IMPACT OF HARVEST OPERATIONS ON PARASITISM OF THE WHEAT STEM SAWFLY, *Cephus cinctus* Norton (Hymenoptera: Cephidae)

by

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ABSTRACT

Wheat stem sawfly, *Cephus cinctus*, has been a long term pest management challenge for wheat producers in Alberta, Saskatchewan, North Dakota and Montana. Many studies have laid the groundwork for biological control of this pest. Two species of parasitoids, *Bracon cephi* and *B. lissogaster*, have been shown to effectively attack *C. cinctus* in wheat *Triticum aestivum* L. Their effectiveness as part of an integrated pest management plan, however, has been highly variable. A survey was conducted to assess the distribution of the two *Bracon* parasitoids. A two pronged approach was used to better understand parasitoid spatial dynamics and parasitoid promotion. First, intensive field sampling was performed to determine the overwintering location of parasitoid cocoons in wheat fields. Second, wheat stems were cut at varying lengths to stimulate harvest management techniques that producers could employ. *B. cephi* occurred at most locations where sawflies were an agricultural concern, although the level is sometimes very low. *B. lissogaster* was only found in wheat in Montana. The vast majority of overwintering cocoons (>80%) were consistently found in the bottom third of standing wheat stems when measured prior to harvest. This is what should be left standing because it protects critical overwintering habitat. Removing only the wheat heads at harvest resulted in maximum parasitoid conservation. Special efforts to conserve parasitoids in solid stem wheat should be concentrated in areas of each field supporting above average crop growth because these high biomass areas harbor more overwintering cocoons. In hollow stem wheat the area 7.5 to 30 meters from the field margin is the most critical to conserve. If the hollow stem wheat has lower levels of infestation (less than 60% infested) the area to be conserved should extend to the field margin. These recommendations should be incorporated with other management practices that encourage sawfly parasitoids such as: solid stem wheat varieties, avoiding the use of insecticide during parasitoid flight, larger block fields, minimum tillage and chemical fallow. The improvement of parasitoid activity should further be incorporated into a complete integrated pest management approach including solid stem wheat, crop rotation, larger block fields and trap strips.

CHAPTER ONE

LITERATURE REVIEW

Introduction

Wheat stem sawfly, *Cephus cinctus* Norton, is considered the most serious chronic insect pest of wheat, *Triticum aestivum* L., production in Montana and has been an economically important pest of wheat almost since cultivation began in the Northern Great Plains (Weiss and Morrill 1992). Annual losses have fluctuated over this time, but there have been some significant peaks over the past 120 years. The published literature contains a vast body of knowledge on the biology and control of the wheat stem sawfly as researchers across the Northern Great Plains have sought to understand the pest and struggled to find control measures that would be accepted and widely adopted by producers. A significant complement of parasitoids has been identified (Morrill 1997) but only two have had a significant impact on sawfly populations in wheat fields. *Bracon cephi* (Gahan) and *Bracon lissogaster* Muesebeck (Hymenoptera Braconidae) have both been observed to heavily parasitize the larvae of wheat stem sawfly in wheat stems (Morrill 1997). It has also been observed that harvesting operations have a significant impact on the survival of overwintering *Bracon* spp. larvae. (Morrill unpublished data). The purpose of the research associated with this Master of Science degree was to elucidate the impacts of harvest operations on these two *Bracon* spp. parasitoids of wheat stem sawfly. Recommendations for harvest management to increase populations of the parasitoids were developed as a result of this project.

History of the Wheat Stem Sawfly

Cephus cinctus was originally described by Norton in 1872 from an adult collected in Colorado (Norton 1872) and is generally considered to be native to North America (Criddle 1922; Ainslie 1929), although a recent theory has been published that suggests *C. cinctus* was introduced from Asia (Ivie 2001). Since originally described, *C. cinctus* has been collected from Minnesota to California (Ainslie 1920). Original accounts of its activity were from both native and introduced grasses with the occasional mention of minor infestations in cultivated small grains (Ainslie 1929). In 1891 Riley and Marlatt described several sawfly collected and reared by Albert Koebele from wild grasses collected near Alameda, California as *Cephus occidentalis* (now considered to be a junior synonym of *C. cinctus*) (Ainslie 1929). In connection with that description the following prophetic statement was made:

"The economic importance of this species arises from the fact that it may be expected at any time to abandon its natural food-plant in favor of small grains, on which it can doubtless successfully develop."

Time has certainly proven that prediction to be correct. In fact, verification was not long in coming. In 1895 sawfly adults were collected in wheat near Indian Head, Northwest Territories (now Saskatchewan) and wheat stems containing sawfly larvae (although damage was very slight) were identified in Souris, Manitoba (Ainslie 1929). Sawfly damage in wheat occurred at Indian Head in 1896 and near Moose Jaw, North West Territories (now Saskatchewan) in 1897. In 1909 H.B. Penhallow reported on a

survey of about one hundred fields from Minot, North Dakota, north to the Canadian border including several miles into Canada. In that survey sawfly larvae were found in 5 to 25 % of the stems in all but one field (Ainslie 1929). Small but severe outbreaks were reported in Alberta, Saskatchewan, and Manitoba between 1906 and 1910 (Holmes 1978) and in North Dakota in 1917-19 (Ainslie 1929). In 1921 sawfly damage was extensive across Saskatchewan and Manitoba and by 1938 the damage on the Canadian prairies was estimated at 545,000 tonnes of wheat (Holmes 1978). Significant outbreaks occurred in Montana in 1925-1928 and again in 1943 –1953 (Morrill 1983). From the 1930's significant outbreaks persisted in Saskatchewan and Alberta through the mid-1950's and continued in some areas until the early 1960's (Holmes 1982). Minor and sporadic outbreaks occurred in Saskatchewan in 1987, 1988, 1990-1992 and in Alberta in 1990 (WCCP 1987; WCCP 1988; WCCP 1990; WCCP 1991; WCCP 1992). The current major outbreak in the Canadian prairies started with localized outbreaks in 1998 in Alberta and 1999 in Saskatchewan and is still ongoing (WCCP 1998; WCCP 1999; WCCP 2000; WCCP 2001; WCCP 2002; WCCP 2003; WCCP 2004). Sawfly was reported through much of southeastern Alberta in 2001 with severe damage as far north as Alberta, south through Hanna, Oyen, Medicine Hat, and Lethbridge (C. Weeks, T. Wallace, D. Spencer, and R. Dunn personal communication). In 2004 sawfly was of concern throughout most of its traditional range in Canada (WCCP 2004).

Economic Impacts of *Cephus cinctus*

A recent survey of wheat stem sawfly in Montana showed that it was still widespread and causing significant damage (Blodgett 1997) with an estimated 400,000 tonnes lost in 1996. Between 1938 and 1948 the annual losses due to sawfly damage in the Canadian prairies was estimated to be 560,000 tonnes with a high of 700,000 tonnes in 1944 (Platt and Farstad 1949). Annual losses in the early 1940's of 84,000 to 140,000 tonnes were reported from North Dakota (Farstad and Jacobson 1945) and losses of 62,000 tonnes from Montana in 1952 (McNeal et al. 1955). Wheat stem sawfly can be present in numbers large enough that virtually every stem is infested and cut by larvae (Ainslie 1929). In these situations, losses due to stem breakage can be extreme and special management measures may be needed to recover grain from severely lodged fields. Lodging of stems and the inability of harvest operations to retrieve all of the lodged heads are the most obvious impacts. Extra harvesting operations and increase in time to complete harvest also cause financial losses. Feeding damage by sawfly often goes unnoticed and has proven to be somewhat difficult to quantify. Direct yield loss from sawfly tunneling has been calculated to range from 5 to 30 percent and is the result of both fewer kernels per head and less grain weight per head (Seamans et al. 1938; Munro 1947; McNeal et al. 1955; Wallace and McNeal 1966; Morrill et al. 1994). Care must be taken in interpreting yield loss studies because the female sawfly tends to select only the largest stems (main tillers) (Holmes et al. 1963; Morrill et al. 1992). Comparing infested stems with non-infested stems may skew the results due to the fact that smaller stems naturally yield less that the larger ones (Morrill et al. 1992). In a study comparing

equal sized stems it was concluded that sawfly reduced the yield in infested stems by an average of 17% (Holmes 1977).

Biology of *Cephus cinctus*

Most of the life cycle is spent inside the stem of host plants of the grass family, Gramineae. The adults generally emerge when host plants are in the stem elongation phase. Adults live for approximately 7 d (Criddle 1922) although this is greatly influenced by climatic conditions (Ainslie 1929). During this interval they must mate and lay eggs. As is common among the Hymenoptera, female larvae develop from fertilized eggs and males from unfertilized eggs (McKay 1955). In choosing oviposition sites, females tend to select larger stems, and in these larger stems fertilized (female) eggs are laid (Holmes 1954, Morrill et al. 2000, Morrill and Weaver 2000). It has also been observed that a higher proportion of females are obtained from early season eggs than later in the season and when the infestation is the result of migration from an adjacent field, that higher ratios of females to males are found on the outside portion of the field as opposed to the inside (Holmes 1954). Females produce up to 50 eggs each but this number is greatly influenced by the condition of the host plant in which the individual developed (Holmes 1978, Carcamo et al. 2002). Although females lay only one egg in a stem and then move onto another stem, other female sawflies have been observed to visit that stem and lay another egg (Criddle 1922). There does not appear to be any inhibition of subsequent oviposition by later arriving females as it is common to have several eggs laid in choice stems by a series of different females (Criddle 1922, Holmes 1978). Stem

diameter and maturity are the critical factors that impact the choice of a particular stem for egg laying, with larger, more elongated stems being preferred (Holmes et al. 1960).

Eggs hatch in about 8 d and the larvae start to feed almost immediately (Criddle 1922). Only one larva survives per stem, the survivor having cannibalized all other eggs and larvae (Criddle 1922, Holmes 1978). Most of the life cycle is passed in the larval stage. Feeding up and down the stem, the larvae develop through 4 or 5 instars (Holmes 1978). The end of feeding is triggered by the drop in stem moisture accompanied by an increase in the penetration of light of the green and yellow part of the spectrum (Holmes 1978). The larvae then migrate to the base of the stem where they chew a V shaped notch and then plug the stem below the notch with frass (Holmes 1978). The date of cutting, however, is governed largely by moisture levels in the wheat stem and cutting is delayed until the stem starts to dry (Holmes 1978). Inside the stub the larva produces a hibernaculum that isolates the larvae from the inside walls of the wheat stem (Holmes 1978). Sawfly larvae commence an obligatory diapause in the fall and then enter into the pupal stage in the spring (Criddle 1922). Although sawfly larvae are generally considered to be hardy, temperatures of –22ºC for 3 hours killed 50% of larvae (4-8 hours at –20ºC also resulted in 50% mortality) (Morrill et al. 1993). Presumably sawfly larvae are able to successfully overwinter because they are actually below the soil surface in the stem of the plant where temperatures are more moderate than air temperatures. The pupal stage is short, lasting (again depending on conditions) about 16 d (Criddle 1922). Several studies have been performed on factors that govern the transition from larva to pupa. It has been observed in the field that occasionally larvae do not enter the pupal stage and instead commence a secondary diapause until the following year (Salt 1947,

Church 1955). Temperatures in excess of 35ºC were required to return the larvae to diapause once it was broken in the spring (Salt 1947). High temperatures alone will not cause sawfly larvae to return to diapause and desiccation is also required to prevent larvae from entering the prepupal stage (Church 1955). This secondary diapause may be a survival mechanism for extremely dry spring conditions. Larvae in secondary diapause have been shown to emerge under favorable conditions the following spring (Church 1955). Once the larvae have begun metamorphosis, a secondary diapause cannot be commenced and the resulting severe desiccation leads to the death of the sawfly. After metamorphosis the adults chew their way out of the plugged end of the cut wheat stem and emerge to start the cycle over again.

Sawfly Control

Introduction to Sawfly Control

Control strategies for wheat stem sawfly have a long history since the first outbreaks in late 1800's. Criddle (1922) suggested plowing of infested stubble, early cutting of rye grass and bromegrass, early cutting of wheat, trap cropping, and alternate crops as control measures. Some of these practices still form the basis of recommendations but run into practical problems in implementation. Other control approaches that have been attempted or added over the years are: burning, time of seeding, row spacing/seeding rates, chemical control and the planting of resistant wheat. Following is a thorough review of these various practices.

Plowing and Tillage

At the turn of the century, there were very few cultural practices that farmers could employ, but tillage was one that was available to them. Tillage was effective when performed carefully with a plough that would turn the soil over, completely burying the crop stubble. If the stubble was not placed in the bottom of the furrow with several inches of soil over it the sawfly would easily emerge (Ainslie 1929). Sawfly adults are capable of emerging from several inches of soil cover (Ainslie 1929) making methods using cultivating and disking implements ineffective. Ainslie also noted that wheat stubble was necessary to capture moisture for succeeding crops. Shallow tillage may in some instances cause 35 to 70 % mortality in larvae by exposing the larvae to desiccation (Holmes 1982). A one-way disc was the most effective of modern implements but timing is critical; tillage before the larvae moved into the prepupal stage would cause them to return to diapause (Holmes 1982). Control depended on the drying of the larvae and favorable weather conditions drastically reduced control. Furthermore, survival of 30 to 70% of the population leaves sufficient sawflies to cause severe infestations. Lessons learned in the 1930's demonstrated the importance of maintaining residue cover to protect the soil. The recent move to direct seeding has further underlined the importance of residue to protect the soil in dryland farming systems and is in direct accordance with soil conservation management goals.

Early Harvest of Grasses and Mowing of Headlands

The underlying concept is to control the sawfly in headland grasses that act as a reservoir for sawfly. Harvesting or mowing the grasses in July before the larvae have

migrated down the stem kills many sawfly larvae. This is mentioned by Ainslie (1929) and is immediately coupled with the caution that such a practice would also destroy any parasitoids that were in the grasses, so a blanket recommendation for this practice is not advisable (Ainslie 1929). A recommendation to control sawfly by early cutting of headland and neighboring grasses is of little value since the major source of sawfly is the stubble from previous wheat crops.

Burning

At first glance, burning seems to be a viable alternative as it would seem logical that it would destroy the overwintering larvae. Ainslie (1929) noted after examining a large number of clumps of *Elymus condensatus* in Utah that sawfly larvae overwintering in the dense clumps were not adversely affected by an intense fire. Similar observations have also been made for wheat stubble, so stubble burning was discarded as a potential control practice (Ainslie 1929). The practice of burning stubble also exposes the soil to extreme risk of soil erosion and kills nearly all parasitoids as well.

Chemical Control

An evaluation of insecticides for control of sawfly was conducted in North Dakota in 1947 (Munro et al. 1949). Six different insecticides were tested (and were also tested again in 1948) and the conclusion was that none of the products provided satisfactory control. A study in Alberta that screened ten different insecticides came to the same conclusion (Holmes 1952). Little has changed with newer insecticides and improved application techniques (Morrill unpublished data). Systemic insecticides, like

carbofuran, and seed treatments were recently found to be ineffective (Morrill unpublished data).

Early Cutting of Wheat and Trap Strips

The concept is much the same as early harvesting of grasses to destroy the sawfly before they move to the base of the stem to overwinter. In most cases the trap strip would be spring wheat seeded a week or more prior to the main crop to make it more attractive to the sawfly (Farstad 1942). Farstad also noted that spring rye (*Secale cereale* L.) was effective as a trap strip but that oats (*Avena sativa* L.) was not. Trap strips using fall planted winter wheat were also shown to be effective in protecting spring wheat and solid stem wheat was effective for reducing losses by utilizing it as a border around hollow-stem wheat (Morrill et al. 2001). In order to be effective, trap strips (excluding the solid-stemmed wheat) must be cut for green-feed (about mid July) before the sawfly migrates to the base of the stem (Morrill et al. 2001). Under heavy sawfly pressure, trap strips are less capable of preventing migration of sawfly into the portion of the crop to be protected. Producers are reluctant to adopt trap strips because of their inconvenience and difficulty in managing different crops or crop stages that are in close proximity.

Row Spacing/Seeding Rates

A study of seeding rates and row spacing showed that increasing the density of seeding and decreasing the row spacing decreased the level of infestation (Luginbill 1958). This result is likely due to the preference of the female to lay eggs in the larger stems that occur in less dense seeding rates and wider row spacings and is likely an

artifact of small plot research. In a field situation, faced with no other choice, a female sawfly will oviposite in virtually any stem.

Time of Seeding

Delaying seeding of wheat to avoid being in the stem elongation stage during the sawfly oviposition period is another long-standing recommendation (Callenbach and Hansmeier 1944). Delaying seeding date can reduce the impact or even totally avoid damage by sawfly (Morrill and Kushnak 1999). In a seven-year study seeding delays of 12 to 20 days from the local early seeding activity resulted in a significant reduction in infestation in 4 years and complete avoidance of infestation in the other 3 years. The problem with delayed seeding is that early seeded crops tend to out-yield later seeded crops due to better utilization of available moisture (Morrill and Kushnak 1999). It is also somewhat difficult to give a fixed date for late seeding to avoid sawfly due to the highly variable nature of sawfly emergence. The authors of this study suggest that growers plant the fields with a history of heavy sawfly infestations last in their production program.

Field Modification

J.A. Callenbach discussed not having to abandon strip cropping in favor of block farming (Callenbach and Hansmeier 1944; Callenbach and Hansmeier 1945). The reasoning behind that statement is not presented but it is safe to assume that the comment was in response to suggestions that strip cropping was favored sawfly infestations. Strip cropping was originally introduced to help producers protect their fields from wind erosion. Farming techniques, machinery and availability of broad-spectrum herbicides

have now made possible summer fallowing large blocks of land with minimal risk of wind erosion. Because of the field border effect of sawfly migrating into a field, larger fields are often not impacted as greatly as repeated narrow strips, that become completely infested (Morrill et al. 2001). Converting to large block fields rather than maintaining the narrow strips is now a recommendation as part of an integrated control strategy for wheat stem sawfly.

Alternate Crops and Crop Rotation

From the beginning of the sawfly problems it was obvious that non-grass crops were not impacted by sawfly (Ainslie 1929). Oat and flax (*Linum usitatissimum* L.) were suggested to be entirely free of attack by *C cinctus*. Oviposition by sawfly in oat, wild oat (*Avena fatua* L.), and flax has been demonstrated but the developing larvae do not survive to the overwintering stage in either (Farstad 1944; Sing 2002). Durum (*Triticum turigidum* L.) was initially considered to be resistant to attack from sawfly but in 1919 serious damage was reported in durum wheat (Ainslie 1929). A similar situation developed with winter wheat. Winter wheat originally avoided attack by the sawfly but by 1985 winter wheat in Montana was consistently being severely attacked (Morrill and Kushnak 1996). Sawfly are able to successfully complete their life cycle on barley (*Hordeum vulgare* L.). Generally there is no cutting in barley although occasionally it does occur (Anonymous 1947). Mustard (*Sinapis arvensis* L.), canola (*Brassica napus* L.), peas (*Pisum sativum* L.), lentils (*Lens culinaris* Medic.) or chickpeas (*Cicer arietinum* L.) are all suitable rotation crops because they do not support sawfly survival and reproduction. Crop rotation to non-susceptible crops will reduce the sawfly

populations but the production of wheat with limited rotation is still the most common practice in dryland areas of Montana, southern Alberta and southern Saskatchewan.

Resistant Wheat

Solid-stem wheat has been the most successful control measure for sawfly with the introduction of Rescue in 1948 (Platt et al. 1948). A study of three varieties of wheat (Thatcher, Red Bobs, and Rescue) showed that sawflies were unable to maintain their population in Rescue and over a 5-year period the population gradually declined and failed (Holmes and Peterson 1957). The authors observed that a percentage of Rescue stems are successfully colonized and cut by sawfly larvae and a small portion of the population did complete its life cycle (Holmes and Peterson 1957). They also concluded that the breakdown of this resistance was unlikely to happen. Near Choteau, Montana, adoption of Rescue wheat by growers to manage sawfly resulted in a crash in the population over a seven-year period from 1950 to 1956 (Luginbill and Knipling 1969). While very effective, Rescue solid stem wheat was not favored by growers in the long term due to lower potential yields than hollow stem varieties (Morrill 1983), less desirable milling and baking qualities and a lack of rust resistance (of particular interest in North Dakota) (Stoa 1947). Also, environmental conditions (cloudiness during stem elongation) can reduce the degree of stem solidness (Eckroth and McNeal 1953). Inconsistency of control was noticed before the variety was even released but the reasons for the failures were not understood (Platt et al. 1948). This has also contributed to a reduced utilization of the resistant varieties.

Overview of Wheat Stem Sawfly Natural Enemies

Natural Enemies of Sawfly

Parasitism of wheat stem sawfly was noted early in sawfly investigations. To date, nine Hymenopteran species have been associated with *C. cinctus* as parasitoids (Table 1). Ainslie (1929) noted that *Pleurotropis utahensis* Crawford (Hymenoptera: Chalcidae) was particularly active on sawfly larvae found in native grasses by attacking the sawfly larvae in their hibernation chamber. *Microbracon cephi* Gahan (=*Bracon cephi*)(Hymenoptera: Braconidae) was also reported to attack sawfly larvae. Neither parasitic species were active in wheat (Ainslie 1929). C.F.W. Muesebeck described *Bracon lissogaster* (Hymenoptera: Braconidae)from individuals reared from sawfly-infested grasses by H.W. Somsen in 1950 (Muesebeck 1953). In 1956, Somsen noted very limited activity of *B. lissogaster* in wheat. *Scambus detritus* Holmgren (Hymenoptera: Ichneumonidae) was reported as a parasite of *C. cinctus* in 1952 from three individuals reared from sawfly-infested wheat stems (Holmes 1953). E.G. Davis noted *B. lissogaster* and *B. cephi* as well as *Eupelmella vesicularis* Retzius (Hymenoptera: Eupelmidae), *Eupelmus allynnii* French (Hymenoptera: Euchartidae), *Eurytoma atripes* Gahan (Hymenoptera: Eurytomidae), *Pleurotropis utahensis*, and *Scambus detritus* as parasites of *C. cinctus* but acknowledged that while high levels of parasitism could occur in native grasses they were not effective in wheat (Davis 1955). *Phyllobaenus dubius* Wolcott (Coleoptera: Cleridae) has recently been added to the list of insects attacking *C. cinctus* in wheat (Morrill et al. 2001). Although the effectiveness and

life history of this predatory beetle in relation to sawfly has yet to be elucidated it is clear that *P. dubius* is directly attacking sawfly larvae (Morrill et al. 2001).

Eupelmella vesicularis and *Eurytoma atripes* have both been shown to parasitize *C. cinctus*, but also are active as hyperparasitoids of *B. cephi* (Nelson 1953). Their activity was considered by Nelson to be of little consequence for either *C. cinctus* or *B. cephi* (Nelson 1953).

Collyria calcitrator (Gravenhorst) (Hymenoptera: Ichneumonidae) was released in Canada near Swift Current, Saskatchewan and showed initial promise by actively parasitizing *C. cinctus* (Smith 1931). Dissections of sawfly larvae at the release points showed parasitized larvae but further sampling in subsequent years recovered no adult parasitoids. *C. calcitrator* and *Bracon terebella* Wesmael (Hymenoptera: Braconidae) were released near Minot, North Dakota and near Choteau, Montana in 1952-54 but none of these releases were successful in the long term (Turnbull and Chant 1961) even though initial low levels of the parasitoid were recovered in North Dakota.

Horned larks (*Eremophila alpestris* L.) have been observed in large numbers splitting sawfly infested wheat stubs and feeding on the overwintering larvae (Davis 1955). This is not likely to be a significant natural control considering that serious infestations would equal millions of sawfly larvae in an average sized field.

Table 1: Parasitoids/predator of *Cephus cinctus* - adapted from Morrill 1997 (Morrill 1997, Morrill et al. 2001)

Parasitoid/ Predator	Order:Family	Host(s)	Habitat	Reference
Bracon cephi	Hymenoptera: Braconidae	*C. cinctus*	Wheat/ Grass	Nelson and Farstad 1953
Bracon lissogaster	Hymenoptera: Braconidae	*C. cinctus*	Wheat/ Grass	Somsen and Luginbill 1956
Eupelmella vesicularis	Hymenoptera: Eupelmidae	*C. cinctus* *B. cephi* *M. destructor*	Grass	Nelson and Farstad 1953
Eupelmus alynii	Hymenoptera: Euchartidae	*C. cinctus* *B. cephi*	Grass	Krombein et al. 1979
Eurytoma atripes	Hymenoptera: Eurytomidae	*C. cinctus* *B. cephi* *M. destructor*	Grass	Nelson and Farstad 1953
Homoporus febriculosus	Hymenoptera: Pteromalidae	*B. cephi* *M. destructor*	Grass	Nelson and Farstad 1953
Pleurotropis utahensis	Hymenoptera: Chalcidae	*C. cinctus*	Grass	Neilson 1949
Pediobius nigritarsis	Hymenoptera: Eulophidae	*C. cinctus*	Grass	Krombein et al. 1979
Scambis detritus	Hymenoptera: Ichneumonidae	*C. cinctus* *C. pygmaeus*	Grass	Holmes 1953
Phyllobaenus dubius	Coleoptera: Cleridae	*C. cinctus*	Wheat	Morrill et al. 2001

Host Location by Parasitoids

Finding a concealed host such as a sawfly larva requires complex adaptations by the parasitoid. First, at the field level, the female wasp must find a suitable host plant for the sawfly, determine which stem is infested and then find the larva in the stem. Many papers have shown that parasitoids are attracted by the common odors produced by host plants in order to find the proper habitat to search for its host (Turlings 1998). Early reports of the lack of parasitism in wheat suggest that parasitoids were not recognizing wheat as a place to hunt for their hosts and the sawflies were able to utilize wheat unmolested. Once the host habitat has been located, parasitoids have been shown to make very efficient use of volatile chemicals emitted by herbivore damaged plants to identify plants under attack (Turlings 1998). Sawfly larvae are well hidden within the stem of grass family plants, so the parasitoid has a further challenge to overcome. There has been individual adaptation documented, as well, where parasitoids use vision, mechano-reception or chemo-reception to pinpoint their host (Turlings 1998). In the case of sawfly parasitoids it is likely that vibrations are being used to pinpoint the position of the sawfly larva in the stems. The two *Bracon* species attacking sawfly very accurately locate and paralyze sawfly larvae by stinging (Nelson and Farstad 1953, Somsen and Luginbill, Jr. 1956). The sawfly larva is then immobilized so when the egg hatches the parasitoid larvae can immediately begin to feed.

Biology and Background of *Bracon cephi* and *Bracon lissogaster*

Bracon cephi was described first as *Microbracon cephi* by A.B. Gahan from *C. cinctus* infested grasses (Gahan 1918). *B. cephi* was not initially found in cultivated crops but rather in grasses and was of little value in controlling sawfly that was attacking wheat (Criddle 1922, Ainslie 1929). *Bracon lissogaster* was first described in 1953 by C.F.W. Muesebeck based on a study of 17 females and 28 males that were reared from sawfly infested grass stems collected near Choteau, Montana (Muesebeck 1953). Originally it was known mostly from its activity in native grasses but a population was noted to have heavily parasitized sawfly in wheat in a test plot that was infested with *Agropyron* grasses and also in a field of barley with volunteer wheat (Somsen and Luginbill 1956). Somsen (1956) also mentioned that although *C. cinctus* heavily infested species of introduced grasses no parasitism by *B. lissogaster* was observed in them. Somsen (1956) did report, however, rearing 'parasitoids from the native grasses *Agropyron smithii* Rydb. and *Stipa viridula* Trin. Early parasitism in large wheat fields was not significant, never more than a fraction of 1 percent (Somsen and Luginbill, Jr. 1956). Munro et al. (1949) reported significant parasitism by *Microbracon cephi* (*B. cephi*) in North Dakota in 1948. It was noted that *B. cephi* was effective in reducing severe sawfly infestations (Nelson and Farstad 1953, Holmes et al. 1963).

The geographic range of these two parasitoids is somewhat confusing. *B. lissogaster* may well be the predominant parasitoid in western and central Montana and *B. cephi* is the most important parasitoid in Canada and North Dakota. It may also be a case of mistaken identification as it is very difficult to distinguish between individuals of

B. cephi and *B. lissogaster*. A recent paper describes characters used to distinguish between the two species (Runyon et al. 2001).

Both *B. lissogaster* and *B. cephi* are ectoparasites of *C. cinctus*, and neither have been described from other hosts. They lay eggs on or near the larvae that have been immobilized by stinging (Nelson and Farstad 1953, Somsen and Luginbill 1956). While *B. cephi* lays only one egg per larva, *B. lissogaster* may lay several (1-4) on one larva (Nelson and Farstad 1953, Somsen and Luginbill 1956). The *B. lissogaster* larvae feed for 6-8 days (Somsen and Luginbill 1956) consuming the sawfly larva and then spin a cocoon inside the stem of the wheat plant. Nelson (1953) noted that *B. cephi* goes through a partial second generation while Somsen (1956) noted a complete second generation in *B. lissogaster*. The second generation has been problematic in the survival of the parasitoids in wheat production systems because often the second generation is unable to reproduce before harvest (Holmes et al. 1963, Morrill 1997). In grasses, however, the second generation is often complete as these grasses retain higher moisture levels later into the summer (Holmes et al. 1963). This may indicate the need to use grass refuge strips for the second generation of parasitoids. Once feeding is complete the larva spins a silken cocoon. In both species, the first generation larvae quickly go into a short pupal stage. Overwintering parasitoids go into a larval diapause and come out of diapause to complete metamorphosis in the following spring. Upon completion of metamorphosis the emerging adult chews a small hole in the wheat stem to escape.

Ability to withstand extreme winter temperatures is the result of very high levels of glycol accumulation in the parasitoid larvae (Salt 1959). As a result, the larvae can avoid freezing in all but the coldest weather. Survival is also impacted by harvest

operations and the larvae are unlikely to survive harvest if they form their overwintering cocoon in the two uppermost internodes of the plant (Holmes et al. 1963). The same study showed that first generation parasitism by *B. cephi* tended to be in the upper internodes of the plant and that second generation parasitism tended to be in the lower internodes. The distribution of the parasitoid larvae is determined by the distribution of the sawfly larvae at the time of oviposition by the female parasitoid. High sawfly densities have been reported to cause lower levels of parasitism due to destruction by the sawfly larvae (Holmes et al. 1963, Morrill 1997)

Bracon cephi larvae are seldom observed to overwinter in the stubs of wheat plants (Holmes et al. 1963). This means that once the stub has been cut and plugged the sawfly larva is essentially free from attack by the female wasp. Holmes et al. (1963) observed that factors delaying maturity of wheat increase the level of parasitism due to the greater success of the second generation. Holmes (1953) showed that a series of years with a relatively wet August increased the level of parasitism for that reason.

Stubble Height and Farming Systems

If the survival of overwintering larvae of the *Bracon* species is favored by taller wheat stubble, then a recommendation to leave taller stubble would have impacts on subsequent farming operations. The taller stubble would have to remain in place until the following July to allow the parasitoids to emerge. Seeding into or even working tall residues can present problems for conventional equipment. Generally the recommendation is to leave the stubble no longer than 5 cm longer than the row spacing

of the seeding implement (Beck 1998). Residue clearance and machinery costs have driven the adoption of wider row spacing for seeding. Research conducted at Indian Head, Saskatchewan, supported this trend by showing that yields did not decrease with increased row spacing (Lafond 1994). Many other studies, conducted both before and after the studies at Indian Head, Saskatchewan, have not supported wider row spacings. Row spacings of 20 to 25 cm consistently outproduce wider row spacings (Beuerlein and Lafever 1989; Solie et al. 1991). One way to increase residue clearance but maintain narrow row spacing is to divide the seeding implement into 4 or 5 ranks of openers. Another way is to seed with disc style openers such as those developed by Dwayne Beck in North Dakota (Beck 1998). There is a definite difference between anchored, fresh crop residue such as that encountered in recropping systems and residue that has stood for 19 or 20 months (such as in a chemical fallow system). Fresh residue is well anchored and usually remains anchored through the seeding operation. The older residue is brittle and tends to break off and cause plugging problems with the seeding implement. In chemical fallow systems it may be necessary to mow or otherwise deal with residue left longer to enhance parasitoids once they have emerged. Such operations would increase management costs. Fortunately, the move to reduced tillage across the Great Plains and Canadian Prairies has greatly increased our understanding of how to deal with crop residues in seeding systems (Larney et al. 1994).

Taller stubble changes the field environment in many ways, increasing snow capture, decreasing the wind speed at the soil surface, and thus reducing soil moisture evaporation losses. This also results in a change in the population of other organisms in the field such as insects, weeds and diseases. For example, retained crop residues have

been shown to increase the survival of *Fusarium* species (Bailey 1996). *Fusarium* species have been shown to cause mortality to overwintering sawfly larvae in field conditions (Morrill and Weaver unpublished data). These no-till practices also have a positive impact on soil organisms such as earthworms and result in healthier soils (Clapperton et al. 1997). Research on reduced tillage systems has generally indicated that the advantages of retaining crop residues on the soil outweighed the disadvantages, but producers must be made aware of the challenges in order to manage them effectively.

Objectives

Overall Objective:
Determine effects of harvest practices on the survival of the *C. cinctus* parasitoids *B. cephi* and *B. lissogaster*. This information will then be used to develop recommendations on agronomic practices that will enhance survival of these wheat stem sawfly parasitoids.

Working Hypothesis:
B. cephi and *B. lissogaster* populations are adversely affected by harvest operations and management practices could be developed that would enhance their survival in wheat fields.

Null Hypothesis:
Harvest practices have no impact on *B. cephi* and *B. lissogaster* populations in wheat fields.

Specific Objective 1: Investigate the current status of *C. cinctus* and its parasitoids across Montana, and in Alberta and Saskatchewan.

Working hypothesis 1: Parasitoids occur over a wide geographic area in association with *C. cinctus* with *B. cephi* predominating in eastern Montana and in the Canadian prairies and *B. lissogaster* predominating in central Montana.

Null hypothesis 1: There is no geographical pattern to the occurrence of the parasitoids *B. cephi* and *B. lissogaster* in association with *C. cinctus*.

Specific Objective 2: Determine the overwintering location of *B. cephi* and *B. lissogaster* larvae within wheat stems and their spatial distribution within wheat fields.

Working Hypothesis 2: *B. cephi* and *B. lissogaster* overwintering larvae have a predictable location within the field and within wheat stems.

Null Hypothesis 2: Location of the overwintering larvae of *B. cephi* and *B. lissogaster* shows no pattern within the field or within wheat stems.

Specific Objective 3: Determine the impact of harvest operations on *B. cephi* and *B. lissogaster*.

Working hypothesis 3: Harvest operations reduce the survival of *B. cephi* and *B. lissogaster*. Survival is greater with reduced destruction of wheat stems by harvest operations. Survival is greater in standing stubble than in residues laying on the soil. A predictable survival pattern exists where: Standing not harvested > standing with just heads removed> standing with only top 1/3 removed > harvested close to soil surface not chopped >harvested close to soil surface and chopped.

Null Hypothesis 3: Harvest operations have no impact on survival of *B. cephi* and *B. lissogaster.*

CHAPTER 2

MATERIALS AND METHODS

Adult Survey (Objective 1)

Survey Area Selection

The survey was concentrated in areas where sawfly losses were a perennial problem. Historical records, sawfly maps, researchers, and contact with extension workers were utilized to determine focal areas in which to start. Decisions to select winter wheat versus spring wheat fields were made based on the prevalence of each crop in the areas surveyed. In Montana a survey conducted by Blodgett in 1995-1996 (Blodgett 1997) was the starting point (Table 2). This was modified using results from other informal surveys conducted by Wendell Morrill and David Weaver. A number of county agents throughout the state were also contacted.

In Alberta, contacts were made with Alberta Agriculture, Food and Rural Development Crop Specialists: Rob Dunn (Lethbridge), Trevor Wallace (Oyen), Dave Spencer (Medicine Hat) and Curtis Weeks (Coronation) to determine the locations of current sawfly infestations.

Table 2: Wheat stem sawfly survey 1995-96 (Modified from Blodgett 1997)

County	Total acres farmed	Projected loss (bu.)	Rank	Loss/ cropped acre (bu./ac.)	Rank
Blaine	192,000	12,000	19	0.06	19
Carbon	15,000	22,400	17	1.49	13
Cascade	164,000	1,624,000	4	9.90	2
Chouteau	560,000	3,116,000	1	5.56	4
Daniels	209,000	31,200	16	0.15	18
Dawson	285,000	0		0.00	
Fallon-Carter	85,000	53,900	15	0.63	15
Glacier	152,000	286,000	13	1.88	12
Hill	509,000	2,399,000	3	4.71	8
Judith Basin	83,000	457,000	9	5.51	5
Liberty	130,000	704,000	7	5.41	6
McCone	208,000	2,506,000	2	12.0	1
Phillips	147,000	650,000	8	4.42	10
Pondera	202,000	919,000	6	4.55	9
Roosevelt	295,000	308,000	11	1.04	14
Sheridan	159,000	NA		NA	
Stillwater	52,000	304,000	12	5.85	3
Teton	173,000	925,000	5	5.35	7
Toole	77,000	18,000	18	0.23	17
Valley	292,000	91,000	14	0.31	16
Yellowstone	103,000	344,000	10	3.34	11
Statewide	**4,265,000**	**14,722,000**		**3.45**	

Saskatchewan was surveyed while traveling between eastern Montana and Alberta. Swift Current, Saskatchewan was selected because of a Research Center Press release that mentioned the presence of parasitoids in the sawfly testing nursery maintained by the center's wheat breeders at the Center (Clarke 2002). Contact with Fran Clarke at the Agriculture and Agri-Food Canada Research Station confirmed this situation. During the survey in 2002, conversations with Scott Hartley, entomologist, and Pat Gerwing, agrologist at Swift Current, both with Saskatchewan Agriculture, Food and Rural Revitalization gave further insights as to the extent and locations of the sawfly problems in Saskatchewan.

The three general areas selected in Montana were: 1) Chouteau, Cascade, Pondera, and Teton Counties in the "Golden Triangle", 2) McCone and Valley Counties (NE Montana), and 3) Wheatland, Sweetgrass, Stillwater, and Yellowstone Counties in south-central Montana. Some fields located between these target areas were also sampled. Three general areas were selected in Alberta: 1) south of Lethbridge (along Highway 61 Foremost to Wrentham), 2) northwest of Lethbridge, Picture Butte to Vulcan), and 3) eastern Alberta (Highway 41 - Medicine Hat to Oyen). In Saskatchewan, the only predetermined sampling location was in Cabri area.

Samples in 2003 were much more precisely defined. Some fields that were still of interest were sampled again, based on previous data. New sampling areas included fields located in western Pondera and western Teton counties of Montana (specifically around the town of Choteau) and near Assiniboia in Saskatchewan

Very little sampling was performed in 2004. A specific trip to southern Alberta (Milk River and Foremost) was undertaken in order to sample for *B. lissogaster*. Limited sampling was also performed in the Medicine Hat area in 2004.

Field Selection

Almost all sweep net sampling targeted fields of wheat growing next to chemically fallowed wheat stubble from the previous growing season. This was because indications from previous research that suggested that chemical fallow enhanced parasitoid survival (Runyon et al. 2002). It was not always possible to obtain sites that fit this description and notes were made to reflect this. Sampling locations were selected 15 to 30 km apart in target areas and further apart in non-target areas.

Sampling Protocol

Sweep net samples targeting adult sawflies were collected by using a standard heavy canvas sweep net (38 centimeters in diameter with a 90 centimeter handle). Each sweep consisted of a 180° arc swept rapidly through the wheat with no more than 75% of the sweep net into the crop, performed while walking at a brisk pace. In short crops, the sweeps were taken as close to the ground as possible without collecting soil in the sweep net. A field sample consisted of 150 sweeps. These were usually broken up into subsets of 50 sweeps each. In 2003 this was reduced to 75 sweeps per field to reduce time required to process samples. The sweep net samples were taken while walking approximately 2 meters from the field edge. For each sample (or sub-sample) the insects that were captured were transferred by emptying the sweep net contents into a four-liter zip-lock bag. The bag was then closed, labeled and placed into a large cooler with ice to

cool the insects. At the end of the sampling day, some insects were placed into killing jars with ethyl acetate, and pinned for reference samples. The rest of the samples were transferred to 70% ethanol and placed back into the cooler. Upon returning to the laboratory at Bozeman, the samples were placed into a -10º C freezer until they could be sorted and counted. Notes taken at each location included the GPS location at point of entry into the field, date of sample, closest town, date, time of day, wind condition, temperature, cloudiness, and observations of the field conditions.

Sample Processing

When the samples were sorted, male and female sawfly numbers were recorded. Braconids were sorted separately as well, with number of males and females recorded for both *B. cephi* and *B. lissogaster*. The number of *P. dubius* were also recorded (and kept in alcohol). In most cases, the remainder of the sample was carefully sorted with samples kept of the common insects; all Hymenoptera and Coleoptera were removed and placed into a separate vial and labeled as residuals.

In 2002, all sorted samples were placed into 70% alcohol. In 2003, all sorted samples were placed into 95% alcohol and placed back into -10° C storage. Samples from both years are available for use in genetic studies of sawfly populations. Similar studies could also be conducted on the samples of the two *Bracon* species and the *P. dubius*. The rest of the samples may be valuable in the future if someone is interested in sorting them for other Hymenoptera and Coleoptera species that are collected when using a sweep net in wheat fields.

Location of Overwintering Parasitoids (Objective 2)

Site Selection

The selection of sites for more intense sampling was based on the presence of both substantial numbers of sawfly adults and braconids in the survey samples from the adult survey conducted earlier during the flight period (Table 5 and Table 6). The sites for more intense sampling were selected from different geographic regions. In 2002, there were five sampling locations from Montana, four from Alberta and one from Saskatchewan (Table 3 and Figure 1). A second sample from the Oyen site was taken at a later date because of concerns that the first sample was taken too early and because of a later than expected availability of the site due to the producer's decision to delay harvest operations.

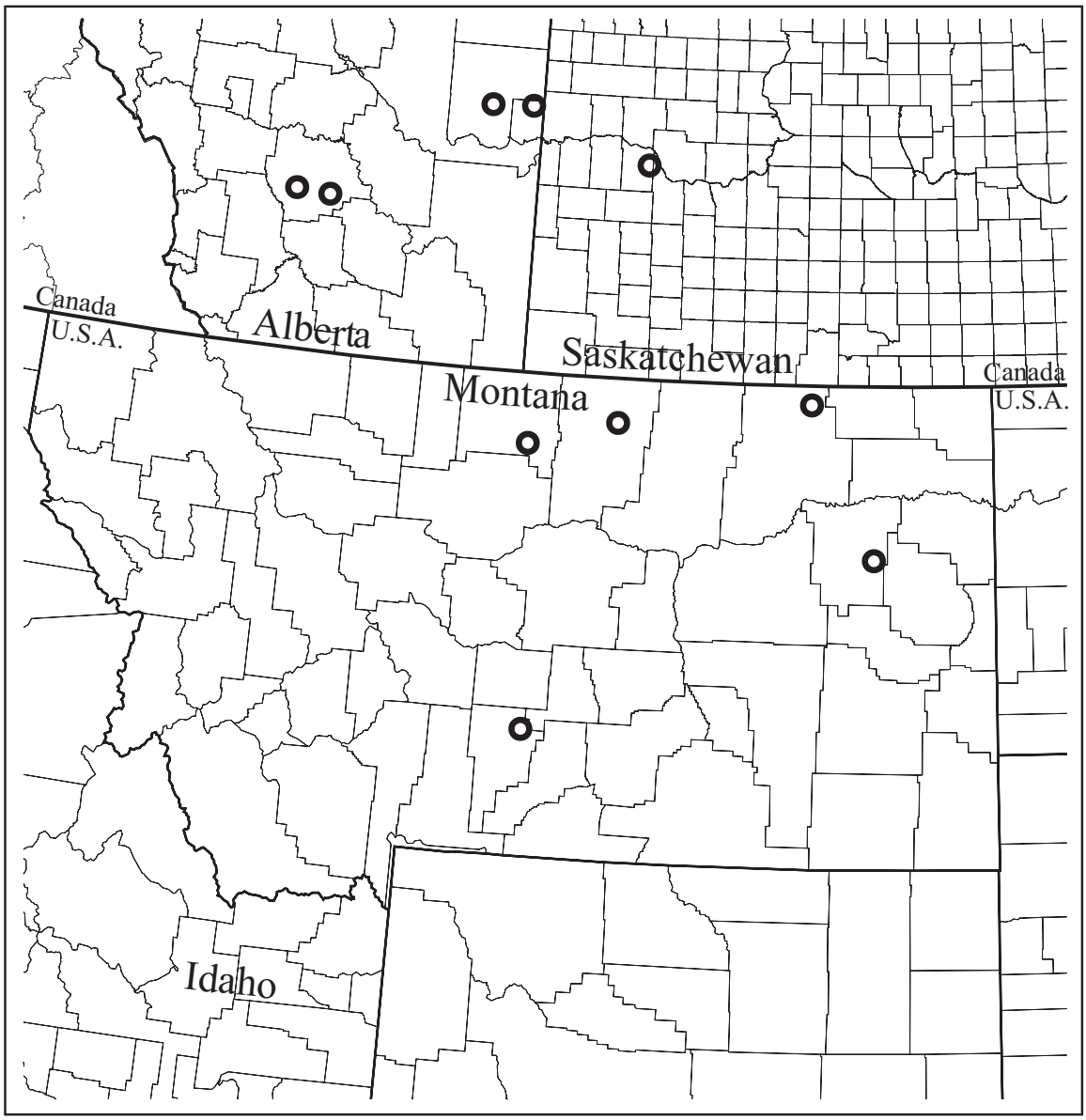
In 2003, there were 9 fields selected for samples: five from Montana, three from Alberta and one from Saskatchewan (Table 4 and Figure 2). Two fields were selected in close proximity to one another at Laredo, MT. One Laredo field was winter wheat, which was adjacent to the field sampled in the previous year and the other was a nearby spring wheat field.

Table 3: Fields selected for intensive sampling and stem dissection in 2002

Location	Crop	Row Spacing	Producer
Opheim MT	Spring Wheat	22.5 cm	Don Fast
Circle MT	Spring Wheat	22.5 cm	Victor Wagner
Rapelje MT	Spring Wheat	30 cm	Paul Broyles
Laredo MT	Spring Wheat	30 cm	Ken Wilson
Harlem MT	Spring Wheat	30 cm	Harlem Hutterian Brethren
Lomond AB	Spring Wheat	25 cm	Marvin Maronda
Vulcan AB	Spring Wheat	25 cm	Byron Matlock
Acadia Valley AB	Spring Wheat	25 cm	Triple M Farms
Oyen AB	Spring Wheat	30 cm	Graham Caske
Cabri SK	Spring Wheat	25 cm	Jim Moen

Table 4: Fields selected for intensive sampling and stem dissection in 2003

Location	Crop	Row Spacing	Producer
Opheim MT	Spring Wheat	30 cm	Don Fast
Brockway MT	Spring Wheat	25 cm	Del Gackle
Laredo MT	Spring Wheat	25 cm	Ken Wilson
Laredo MT	Winter Wheat	30 cm	Gary Gregoire
Gildford MT	Winter Wheat	25 cm	Bruce Kapperud
Lomond AB	Spring Wheat	25 cm	Marvin Maronda
Vulcan AB	Spring Wheat	25 cm	Byron Matlock
Acadia Valley AB	Spring Wheat	25 cm	Triple M Farms
Assinboia SK	Spring Wheat	30 cm	Jim Triska



2002 Field Study Locations

Figure 1: 2002 field study locations

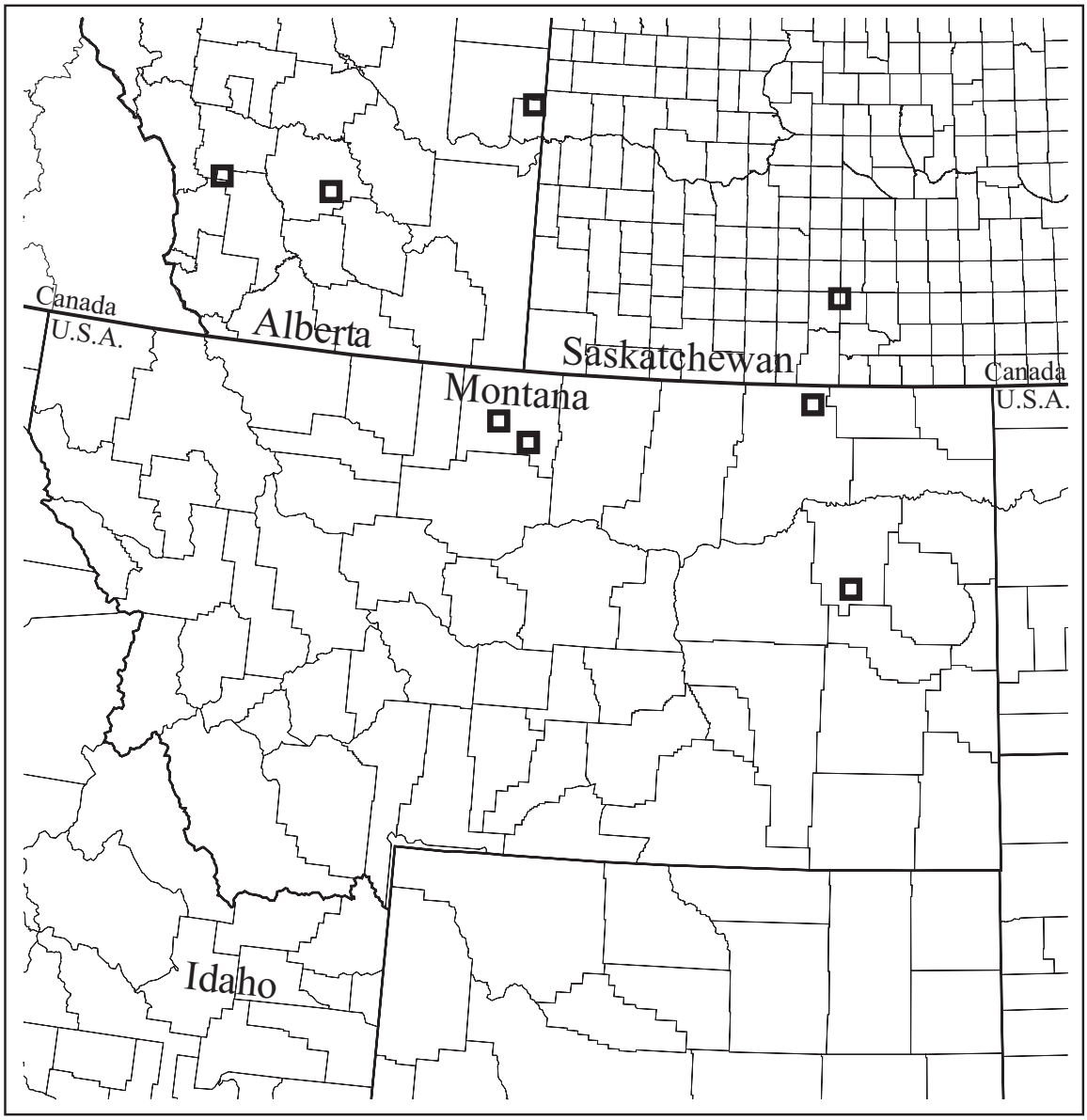


Figure 2: 2003 field study locations

Table 5: Sweep net data used for selecting 2002 fields.

Location	Date	Crop	GPS N	GPS W	Sweeps	C.c male	C.c. female	B.c. male	B.c. female	B.l. male	B.l. female
Acadia Valley AB	7/2/02	Wheat	51 13.471	110 08.312	150	48	15	64	36	0	0
	7/12/02				50	117	31	14	24	0	0
Cabri SK	7/11/02	Durum	50 47.427	108 32.821	150	139	65	2	6	0	0
Lomond AB	7/5/02	S.S. Wheat	50 19.131	112 42.299	150	33	7	55	4	0	0
Oyen AB	7/2/02	Wheat	51 12.628	110 40.760	150	139	66	7	2	0	0
Vulcan AB	7/19/02	Wheat	50 20.353	113 08.566	150	1	10	5	17	0	0
Circle MT	6/25/02	Wheat	47 33.003	105 32.107	150	39	7	21	3	0	0
Harlem MT	6/24/02	Wheat	48 37.590	108 45.902	150	20	7	3	0	0	0
Laredo MT	6/24/02	Wheat	48 24.559	109 52.560	150	3	36	5	2	0	0
Opheim MT	6/25/02	S.S. Wheat	48 50.303	106 19.916	150	0	0	0	0	0	0
	7/11/02				20	174	162	45	39	0	0
	7/15/02				50	335	385	70	82	0	0
Rapelje MT	6/18/02	Wheat	46 02.666	109 42.299	150	5	29	0	0	0	0
	7/10/02				150	0	0	9	6	0	0

S.S. Wheat =solid-stem; C.c. = *Cephus cinctus*; B.c. = *Bracon cephi*; B.l. = *Bracon lissogaster*

Table 6: Sweep net data used for selecting 2003 fields

Location	Date	Crop	GPS N	GPS W	Sweeps	C.c male	C.c. female	B.c. male	B.c. female	B.l. male	B.l. female
Acadia Valley AB	6/14/03	Headland	51 13.466	110 08.350	100	3	2	1	0	0	0
	7/1/03	Wheat			75	1521	312	41	15	0	0
Assiniboia SK	6/25/03	Wheat	49 43.651	106 00.955	75	187	6	26	6	0	0
	6/25/03	Brome			75	38	6	154	20	0	0
Lomond AB	7/1/03	S.S. Wheat	50 19.845	112 42.131	75	711	116	45	44	0	0
Vulcan AB	7/1/03	Wheat	50 20.345	113 68.309	75	855	139	27	50	0	0
Brockway MT	6/16/03	Wheat	47 18.674	105 49.217	75	124	49	4	1	0	0
	6/16/03	Crested Wheat			50	12	0	28	1	0	0
Gildford MT	6/19/03	Wheat	48 33.765	110 15.527	75	3	10	29	3	1	0
	6/24/03	Winter Wheat	48 33.991	110 15.909	75	4	3	4	6	0	0
	6/24/03	Wheat	48 34.002	110 15.909	50	12	14	39	19	7	0
	6/24/03	Wheat	48 33.992	110 16.760	30	2	7	38	16	3	0
Laredo MT	6/19/03	Winter Wheat	48 24.555	109 52.558	75	3	17	4	3	1	0
	6/19/03	Wheat			75	1	3	2	5	0	0
Opheim MT	6/16/03	Headland	48 50.303	106 19.916	75	3	0	7	1	0	0
	6/25/03	Wheat			75	1	2	0	0	0	0

S.S. Wheat =solid-stem; C.c. = *Cephus cinctus*; B.c. = *Bracon cephi*; B.l. = *Bracon lissogaster*

Sample Collection

Forty samples were collected from each field in a grid pattern of five depths into the field (1.5, 8.75, 15, 30 and 45 m) repeated at intervals of 45 m along the field (Figure 3). Before sampling, the grid was laid out in the field using tape measures and the sampling points were marked with pin flags. Once the sampling grid was laid out, the bases of the wheat stems were spray-painted. This effectively marked the soil level on all of the stems to facilitate stem length measurements during dissections.

Sample A1 was always the starting point for grid placement. This point was selected randomly by counting a random number of walking strides (between ten and thirty) past the estimated distance along the field that would avoid collecting samples in the double-seeded corners of the field. Samples in selected fields consisted of all stems (including any cut stems) and as many of the stubs as possible from 90 centimeters of row. The samples were hand pulled when soil conditions allowed, and dug with a shovel when soil conditions were too dry for hand pulling. These samples were bundled in sub-samples of 30 cm each and the three sub-samples were bound together and labeled with the location.

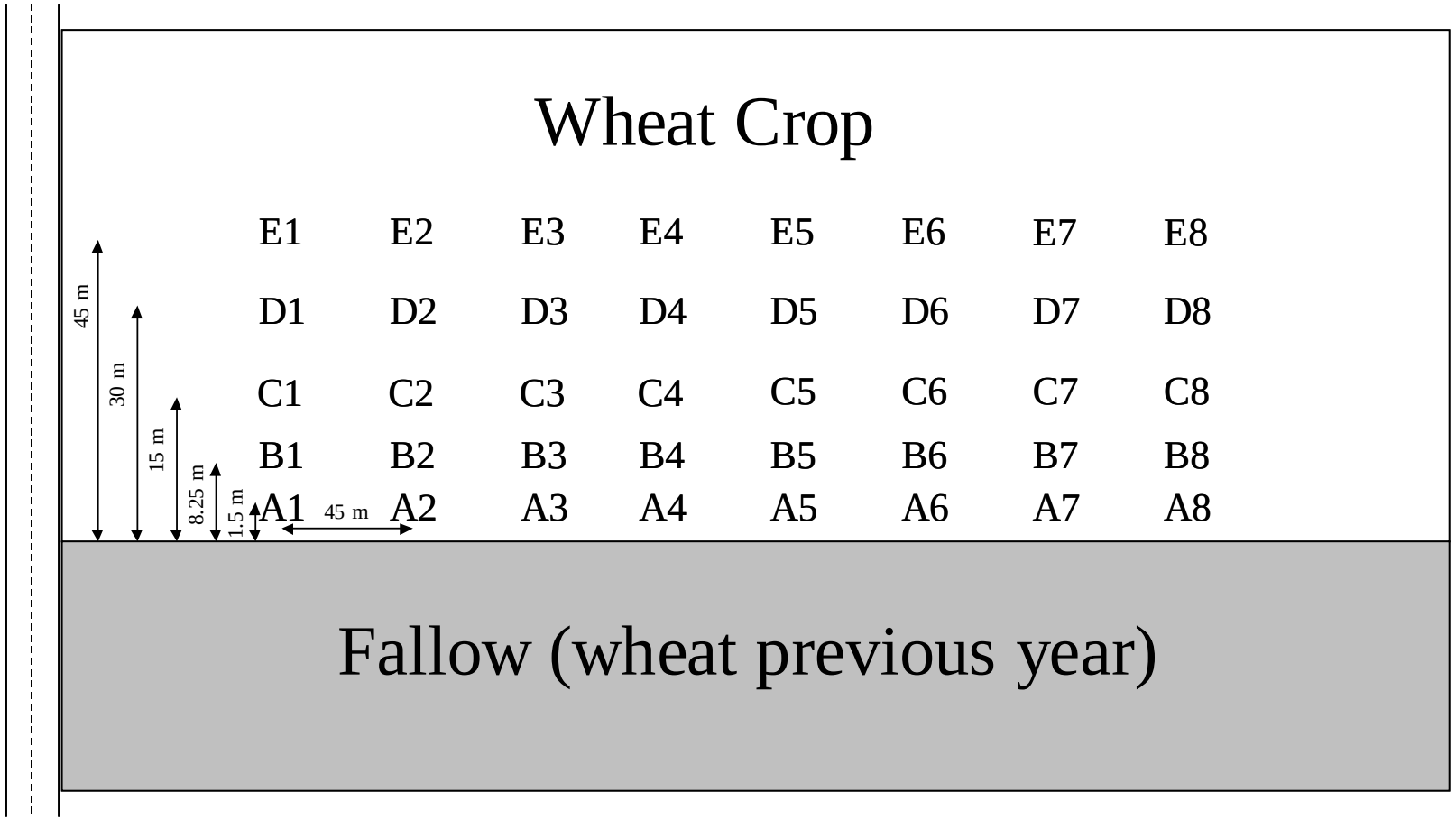


Figure 3: Sampling plan of fields selected for study

Drying and Storage of Plant Samples

Field samples that were wet or still moist were dried by standing the bundles in either a greenhouse (very wet samples) or in the laboratory until dry. Air-dry samples were loaded into 210-liter plastic barrel liners and placed in an unheated storage unit. Closer to processing time, the samples were moved into the wet cold storage chamber in the Plant Growth Center. Samples were held for at least one month prior to processing to allow for final development of parasitoid cocoons.

Sample Processing

Stems were numbered in the order they were processed with numbering starting over at the beginning of each subsample (Data Sheet Figure 4). The numbering facilitated tracking during data entry and data validation. The above ground stem length of each stem was measured between the bottom of the paint mark and the base of the rachis. Very short stems that did not have a viable head (no seeds) were not dissected (or counted). Stem length was not recorded for broken stems or cut stems with no accompanying lower cut stem section (stub). The part of the broken stem that was missing was noted. Broken pieces were kept until the end of the sample and they often could be pieced together, and then recorded as complete stems. Care in handling and processing limited the number of broken stems. Stems were dissected by using an Exacto knife to split the stem along its length as described by J.B. Runyon (2001). The stems were classified as either infested or uninfested, based on the presence or absence of the characteristic frass produced by larval feeding of the wheat stem sawfly. Uninfested stems required no further information recording. Larvae in infested stems were further

classified as cut stem (normal development), live in the stem (rare), dead, not found (error in processing or very small, usually dead, larva), or parasitized. The height above soil level was recorded for dead larvae and abnormal cutting. If a parasitoid was present, the following information was recorded: emergence hole or cocoon, height above soil level, and internode of occurrence, starting from the bottom. The internode number was determined by counting up from the base of the plant. Spring wheat generally had five internodes and winter wheat generally had six internodes. From this method, it is possible to get a three-dimensional view of where the parasitoids are found in the field. Parasitoid cocoons were usually not damaged by the dissection process. These were saved for use in other research programs. Adult *Bracon* spp. that had not emerged were noted and entered as an emergence hole – the rationale being that in a more natural situation (in the field rather than cold, dark storage) they would have emerged. The date of stem dissection was recorded along with the name of the person who did the dissection.

Occasionally other insects (or phenomena) were found in a stem. Clerid beetle larvae and straw-worm adults (*Tetramesa grandis* (Riley) Hymenoptera:Eurytomidae) were the most common findings of note. These were recorded in the notes section of the data sheet in case this information was required at a later date.

Efforts were made to match the cut top stems with their stubs from within the same subsample. This process was usually very successful and resulted in more complete stem measurements. Cut top stems without the corresponding cut bottom portion and broken stems were not measured to determine stem heights.

Parasitoid Overwintering Location Study (Scott Meers) Page ____ of ____

Location: ____________________ Sample Number ________________________

Date(s) stems split ________________ Stem Splitters _______________________________

Stem #	Stem length (mm)	Notes (use back of page if necessary)	Not infested	Infested live larva (mm)	Infested dead larva (mm)	Infested no larva	Cut Stem	Broken stem - top, bottom or both ends	Infested-parasitoid emerge hole (mm)	Infested-parasitoid cocoon (mm)	Inter-node (from bottom)

Figure 4: Data sheet (reduced from actual size)

The technical support staff performing dissections were monitored for accuracy of their work. Infested stems with no larva or parasitoids were considered to be errors. Technicians were encouraged to keep the number of such entries at a low level by taking time to locate the missing larva. These incorrect entries were often due to the presence of a small, dead sawfly larvae that had dried up, making them hard to find, and occasionally due to inattentiveness in the dissection. Prior to analysis, the data were subjected to a series of integrity checks (Appendix A).

Statistical Analysis

Linear regression modeling of cocoon location predictors was performed using "R" Statistical Software (R Version 2.0.1 2004). R- square values were obtained from simple linear regression. Larger models to predict cocoon location were built "stepwise" using multiple linear regression in "R" Statistical Software.

The relationship between cocoon numbers and biomass was evaluated with a Mantel test using PC Ord Statistical software (McCure and Medford 1999). Data vectors were forty rows by one column, dissimilarity matrices were created using Euclidean distance calculations and the test statistic was evaluated using the randomization method (9,999 randomizations) (McCure and Grace 2002).

Effect of Spray Paint Trial

In preparation for the first field collections, a small trial was conducted to determine the impact of spray paint on insects that might be in the stem. Oil base spray paint (Krylon ColorWorks ®) was applied to the point of complete coverage on 25 stubs

freshly removed from cold storage. The sawfly emergence from the painted stubs was compared to the emergence from 400 stems removed from cold storage to be reared for other experiments. Other than the spray paint the samples were treated identically. Results were compared using a paired T-test in "R" Statistical Software. (R Version 2.0.1 2004)

Harvest Practices and Parasitoid Survival (Objective 3)

Harvest Plot Design

In 2002 and 2003, plots were specifically seeded for this study on station at the Western Triangle Research Station near Conrad, Montana. This site was selected because of the presence of high population densities of sawflies and parasitoids. The wheat cultivar 'Reeder' was chosen for these plots because it is very attractive to sawfly adults (Weaver, unpublished data), and larval survival is apparently high. The extended ripening season of Reeder (Lanning et al. 2003) also should maximize the opportunity of parasitoids to find their host.

Conrad MT.

In 2002 the plot area was seeded on April 29 and plots were established in early September (Figure 5). The 3 acre plot area was managed as a large block of wheat (just like a producer's field). In early September the plots were laid out (Figure 5). Individual plots 3.05 meters wide and 22.90 meters long were staked out in the block of wheat. The easterly 5 replicates were set out in a random complete block and the westerly area was set up in a block of the "short" harvest treatments and a block of the "tall" harvest

treatments. Before the harvest treatments were performed, 30 cm long samples were taken at both ends of each individual plot. These stems were dissected and the number and stem location of all the parasitoids were recorded to establish the baseline population of parasitoids. The plots were set up with 5 treatments: 1) Standing: left unharvested as a positive check, 2) Heads Off: cut at a level just low enough to remove most heads, 3) Two Thirds Cut: cut at approximately 2/3 of the standing height, 4) One Third Whole: cut at 1/3 of standing height with the straw left long, as it would be when unchopped while passing through a combine, 5) One Third Chopped: cut at 1/3 of standing height with the straw cut in smaller pieces, as it would be when chopped while passing through a combine.

Swift Current 2002.

The Swift Current site was made available within the sawfly nursery used by the wheat breeders of the Agriculture and Agri-Food Canada Semiarid Prairie Agricultural Research Station. The site is used to test new lines of sawfly resistant wheat. The plot area was not very large and therefore the treatments had to be small and imposed by hand using a battery powered hedge trimmer. The 5 treatments were the same but only 5 replicates were established because of the restricted plot area (Figure 6). Each individual plot was 1 m by 1.5 m. A single row 1.5 m sample was taken from behind the middle treatment of each block. All stems from this sample were split and number and location of parasitoids was recorded.

The plant breeders chose ‘Glenlea’ wheat because they felt the large hollow stems favored the production of large, very healthy sawfly larvae (Fran Clarke personal

communication). Gleanlea wheat is one of the latest maturing spring wheat varieties used in Canadian production systems (Chapman 2003) and therefore favored the parasitoids as well. Parasitoids were viewed as a "problem" for the researchers because the large numbers of sawflies that were killed by the parasitoids tended to reduce the cutting level of the wheat, which the primary measures used by wheat breeders to measure sawfly resistance (F. Clarke personal communication). The plot area had received substantial damage from hail approximately 2 weeks before the plots were laid out. The same five treatments were used as in Conrad except that the wheat was not harvested because the plot treatments were imposed using a hedge trimmer. The heads were cut off and allowed to fall to the ground, and then the treatments were imposed on the remaining three plots by cutting to the appropriate height. In the chopped plot, the stems were cut to approximately 5 cm pieces.

Conrad 2003.

For 2003, the plots were again set up at the Western Triangle Research Station near Conrad, MT. The wheat block was seeded in late May. The seeding date was later than ideal for both wheat production in the area and maximization of sawfly infestation. This meant that there was significant concern that there would not be enough sawfly in the late crop to allow for high densities of parasitoids. The plot area was again managed as a normal wheat field until harvest time with the exception of releases of sawfly into the plot area at the time of stem elongation. On two dates (June 27 and July 3), approximately 75 adult female sawflies were released at each of 26 points in the plot area. The release points were at the border between the treatments that would be imposed

at harvest time. The sawflies were collected 16 km away near Pendroy, MT. The 10 replicates were set up in a randomized complete block design (Figure 7). A 30 cm sample of wheat stems was taken from the middle of each plot and all the stems dissected. The number and location of parasitoids was documented.

Lomond 2003.

The second plot in 2003 was located near Lomond, Alberta. The site was chosen because large numbers of sawfly and parasitoids were collected there in both 2002 and 2003. The plots were set up in 10 blocks as a randomized complete block design (Figure 8). Each individual treatment was 1.5 by 1.5 m (2.25 m^2) and the entire treatment area was harvested in the spring of 2004. The plots were imposed using a hedge trimmer just as they were in Swift Current the year before. Thirty cm of row stem samples were collected at the front and back of each plot.

Crop Residue Collection

In all four plots, the treatments were left over the winter and all material was collected (residue on the ground, standing residue with as much attached root material as possible) in the following spring. With the exception of Swift Current, the area collected was 1.5 by 1.5 m (2.25 m^2). At Swift Current, the plot size was 1.0 by 1.5 m (1.5 m^2). The samples were air dried if wet and then placed in cold storage until they could be placed in the emergence barrels.

Materials

Emergence barrels were constructed from 170 liter plastic barrel liners. The barrel liners were reinforced with 10 cm wire mesh so they would be self supporting.

This approach was taken to limit costs and facilitate storage of the equipment after the project was completed. Barrel lids were constructed from poster board and a hole was cut in the center of the lids to insert an emergence cage. The emergence cage was constructed from a 500 ml plastic jar with the center cut out of the lid. The jar lid was glued to the poster board lid over the hole. A cone made of clear plastic (overhead film) was placed inside the jar to guide the insects into the jar and help retain them. Insects could be removed and counted by unscrewing the jar from the lid.

Insect Collection

Insects were removed from the jar using an aspirator. Date, number, species and sex of emerging parasitoids were recorded. Experience has shown that misting with water enhanced the emergence of the parasitoids (Justin Runyon pers. comm.) so the material inside the barrels was misted twice a week using approximately 25 ml of water per barrel. Emergence barrels were held 2 weeks past last emergence before disassembly to ensure all eclosed specimens were collected and recorded. In 2002 all materials in the barrels were carefully sorted and the number of parasitoids that had become trapped and did not fly to the emergence cages were recorded.

Statistical Analysis

Parasitoid numbers from all four of the trials were analyzed using "R" statistical software (R Version 2.0.1 2004). Analysis of variance (ANOVA) was used to determine if there were significant differences among harvest treatments. Differences were separated using Tukey's procedure for multiple comparisons at a family confidence level of 95%. The difference between total parasitoids emerged and parasitoid totals including

insects recovered from barrel residues was evaluated with a 2-factor analysis of variance using “R” statistical software.

Chopping and Shredding Trial

Extra material was collected from the Swift Current site in 2002. This material was divided by weight into 9 equal portions. Three of these portions were left entire as a check. Three portions were cut into 10 cm pieces and three portions were shredded using a string weed eater. This shredding duplicates harvest equipment that chops crop residue prior to redistribution on the field. These 9 portions were placed into emergence barrels as described above and emergence of parasitoids was documented. Parasitoid numbers were analyzed using “R” statistical software (R Version 2.0.1 2004). Analysis of variance was used to determine if there were significant differences between the treatments. Differences were separated using Tukey’s procedure for multiple comparisons at a family confidence level of 95%.

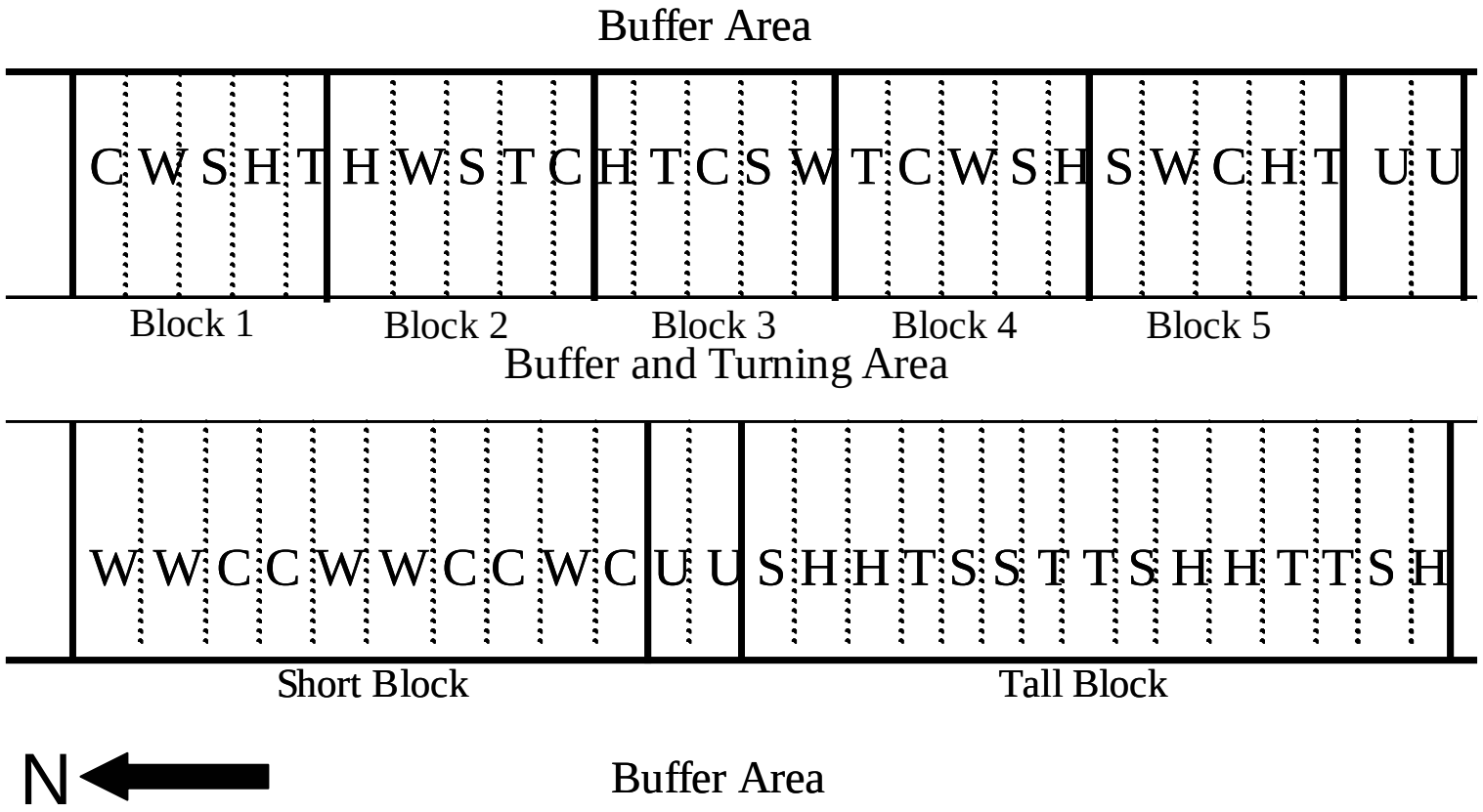


Figure 5. Conrad Harvest Plot 2002

C = 1/3 Chopped H = Heads Off
W = 1/3 Whole S = Standing
T = 2/3 U = Unused Buffer

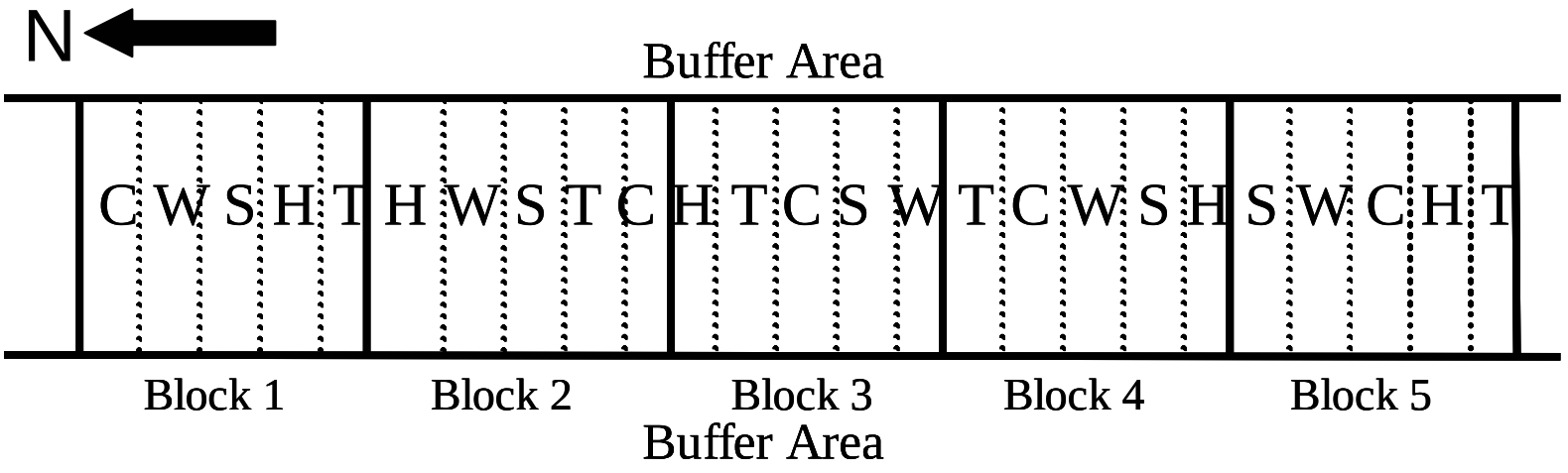


Figure 6. Swift Current Harvest Plot 2002

C = 1/3 Chopped H = Heads Off
W = 1/3 Whole S = Standing
T = 2/3

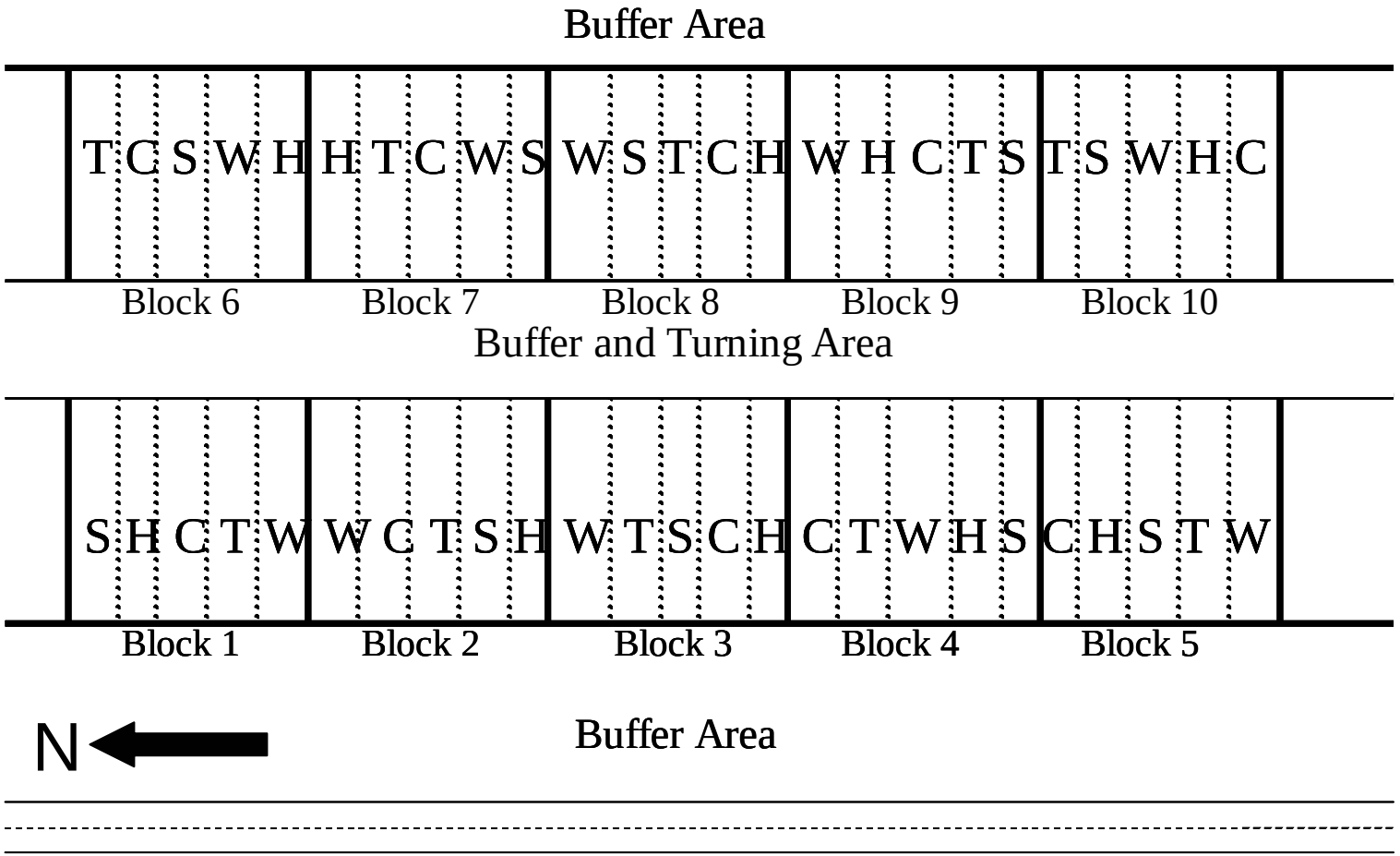


Figure 7. Conrad Harvest Plot 2003

C = 1/3 Chopped H = Heads Off
W = 1/3 Whole S = Standing
T = 2/3

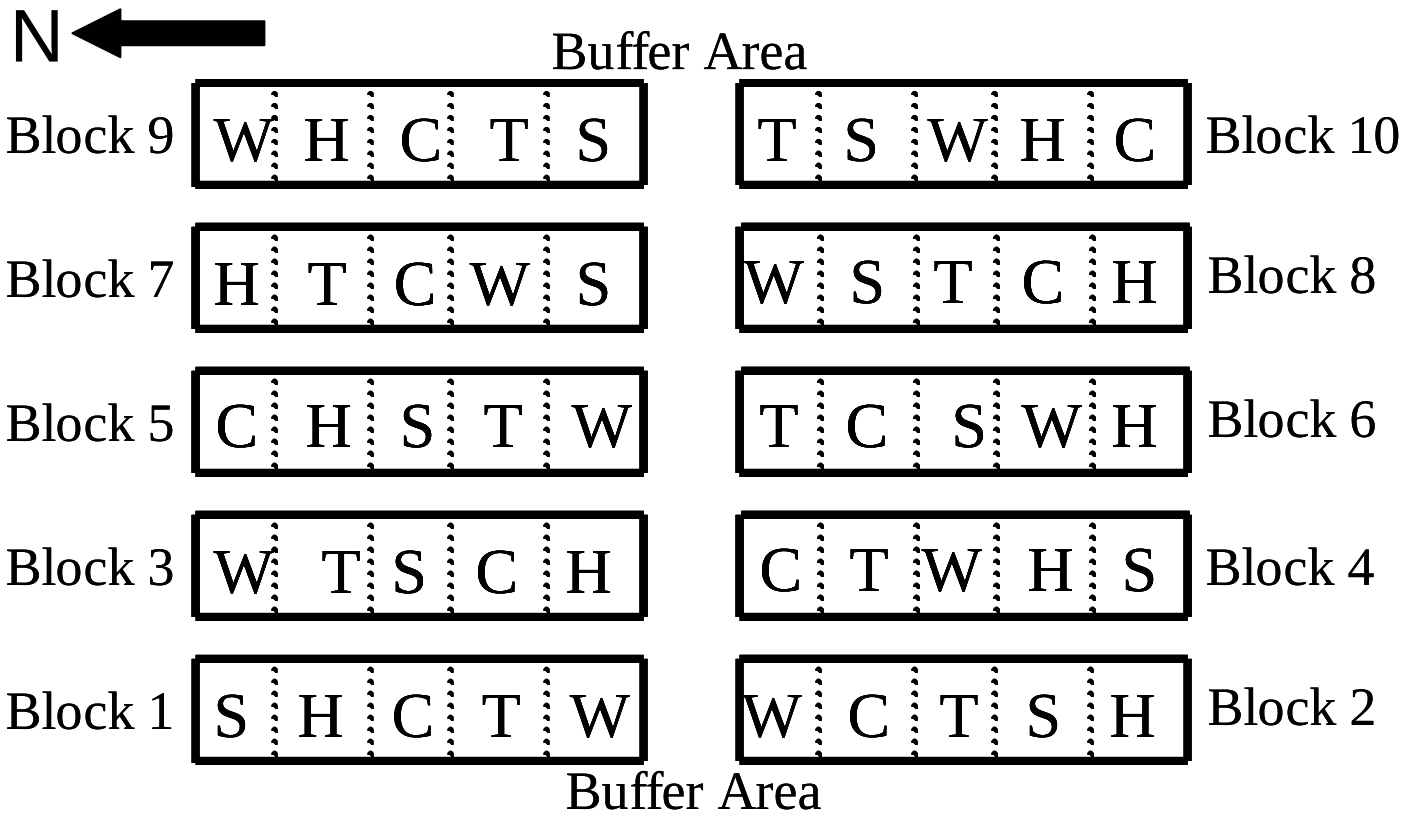


Figure 8. Lomond Harvest Plot 2003

C = 1/3 Chopped H = Heads Off
W = 1/3 Whole S = Standing
T = 2/3

CHAPTER 3

RESULTS

Adult Survey (Objective 1)

The sampling protocol was consistent among fields. Within the constraints of survey sampling, it was not possible to perform repetitive sampling throughout the sawfly and parasitoid flight period at each location. Furthermore, variables including weather conditions such as wind, relative humidity and intensity of solar radiation and time of day all impact sweep net catches. For these reasons, survey results must be considered as presence/absence sampling rather than definitive statements about the relative sizes of the populations. This means that finding a few or many sawflies, parasitoids or predators means only that they are present at that site. Absence of a particular insect group may indicate only that they were not found. The insect under investigation may be present a levels too low to be detected by sweep net sampling. This important clarification sets constraints on the interpretation of the survey results.

2002 Survey

Throughout Montana, southern Saskatchewan and southern Alberta in 2002, sawflies were found in all areas surveyed (Figure 9) with the exception of the area southwest of Bozeman, which is largely non-agricultural. Sawflies have been collected from those sites in previous surveys (W. Morrill unpublished data). Sweep net samples in the Swan Valley of Idaho showed no sawfly larvae, although larval tunneling was observed in smooth bromegrass (*Bromus inermus* L.) samples. It is a logical finding that

sawflies were collected from most areas surveyed because efforts were targeted at areas with historical sawfly problems.

In 2002, parasitoids were found in most areas as well, although not at every location. Two notable areas that were devoid of parasitoids were the Bozeman to Three Forks area and southern Alberta from Medicine Hat through Lethbridge and south to Foremost. *B. cephi* was the predominant parasitoid in Montana with only single specimens of *B. lissogaster* found at three sites in 2002. These sites were in the "Golden Triangle" area north of Great Falls. In all samples from Canada containing parasitoids, only *B. cephi* was collected (Figure 11).

Samples of sawflies that were collected in this survey were included in a study of mitochondrial DNA to study genetic variations within the Northern Great Plains populations (Figure 14).

2003 Survey

Sampling in 2003 (Figure 10) focused on areas with sawfly problems and was used primarily for scouting potential locations for parasitoid distribution (Objective 2) studies. Additionally, a sampling trip into the Choteau, Montana area was added to sample for *Collyria calcitrator* that was released there in 1954 (Davis et al. 1955). No *Collyria* were found.

In 2003, *B. cephi* was once again the predominant parasitoid species collected and no *B. lissogaster* were found in Canada (See Figure 12). Only thirteen sites had *B. lissogaster* in the Montana samples and all but two of these were in the Golden Triangle area. The two locations outside of the Golden Triangle were at Harlem in a wheat field

and at Big Timber in a roadside smooth bromegrass stand. In all but three sites, *B. cephi* and *B. lissogaster* were found at the same locations. In all locations where both species occurred, *B. cephi* was found in greater numbers.

Phyllobaenus dubius

In 2002, the predatory beetle, *Phyllobaenus dubius*, was found at four locations. Twenty locations with *P. dubius* were found in 2003. The maximum found at any one location was at Frazer, MT in 2003 with one *P. dubius* for every three sweeps. In both years *P. dubius* was found over a wide geographic distribution (Figure 13).

Exclusively Female Sawfly Populations

A population of solely female sawflies was reported northwest of Lethbridge, Alberta in the 1930's (Farstad, 1938). The occurrence of thelytokous parthenogenesis is of great importance to population dynamics because of increased fecundity due to the all female population. No sampling was targeted specifically in the Nobleford area of Alberta where this population was originally found. In all of the sampling carried out in this study, there were nine locations that had only female sawflies. Of these, seven locations comprised either one or two individuals. The remaining two locations were sampled at other times, and male sawflies were collected on those sampling dates. Therefore, no evidence of an exclusively female population was found in this survey work.

2004 Survey

Specimens of *B. lissogaster* were found in Alberta, just north of the Sweetgrass Hills and also northeast of Medicine Hat. In both cases the samples were from roadside stands of smooth bromegrass and sawfly adults were also found in the sweep net samples. At this time, confirmation of specimen identification by Robert Wharton, Texas A&M University, is pending. The other finding of significance was *B. cephi* specimens taken from a wheat field just north of Foremost, Alberta. This was in an area in which these parasitoids were not found in the previous two years of sampling.

Meteorus versicolor

Meteorus versicolor Wesmael (Hymenoptera, Braconidae), was found in high numbers in a field northeast of Brooks, Alberta on July 1, 2003. Several specimens were pinned and others were kept in alcohol for identification at a later date. These samples were identified with the assistance of Dr. R. Hurley, curator of the Montana State University Entomology Collection. This species was often noted as "other interesting Hymenoptera" while sorting sweep net samples from other locations. Specimens of *M. versicolor* were confirmed from several sites in Montana, Alberta, and Saskatchewan in both 2002 and 2003. The concern with this species was two-fold: at first glance it was similar to the *Bracon* species of interest in his study, risking improper determination while sorting samples, and secondly, it raised the possibility of a new species of parasitoid attacking the wheat stem sawfly.

The misidentification of this species was not likely to have critical importance due to low numbers collected at all locations except at Brooks, and also because of its

distinctly different body structure than *Bracon* spp. The possibility of this insect being a parasitoid of sawfly is also unlikely because all host records of this species are from Lepidoptera (Krombein et al. 1979). No potential host for *M. versicolor* was identified in this situation.

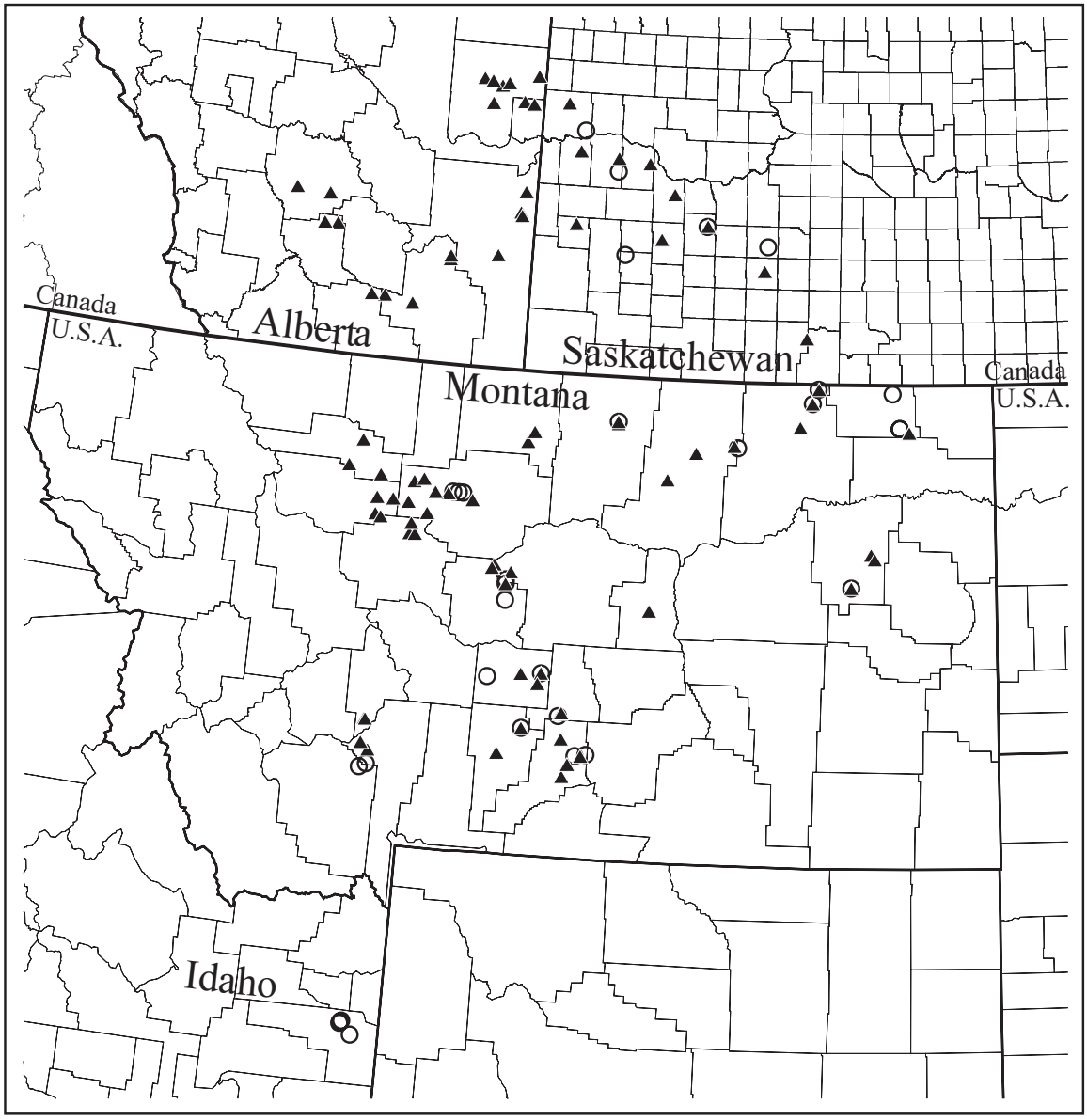


Figure 9: 2002 sweep net sampling and C. cinctus collection sites.

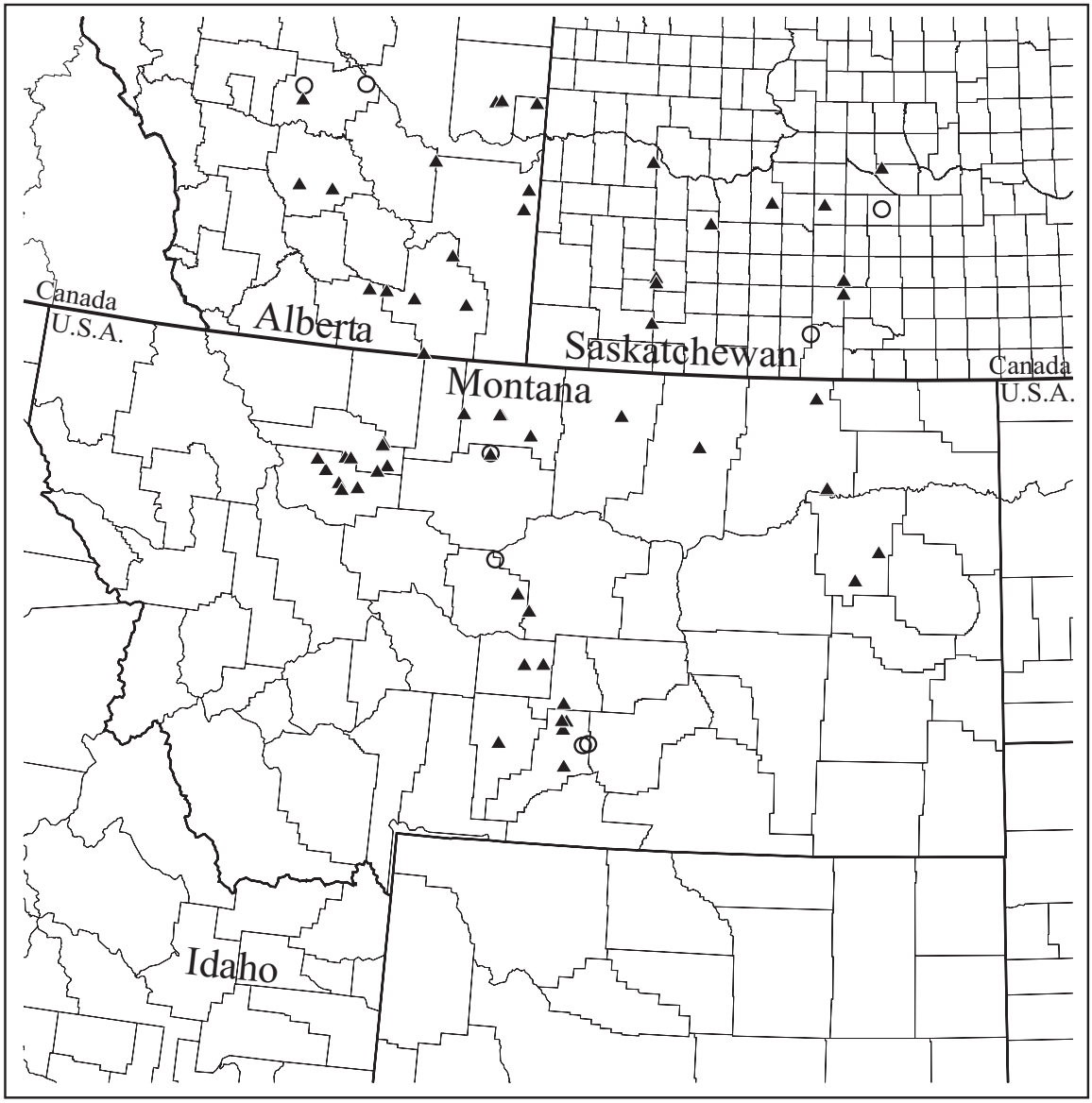


Figure 10: 2003 sweep net sampling and C. cinctus collection sites.

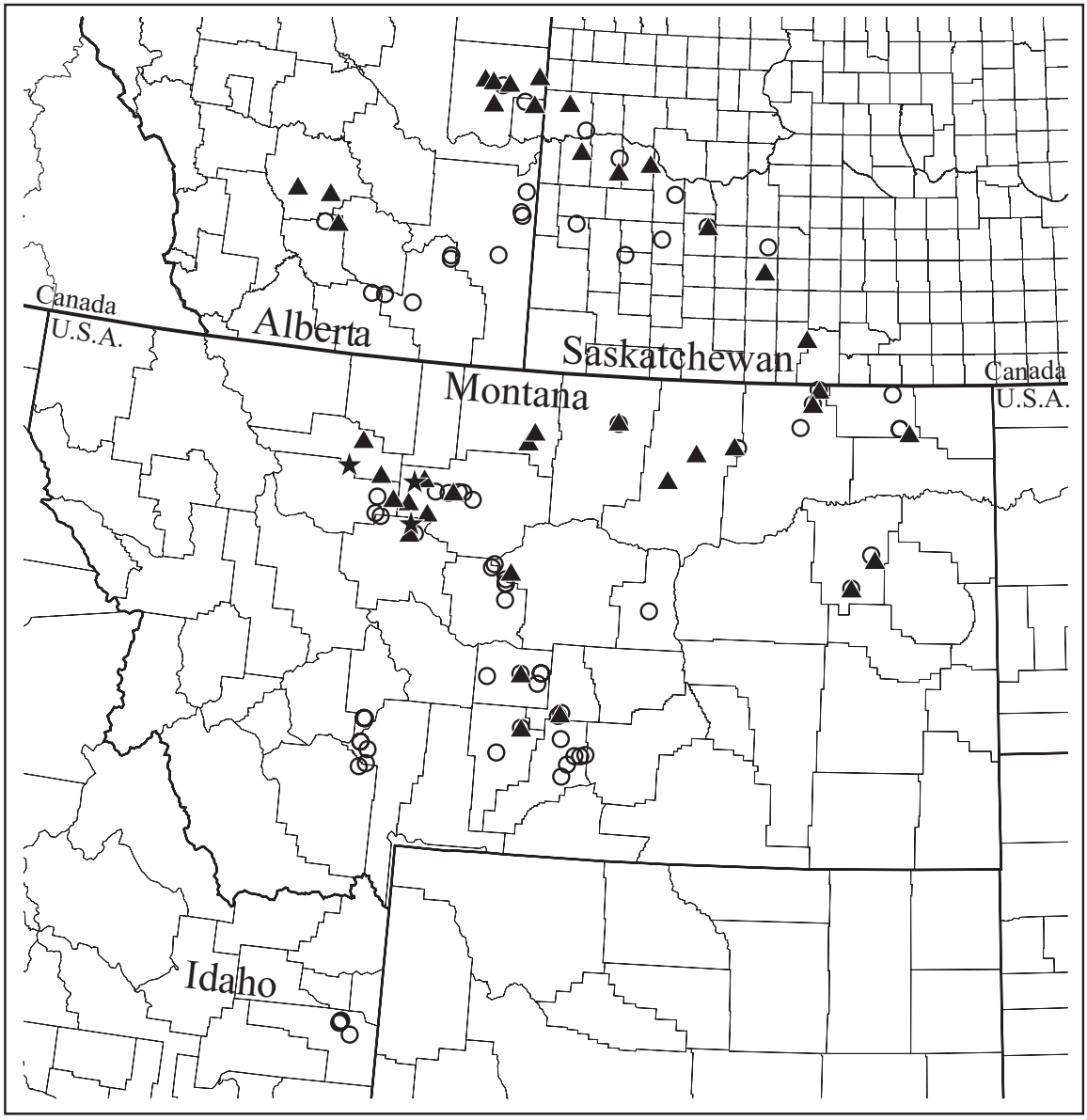


Figure 11: Locations where *Bracon* spp. found in sweep net samples in 2002.

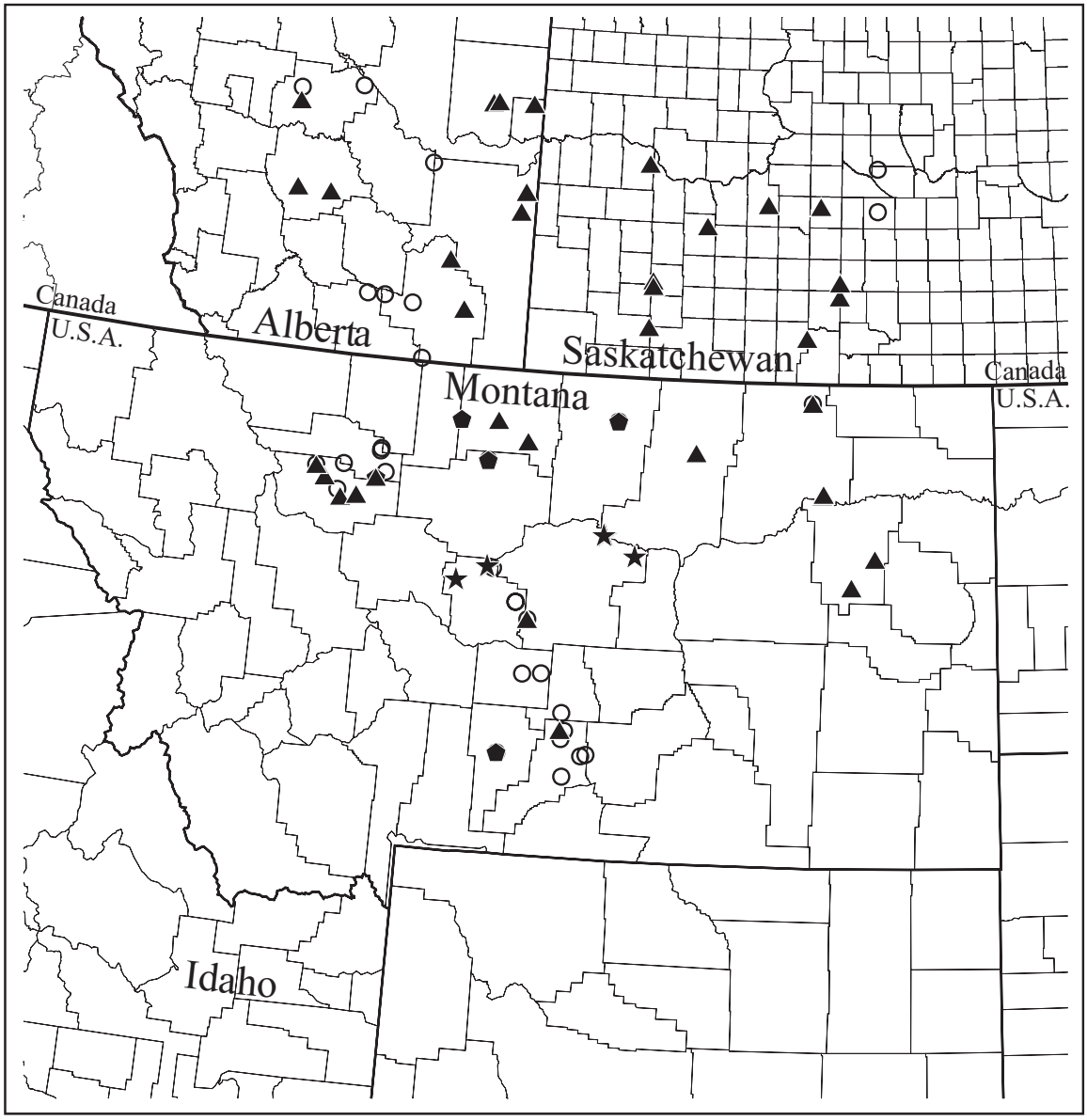


Figure 12: Locations where *Bracon* spp. found in sweep net samples in 2003.

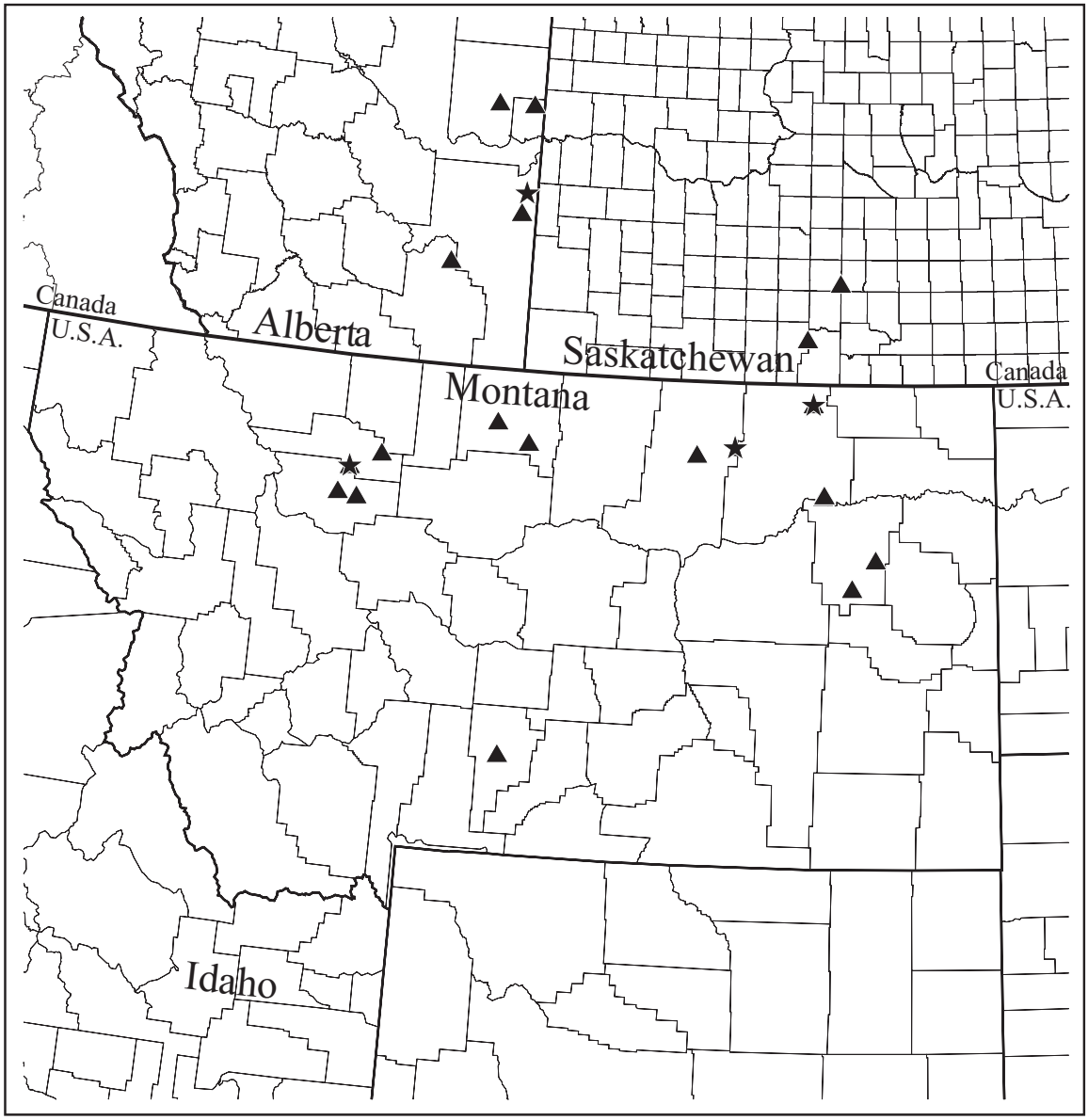


Figure 13: Locations of *P. dubius* found in sweep net samples in 2002 and 2003.

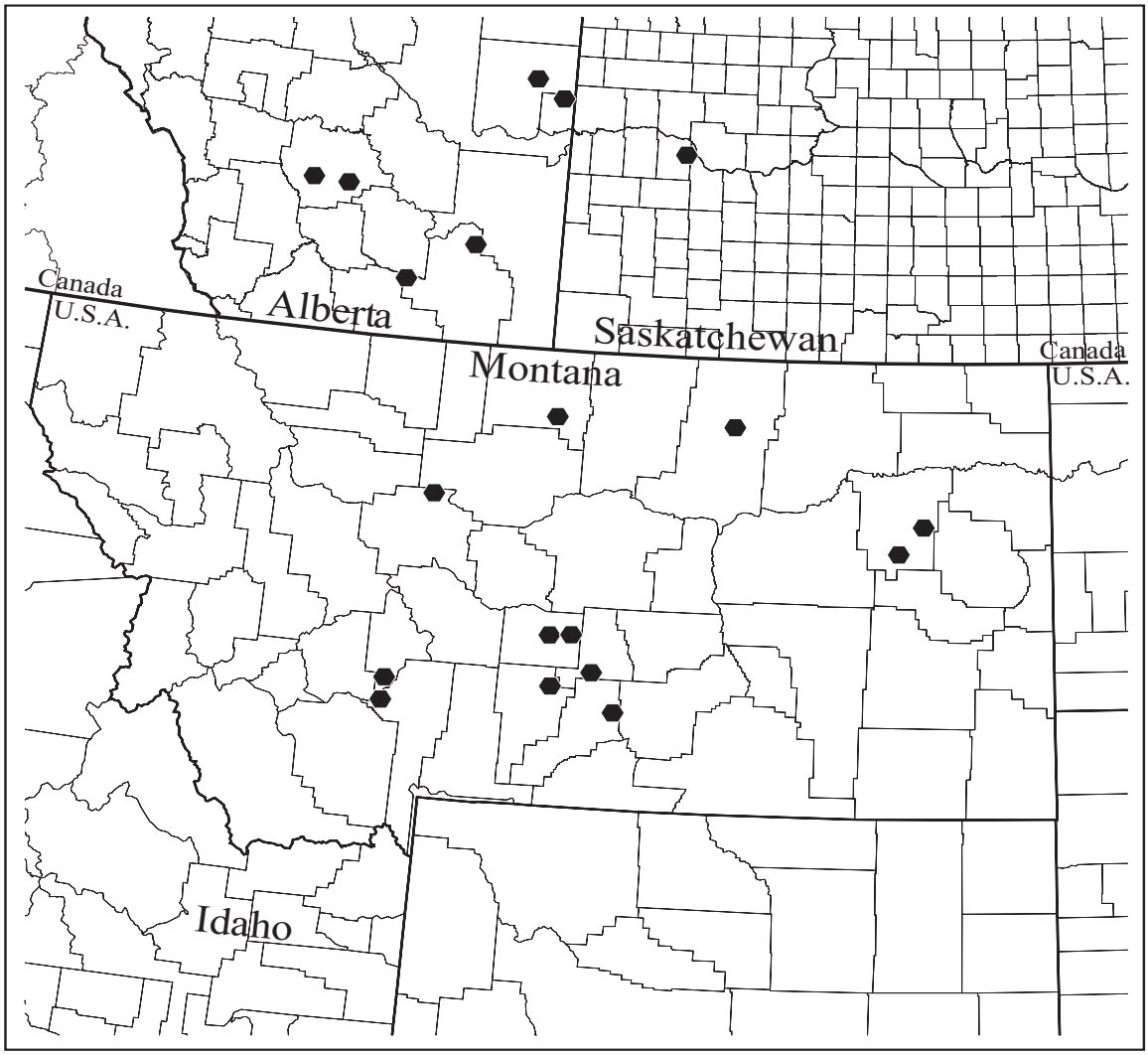


Figure 14: Locations *C. cinctus* where collected mitochondrial DNA analysis (2002)

Location of Overwintering Parasitoids (Objective 2)

General Observations 2002

Percent infestation and percent of stems cut is expressed as the percentage of all stems that were split. Percent parasitized is expressed as the percentage of all stems that were infested, because a stem must be infested before parasitism can occur.

Four fields that had substantial numbers of parasitoids were: Lomond, Vulcan, and Oyen in Alberta, and Opheim in northeastern Montana. The other six fields had much lower numbers of parasitoids. Of these one was in Alberta, one in Saskatchewan and 4 in Montana. All four of the Montana fields with low levels of parasitism also had low levels of expressed sawfly infestation. The Rapleje field had virtually no sawfly infestation despite collecting adult sawflies in sweep net samples earlier in the season (Table 5). A solid-stemmed variety was planted and had very high expression of the solid-stem trait. This situation resulted in high mortality among newly hatched sawfly larvae and, therefore, low levels of infestation. The lack of hosts obviously resulted in the absence of parasitoids. The three other fields had low levels of infestation and low numbers of parasitoids.

Two other fields had solid stem wheat in 2002: Lomond, Alberta and Opheim, Montana. These two fields had high levels of parasitism (Table 7). It is important to note that all of the fields were selected on the basis of relatively high levels of sawfly and parasitoids in sweep net samples during spring surveys.

The Oyen field was sampled because the producer changed his mind on harvest operations. Initial sampling was performed on August 7th ahead of a planned swathing

operation. On August 24, the crop was still standing unswathed and was sampled again. The later sampling date showed higher levels of parasitism.

The ratio of parasitoid cocoons to emergence holes for the four fields with the greatest numbers of parasitoids range from 4.8:1 and 10.4:1 showing the increase of parasitoids due to the success of the second generation of parasitoids. This is well illustrated by the two collection dates at the Oyen location. The ratio of cocoons to emergence holes increased from 0.8:1 to 4.8:1 because the second generation had time to parasitize more hosts.

General Observations 2003

Higher numbers of parasitoids in 2003 indicated that population levels were increasing due to success in previous years (Table 8). The maximum ratio of cocoons to emergence holes was 1.3:1 and many locations had fewer second generation cocoons than first generation emergence holes. This was likely due to the warm, dry summer contributing to an early fall which in turn limited the number of second generation braconids available to parasitize the sawfly larvae. The difference in the ratios was confirmed using a T-test. This returned a P-value of 0.0058, showing that there is a significant difference in the ratios of cocoons to emergence holes between the two years.

It is interesting to note that the rate of cutting at Opheim, MT fell from 21 % in 2002 to 3.5 % in 2003 as parasitism and other causes of mortality severely reduced the sawfly population. In Lomond, AB there was the same trend with higher sawfly mortality and decreased amounts of stem cutting. At Laredo, MT, the winter wheat field was adjacent to the 2002 sampling site and showed an increase in sawfly infestation and

stem cutting. In Alberta, both Vulcan and Acadia Valley showed this type of increase in sawfly infestation and stem cutting. Acadia Valley showed a modest increase in the first generation of parasitoids over 2002 but the second generation was largely unsuccessful.

It is noteworthy that parasitism never accounts for all of the sawfly larvae mortality in the stem and the cause of this merits further investigation. The Assinboia, SK, Brockway, MT, Gildford, MT, and the Laredo, MT spring wheat sites were newly sampled fields in 2003 and did not have the historical background available make comparisons.

Location of Parasitoids in the Field 2002

Only four fields in 2002 had sufficient numbers (near or above 80 cocoons – average of two per field sample location) of parasitoids to evaluate the pattern of cocoon distribution in the fields: Opheim MT, Lomond AB, Vulcan AB and Oyen AB (Figure 15 - 22). The Oyen field was marginal for this purpose because most of its parasitism was clustered at the end of the field. That field end was adjacent to an extensive ungrazed native pasture. In the Oyen field it is interesting to note that the edge of the field had low numbers of parasitoids and higher numbers occurred deeper into the field. This same pattern clearly occurred at the Opheim field as well. This edge effect is dealt with later in the results section. The Vulcan field had two sampling sites with very high numbers of parasitoids. This made associations difficult to establish but the overall pattern appeared to show a slight depression in numbers at the field edge. Lomond shows a similar depression in numbers along the edge, but has two distinct areas of higher parasitoid numbers that appeared to be associated with topographical variation in the field. These

patches align very well with areas of superior crop growth measured as biomass. Biomass is quantified as the total stem length from that sample.

Location of Parasitoids in the Field 2002.

In 2003, four fields had greater than 200 parasitoid cocoons in total: Lomond AB, Opheim MT, Vulcan AB, and Assiniboia, SK (Figure 23 - 30). Of these, two had highest numbers of parasitoids at the field edge and the other two appeared to have a slightly depressed level of parasitism in the outside samples. Brockway (Figure 31) and Gildford (Figure 32) both had less than 100 parasitoids and both appear to have the highest levels of parasitism in the outside samples. The Laredo spring wheat field (Figure 33) was bordering land that was fallow the previous year and had low levels of sawfly infestation. It is interesting to note that in this case the limited sawfly infestation was concentrated in the middle of the field and that the parasitoids located the sawfly larvae at those locations (Figure 34). There was no apparent explanation of the cause of this unusual concentration of sawfly. Figures 15 to 34 have varying scales on the Z axis, care must be taken in comparing results from field to field.

Table 7: Summary of fields sampled in 2002.

Location	Number of Stems	% Infested	Parasitoids	% Parasitized	Parasitoid Cocoons	Emergence Holes	% Cut Stems	Ratio of Cocoons:EH
Acadia Valley AB	1731	78.5	38	2.8	32	6	13.9	5.3:1
Cabri SK	1379	60.7	3	0.4	2	1	6.2	2:1
Lomond AB	3809	74.5	605	21.3	548	57	32.7	9.6:1
Oyen 1 AB	2490	80.3	35	1.8	16	19	27.5	0.8:1
Oyen 2 AB	3880	78.4	87	3.8	72	15	48.7	4.8:1
Vulcan AB	2994	62.1	159	8.5	145	14	45.1	10.4:1
Circle MT	2638	5.4	26	18.3	13	13	0.4	1:1
Harlem MT	1566	8.2	20	15.5	10	10	3.0	1:1
Laredo MT	3365	14.6	14	2.8	6	8	11.7	0.8:1
Opheim MT	3979	67.9	1250	46.2	1123	127	21.3	8.8:1
Rapelje MT	1936	0.9	0	0	0	0	0.2	NA

EH = Emergence Holes

Table 8: Summary of fields sampled in 2003.

Location	Number of Stems	% Infested	Parasitoids	% Parasitized	Parasitoid Cocoons	Emergence Holes	% Cut Stems	Ratio of Cocoons:EH
Acadia Valley AB	3683	98.8	51	1.4	14	38	87.0	0.4:1
Assinboia SK	3225	22.2	389	54.3	218	171	4.9	1.3:1
Lomond AB	1803	75.0	1803	42.3	571	1232	15.1	0.5:1
Vulcan AB	4686	91.7	648	15.1	212	436	62.6	0.5:1
Brockway MT	3818	24.5	148	15.8	83	66	9.8	1.3:1
Gildford MT WW	3955	71.0	275	9.8	84	191	23.7	0.4:1
Laredo MT	3366	11.8	109	27.5	34	75	5.1	0.4:1
Laredo MT WW	5369	73.6	55	1.4	15	40	20.8	0.4:1
Opheim MT	4735	25.3	638	53.3	361	277	3.5	1.3:1

EH = Emergence Holes

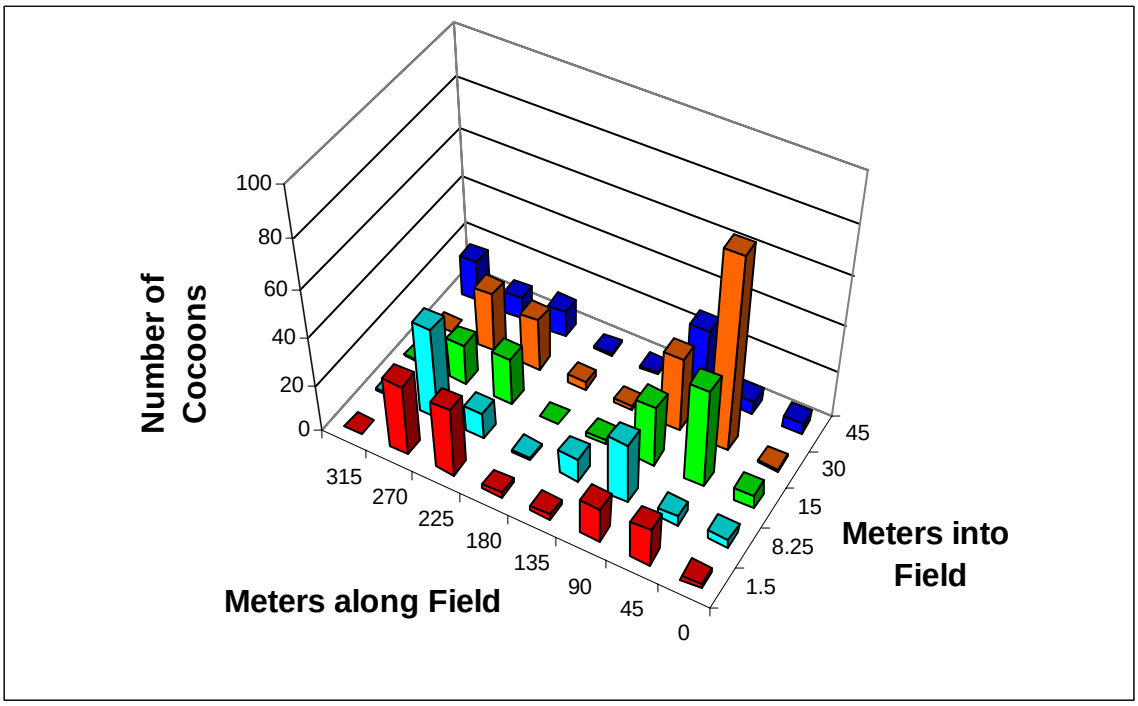


Figure 15: Parasitoid cocoon location – Lomond 2002

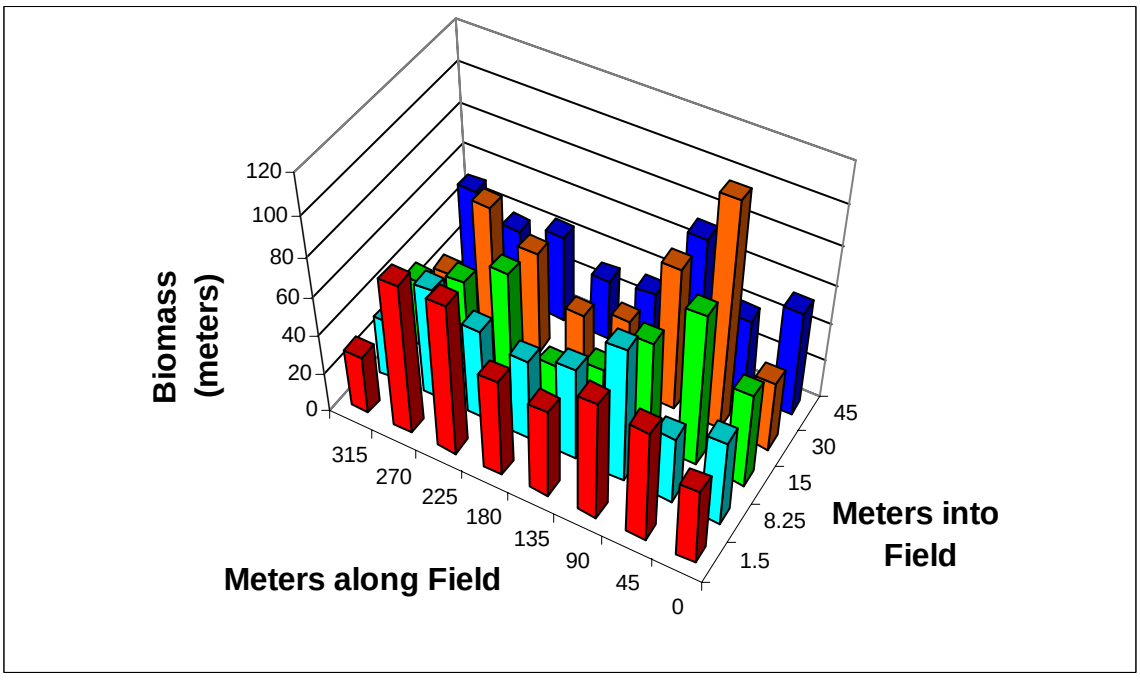


Figure 16: Biomass – Lomond 2002

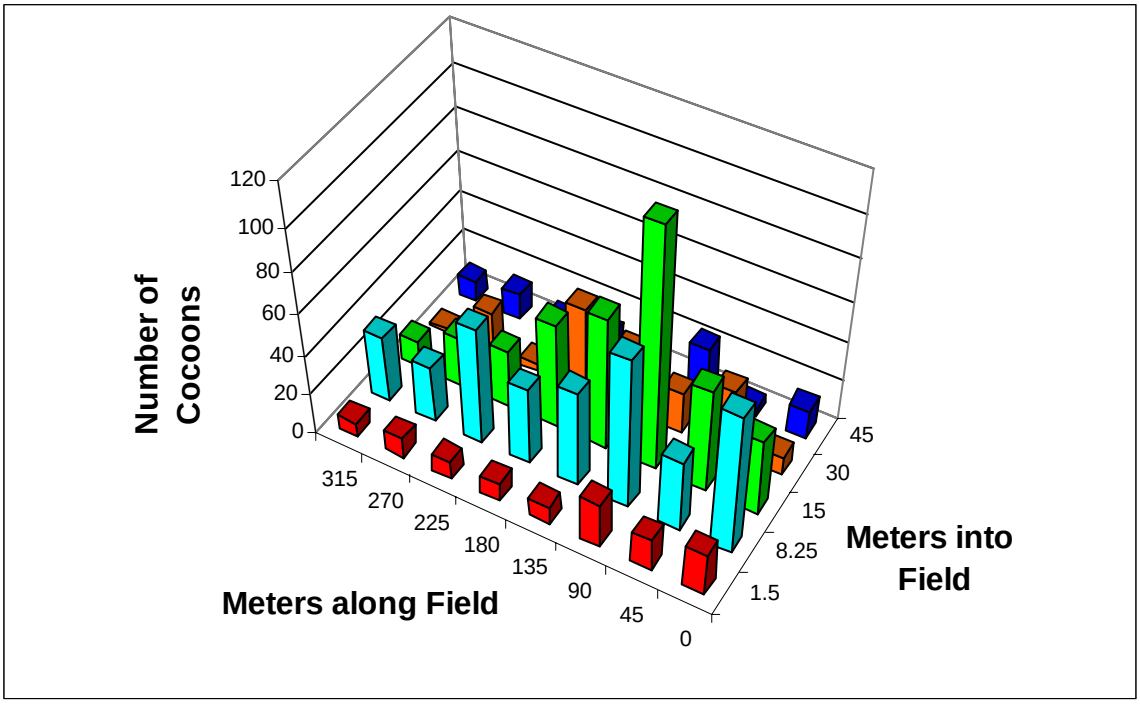


Figure 17: Parasitoid cocoon location – Opheim 2002

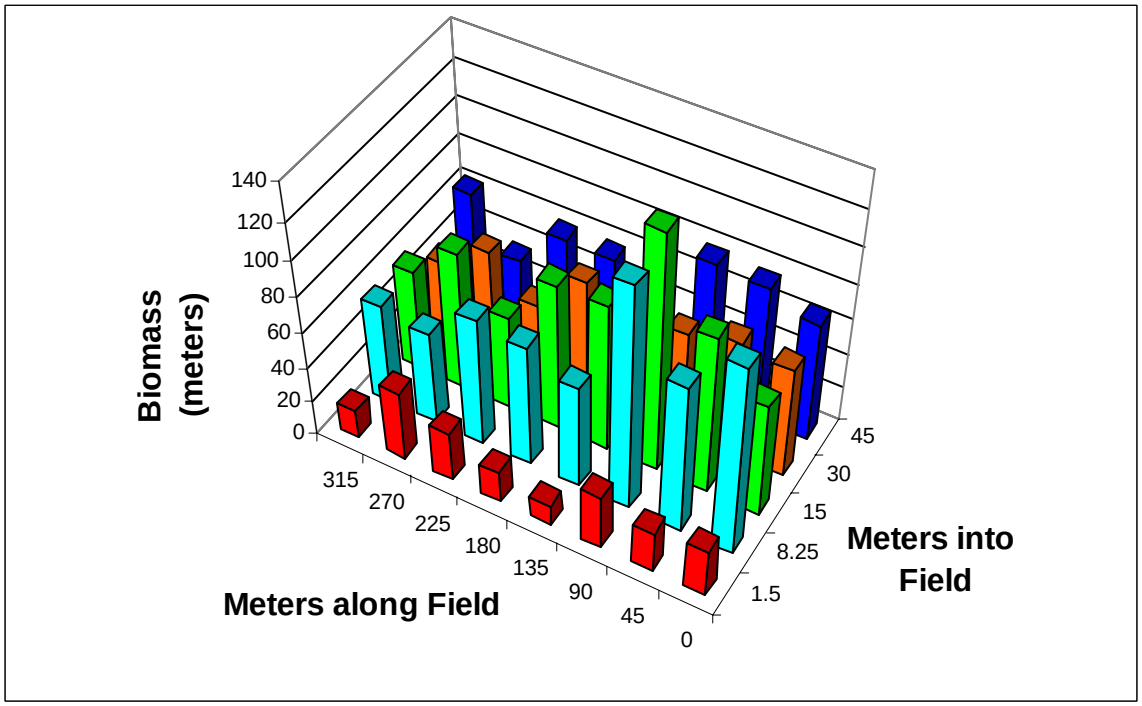


Figure 18: Biomass – Opheim 2002

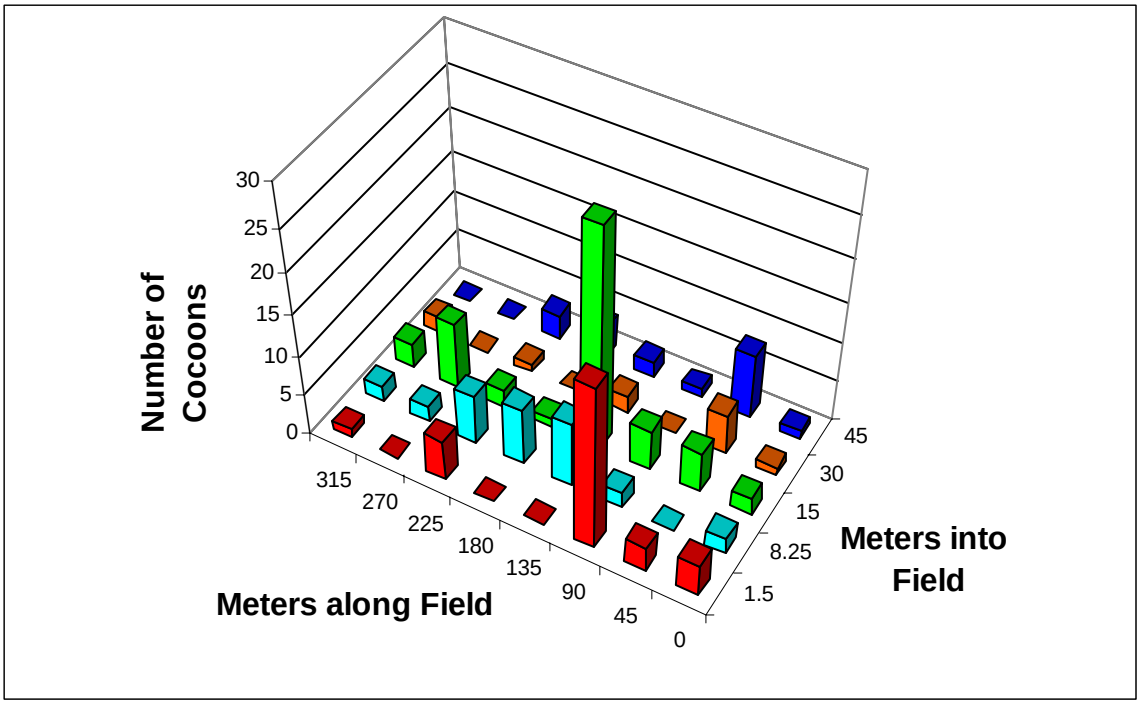


Figure 19: Parasitoid cocoon location – Vulcan 2002

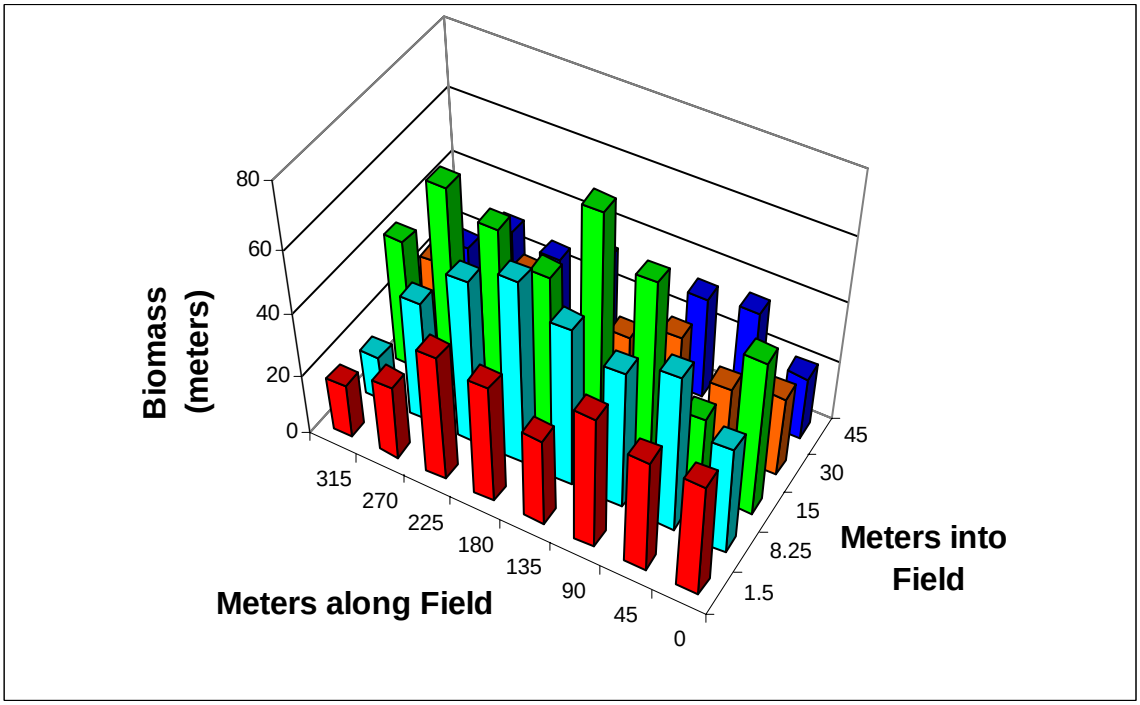


Figure 20: Biomass – Vulcan 2002

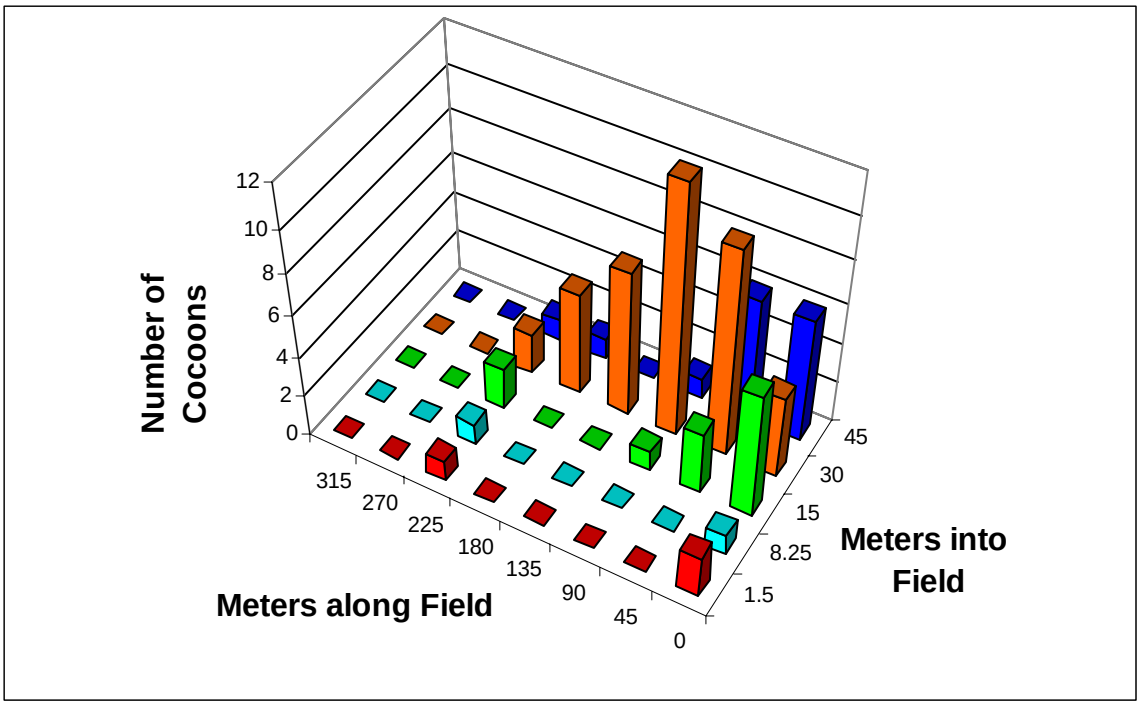


Figure 21: Parasitoid cocoon location – Oyen 2002

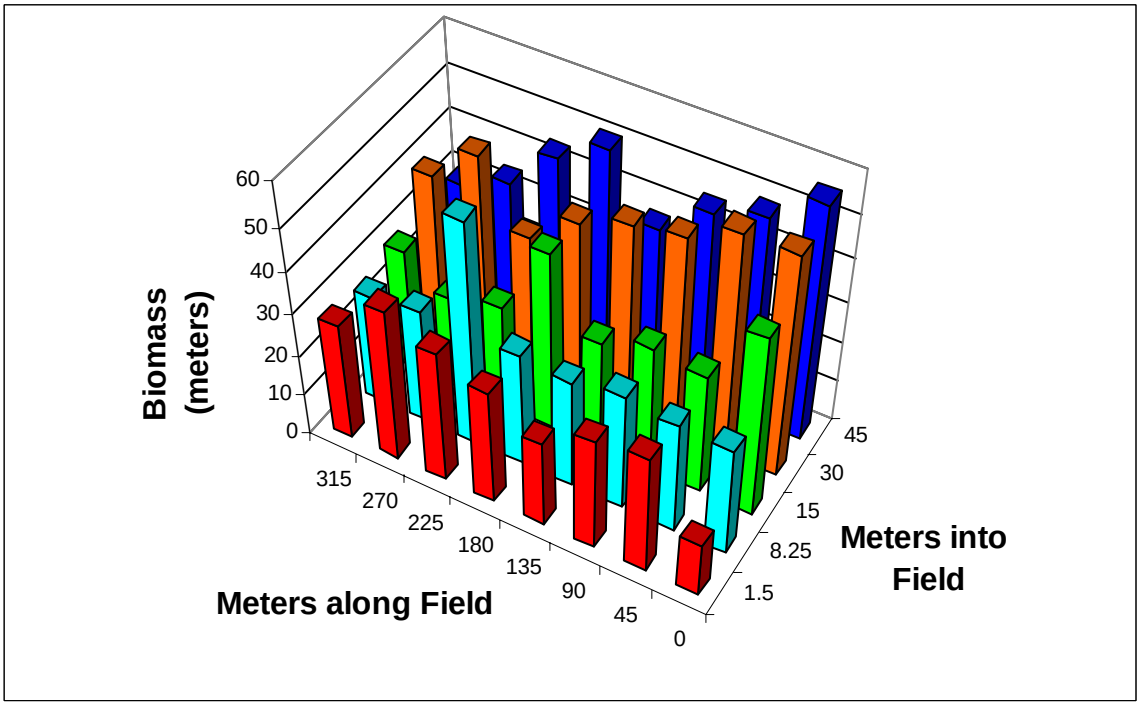


Figure 22: Biomass – Oyen 2002

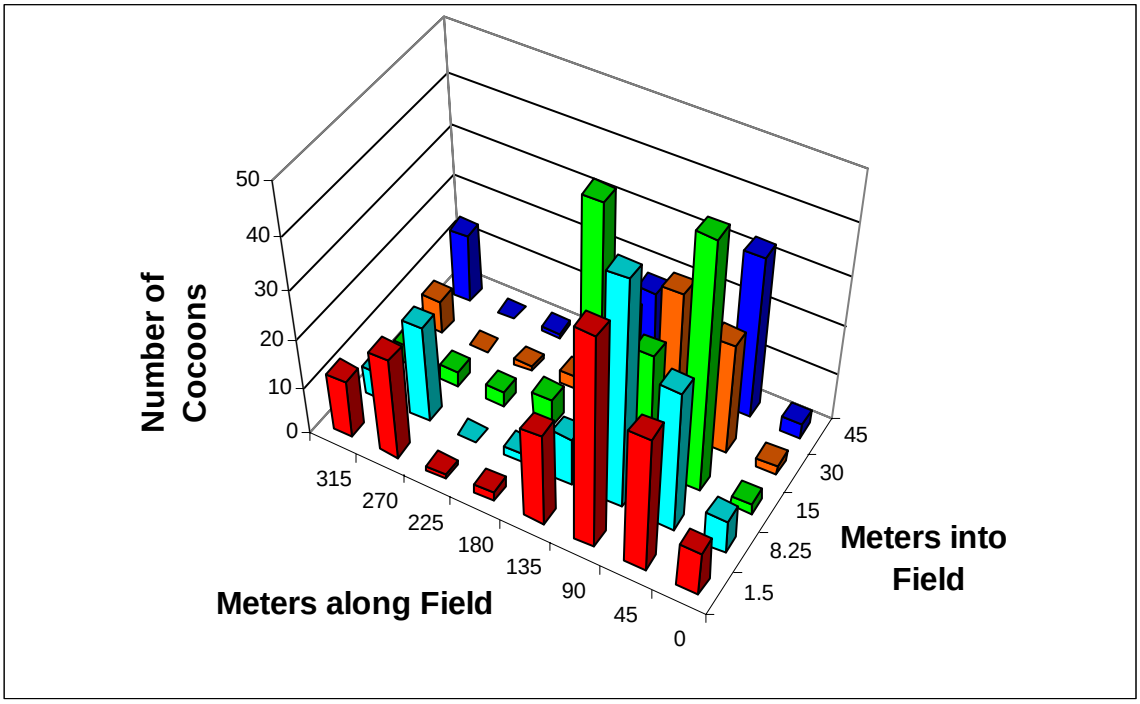


Figure 23: Parasitoid cocoon location – Lomond 2003

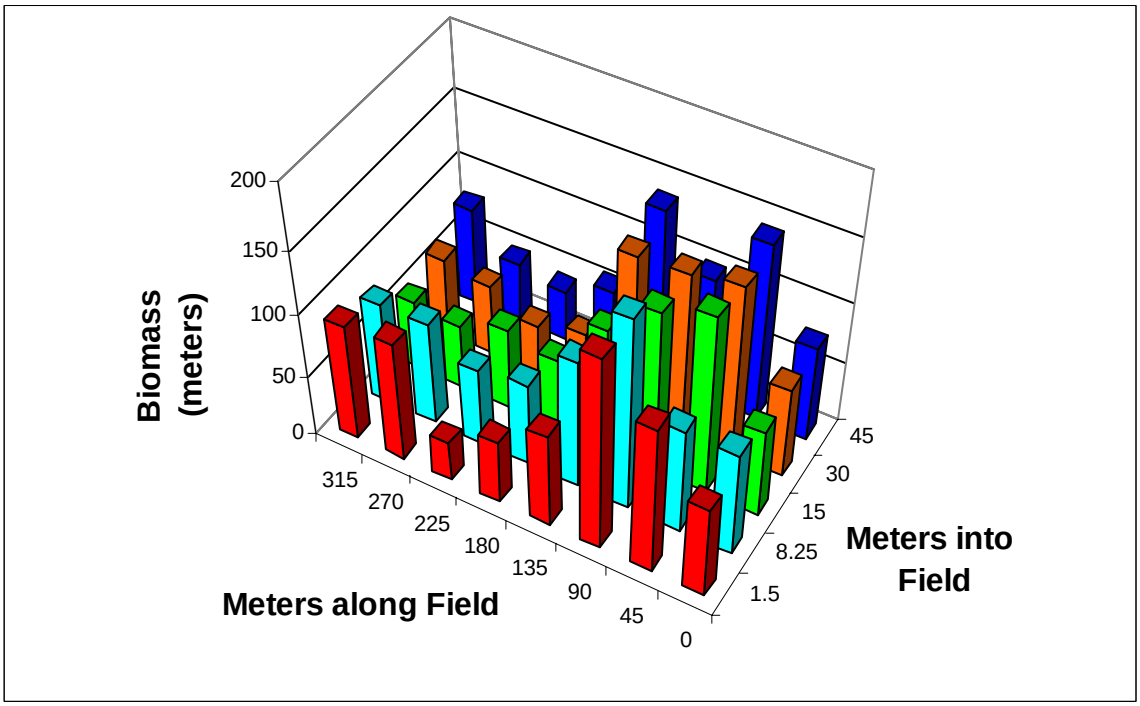


Figure 24: Biomass – Lomond 2003

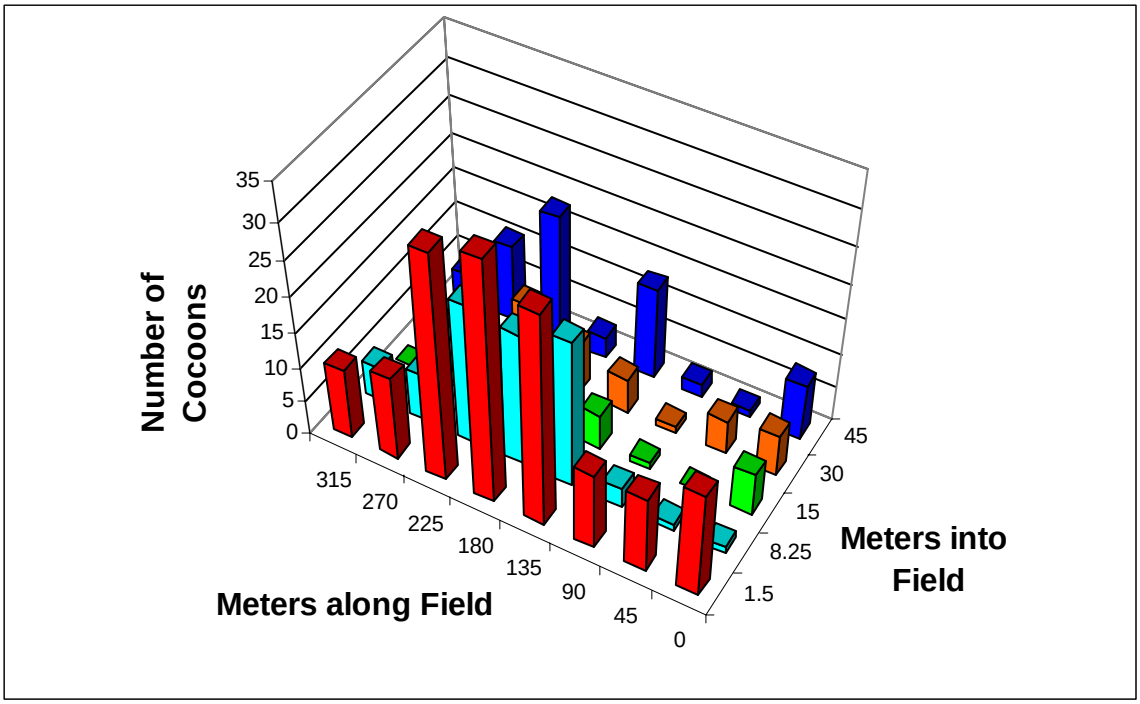


Figure 25: Parasitoid cocoon location – Opheim 2003

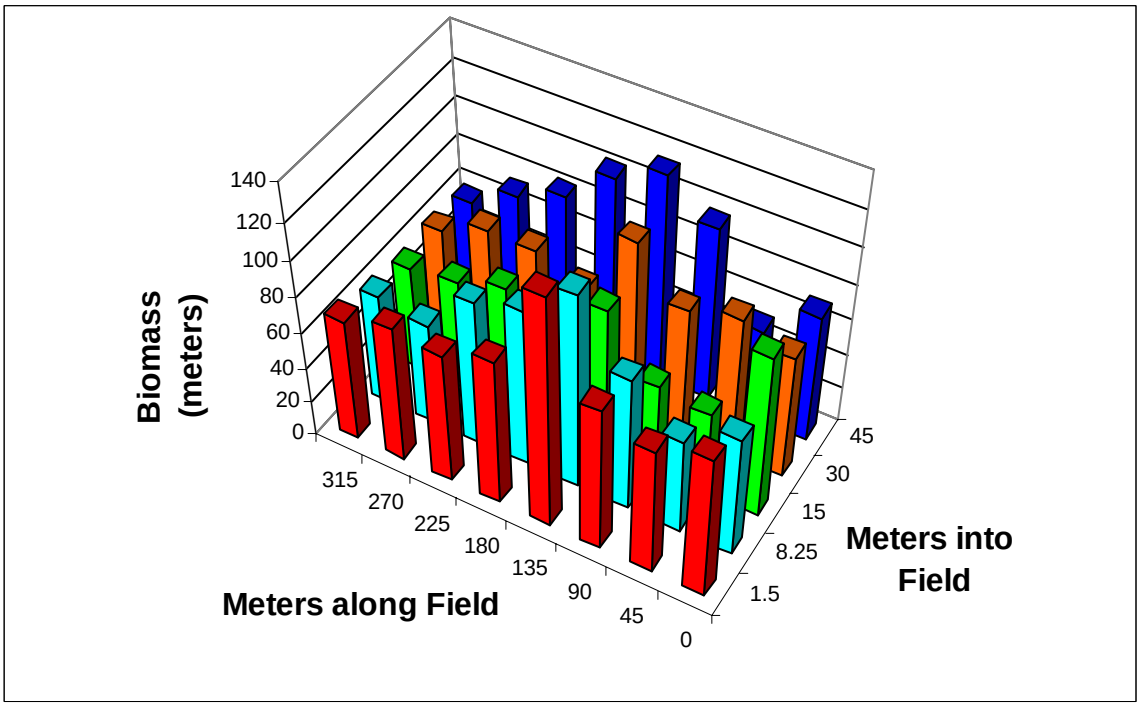


Figure 26: Biomass – Opheim 2003

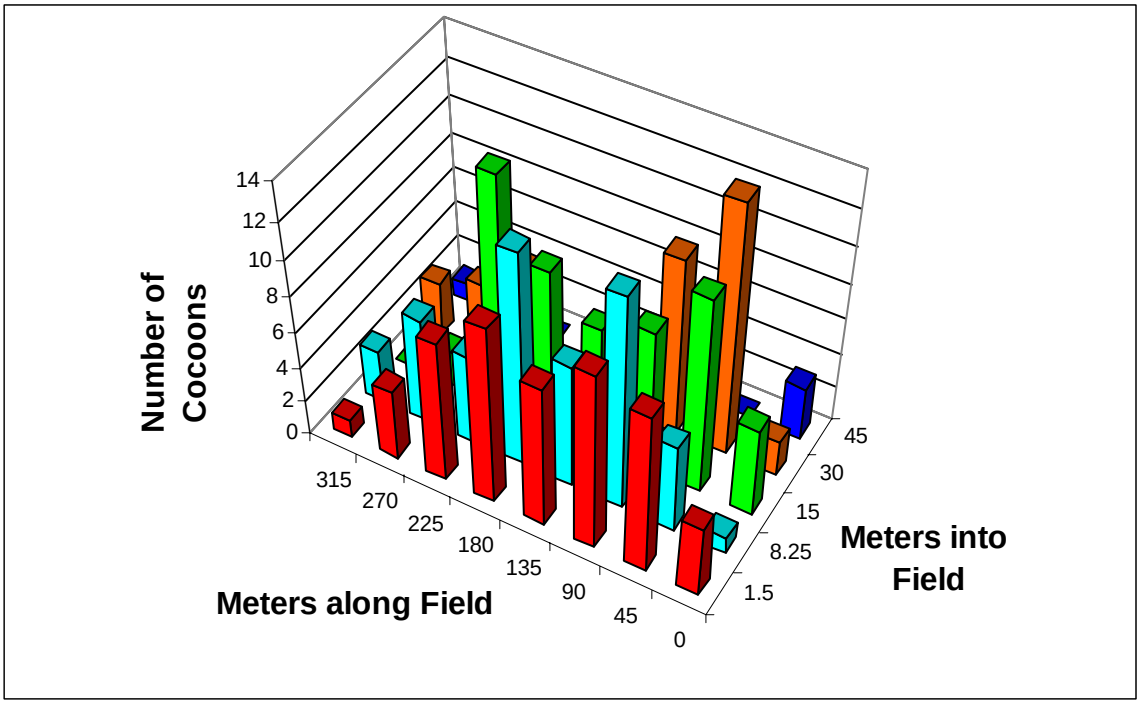


Figure 27: Parasitoid cocoon location – Vulcan 2003

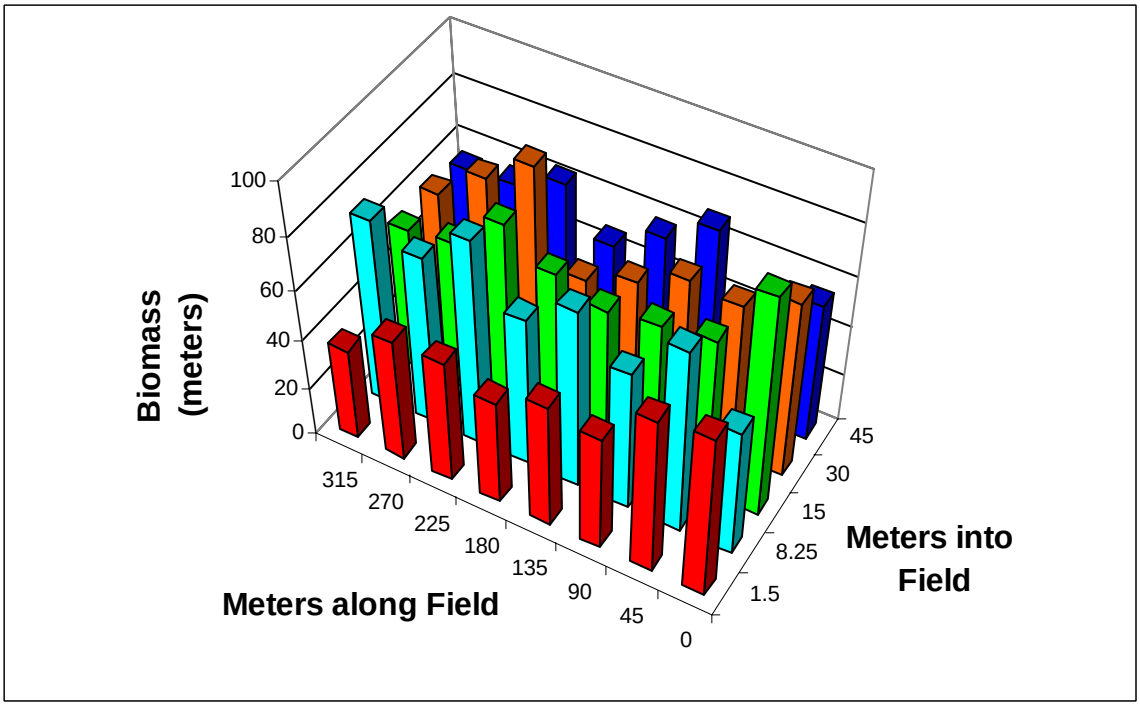


Figure 28: Biomass – Vulcan 2003

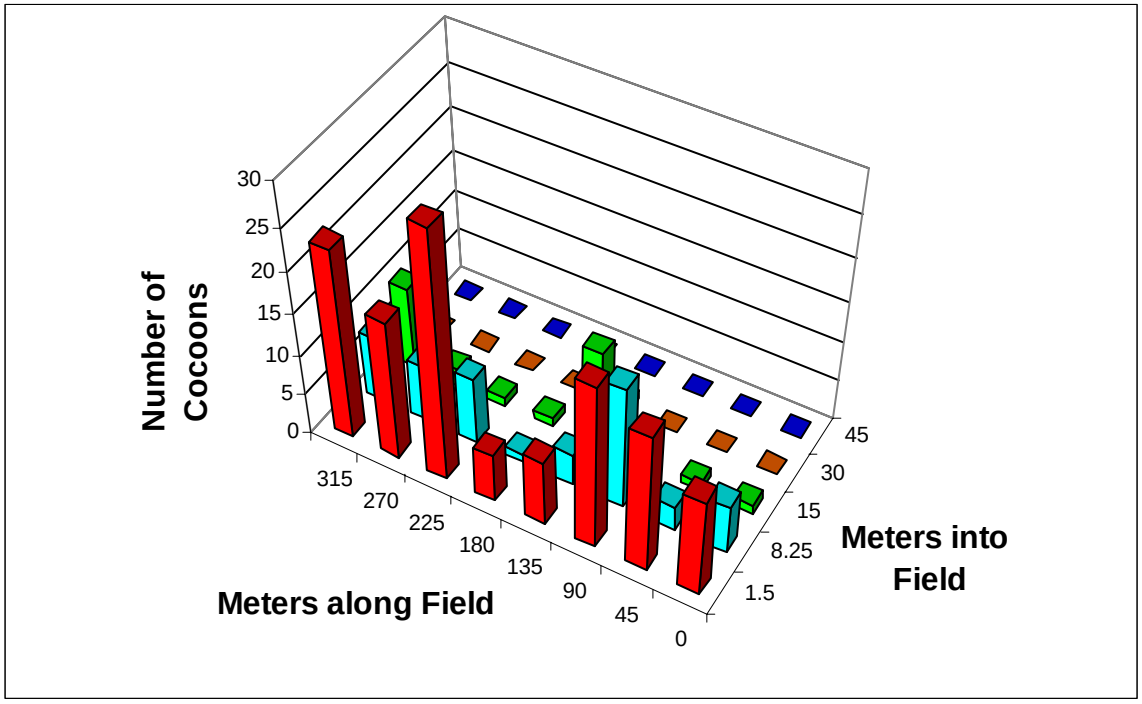


Figure 29: Parasitoid cocoon location – Assiniboia 2003

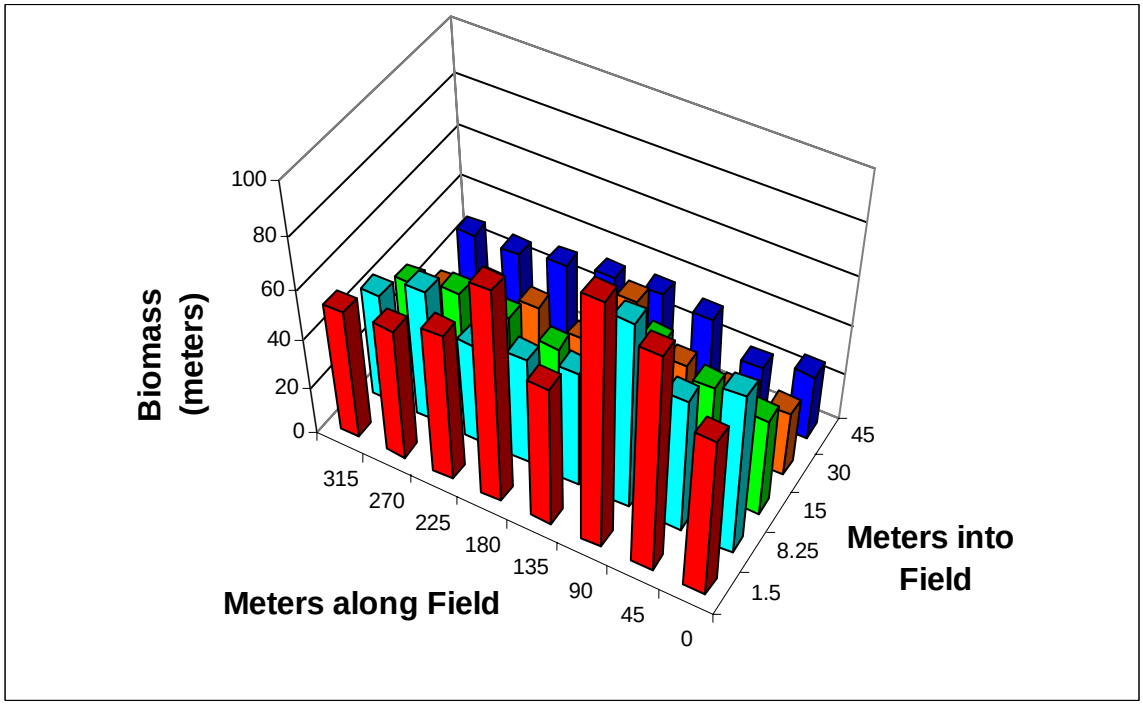


Figure 30: Biomass – Assiniboia 2003

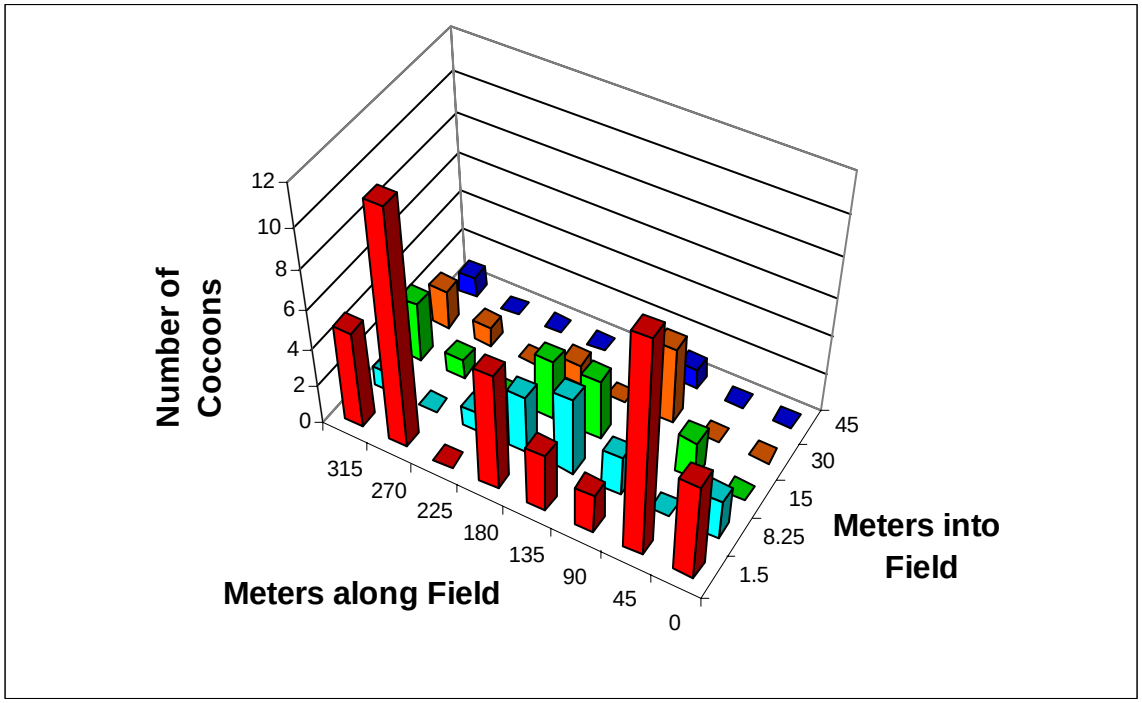


Figure 31: Parasitoid cocoon location – Brockway 2003

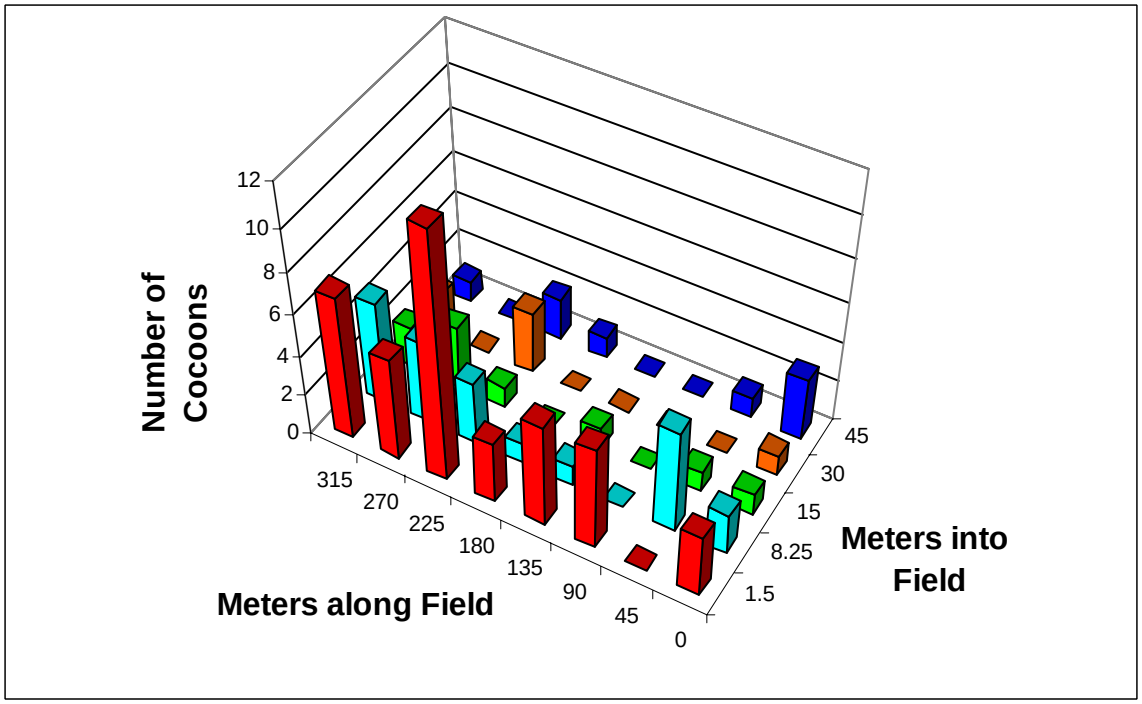


Figure 32: Parasitoid cocoon location – Gildford Winter Wheat 2003

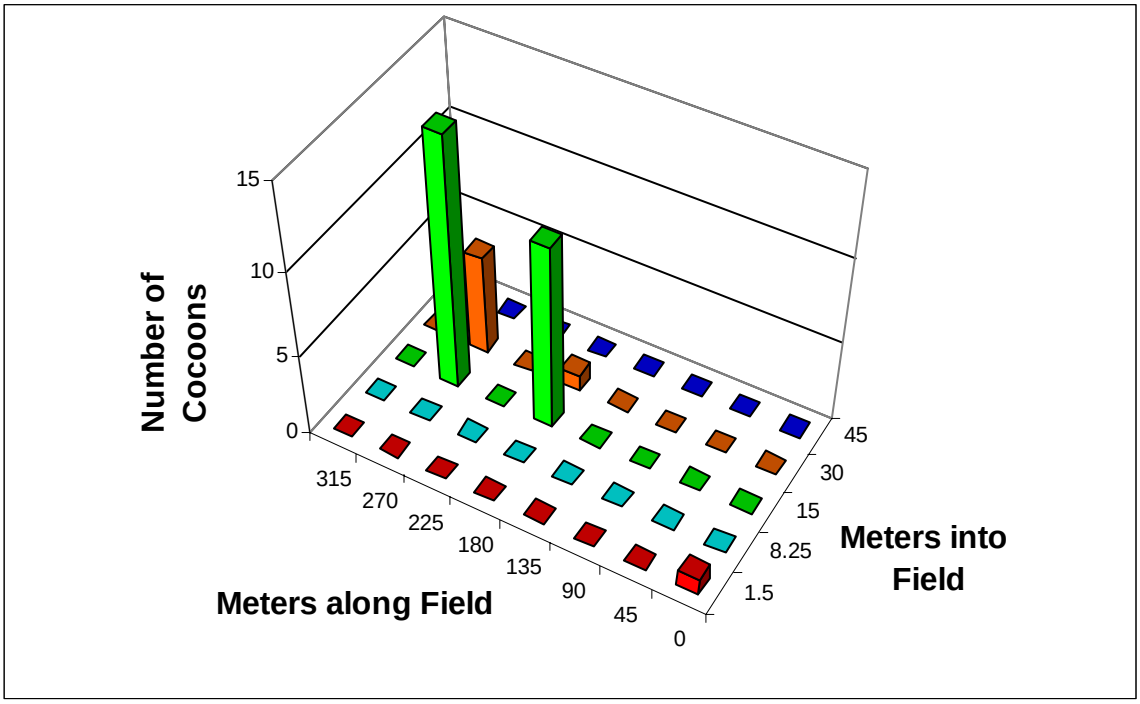


Figure 33: Parasitoid cocoon location – Laredo Spring Wheat 2003

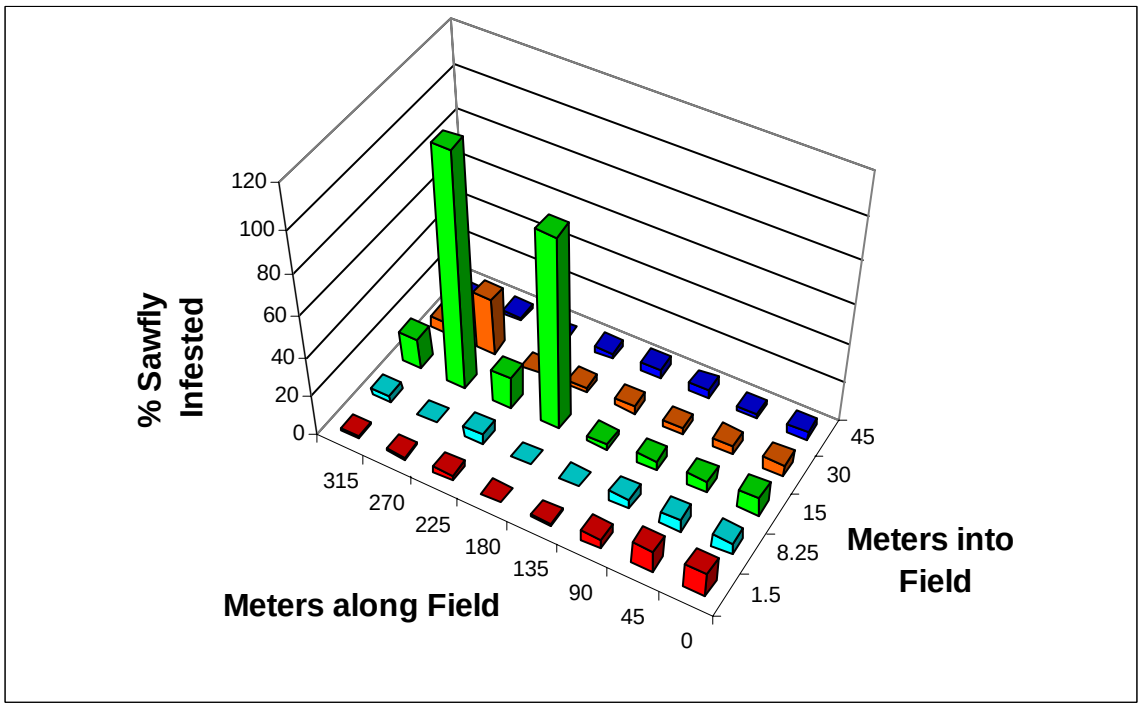


Figure 34: Sawfly Infestation – Laredo Spring Wheat 2003

Predicting Parasitoid Location in the Field

The purpose of measuring the location of the parasitoids in the field was to help producers understand where they would carry out different management practices to enhance parasitoid populations. If these practices are difficult or expensive to execute, producers need to know what part of the field is the most critical habitat for population enhancement and what is the best predictor of where the parasitoids are overwintering. With this in mind linear models were created for the ten fields (with 70 or more overwintering cocoons) using seven possible predictors. The R-square values from this exercise are reported in Tables 9 and 10.

Table 9: 2002 Fields - R squared values predicting cocoon location

	Lomond, AB	Oyen, AB	Vulcan, AB	Opheim, MT
Depth	0.00020	0.12*	0.037	0.086
Distance	0.0071	0.22*	0.018	0.086
Average Height	0.72*	0.22*	0.090	0.37*
Stem Density	0.62**	0.19*	0.32✞	0.56**
Biomass	0.83**✞	0.32**	0.31**	0.62**✞
Infestation	0.28**	0.13*	0.17*	0.15*
Stems Cut	0.083	0.37**✞	0.23*	0.013

✞ "Best" predictor
*Pr < 0.05
**Pr < 0.001

Table 10: 2003 Fields - R squared values predicting cocoon location

	Lomond AB	Vulcan AB	Assiniboia SK	Opheim MT	Brockway MT	Gildford MT (WW)
Depth	0.026	0.23*✞	0.48**	0.12*	0.28**	0.25**
Distance	0.15*	0.063	0.014	0.017	0.0002	0.072
Average Height	0.55**	0.05	0.32**	0.11*	0.02	0.08
Stem Density	0.61**	0.12*	0.47**	0.29**	0.20*	0.006
Biomass	0.69**✞	0.02	0.48**	0.26**	0.12*	1.4e-05
Infestation	0.37**	0.15*	0.81**✞	0.53**✞	0.44**✞	0.34**✞
Cut	0.005	0.02	0.22*	0.0008	0.37**	0.09

✞ "Best" predictor
*Pr < 0.05
**Pr < 0.001

In both years, biomass and sawfly infestation were consistently significant predictors of overwintering parasitoid locations for these ten fields. In three of the ten fields, biomass was the best predictor of parasitoid location. It is interesting to note that all three of these fields were planted to solid stem wheat varieties while all of the rest of the fields in the study were hollow stem wheat varieties. In the two other fields in 2002, biomass was the second best predictor and was not much different from the "best" predictor. Visually the areas with more cocoons appear to be those with higher biomass (Figures 15 to 30). This relationship was further explored using the Mantel test (Table 11). Again, the three fields with solid wheat had a strong relationship between the pattern of higher biomass and higher cocoon numbers. Assiniboia also showed this relationship. The remaining fields also had a positive relationship but not nearly as strong as those mentioned above. Biomass is a proxy for crop growth and health, the cocoons concentrating in areas of high biomass is the result of a tritrophic relationship between the growing conditions of the crop, the sawfly, and the parasitoids.

Table 11: Mantel Test (Cocoon Numbers and Biomass)

Location/Year	R	p-value
Lomond 2002*	0.84	0.0001
Opheim 2002*	0.59	0.0001
Oyen 2002	0.35	0.0002
Vulcan 2002	0.37	0.005
Lomond 2003*	0.73	0.0001
Opheim 2003	0.25	0.02
Assiniboia 2003	0.67	0.0001
Vulcan 2003	0.20	0.006

* Solid stem variety

Distance along the field edge was seldom significant, showing up in only two fields and with low R-squared values in both cases. In Oyen, distance along the field was significant. This could be the result of being adjacent to ungrazed native range. Often both average height and stem density were significant. These two, however, are each part of the biomass predictor that is frequently better. In one instance, stem cutting was the best predictor (marginally better than biomass) but for the most part it was not a good predictor.

Depth into field was a significant predictor in only the Oyen field in 2002 and in all but the Lomond field in 2003 (where biomass was a much stronger predictor). The fit may not be best with a linear model however, and may fit better with a curvilinear model. In some cases a decay line would fit best and in others a quadratic function would be best with lower numbers at the edge, greater numbers further in, and then falling off again even deeper into the field (Table 12). Results of these analyses clearly show that the relationship with depth is better described by a curvilinear regression.

Table 12: Curvilinear models versus linear models for cocoons and depth

Location/Year	Function Type	R-squared	Linear Model R-squared
Lomond 02	NA	NA	0.002
Opheim 02	Quadratic	0.43	0.09
Vulcan 02	NA	NA	0.04
Oyen 02	Quadratic	0.29	0.12
Lomond 03	NA	NA	0.03
Opheim 03	Decay	0.33	0.12
Vulcan 03	Decay	0.25	0.23
Assiniboia 03	Decay	0.65	0.48
Brockway 03	Decay	0.42	0.28
Gildford 03	Decay	0.38	0.25

All curvilinear R-squared values reported have P-value <0.05

Infestation, expressed as number of infested stems, was the best predictor in four of the fields (all in 2003). This is a logical finding because parasitoids need sawfly larvae to parasitize. It would follow that areas of greatest sawfly density would align with greatest parasitoid density, but this was not always the case. For this reason a series of scatter plots were created to investigate this further (Figures 35 to 45). At Assiniboia in 2003, regressing the number of cocoons against percent infested stems (Figure 42) gave an R-square of 0.81 ($P < 0.001$), showing strong correlation. Assiniboia has very few samples with sawfly infestation levels greater than 60%. On the other hand, Vulcan 2003 (R-square = 0.15, $P < 0.05$) (Figure 41) has virtually 100 % infestation at all sample locations and therefore is a straight line at the top of the graph. The rest of the scatter plots (Figure 35 - 44) have a “wedge” shape pattern with increasing number of parasitoids in samples as they approach 60% infestation. Above the 60% level there are some high number of parasitoids and some very low number of parasitoids, forming the

wedge shape pattern. This is a curious but consistent pattern throughout the rest of the fields that are plotted.

In order to create more explanatory models, multiple regression models using biomass, depth and infestation were created (Tables13 and 14). In most cases multiple regression did not provide a much better prediction of cocoon location than the best single predictor. Vulcan in 2002, Opheim in 2003 and Brockway in 2003 all showed an increase in regression fit using biomass and infestation together as predictors. Opheim 2002 produced a strong model using all three predictors of biomass, depth, and infestation.

Table 13: Multiple Linear Regressions for 2002 Data

R-square	Lomond 02	Opheim 02	Vulcan 02	Oyen 02
B+I	**0.84**	**0.74**	**0.49**	**0.38**
Pr B	7.9e-09	0.023	0.83	0.11
Pr I	0.15	0.0002	0.001	0.08
B+D	**0.84**	**0.79**	**0.31**	**0.32**
Pr B	2.5e-16	2.3e-13	0.0004	0.002
Pr D	0.26	3.6e-06	0.87	0.87
B+D+I	**0.85**	**0.81**	**0.51**	**0.38**
Pr B	2.5e-08	0.0002	0.78	0.23
Pr D	0.42	0.0013	0.25	0.86
Pr I	0.24	0.076	0.0006	0.087

Bold = R-square value
B = Biomass
D = Depth into Field
I = Infestation

Table 14: Multiple linear regressions for 2003 data.

R-square	Lomond 03	Opheim 03	Vulcan 03	Assiniboia	Brockway	Gildford
B+I	**0.72**	**0.71**	**0.08**	**0.78**	**0.76**	**0.34**
Pr B	0.0030	0.0091	0.087	0.14	0.88	0.0068
Pr I	0.047	4.9e-09	0.26	3.0e-08	5.4e-13	9.1e-05
B+D	**0.71**	**0.40**	**0.07**	**0.55**	**0.48**	**0.26**
Pr B	2.7e-11	0.00018	0.18	0.020	0.97	0.48
Pr D	0.14	0.0057	0.32	0.024	1.6e-06	0.00086
B+D+I	**0.7l**	**0.71**	**0.083**	**0.79**	**0.77**	**0.37**
Pr B	0.0023	0.016	0.25	0.057	0.97	0.028
Pr D	0.39	0.83	0.76	0.12	0.37	0.18
Pr I	0.12	3.6e-07	0.57	1.7e-07	7.3e-08	0.015

Bold = R-square value
B = Biomass
D = Depth into Field
I = Infestation

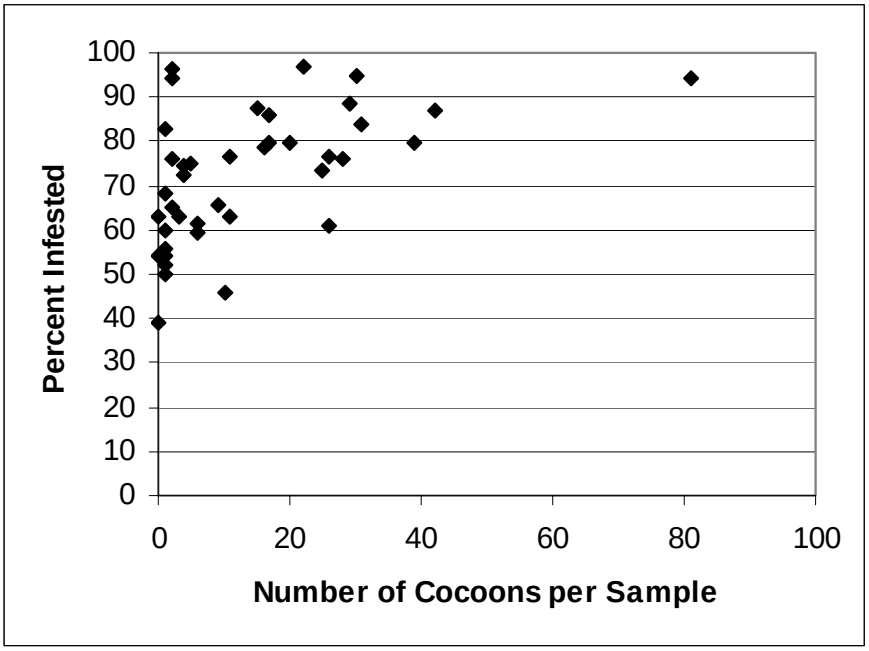


Figure 35: Cocoons as a Function of Infestation Lomond 2002

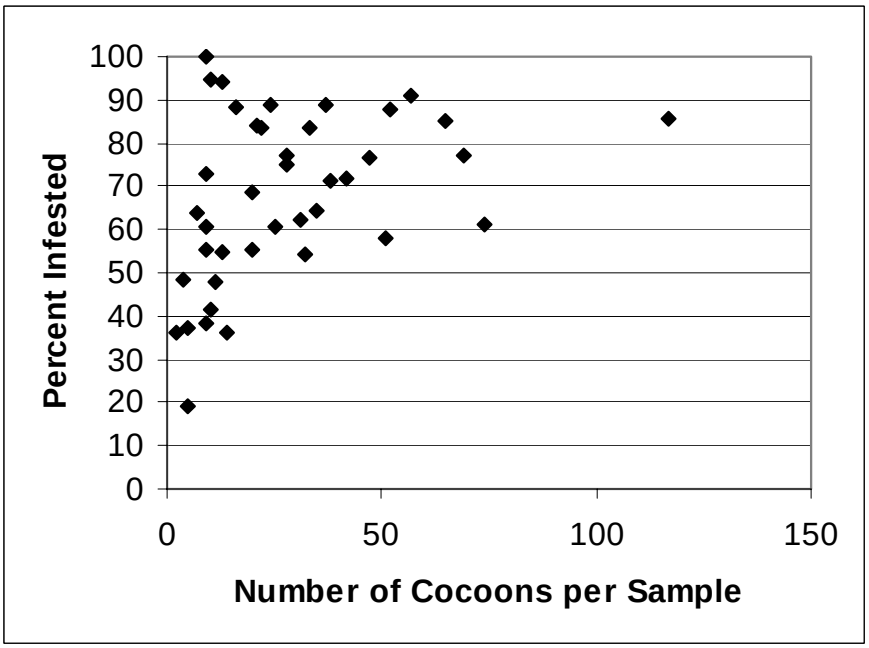


Figure 36: Cocoons as a Function of Infestation Opheim 2002

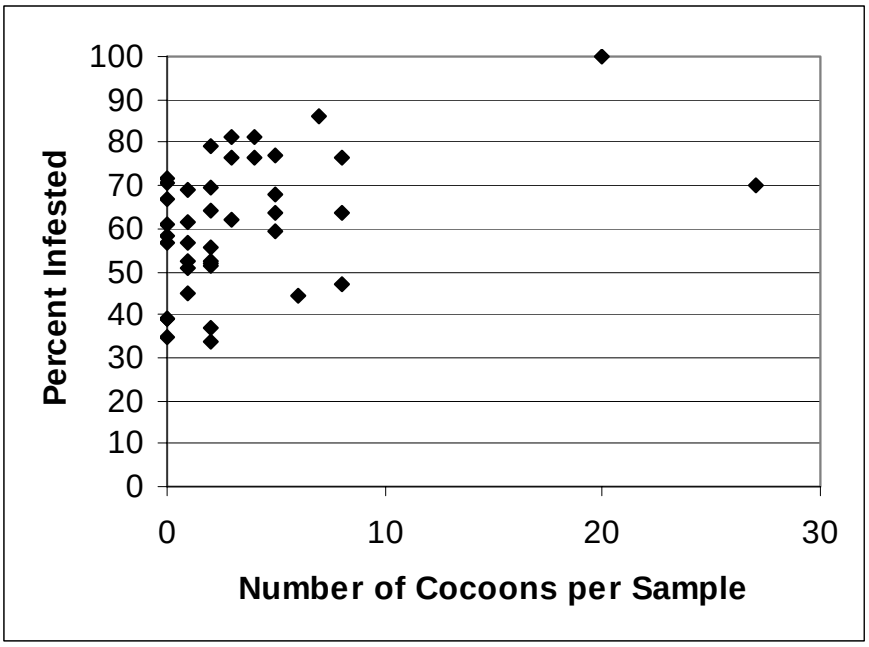


Figure 37: Cocoons as a Function of Infestation Vulcan 2002

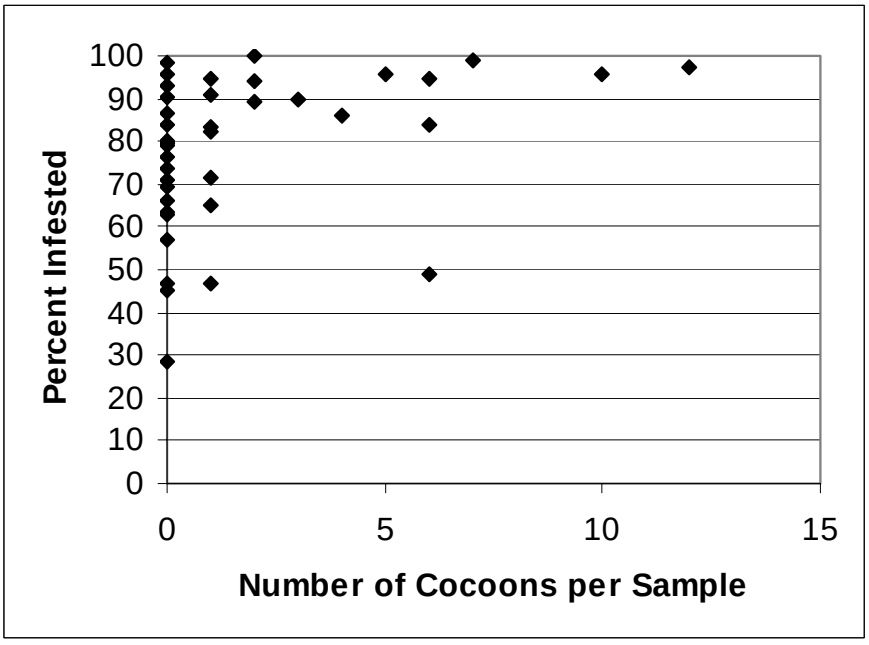


Figure 38: Cocoons as a Function of Infestation Oyen 2002

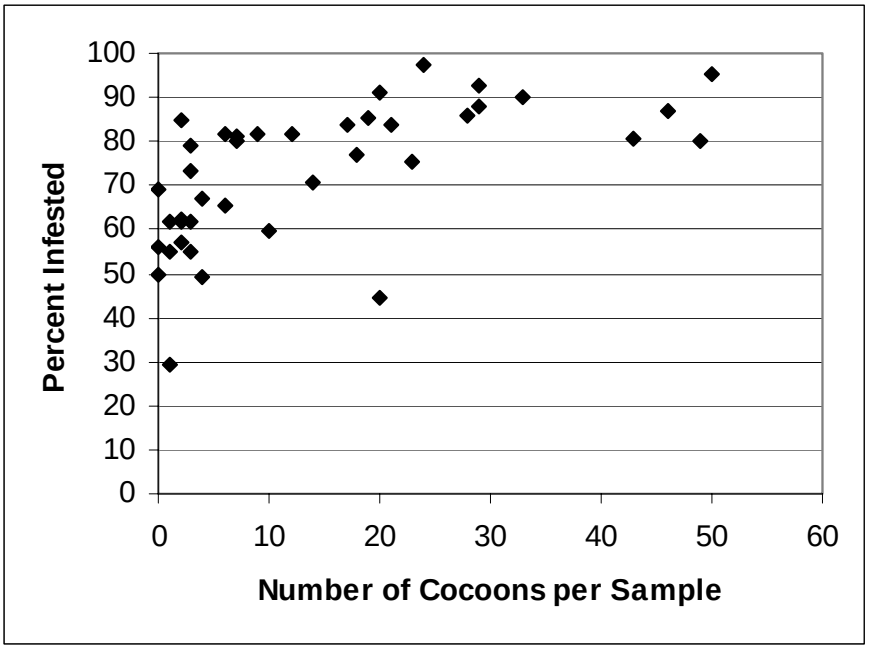


Figure 39: Cocoons as a Function of Infestation Lomond 2003

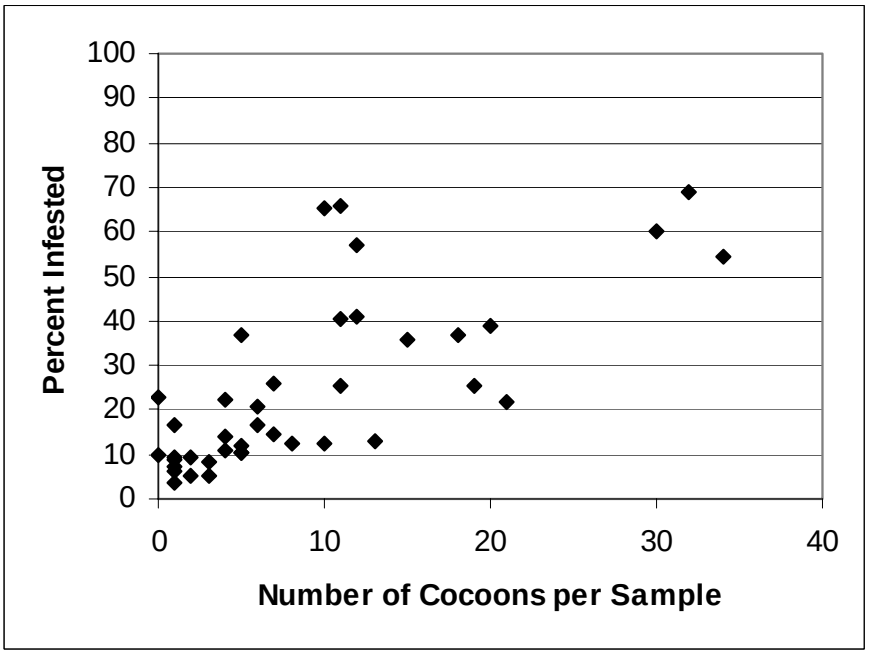


Figure 40: Cocoons as a Function of Infestation Opheim 2003

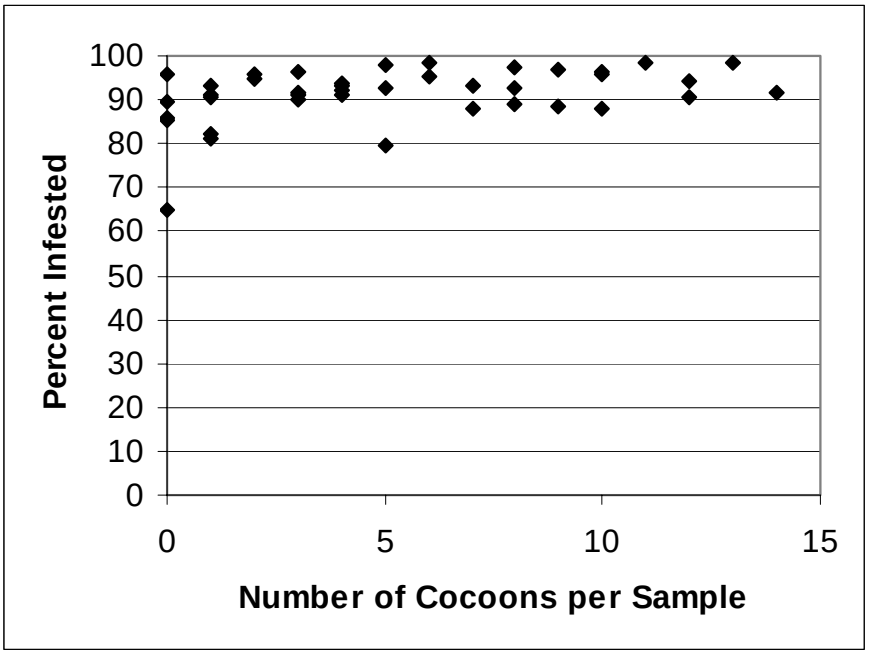


Figure 41: Cocoons as a Function of Infestation Vulcan 2003

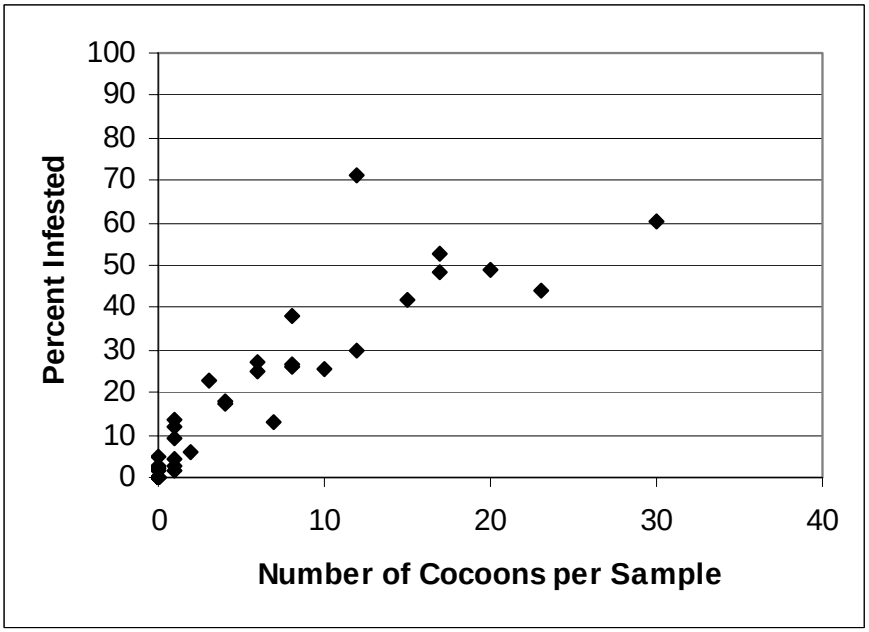


Figure 42: Cocoons as a Function of Infestation Assiniboia 2003

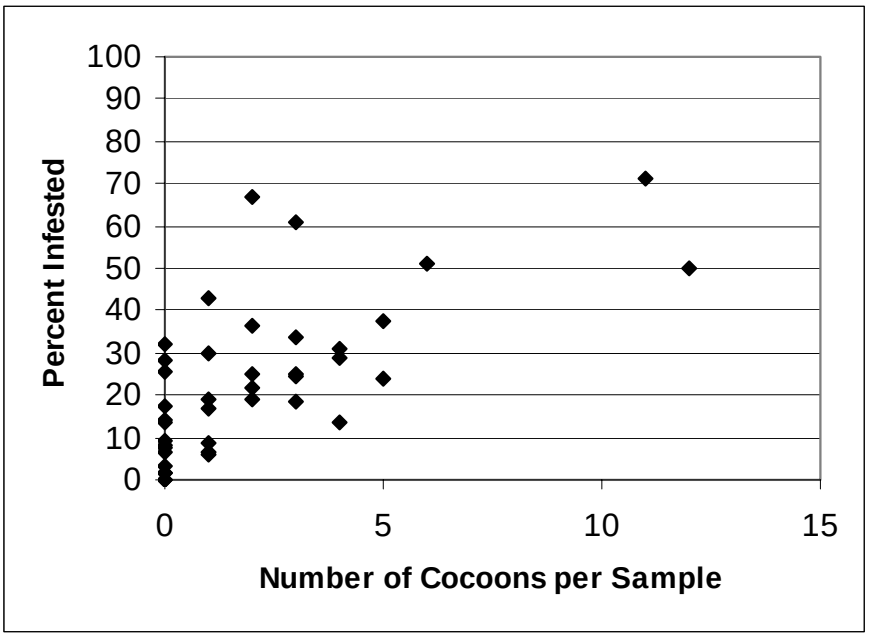


Figure 43: Cocoons as a Function of Infestation Brockway 2003

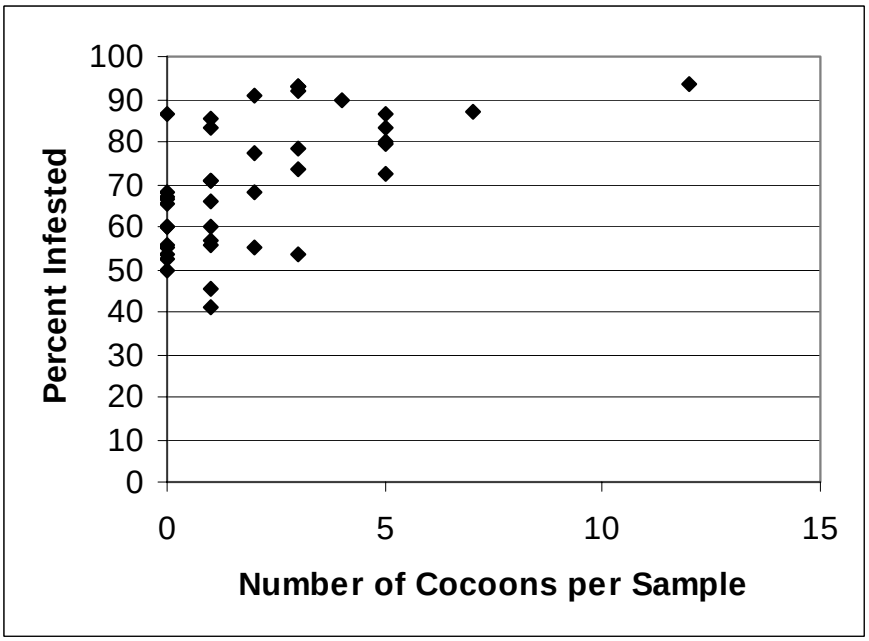


Figure 44: Cocoons as a Function of Infestation Gildford 2003

Parasitoid Location in Stem

The four fields with the highest number of parasitoids from 2002 and 2003 are shown in Figures 45 and 46. These plots show the distribution of parasitoid cocoons in the dissected stems. The location in the stem is expressed as the portions of the stem in 10% increments plus one below ground increment. The cocoons are expressed as the proportion of the total in that field to standardize the data and facilitate comparison between fields.

In 2002 there is strong similarity for parasitoid location between the fields. In 2003 the similarity is not as strong but the same general pattern is evident. Brockway and Laredo were not included in the 2003 plot because they had matured very quickly due to extreme drought and this may have had a major impact on the parasitoid cocoon location. What is clear is that the bottom 30% of the stem is where the vast majority of overwintering cocoons occurred. Parasitoid cocoons in the winter wheat crops from Laredo and Gildford (Figure 47) did not follow the pattern in Figures 45 and 46.

The location of parasitoid emergence holes was also recorded throughout this study. These are individual fields and use actual numbers in each portion of the stem. These data show that the location of emergence holes in the stem tracked the location of overwintering cocoons quite closely (Figures 48 and 49) showing the same general pattern in both years. The success of second generation in 2002 is reflected in the much higher number of parasitoid cocoons than emergence holes. There were more emergence holes in relation to cocoons in 2003. This reflects the lack of success in the second

generation of parasitoids because the emergence holes are out-numbering the overwintering cocoons.

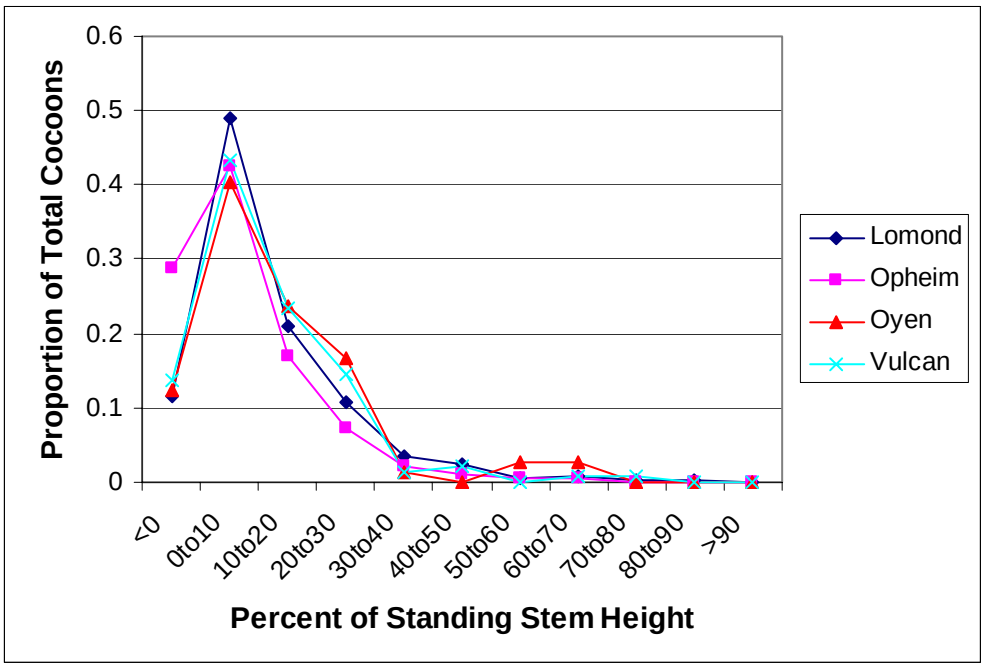


Figure 45: Parasitoid location in the stem 2002

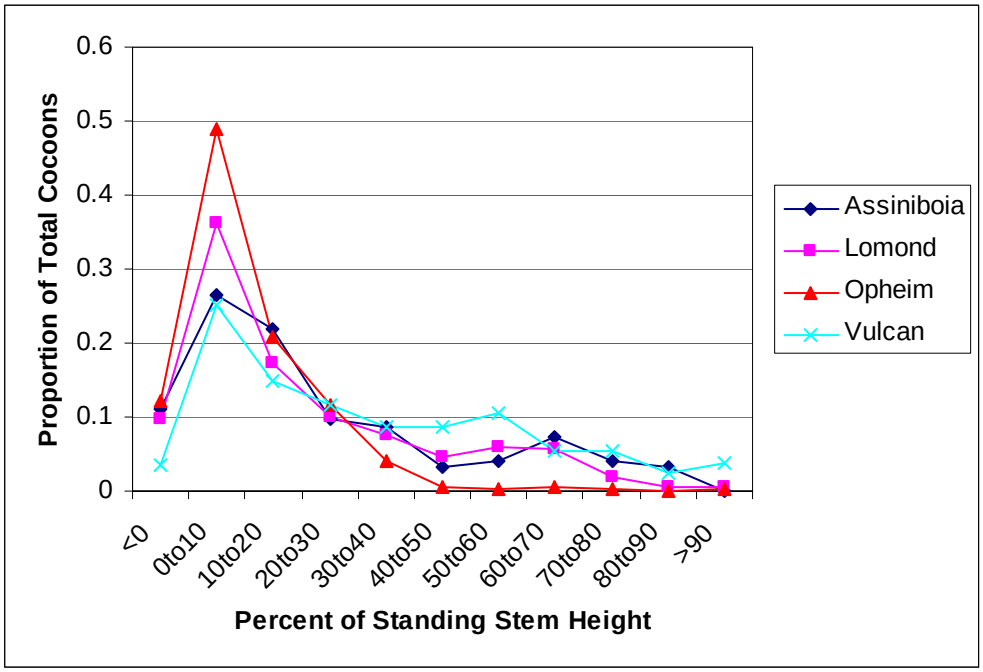


Figure 46: Parasitoid location in the stem 2003

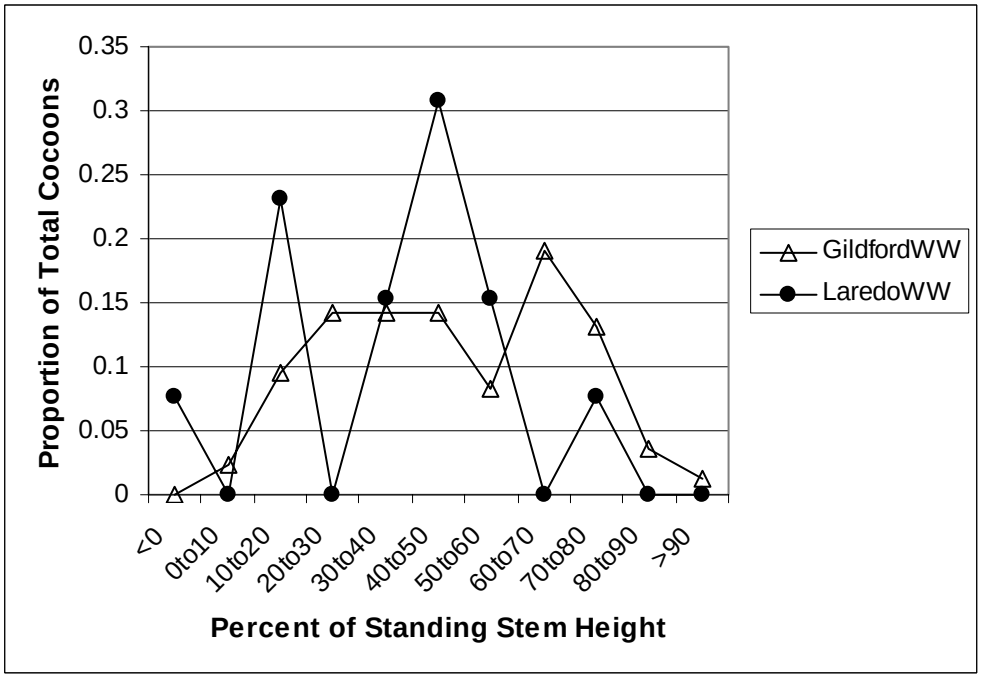


Figure 47: Parasitoid location in the stem – 2003 winter wheat

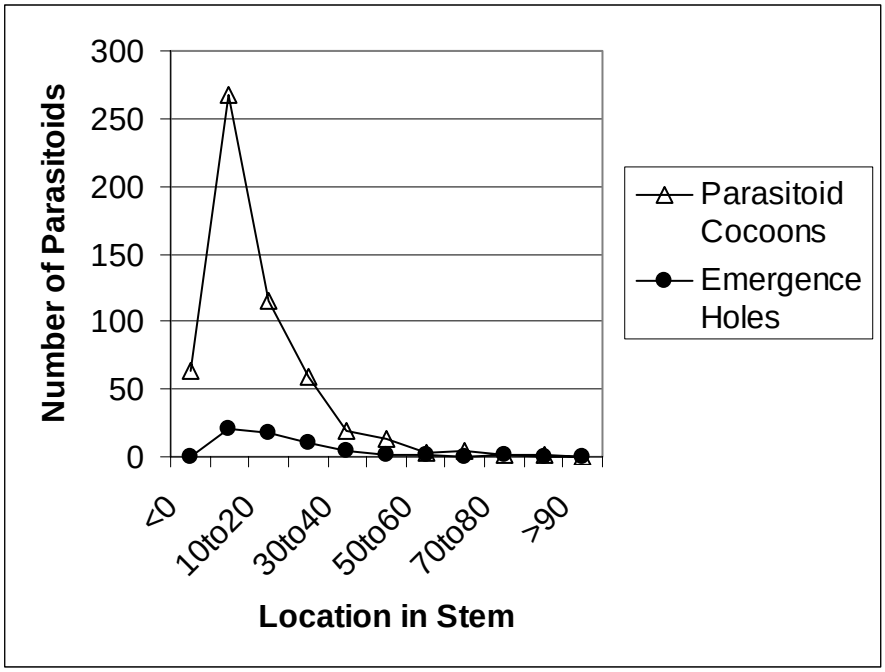


Figure 48: Emergence hole & cocoon location in stem - Lomond 2002

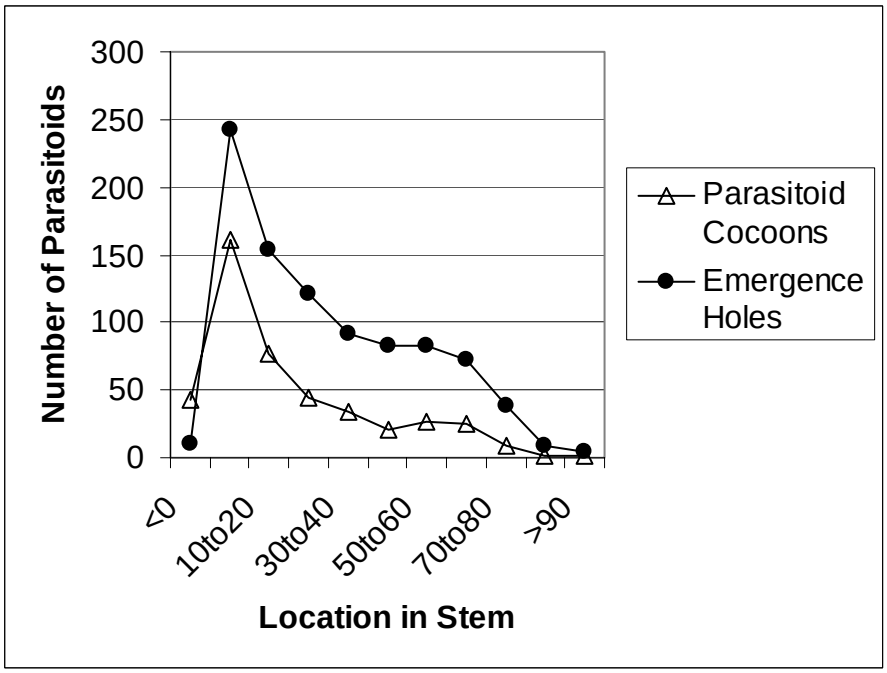


Figure 49: Emergence hole & cocoon location in stem – Lomond 2003

Effect of Spray Paint Trial

This trial was run in preparation for the first field collection season. The purpose was to determine if spray painting of the wheat stems to mark the soil level would have any impact on the survival and emergence of the insects inside the stem (Table 15).

Table 15: Comparison of sawfly emergence in painted and unpainted stems

	Painted			Control		
Date (2002)	Emerged	Not Emerged	Percent Emergence	Emerged	Not Emerged	Percent Emergence
5/8-6/19	19	6	76	306	94	76.5
5/17-6/26	21	4	84	298	102	74.5
5/21-7/2	17	8	68	278	122	69.5
1/29-7/10	19	6	76	293	107	73.25

A paired t- test was performed on the difference between the percent of emergence (t = 1.0316; df = 3; P = 0.3782). This result clearly shows that there is no statistical difference between the painted and unpainted stubs in respect to percent sawfly emergence. This demonstrates that painting of the material before collection to mark the soil level did not compromise the viability of insects inside.

Harvest Practices and Parasitoid Survival (Objective 3)

Conrad 2002

The height of the head removal treatment was 52.5 cm the two-thirds treatment 35 cm and the one-third height treatments both were 12.5 cm. The Conrad harvest plots had a total of 3101 parasitoids emerging (1499 male and 1602 female) between May 28 and July 21, 2003. Males generally emerged before females (Figure 52). An analysis of variance of parasitoid numbers was performed to discern the effect of treatments and the blocking style (random vs. height blocking) shows that there is significant difference due to the treatments (F =5.75; df (Treatment) = 4 P = 0.0008) but not a significant difference due to blocking style (F = 0.0009; df (Blocking) = 1; P = 0.97). With this lack of significance due to blocking style, the analysis of variance was run with treatment only. This analysis showed that there is a strongly significant treatment effect (F = 5.88; df = 4; $P < 0.001$). These mean differences were separated using Tukey's HSD procedure for multiple comparisons (family confidence level of 95%). There were differences between the standing crop check and the head removal treatments compared with the three treatments where the crop was cut shorter (1/3 or 2/3 of the standing height) (Figure 51). There was no difference between removing the heads and the unharvested check. There also was no difference between cutting heights of two-thirds and one-third of standing height. There was also a lack of a difference between chopped and whole straw in the one-third standing height treatments.

The difference in results using parasitoid counts including those retrieved by sorting through barrel residues (Figure 51) and the results not including the barrel residues (Figure 50) is also of note. This was analyzed using two-factor analysis of variance including treatment and counts with or without barrel residues ($F = 0.14$; df = 1; $P = 0.71$). These results clearly show that it was not necessary to sort through the barrel residues to collect missing parasitoids because they do not significantly impact the final analysis. This also confirmed that these emergence barrels work very well.

Swift Current 2002

The Swift Current harvest management plots did not show any significant treatment effects ($F = 0.45$; df = 4; $P = 0.77$) (Figure 54). These plots received severe hail damage to the standing stems and this may have impacted the final results. A total of 316 parasitoids emerged from this trial. Relative emergence of male and female parasitoids in this trial is shown in Figure 55. The height of the heads off treatment was 60 cm the two-thirds treatment 40 cm and the one-third height treatments both were 20 cm.

Conrad 2003

In 2003, the plots at Conrad were seeded so late that the wheat was not elongating at the time of the major sawfly flight. To compensate, sawflies were collected near Pendroy, MT and released to "inoculate" the plot site on June 27 and July 5th. Approximately 150 female sawflies (approximately 75 on two separate occasions) were released bordering every other plot (26 release sites and approximately 3900 female

sawfly in total). Low levels of sawfly infestation occurred (2.5%) along with parasitism (67.4 % of infested stems). Of the parasitized sawfly larvae about half (53%) were recorded as emergence holes and half (47%) as overwintering cocoons. The plots were set out and collected in the same manner as 2002. The height of the head removal treatment was 45 cm, the two-thirds treatment 30 cm and the one-third height treatments both were 15 cm.

In total 226 parasitoids were reared (152 male and 74 female, Figure 58). An analysis of variance was performed with treatment plus blocks. This analysis showed that there was a treatment effect ($F = 3.81$; df = 4; $P = 0.01$) and also a blocking effect ($F = 5.06$; df = 9; $P < 0.001$). The significance in the blocking shows that the block design was a wise decision. The mean differences for the treatments were separated using Tukey's HSD procedure for multiple comparisons (family confidence level of 95%). Figure 56 shows the same trend as the previous years results but there are few differences between the treatments. The untreated check showed a greater number of parasitoids emerged than for the two short treatments. There was no difference when comparing parasitoid numbers between only removing the heads or the numbers from either the two-thirds height treatment and the unharvested check. There was also no difference between the numbers for the cutting heights of two-thirds and one-third of the standing crop height. There was no difference between the numbers of parasitoids emerging from chopped and whole straw in the one-third standing crop height treatments. The lack of differences is the result of the low numbers of parasitoids and the patchiness of their distribution in the plots.

Lomond 2003

The height of the head removal treatment was 60 cm, the two-thirds treatment 40 cm and the one-third height treatments both were 20 cm. The Lomond emergence barrels produced 5507 parasitoids (3178 male, 2329 female). Males again emerged before females (Figure 59). An analysis of variance was performed with treatment and blocks only in the model. This analysis showed that there was a significant treatment effect (F = 18.8; df = 4, P <0.0001) and a blocking effect (F= 19.0; df = 9; P = <0.0001). This confirms the importance of blocking. The mean differences in parasitoid numbers across treatments were separated using Tukey's HSD procedure for multiple comparisons (family confidence level of 95%). Figure 57 shows the differences between the numbers of parasitoids for the standing crop check and head removal treatments as compared to the numbers for the three treatments where the crop was cut shorter (1/3 or 2/3 of the standing height). There is no significant difference between the parasitoid numbers obtained after just removing the heads and those for the unharvested check. There was no difference between parasitoid numbers at the cutting heights of two-thirds and one-third of standing height. There was no difference between the numbers emerged for chopped and whole straw in the one-third standing height treatments.

Chopping vs. Shredding Trial

A small trial was run using extra material collected from the Swift Current site (Figure 53). The shredded straw was an attempt to mimic the condition of straw that is created using modern straw chopping technology on harvest equipment. It was compared

to straw chopped into 7.5 cm pieces and the check straw that was left whole. The chopping study using Swift Current material showed treatment difference (F = 7.75; df = 2; P = 0.02). The chopped material was not different from the check. The shredded material had no emergence of parasitoids and this was lower than the numbers for the check and for the chopped material. It is important to note that this material was stored in cloth bags in an unheated shed and not subject to the full impact of winter stresses such as moisture, fungus and insect attack as they would have been in a natural situation.

Figure 50: Conrad harvest plot trial 2002/03 parasitoid emergence before residues were added

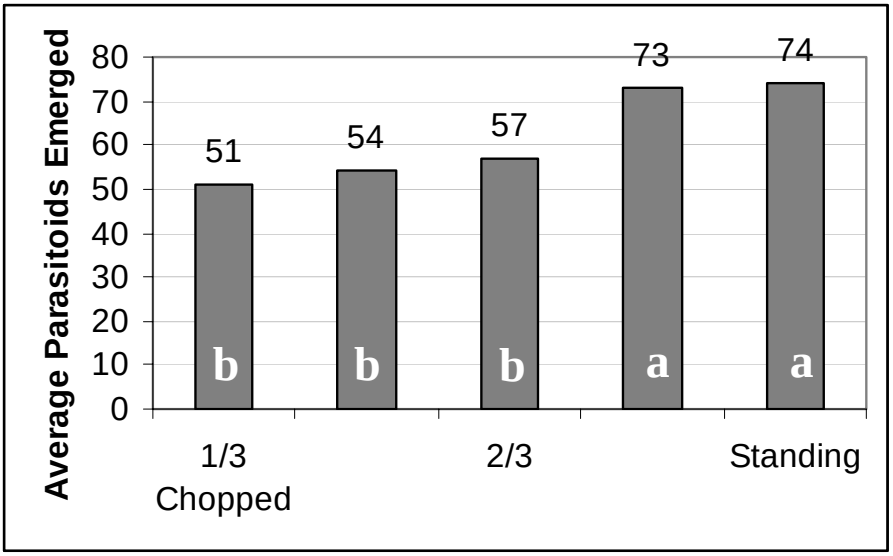


Figure 51: Conrad harvest plot trial 2002/03 parasitoid emergence after residues were added

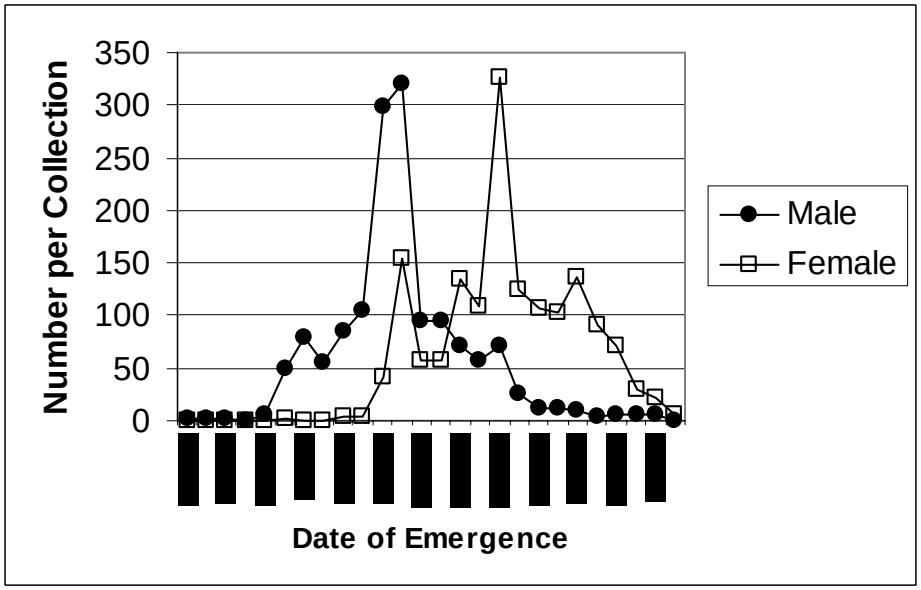


Figure 52: Conrad harvest plot trial 2002/03 parasitoid emergence timing

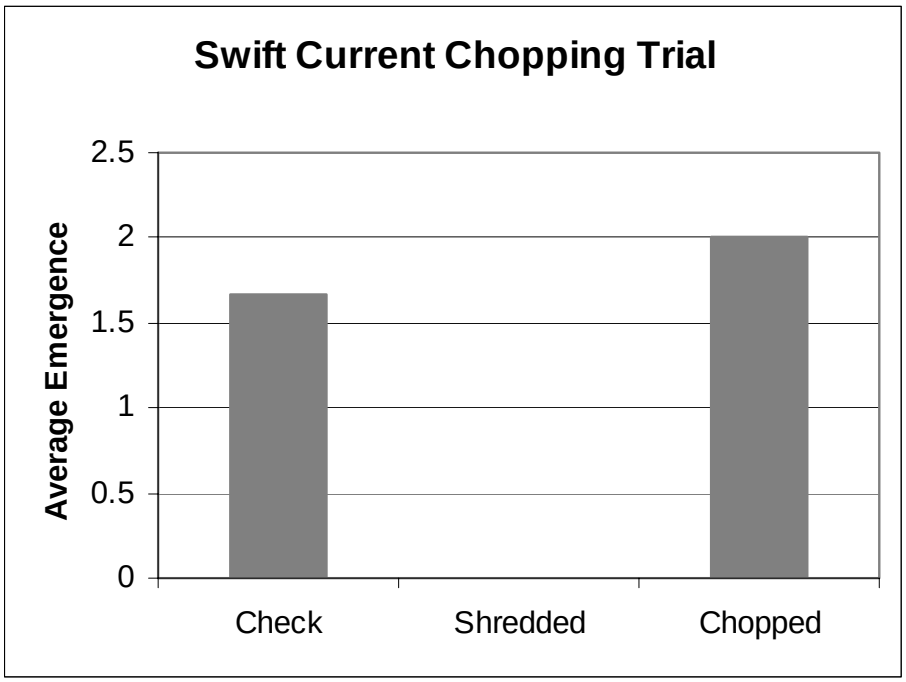


Figure 53: Swift Current chopping trial parasitoid emergence

Figure 54: Swift Current harvest plot trial 2002/03 parasitoid emergence

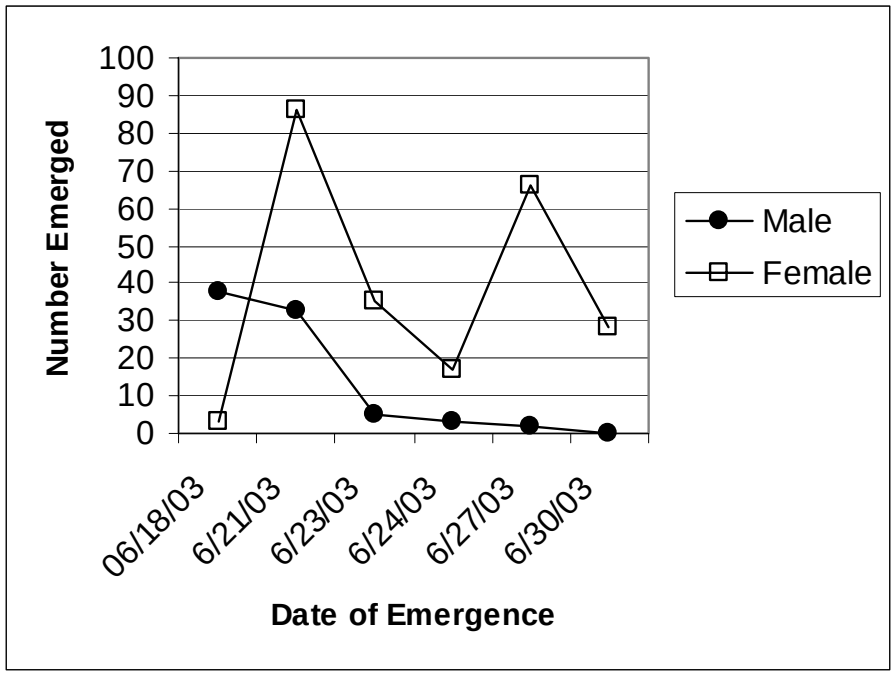


Figure 55: Swift Current harvest plot trial 2002/03 parasitoid emergence timing

Figure 56: Conrad harvest plot trial 2003/04 parasitoid emergence

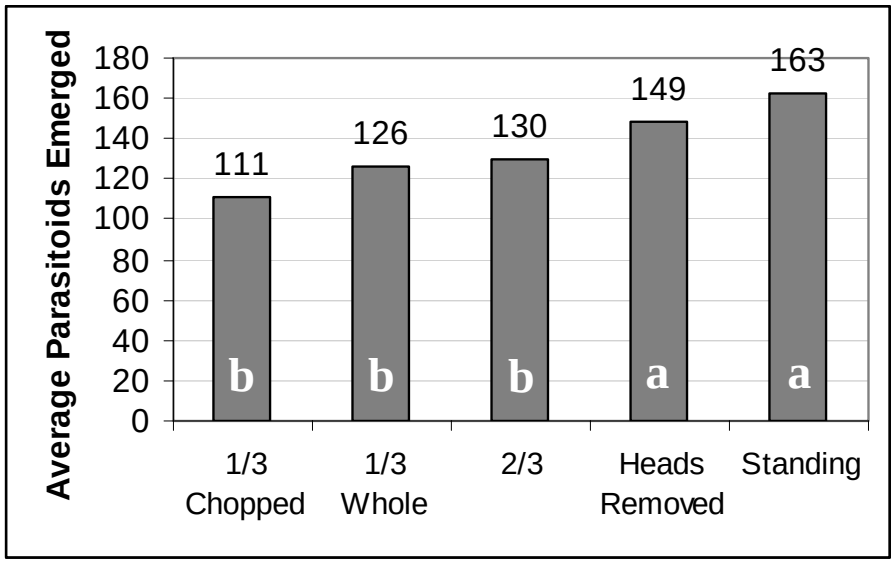


Figure 57: Lomond harvest plot trial 2003/04 parasitoid emergence

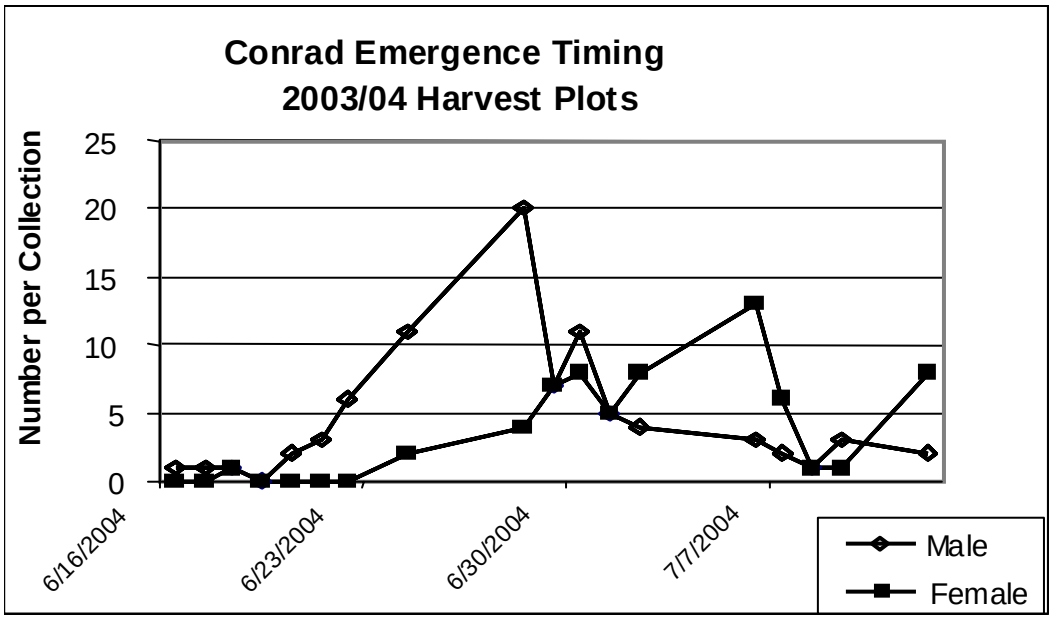


Figure 58: Conrad harvest plot trial 2003/04 parasitoid emergence timing

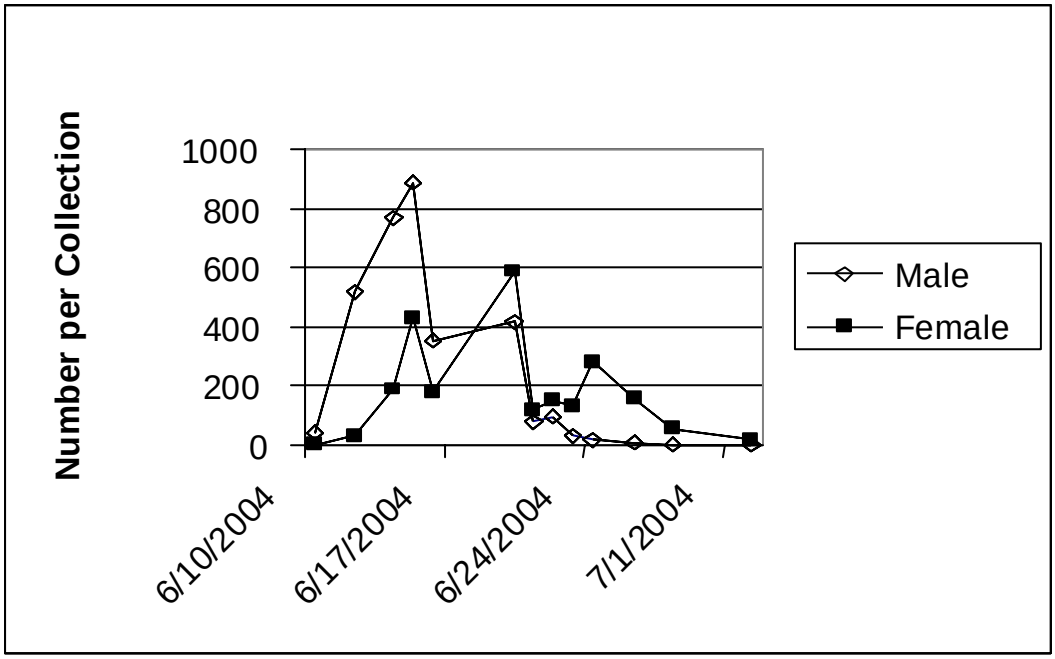


Figure 59: Lomond harvest plot trial 2003/04 parasitoid emergence timing

CHAPTER FOUR

DISCUSSION

Introduction

B. cephi and *B. lissogaster* are the most important natural enemies of wheat stem sawfly (Morrill et al. 1998). Their effectiveness in controlling sawfly has been highly variable and the major factors affecting this variability are seeding date, sawfly infestation level and weather (Holmes et al. 1963). Holmes (1963) concluded that among these factors that weather is the strongest factor influencing parasitoid success, specifically the amount of rainfall and heat units accumulated in the growing season. Rainfall and heat units together determine harvest date. The later the harvest, the more successful the second generation of parasitoids is, and as a result, the higher the level of parasitism. If there are successive late harvests parasitoid numbers increase dramatically (Holmes 1982). For example heavy rates of parasitism resulted in major reductions of sawfly populations across the Canadian prairies between 1955 and 1957 due to repeated later than normal harvests (Holmes 1982).

Improvements in understanding the dynamics of natural enemies in agricultural systems have shown that improving conditions for parasitoid survival in the field can result in improved pest management (Landis et al. 2000). Annual cropping systems are inhospitable environments because they are subject to a wide variety of disturbances and have few resources to support parasitoids. Many of the factors limiting the effectiveness

of natural enemies in agricultural systems include pesticides, lack of adult food, lack of alternative hosts and lack of overwintering habitats. These factors can be viewed as direct results of the disturbance regimes of annual cropping systems (Landis et al. 2000). Some of these factors also impact the success rate of *Bracon* spp. which parasitize the wheat stem sawfly.

Level of Parasitism

The maximum level of parasitism in this study was 54 %. Up to 90% parasitism by *Bracon* spp. has been reported in wheat fields (Morrill et al. 1998). The results from the sweep net sampling and stem splitting indicate that weather had a large impact on the success of the *Bracon* spp. in this study. Resources required for *B. cephi* and *B. lissogaster* are not well understood but possibly include weed flowers, leaf surface compounds, aphid honeydew, wheat pollen, and dew (Landis et al. 2000). These are all documented as resources used by other parasitoids (Landis et al. 2000). Host feeding by *Bracon* spp. females has not been reported. The first generation of *B. cephi* emerges at approximately the same time as sawfly and the mated females must survive until the sawfly larvae are large enough to parasitize. Sawfly eggs take 6-7 d to hatch, larval growth can take up to 60 d to maturity (Ainslie 1923). The time lag between emergence and oviposition of first generation could be up to three weeks (Nelson and Farstad 1953) although Holmes et al. (1963) reported a shorter time frame. It is important, therefore, that the female parasitoid can survive for at least two weeks and preferably 3 weeks or longer to allow time for enough sawfly larval growth to allow for successful parasitism.

The observation of dramatically lower adult parasitoid numbers at Opheim (both female and male) after a weekend of record breaking temperatures in July 2002 suggests that hot dry temperature extremes can have negative impact on their populations and likely, therefore, parasitism rates. The negative impact of high temperatures on the lifespan of parasitoids is well documented (Orr et al. 1997, Landis et al. 2002).

The presence of sawfly and parasitoids in summer population surveys did not guarantee that they would be found in stems as was observed seen for several locations in 2002. The indications again were that hot and dry weather lowered the success rate of the parasitoids as seen for Circle, MT, Cabri, SK and Acadia Valley, AB in 2002 and in virtually all of the fields sampled in 2003.

At the Oyen site, the ratio of cocoons to emergence holes increased from 0.8:1 to 4.8:1 over the two-week period between the two sampling dates. This clearly shows the increase in parasitoid numbers due to the success of the second generation and the importance of extra time for oviposition by the second generation.

Further evidence of the impact of weather shows up in the ratios of cocoons to emergence holes. In 2002, all four fields with highest parasitism levels had ratios of cocoons to emergence holes between 4.8 and 10.4 to 1. The emergence holes are generally indicative of the first generation *Bracon* spp. while the cocoons are most likely from second generation parasitoids (Holmes 1963). This shows an increase in the numbers of parasitoids in the second generation at these sites in 2002.

In 2003, the maximum ratio of cocoons to emergence holes is 1.3:1 and many locations had fewer second generation cocoons than were present for the first generation.

This is likely due to the unusually hot, dry summer and early harvest (Breitkreuz 2003, Anonymous 2004), which in turn lowered the success rate of the second generation. It could also be partially explained by first generation larvae that went into diapause due to the hotter and dryer conditions. When performing stem dissections after harvest it was not possible to separate a partial first generation from the second generation diapausing larvae so there may be some blending of generations in the ratios. It is clearly evident that 2002 was a better year for increases in parasitism than 2003. The large populations present at some sites in 2003 were obviously a carry-over from successful parasitism in the previous year. This phenomenon has been noted before (Holmes et al. 1963).

Parasitism and solid stem wheat were responsible for substantial reductions in sawfly populations at two locations, Opheim, MT and Lomond, AB, where the percentage of sawfly-cut stems fell substantially in 2003, despite high levels of infestation in 2002. The much lower levels of infestation at Opheim in 2003, occurred despite the producer having switched to hollow stem wheat.

Previous researchers have noted reduced larval sawfly survival when premature ripening occurred due to drought (Seamans 1945, Platt and Farstad 1946). This appeared to be the case for several of the fields in this study in 2003, most notably, Cabri, SK in 2002, and in Montana in 2003, in the Brockway and Laredo spring wheat and in the Gildford and Laredo winter wheat.

Density dependent theory would suggest that as the percent of infested wheat stems increased the level of parasitism would also increase. This was seen clearly in this study up to a level of approximately 60 % infestation. Above the 60 % level there was

both high and low levels of parasitism, creating a wedge-shaped pattern. There are a number of possible explanations of this wedge-shaped pattern. First, fewer cocoons at lower infestation levels may indicate search limitations of the female parasitoids. Second, the lower number of cocoons at lower infestations levels may result from poorer net volatile signaling by wheat plants (Turlings and Benrey 1998). Third, the reduced success of parasitoids at higher infestation levels is likely due to cannibalism by other sawfly larvae in the stem (Holmes et al. 1963). Fourth, abundant volatile signaling may also reduce efficiency of host seeking (Turlings and Benrey 1998). It is likely that these, and perhaps other factors interacted to cause this pattern to occur. The structure of this study, however, did not allow for a definitive answer to this question because this would require a carefully designed and executed experiment to measure the many influencing factors.

Phyllobaenus dubius

P. dubius was found in a wide range of sweep net samples in 2003, and in fewer samples in 2002 (Figure 13). *P. dubius* is recognized as a predator of *C. cinctus* (Morrill et al. 2001). It is of interest that this predator was widespread across the area impacted by wheat stem sawfly. As indicated by Morrrill et al. (2001), the impact of this predator on the sawfly population is not well understood. This wide distribution, however, suggests that it is probably an important part of the system on a large scale. Although it is not clear if *P. dubius* is a specialist predator, or a generalist, the wide distribution suggests that *P. dubius* predation on wheat stem sawfly is not a recent adaptation. Larvae

of the *P. dubius* were commonly encountered during stem dissections as well, both in intact stems, but more commonly in stubs. Many questions on the life cycle and importance of this predator remain, but there is little doubt that *P. dubius* is a factor in regulating sawfly populations.

Parasitoid Location in Stems

An important aspect of conservation biological control is habitat management to improve overwintering success. Generally this focuses on providing refuge areas such as undisturbed grasses or shelterbelts (Thomas et al. 1991) but in this system the overwintering habitat is the wheat stem. The purpose of this portion of the research was to quantify what part of the stem is the critical overwintering habitat.

The majority of parasitoid cocoons were found in the lower third of the stems. There was strong agreement in the data among fields and years for the location of overwintering parasitoids in the stem. This is a refinement of the overwintering cocoon location suggested by Holmes et al. (1963) that few parasitoids were found in the top two internodes. The shredding experiment shows that harvest operations, specifically shredding of straw, has a strong negative impact on survival of parasitoids. Any parasitoids located in straw going through a combine equipped with residue shredding attachments are likely to be killed.

Premature ripening of the crop affected the pattern of parasitoid cocoons overwintering in the stem. Premature ripening has been previously implicated in lower levels of parasitism (Seamans 1945, Platt and Farstad 1946). The lack of late season

parasitism, when the sawfly larvae had migrated toward the base of the stem, results in a greater than normal proportion of parasitoids higher in the stem. This is not due to increased numbers but rather a greater proportion due to the failure of parasitoids to encounter the sawfly larvae lower in the stem. The two winter wheat fields sampled in 2003 had greater numbers of cocoons in the upper portion of the stem likely because of very rapid maturity brought on by high temperatures and drought. The overwintering parasitoid cocoons in winter wheat may not follow the pattern found in spring wheat (majority of cocoons in the bottom third of the stem) because the crop typically matures before the second generation of parasitoids can be fully effective.

Parasitoid Location in the Field

If producers should apply specific harvest management practices to conserve parasitoids, it is helpful to know what part of the field is critical habitat. This would indicate which portions of the field should receive special treatment and the rest of the field to be treated normally. This would be very important if the special management practices caused extra cost or inconvenience. The distribution of the *Bracon* spp. in this study were expected to closely follow the infestation of sawfly because in most systems parasitoids typically are found in greater numbers in areas where there are greater numbers of their host (density dependent theory) (Berryman 1999).

As expected, sawfly infestation is a significant predictor in all fields with cocoons in sufficient numbers to analyze. The expected linear relationship between level of sawfly infestation and parasitism success was not always seen, however. Under 60% infestation,

there is a roughly linear relationship but at higher infestation levels there was no consistent linear relationship. This may be as result of the destruction of parasitoids by sawfly larvae in stems having multiple sawfly (Holmes et al. 1963) and also probably is impacted by inefficient host seeking. In a biological system, infestation level may be a reasonably good predictor of parasitoid location but it is not a relevant management indicator for agricultural producers because it is very difficult to measure in a field situation.

The distance from the edge of the field is often a good predictor of where the parasitoids will be, but it is not a linear relationship. In some cases there is an edge effect with high numbers at the edge decreasing deeper into the field. In other cases, there is a depression in numbers at the edge of the field, with higher numbers of parasitoids slightly further in and the numbers decline again further into the field, resulting in a quadratic pattern. This raises a question as to the reason for a depression at the edge of the field. This appears to once again support the active destruction of parasitoids by other sawflies in the stem or that when very large numbers of hosts are available the host seeking is no longer efficient. Care must also be exercised because field margins are often impacted by higher numbers of other insects (especially grasshoppers in this study), herbicide drift (from adjoining chemically fallowed land) or mechanical damage (cultivation implements).

The outer edge of the field may or may not harbor larger parasitoid numbers, but it is clear that parasitoid numbers typically decrease at depths greater than 30 meters into the field. It is important then to apply management techniques that have the potential to

increase parasitoid survival in the first 30 meters from the edge of fields. The outer edge of the field would logically appear to be the most important habitat, but it may not be as critical as originally predicted. This may be of some importance because the outer five meters of the field often has the highest levels of stem cutting and may need to be swathed close to the ground to conserve as much grain as possible.

Another good predictor of the incidence of parasitoid cocoons is crop biomass. It is interesting that in all three of the solid stem wheat fields sampled in this project, biomass was the best predictor of parasitoid location. In areas where crop growth is best, solid stem wheat has a lower incidence of stem pith formation. Platt (1941) showed that solid stem wheat showed better expression of solidness when plants were widely spaced rather than when planted closely together. Expression of solidness is most affected by light, and in heavier crop stands internal crop shading blocks light from the later forming tillers. Further to this idea, main tillers are most susceptible in hollow stem varieties, but tillers were most susceptible in solid stem varieties (Platt 1946). The hollow tillers may have resulted in more successful parasitism in areas of better crop growth. In areas with poorer growth there would be less internal shade, and fewer tillers, which would result in few sawfly larvae being available to parasitize. This is indicative of a tritrophic system at work. For a producer, looking to effectively manage parasitoid numbers, those management techniques are more important in areas of better crop growth, and particularly so in fields of solid stem wheat.

In only one field (Oyen 2002) was distance along the field border a significant predictor of the location of larger numbers of parasitoid cocoons. This was probably

driven by the presence of a nearby nectar source, because the 2002 Oyen field was immediately adjacent to an extensive area of unutilized native pasture. Four other fields were immediately adjacent to potential nectar sources: Acadia Valley, AB in 2002 and 2003, Cabri, SK in 2002, and Assiniboia, SK in 2003. The Acadia Valley field had a small alfalfa field to the west. It did not appear to increase the number of parasitoids adjacent to it. The Cabri site had a field of chickpeas along the entire east border of the field. The Assiniboia site had a field of flax at the north end of the field. None of these potential sources of nectar appeared to be of value to the sawfly parasitoids. This may be as a result of improper floral architecture that did not allow effective feeding by foraging parasitoids (Orr and Pleasants 1996).

Modeling of parasitoid location using several predictors revealed that good prediction of parasitoid location is obtained. The three best predictors for this analysis are: infestation, biomass and depth into the field. It is important to note that infestation is not independent of the other two factors, so added value may not be realized by modeling the location of parasitoid cocoons in this way. For producers, biomass and depth are relatively easy to assess. Infestation level, on the other hand, is very difficult to assess quickly and therefore is of limited value to producers.

In 2003, the Laredo spring wheat had an isolated area of sawfly infestation deep into the field. It is interesting to see that the parasitoids were able to find this pocket of sawfly larvae. This suggests a strong searching ability of the adult females of these *Bracon* spp. This strong searching ability would further suggest that these sawfly parasitoids can move substantial distances to find their host and find them in fragmented

habitats. From an agricultural standpoint, female *Bracon* spp. may be able to move to other fields if the field adjacent to where they emerge is lacking sawfly larvae to parasitize.

Harvest Plots

The emergence timing of parasitoid males and females supports the finding that the males emerge in advance of the females. This is a common characteristic of male Hymenoptera and is presumably an adaptive characteristic, allowing earlier emerged males better access to females as they emerge and prepare to mate (Holmes et al. 1963).

Results from emergence barrels clearly show that *B. lissogaster* emerges later than *B. cephi*. The adaptive significance of this is not clear, but in the July heat wave this would have provided an advantage. The July heat wave of 2002, as was mentioned already, is highly atypical. In non- traditional areas for *B. lissogaster* collection, in Canada and near Big Timber, MT, specimens were collected on bromegrass and not in wheat fields. This may indicate of *B. lissogaster* in these areas are still better adapted to species of perennial grass. In areas where *B. lissogaster* was found in wheat there was a high proportion of winter wheat grown. *B. lissogaster* may be univoltine rather than bivoltine in these situations, making it better adapted to winter wheat than spring wheat. The failure of *B. cephi* to reliably complete the second generation on winter wheat may provide a specific niche for *B. lissogaster*.

The results of the harvest plot experiments were consistent with the exception of the Swift Current plots, which were impacted by hail damage. The only harvest

treatment that significantly increased survival of parasitoids is the treatment that removed the heads only, and was not different from the unharvested, check treatments. A stripper-header type of harvest operation would conserve more parasitoids than the conventional operation. Stripper-header operations are not common in wheat production systems, but the technology is available and some producers are utilizing it (Anonymous 2005, Taillieu 2003). It is interesting that there is greater survival of parasitoids in the treatment that removed only the heads even though there are very few parasitoids found in the extra stem portion conserved when compared to the 2/3 or 1/3 cutting height treatments. This increase in numbers is likely due to more frequent introduction of insect predators, fungi, water and other stressors in the stems that are cut lower.

There is a slight increase in parasitoid numbers if crop is harvested at the 2/3 standing crop height when compared to harvest at 1/3 standing crop height, but it was never significantly different. Similarly, there seems to be no difference in parasitoid numbers between straws chopped into 3-4 inch pieces when compared to numbers for straw left whole for the 1/3 standing crop harvest height. The results for the two 1/3 height treatments may suggest that all straw laying on the ground is the same, but this is not clear. Also, a small straw chopping and shredding trial showed that intact pieces are capable of supporting parasitoids, while where the straw is shredded, as it is in conventional straw management techniques, there is no survival of the parasitoids. In other words, parasitoids are killed if the straw goes through most modern combines equipped with straw shredding attachments. What happens to parasitoids in stem pieces laying on the ground through the winter is unknown, but these results suggest that they

may not survive. The vast majority of parasitoids in these trials were found in the undisturbed bottom 1/3 of the stems. Indications are that leaving 1/3 of the standing crop height at harvest is sufficient to provide good parasitoid levels of survival. Cutting the crop lower than one third of its standing height is sure to have an impact on parasitoid survival, but this study did not assess this impact.

CHAPTER FIVE

RECOMMENDED PRACTICES

Based on these studies, the flowing recommendations can be made to producers to improve the performance and survival of parasitoids in wheat production systems.

Recommendation One

At least one-third of the length of the standing crop should be left as standing crop residue during harvest operations. This will protect critical parasitoid overwintering habitat.

Recommendation Two

Special efforts to conserve parasitoids should be concentrated in the critical areas of the crop. In solid stem wheat these are areas supporting better crop growth. These areas harbor far more overwintering parasitoid cocoons than areas of relatively poor crop growth. In all hollow stem wheat the area 7.5 to 30 meters from the field margin is the most critical to conserve. If the hollow stem wheat has lower levels of infestation the area conserved should extend to the field margin. In this area special efforts should be undertaken to leave as much crop residue as possible.

Recommendation Three

Removing only the wheat heads at harvest results in maximum parasitoid conservation. This is possible using specialized stripper-header equipment. While stripper header equipment is not widely used in this study area, some producers have been effectively utilizing it.

Recommendation Four

These recommendations should be incorporated with other management practices that encourage sawfly parasitoids. These include: solid stem wheat varieties, careful timing of insecticide use for controlling other pests, reduced tillage and chemical fallow. The improvement of parasitoid activity should incorporated into a complete integrated pest management plan that includes practices such as larger block fields, careful use of trap strips, crop rotation and solid stem wheat.

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APPENDIX A

DATA ENTRY AND DATA INTEGRITY VALIDATION

Data Entry and Data Integrity Methodology

Data were entered into an excel spreadsheet at a later date. Formulae were used in the data entry form to facilitate entry of repetitive information. Once data entry was completed the data sets were subjected to a data integrity check of the following steps:

1) Add sort number column.

2) Convert formulae to values.

3) Sort by stem heights. Check unusual data at both ends of column

4) Divide the stem height entries by 5. Check all entries that are not whole numbers.

5) Move through each column using the “End” up and “End” down functions to find data gaps.

6) Sort - Broken stems descending + stem heights ascending. Look for broken stems that have heights associated.

7) Sort - Stem Heights descending + Broken descending + Cut descending. If there is no height entry then it must either be broken or cut. Also checked the entries that are both broken and cut as they were often mistakes.

8) Sort - Sawfly cut descending + sawfly infested ascending. All cut stems must be infested.

9) Sort - Sawfly infested descending + sawfly cut descending + parasitoid infested descending. Check that the cut stems with parasitoids are accurate. Scroll down the sawfly-infested “Y” column to locate errors. Often errors appeared at the bottom of the “Y” portion of the sawfly-infested column.

10) Sort - Parasitoid infested descending + sawfly infested ascending. Check that all entries of parasitoids also are sawfly infested. Entries that are in the wrong column show up here as well.

11) Sort - Parasitoid infested descending + cocoon descending + emergence hole descending. Check that all entries in parasitoid infested have corresponding entries in the type of parasitoid and that heights are associated with all entries and that Parasitoid Cocoon and Emergence Hole columns have corresponding entry in Parasitoid Infested column. These show up at the bottom of "Y" portion of the parasitoid infested column.

12) Sort - Cocoon height ascending + stem height ascending – all cocoons must have parasitoid infested column and PC column. Check for cocoon heights that are higher than stem length. Also check that all entries with heights have infested column entries.

13) Sort - Emergence hole heights ascending + stem height ascending – all emergence holes must have parasitoid infested column and the emergence hole column. Check for emergence hole heights that are higher than stem length and all entries with heights have infested column.

14) Sort back to original format and delete sort number column.

In all cases if a discrepancy was found it was checked against the paper data entry form.

15) The data entry was then audited by checking 10% of all the entries for each field for accuracy.