-seeded canola would come into bud and flower much earlier than canola seeded in spring, and could serve as an important sink for adult weevil populations. Delaying seeding of canola in areas of the province severely infested by cabbage seedpod weevil may comprise an important component of an integrated management strategy for this pest.

Differences in susceptibility to weevil attack were observed among the three cultivars of *B. napus* that were compared. The Hylite 201 and Hyola 401 cultivars were similar and susceptible to attack by the weevil, but Option 500 was significantly more resistant. Similar results were obtained both in pan trap collections of weevil adults and in emergence trap studies. Planting a less susceptible variety like Option 500 may be important in the integrated management of cabbage seedpod weevil in canola.

The order of susceptibility to infestation by cabbage seedpod weevil among the species of Brassicaceae evaluated in this study was *Brassica napus* > *Brassica juncea* > *Sinapis alba*. Cultivars of *B. juncea* and *S. alba* have recently been developed that are considered "canola quality"; i.e., they produce seed with oil in quantities similar to that of conventional cultivars of *B. napus*, and the oil quality is also similar to *B. napus* in the content of its fatty acids. In view of the reduced susceptibilities of *B. juncea* and *S. alba* to attack by the weevil, these crops may be more appropriate for canola growers in southern Alberta than conventional crops of *B. napus*. Moreover, the complete resistance of *S. alba* to attack by cabbage seedpod weevil indicates that this species can serve as a genetic source of resistance to this pest. Through the use of modern techniques of biotechnology, it should be possible to develop canola cultivars resistant to cabbage seedpod weevil, using *S. alba* as a resistance source.

In 1998 and 1999, no evidence of parasitism was observed in either larvae or adults of Alberta populations of *C. obstrictus*. In 2000, however, parasitoids infesting cabbage seedpod weevil adults were found at three sites near Lethbridge. At one site, hundreds of weevils were collected and placed into screened cages to capture emerged parasitoid adults; parasitism levels of approximately 18% were then recorded from this site. The identity of this parasitoid has not yet been verified, but it is a member of the Hymenoptera family Braconidae, subfamily Euphorinae. It is probable that this is the European parasitoid *Microctonus melanopus* Ruthe, a species previously found to be significant in reducing survival of adult weevils in Idaho and Washington.

Pan trap sampling was effective for monitoring adult weevil populations in the seedling and rosette stages of canola development, but as crop development proceeded, sweep net sampling was more effective. Because adults of *C. obstrictus* are most attracted to canola in the bud to flowering stages, it is recommended that canola growers use sweep net sampling to monitor populations of cabbage seedpod weevil in their crops.

Our surveys to monitor changes in the distribution and abundance of the cabbage seedpod weevil indicated active and rapid dispersal of this species. From 1997 to 2000, the cabbage seedpod weevil has extended its range northward and eastward at a rate of approximately 60 km per year. It is probable that the eventual range of this pest will comprise all regions of canola production throughout western Canada, including the Peace River region.

Data from these studies indicate that cyhalothrin-lambda (Matador®), deltamethrin (Decis®), and chlorpyrifos (Lorsban® 4E) were effective for reducing adult populations of cabbage seedpod weevil in canola. Weevil mortality was affected by dose of chlorpyrifos; in all three trials, greatest effectiveness was achieved at the highest application rate of 576 g a.i. per ha. Mortality levels with chlorpyrifos at 576 g a.i. per ha were slightly lower than those observed with the pyrethroid compounds evaluated: averaged over the three trials, mortalities 48 h after treatment with Decis® EC and Matador® EC were 95 and 96%, respectively, compared with 87% for Lorsban® 4E (576 g a.i. per ha). Application of Lorsban® 4E also resulted in reduced numbers of weevil exit holes and improved seed yields relative to those of the control plots. Lorsban® 4E applied at 576 g a.i. per ha reduced

weevil exit holes by approximately 31 (Trial 1), 46 (Trial 2), and 22% (Trial 3), and seed yields were improved by 36 (Trial 1), 24 (Trial 2), and 23% (Trial 3) relative to those of the untreated controls. Reductions in weevil exit holes with the pyrethroid compounds averaged approximately 28%, and yield improvements averaged 23%.

The relatively high numbers of cabbage seedpod weevil exit holes in canola pods following insecticidal applications that were quite effective for reducing populations of adults must indicate either re-invasion of the plots from the surrounding canola fields after the applications were made, or that the sprays were applied too late in the season after oviposition was initiated. It is also possible that a combination of these two events occurred. In this study, the insecticides were applied relatively early in flowering (25% flower) to minimize negative effects on non-target arthropod species, but to have greatest efficacy, it may have been preferable to apply the products earlier – at the bud stage of canola development. Insecticidal applications at bud would also minimize harm to non-target pollinators compared with sprays during flowering. In the Pacific Northwest of the U.S.A., canola growers often make two applications of insecticide to optimize control of the cabbage seedpod weevil, but the second application is targeted at the new-generation adults that emerge from infested soil and feed on green pods late in the season (McCaffrey et al. 1986). It is clear that further study is needed to optimize the timing of foliar insecticide applications for control of cabbage seedpod weevil in canola in Alberta, and to determine whether one or two sprays are most effective for weevil control.

Although the cabbage seedpod weevil was only recently discovered infesting canola in Alberta, it can evidently survive growing conditions in western Canada and it now comprises an important component of the insect pest complex of canola. Outbreaks occurred in southern Alberta both in 1999 and 2000, and crop losses in many commercial canola fields in southern Alberta were severe. Late in 2000, it was evident that adult populations were low, evidently because drought in southern Alberta reduced its survival. Although insecticide application for the cabbage seedpod weevil is the only available control strategy presently available to canola growers, development and implementation of an integrated management strategy is necessary for the sustainable production of canola in regions where populations of this pest in canola exceed economic threshold values.

Conclusions

Prior to the completion of this research project, no information was available on the biology and control of cabbage seedpod weevil in spring canola in Canada. Our studies have shown that cabbage seedpod weevil emerges from its overwintering sites in mid-April and then feeds on brassicaceous host plants like flixweed (*D. sophia*), pennycress (*T. arvense*), wild mustard (*S. arvense*), volunteer canola (*B. napus* and *B. rapa*), and hoary cress (*Cardaria* spp.). Adults migrate to canola crops when they enter the bud and flowering stages, and can cause "bud-blasting" by feeding on pollen within buds, destroying vascular tissue in the process. Eggs are laid into small pods, moreso on the lower regions of canola racemes than on upper regions. Larvae feed on developing seeds, consuming approximately five seeds, or about 18% of the yield of a pod, during their development. Pupation occurs within earthen cells, and adult emergence occurs approximately 10 days later. New generation adults feed on seeds within immature pods, causing drastic reductions in crop yield and quality.

Our research has provided important background information on the biology of this pest in canola, but further studies are needed to meet the challenges posed by this serious pest of canola. Research should be undertaken to evaluate various cultural control strategies like trap cropping, fall seeding, altering seeding rates, fertility regimes, and row spacings to identify those practices most effective in increasing the competitiveness of the crop relative to the pest. Biological control of the cabbage seedpod weevil should be enhanced. In the United States and Europe, biocontrol agents cause major reductions in cabbage seedpod weevil populations, but in Alberta, only small populations of parasitoids were found. Research should be undertaken to identify and evaluate different biological control agents of cabbage seedpod weevil, to obtain any necessary regulatory approvals for their release in western Canada, and to eventually release biocontrol agents at different sites throughout western Canada. Finally, a germplasm development program should be initiated to evaluate species and cultivars of Brassicaceae to identify sources of resistance, to use biotechnological approaches to locate the genes for resistance in the genome, and to then

transfer resistance genes to commercial cultivars of canola. By using such a multi-faceted approach to pest management that involves attacking cabbage seedpod weevil infestations from several different angles at the same time, it should be possible to limit crop losses from this pest and improve the profitability of canola production in western Canada.

Implications of the Study to Alberta's Agricultural Industry

Results of this study have important implications for Alberta's canola producers:

- Adults of cabbage seedpod weevil invade canola crops in spring, with abundance levels increasing from the seedling to the flowering stages. Crops become particularly susceptible to infestation by adults when they reach the bud stage. Canola growers should monitor their crops carefully, beginning at the bud stage and continuing until pod ripening occurs.

- Standard sweep net samples should be used to monitor adult populations of cabbage seedpod weevil, beginning as soon as canola plants are large enough to sample in this way. Although not verified by empirical research, an economic threshold of three to four adults per sweep sample is recommended on the basis of early research results and semi-quantitative assessments by researchers. The recommended monitoring protocol is for canola growers to select 10 locations within each field and at each location count the number of weevils from 10, 180° sweeps. Locations should include both the perimeter and inside of the field to obtain the most accurate estimate of weevil numbers throughout the field.

- early in their invasion phase of canola crops, adult weevils are often clumped near the field edges. Canola growers should monitor their fields carefully in the rosette stage to identify the time of weevil invasion, because it may then be possible to only spray field edges rather than the entire crop.

- early in the season, cabbage seedpod weevil adults migrate to cruciferous weeds (e.g., flixweed, pennycress, hoary cress, wild mustard) and volunteer canola before canola crops enter the bud to flowering stages, where they feed primarily on pollen. Canola growers should be encouraged to manage fields so that populations of these weeds are minimized, thereby eliminating important refuge sites for cabbage seedpod weevil adults.

- of the insecticides evaluated here, the synthetic pyrethroid compounds (e.g., deltamethrin or Decis®, and cyhalothrin-lambda or Matador®) were most effective for reducing populations of cabbage seedpod weevil in canola. These products are also known to have little residual insecticidal activity, which is a key benefit when spraying crops in early flower when pollinators are abundant. Synthetic pyrethroids should therefore be considered as important components in the integrated management of this pest.

- crops of *B. napus* are very susceptible to infestations of cabbage seedpod weevil, but *B. juncea* appears to be less susceptible and *S. alba* is completely resistant to this pest. In areas infested annually by high densities of cabbage seedpod weevil, growers should consider sowing *B. juncea* or *S. alba* instead of *B. napus*.

- in Alberta, little evidence was found for parasitism in cabbage seedpod weevil adult or larval populations. One parasitoid species was reared from a weevil population near Lethbridge, and it appears to be the same species that is responsible for significant parasitism of this pest in the northwestern U.S. and Europe. Researchers and agrologists should work to conserve populations of natural enemies of cabbage seedpod weevil, and a biological control program for this pest should be pursued. Canola growers can conserve natural enemy populations by avoiding insecticide applications unless weevil populations exceed the economic threshold.

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Table 1. Mean (± S.E.) cabbage seedpod weevil adults collected per pan trap sample from plots seeded on 'early' (21 April), 'normal' (1 May), and 'late' (13 May) dates in 1998. Means in the column followed by the same letter are not significantly different using analysis of variance and Tukey's studentized test, after performing $\log_{10}(x + 1)$ transformations on the data.

Seeding Date (1998)	**Mean ± S.E.**
'early' (21 April)	1.37 ± 0.15 *a*
'normal' (1 May)	0.98 ± 0.14 *a*
'late' (13 May)	0.99 ± 0.14 *a*

Table 2. Mean percent mortalities of caged adults of *Ceutorhynchus obstrictus* at 1, 12, and 48 hours after application of various insecticidal compounds.

Product	g a.i. per ha	Mean percent mortality 1 h	12 h	48 h
Admire	100	55	38	95
Admire	50	33	48	80
Di-Syston	400	0	100	100
Di-Syston	200	0	100	100
Decis EC	5	55	100	100
Decis FLO	5	23	88	100
Dylox	400	0	33	67.5
Dylox	200	0	3	10
Furadan 480F	130	33	95	100
Furadan 480F	65	10	93	100
Metasystox-R	300	0	100	100
Metasystox-R	150	0	98	100
Lorsban 4E	360	100	100	100
Lorsban 4E	180	100	100	100
Spinosad	60	0	0	2.5
Controls	0	0	3	2.5

Table 3. Total numbers of adults of *Ceutorhynchus obstrictus* per 80, 180° sweep net samples collected from all four replicate plots before treatment and 24 and 48 h after application of selected insecticides. Data are for field trials conducted near Lethbridge, AB in plots of *Brassica napus* on 8 to 10 July 1998 (Trial 1) and 9 to 11 July 1998 (Trial 2).

Trial 1

Product	Total no. adults			Abbott's adjusted mortality
	Pre-treatment	24 h post-treatment	48 h post-treatment	
Controls	39	31 a*	20 a*	
Admire	32	11 ab	4 b	76%
Dylox	37	7 b	7 ab	63%
Metasystox-R	45	23 ab	7 ab	70%
Decis	34	9 b	0 b	100%
Lorsban High	41	5 b	7 b	67%
Lorsban Low	44	15 ab	3 b	87%
Spinosad	32	13 ab	8 ab	51%

*Means in a column followed by the same letter do not differ significantly ($P > 0.05$), Tukey's studentized range test.

Trial 2

Product	Total no. adults			Abbott's adjusted mortality
	Pre-treatment	24 h post-treatment	48 h post-treatment	
Controls	51	26 a*	24 a*	
Admire	38	13 ab	15 abc	16%
Dylox	41	6 b	5 bc	74%
Decis	32	9 b	9 bc	40%
Metasystox-R	19	15 ab	15 ab	-
Lorsban High	34	11 b	8 bc	50%
Lorsban Low	34	6 b	4 c	75%
Spinosad	31	8 b	10 bc	31%

*Means in a column followed by the same letter do not differ significantly ($P > 0.05$), Tukey's studentized range test.

Table 4. Percent reductions of adults of *Ceutorhynchus obstrictus* from plots sampled 24 and 48 h after application of selected insecticides. Data are for field trials conducted near Lethbridge, AB on 29 June to 1 July 1999 in plots of *Brassica napus*, and are adjusted for changes in *C. obstrictus* populations in control plots using Abbott's formula.

	TRIAL 1		**TRIAL 2**		**TRIAL 3**	
Product	24 h Post	48 h Post	24 h Post	48 h Post	24 h Post	48 h Post
Matador EC	73	92	0	98	82	96
Decis EC	71	86	84	100	83	97
Lorsban 360	54	48	24	36	25	39
Lorsban 480	64	73	26	69	61	77
Lorsban 576	56	82	70	83	78	84

Table 5. Percent reductions of adults of *Ceutorhynchus obstrictus* from plots sampled 24 and 48 h after application of selected insecticides. Data are combined in the analysis for all three field trials conducted near Lethbridge, AB in plots of *Brassica napus* from 29 June to 1 July 1999. Values are adjusted for changes in *C. obstrictus* populations in control plots using Abbott's formula.

Product	24 h Post	48 h Post
Matador EC	83	96
Decis EC	81	95
Lorsban 360	47	54
Lorsban 480	61	79
Lorsban 576	71	87

Table 6. Mean seed yields of 25 plants of *Brassica napus* per treatment from plots subjected to applications of selected insecticides for control of cabbage seedpod weevil in field trials conducted from 29 June to 1 July 1999. Means in a column followed by the same letter indicate no significant difference using analysis of variance and Tukey's studentized test.

	TRIAL 1	**TRIAL 2**	**TRIAL 3**
Product	g seed	g seed	g seed
Matador EC	110.75 a	130.14 a	66.49 a
Decis EC	97.37 a	127.01 a	83.82 a
Lorsban 360	74.64 a	98.86 a	66.24 a
Lorsban 480	97.15 a	107.07 a	88.66 a
Lorsban 576	118.92 a	117.59 a	95.15 a
Controls	75.90 a	88.98 a	73.28 a

Table 7. Mean seed yields of 25 plants of *Brassica napus* per treatment from plots subjected to applications of selected insecticides for control of cabbage seedpod weevil. Data are combined in the analysis for all three field trials conducted near Lethbridge, AB from 29 June to 1 July 1999.

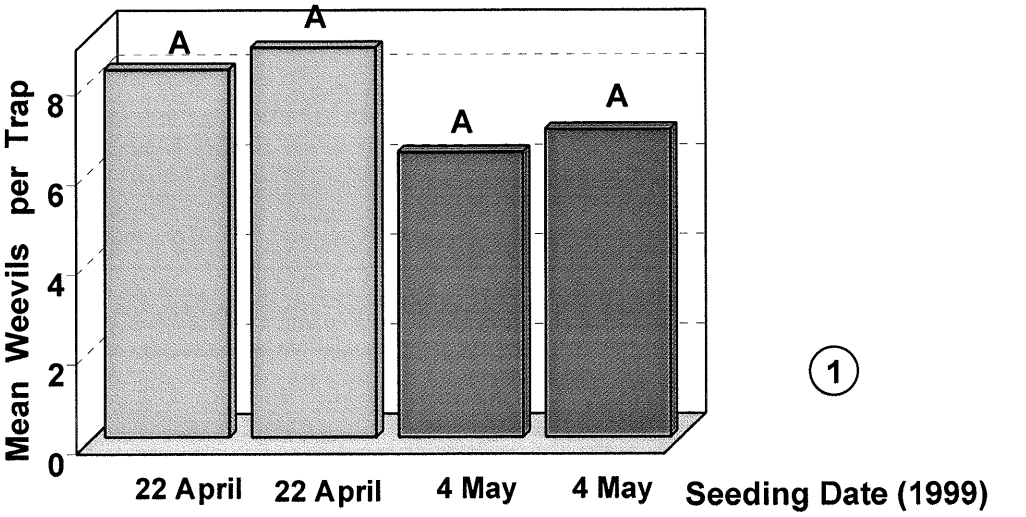
Product	g seed
Matador EC	102.46
Decis EC	102.73
Lorsban 360	79.91
Lorsban 480	97.63
Lorsban 576	110.55
Controls	79.39

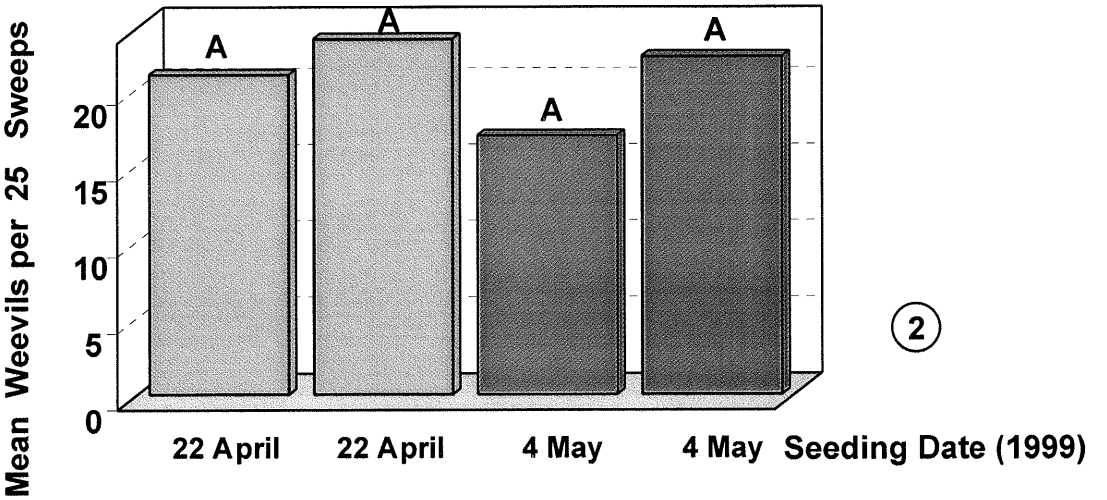
Table 8. Mean percentages of pods of *Brassica napus* with exit holes from larvae of cabbage seedpod weevil for plants subjected to applications of selected insecticides in three field trials conducted near Lethbridge, AB from 29 June to 1 July 1999.

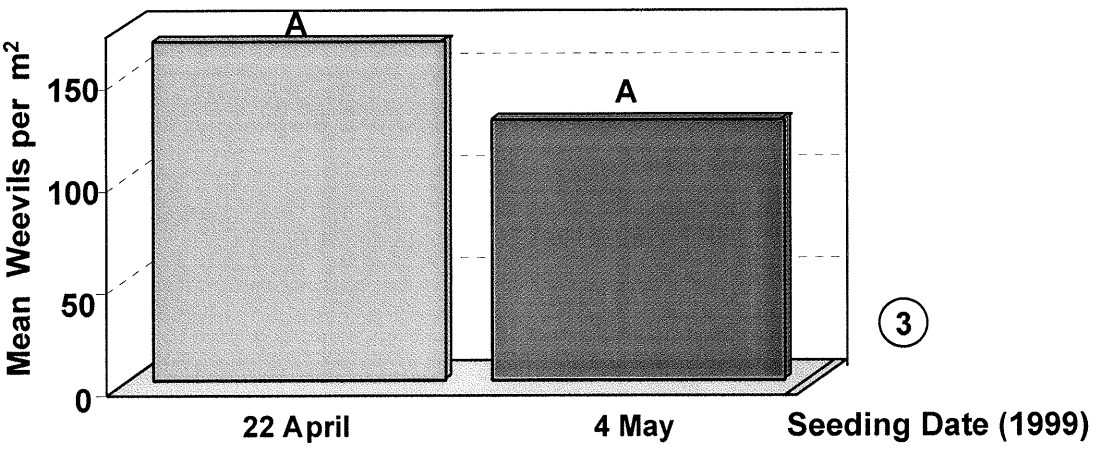
Product	TRIAL 1 % pods infested	TRIAL 2 % pods infested	TRIAL 3 % pods infested
Matador EC	42.4	28.4	12.4
Decis EC	32.5	31.1	24.4
Lorsban 360	37.0	38.7	31.4
Lorsban 480	37.8	34.5	23.2
Lorsban 576	27.7	29.0	21.5
Controls	40.4	53.9	27.7

Table 9. Mean percentages of pods of *Brassica napus* with exit holes from larvae of cabbage seedpod weevil for plants subjected to applications of selected insecticides. Data are combined in the analysis for all three field trials conducted near Lethbridge, AB from 29 June to 1 July 1999.

Product	% pods infested
Matador EC	27.73
Decis EC	29.33
Lorsban 360	35.70
Lorsban 480	31.83
Lorsban 576	26.07
Controls	40.67







Figs. 1 - 3. Effects of seeding date on infestations of cabbage seedpod weevil.
Fig. 1, Mean numbers of cabbage seedpod weevil adults collected per pan trap in canola seeded on different dates in 1999; Fig. 2, Mean numbers of cabbage seedpod weevil adults collected with sweep net samples from canola seeded on different dates in 1999; Fig. 3, Mean numbers of cabbage seedpod weevil adults emerging from canola seeded on different dates in 1999.

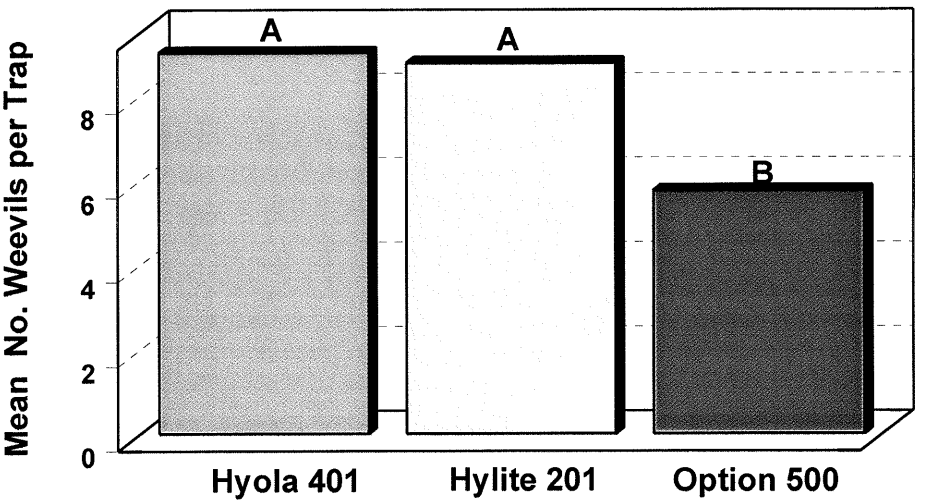


Fig. 4. Mean numbers of cabbage seedpod weevil adults collected in pan traps in plots of *Brassica napus* cvs. Hyola 401, Hylite 201 (apetalous), and Option 500. Letters on histograms indicate statistical significance: means with the same letter indicate no statistically significant difference using analysis of variance and Tukey's studentized test ($P > 0.05$).

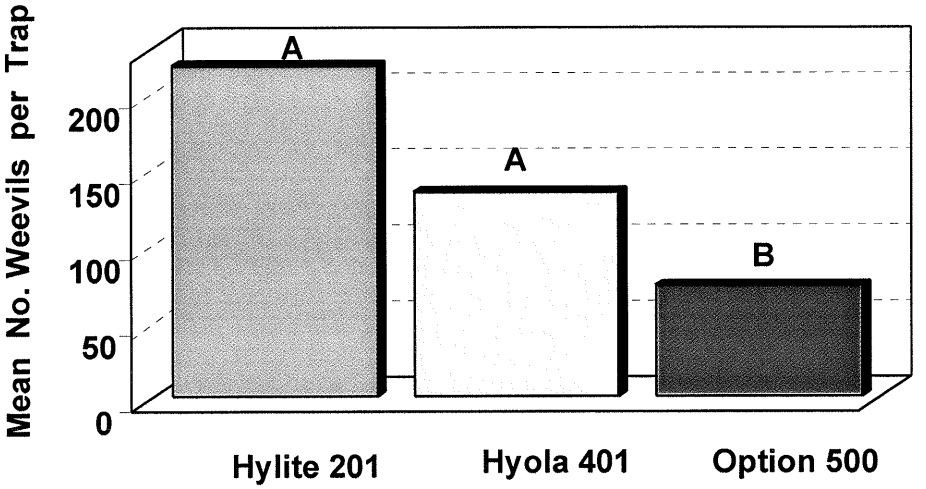


Fig. 5. Mean numbers of cabbage seedpod weevil adults collected per 1 m^2 emergence trap set in plots of *Brassica napus* cvs. Hylite 201 (apetalous), Hyola 401, and Option 500. Letters on histograms indicate statistical significance: means with the same letter indicate no statistically significant difference using analysis of variance and Tukey's studentized test ($P > 0.05$).

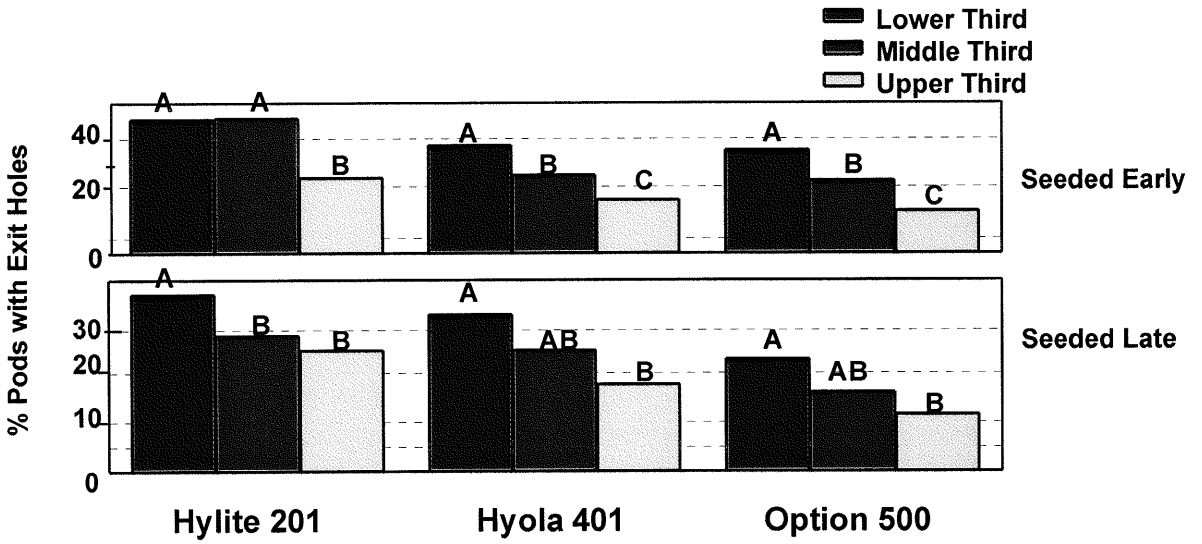


Fig. 6. Mean percentages of pods of *Brassica napus* cvs. Hylite 201, Hyola 401, and Option 500 with exit holes from larvae of cabbage seedpod weevil on lower, middle, and upper regions of racemes on plots seeded early (22 April 1999) and late (4 May 1999) in the season. Letters on histograms indicate statistical significance: means within a cultivar and seeding time with the same letter indicate no significant differences using analysis of variance and Tukey's studentized test ($P = 0.05$).

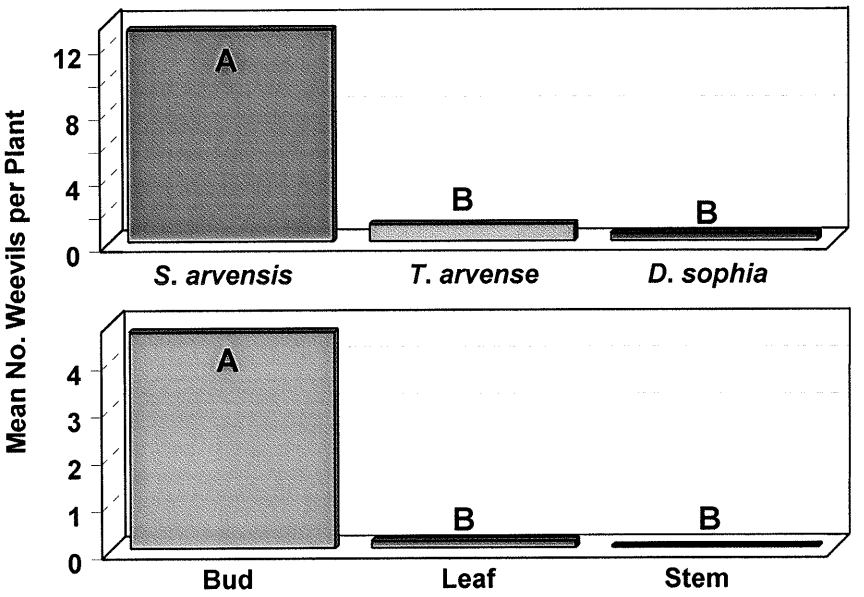


Fig. 7. Mean numbers of cabbage seedpod weevil adults collected per plant for wild mustard (*Sinapis arvensis*), stinkweed (*Thlaspi arvense*), and flixweed (*Descurainia sophia*), and mean numbers of weevil adults collected on different plant parts, including buds, leaves, and stems. Letters on histograms indicate statistical significance: means with the same letter indicate no significant differences using analysis of variance and Tukey's studentized test ($P > 0.05$).

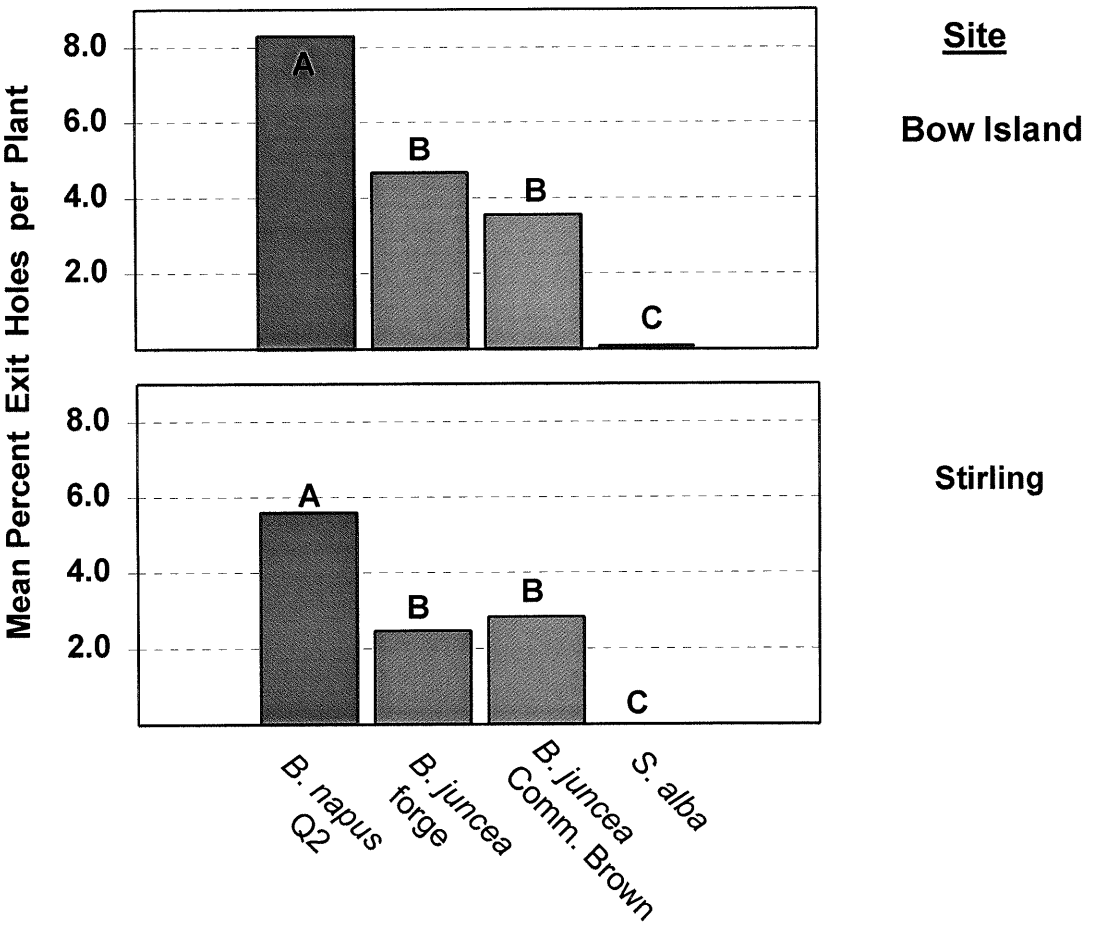


Fig. 8. Mean percent exit holes per plant by cabbage seedpod weevil larvae in *Brassica napus* cv. Q2, *Brassica juncea* cv. Forge, *B. juncea* cv. Commercial Brown, and *Sinapis alba* cv. AC Pennant at the Bow Island and Stirling sites in 1999. Letters on histograms indicate statistical significance: means within a study site with the same letter indicate no significant differences using analysis of variance and Tukey's studentized test.

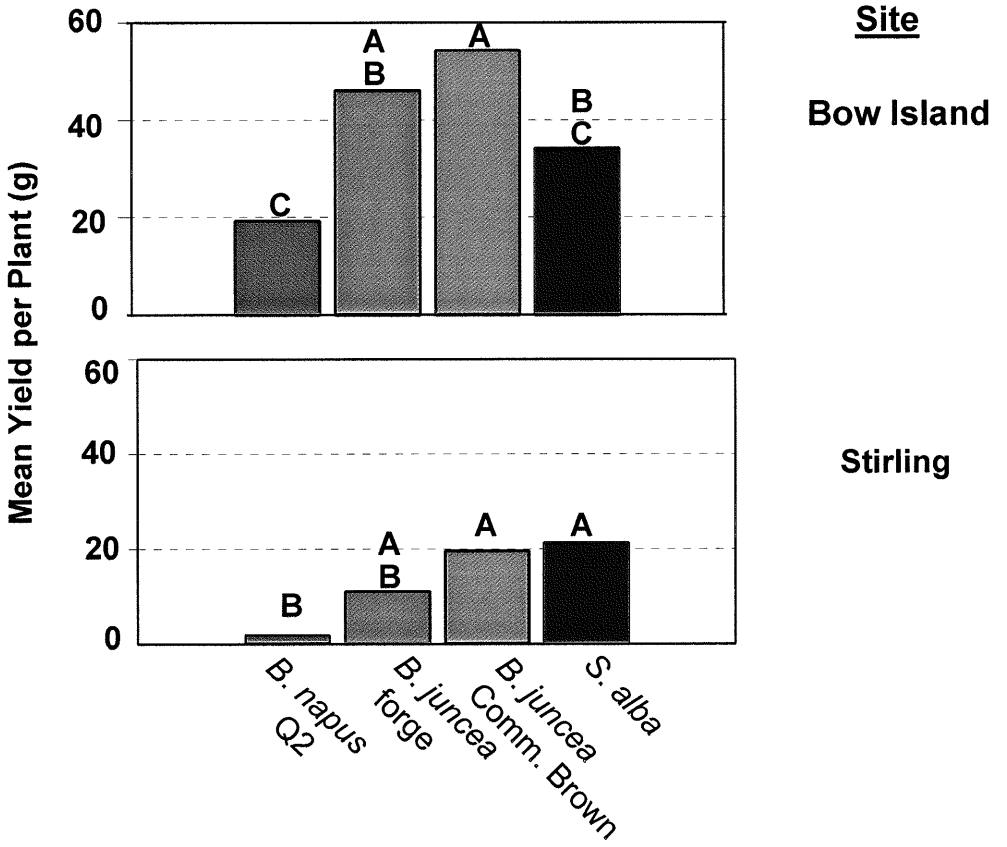
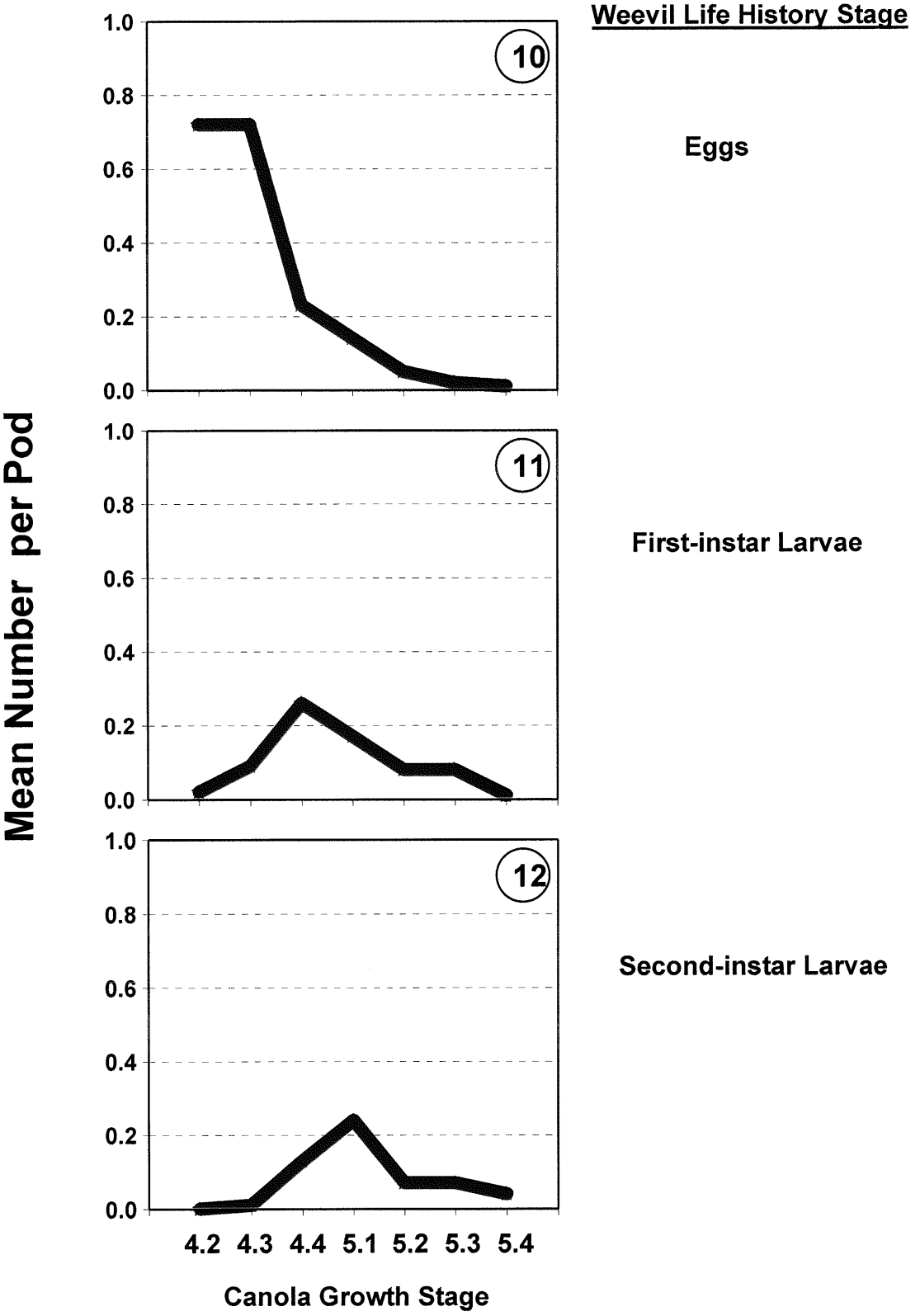
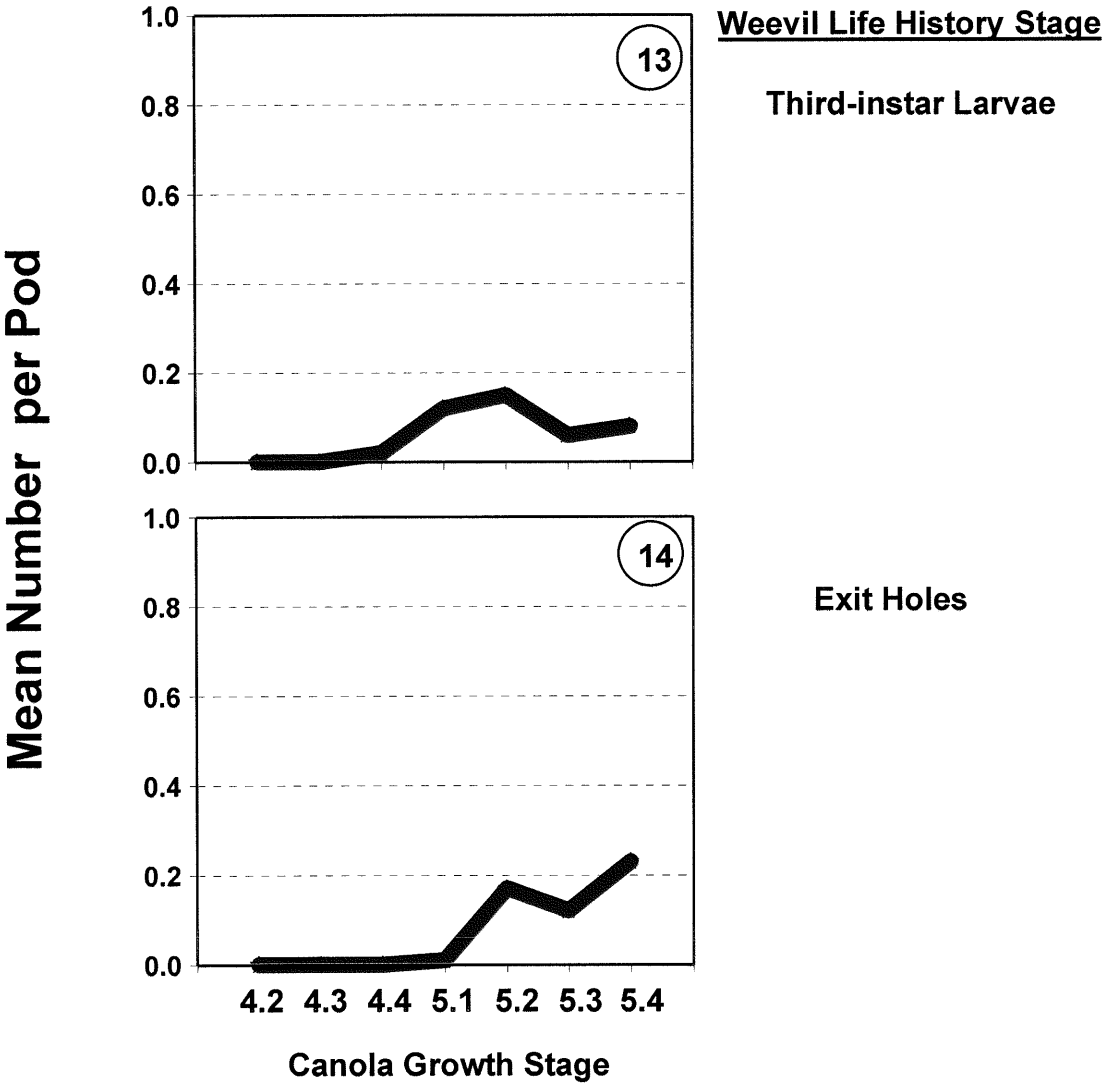


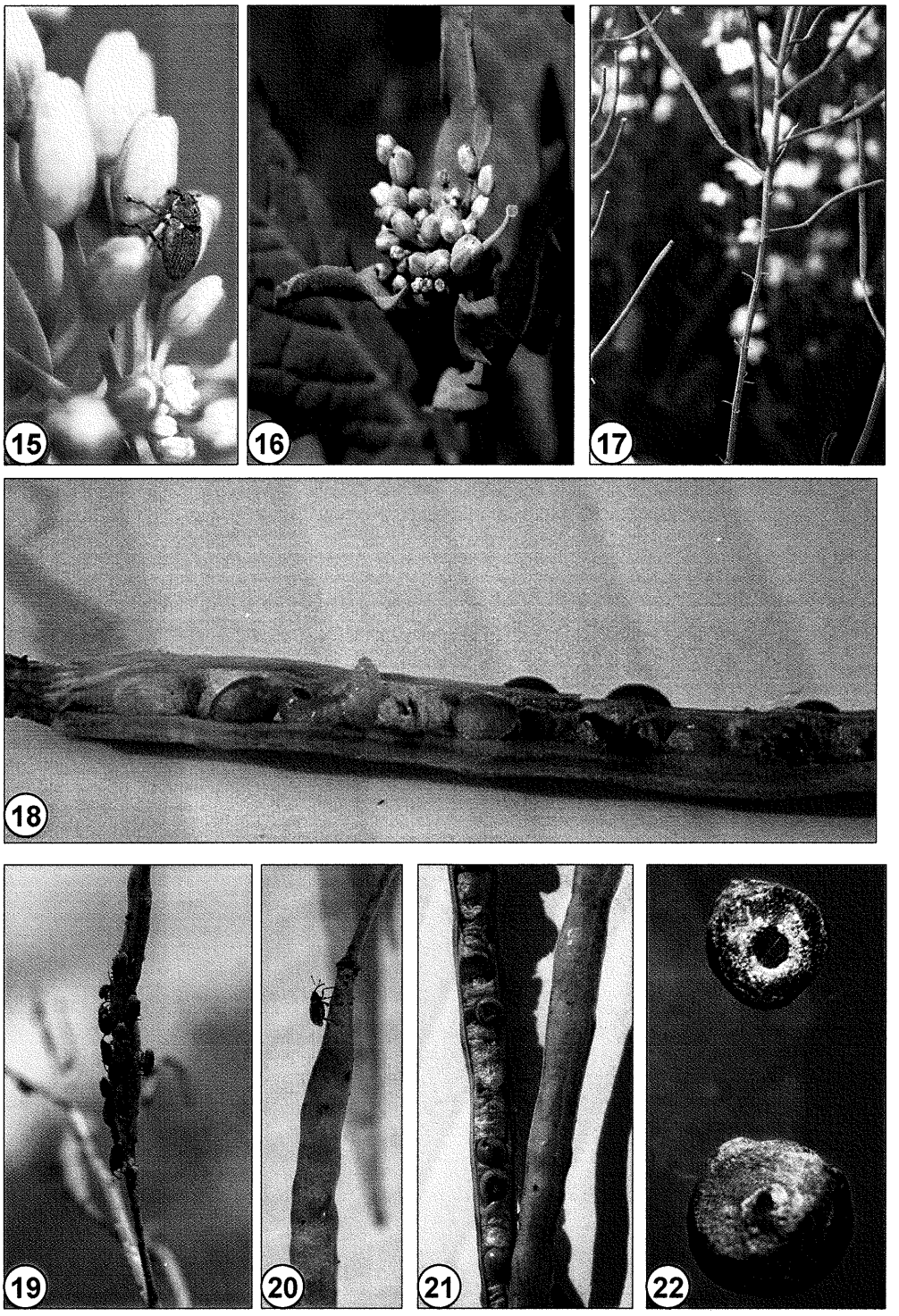
Fig. 9. Mean seed yields per plant of *Brassica napus* cv. Q2, *Brassica juncea* cv. Forge, *B. juncea* cv. Commercial Brown, and *Sinapis alba* cv. AC Pennant at the Bow Island and Stirling sites in 1999. Letters on histograms indicate statistical significance: means within a study site with the same letter indicate no significant differences using analysis of variance and Tukey's studentized test.



Figs. 10 to 12. Development of pre-imaginal life history stages of cabbage seedpod weevil in relation to developmental stage of canola host plants. Fig. 10, Mean number of eggs deposited per pod of *Brassica napus* at different developmental stages; Fig.11, Mean number of first-instar larvae per pod of *B. napus* at different developmental stages; Fig.12, Mean number of second-instar larvae per pod of *B. napus* at different developmental stages.



Figs. 13 and 14. Development of pre-imaginal life history stages of cabbage seedpod weevil in relation to developmental stage of canola host plants. Fig. 13, Mean number of third-instar larvae per pod of *Brassica napus* at different developmental stages; Fig. 14, Mean number of exit holes per pod of *B. napus* at different developmental stages.



Figs. 15 to 22. Damage to canola by cabbage seedpod weevil.
Fig. 15, Adult feeding on pollen within buds; Fig. 16, Damaged canola flower buds ("bud-blasting"); Fig. 17, Canola raceme with no pod development on its lower portion from bud destruction; Fig. 18, Seed damage by larval feeding within pods; Fig. 19, Feeding on pods by new generation adults; Fig. 20, Damage to pods by new generation adults; Fig. 21, Damage to developing seeds by new generation adults; Fig. 22, Damage to canola seeds by adults.

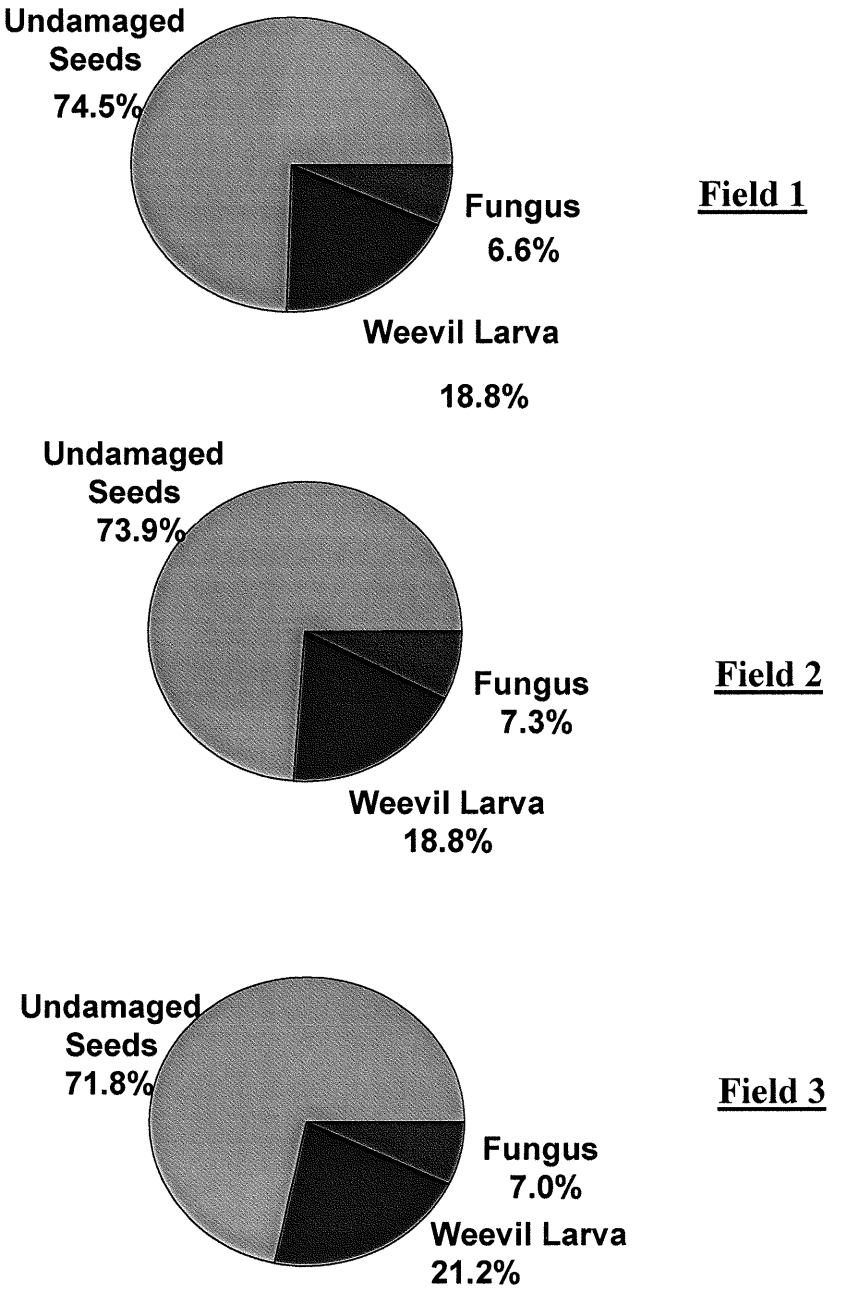
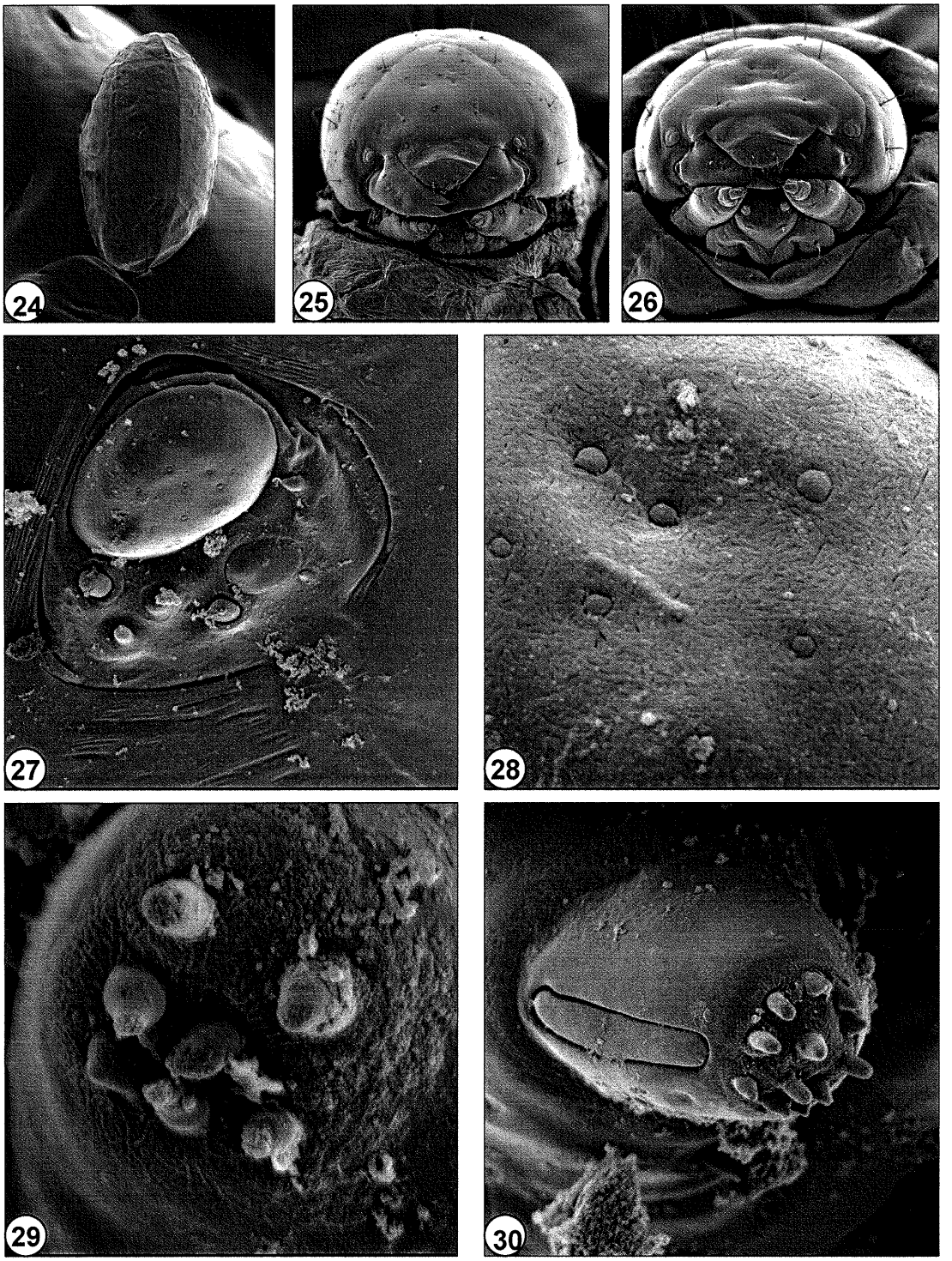


Figure 23. Percentages of undamaged seeds, seeds damaged by fungal attack, and seeds consumed by larvae of cabbage seedpod weevil from pods of *Brassica napus* collected in fields near Lethbridge, AB in August 2000. All pods collected had exit holes from cabbage seedpod weevil larvae.



Figs. 24 to 30. Scanning electron micrographs of cabbage seedpod weevil. Fig. 24, Egg; Fig. 25, First-instar larva; Fig. 26, Third-instar larva; Fig. 27, Antenna; Fig. 28, Apical antennal segment with sunken sensillae; Fig. 29, Apical segment of labial palpus with sensillae; Fig. 30; Apical segment of maxillary palpus with sensillae.

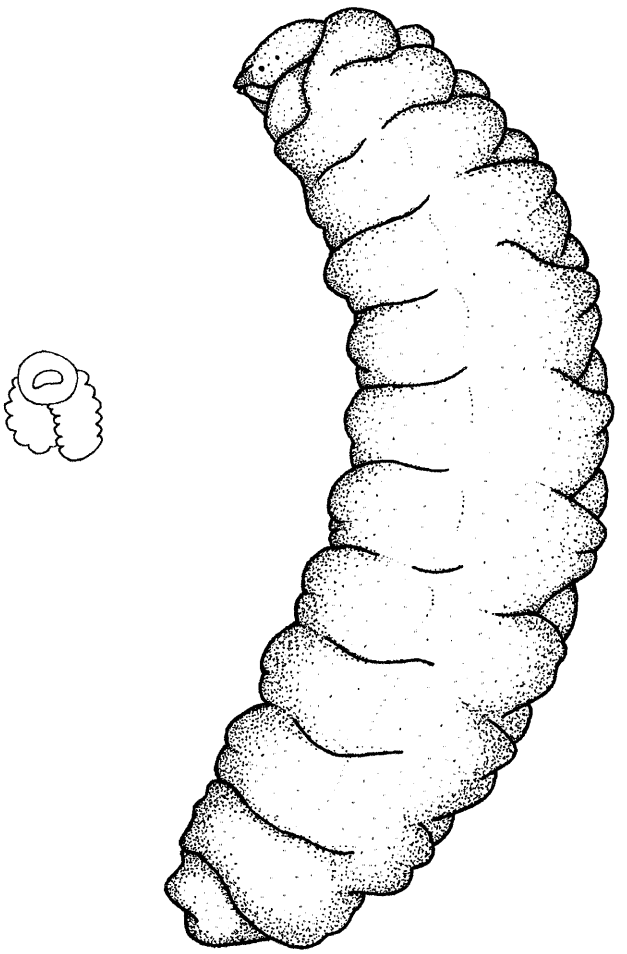
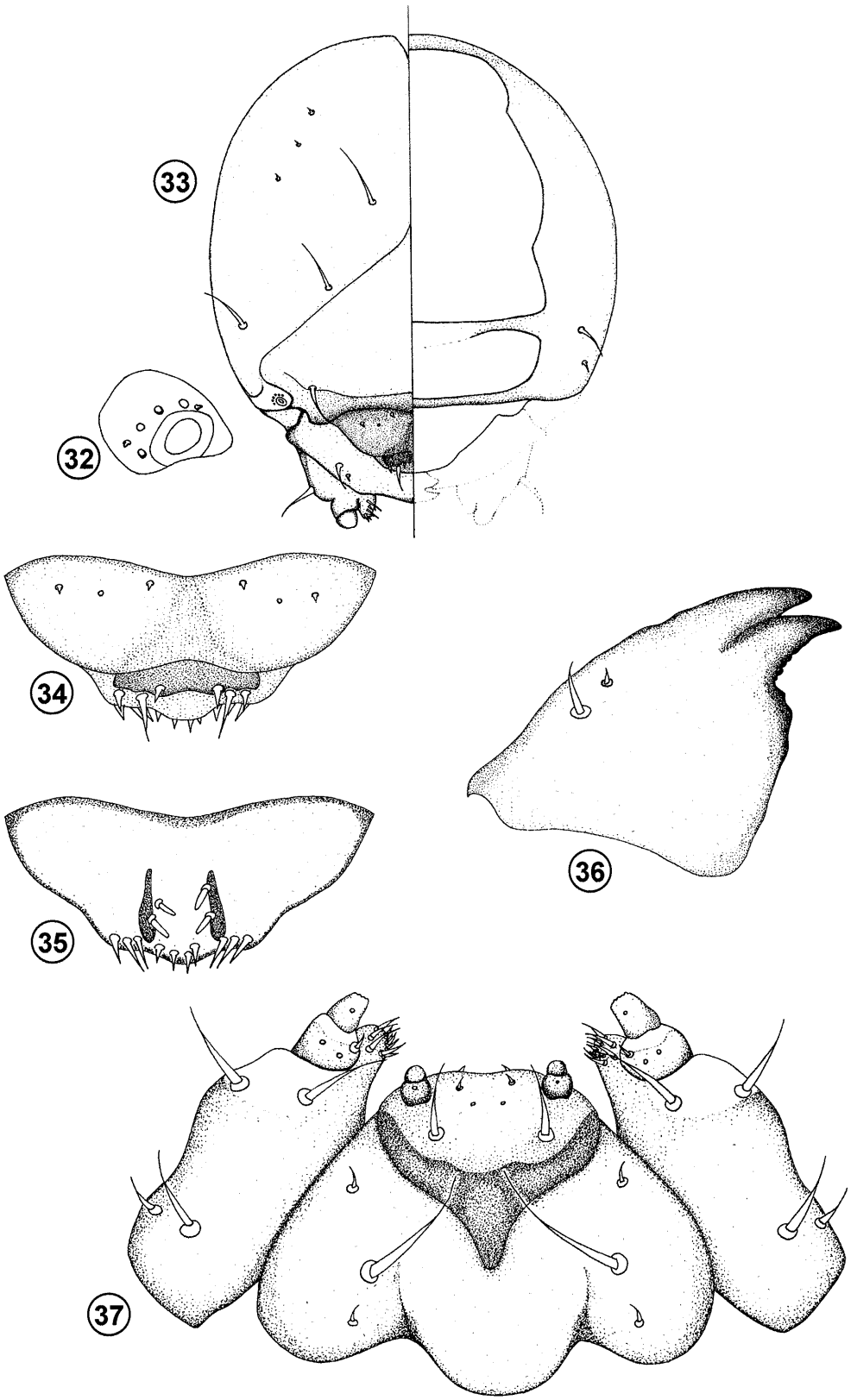


Fig. 31. Third-instar larva of *Ceutorhynchus obstrictus*, habitus and spiracle.



Figs. 32 to 37. Taxonomic characters of the third-instar larva of *Ceutorhynchus obstrictus*. Fig. 32, Antenna, frontal view; Fig. 33, Head capsule with anterior (left) and posterior (right) views; Fig. 34, Labrum; Fig. 35, Epipharynx; Fig. 36, Mandible; Fig. 37, Maxillae and labium (ventral).

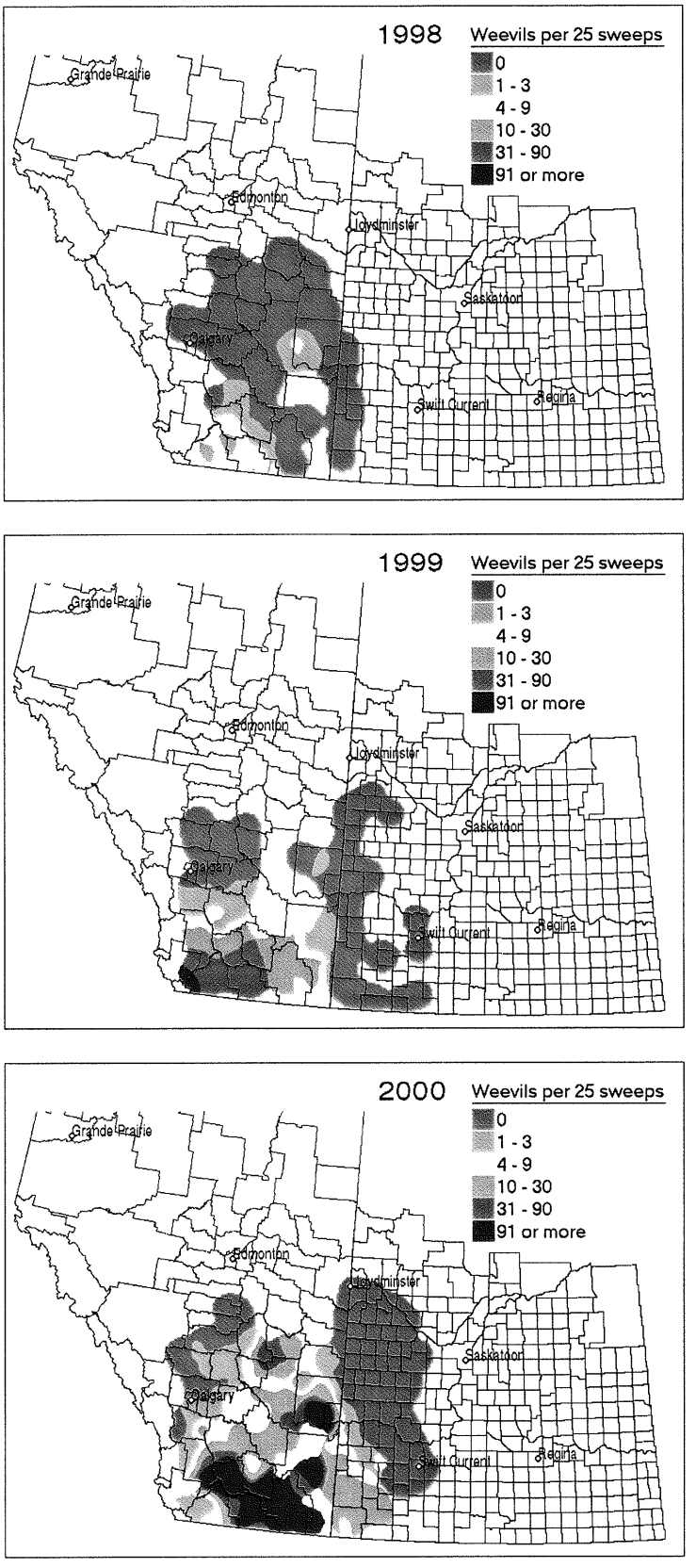


Fig. 38. Distribution and abundance of the cabbage seedpod weevil in western Canada from 1998 to 2000.

Presentations and Publications Arising from the Project

Kuhlmann, U., L.M. Dosdall, and P.G. Mason. 2001. *Ceutorhynchus obstrictus* (Marsham), Cabbage Seedpod Weevil (Coleoptera: Curculionidae). *In*: P.G. Mason and J.T. Huber (eds.). Biological Control Progammes in Canada 1981-2000. CAB International, Wallingford, Oxon, UK. *In Press*.

Hartley, S., and L. Dosdall. 2001. Seedpod weevil attacks canola. Grain Magazine. Publication No. 08180, Diseases, Weeds, and Insects issue, pp. 10-11.

Dosdall, L.M. 2001. New research developments on the biology and control of cabbage seedpod weevil, *Ceutorhynchus obstrictus* (Marsham) in canola. Proceedings of the 2001 Agronomy Update Conference, Lethbridge, AB, pp. 150-154.

Dosdall, L.M. 2000. Chemical control strategies for the cabbage seedpod weevil, *Ceutorhynchus assimilis* Paykull, in canola. Alberta Agriculture, Food and Rural Development Technical Report, 12 pp.

Dosdall, L.M. 2000. Biology and control of the cabbage seedpod weevil, *Ceutorhynchus assimilis*, in canola. Proceedings of the 2000 Agronomy Update Conference, Edmonton, AB, pp. 53-54.

Dosdall, L.M., H. Carcamo, and D. Johnson. 2000. "Temporal and spatial distribution patterns of cabbage seedpod weevil, *Ceutorhynchus assimilis* Paykull (Coleoptera: Curculionidae), in canola". Annual Meeting of the Entomological Society of Alberta, Edmonton, AB.

Dosdall, L.M. 2000. Biology of cabbage seedpod weevil in spring canola in western Canada". Joint Meeting of the Entomological Societies of Canada, Alberta, and Quebec, Montreal, PQ.

Dosdall, L.M., D. Moisey, and R. Dunn. 1999. Monitoring the cabbage seedpod weevil for development of an integrated pest management system. Alberta Agriculture, Food and Rural Development Technical Report, 14 pp.

Dosdall, L.M. 1999. "Biology and control of the cabbage seedpod weevil in canola". Annual Meeting of the Entomological Society of Alberta, Waterton, AB.

Dosdall, L.M. 1999. "Cabbage seedpod weevil: A new pest of canola in Alberta". Western Forum on Pest Management Meeting, Penticton, BC.

PRINCIPAL RESEARCHER – BIOGRAPHICAL DATA

Name (surname first):

Dosdall, Lloyd M.

Post-Secondary Education and Training Relevant to Proposal:

Institution	Field of Specialization	Degree/Diploma	Year Completed
University of Saskatchewan	Biology	B. Sc. Honors	1974
University of Saskatchewan	Entomology	M. Sc.	1977
University of Saskatchewan	Education	B. Ed.	1980
University of Saskatchewan	Entomology	Ph. D.	1987

Relevant Professional Experience (begin with present position):

Dates	Position or Function	Employer	Location
1999 – present	Research Entomologist	Alberta Agriculture	Edmonton, AB
1999 – present	Adjunct Professor	University of Alberta	Edmonton, AB
1989 – 1999	Field Crops Entomologist	Alberta Research Council	Vegreville, AB
1987 – 1989	Research Associate	University of Manitoba	Winnipeg, MB

Research Activities Related to Research Proposal (list up to 4 projects):

Title	Date
Investigations on the biology and control of the cabbage seedpod weevil in canola	1998-present
Evaluation of cultural practices, including altering seeding dates, plant densities, and tillage regimes for reducing infestations of root maggots and flea beetles in canola	1990-present
Investigation of the native parasitoid and pathogen complexes of bertha armyworm in Alberta, and study of factors influencing attractiveness of canola host plants to bertha armyworm	1992-present
Evaluation of the importance of soil nutrients and soil physical properties on infestations of root maggots in canola	1995-present

Relevant Articles Published in Refereed Journals and Other Relevant Works in the Last Three Years

Gavloski, J., U. Ekuere, A. Keddie, **L. Dosdall**, L. Kott and A. Good. 2000. Identification and evaluation of flea beetle resistance within Brassicaceae. Canadian Journal of Plant Science 80: 881-887.

Justus, K.A., **L.M. Dosdall**, and B.K. Mitchell. 2000. Oviposition by *Plutella xylostella* (L.) (Lepidoptera: Plutellidae) and the effects of phylloplane waxiness. Journal of Economic Entomology 93: 1152-1159.

Dosdall, L.M., A. Good, B.A. Keddie, U. Ekuere, and G. Stringam. 2000. Identification and evaluation of root maggot (*Delia* spp.) (Diptera: Anthomyiidae) resistance within Brassicaceae. Crop Protection 19: 247-253.

Dosdall, L.M., and M.G. Dolinski. 2000. Biology and control of the cabbage seedpod weevil, a new pest of canola in Alberta. Alberta Agriculture, Food and Rural Development Technical Report, 20 pp.

Dosdall, L.M., D. Moisey, and R. Dunn. 1999. Monitoring the cabbage seedpod weevil for development of an integrated pest management system. Alberta Agriculture, Food and Rural Development Technical Report, 14 pp.

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

Dosdall, L.M., L.Z. Florence, P.M. Conway, and N.T. Cowle. 1999. Tillage regime, row spacing, and seeding rate influence infestations of root maggots (*Delia* spp.) (Diptera: Anthomyiidae) in canola. Can. J. Plant Sci. 78: 671-681.

Dosdall, L.M., M.A. MacFarlane, and P. Palaniswamy. 1999. Biology and larval morphology of *Ceutorhynchus neglectus* Blatchley (Coleoptera: Curculionidae), a minor pest of canola in western Canada. Can. Entomologist 131: 231-242.

Dosdall, L.M., and D.W. Parker. 1998. First report of a symphoretic association between *Nanocladius branchicolus* Saether (Diptera: Chironomidae) and *Argia moesta* (Hagen) (Odonata: Coenagrionidae). Amer. Midl. Naturalist 139: 181-185.