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Integrating the building blocks of agronomy into an integrated pest management system for wheat stem sawfly

by

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Abstract

The wheat stem sawfly (*Cephus cinctus* Norton [Hymenoptera: Cephidae]) is a serious threat to wheat (*Triticum aestivum* L.) and other cereal grains in the northern Great Plains. Insecticides have proven ineffective for sawfly control and may be detrimental to beneficial insects. The management of wheat stem sawfly, therefore, requires the integration of host plant resistance, agronomic and biological control strategies. Recent studies in Alberta, Canada have assessed the response of wheat stem sawfly and its natural enemies to cultivar selection, residue management, seeding rates, fertility regimes, and harvest management. Solid-stemmed cultivars are usually agronomically superior to susceptible cultivars when sawflies are present. The stubble disturbance associated with residue management and direct-seeding in a continuous cropping system can reduce sawfly populations compared to a wheat-fallow system. Increased seeding rates can optimize yield, but an inverse relationship between pith expression (stem solidness) and higher seeding rates may occur. Positive yield responses are typically observed with N rates > 30 kg N ha^{-1}, but increased insect stem cutting by sawfly occurs with higher N rates. Increasing cutter bar heights during combine harvest will conserve natural enemies, and chopping straw for improved residue management in the spring will not likely affect wheat stem sawfly parasitoids that overwinter in the straw. In summary, an integrated strategy to manage wheat stem sawfly consists of diligent pest surveillance, planting solid-stemmed cultivars, continuous cropping with appropriate pre-seed residue management, seeding rates no greater than 300 seeds m^{-2}, 30 to 60 kg N ha^{-1}, and harvest cutting heights of at least 15 cm to conserve parasitoids.

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Table of Contents

List of Tables

List of Figures

List of Appendices

List of Abbreviations

AAFC	Agriculture and Agri-Food Canada
AC	Agriculture Canada
ANOVA	Analysis of variance
CDC	Crop Development Centre
cm	Centimeter
CV	Coefficient of variation
EDTA	Ethylenedianimine Tetra-Acetate
g	Gram
g a.i.	Grams of active ingredient
GDD	Growing degree day
kg	Kilogram
kg ha^{-1}	Kilogram per hectare
kg N ha^{-1}	Kilograms of nitrogen per hectare
LRC	Lethbridge Research Centre
LSD	Least significant difference
Mg ha^{-1}	Megagrams or tonnes per hectare
mm	Millimeter
N	Nitrogen
NDVI	Normalized difference vegetation index
SAS	Statistical Analysis System
SE	Standard error
SED	Standard error of the difference
USA	United States of America
WSS	Wheat stem sawfly

1.0 Biology and integrated management of wheat stem sawfly and the need for continuing research[1].

1.1 Introduction

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), has been a major pest of wheat, *Triticum aestivum* L. (Poaceae), in the northern Great Plains of North America for more than 100 years. Within this geographical region the areas subjected to greatest attack are southern Alberta and Saskatchewan, southwestern Manitoba, eastern and northern Montana, North Dakota, northern South Dakota, and western Minnesota. The species was described from a specimen collected from native grass in Colorado (Norton 1872; Davis *et al.* 1955), and adults were reared from larvae collected in Alameda, California (Ainslie 1920; Holmes 1979). Comstock (1889) first reported a species of stem sawfly as a wheat pest in northern New York. *Cephus cinctus* was first observed infesting wheat in Canada in 1895 near Souris, Manitoba and Indian Head, Saskatchewan (Fletcher 1896). Reports of *C. cinctus* infestations followed the westward movement of wheat production across the Canadian prairies and the northern states of North Dakota and Montana (Fletcher 1904; Ainslie 1920). By 1910, infestations of wheat stem sawfly were reported as far west as Claresholm, Alberta (Holmes 1979).

There are dissenting views from the common assumption that *C. cinctus* is indigenous to North America. Ivie and Zinovjev (1996) proposed that *C. cinctus* is a senior synonym of the Siberian species *Cephus hyalinatus* Konow. Ivie (2001) described inconsistencies in the ecological relationships between *C. cinctus*, native hosts, and native parasitoids. He noted that stems of native host plants often are of insufficient diameter to support *C. cinctus* pre-imaginal development, and stated that parasitoids were poorly synchronized with their hosts. This seems unlikely, however, because a strong oviposition preference for an introduced marginal host with very narrow stems has been documented (Perez-Mendoza *et al.* 2006). Ivie (2001) also argued that early insect collectors in North America did not encounter *C. cinctus* and suggested that introduction could have occurred through the transport of straw or crowns from plants containing live larvae. The probability of introducing straw containing living larvae is low, however, because most larvae overwinter near the crown (Ainslie 1929). Larvae would also have been at risk to destruction by pathogens (Criddle 1922b) because of the likelihood of very humid transport conditions. In addition, crowns (commonly imported for medicinal purposes early in the 20th century) would likely have been stored indoors. Thus, completion of obligate low temperature diapause (and subsequent adult emergence) (Holmes 1982) prior to crown pulverization for medicinal extractions (Ivie

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2001) seems improbable. Other unpublished work shows that it is relatively unlikely that *C. cinctus* is of recent Eurasian origin (M.C. Bon, personal communication). This debate will likely continue.

The economic importance of wheat stem sawfly was evident early in the settlement of the Prairies. The first recorded severe infestation and damage to wheat occurred in 1922 in western Canada (Criddle 1923). Criddle (1923) characterized the extensive damage and economic losses as the sawfly's "free hand" that evolved from the elimination of natural population checks such as the limited food supply associated with native grass host abundance and health, and because natural enemies of the sawfly had not successfully adapted to this shift in host preference.

Wheat stem sawfly outbreaks were historically short-lived because wheat crops were often destroyed by rust epidemics, eliminating preferred host plants (Platt and Farstad 1949) and parasitoids reduced sawfly populations (McGinnis 1950). The development of rust-resistant wheat cultivars that served as healthy hosts for *C. cinctus* (McGinnis 1950), coupled with the severe drought of the late 1930's, favoured sustained increases in wheat stem sawfly populations in the northern Great Plains (Morrill 1983). Cultural practices to mitigate soil erosion (most notably the introduction of the low disturbance Noble blade to replace the mould board plough, as well as strip farming as an alternative to farming large blocks of land) provided undisturbed overwintering habitat facilitating the increase of wheat stem sawfly populations, and leading to dispersal of sawflies across entire fields instead of being localized at field margins (McGinnis 1950). The urgency for adoption of cultural control practices to mitigate damage is clear in a "War-Time Production Series" report (Farstad *et al.* 1945): descriptions synonymous with warfare were used to describe management strategies (*e.g.*, "drive out", "kill", "protect" and "salvage") and upper case lettering in some sentences underscored the message (*e.g.*, "ALL TRAPS MUST BE DESTROYED ABOUT MID-JULY TO KILL THE MILLIONS OF SAWFLY GRUBS IN THEM"). In theory, the recommended cultural practices to manage wheat stem sawfly had potential for reducing infestation levels, but the rate of adoption of cultural control methods during that time is unknown.

In the same period, the first efforts were initiated to develop a wheat cultivar resistant to wheat stem sawfly infestation. Dominion of Canada researchers from Swift Current and Lethbridge evaluated germplasm from New Zealand, Spain, Morocco, and Portugal that expressed greater amounts of pith within the culm of the stem than varieties grown in western Canada at the time (Kemp 1934). The interaction between wheat stem sawfly and solid-stemmed hosts was assessed because Kemp (1934) believed that mechanical restriction within solid stems could be detrimental to larvae. Additional tests were performed that identified line S-615, originally selected from Portugal (Platt and Farstad 1949), as a suitable parent with considerably reduced occurrence of stem cutting caused by mature larvae (Platt and Farstad 1946). A cross between S-615 and Apex, a hollow-stemmed and rust-resistant variety, produced the first solid-stemmed commercial variety aptly named 'Rescue' (Platt *et al.* 1948). The development of this variety, however, did not prove to be a "magic bullet" and damage from wheat stem sawfly was still severe through 1954 (Holmes 1982).

Several factors during the 1950's resulted in reductions of wheat stem sawfly populations. Heavy rainfall and a severe wheat rust outbreak during the 1954 growing season significantly reduced sawfly populations. In 1956, rates of parasitism were very high and subsequently reduced infestations (Holmes 1982). Periods of resurgence that followed were generally short-lived and sporadic through the entire wheat stem sawfly distribution area (Holmes 1977, 1982; Morrill 1983). Damage in Montana, however, increased significantly in the mid-1990s (Morrill *et al.* 1998), and a major resurgence of *C. cinctus* occurred in southern Alberta in 1998-99, and soon after in Saskatchewan (Meers 2005; Beres *et al.* 2007). Currently, extensive damage to wheat caused by *C. cinctus* persists throughout the northern Great Plains, particularly in Montana, southern Alberta, and Saskatchewan.

Our review comes more than a century after the first report of wheat stem sawfly attacking wheat in Canada. *Cephus cinctus* remains one of the most economically important insect pests of wheat in the northern Great Plains in spite of enormous efforts to control it in Canada and in the United States. This serves as a testament to the resiliency of this insect and the difficulty of developing successful strategies for its management. Here we provide overviews of wheat stem sawfly biology, the efficacy of cultural and biological management strategies, and future directions for global research activities to manage wheat stem sawfly.

1.2 Wheat stem sawfly life cycle

Timing of wheat stem sawfly adult emergence is influenced by temperature (Perez-Mendoza and Weaver 2006) and thus, latitude. In Manitoba, adults have been observed emerging from 10 June through 10 July from previous year host plants, usually wheat stubble (Criddle 1922a). Adults are shiny black and approximately 12 mm long with yellow abdominal bands, large prominent eyes, club-shaped antennae with approximately 20 segments, and a slightly compressed abdomen (Fletcher 1904). Males are haploid with nine chromosomes and typically emerge before females (Holmes 1979). Copulation takes place immediately after emergence unless environmental conditions such as wind or rain inhibit activity (Wallace and McNeal 1966). Some competition exists between males; males have been observed nipping at the antennae of challengers (Wallace and McNeal 1966). Fertilized eggs produce diploid females and unfertilized eggs produce male offspring. Therefore, most early eggs deposited produce female offspring, and most laid toward the end of the flight period (when males are less abundant) produce males (Holmes 1979).

Oviposition occurs a few days after adult emergence. An ovipositing female uses her saw-like ovipositor to slice an opening into the elongating internode of a wheat stem and insert an egg. The female selects an oviposition site, usually a hollow region (Seamans 1945) historically reported to be between the second to fourth internode, by first climbing to the apex of the top leaf where she turns and points downward to the most suitable site on the stem just above the node. Stems that are succulent and from which the spike has yet not emerged (boot stage) are preferred (Holmes and Peterson 1960). There is also a preference toward larger diameter stems. The sex ratio of offspring is female-biased in larger stems, whereas ratios from smaller stems are male-biased (Wall 1952; Morrill *et al.* 2000; Cárcamo *et al.* 2005). Most oviposition occurs about mid-day during a four-day period and each female deposits only one egg per stem (Holmes 1979). However, multiple eggs often occur in stems because subsequent females are unaware of earlier oviposition (Criddle 1923; Buteler *et al.* 2009). Nansen *et al.* (2005b) proposed that females could possibly detect chemical signals emitted from host plants containing larvae and avoid those, but this proved to be incorrect (Buteler *et al.* 2009).

Female behaviour suggests that a number of host attributes must be present before oviposition will occur (Buteler *et al.* 2010), at least when host plants are abundant. When hosts are scarce, however, females may be less discriminating: Holmes and Peterson (1960) observed that in laboratory conditions females will attempt to oviposit in glass rods, desiccated wheat stems, or wooden rods.

Each female is capable of carrying up to 50 eggs, which are usually equal in size and maturity (Ainslie 1920). Each egg is crescent-shaped, milky white or translucent, and usually 1.00 – 1.25 mm long depending upon the size of the female that produced it (Ainslie 1929). Each egg lies freely within the cavity of the stem or in a hollow created by the ovipositor during egg deposition (Ainslie 1929). Larvae develop rapidly and begin to take shape by the third day. By the sixth or seventh day after oviposition, each larva breaks free of its egg sac and enters the stem cavity (Ainslie 1920).

Newly hatched larvae are transparent and colourless (Criddle 1923; Ainslie 1929), but appear yellowish-brown soon after feeding begins. In stems containing more than one larva, the first larva to hatch is usually the one that survives, although the lower-most larva has an advantage over others in the same stem (Criddle 1923). Stem boring activity begins immediately after hatching. Newly hatched larvae destroy other eggs (and each other) until usually only one larva remains in a stem (Criddle 1923; Holmes 1982). It is unknown if destruction of eggs and larvae is the result of intentional cannibalism or an indirect consequence of indiscriminate feeding activity. Although multiple larvae in a stem are usually reduced to a single survivor within a few weeks (Criddle 1923), two or more larvae have been recovered from post-harvest stems and stubs at Lethbridge, Alberta (B. Beres, personal observation).

Cephus cinctus exhibits a distinct spatio-temporal pattern of distribution. It begins with the concentration of adults at field edges as they emerge from stubble and migrate to the nearest suitable hosts, which are usually plants within an adjacent wheat field (Holmes 1982). Females oviposit first within the field margin which usually results in more severe damage along edges compared to the field interior. Infestations are initially clustered, a behavioural trait that might relate to oviposition strategies when only native grasses were available and spatially dispersed in bunches (Nansen *et al.* 2005a, 2005b). Oviposition gradually moves toward the center of the field and there is a more uniform distribution of eggs in the field as the flight period progresses (Nansen *et al.* 2005a). Nansen *et al.* (2005a) hypothesized that signalling compounds are released from plants after larval eclosion and commencement of herbivory; this would deter further infestation and motivate females to seek out uninfested hosts. Females, however, cannot differentiate between infested and uninfested stems (Buteler *et al.* 2009) and other evidence for this mechanism is lacking. Uniformity of egg distribution, interestingly, does not lead to a more uniform larval distribution; larvae remain mainly concentrated on field margins (Nansen *et al.* 2005a). Survival of larvae in the interior of fields may be inconsistent because most of these larvae hatch from eggs deposited later in the flight period and they may not have sufficient time to prepare for overwintering before the onset of host senescence(Nansen *et al.* 2005c).

The larva feeds within the stem until the plant is nearly mature; therefore, the duration of this period varies with host plant phenology. Toward the end of the growing season, an obligatory diapause is triggered by two environmental cues. The first occurs when host plants are sufficiently mature that visible and infrared light penetrate the stem wall (Holmes 1979), inducing the larva to move downward to the base of the plant. The second cue, when plant moisture drops and moisture content of the kernels fall within the range of 41 – 51% (Holmes 1979), induces the larva to respond by preparing its hibernaculum. A neat v-shaped groove is made entirely around the inside of the stem at ground level, which does not sever but is weakened and topples easily when exposed to wind (Ainslie 1929). The larva then fills the girdled section with frass, creating a solid plug in the pith cavity that seals the stub when the stem above topples. Below the plug the larva encases itself in a silken-like cocoon and overwinters as a mature fifth instar (Holmes and Peterson 1960).

As long as the chamber and cocoon remain sealed, the larva is well protected from environmental degradation or predation. A larva within sealed hibernaculum can survive for months of immersion in water (Ainslie 1929) and the larval supercooling point ranges from -20 and -28^{o} C (Holmes 1979). Overwintering larvae remain very near host root crowns. Temperatures at the crowns are generally 9 to 28 ^{o}C warmer than ambient winter air temperatures (Morrill *et al.* 1993) and more stable than the air temperatures at 15 cm above the crowns (Beres, unpublished data), allowing larvae to withstand consecutive days of cold temperatures. Cárcamo and Beres (2006) reported almost 100% survivorship of larvae exposed to -20 ^{o}C for 10 or fewer consecutive days. However, the rate of mortality increased sharply when exposure was longer than 10 days (Cárcamo and Beres 2006), or if wheat stubs (and cocoons) have been disturbed by tillage (Morrill *et al.* 1993). Mortality rates are high after a few hours of direct exposure to -22 ^{o}C.

Diapause is completed after 90 days of exposure to 10 ^{o}C, usually by mid to late spring. Prior to pupation, if temperatures approach 35 ^{o}C (Salt 1947), or conditions are extremely dry (Holmes 1979), larvae re-enter diapause and will remain in that state until the following spring. However, if these conditions arise after pupation has occurred, diapause cannot be re-entered and malformed prepupae or pupae will result(Holmes 1979). An extremely dry winter and spring in 1937 caused a resumption of diapause in many larvae across the Canadian prairies (Holmes 1979). There are no known reports of this occurrence in recent decades even though the western prairies endured extreme drought and high temperatures in 2001 and 2002. Possibly this is because the current adoption of conservation tillage practices (as opposed to the extensive cultivation of the 1930s) may limit exposure of wheat stubs to desiccation and high temperatures through lower evapotranspiration rates (Lindwall and Anderson 1981).

Pupation occurs over usually no more than 21 days (Criddle 1923). The pre-pupal period begins in early to mid-May and the first pupae develop in late May (Holmes 1979). After pupation, each newly eclosed adult chews through the frass plug or the side of the stub (Holmes and Peterson 1960).

1.3 Plant injury caused by wheat stem sawfly larvae.

Adult sawflies inflict little injury on host plants but the stem boring activity of larvae is destructive and can result in severe losses. The first damage occurs soon after a larva hatches from an egg and begins boring through parenchyma tissue and vascular bundles of its host, causing a significant reduction in photosynthetic capacity (Macedo *et al.* 2005). The stem can be thoroughly bored in a few weeks, as the larva feeds both downward and upward in the stem (Criddle 1923). There may be little external evidence of boring activity unless the stem is opened longitudinally to check for the presence of frass (Holmes 1979). Macedo *et al.* (2007) observed 12% higher photosynthetic rates in uninfested than in infested wheat plants and this appears to be linked to further reductions in yield resulting from abiotic influences and plant variety (Delaney *et al.* 2010). Seamans *et al.* (1944) found that stem boring associated with heavy sawfly infestation resulted in a 10% yield loss in heads of Marquis wheat. Holmes (1977) separated cut from uncut infested spring wheat stems and found that head weight was reduced by 17% in cut stems and by 11% in uncut stems. Winter wheat is also a host for wheat stem sawfly, particularly in western Montana where sawflies have synchronized emergence patterns to exploit this host. Morrill *et al.* (1992) reported a range of 2.8-10.0% in winter wheat head weight loss and noted that infestation rates were higher in larger-diameter stems, which also normally produce heads bearing seed of greater kernel weight.

The initial phase of herbivory is only evident upon close examination of the sub-nodal region immediately below one or more nodes, which can appear discoloured or spotted after larval boring (Morrill *et al.* 1992). However, late season stem girdling by mature larvae is readily apparent because this causes stems to topple easily in windy conditions (Ainslie 1920). This stem cutting results in additional yield losses because it is difficult to harvest fallen stems effectively. Ainslie (1920) and Criddle (1922b) estimated losses from stem cutting at approximately 30% of attainable yield and about 25% of the 1921 crop, respectively. In subsequent outbreaks prior to the release of the first solid-stemmed cultivar, annual losses in the Canadian prairies exceeded 544 000 tonnes (Platt and Farstad 1949). Losses in the 1950's in Montana and North Dakota were 61 000 and 154 000 tonnes, respectively (Davis 1955). In more recent years, damage and losses in Montana in the mid-1990's were projected to exceed 402 000 tonnes annually (Blodgett *et al.* 1997). In a European study, Ozberk *et al.* (2005) concluded that yield losses from *Cephus pygmaeus* (L.) would be \$69 ha^{-1} for durum and bread wheat. Beres *et al.* (2007) used the strong positive correlation between stem cutting and grain losses to show that losses could be estimated based on stem cutting. Using this approach, and based on modern commodity prices, close to 50% stem cutting could result in economic losses in excess of \$100 million annually across the Canadian prairies. Recovery operations to minimize losses typically involve using a swather equipped with a pickup reel and crop lifters. The added energy cost of an extra operation is likely to exceed \$30 ha^{-1} at current fuel prices, and the fixed cost of equipping a swather or combine with a pickup reel and crop lifters is close to \$10,000 (Alan Gajdostik, personal communication). The recovery of toppled stems also requires a very low table cutting height, which leaves little anchored stubble, and exposes fields to increased risk of soil erosion and reduced snow capture.

1.4 Cultural control

Wheat stem sawflies spend up to 10 months of the year as larvae within host plants; thus early control tactics targeted the larva through destruction of the stub. Fletcher (1904) recommended burning any stubble that was not turned over in the fall, but Ainslie (1920) concluded that larvae housed within the bunchgrass stems suffered little, if any damage from burning. Ainslie (1920) also described Criddle's 1907 experiments to test the effects of increased heat intensity through burning a deep layer of straw previously spread over infested stubble. No larvae were killed by Criddle's treatments (Ainslie 1920) and the negative effects of burning can be severe. Serious soil erosion may result from removal of residue (Lal 1997; Lafond *et al.* 1996) and natural enemies of the sawfly, housed within stems but above ground, could perish.

Tillage was another early recommendation for wheat stem sawfly control. Criddle (1922b) recommended ploughing infested stubble to a depth of at least 15 cm and completely burying all stubs between 1 August and 5 June of the following year (fall tillage was preferred because of increased potential for pathogens to rot stubs and destroy larvae). Criddle (1922b) also recommended packing of ploughed furrows to seal the soil and prevent successful emergence of adults from stubs. Although tillage was believed to provide effective control during this period, the method did not destroy all sawflies. In spite of increasing larval mortality as burial depths increased to 15 cm or more, some adult emergence still occurred (Ainslie 1920). Furthermore, ploughing under wheat stubble significantly increases the mortality of the *C. cinctus* parasitoids *Bracon lissogaster* Muesebeck and *Bracon cephi* (Gahan) (Hymenoptera: Braconidae) (Runyon *et al.* 2002).

When it became apparent that ploughing left fields prone to soil erosion during periods of drought and high winds, farmers began to adopt cropping practices to mitigate soil erosion and replaced the plough with low disturbance tillage equipment such as the Noble blade (Mathews 1945). Although this was thought to enhance the survivorship of *C. cinctus* (McGinnis 1950) because the practice did not sufficiently bury stubs (Morrill *et al.* 1993), stub burial is not critical to kill overwintering larvae. Shallow tillage can provide effective wheat stem sawfly control if the operation fully exposes host plant root crowns by uprooting and removing all soil from them (Holmes and Farstad 1956). Furthermore, the practice should be performed in the fall or late May after larvae have pupated and cannot return to diapause (Holmes and Farstad 1956). Tillage operations that did not free the soil from the crown produced the same rate of spring larval survival as did untilled treatments (Goosey 1999). Goosey (1999) also reported that a rotary harrow operation following tillage was usually more effective for removing soil from crowns compared to the Noble blade or not harrowing after cultivation. Morrill *et al.* (1993) performed tillage in fall and in mid-May and reported that the spring operation did not cause the larvae to return to diapause. It was recommended that only field margins should be tilled to minimize soil drift. Other studies have reported no effect of tillage on *C. cinctus* survivorship (Weiss *et al.* 1987). Moreover, factors such as larval development time or operational implements may not be as important as environmental conditions; efficacy of tillage and harrowing to uproot and remove soil from crowns is influenced by soil moisture and texture.

Field configurations were modified in many areas to mitigate soil erosion. Large tracts of monoculture were replaced with alternating strips of crop and fallow land. This increased *C. cinctus* abundance which easily dispersed across the narrow strips, caused widespread stem cutting, and greatly impeded harvest operations (McGinnis 1950; Morrill *et al.* 2001b; Weaver *et al.* 2004). An early approach to minimize dispersal beyond field edges involved the use of trap crops or border management. The earliest trap crop was rye grass, *Lolium perenne* L. (Poaceae), planted in ditches and headlands of wheat fields so that invading *C. cinctus* would deposit most eggs into rye grass stems, which would then be destroyed by mowing in July (Criddle 1922a). Criddle (1922a) noted that brome grass, *Bromus* *inermis* Leyss. (Poaceae), might be a superior trap crop because larvae generally did not survive in brome grass and mowing would not be required. Also, brome grass elongates earlier in spring than does wheat, thus becoming the primary host if situated beside a wheat field (Seamans 1928). Cutting of native grasses or brome grass surrounding wheat field edges and headlands was not recommended because parasitism rates of *C. cinctus* were generally higher in the grasses than in wheat or rye grass (Criddle 1922a).

Annual crops have also been used as trap crops. Volunteer wheat in fallow strips has higher infestation rates than do adjacent wheat fields (Seamans 1928). A perimeter of wheat could also be planted on a fallow field adjacent to a wheat field to attract adults emerging from the previous year's crop. A space between the trap strip and the wheat field equal to the width of the trap strip ('2-3 rod widths' or 10 – 15 m) was left bare to entice adult sawflies to remain in the trap crop (Farstad *et al.* 1945). The trap crop was then ploughed under in mid to late July to destroy larvae. There is still potential for this strategy to work in regions with a wheat-fallow cropping system. In the southern prairies of Canada, however, most producers favour continuous cropping practices and no longer leave fields fallow.

An updated approach to trap strips involves within-field border management; *i.e.*, sowing the perimeter of a wheat field to an immune or resistant crop and then planting the interior of the field to a hollow-stemmed wheat cultivar. The goal of this strategy is to intercept incoming sawflies from adjacent infested stubble so that most infestation occurs within the trap perimeter (Beres *et al.* 2009; Morrill *et al.* 2001b) and conserve beneficial insects (the trap crop harvested rather than destroyed). Trap effectiveness is maximized when insect and trap crop phenologies are in synchrony and the main crop developmental stage lags behind. This is achieved by seeding trap and main crops at different dates or selecting trap and main cultivars that differ significantly in growing degree-day requirements. One approach used in Montana is to plant solid-stemmed winter wheat trap borders around fields that will be seeded to a hollow-stemmed spring wheat cultivar (Morrill *et al.* 2001b). The strategy requires multiple seeding operations in the same field and so may be considered impractical for large farm operations. Beres *et al.* (2009) used a single seeding operation for fields and borders and reported that the traps were generally ineffective due to high wheat stem sawfly pressure and higher than expected stem cutting in the solid-stemmed wheat treatments.

Certain cropping practices that were incompatible with deep tillage led to development of alternative trap crops. Ainslie (1920) noted that tillage of infested stubble was not adopted in regions where producers grew winter cereals (Poaceae) because the practice of planting into standing stubble was advocated for increased winter cereal survival. However, improved survivorship of overwintered sawflies was partially offset because winter cereals are usually too advanced to be preferred hosts for *C. cinctus* at more northern latitudes (Criddle 1922b). Fall rye, *Secale cereale* L. (Poaceae), was the dominant winter cereal of this time, although winter wheat was also grown. The use of fall rye was considered an effective cropping strategy because its relatively early harvest in late summer had the potential to kill larvae in the stem before they moved to the base of the stem to overwinter. Samples collected from harvested fall rye showed 85% mortality of larvae infesting the crop (Criddle 1922a).

Other crops recommended as alternatives to bread wheat for wheat stem sawfly management included oats (*Avena sativa* L.), barley (*Hordeum vulgare* L.), and durum (*Triticum turgidum* L.) (Poaceae) as well as non-cereals such as flax (*Linum usitatissimum* L. (Linaceae)) and sweetclover (*Melilotus officinalis* (L.) Lam. (Fabaceae) (Criddle 1922a). The mechanism of resistance for oats has not been fully elucidated. One explanation is that larvae succumb shortly after hatching because of excess sap produced by host oat plants (Criddle 1923). Larval death in oats could also be a form of antibiosis and is currently under study at Montana State University. The response of barley and durum to wheat stem sawfly attack is genotype-specific. Durum was initially considered immune but field damage was noted in Canada (Criddle 1922a) and the USA (Ainslie 1920). Other studies determined that some varieties of durum and barley were less prone to infestation and produced significantly fewer larvae than did wheat (Farstad and Platt 1946; Goosey *et al.* 2007). It is now known that *C. cinctus* can complete its life cycle in all cereal crops except oats, and therefore cereal crops can be a source of inoculation in the following year even if little damage was observed in the previous fall. Durum wheat and barley are not as susceptible to stem lodging as is the bread wheat class, thereby masking stem cutting damage caused by larval activity. Lodging susceptibility is largely a function of straw strength and composition (J. Clarke, personal communication).

The risk to crop harvests of using cereal trap crops is high because infestations as low as 10 - 15% in one year can lead to rates as high as 80% in the following year (Farstad *et al.* 1945; Holmes 1982). Non-cereal trap crops provide the best alternative cropping strategy. Opting out of growing wheat for two years was recommended but considered drastic in the 1920's through the 1940's when few cropping alternatives existed (Criddle 1923; Farstad *et al.* 1945). Recent cropping systems research in the Canadian prairies has shown the benefit of rotational diversity. A rotation of canola (*Brassica napus* L. (Brassicaceae)), wheat, and field pea (*Pisum sativum* L. (Fabaceae)) optimized production of all three rotational phases in Saskatchewan (Brandt *et al.* 2008); and, compared to continuous wheat, grain protein and yield of wheat improved following pulse (Fabaceae) crops (Miller *et al.* 2002). It should be noted that these studies were agronomic and did not attempt to determine wheat stem sawfly infestation during the wheat phase of the rotation.

Wheat row spacing and seeding rates can influence *C. cinctus* infestation rates, and the response varies between solid- and hollow-stemmed cultivars. Luginbill and McNeal (1958) reported that narrow row spacing and high seeding rates reduced stem cutting in 'Thatcher', a hollow-stemmed cultivar, but the same treatments reduced pith expression and led to increased stem cutting damage in 'Rescue', a solid-stemmed cultivar. Wider row spacing and lower plant densities may create more opportunity for light to penetrate the canopy, which could lead to greater pith expression, and a resultant increase in water soluble carbohydrates and drought tolerance (Saint Pierre *et al.* 2010). For hollow-stemmed cultivars, high seeding rates and narrow row spacing resulted in lower whole-plant moisture, which is less attractive to ovipositing females than plants with higher moisture content (Luginbill and McNeal 1958). Similar results for the interaction of seeding rate and pith expression were observed in a study in Syria, but effects from row spacing were inconsistent (Miller *et al.* 1993). Faris and DePauw (1981) observed optimum seeding rates as high as 675 seeds m^{-2} for cultivars with high yield potential, whereas check cultivars such as 'Neepawa' did not respond to seeding rates above 300 seeds m^{-2}.

Seeding date can also influence *C. cinctus* infestations. An early recommendation was to delay seeding wheat and to plant immune crops such as oats or non-cereals first (Criddle 1922a; Farstad *et al.* 1945). Jacobson and Farstad (1952) reported that seeding after 21 May reduced high infestation levels to as low as 13%, and also resulted in significantly more males. This is likely because sawflies are haplodiploid, with the sex of the progeny determined by selective egg fertilization at the time of oviposition (Cook, 1993; Flanders, 1946). Male offspring are produced from unfertilized eggs so the male-bias sex ratio produced at later seeding dates indicates a lack of available males for mating later in the sawfly flight, which would disrupt mating habits in successive years as there would be fewer female offspring available for copulation (Holmes and Peterson 1963a). Other studies reported that consistently lower infestation levels were only realized with planting dates after 1 June, but this seriously reduced potential crop yields (McNeal *et al.* 1955; Morrill and Kushnak 1999). Therefore, a realistic approach for "safe" planting dates is for fields prone to attack to be planted last (Morrill and Kushnak 1999).

Crop nutrient management can influence *C. cinctus* infestation rates through effects on crop canopy architecture and overall plant health. Luginbill and McNeal (1954) observed that application of nitrogen and phosphorous to wheat generally resulted in an increase in stem cutting. Nitrogen applied separately did not influence stem cutting whereas a slight increase in cutting was observed when phosphorous was applied alone. In contrast, phosphorous-deficient wheat plants in a Montana greenhouse study were most susceptible to sawfly damage (Delaney *et al.* 2010). In a Saskatchewan study, no effects of nitrogen or phosphorous could be detected due to the strong influence of environmental factors (DePauw and Read 1982). Similarly, significantly more stem cutting in fertilized plots was observed in only one of eight experiments in a North Dakota study (O'Keeffe *et al.* 1960). The disparity among these study results underscores the stochastic nature of site-specific, soil-plant fertility dynamics.

Actions taken prior to harvest can reduce the severity of losses from unrecovered lodged stems at harvest. Swathing heavily infested wheat ensures that stems are collected in a windrow before stem cutting (Criddle 1915). A Montana study reported stem cutting reductions of 33 and 23% when infested wheat was swathed at 41 and 48% grain moisture, respectively, with no apparent reductions in crop value (Goosey 1999). However, the early swathing resulted in lowered grain test weight and higher protein levels, suggesting that starch formation (*i.e.*, grain filling) was incomplete. A swathing operation, however, does not usually affect sawfly survival because most larvae have migrated to the base of the plant to prepare for overwintering). Other studies have reported that swathing prior to physiological maturity (*i.e.*, > 35% kernel moisture) can reduce yield and grain weight, and swathing at > 58% kernel moisture results in severe yield losses (Molberg 1963). Early swathing of wheat may have some effect on *C. cinctus* survival, but is impractical because larval mortality was only observed when moisture of swathed grain was between 55 and 61%, and stem cutting occurred when grain moisture declined to 40% (Holmes and Peterson 1965). Holmes and Peterson (1965) noted that greater efficacy could be achieved when grain moisture is high by cutting longer stems, thus reducing stubble height , and suggested that early swathing may be appropriate if restricted to field edges or severely infested fields.

1.5 Chemical control

Several studies have investigated the efficacy of insecticidal applications to manage *C. cinctus*, but few results have been published because most have been negative. Several unpublished studies in Montana reported that systemic seed treatments of imidacloprid applied at varying rates and foliar-applied chlorpyrifos, carbofuran, and cyhalothrin-lambda had no significant effects on sawfly survivorship (Goosey 1999). A study conducted in Lethbridge, Alberta and Swift Current, Saskatchewan (Beres *et al.* unpublished) found no differences in infestation or stem cutting after application of thiamethoxam at rates of 0, 20, and 90 g a.i. per 100 g seed.

Heptachlor is the only tested insecticide that has consistently caused significant larval death. in a Montana study, 75 to 86% of sawfly larvae were killed following application of heptachlor at 20 g a.i. per 100 kg seed (Wallace 1962). A Canadian study validated these results but noted that control was usually restricted to times when larvae were active in the first two internodes and where the insecticide was more concentrated (Holmes and Peterson 1963b). A third study examined the systemic activity of heptachlor through host plant phenological stages: higher application rates resulted in trace amounts in grain but the lowest rate (20 g a.i. per 100 kg) resulted in residues in straw but not grain (Wallace and Butler 1967). Heptachlor, however, has been banned in the United States since 1988 because it is persistent in soil and has been found in crops 15 years after application (Anonymous 1999) (this chemical is also no longer registered in Canada).

Cephus cinctus spends most of its life cycle protected within host stems so it is doubtful that a pesticide can be developed that will target larvae without compromising grain safety or killing beneficial insects that attack larvae. Foliar applications to field edges (where the greatest amount of adult activity occurs) might be efficacious but would require extremely careful monitoring of adults and timing of spray applications because of the extended period of adult emergence. Sprays applied too early would likely kill only males; later applications would increase female mortality but likely after most eggs have been deposited. The tactic would also be detrimental to parasitoids because the first generation of *B. cephi* would be in flight and mainly concentrated along the field edge.

1.6 Host plant resistance

1.6.1 Gene deployment

Although two other sources exist, all solid-stemmed spring and winter wheat cultivars developed to 2010 derive resistance from the line S-615. Resistance in 'Golden Ball', a durum cultivar, is superior to, and more stable than, resistance in cultivars derived from S-615 (Platt and Farstad 1949). Resistance in tall wheatgrass, *Thinopyrum ponticum* (Podp.) Z.-W. Liu & R.-C. Wang (Poaceae), also shows promise but attempts to transfer this resistance to common wheat have failed (Platt and Farstad 1949).

Stem solidness is a qualitative trait controlled by three to four primarily recessive genes in the S-615 source (Cook *et al.* 2004; Lanning *et al.* 2006), but only a single dominant gene in Golden Ball (Platt and Farstad 1949; McKenzie 1965; Clarke *et al.* 1998). The recessive nature of the S-615 genes controlling resistance leads to inconsistent pith expression in the field (Hayat *et al.* 1995). This was acknowledged shortly after the release of Rescue (containing resistance derived from the S-615 source) when high susceptibility to stem cutting was noted at Regina, SK (Platt and Farstad 1949). It was later determined that genes conferring pith development in plant stems are influenced by photoperiod: intense sunlight results in maximum expression and pith development; shading or cloudy conditions inhibit pith development (Eckroth and McNeal 1953; Holmes 1984). The dominant gene resistance in Golden Ball results in good pith expression across a range of environmental conditions (Platt and Farstad 1949). Therefore, efforts began in the 1940's to transfer the source of resistance from Golden Ball (durum wheat) to common wheat (Platt and Larson 1944), but the genes for solidness were suppressed and only hollow-stemmed offspring were produced. This gene suppression was overcome by crossing Golden Ball with a species of goatgrass, *Aegilops* L. (Poaceae), to create a synthetic hexaploid, and then backcrossing the offspring to the hexaploid wheat cultivar, 'AC Elsa' (Clarke *et al.* 1998, 2002). Two germplasm lines were developed using this method and have been released (Clarke *et al.* 2005).

1.6.2 Cultivar development

Solid-stemmed cultivars available in 2010 in the Canada Red Western Spring class are 'AC Abbey', 'AC Eatonia', and 'Lillian' (DePauw *et al.* 1994, 2000, 2005). Solid-stemmed spring wheat cultivars available in Montana include 'Fortuna', 'Lew', and 'Choteau'. Montana historically classified the ‘Amidon’, ‘Glenman’, ‘Conan’, ‘Corbin’, and ‘Scholar’ cultivars as semi-tolerant to *C. cinctus*, but these cultivars are not favoured due to significant risk to efficacy when facing heavy sawfly pressure.

Resistance in winter wheat is also important because of a biotype of *C. cinctus* in Montana that has gradually adapted to become synchronous with winter wheat phenology by emerging 10 to 20 days earlier than normal. The adaptation seems to have occurred as a response to a shift in Montana from spring to winter wheat production (Morrill and Kushnak 1996). Solid-stemmed winter wheat cultivars available to Montana producers include ‘Vanguard’ (Carlson *et al.* 1997), ‘Rampart’, and ‘Genou’ (Bruckner *et al.* 1997, 2006).

The use of solid-stemmed cultivars helps mitigate crop losses but can also affect the survivorship of *C. cinctus*. The mechanical pressure of developing pith in solid stems can result in egg mortality and degree of mortality is influenced by cultivar. In studies of egg and larval mortality (Holmes and Peterson 1961, 1962), mortality was highest in ‘Golden Ball’ (*versus* ‘Rescue’) but not affected in hollow-stemmed cultivars and, in oats, eggs survived but all larvae died. In other work, hollow-stemmed cultivars with large stem diameters maximized sawfly fitness and solid-stemmed cultivars reduced adult female weight, size, and fecundity (Morrill *et al.* 2000; Cárcamo *et al.* 2005). Holmes and Peterson (1957) studied the long-term effects of wheat cultivar on *C. cinctus* and reported that sawfly populations restricted to the solid-stemmed cultivar ‘Rescue’ declined over a five-year period to almost zero.

Solid-stemmed cultivars generally exhibit lower grain yield and quality than hollow-stemmed cultivars. There is also a concern of additional wear on machinery because solid stems require more energy to thresh and reduce ground speed of combines (B. Buckman personal communication). Inconsistent pith expression, as influenced by photoperiod during stem elongation, has resulted in higher than expected levels of stem cutting in solid-stemmed cultivars. Beres *et al.* (2007) reported that solid-stemmed cultivars could produce grain yield and protein content levels comparable or superior to those of hollow-stemmed cultivars in an environment of moderate to high *C. cinctus* pressure. ‘Lillian’, a solid-stemmed cultivar released in Canada in 2006, has provided superior yields even in the absence of sawfly pressure. Although inconsistent pith expression (first noted with the release of ‘Rescue’) has been observed with ‘Lillian’, many producers have continued with this cultivar because *C. cinctus* pressure is currently high in Saskatchewan and Alberta (B. Beres personal observations).

1.6.3 Cultivar blends

Blending two cultivars (one hollow-, one solid-stemmed) with compatible maturity, market class attributes, and complementary strengths (Bowden *et al.* 2001) may be a feasible approach to management of wheat stem sawfly. This practice is commonly used in Kansas to achieve yield stability because abiotic and biotic stresses can be inconsistent and unpredictable. A Montana study reported that the strategy was successful at minimizing damage at low to moderate levels of sawfly pressure, but not at high levels (Weiss *et al.* 1990). Similarly, a 1:1 blend of solid-stemmed 'AC Eatonia' and hollow-stemmed 'AC Barrie' resulted in an 11% increase in yield potential in comparison to a monoculture of 'AC Barrie' in Alberta (Beres *et al.* 2009). Quality was also improved by using a blend of cultivars with contrasting protein accumulation potential (Beres *et al.* 2007).

1.7 Biological control

Nine species of Hymenoptera are known to parasitize *C. cinctus* (Morrill *et al.* 1998; Meers 2005). The shift of host preference of *C. cinctus* from native and exotic grasses to wheat was rapid, but the parasitoids have been slow to follow. Ainslie (1920) and Criddle (1923) reported parasitoids of *C. cinctus* in larvae in grass stems but not in wheat stems and only two of the nine parasitoids have been recorded in *C. cinctus* populations in wheat (Morrill *et al.* 1998).

Criddle (1923) suggested that *Bracon cephi* (Gahan), a sympatric idiobiont ectoparasitoid (Runyon *et al.* 2001), had great potential for wheat stem sawfly control because it was largely responsible for larval parasitism rates as high as 85% in grasses. Criddle (1923) speculated that the inability of parasitoids to adapt to wheat was due to tillage and harvest practices and, in the case of *B. cephi*, because of its bivoltine life cycle. Emergence of the first generation of *B. cephi* and of sawfly adults is approximately synchronous but the second generation emerges in August when early harvest and subsequent ploughing can negatively impact the parasitoids. In wheat, Criddle (1923) only observed parasitism from the first generation.

Bracon cephi eventually adapted to parasitizing sawfly larvae in wheat and has become the most important parasitoid of *C. cinctus* in Canada (Nelson and Farstad 1953) and North Dakota (Meers 2005). A female locates a host larva by traversing a stem and then, if she senses the presence of a host larva, straddling the stem with her antennae at the place where she will insert her ovipositor. The ovipositor is used to inject venom to immobilize the larva and then deposit an egg near it. Upon hatching, the parasitoid larva searches for and attaches itself to the paralyzed *C. cinctus* larva and immediately begins feeding. The host is consumed in approximately 10 days at which point the fully developed parasitoid larva spins a cylindrical cocoon where it pupates and enters diapause. Adults of the second generation emerge in August by chewing a circular hole through the stem (Nelson and Farstad 1953).

Parasitism of wheat stem sawfly larvae by the first generation can significantly reduce further yield loss (Buteler *et al.* 2008), although host stem size preferences of adult female sawflies complicates the assessment, just as it does for yield losses. Successful parasitism by the second generation is dependent on crop maturity and the timing of host larva overwintering preparations (Holmes *et al.* 1963). If wheat crops are delayed and maturity is not reached until mid-August, the rates of parasitism by the second generation can be very high. If crops mature early, stems have usually toppled from cutting, and host larvae are safely housed within hibernacula before the second generation of *B. cephi* has completely emerged (Holmes *et al.* 1963). Later seeding would enhance *B. cephi* success but, in many parts of southern Alberta, seeding is now more common in April than in May. This is partially offset by the adoption of later maturing, high yielding cultivars. Success of *B. cephi* is therefore variable. Low efficacy of *B. cephi* occurs when activity of the second generation is low and when the first generation, overwintering in the upper internodes of the wheat crop, is lost during harvest and threshing (Holmes 1979).

Bracon lissogaster (Muesebeck), the second major parasitoid of *C. cinctus* in wheat, also was slow to shift to sawfly populations in wheat but is now active in Montana and North Dakota (Meers 2005) and was recently found in southern Alberta (Cárcamo *et al.*, unpublished). Its life cycle is similar to *B. cephi* but it can more readily complete a second generation in late fall, which is attributed to immediate oviposition by adult females after they emerge (Somsen and Luginbill 1956). The second generations of *B. cephi* and *B. lissogaster* are also less likely to be cannibalized by *C. cinctus* larvae than are the first generations. First generation females of both species will often oviposit in stems containing multiple *C. cinctus* eggs. This can result in a significant reduction in parasitism rates because of cannibalism of parasitized larvae by other *C. cinctus* larvae (Weaver *et al.* 2005).

A predatory beetle, *Phyllobaenus dubius* (Wolcott) (Coleoptera: Cleridae), attacks larvae of *C. cinctus* (Beres *et al.* 2009; Morrill *et al.* 2001a). The life history and biology of *P. dubius* has not been detailed but its geographic range could be extensive (Meers 2005). Clerid beetles are most often associated with forest ecosystems but eighteen species have now been recorded in prairie ecosystems (Mawdsley 2002). Most prairie clerids have annual life cycles with adult emergence, mating, and oviposition in spring or early summer, larval development in the summer, and pupation in either fall or spring (Mawdsley 2002). Most clerids are prey generalists, but some may be more specialized (Mawdsley 2002). *Phyllobaenus dubius* is small (4.5 to 5.0 mm long) and adults and larvae can forage within wheat stems. *Phyllobaenus dubius* was first observed in large numbers in wheat stem sawfly-infested fields in 1997; the beetle larvae were overwintering in wheat stubs in cocoons along with cadavers of larval *C. cinctus* (Morrill *et al.* 2001a). Most aspects of *P. dubius* biology, as well as its potential for controlling *C. cinctus* populations, remain unknown.

Crop management practices can significantly influence the abundance and efficacy of *C. cinctus* parasitoids. Reduced tillage resulted in higher rates of parasitism and less stem cutting than in adjacent fields that were aggressively tilled (Runyon *et al.* 2002). The use of solid-stemmed cultivars in zero tillage cropping systems conserved parasitoids and reduced sawfly populations (Weaver *et al.* 2004).

Conservation of parasitoids can also be accomplished by increasing stubble height at harvest and by restricting insecticide use during peak flight periods of the adult parasitoids (Meers 2005; Chapter 4).

Introduction of foreign biocontrol agents can improve the efficacy of biological control. *Collyria calcitrator* (Gravenhorst) (Hymenoptera: Ichneumonidae), a parasitoid of European wheat stem sawfly, *Cephus pygmaeus* L., was the first biological control agent released to manage *C. cinctus* in North America. However, establishment attempts in Saskatchewan (Smith 1931), Montana, and North Dakota (Davis 1955) were unsuccessful. Specimens of *Collyria coxator* (Villers), another parasitoid of *C. pygmaeus*, were collected in England and a population has become established in eastern North America (Shanower and Hoelmer 2004). Exploration in China identified *Collyria catoptran* (Wahl) as a potential candidate for introduction to North America (Shanower and Hoelmer 2004; Wahl *et al.* 2007). Evaluation of this species is underway to determine its suitability as a potential biocontrol agent of *C. cinctus.*

Pathogens can be used as biocontrol agents to manage insect pests (Lacey *et al.* 2001) and studies of pathogens and their efficacy for the control of *C. cinctus* have reported some success (Piesik *et al.* 2009 Wenda-Piesik *et al.* 2006, 2009). Many pathogens, however, seem to occur as secondary parasites of dead larvae and, therefore, lack potential as agents for the biological control of *C. cinctus*.

1.8 Pheromone monitoring and host plant semiochemicals

The effectiveness of trap cropping or border management for control of *C. cinctus* could be enhanced through the development of sawfly attractants (Hardin 2001). Research into the pheromone components of wheat stem sawfly is a complex task because the primary compounds are present but variable in both sexes and host volatiles and other factors are also involved (Hardin 2001). Cossé *et al.* (2002) and Bartelt *et al.* (2002) were the first to describe pheromones of *C. cinctus*: most compounds identified were present in both genders but the quantity differed significantly between males and females. For example, males produced three times the amount of 9-acetyloxynonanal found in females (and males in groups produced significant quantities of phenylacetic acid) whereas hexadecanal was the primary compound in females (Cossé *et al.* 2002).

Cossé *et al*. (2002) used coupled gas chromatographic-electroantennographic detection (GC-EAD) to study the effects of pheromone components on the behaviour of adult *C. cinctus*. They also conducted field assays to determine if 9-acetyloxynonanal could be used as a female attractant in traps. Trap catch was dose-dependent and there was no significant difference in the sex ratio of trapped individuals (Cossé *et al.* 2002). Bartelt *et al*. (2002) noted the complexity of the *C. cinctus* pheromone system and that it may be influenced greatly by field behaviour and is driven by natural oxidation of cuticular waxes. Future research could benefit from a focus on collecting a female-specific chemical signal that is driven by the various environmental factors (Cossé *et al.* 2002).

Semiochemical-based pest management could influence oviposition behaviour of *C. cinctus* if a bait and trap can be developed that would attract and capture females prior to oviposition. Rather than using a synthetic male-produced pheromone, the synthesis and use of a plant host volatile naturally attractive to ovipositing females could be effective. Studies have been successful in discriminating synthetic wheat volatiles that elicit responses from individual female *C. cinctus* (Piesik *et al.* 2008). In a comparison of the emission of the behaviourally-active host volatile, (*Z*)-3-hexenyl acetate, between 'Reeder', a hollow-stemmed cultivar, and 'Conan', a solid-stemmed cultivar, and its attractiveness to female *C. cinctus*, Weaver *et al.* (2009) noted greater emission by, and greater attractiveness to, 'Reeder'. This host preference could be exploited in a trap cropping strategy (Weaver *et al.* 2009). Subsequent research using RILs from the two parent varieties has identified the quantitative trait loci in wheat that are associated with preference (Sherman *et al.* 2010). Efforts are now underway to develop markers to aid in breeding efforts.

1.9 Future research needs

Although wheat stem sawfly currently has regained outbreak status in many parts of the northern Great Plains, resources to study the pest are limited. In Canada, maintenance breeding is all that officially remains of a major research effort to manage this pest and illustrates the tendency to rely upon a single strategy to address an insect pest problem. A holistic approach involving multiple institutes representing several disciplines of research would be preferable (Anderson 2005, 2008).

Cultural methods will remain critical for managing wheat stem sawfly (Weaver *et al.* 2004). Our review underscores the need to encourage producers to adopt practices that reduce sawfly infestations and enhance beneficial insect populations (Weaver *et al.* 2004). Integrated approaches are lacking, and too often the adoption of a 'resistant' variety is assumed to solve the problem in a single growing season. Moreover, solid-stemmed cultivars are only available in the bread wheat class in Canada. Five other classes of wheat are grown within the geographical range of *C. cinctus,* and there is currently a trend to reduce production of bread wheat in favour of general purpose markets such as the ethanol feedstock market. Furthermore, the entire production area for durum wheat lies within the geographic range of *C. cinctus*, and durum wheat production is also expected to increase and displace bread wheat. Breeding objectives should be expanded so that solid-stemmed durum, soft white spring wheat, and winter wheat cultivars are available. Pheromone- and semiochemical-based research, and plant breeding efforts should be merged as there may be opportunity to develop cultivars with specific volatile emissions that attract or repel female *C. cinctus* (Weaver *et al.* 2009). Research is also needed to evaluate the use of cultivar blends, or combinations of solid- and hollow-stemmed wheat that can be seeded strategically in a field based on predicted patterns of infestation. Thus, cultivar selection should be considered a management tool that provides the foundation on which an integrated pest management (IPM) strategy is built, and which contributes to the higher goal of optimizing an integrated crop management (ICM) strategy.

What are some considerations for the development of IPM and ICM strategies for the wheat stem sawfly? Unlike other serious cereal pests such as orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), or the clear-winged grasshopper, *Camnula pellucida* (Scudder) (Orthoptera: Acrididae), insecticidal control has proven ineffective for wheat stem sawfly control. Therefore, successful management requires greater complexity. The appropriate selection of cultivars prior to seeding can have positive effects throughout the growing season if that cultivar is managed properly. Not only should market opportunities or abiotic/biotic pressure influence selection, but so should the enhancement of beneficial insects. For example, cultivars or even classes of cereals that require more growing degree-days (Blake *et al.* 2007) should be favoured because this allows completion of the second generation of *B. cephi* or *B. lissogaster*, which has long term benefits on population dynamics (Holmes *et al.* 1963) and potential immediate impacts (Buteler *et al.* 2008). An additional advantage is that the later-maturing cultivars recently released also have higher yield potential because there is usually a positive correlation between yield and time to maturity (Blake *et al.* 2007). However, the risks of early frost and reduced yield from delayed seeding often outweigh the benefit derived from reduced *C. cinctus* infestation; an effective compromise might be early-seeded, long season cultivars. Target densities of plant populations must vary with cultivar selection. Solid-stemmed wheat varieties are more efficacious at lower densities (Luginbill and McNeal 1958), but higher densities of hollow-stemmed wheat may increase grain yield, reduce infestation of *C. cinctus*, and decrease the competitive ability of weeds. Cultivar development and genetic gain has advanced considerably in recent decades and a review of seeding rates for modern hollow- and solid-stemmed cultivars is warranted. Thus, research is needed to better define target plant populations so that an appropriate balance between yield potential, wheat stem sawfly management, and overall crop competitiveness is achieved.

The inconsistency in pith development, the trait that confers ‘resistance’ in solid-stemmed cultivars, should not dissuade producers from growing solid-stemmed cultivars in areas prone to attack as cultivar selection is key to a successful IPM strategy for wheat stem sawfly. The efficacy of solid-stemmed wheat could be enhanced if precipitation-related parameters could be modeled to predict the in-season tolerance level of solid-stemmed wheat cultivars to wheat stem sawfly. A model that can accurately predict pith expression could serve as a vital quality assurance tool to prevent losses by alerting producers if in-season precipitation patterns have caused less than ideal pith expression in a solid-stemmed cultivar. Such a tool would allow for preventative measures to be deployed such as swathing ahead of harvest to prevent the loss of cut stems (Chapter 4).

Plant nutritional requirements can change as seeding rates are modified, and may deviate from traditional requirements where fertilizer response rates are known, but more research is needed to investigate this relationship. The inconsistent results from studies of macronutrients and lack of information regarding micronutrients warrant further investigation. For example, recently there has been emphasis on the potential benefit of micronutrient fertilizer, but little is known about benefits to a solid-stemmed wheat system. Fertilizer management and plant density can dramatically alter crop canopy architecture, which warrants the integrated study of multiple factors to better predict effects on pests in modern cropping systems (Anderson 2005; Dosdall *et al.* 1999).

The effects of crop residue management prior to seeding, or residue alteration from seeding operations are either unknown or generally considered to be ineffective (Runyon *et al.* 2002; Weiss *et al.* 1987), particularly if soil is not completely removed from root crowns (Goosey 1999). These conclusions were drawn from studies that did not incorporate residue management and direct seeding systems typical of modern farming operations. However, the shift toward zero tillage, direct seeding systems, and continuous cropping requires that an alternative to tillage be developed as a sustainable tool for the management of *C. cinctus*. A wheat-fallow cropping system still exists in many parts of the *C. cinctus* distribution area (Weaver *et al.* 2004), and financial pressure from increased input costs has resulted in shifting of some continuously cropped hectarage back to crop-fallow.

Low disturbance seeding systems and fallowing of infested wheat fields should enhance overwintering populations, but to what degree? Would a better strategy be to re-crop infested wheat stubble and fallow another crop phase instead? If the proper cultivar or combination of cultivars is selected and appropriately managed there is greater opportunity to lessen the impact of harvest operations on beneficial insects because cutting heights may be increased in response to lower rates of stem cutting. Future studies should validate this approach and determine the effect of chopping straw residue at harvest as opposed to windrowing intact stems for subsequent use as livestock bedding or bioprocessing.

Furthermore, there is also a need to couple agronomics with biocontrol release programs. When agronomic and biocontrol strategies are employed together in an ICM system, the incremental benefits of each approach may have an overall additive effect that reduces wheat stem sawfly populations, and would contribute to a sustainable crop production system. Rather than eradication of *C. cinctus*, the management goal should be achievement of a level of co-existence that optimizes crop productivity and maintains the abundance of natural enemies.

1.10 Summary

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), is historically one of the most important economic insect pests in the northern Great Plains of North America. Within this geographical region the areas subjected to greatest attack are southern Alberta and Saskatchewan, southwestern Manitoba, eastern and northern Montana, North Dakota, northern South Dakota, and western Minnesota. Cumulative grain yield losses and annual economic losses associated with this pest can exceed 30% and $350 million, respectively. Solid-stemmed cultivars of wheat, *Triticum aestivum* L. (Poaceae) tolerant of infestation are critical for *C. cinctus* management, but outbreaks of this pest continue to occur even after six decades of cultivar development. Furthermore, chemical control (a primary control option for other cereal (Poaceae) insect pests) has proven ineffective and underscores the need to integrate resistant cultivars into a comprehensive integrated pest management program. We provide overviews of wheat stem sawfly biology, recent advancements in applied research, the efficacy and integration of cultural and biological management strategies, and future directions for global research activities to manage wheat stem sawfly.

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1.13 How the PhD arose

I have been employed with Agriculture and Agri-Food Canada fulltime since 1993. In 2000, I was promoted to a Biologist position and directed to initiate agronomy projects in support of sustainable crop production systems. I had already been extensively involved in wheat development, so the resurgence of the wheat stem sawfly in 2000 presented an opportunity to develop an agronomic package for sustainable wheat production in areas prone to wheat stem sawfly attack. Leading up to the studies that comprise the PhD thesis, studies were completed and published that related to the reestablishment of a sawfly nursery (1), quantification of sawfly damage (2), and an evaluation of alternative planting strategies (3).

1. Beres, B.L., H.A. Cárcamo, and J.R. Byers. 2005. The wheat stem sawfly: a nursery tale from the short grass prairie. [Online]. Available by Biological Survey of Canada (Terrestrial Arthropods) http://www.biology.ualberta.ca/bsc/grasslandarticles/wheatstemsawfly.pdf (verified 21 September 2010).
2. Beres, B.L., Cárcamo, H.A., and Byers, J.R. 2007. Effect of wheat stem sawfly damage on yield and quality of selected Canadian spring wheat. Journal of Economic Entomology 100: 79-87.
3. Beres, B.L., Cárcamo, H.A., and Bremer, E. 2009. Evaluation of alternative planting strategies to reduce wheat stem sawfly (Hymenoptera: Cephidae) damage to spring wheat in the Northern Great Plains. Journal of Economic Entomology 102: 2137-2145.

Additional questions arose from the results of these studies and from the challenges that producers expressed at grower meetings. I was also keen to further develop my skills set in agronomy, plant science, entomology, and statistics, which I felt were necessary to be an effective scientist and to publish high quality research articles. This led directly to the PhD research presented in this thesis.

1.14 Contributions to the thesis.

Brian Beres planned, supervised, and assisted in all research activities, performed all data analyses, and was the primary author of the manuscripts.

Dr. Dean Spaner assisted in planning the experiments, gave advice and suggestions throughout the project, contributed towards editing and revising the manuscript, and facilitated all research.

Dr. Lloyd Dosdall mentored me through an independent reading course on arthropods, gave advice and suggestions throughout the project, and contributed towards editing and revising the manuscripts for Chapters 1, 2, 3, and 5.

Dr. Maya Evenden gave advice and suggestions throughout the project, and contributed towards editing and revising the manuscripts for Chapters 2, 3, and 5.

Dr. Rong-Cai Yang mentored me through a statistics course, gave advice and suggestions throughout the project, and contributed towards editing and revising the manuscripts for Chapters 2 through 5.

Dr. Ross McKenzie mentored me through a soil science course, participated in research activities related to the study described in Chapter 3, and contributed towards editing and revising the manuscript for Chapter 3.

Dr. Héctor Cárcamo participated in research activities related to all data chapters and towards editing and revising all manuscripts.

Mr. Toby Entz provided statistical guidance, advice and mentorship for the data analyses related to all data chapters.

Dr. David Weaver contributed towards editing and revising the manuscripts for Chapters 1 and 5.

1.15 Hypotheses and objectives of thesis

The overall hypothesis of this thesis was to determine if modifications to the agronomic components of an IPM system could contribute to the mitigation of damage caused by the wheat stem sawfly.

The specific objectives of the present thesis research were to:

1. To determine if residue management and recropping infested wheat stubble would inhibit WSS emergence
2. Develop an integrated nutrient and planting strategy specific to solid-stemmed spring wheat using modern farming techniques.
3. To determine if changes to cultivar selection and sowing density would alter WSS infestation patterns.
4. Quantify responses by WSS endemic parasitoids to variety, stubble height and straw management at harvest.

The underlying null hypotheses tested were:

1. The implements used in modern direct-seeded, continuously cropped systems would not affect WSS populations.
2. Physiological crop changes to pith in the culm of wheat will not occur with increasing planting densities and nitrogen rates.
3. Tolerance to WSS infestation is not modulated with changes to planting density regime.
4. Post-emergent applications of micronutrient blends will not influence pith expression in solid-stemmed wheat.
5. The response of hollow- and solid-stemmed cultivars to sowing density will not differ and not affect WSS infestation patterns.
6. Harvesting methods will not affect overwintering populations of WSS endemic parasitoids.

2.0 Do interactions between residue management and direct seeding system affect wheat stem sawfly and grain yield?[2]

2.1 Introduction

In the southern prairies of Canada, Montana, North and South Dakota, and western Minnesota, one of the most economically important insect pests of wheat (*Triticum aestivum* L.) is the wheat stem sawfly (WSS), *Cephus cinctus* Norton (Hymenoptera: Cephidae) (Beres et al., 2007; Weiss and Morrill, 1992). The wheat stem sawfly has been a serious pest of wheat since widespread production of the crop began in the late 19th century (Comstock, 1889). A comprehensive review of wheat stem sawfly biology and management can be found in Beres et al. (2011a; Chapter 1). Adults emerge from the previous year's crop stubble in late spring through early summer and, following mating, the female seeks out a suitable oviposition host plant, which is usually in an adjacent wheat field (Criddle, 1922a). A healthy female can carry up to 50 eggs, therefore, the population can increase exponentially in a single generation (Ainslie, 1920). By the sixth or seventh day after an egg is deposited into a wheat stem, a larva will hatch and begin to bore the culm of the stem (Criddle, 1923). This activity continues throughout the growing season up to physiological maturity of the plant. Chlorosis associated with plant ripening and the reduction of whole plant moisture cues the larva to begin preparation to overwinter (Holmes, 1979). The larva moves to the base of the stem, notches a v-shaped groove around the stem, fills the region with frass (excrement), and encases itself in a thin cocoon below the groove. The groove weakens the stem and causes it to easily topple to the ground, which proves difficult to recover at harvest (Ainslie, 1929). The injury caused by the stem boring reduces photosynthetic rates (Macedo et al., 2007) and results in losses of spike weight that range from 10 to 17% (Holmes, 1977; Morrill et al., 1992; Seamans et al., 1944). An additional loss in yield potential occurs when toppled stems are not recovered at harvest (Ainslie, 1920; Beres et al., 2007). Thus, overall yield potential in wheat infested by WSS can be reduced by >25% or more, and the loss of anchored residue results in greater vulnerability to soil erosion and lower snow retention potential.

In addition to the use of cultivars with solid stems that better tolerate the stem boring activity of the sawfly larvae, seeding and cultivation strategies used in wheat production can impact insect pest populations (Chapter 5; Beres et al., 2011b; Morrill et al., 1993; Weaver et al., 2004). Tillage was one of the first control methods advocated to manage WSS populations. Criddle (1922b) recommended that infested stubble be turned over and sealed using a mould-board plough, preferably in fall so that pathogens attacking the rotting stubble would also invade the overwintering larvae. Although considered

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[2] *This chapter has been published in:* B. L. Beres, H.A. Cárcamo, L.M. Dosdall, M.L. Evenden, R.C. Yang, and D.M. Spaner. 2011. Do interactions between residue management and direct seeding affect wheat stems sawfly and grain yield? Agronomy Journal 103: 1635-1644.

effective, ploughing did not kill all sawflies (Ainslie, 1920), and it destroyed beneficial insects that attack WSS (Runyon et al., 2002). The plough was eventually replaced with low disturbance implements such as the Noble blade (Mathews, 1945), and concomitant with large blocks of fallow, the change in farming practice likely enhanced WSS populations (McGinnis, 1950; Weaver et al., 2004). Other studies that investigate tillage as a management tool for WSS report that burial of stubs is not necessary, but removal of soil from the crown is necessary so that overwintering stubs are exposed to lethal temperatures (Holmes and Farstad, 1956). Similar numbers of larvae emerge from tillage operations that do not remove soil from the crown compared to undisturbed stubble (Goosey, 1999). Morrill et al. (1993) reported that WSS mortality in shallow-tilled fields was 90% and 10% in fields that were left undisturbed.

Biological tilling can also reduce WSS overwintering success. In a Montana study (Hatfield et al., 2007), sheep were grazed in fields of winter wheat stubble that had been infested with WSS. Compared to the control or mechanical tillage, mortality of WSS was greatest in plots that had been grazed by sheep. The effects of trampling caused by the foraging activity of sheep also increased WSS mortality. This method may have promise in areas with a crop-livestock interface, but further study is required to determine impacts to soil health from extensive grazing and trampling.

The timing of tillage operations may also be an important factor in reducing WSS populations. Holmes and Farstad (1956) recommended late spring operations in place of fall or early spring as larvae entering the pupal stage of development in late spring cannot return to diapause. However, there is disagreement over the efficacy of tillage as a management tool (Weiss et al., 1987), and concern that tillage negatively impacts soil health, which creates an incongruity between conventional tillage and modern conservation farming systems.

Traditionally, producers adopted systems of frequent summer fallow, monoculture cereal production, and intensive mechanical tillage (Zentner et al., 2002). The utility of conventional tillage diminished with the innovation of non-residual herbicides such as glyphosate for weed control. The benefits of minimum or no-till systems have been reported extensively (Janosky et al., 2002; Lindwall and Anderson, 1981); and Derksen et al. (2002) suggested that the conventional wheat-fallow system in the northern Great Plains could be modified with diversified cropping systems. Benefits of minimum tillage, no–till and direct seeding practices include increased soil moisture retention, improved residue preservation and reduced soil erosion (Larney et al., 1994; Peterson et al., 1996; Roget et al., 1987). Lower prices for cereal grains, improvements in equipment and machinery design, influence of government policy, and concern for environmental sustainability of intensive tillage also contributed to the shift in land use (Zentner et al., 2002). The result was a significant reduction in the area left fallow each year across the Canadian prairies (Fig. 2-1a) (Anonymous, 2009) and in Montana and North Dakota, USA (Fig. 2-1b) (Anonymous, 2007).

Despite the adoption of conservation farming, there is still a sizeable area fallowed in semi-arid regions of the northern Great Plains. Of the approximate 5,000,000 hectares of land fallowed each year in Canada and Montana (Fig. 2-1), a portion is due to weather-related factors that prevent timely sowing of spring annual crops; however, the remaining portion is by design and part of cropping systems that integrate summer fallow phases, which tend to be concentrated in the semi-arid regions prone to wheat stem sawfly attack. Furthermore, the replacement of narrow strips alternating wheat and fallow with large blocks of wheat-fallow may enhance the ability of the WSS to persist from year to year (Weaver et al., 2004). A better understanding of the impact that modern seeding systems have upon WSS populations is required. As an alternative to wheat-fallow systems and conventional tillage to manage WSS, our objective was to determine if residue management and recropping infested wheat stubble would inhibit WSS emergence and to test the hypothesis that the implements used in modern direct-seeded, continuously cropped systems would affect wheat stem sawfly populations.

2.2 Materials and methods

A location in the traditional distribution area of the wheat stem sawfly was selected at Coalhurst, near Lethbridge, Alberta, Canada (49º 44' N, 112º 57' W). The site is an Orthic Dark Brown Chernozem clay loam soil (Typic Boroll) with 27% sand, 32% silt, 41% clay with 3.9% organic matter content and a pH of 7.5. The site was established in the early 1960's as a nursery to conduct field evaluations requiring wheat stem sawfly infestation (Beres et al., 2005; Peterson et al., 1968). The site is managed with alternating 9.3 m wide x 325 m long strips of spring planted wheat and summer fallow (chemical). Soil nutrient status was determined from soil samples collected in fall and submitted to a commercial soil testing laboratory. Nitrogen and P_2O_5 fertilizer was applied mid-row or side-banded at seeding according to recommended rates for dryland wheat production (Beres et al., 2008; Selles et al., 2006). Separate experiments were established on the spring wheat stubble each fall using the winter wheat (*Triticum aestivum* L.) cultivars 'AC Bellatrix' (2003, 2004) or 'AC Radiant' (2005), and in spring using the hard red spring wheat cultivar 'AC Barrie' (McCaig et al., 1996). Susceptible cultivars (hollow stem) were used to maintain a robust population of sawflies in the nursery and to avoid any confounding negative effects that a solid-stemmed wheat crop might have on the sawfly population. A new strip of spring wheat stubble that was infested the previous growing season with wheat stem sawfly was selected for each year of the study for a period of 3 years (2003-04; 2004-05; 2005-06). The year in which crop insects were collected and crops were harvested is used to designate the study year; for example, winter wheat sown in the fall of 2003 is assigned the experimental year 2004.

A split-plot, 5x5 factorial, arranged in a randomized complete block experimental design was used each year. To study effects of residue management, five pre-seed harrow treatments were assigned to the main plot, which consisted of a 1) heavy tine harrow (Rite Way Manufacturing, Regina, SK, Canada) with light spring tension - 20^o tine angle (Fig. 2-2a), 2) heavy tine harrow with high spring tension - 5^o tine angle (Fig. 2-2a), 3) a rotary drum harrow (Phoenix rotary harrow, Excel Industries LLC, Waseca, MN, USA) with low angle (25^o) setting (Fig. 2-2b), 4) rotary drum harrow with high angle (45^o) setting (Fig. 2-2b); and 5) a control – 'no pre-seed harrowing'). The five levels of direct seeding system treatments to recrop the infested spring wheat stubble were assigned to the subplot and consisted of a commercial zero tillage air drill configured with knife-type openers spaced 23 cm (1) or 30 cm (2) apart; a commercial zero tillage air drill configured with high disturbance shovel-type sweep openers spaced 23 cm apart (3); a low disturbance plot seeder equipped zero tillage disc-type openers spaced 20 cm apart (4); and a control of 'no seeding – chemical fallow' (5). The commercial zero tillage air drills were manufactured by Vale Farms (Conserva Pak Models CP 129A and CP1212A, Indian Head, SK, Canada) and equipped with a Valmar air delivery system (Valmar Airflo Inc., Elie, MB, Canada). The low disturbance plot seeder was manufactured by Fabro Manufacturing (Swift Current, SK, Canada) using John Deere MaxEmerge™ (Moline, Illinois, USA) disc openers and a Flexi-Coil air manifold product delivery system (CNH, Saskatoon, SK, Canada). The pre-seed harrowing and direct seeding treatments were performed at a perpendicular angle to the direction of the wheat stubble rows infested with wheat stem sawfly. Treatment combinations were replicated three times with subplot experimental unit dimensions 3.3 m wide x 10 m long. Each study area was treated with glyphosate (RoundUp®, Monsanto, St. Louis, MO, USA) a few days prior to seeding applied at a rate of 900 g a.i. ha^{-1} using a motorized sprayer calibrated to deliver a carrier volume of 45 L water ha^{-1} at 275 kPa pressure.

Shortly after the spring wheat experiment was sown, a 1 m x 1 m triangular emergence cage (Dosdall et al., 1996) was placed near the center of each subplot for both winter and spring wheat experiments. The primary collection device consisted of a 700 mL glass jar with a funnel-shaped, amber lumite 530 micron mesh screen (BioQuip Products, Rancho Dominquez, CA, USA) inserted into the jar and secured by a ring-lid. The jar was inverted and placed through a circular opening on top of the cage cut wide enough to accommodate the outside diameter of the ring-lid. Sticky cards (Contech Inc, Delta, B. C. Product No. 611 – bright yellow) measuring 7.6 cm x 12.7 cm were mounted on wooden stakes and placed inside the emergence cage to act as a secondary trap. To encourage movement into the collection devices, plant growth inside the cage was terminated with an application of glyphosate. Three times weekly, from 21 June to 26 July, newly eclosed adults emerging from the previous crop stubble were collected from the cage jars and sticky cards. Specimens of WSS were grouped by gender and separated from the wheat stem sawfly parasitoid, *Bracon cephi* (Gahan) (Hymenoptera: Braconidae). Prior to crop harvest, the emergence cages were removed and at crop maturity, a 1.5 m wide strip running the length of the plot was harvested from each subplot with a Wintersteiger Expert (Wintersteiger AG, Salt Lake City, UT, USA) plot combine equipped with a straight cut header, pickup reel and crop lifters.

Data were analyzed with the PROC MIXED procedure of SAS (Littell et al., 2006). Count data for insects were subjected to log transformations [$\log_{10}(x+1)$] to stabilize variances among treatments (Steel et al., 1997). Homogeneity of error variances was tested and any outlier observations were removed before a combined analysis over years was performed. For the combined analysis of data over the three years of the study, the model was:

$Y = \mu$ + year + replicate(year) + harrow + replicate(year) x harrow + seeding system + year x harrow + year x seeding system + harrow x seeding system + year x harrow x seeding system + ε.

Where ‘μ’ is the overall expected response, ‘harrow’ refers to the main plot pre-seed harrowing treatments, ‘seeding system’ refers to the seed drill treatments used to recrop the infested wheat stubble, and ‘ε’ refers to the residual error variance not accounted for in the model. For analyses of both raw and transformed data, the effects of replicate, year, and interactions of replicate, year and the main plot ‘harrow’ were considered random; treatment effects were considered fixed and significant if $P \leq 0.05$. Year was considered a random effect in order to remove the variability among years from the residual error and to get the average treatment effects over the three years where wheat stem sawfly pressure was rated moderate to high (Fig. 3). Mean separation tests were performed using a Fisher’s protected LSD (Steel et al., 1997). Pearson correlation coefficients were calculated between wheat stem sawfly emergence and grain yield in both spring wheat and the winter wheat systems using the PROC CORR procedure of SAS (Littell et al., 2006).

A grouping methodology, as described by Francis and Kannenberg (1978), and later adapted to agronomy studies (Beres et al., 2010; Gan et al., 2009; May et al., 2010), was used to further explore treatment responses. The mean and coefficient of variation (CV) were estimated for each level of the treatment and plotted. The overall mean of the treatment means and CVs was included in the plot to categorize the biplot ordination area into four quadrats/categories: Group I: High mean, low variability (optimal); Group II: High mean, high variability; Group III: Low mean, high variability (poor); and Group IV: Low mean, low variability.

2.3 Results and discussion

Populations of wheat stem sawfly during the study period were moderate to severe. The range of individuals emerging was 22 to 45 adults m^{-2} in the spring wheat and 36 to 65 adults m^{-2} in the winter wheat experiments; both were planted on spring wheat stubble. This translates to a range of 220,000 to 640,000 individuals ha^{-1}. The emergence of adults was greatest in 2005, which peaked in the first week of July (Fig. 2-3a). Emergence peaked one week later in 2004 and a week earlier in 2006 despite a later sowing date. However, using growing degree day (GDD) accumulation from 1 May of each year collected at the Agriculture and Agri-Food Canada meteorlogical site in Lethbridge, Alberta (Tbase=5° C), the peak emergence for all three years appears similar and within a range of 17 growing degree days (578-595 GDD) (Fig. 2-3b). The fit of the emergence data to a relatively precise GDD accumulation requirement suggests that pheromone trapping in conjunction with targeted pesticide applications may have more potential than previously thought. The selection of the 5° C base temperature matches well with a 4.6° C GDD base for spring wheat development in the semi-arid prairie (Davidson and Campbell, 1983) and with an overwintering wheat stem sawfly threshold of approximately 4° C derived from data in Perez-Mendoza and Weaver (2006) (M. Buteler and D. Weaver personal communication). The first two years also had similar populations, but the flight period in 2006 was shorter, peaked earlier (28 June), and ended abruptly with lower overall adults. This may be due to increasing numbers of parasitoids and insect-host asynchrony effects from below average rainfall during 1 June to 31 July, which may have caused earlier initiation of stem elongation leading to an earlier harvest date compared to the other years of the study (Table 2-1; Fig. 2-3).

The sex ratio of this species is usually equal (McGinnis, 1950), but our collections comprised approximately three times more WSS females than males (Table 2-2). Sawflies are haplodiploid, with the sex of the progeny determined by selective egg fertilization at the time of oviposition (Cook, 1993; Flanders, 1946). Luginbill and McNeal (1958) reported that females prefer plants with large stems for oviposition, and Morrill et al. (2000) found that plants with large stems confer several fitness advantages on WSS progeny. Sex ratios of WSS are male-biased in small stems and female-biased in large stems (Cárcamo et al., 2005; Morrill et al., 2000). The wheat crops planted in our study sites in the year preceding WSS emergence collections were hollow stem plants seeded at the recommended rate and grown in soil treated with optimal fertilizer application. It is probable that these conditions favored development of vigorous plants, with large stems, and this resulted in a female-biased sex ratio of offspring. Although we cannot confirm its presence, van Wilgenburg et al. (2006) noted that the presence of *Wolbachia* bacteria could affect sex determination in the Hymenoptera.

In the spring wheat study, heavy tine harrows and the high angle setting on the rotary harrow reduced female and total WSS but had no effect on male WSS emergence (Table 2-2). A reduction in adult emergence from harrowing in the winter wheat study occurred only with the 5° (high tension) heavy harrow. Using a tine harrow with an angle setting of 5° (high tension) prior to seeding reduced WSS adult emergence by approximately 35% in both the winter wheat and spring wheat systems. Morrill et al. also reported negative impacts to WSS populations (1993) if the operation sufficiently exposed the stubble. The authors do not report the percentage of stubs uprooted onto the soil surface from harrowing or what type of harrow implement was used. However, the operation seemed to create high disturbance of the stubble as the authors recommend only harrowing field border to limit the risk of soil erosion (Morrill et al., 1993).

The seed drill factor also affected emergence patterns of WSS (Table 2-2). Irrespective of seed drill type, recropping spring wheat stubble infested with WSS reduced the adult population compared to leaving the stubble undisturbed in both the fall and spring systems. In the winter wheat system, greater reductions in sawfly emergence were observed with drills equipped with knife and sweep opener configurations spaced 23 cm apart, whereas in the spring system, the sweep and wider row spacing of the knife opener (23 cm) was more effective than the disc drill and narrow spacing of the knife opener (Table 2-2). This can be explained because the disc drill provides the least disturbance to stubble at seeding, which is highly desirable when sowing winter wheat (Fowler, 1983), and less disturbance would have the least impact on diapausing larvae of WSS.

There was a significant interaction between harrowing and seed drill in the spring wheat system (*P* < 0.049) (Table 2-3). When compared to the 'chemical fallow' or control of 'no harrowing', combinations of the other harrow and recropping treatments should decrease wheat stem sawfly emergence in order to be considered effective. After the harrowing, the heavy tine harrow set at 5^{o} tension and the 45^{o} rotary harrow had the lowest total WSS emergence, which was further reduced by 50% or more in the tine harrow main plots when using any drill configuration except the knife opener spaced 23 cm apart (Table 2-3). Reducing the tension of the tine harrow to 20^{o} diminished efficacy before recropping, but if followed by the drill configured with 30 cm knife or sweep openers, the emerging population was reduced by approximately 70%. A similar result was observed if a 25^{o} rotary harrow was used with the drill equipped with 30 cm knife openers, but no additional reductions were observed when using the 45^{o} rotary harrow. The results suggest that in a spring wheat system the most effective system for reducing WSS emergence would be to combine pre-seed heavy tine harrows with a drill configured with knife openers spaced 30 cm apart, and that higher spring tension may improve efficacy. This recommendation could be easily implemented as most air drills equipped with knife openers similar to ones used in this study are generally sold in the 30 cm row spacing configuration, and heavy tine harrows are commonly used to manage crop residue.

Previous studies reported that shallow tillage or operations involving harrows following tillage were only effective if the crown was uprooted and all soil was removed (Goosey, 1999; Holmes and Farstad, 1956; Morrill et al., 1993), which causes WSS mortality from exposure and desiccation. Modern farm systems incorporate harrowing prior to seeding to spread out trash cover to facilitate even crop stand establishment. Furthermore, because the low disturbance disc drill was sometimes as effective at reducing WSS emergence as the other drills, our results cannot be explained by crown upheaval and removal of all soil from the crown. It is possible that the treatments most effective at reducing WSS emergence damaged the anchored stubble sufficiently to kill the sawflies through exposure, or inflicted lethal effects on the pupae in spring.

Mean trap captures of the parasitoid *Bracon cephi* averaged over all years of the study were generally low and in the range of 1 to 7 specimens per m^2 (Appendices 7-1 and 7-2). This is not surprising as there is generally a lag phase before the population of a natural enemy increases in response to host populations. The practice of pre-seed residue management using the harrows selected in this study did affect *B. cephi* emergence, however, the difference was never greater than two individuals per m^2 (Appendix 7-1). The interactive effect of harrowing and recropping also affected parasitoid populations for both spring ($P < 0.048$) and winter systems ($P < 0.038$) and is summarized in Appendix 7-2. The magnitude of reduction was greater in the winter wheat system as parasitoids were more abundant, which suggests operations performed in the fall are not as detrimental to *B. cephi*. The combination of high tension heavy tine harrows and the air drill equipped with a 30 cm row spacing, which was most effective at reducing WSS emergence, reduced the parasitoid population by 1 individual per m^{-2} (Appendix 7-2). However, the overall population density of *B. cephi* could be too low in this study to draw definitive conclusions. Other studies report that aggressive tillage such as ploughing under wheat stubble significantly increases the mortality of the *C. cinctus* parasitoids *Bracon lissogaster* (Muesebeck) and *B. cephi* (Runyon et al., 2002). The methods employed in our study are not as destructive as ploughing or other aggressive forms of tillage; for example, the rotary harrow is commonly used for in-crop weed control in organic farming systems (Frick and Johnson, 2002). Thus, it is not clear if the reductions of *B. cephi* observed when harrowing or direct seeding into stubble infested with WSS interfered with parasitism patterns.

The merit of any cultural practice used to control an insect must include grain yield as a proxy for sustainability. Grain yield was affected by the seed drill factor but pre-seed harrowing did not influence grain yield in the spring or winter wheat systems (Table 2-4). For spring wheat, grain yield was optimized with the drill configured with knife openers. In fall, plots seeded with the low disturbance disc drill produced more grain than those seeded with the other drills. In another study in southern Alberta, a drill equipped with disc openers improved plant population stands in winter wheat compared to a hoe or knife opener but grain yield was unaffected (McKenzie et al., 2007). The grain yield from plots seeded with the drill equipped with sweep openers was inferior to that from plots seeded with the other drills in both fall and spring (Table 2-4). These observations make agronomic sense as low stubble disturbance is a key to successful overwintering of winter wheat. The sweep opener is an outdated configuration but was selected to create an environment of high stubble disturbance, which likely inhibited seed to soil contact in the spring system and led to greater winterkill in the fall system. The interaction of harrowing and seed drill was significant ($P < 0.041$) and explored further in the spring wheat system (Table 2-5). The combinations that consistently reduced WSS populations also optimized grain yield potential.

A biplot of the yield responses confirmed that pre-seed harrowing in combination with a drill equipped with knife openers produced high grain yield and achieved greater overall stability when planting spring wheat. However, in the winter wheat system, treatments that caused lower stubble disturbance enhanced grain yield. For example, the disc drill with or without harrowing, or the knife opener drills without any pre-seed harrowing produced high grain yield and achieved high overall stability (Fig. 2-4).

Correlation analyses of the variables grain yield and total WSS emergence showed a marginal ($P=0.06$) inverse relationship between grain yield and the total WSS that emerge from the spring wheat system (Table 2-6). However, in the winter wheat system, grain yield and WSS emergence were positively correlated ($P=0.003$) and suggest the producer must suffer a yield penalty in order to lower populations of WSS in winter wheat (Table 2-6). Therefore, the practice of recropping to manage WSS is primarily recommended in spring, but, if performed in the fall, caution should be exercised to ensure that adequate snow trap potential (STP) is maintained (>20) after fall operations if the goal is direct-seeded winter wheat ie. STP = [stubble height (cm) × stubble stems m^{-2}]/100 (Fowler, 2002). An alternative may be to perform residue management or harrow operations in the fall and direct-seed a spring annual crop into the stubble in spring.

Although we chose continuous wheat, any spring annual crop could be used when recropping infested wheat stubble. Several studies report benefits when broad leaf crops such as pulses are integrated into a semi-arid cropping system (Brandt, 1996; Miller and Holmes, 2005; Miller et al., 2002; Miller et al., 2003; Zentner et al., 2002). Other studies report a decline in winter wheat yield when fallow phases are removed, although overall system profitability is maintained or even improved (Lyon et al., 2004).

Aggressive forms of tillage for the control of an insect or weed population are no longer considered sustainable in the northern Great Plains (Larney et al., 1994). The results of our study indicate that continuous cropping may be a sustainable form of stubble disturbance as part of integrated pest management strategy for wheat stem sawfly. Many producers opt for a wheat-fallow system based on the assumptions of water conservation during the fallow phase. The challenge, therefore, is to assess the effect of continuous cropping on the economic stability of the overall system. Even though chemical fallow is less destructive to soil health than conventional tillage, the practice is not efficient at conserving water. Only 15 – 20% of soil water remains in the upper 2 m of the soil profile for use by the successive crop (Stoskopf, 1985). In the context of economic sustainability, continuous wheat is more profitable than a wheat-fallow system in a semi-arid environment in the brown soil zone of Saskatchewan (Zentner et al., 2006). Therefore, our results support other published works that suggest fallow could be eliminated, and that the benefits derived from continuous cropping include reduced pest pressure and an improvement to overall system profitability.

2.4 Conclusions

The WSS remains a key pest of hard red spring wheat, durum wheat (*Triticum turgidum* L.) and winter wheat throughout the northern Great Plains. We conducted this study to determine if the implements used in modern direct-seeded, continuously cropped systems would affect wheat stem sawfly populations. Pre-seed heavy tine harrowing treatments (residue management) reduced adult sawfly emergence but usually required a high tension setting. No-till planting into infested spring wheat stubble also lowered WSS emergence compared to leaving the field fallow. Grain yield was optimized in spring wheat with air drills equipped with narrow knife openers, and optimized in winter wheat with the low disturbance disc drill configurations. It is unclear if the stubble disturbance would negatively affect parasitism patterns of the WSS parasitoid population. The results indicate that there would be an incremental benefit of continuous cropping rather than fallowing infested wheat fields, however, the practice may only be sustainable in spring annual cropping systems as yield reductions were observed in fall treatments most effective at reducing WSS emergence. Moreover, these strategies should not be used in isolation as the reductions did not eliminate the WSS population. A systems approach is required that integrates these practices with diversified crop phases and resistant cultivars (Beres et al. 2011a). Future directions in cultural management practices should integrate multiple management strategies and include plant density, nutrient and harvest management. Continued research in the conservation of the beneficial parasitoid *B. cephi* should focus on the impacts of both preharvest and harvest management practices.

2.5 Summary

Most semi-arid regions of the northern Great Plains are prone to wheat stem sawfly (Hymenoptera: Cephidae, *Cephus cinctus* Norton) attack. As an alternative to the wheat-fallow system, our objective was to determine if continuous cropping infested wheat (*Triticum aestivum* L.) stubble would inhibit wheat stem sawfly (WSS) emergence. Adult sawfly emergence from undisturbed stubble was compared to stubble harrowed with heavy tine or rotary drum harrows prior to recropping. Adult emergence from a control of 'no recropping' was compared to direct seeding infested stubble with 1) air drills configured with knife-type openers spaced 23 or 30 cm apart, 2) an air drill configured with high disturbance shovel-type sweep openers, and 3) a low disturbance air drill equipped with disc openers. Pre-seed heavy tine harrowing reduced adult sawfly emergence but usually required a high tension setting. No-till planting into infested spring wheat stubble also lowered WSS emergence compared to leaving the field fallow. A system of heavy tine harrows and an air drill equipped with knife openers spaced 30 cm apart reduced WSS adult emergence in spring by 50 – 70%. Grain yield was optimized in spring wheat with air drills equipped with narrow knife openers; in winter wheat optimal yield was obtained with the low disturbance disc drill configurations. Our results indicate incremental benefits from continuous cropping rather than fallowing fields infested with WSS, which is a sustainable alternative to conventional tillage. A systems approach is recommended that integrates these practices with diversified non-host crop phases and resistant cultivars.

2.6 Acknowledgements

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2.7 Tables

Table 2-1. Summary of test site and agronomic practices.

Variable			
Location	Coalhurst, Alberta, Canada		
Latitude and longitude	49°44′N, 112°57′W		
Water management	Rainfed		
Crop year	2003-2004	2004-2005	2005-2006
Dates			
Residue management	27 Sept.	10 Sept.	7 Oct.
Winter wheat seeding	27 Sept.	10 Sept.	7 Oct.
Spring wheat seeding	24 April	13 April	12 May
Winter wheat harvest date	3 Sept.	8 Sept.	28 Aug.
Spring wheat harvest date	3 Sept.	8 Sept.	28 Aug.
Precipitation (mm)			
1 Sept. to 31 March (LT average = 145)	113.4	144.4	247.5
1 April to 13 May (LT average = 83)	126.2	38.6	71.0
1 June to 31 July (LT average = 107)	120.1	281.8	97.9
Total (long term average = 335)	359.7	464.8	416.4

Table 2-2. Effect of residue management and direct seeding of winter and spring wheat planted into infested spring wheat stubble on adult wheat stem sawfly (WSS) emergence near Coalhurst, Alberta, Canada 2004-06.

		Winter Wheat			**Spring Wheat**		
		No. adults m^{-2}			No. adults m^{-2}		
Factor	Treatment	Males	Females	Total WSS	Males	Females	Total WSS
Harrow (main plot)	Control-no harrow	14 a† (1.2)	38 a (3.2)	52 a (4.1)	7 (1.0)	27 a (3.1)	34 a (3.9)
	Heavy tine 20°	13 ab (1.5)	31 ab (2.5)	44 ab (3.7)	6 (1.1)	19 b (3.3)	24 b (4.3)
	Heavy tine 5°	9 b (1.1)	25 b (2.5)	35 b (3.4)	6 (0.8)	17 b (2.4)	23 b (3.0)
	Rotary harrow 25°	13 a (1.4)	33 a (3.0)	46 a (3.9)	7 (1.0)	24 a (2.6)	32 a (3.4)
	Rotary harrow 45°	14 a (1.5)	36 a (3.4)	51 a (4.6)	5 (0.7)	19 b (2.3)	25 ab (2.9)
Seed Drill (subplot)	Chemical fallow – no seeding	17 a (1.6)	48 a (3.7)	65 a (5.0)	11 a (1.4)	32 a (4.2)	45 a (5.4)
	Disc opener	14 a (1.3)	33 b (2.6)	48 b (3.4)	6 b (0.9)	18 bc (2.1)	24 bc (2.8)
	Knife opener 30 cm row spacing	10 b (1.3)	30 b (2.4)	42 bc (3.3)	4 bc (0.4)	18 c (2.0)	22 c (2.3)
	Knife opener 23 cm row spacing	11 b (1.3)	26 b (2.4)	38 c (3.3)	5 b (0.5)	20 b (2.2)	25 b (2.5)
	Sweep opener 23 cm row spacing	10 b (1.0)	26 b (2.6)	36 c (3.4)	5 c (0.7)	18 bc (2.4)	23 c (3.0)
Pr > F	Harrow (H)	0.047	0.042	0.039	0.211	0.008	0.026
	Drill (D)	<0.0001	<0.0001	<0.0001	<0.0001	0.0004	<0.0001
	H x D	0.714	0.697	0.321	0.036	0.294	0.049

† Within main effect, means within columns sharing the same letter are not significantly different (P>0.05; Fisher's Protected LSD). The numbers in parentheses are the standard error of the treatment. ANOVA and mean separation tests performed on transformed means [log10(x+1)].

Table 2-3. Mean responses summarizing the pre-seed harrowing by seed drill interaction for adult wheat stem sawfly (WSS) emergence (adults m^{-2}), collected in spring wheat planted into infested spring wheat stubble at Coalhurst, Alberta, Canada, 2004–2006.

Effect		**Harrow (Main Plot)**					
	Treatments	Control No Harrowing	Heavy Tine 20° Setting	Heavy Tine 5° Setting	Rotary Harrow 25° Setting	Rotary Harrow 45° Setting	Mean over all harrow treatments
Seed Drill (Subplot)	Chemical Fallow No recropping	54 a† (13.8)	56 a (18.3)	34 a (9.3)	45 a (9.2)	37 a (8.5)	45 a (5.4)
	Disc Opener 18 cm row spacing	29 b (5.8)	23 b (5.0)	15 b (4.5)	31 ab (9.0)	25 a (6.3)	25 bc (2.8)
	Knife Opener 30 cm row spacing	29 b (6.3)	15 d (4.5)	20 b (5.4)	23 b (4.6)	22 a (4.8)	22 c (2.3)
	Knife Opener 23 cm row spacing	35 ab (7.0)	18 bc (3.4)	27 a (6.0)	25 b (5.2)	22 a (5.0)	25 b (2.5)
	Sweep Opener 23 cm row spacing	24 b (6.0)	17 cd (5.8)	18 b (6.2)	34 ab (7.7)	24 a (7.9)	23 c (3.0)
	Mean over all seed drill treatments	34 a (3.9)	24 b (4.3)	22 b (3.0)	32 a (3.4)	25 ab (2.9)	--

† Means within columns sharing the same letter are not significantly different ($P>0.05$; Fisher's Protected LSD). The numbers in parentheses are the standard error of the treatment. ANOVA and mean separation tests performed on transformed means [log10(x+1)].

Table 2-4. Grain yield of winter wheat and spring wheat direct seeded into spring wheat stubble.

		2004-2006	
		Spring wheat	**Winter wheat**
Factor	Treatment	kg ha $^{-1}$	
Harrow (main plot)	Control-no harrow	2438 (122)	2568 (100)
	Heavy tine 20°	2482 (123)	2344 (110)
	Heavy tine 5°	2573 (115)	2342 (109)
	Rotary harrow 25°	2530 (129)	2366 (118)
	Rotary harrow 45°	2620 (123)	2468 (121)
Seed Drill (subplot)	Disc opener	2483 b† (117)	2706 a (112)
	Knife opener 30 cm row spacing	2605 ab (99)	2411 b (87)
	Knife opener 23 cm row spacing	2715 a (124)	2342 bc (94)
	Sweep opener 23 cm row spacing	2294 c (87)	2206 c (94)
Pr > F	Harrow (H)	0.487	0.804
	Drill (D)	<0.0001	<0.0001
	HxD	0.041	0.677

† In main effect, means within columns sharing the same letter are not significantly different (P>0.05; Fisher's Protected LSD). The numbers in parentheses are the standard error of the treatment.

Table 2-5. Mean responses summarizing the spring pre-seed harrowing by seed drill interaction for grain yield of spring wheat direct seeded into spring wheat stubble at Coalhurst, Alberta, Canada, 2004–2006.

Effect		**Harrow (Main Plot)**					
	Treatments	Control No Harrowing	Heavy Tine 20° Setting	Heavy Tine 5° Setting	Rotary Harrow 25° Setting	Rotary Harrow 45° Setting	Mean over all harrow treatments
Seed Drill (Subplot)	Chemical Fallow No recropping	--	--	--	--	--	--
	Disc Opener 18 cm row spacing	2532 a† (332)	2334 bc (247)	2330 b (98)	2778 a (334)	2412 b (205)	2483 b (117)
	Knife Opener 30 cm row spacing	2471 ab (232)	2758 a (225)	2656 ab (227)	2471 bc (186)	2678 ab (279)	2605 ab (99)
	Knife Opener 23 cm row spacing	2553 a (286)	2611 ab (284)	2915 a (252)	2673 ab (299)	2849 a (306)	2715 a (124)
	Sweep Opener 23 cm row spacing	2207 b (127)	2223 c (230)	2318 b (256)	2187 c (189)	2527 b (195)	2294 c (87)
	Mean over all seed drill treatments	2438 a (122)	2482 a (123)	2573 a (115)	2530 a (130)	2620 a (123)	--

† Means within columns sharing the same letter are not significantly different (P>0.05; Fisher's Protected LSD). The numbers in parentheses are the standard error of the treatment.

Table 2-6. Pearson correlation coefficients relating wheat stem sawfly emergence to grain yield in a spring or winter wheat system.

Pearson Correlation Coefficients			
	males	**females**	**WSS Total**
Winter Wheat	0.15	0.20	0.23
Spring Wheat	-	-0.16	-0.15

† '-' = P >0.10; all other r values presented at P ≤0.10.

2.8 Figures

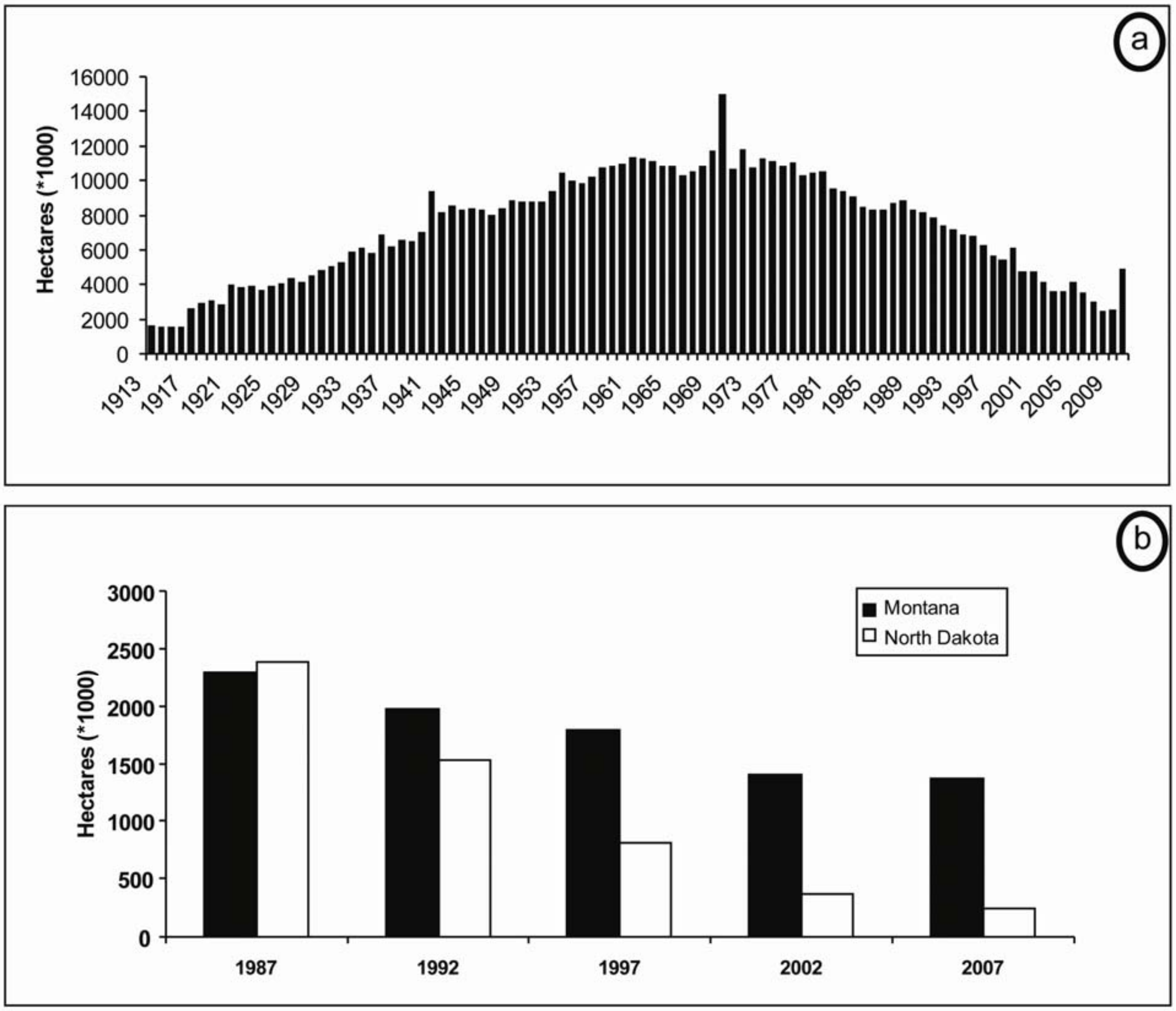

Figure 2-1. Estimated summer fallow area for the prairie provinces of Canada (Fig. 1a), and for Montana and North Dakota, USA (Fig. 1b).

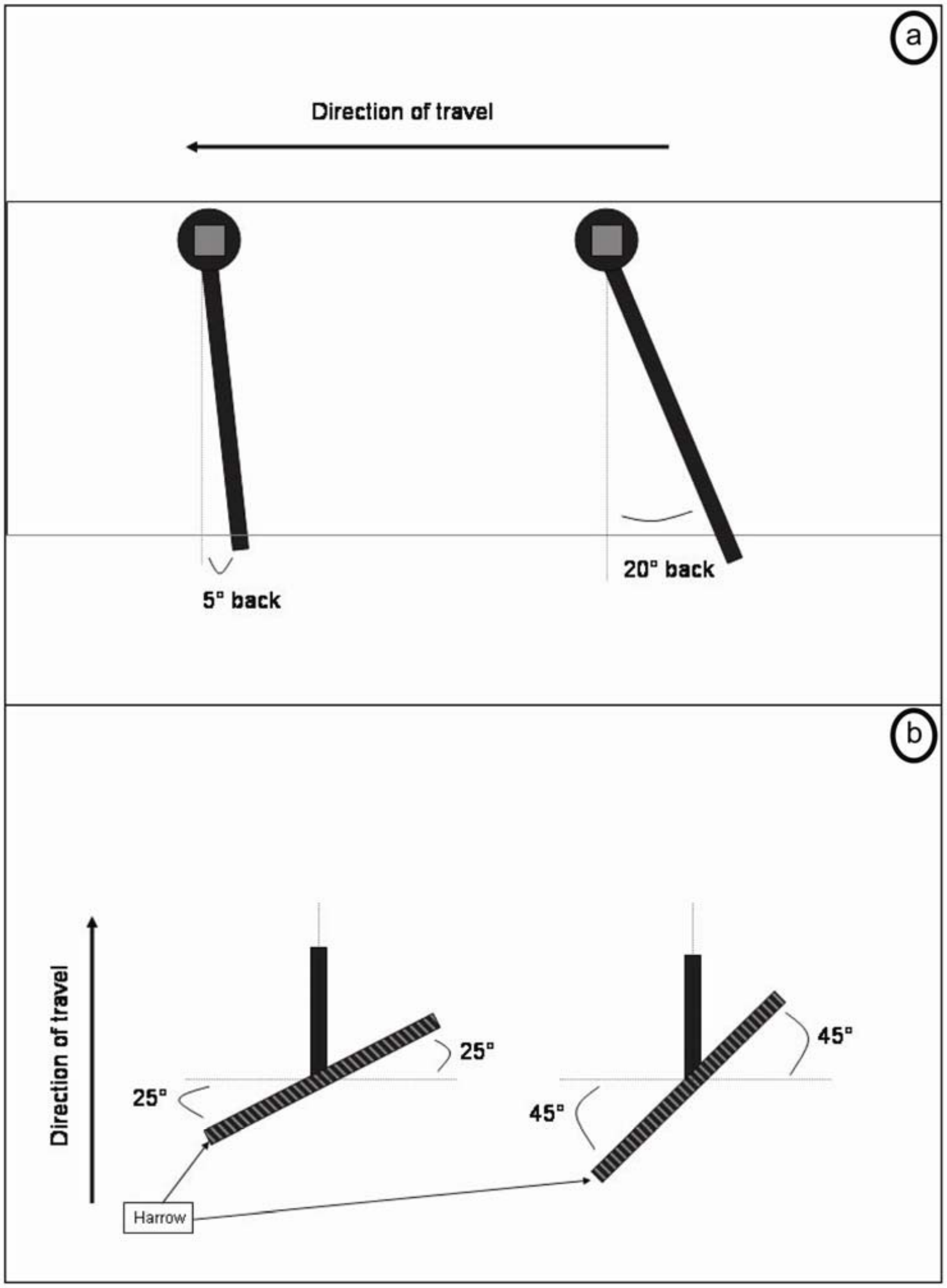

Figure 2-2. Illustration of heavy tine harrow (Fig. 2a) and rotary harrow (Fig. 2b).

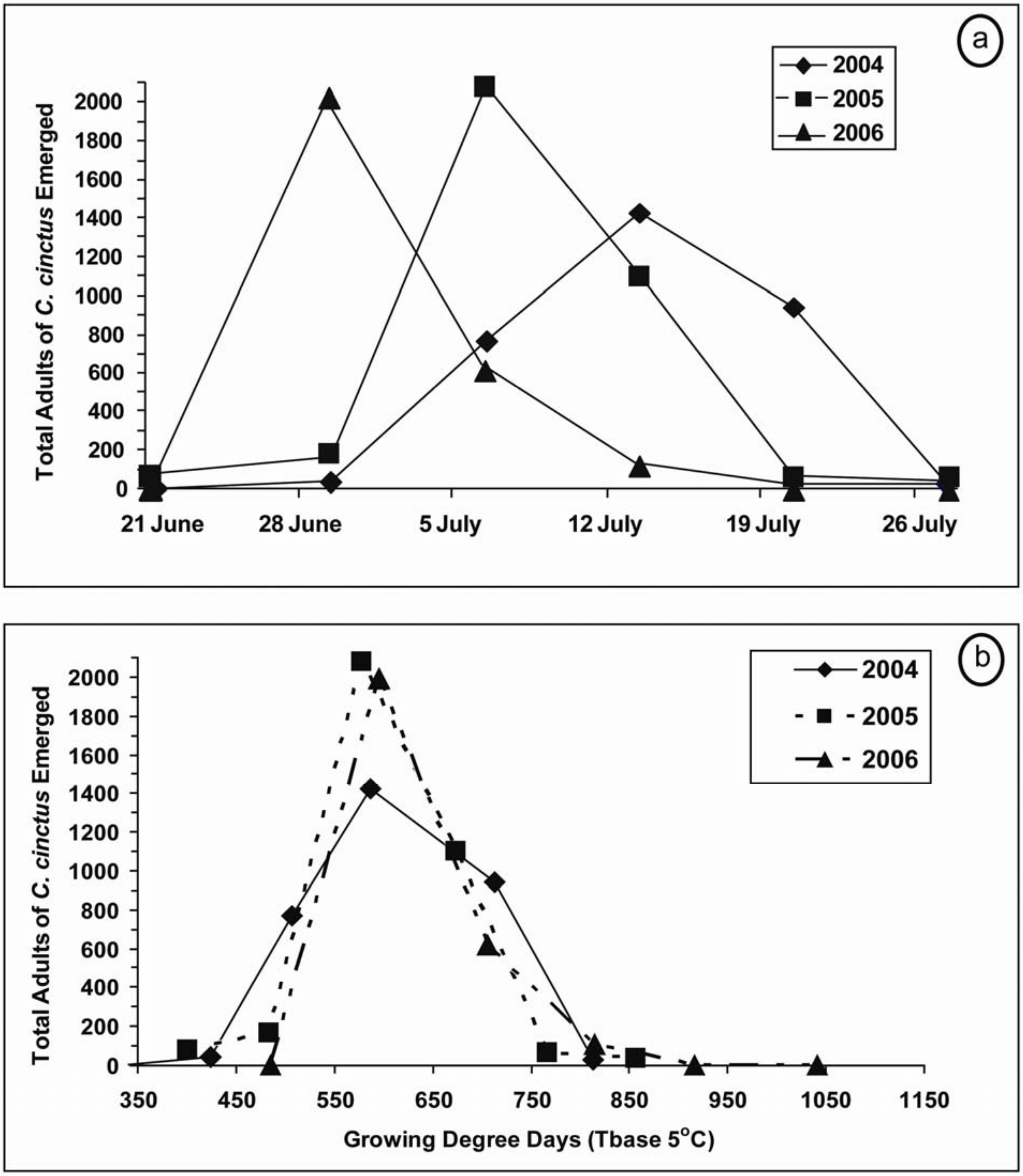

Figure 2-3. Emergence patterns of wheat stem sawfly Cephus cinctus collected from experimental plots near Lethbridge, Alberta, Canada, 2004-06. Emergence over time is illustrated in Fig. 3a and emergence vs. growing degree days is summarizes in Fig. 3b. Growing degree day information was acquired from the Agriculture and Agri-Food Canada meteorological weather site, Lethbridge, Alberta, Canada.

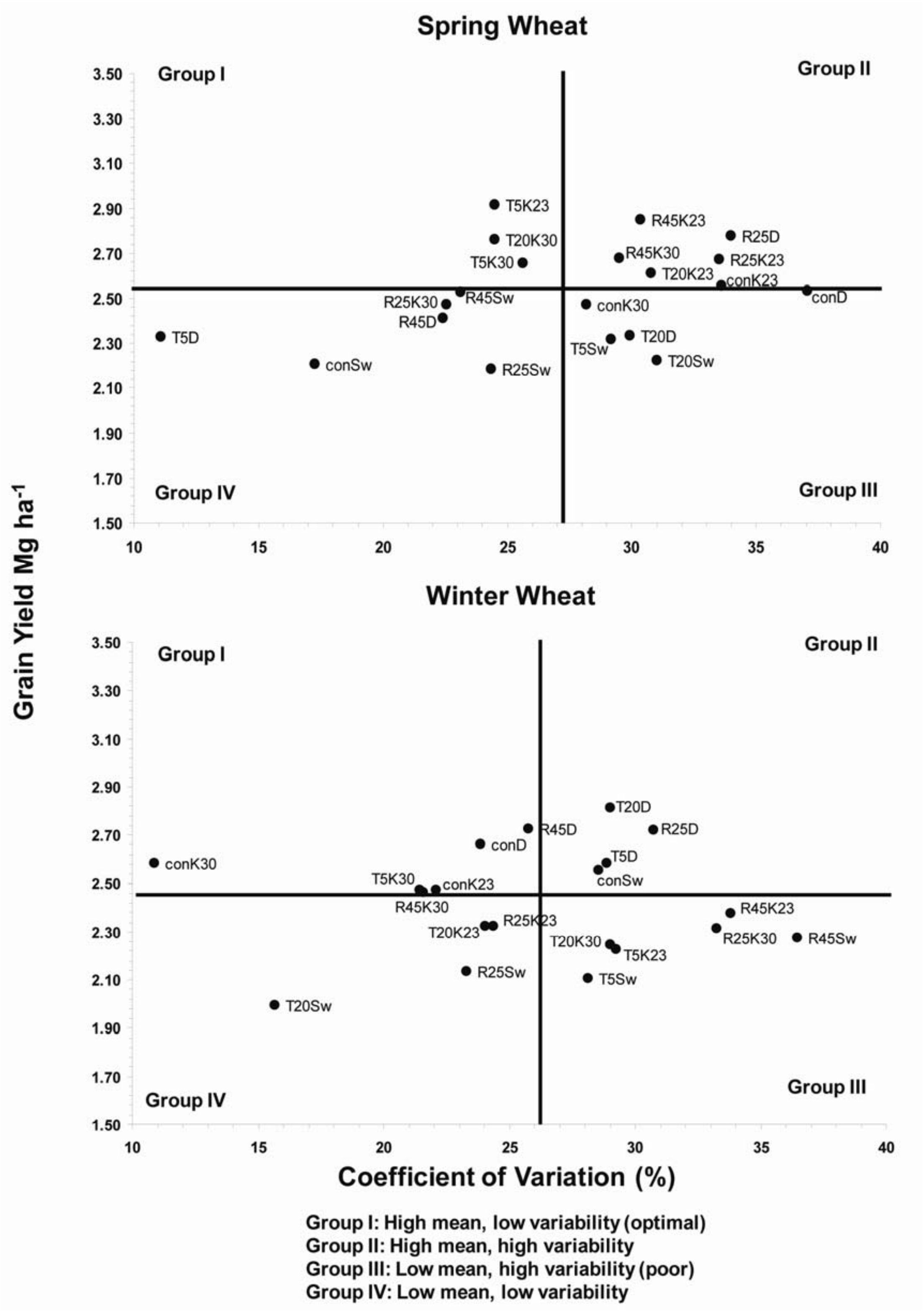

Figure 2-4. Biplot (mean vs. CV) of harrow by seeder combinations for data collected at a study site near Coalhurst, Alberta, Canada, 2004–2006. The first letter of the labels indicates harrow (T = tine harrow, R = rotary harrow, and con = control – no harrowing), the following number indicates the tension for the tine harrow (5^{o} or 20^{o}) or the angle for the rotary harrow (25^{o} or 45^{o}), and the last letter indicates the seed drill configuration (D = disc drill, K23 = knife opener spaced 23 cm apart, K30 = knife opener spaced 30 cm apart, and Sw = sweep opener spaced 23 cm apart).

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3.0 Influence of seeding rate, nitrogen management and micronutrient blend applications on pith expression in solid-stemmed spring wheat.[3]

3.1 Introduction

The wheat stem sawfly (*Cephus cinctus* Norton [Hymenoptera: Cephidae]) (WSS), is one of the most economically important insect pests of wheat (*Triticum aestivum* L.) in the northern Great Plains (Beres et al., 2007; Beres et al., 2011a; Weiss and Morrill, 1992; Chapter 1). A comprehensive review of wheat stem sawfly biology and management can be found in Beres et al. (2011a; Chapter 1); a brief overview is provided here. Adults emerge from the previous year's crop stubble in late spring to early summer and, following mating, the adult female seeks out a suitable host plant to oviposit, usually an adjacent wheat field (Criddle, 1922). A healthy female can successfully lay up to 50 eggs, therefore the population and subsequent damage to wheat can increase exponentially in a single generation (Ainslie, 1920). Shortly after an egg is deposited into a stem of wheat, a larva will hatch and begin boring the stem (Criddle, 1923). This activity continues throughout the growing season until the host plant reaches physiological maturity. Chlorosis associated with plant ripening and the reduction of whole plant moisture cues the larva to begin preparation to overwinter (Holmes, 1979). The larva moves to the base of the stem, notches a v-shaped groove around the stem, fills the region with frass, and encases itself in a cocoon below the groove. The groove weakens the stem and causes it to easily lodge or topple over, which proves difficult to recover at harvest (Ainslie, 1929). The injury caused by stem boring reduces photosynthetic rates (Macedo et al., 2007) and results in grain weight losses ranging from 10 to 17% (Holmes, 1977; Morrill et al., 1992; Seamans et al., 1944). An additional loss in yield potential occurs when toppled stems are not recovered at harvest (Ainslie, 1920; Beres et al., 2007). Thus, overall yield potential in wheat infested by WSS can be reduced by >25% (Beres et al., 2011a; Chapter 1).

The use of solid-stemmed cultivars helps mitigate crop losses and can also affect the survivorship of *C. cinctus*. The mechanical pressure of developing pith in a solid stem can result in mortality of the egg (Holmes and Peterson, 1961), and the boring activity of larvae that do hatch can be restricted, creating negative effects to health, fitness and survivorship (Cárcamo et al., 2005; O'Keeffe et al., 1960). Thus, the efficacy of 'resistance' is based on the plant's ability to develop pith in the culm of the stem, which is influenced greatly by interactions between the genotype and the environment in which it is grown. All solid-stemmed spring and winter wheat cultivars developed to date derive resistance from the line S-615 (Kemp, 1934; Platt and Farstad, 1946), but two other sources exist (Clarke et al., 2005). The recessive nature of the genes controlling resistance derived from S-615 leads to inconsistent pith expression in the field (Hayat et al. 1995). This was acknowledged shortly after Rescue was released when observations of high susceptibility to stem cutting were noted at Regina, SK (Platt and Farstad,

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1949). It was later determined that genes conferring pith development in the culm of a stem are influenced by photoperiod. Intense sunlight results in maximum expression and pith development, whereas shading or cloudy conditions inhibit pith development (Eckroth and McNeal, 1953; Holmes, 1984).

Solid-stemmed cultivars currently available in the Canada Red Western Spring class are 'AC Eatonia' (DePauw et al., 1994), 'AC Abbey' (DePauw et al., 2000), and 'Lillian' (DePauw et al., 2005). Solid-stemmed spring wheat cultivars available in Montana include 'Fortuna' and 'Choteau'. Resistance in winter wheat is also important as Montana has a biotype of WSS that has gradually adapted to become synchronous to winter wheat growth phenology by emerging 10 to 20 days earlier than normal. The adaptation seems to have occurred as a response to a shift away from spring to winter wheat production (Morrill and Kushnak, 1996). Solid-stemmed winter wheat cultivars available to Montana producers include 'Vanguard' (Carlson et al., 1997), 'Rampart' and 'Genou' (Bruckner et al., 1997; Bruckner et al., 2006).

Wheat row spacing and seeding rates can influence *C. cinctus* infestation rates, and the response varies between solid- and hollow-stemmed cultivars. Luginbill and McNeal (1958) reported that narrow row spacing and high seeding rates reduced stem cutting in 'Thatcher', a hollow-stemmed cultivar, but the same treatments reduced pith expression and led to increased levels of cutting damage in 'Rescue', a solid-stemmed cultivar.

Crop nutrient management can significantly change crop canopy architecture and influence overall plant health, which in turn could influence WSS infestation rates. Luginbill and McNeal (1954) observed that when a blend of nitrogen and phosphorous was applied to wheat there was generally an increase in stem cutting. Nitrogen applied separately did not influence cutting whereas phosphorous applied alone produced a slight increase in stem cutting. In contrast, a recent Montana greenhouse study reported that phosphorous-deficient wheat plants were most susceptible to WSS damage (Delaney et al., 2010). In a Saskatchewan study, no effects of nitrogen or phosphorous could be detected due to the strong influence of other environmental factors (DePauw and Read, 1982), which is similar to a North Dakota study that reported significantly more WSS cutting in fertilized plots in only one of eight experiments (O'Keeffe et al., 1960). The disagreement among these studies underscores the stochastic nature of site-specific, soil-plant fertility dynamics. Moreover, the studies did not report any detailed agronomic assessments and no information on the effects of micronutrient blends on pith expression in solid-stemmed wheat has been reported.

The inconsistency in pith development should not dissuade producers from growing solid-stemmed wheat in areas prone to attack as cultivar selection is critical to a successful IPM system for wheat stem sawfly (Beres et al., 2011b; Chapter 5). Beres et al. (2009, 2007) demonstrated that solid-stemmed wheat can be agronomically superior to hollow-stemmed wheat in the presence of WSS pressure, and newer cultivars with the solid stem trait have further improved yield and quality even in the absence of sawflies

(DePauw et al., 2005). This research has resulted in a dramatic increase in planted hectares of solid-stemmed wheat (Anonymous, 2010). 'Lillian' (DePauw et al., 2005), the latest solid-stemmed cultivar to be released, occupies almost one-third of the wheat hectares in Saskatchewan and 20% of the prairie-wide wheat hectares (Anonymous, 2010). Based on the vast area now sown to solid-stemmed wheat, our objective was to develop an integrated nutrient and planting strategy specific to solid-stemmed spring wheat using modern farming techniques. This paper tests the following hypotheses 1) physiological crop changes to pith in the culm of wheat will occur with increasing planting densities and nitrogen rates, 2) tolerance to wheat stem sawfly infestation may be modulated with changes to planting density regime, and 3) post-emergent applications of micronutrient blends may influence pith expression in solid-stemmed wheat.

3.2 Materials and methods

Two study locations in the traditional distribution area of the wheat stem sawfly were selected near Lethbridge (49°41′N, 112°45′ W), AB, Canada and near Bow Island (49°44′N, 111°20′ W), AB, Canada. The Lethbridge site is an Orthic Dark Brown Chernozem clay loam soil (Typic Boroll) with 3.0% organic matter content and a pH of 7.5. The Bow Island site is a Brown Chernozem loam soil (Aridic Boroll) with 2.0% organic matter content and a pH of 6.0. A new area at these locations was selected each year of the study. At Lethbridge, the experiment was planted into a continuously cropped system into a field previously cropped to oats (*Avena sativa* L.). Two experiments were planted at Bow Island, 1) wheat-fallow cropping system and 2) continuous cropping system direct-seeded into spring durum wheat stubble. Thus, three site-years of data were collected for each year during the period 2007 to 2009 for a total of 9 site-years.

A 3 x 5 factorial combination of sowing density and nitrogen rate was arranged in a randomized complete block experimental design with four replicates each year. To study effects of planting density, three levels of seeding rate were selected 1) low density – 100 seeds m^{-2}, 2) moderate density – 300 seeds m^{-2}, and 3) high density – 500 seed m^{-2}. Five levels (0, 30, 60, 90 and 120 kg ha^{-1}) of urea [$CO(NH_2)_2$] nitrogen fertilizer (46-0-0), were banded mid-row at the time of planting. In 2008, a post-emergence application of a water soluble micronutrient fertilizer was added to an additional 90 kg N ha^{-1} treatment of basal nitrogen. The micronutrient blend was commercially available as Yield Max® (18-20-20; Nexus Ag Business Inc., Saskatoon, SK, Canada) and derived from ammonium phosphate, potassium nitrate, urea, ammonium sulfate, sodium borate, copper - chelated Ethylenediamine Tetra-Acetate (EDTA), iron EDTA, Manganese EDTA, Zinc EDTA, and sodium molybdate. The blend was foliar-applied at both the 3-4 leaf stage and again at the flag leaf stage at 5x the recommended rate. An excessive rate was selected to ensure all nutrients would be elevated to levels that would facilitate plant uptake and elicit a notable response if any were to occur as some micronutrients such as Fe, Mn, and Zn are only present in the blend at 0.1% of net weight.

A zero tillage drill manufactured by Fabro Manufacturing (Swift Current, SK, Canada) and configured with single shoot openers (Atom-Jet Industries, Brandon, MB, Canada) spaced 20.3 cm apart was used to plant the experiment in all locations. Experimental plot unit dimensions were 2 m wide x 7 m long. Each study area was treated with glyphosate (RoundUp®, Monsanto, St. Louis, MO, USA) a few days prior to seeding applied at a rate of 900 g a.i. ha^{-1} using a motorized sprayer calibrated to deliver a carrier volume of 45 L water ha^{-1} at 275 kPa pressure. In-crop herbicides were chosen based on the weed spectrum present at each site-year, and applied in early June at label rates. No insecticides were used at any site during the study period.

Three handheld instruments were employed to discriminate differential plant responses to the study treatments by assessing chlorophyll levels or the amount of vegetation in the study plots. The Greenseeker active lighting optical sensor (NTech Industries Inc, Ukiah, CA, USA) consists of two diodes which emit energy in 671 and 780 nm wavelengths. The light reflected back from the crop is measured by a photodiode and the normalized difference vegetation index (NDVI) is computed ($[R_{780}-R_{671}]/[R_{780}+R_{671}]$). The principle is that NDVI relates to biomass and greenness (i.e. chlorophyll levels) and thus N management. Readings were collected from plots at all locations in 2008 and 2009 at Feekes growth stages 3 - 4 and 6 – 8 in 2008 and 2009, respectively. The Field Scout CM1000 chlorophyll meter (Spectrum Technologies, Plainfield, Illinois, USA) was used in 2009 at all locations when the plant growth stage was at approximately Feekes 6 – 8. The chlorophyll meter senses light at wavelengths of 700 and 840 nm which are then used to estimate the quantity of chlorophyll in leaves. The ambient and reflected light at each wavelength is measured. Chlorophyll ***a*** absorbs 700 nm light and, as a result, the reflection of that wavelength from the leaf is reduced compared to the reflected 840 nm light. Light having a wavelength of 840 nm is unaffected by leaf chlorophyll content and serves as an indication of how much light is reflected due to leaf physical characteristics such as the presence of a waxy or hairy leaf surface. The LP-80 AccuPAR Ceptometer (Decagon Devices, Pullman, WA, USA), which measures light in the 400-700 nm (PAR) waveband, was used to determine leaf area index (LAI) by first measuring above the canopy on a leveled tripod in a location with an unobstructed view of the sky and below canopy, placing the ceptometer level and linearly between rows. All measurements were taken within 2 h of solar noon.

Temperature and light intensity data were collected at each site using Hobo Pendant temperature and light loggers (Onset Computer Corporation, Bourne, MA, USA; part no. UA-002-XX). The data loggers were attached near the top of 1m fibreglass‘whisker stakes’ (Imagine That Signs and Designs, Saskatoon, AB, Canada) and positioned at the center of each of the three ranges.

Plant counts were performed in mid- to late-May by staking a 1-m section in two randomly selected areas of the plot. The staked sections were counted again in mid- to late-July to assess spike density. To ensure an adequate estimate of stem solidness (Cárcamo et al., 2007), a 0.50-m section of row was collected in late-July or early-August in two random locations in each plot to determine stem diameter and pith expression or degree of stem solidness in the culm of the main stem. Mean stem diameter was determined by measuring the outside diameter of the first three internodes using a digital caliper. Each stem was then split lengthwise from crown to neck, and starting from the crown each internode was assessed visually for pith development. Ratings were as follows: 1 - Hollow stem - no pith development; 2 - Some degree of pith development - may appear 'cotton like'; 3 - Large hollow tunnel in the stem, or, a huge cavity at a particular point in the internode; 4 - Size of hollow equivalent to a pencil lead, or, some cavitation has occurred at a particular point in the internode; and 5 - Solid stem (DePauw and Read, 1982). Stem cutting data (recorded as '% stems cut') were collected by visually estimating the percentage of stems that had been cut by wheat stem sawfly in each plot. This method is an efficient alternative to the labour intensive method of laboratory assessments. Beres et al. (2007) used both methods in a WSS study and concluded that visual assessments provided a reasonable estimate ($R^2 = 0.66$) of cutting damage validated from stem stubble dissections performed in the laboratory.

Plots were harvested at crop maturity using a Wintersteiger Expert (Wintersteiger AG, Salt Lake City, UT, USA) plot combine equipped with a straight cut header, pickup reel and crop lifters. Grain yield was calculated from the entire plot area and retained post-harvest to characterize seed weight (g 1000^{-1}) and grain bulk density (kg hL^{-1}). Grain protein concentration was determined from whole grain using near infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc, Eden Prairie, MN).

Data were analyzed with the MIXED procedure of SAS (Littell et al., 2006). Homogeneity of error variances was tested using the UNIVARIATE procedure of SAS; any outlier observations were removed before a combined analysis over years and environments was performed. Normality assumptions were also tested on the categorical data 'pith expression' and observational 'stem cutting (%)' data as multiple categories were used for rating pith expression and percentages for stem cutting were generally not extreme (Cochran, 1954). For analyses by environments, replicate was considered random and treatment effects were considered fixed and significant if $P \leq 0.05$. Results by environment indicated similar treatment response patterns among environments; therefore, a combined analysis was performed with replicate, years, environments and their interactions considered random effects and treatment effects treated as fixed effects and significant if $P \leq 0.05$. Response variable least square means generated for each site-year were used to create a Pearson correlation coefficient matrix of stem diameter, stem solidness, wheat stem sawfly damage, and yield components, whole grain protein and canopy reflectance data using the CORR procedure of SAS.

A grouping methodology previously described by Francis and Kannenberg (1978) and later adapted to agronomy studies (Beres et al., 2010b; Gan et al., 2009; May et al., 2010) was used to further explore treatment responses. The mean and coefficient of variation (CV) were estimated for each level of the treatment. Means were plotted against CV for each level of the treatment. The overall mean of the treatment means and CVs was included in the plot to categorize the biplot ordination area into four quadrats/categories: Group I: High mean, low variability (optimal); Group II: High mean, high variability; Group III: Low mean, high variability (poor); and Group IV: Low mean, low variability.

3.3 Results and discussion

Average annual precipitation at Lethbridge and Bow Island during the study period was close to normal but below average rainfall occurred in 2007 at both sites, and in 2009 at Bow Island (Table 3-1). Mean temperature and light intensity were also unique in 2007. Growing season precipitation was 150% of normal at Lethbridge in 2008. Trends in light intensity and temperature were similar at all sites with the notable exception of Bow Island fallow in 2007, where higher light intensity was recorded in August (Fig. 3-1). Light intensity levels were similar for June, July and August at the other sites in 2007; however, light intensity peaked in June for 2008 and 2009 at all sites. Temperature also peaked in 2008 and 2009 at all sites, but was highest in July in 2007, which was the hottest month of the entire study period (Fig. 3-1). Background levels of available soil NO_3^-N were generally low at all sites and lowest in the continuously cropped system at Bow Island (Table 3-1).

Reduced pith expression in solid-stemmed wheat concomitant with increased stem cutting caused by wheat stem sawfly was observed as seeding rates increased over the low rate of 100 seeds m^{-2} (Table 3-2; Fig. 3-2a). Single degree of freedom contrast results indicate that the best fit of the response was linear but the significant quadratic response for pith expression may indicate that the downward trend for pith expression was not strictly linear. The average pith rating of main stems was reduced by 13% when planting density was increased to 300 seeds m^{-2} and an additional 5% when increased to 500 seeds m^{-2}. Similar results were observed for stem diameter. The magnitude of change was greater in stem cutting as visual estimates increased by 38% and 50%, respectively, for moderate and high seeding rates (Table 3-2a). Nitrogen management practices had no effect on stem solidness but did influence stem diameter and visual estimates for stem cutting. Higher nitrogen rates resulted in greater stem cutting and increased stem diameter from 2.17 to 2.44 mm at the highest rate of N (Table 3-2; Fig. 3-2a).

The superior pith expression observed in the low planting density is apparent in the biplot (Fig. 3-3). The lowest planting population produced higher pith and low variability when combined with all fertilized treatments. The moderate planting density also produced above average pith expression and low variability when combined with the 60 kg N ha^{-1} fertilizer rate. However, the visual stem cutting estimate for this treatment (33%) was just above the average of 31%. Lower and stable stem cutting was observed when planting at 100 seeds m^{-2} with 0, 60, or 90 kg N ha^{-1} (Fig. 3-3).

These findings do not correspond with a previous study on planting density that reported an increase in stem cutting of Rescue solid-stemmed wheat with lower plant populations (Luginbill and McNeal, 1958). Rescue planted at a rate of approximately 100 seeds m^{-2} sustained 57% cutting whereas plots sown at 600 seeds m^{-2} had 50% less cutting. The nitrogen results of our study agree with Luginbill and McNeal (1954) as the authors reported no effect when nitrogen was applied alone at rates of 60 kg N ha^{-1} and 120 kg N ha^{-1}. A study comparing unfertilized spring wheat plots to those with basal rates of approximately 40 kg N ha^{-1} also report little effect from fertilization (O'Keeffe et al., 1960); and DePauw and Read (1982) reported that environmental factors were more important for pith expression than fertility management practices. Environmental factors that would affect pith expression are those related to precipitation. Cloudy conditions and reduced photoperiod has a negative effect on pith expression (Holmes, 1984). Shading effects within the canopy could have a similar effect. Leaf area index was greatest for the highest levels of nitrogen and seeding rates (Fig. 3-4), which corresponds to the responses observed in the same treatments for pith expression and sawfly damage. Therefore, the management of crop canopy architecture through appropriate seeding and nitrogen rates will likely influence plant tolerance or cutting susceptibility.

There are two important considerations for plant density and nitrogen management recommendations for solid-stemmed wheat. First, for economic reasons, any recommendation based on this study or previous findings must have agronomic merit. Yield components and grain quality parameter results are summarized in Table 3-3 and Figs. 3-2b and 3-2c. Seeding and nitrogen rates affected all traits except grain bulk density (Table 3-3). With the exception of seed mass and grain bulk density, single degree of freedom contrasts indicate that the response to varying rates of both main effects was primarily linear (Table 3-3; Fig. 3-2c). Grain yield and spike density responses were greater from low to moderate seeding rates but diminished from moderate to high seeding rates. Plant establishment decreased from 87% at the lowest plant density to 62% at 300 seeds m^{-2}, however, plant stands increased proportionally at each seed rate level (Table 3-3). All yield components were optimized at the 60 to 90 kg N ha^{-1} nitrogen rate, but grain protein concentration continued to respond through the 120 kg N ha^{-1} rate. However, grain protein diminished with increased plant density (Table 3-3; Fig. 3-2c). According to the biplot summaries, grain yield and protein associated with the lower rates of nitrogen were either too low or too variable. Increasing plant density to 300 seeds m^{-2} produced high and stable grain yield with 60 to 120 kg N ha^{-1}. The same plant density combined with 90 or 120 kg N ha^{-1} also produced high protein. The low plant density produced high and stable protein at the higher nitrogen rates, and the same combinations also produced consistent grain yield, but the results were average or just below average (Figs. 3-3).

The second consideration is for a system that enhances the plant's ability to produce maximum pith in the culm of the stem. Wallace et al. (1973) reported that a mean pith expression of 3.75 would be required to achieve consistent high tolerance to wheat stem sawfly infestations. We did not observe this degree of stem solidness in Lillian in any of the treatments, which indicates that the weather parameters or the genetic potential of Lillian prevented maximum resistance to wheat stem sawfly infestation. Low plant populations maximized pith expression in our study and all combinations with fertilized treatments at this level displayed acceptable stability. However, low plant populations may not always optimize grain yield. A number of studies report that higher plant populations enhance weed competitive ability, herbicide efficacy and produce higher grain yield (Beres et al., 2010a; O'Donovan et al., 2006).

Therefore, the compromise may be to combine moderate seed rates with moderate to higher levels of nitrogen to maximize pith expression, grain yield and to meet the minimum protein standards (13.5%) required by the Canadian Wheat Board for marketing purposes. This strategy should also provide the best net economic returns as herbicide management and weed competitive ability is enhanced over the low seeding rate. The results underscore the need to further explore plant population effects to elucidate the ideal plant density. Further studies are underway that involve additional seeding rate levels.

Luginbill and McNeal (1954) reported increased susceptibility to cutting in Rescue wheat when nitrogen was combined with phosphorus or phosphorous alone. The results suggest that a balanced application of macronutrients elicits a physiological response in spring wheat that inhibits pith expression. In our study, we were interested in expanding this finding to test if a blend of both macronutrients and micronutrients would create a similar result. Adding a micronutrient blend to a basal rate of 90 kg N ha^{-1} as previously described had no effect on pith expression or cutting susceptibility compared to the same basal rate of N without added micronutrients (Table 3-4). Furthermore, there were no differences observed in grain yield or grain protein concentration. Therefore, the hypothesis that micronutrient blends would have a positive effect on pith expression, grain yield or quality parameters in solid-stemmed wheat was not supported.

Correlation coefficients were generated to further explore relationships between sawfly related parameters and crop production parameters (Table 3-5). Positive relationships exist between stem diameter and grain yield, protein, NDVI and plant chlorophyll, but an inverse relationship exists with plant stands. There was also a positive relationship with stem solidness and stem diameter indicating larger stems generally produce more pith than smaller diameter stems. Negative correlations were observed between stem solidness and stem cutting, stand establishment and spike density. The cause is likely due to shading effects created by higher seeding rates (Fig. 3-4) and subsequent plant stands and spike density, which would inhibit pith and expose the plant to higher rates of stem cutting. The inverse relation between chlorophyll and stem cutting indicates that prolonged ‘greenness’ or delayed crop maturity could reduce stem cutting susceptibility (Table 3-5).

Nitrogen management and the use of micronutrient blends will alter canopy architecture in a similar fashion as seeding rates. However, there was no direct effect on pith expression observed in solid-stemmed wheat that was attributed to anything other than shading effects; fertilization did not influence pith expression but nitrogen did influence cutting susceptibility. Nutrient management should focus on plant health and thus standard amendments are recommended: i.e. 60 kg N ha^{-1}. The results of this study did indicate that low plant populations were often most effective at maximizing pith expression in solid-stemmed wheat and reducing sawfly cutting damage. However, this usually required the highest rates of N fertilizer, and a system of low seeding rates and high nitrogen may not be economical based on current fertilizer input costs and the generally lower grain yield response.

In summary, an integrated planting and nutrient management plan when using a solid-stemmed spring wheat cultivar consists of seeding rates no greater than 300 seeds m^{-2} and 30 to 60 kg N ha^{-1}.

3.4 Summary

The wheat stem sawfly (*Cephus cinctus* Norton [Hymenoptera: Cephidae]) is a serious threat to wheat (*Triticum aestivum* L.) and other cereal grains in the northern Great Plains. Wheat cultivars with high expression of pith in the culm of the stem can minimize losses associated with sawfly infestations. Based on the widespread area now sown to solid-stemmed wheat, our objective was to develop an integrated nutrient and planting strategy specific to solid-stemmed spring wheat using modern farming techniques. Five levels of banded N fertilizer (0, 30, 60, 90, 120 kg N ha^{-1}) were arranged in a factorial combination with three levels of sowing density (100, 300, and 500 seeds m^{-2}) and grown at three sites in southern Alberta, Canada from 2007 to 2009. Increased planting densities optimized yield, but an inverse relationship with pith expression (stem solidness) was observed. Low plant populations (100 seeds m^{-2}) were often most effective at maximizing pith expression in solid-stemmed wheat and reducing sawfly cutting damage. However, this usually required the highest rates of N fertilizer, so a system of low seeding rates and high nitrogen may not be economical based on fertilizer input costs and the generally lower grain yield response (-9%). An integrated planting and nutrient strategy for solid-stemmed spring wheat cultivars consists of seeding rates no greater than 300 seeds m^{-2} and basal nitrogen applications in the range of 30 to 60 kg N ha^{-1}.

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3.6 Tables

Table 3-1. Description of test sites at Lethbridge and Bow Island (fallow and stubble), Alberta, Canada, and summary of agronomic practices performed during the study period 2007-09.

Variable						
Location	**Lethbridge, Alberta, Canada**			**Bow Island, Alberta, Canada**		
Latitude and Longitude	49°41′N, 112°45′W			49°44′N, 111°20′W		
Soil Zone/Series/Texture	Dark Brown Chernozemic Lethbridge Series Clay Loam			Brown Chernozemic Chin Series Silty Loam		
Crop Year	2007	2008	2009	2007	2008	2009
Sowing Date	2 May	13 May	11 May	7 May	7 May	7 May
Harvest Date	13 Aug.	16 Sept.	28 Aug.	8 Aug.	5 Sept.	3 Aug.
Soil NO_3^-N 0-60cm kg N ha^{-1}	40.7	35.7	20.2	13.7^{s} 29.9^{f}	**3.4**^{s} **18.9**^{f}	**4.7**^{s} 42.4^{f}
Precipitation (mm)						
May 1 to Sept. 15	164	380	241	141	270	175
(Bow Island: LT average = 210)						
(Lethbridge: LT average = 251)						
Annual	342	525	417	254	398	303
(Bow Island: LT average = 358)						
(Lethbridge: LT average = 398)						

† Abbreviations: s, stubble; f, chemical fallow. Bold values were determined from the 0-15 cm profile.

Table 3-2. Influence of sowing density and nitrogen rate on solid stem spring wheat (cv. Lillian) tolerance to wheat stem sawfly in rainfed environments in the brown and dark brown soil zones of southern Alberta, Canada 2007-2009.

Factor	**Treatment**	**Stem Solidness (pith expression)†**	**Stem Diameter (mm)**	**Sawfly Damage (% stems cut)**
Seed Rate	**100**	3.03	2.53	24
(seeds m^{-2})	**300**	2.66	2.30	33
	500	2.50	2.18	36
	SED	0.05	0.03	3.52
	Pr > F	<.0001	<.0001	0.0111
Contrasts	**Linear**	<.0001	<.0001	0.0044
	Quadratic	0.0353	0.0374	0.3016
Nitrogen Rate	**0**	2.66	2.17	22
(kg N ha^{-1})	**30**	2.69	2.31	28
	60	2.78	2.37	31
	90	2.77	2.40	37
	120	2.76	2.44	39
	SED	0.08	0.06	4.60
	Pr > F	0.4513	0.0035	0.0061
Contrasts	**Linear**	0.1843	0.0113	0.0314
Pr > F	**Quadratic**	0.8323	0.0923	0.4759
	Cubic	0.6480	0.0184	0.0052
	Quartic	0.2054	0.0409	0.0813
SR x Fert	**Pr > F**	0.9408	0.2236	0.7325

† Pith rating based on average of stem internodes (1 = hollow; 5 = solid).

Table 3-3. Response of solid stem spring wheat (cv. Lillian) yield components and grain protein concentration to sowing density and nitrogen rate in rainfed environments located in the brown and dark brown soil zones of southern Alberta, Canada 2007-2009.

Factor	Treatment	Yield (Mg ha^{-1})	Stand Establishment (plants m^{-2})	Spike Density (heads m^{-2})	Seed Mass (g 1000^{-1})	Grain Bulk Density (kg hL^{-1})	Grain Protein (%)
Seed rate	**100**	2.74	86	293	31.2	70.3	14.2
(seeds m^{-2})	**300**	3.01	212	449	29.8	70.6	13.9
	500	3.00	310	502	29.1	71.1	13.7
	SED	0.11	8.7	18.5	0.35	1.0	0.12
	Pr > F	0.0425	<.0001	<.0001	<.0001	0.6089	0.0046
Contrasts	**Linear**	0.0323	<.0001	<.0001	<.0001	0.3268	0.0013
(Pr > F)	**Quadratic**	0.1528	0.0743	0.0057	0.3380	09820	0.5019
Nitrogen Rate	**0**	2.47	194	345	30.8	71.0	12.6
(kg N ha $^{-1}$)	**30**	2.82	199	401	30.2	70.2	12.8
	60	3.01	208	431	29.8	70.6	13.8
	90	3.16	209	455	29.8	71.3	14.9
	120	3.14	204	443	29.4	70.1	15.4
	SED	0.16	5.4	15.8	0.43	1.1	0.30
	Pr > F	0.0006	0.0551	<.0001	0.0329	0.7606	<.0001
Contrasts	**Linear**	0.0013	0.0085	<.0001	0.1030	0.6801	0.0002
(Pr > F)	**Quadratic**	0.2160	0.7330	0.0804	0.1899	0.2271	0.9989
	Cubic	0.0115	0.6209	0.0007	0.0635	0.7912	<.0001
	Quartic	0.0352	0.1504	0.0044	0.0635	0.9491	<.0001
SR x Fert	**Pr > F**	0.3900	0.1940	0.6579	0.7431	0.6773	0.9237

Table 3-4. Response of solid stem spring wheat (cv. Lillian) to supplemental micronutrient blend applied in-crop at 5x the recommended rate at the 3 leaf stage and repeated at the 6 leaf stage.

Factor	Treatment	Yield (Mg ha^{-1})	Pith Expression†	Sawfly Damage (% stems cut)	Grain Protein (%)
Basal Fertilizer (90 kg N ha^{-1})	**Without Micronutrient**	3.66	2.85	36	14.9
Basal Fertilizer (90 kg N ha^{-1})	**With Micronutrient**	3.45	2.78	35	15.2
	SED	0.18	0.09	4.97	0.37
	Pr > F	<.0001	0.5331	0.0089	<.0001

† Pith rating based on average of stem internodes (1 = hollow; 5 = solid).

Table 3-5. Correlation matrix relating stem diameter, stem solidness and wheat stem sawfly damage to yield components, protein and canopy reflectance data.

Pearson Correlation Coefficients								
	Stem Solidness	**Sawfly Damage**	**Stand Establishment**	**Spike Density**	**Grain Yield**	**Grain Protein**	**NDVI**	**Plant Chlorophyll**
Stem Diameter	0.49	-	-0.41	-	0.43	0.39	0.25	0.43
Stem Solidness	1	-0.30	-0.51	-0.44	-	-	-	-
Sawfly Damage		1	-	-	-0.30	0.40	-	-0.56
Stand Establishment			1	0.72	0.29	-	0.48	0.56
Spike Density				1	0.50	0.29	0.82	0.94
Grain Yield					1	-	0.60	0.88
Grain Protein						1	0.33	-
NDVI							1	0.96
Plant Chlorophyll								1

† '-' = $P > 0.05$; all other r values presented at $P \leq 0.05$.

3.7 Figures

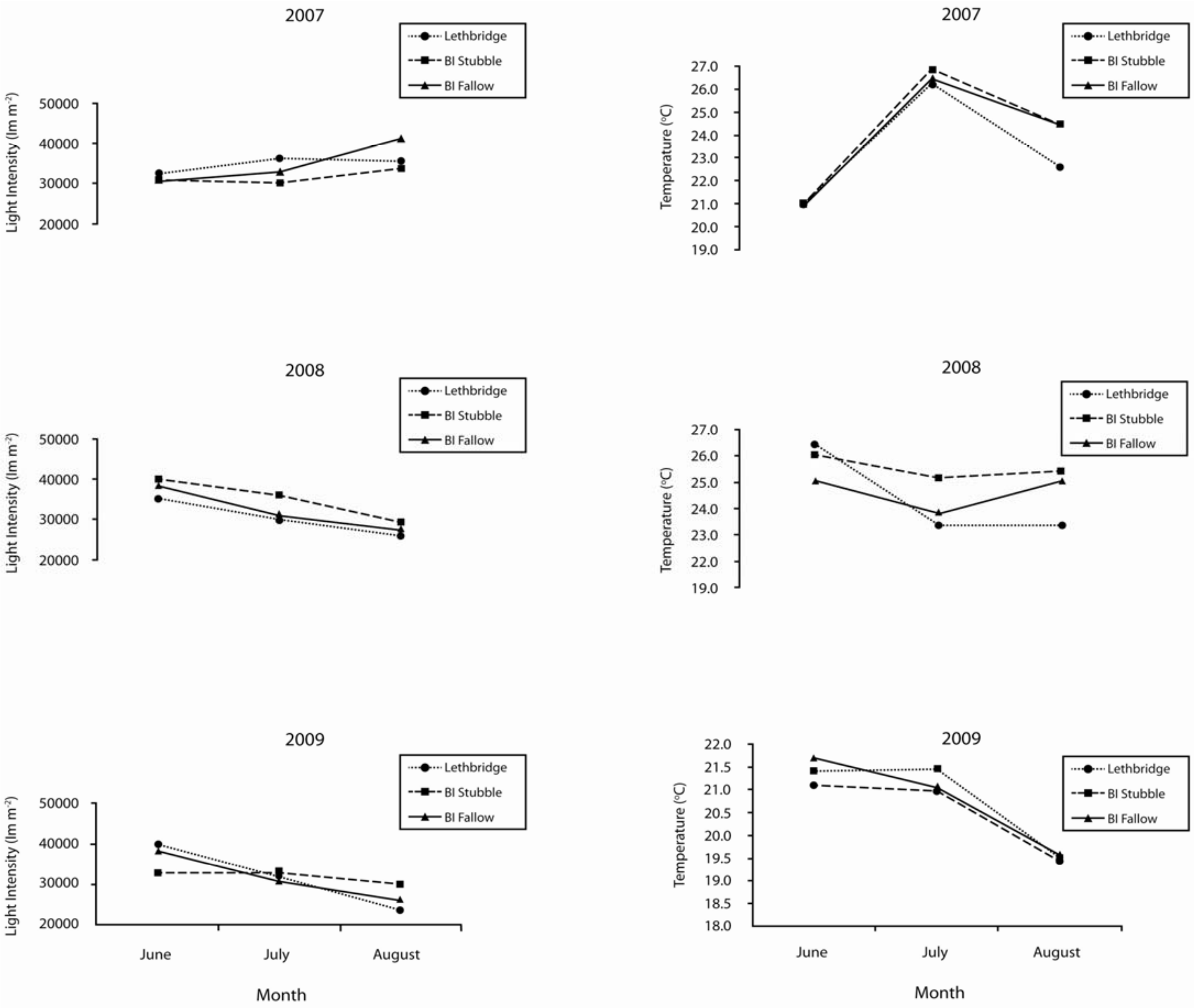

Figure 3-1. Temperature and light intensity received at each study site from June to August 2007-2009 at Lethbridge (continuously cropped) and Bow Island (wheat-fallow and continuously cropped regimes), Alberta, Canada.

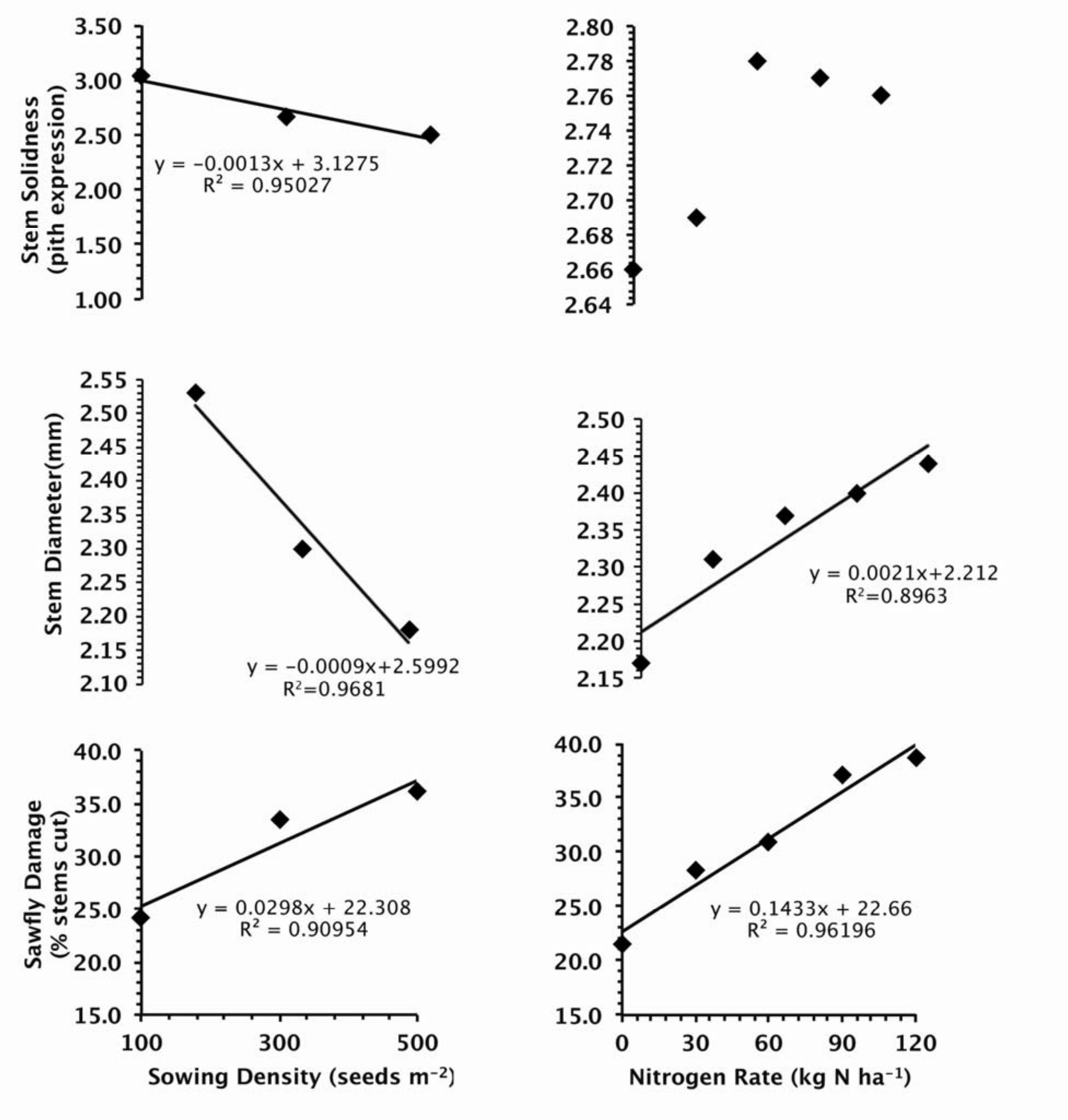

Figure 3-2a. Summary of main effect means for sawfly resistance parameters. Regression lines are presented when $P \leq 0.05$.

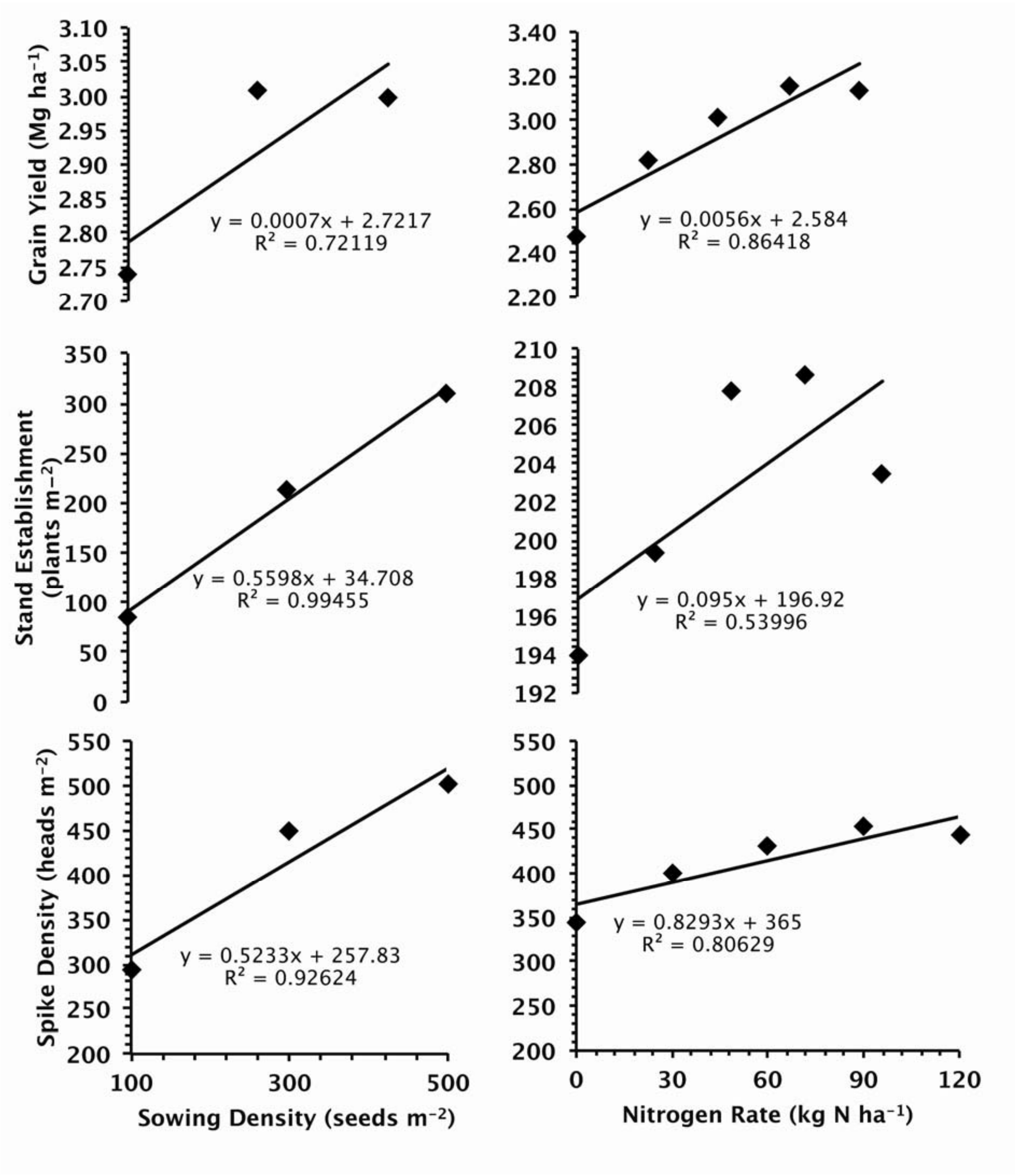

Figure 3-2b. Summary of main effect means for yield and yield components. Regression lines are presented when $P \leq 0.05$.

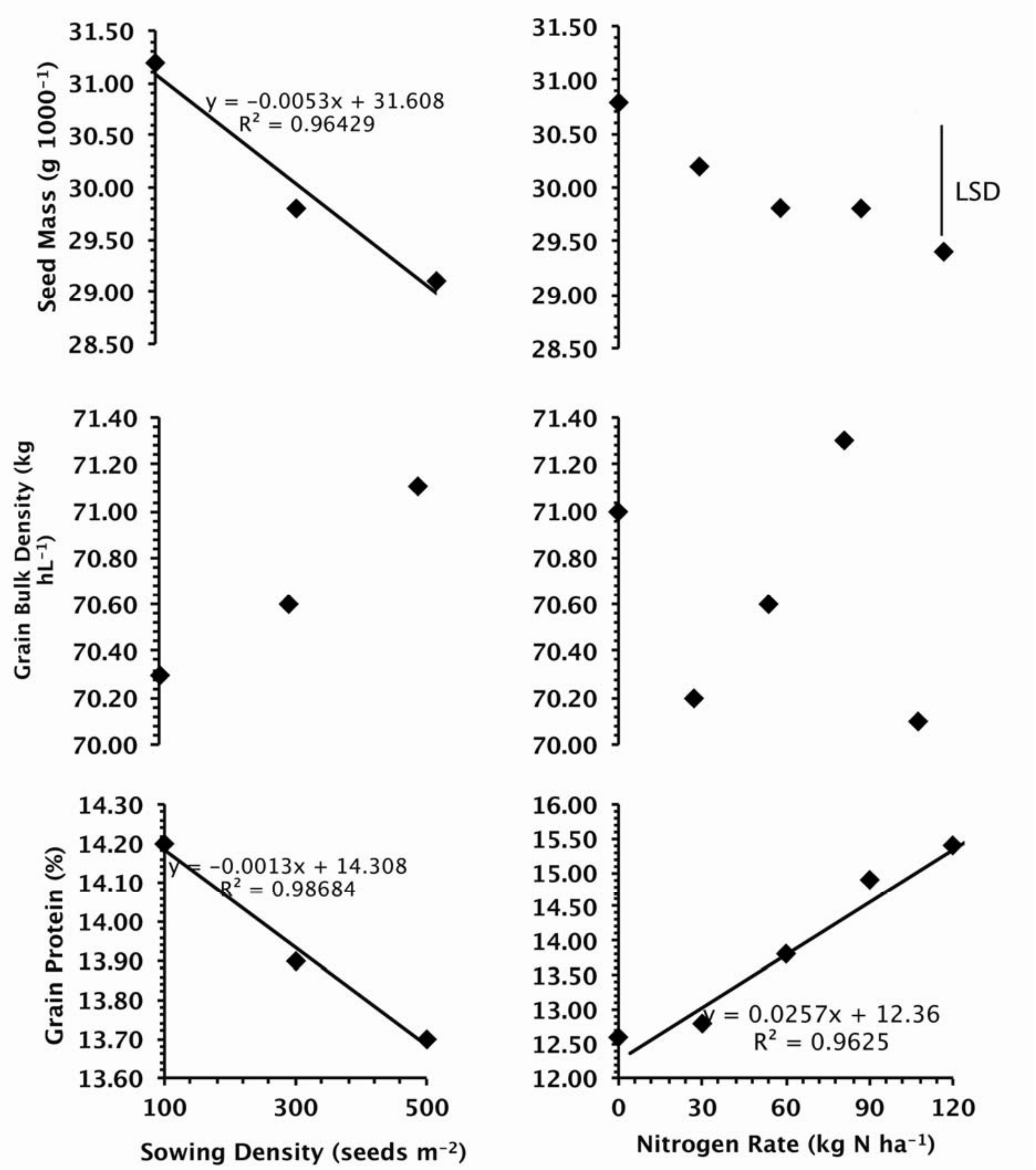

Figure 3-2c. Summary of main effect means grain quality parameters. Regression lines are presented when P ≤0.05.

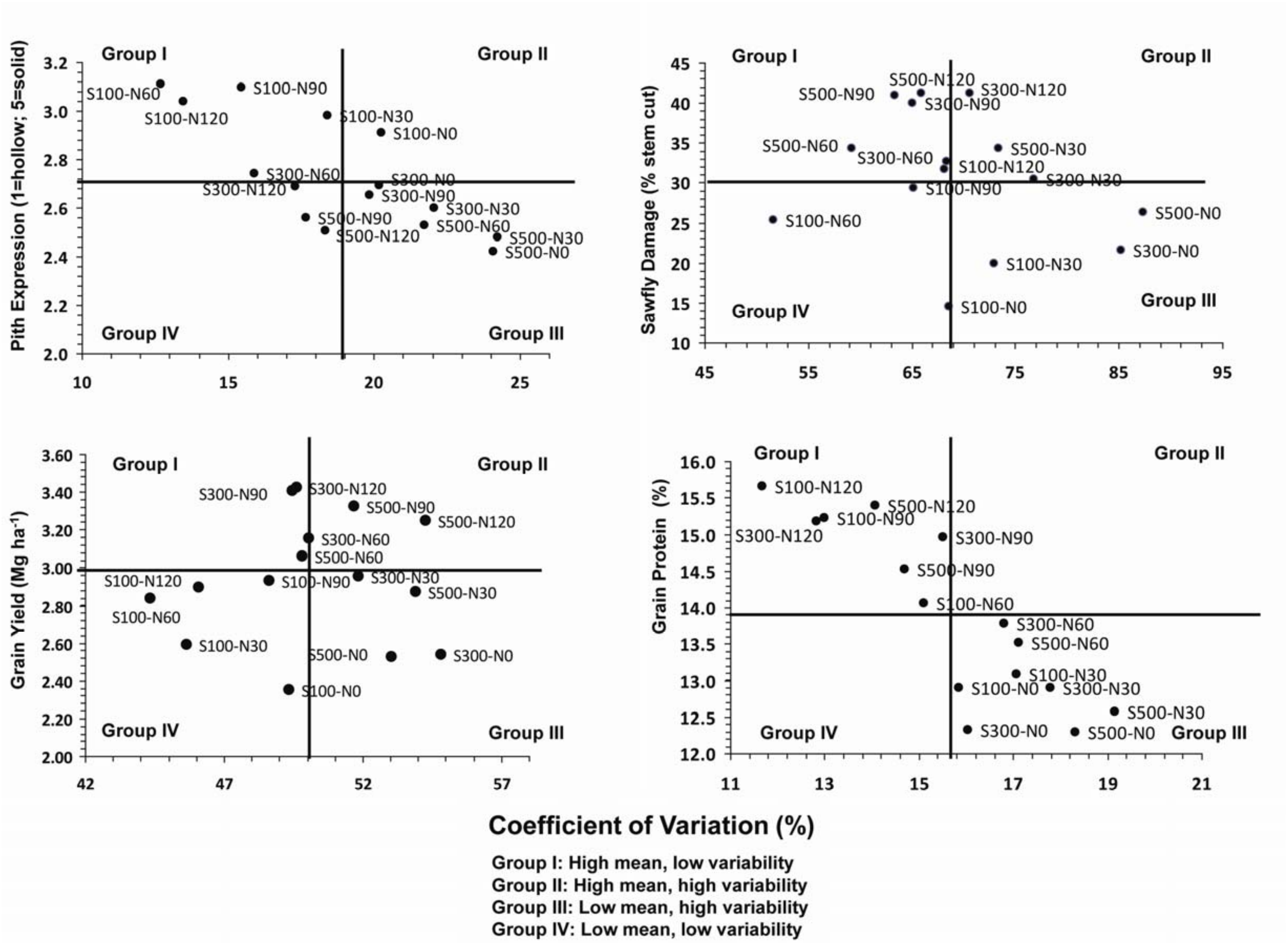

Figure 3-3. Biplot (mean vs. CV) of seed rate by banded N fertilizer rate combinations for data collected at Lethbridge and Bow Island, Alberta, Canada, 2007–2009. The first letter of the labels 'S' indicates the seed rate factor followed by planting density (100, 300, or 500 seeds m^{-2}), the following letter 'N' indicates the nitrogen rate effect followed by the rate of the treatment (0, 30, 60, 90, or 120 kg N ha^{-1}).

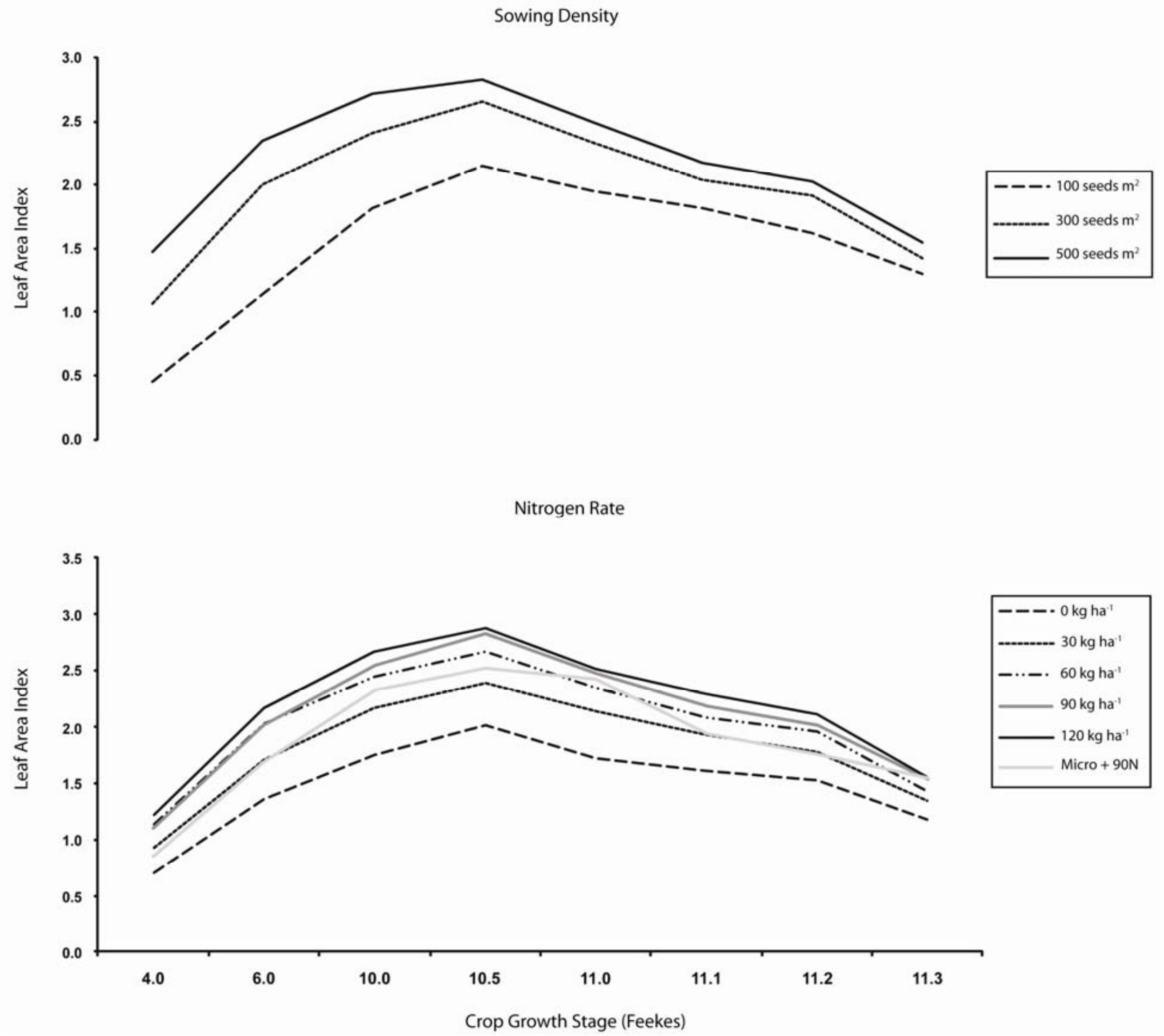

Figure 3-4. Leaf area index readings first recorded at Feekes 4 growth stage for plant density and nitrogen main effects averaged over data collected from Lethbridge and Bow Island, Alberta, Canada, 2007-2009.

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4.0 Integrating spring wheat variety selection, sowing density, and harvest management strategies to manage wheat stem sawfly[4]

4.1 Introduction

The wheat stem sawfly (WSS), *Cephus cinctus* Norton (Hymenoptera: Cephidae), has been a serious pest of wheat in the northern Great Plains since widespread production of the crop began in the late 19th century (Comstock, 1889). In the southern prairies of Canada, and in Montana, North and South Dakota, and western Minnesota it remains one of the most economically important insect pests of wheat (*Triticum aestivum* L.) (Beres et al., 2007; Weiss and Morrill, 1992). A comprehensive review of wheat stem sawfly biology and management can be found in Beres et al. (2011a; Chapter 1). Briefly, adults emerge from the previous year's crop stubble in late spring through early summer and, following mating, the female seeks out a suitable oviposition host plant, which is usually in an adjacent wheat field (Criddle, 1922). A healthy female can carry up to 50 eggs, therefore, the population can increase exponentially in a single generation (Ainslie, 1920). By the sixth or seventh day after an egg is deposited into a wheat stem, a larva will hatch and begin to bore the culm of the stem (Criddle, 1923). The stem boring activity continues throughout the growing season up to physiological maturity of the plant. Chlorosis associated with plant ripening and the reduction of whole plant moisture cues the larva to begin preparation to overwinter (Holmes, 1979). The larva moves to the base of the stem, notches a v-shaped groove around the stem, fills the region with frass (excrement), and encases itself in a thin cocoon below the groove. The groove weakens the stem and causes it to easily topple to the ground, which proves difficult to recover at harvest (Ainslie, 1929). The injury caused by the stem boring reduces photosynthetic rates (Macedo et al., 2007) and results in losses of spike weight that range from 10 to 17% (Holmes, 1977; Morrill et al., 1992; Seamans et al., 1944). An additional loss in yield potential occurs when toppled stems are not recovered at harvest (Ainslie, 1920; Beres et al., 2007). Thus, overall yield potential in wheat infested by WSS can be reduced by >25% or more, and the loss of anchored residue results in greater vulnerability to soil erosion and lower snow retention potential.

The use of solid-stemmed cultivars helps mitigate crop losses and can also affect the survivorship of *C. cinctus*. The mechanical pressure of developing pith in a solid stem confers on the plant a level of 'resistance' through mortality of the egg (Holmes and Peterson, 1961), and hindering the boring activity of larvae that do hatch. Thus, solid-stemmed wheat can cause negative effects to health, fitness and

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[4] *A manuscript of this chapter, excluding sections 4.2.2, 4.3.2 and Fig. 8, has been published in:* B.L. Beres, H.A. Cárcamo, R.-C. Yang, and D.M Spaner. 2011. Integrating spring wheat sowing density with variety selection to manage wheat stem sawfly. Agronomy Journal 103: 1755-1764. *Sections 4.2.2, 4.3.2, and Fig. 8 will be incorporated into a manuscript by S.M. Meers, K.J. Delaney, B.L. Beres, H.A. Cárcamo, P.R. Miller, L.M. Dosdall, and D.K. Weaver, to be submitted to the Journal of Economic Entomology.*

survivorship of WSS (Cárcamo et al., 2005; O'Keeffe et al., 1960). The plant's ability to develop pith in the culm of the stem, however, is influenced greatly by interactions between the genotype and the environment in which it is grown. All solid-stemmed spring and winter wheat cultivars developed to date derive resistance from the line S-615 (Kemp, 1934; Platt and Farstad, 1946), but two other sources exist (Clarke et al., 2005). The recessive nature of the genes controlling resistance derived from S-615 leads to inconsistent pith expression in the field (Hayat et al. 1995). This was acknowledged shortly after the solid-stemmed spring wheat cultivar Rescue was released, when observations of high susceptibility to stem cutting were noted at Regina, SK (Platt and Farstad, 1949). It was later determined that genes conferring pith development in the culm of a stem are influenced by photoperiod. Intense sunlight results in maximum expression and pith development, whereas shading or cloudy conditions inhibit pith development (Eckroth and McNeal, 1953; Holmes, 1984).

Solid-stemmed cultivars currently available in the Canada Red Western Spring class are AC Eatonia (DePauw et al., 1994), AC Abbey (DePauw et al., 2000), and Lillian (DePauw et al., 2005). Solid-stemmed spring wheat cultivars available in Montana include Fortuna and Choteau. Resistance in winter wheat is also important as Montana has a biotype of WSS that has gradually adapted to become synchronous to winter wheat growth phenology by emerging 10 to 20 days earlier than normal. The adaptation seems to have occurred as a response to a shift away from spring to winter wheat production (Morrill and Kushnak, 1996). Solid-stemmed winter wheat cultivars available to Montana producers include Vanguard (Carlson et al., 1997), Rampart and Genou (Bruckner et al., 1997; Bruckner et al., 2006). Solid-stemmed cultivars are available only in the bread wheat class in Canada. Five other classes of wheat are grown within the geographical range of *C. cinctus*; including amber durum spring wheat (*Triticum turgidum* L.), soft white spring wheat, hard red winter wheat, Canada prairie spring wheat, and general purpose wheat. Furthermore, the entire production area for durum in western Canada, Montana, and western North Dakota lies within the geographic range of *C. cinctus*.

Wheat row spacing and seeding rates can influence *C. cinctus* infestation rates, and the response varies between solid- and hollow-stemmed cultivars. Luginbill and McNeal (1958) reported that narrow row spacing and high seeding rates reduced stem cutting in Thatcher, a hollow-stemmed cultivar, but the same treatments reduced pith expression and led to increased levels of cutting damage in Rescue, a solid-stemmed cultivar. Cultivar development and genetic gain has advanced considerably in recent decades and a review of seeding rates for modern hollow- and solid-stemmed cultivars is warranted. Thus, research is needed to better define target plant populations so that an appropriate balance between yield potential, wheat stem sawfly management, and overall crop competitiveness is achieved.

Blending two cultivars (one hollow-, one solid-stemmed) with compatible maturity, market class attributes, and complementary strengths (Bowden et al., 2001) may be a feasible approach for management of wheat stem sawfly (Beres et al., 2011a; Chapter 1). This practice is commonly used in Kansas to achieve yield stability because abiotic and biotic stresses can be inconsistent and unpredictable. Montana studies report that the strategy can be successful at minimizing damage at low to moderate levels of sawfly pressure, but not at high levels (Weiss et al., 1990). Similarly, a 1:1 blend of solid-stemmed AC Eatonia and hollow-stemmed AC Barrie resulted in an 11% increase in yield potential in comparison to a monoculture of AC Barrie in Alberta (Beres et al., 2009).

Thus, cultivar selection should be considered a management tool that provides the foundation on which an integrated pest management (IPM) strategy is built, and which contributes to the higher goal of optimizing an integrated crop management (ICM) strategy (Chapters 1 and 5). Our objectives were 1) to determine if changes to cultivar selection and sowing density would alter wheat stem sawfly infestation patterns, and 2) to study responses by WSS endemic parasitoids to variety, stubble height and straw management at harvest. Thus, the following hypotheses were established: 1) the response of hollow- and solid-stemmed cultivars to sowing density may differ and subsequently affect WSS infestation patterns, and 2) harvesting methods may affect overwinter population of WSS endemic parasitoids.

4.2 Materials and methods

Two study locations in the traditional distribution area of the wheat stem sawfly were selected near Coalhurst (49º 44' N, 112º 57' W), and Nobleford, Alberta, Canada (49°54′N, 112°58′W). Both sites are an Orthic Dark Brown Chernozem clay loam soil (Typic Boroll). A new area at these locations was selected each year of the study, which was initiated in 2006 and completed in 2009 at Nobleford and 2010 at Coalhurst. The Coalhurst site was divided into wheat-fallow and continuous wheat cropping systems; the crop rotation at the Nobleford site was a diverse cropping system that alternated wheat with peas (*Pisum sativum* L.), canola (*Brassica napus* L.), barley (*Hordeum vulgare* L.) and flax (*Linum usitatissimum* L.). Experiments at each site were planted into a field of spring wheat stubble that was naturally infested the previous growing season with wheat stem sawfly. A total of 7 site-years of data were collected for agronomic and insect-related variables.

Soil nutrient status was determined from soil samples collected in fall and submitted to a commercial soil testing laboratory. Nitrogen and P_2O_5 fertilizer were side-banded at seeding or banded in the previous fall at rates according to recommendations for dryland wheat production (Beres et al., 2008; Selles et al., 2006).

4.2.1 Variety selection and sowing density

A split-plot, 4x4 factorial, arranged in a randomized complete block experimental design was used each year. To study effects of cultivar, four commercially grown varieties were selected and assigned to the main plot 1) monoculture hollow-stemmed durum spring wheat (*Triticum turgidum* L. cv. AC Avonlea) susceptible to WSS (Clarke et al., 1998), 2) monoculture solid-stemmed spring wheat (cv. Lillian) with resistance to WSS (DePauw et al., 2005) , 3) hollow-stemmed hard red spring wheat (cv. CDC Go) susceptible to WSS, and 4) a 1:1 blend of Lillian and CDC Go, achieved by using an air drill with separate grain compartments calibrated to meter out seed in equivalent rates to common seed tubes/openers. To study effects of planting density, four levels of seeding rate were selected and assigned to the subplot 1) 150 seeds m^{-2}, 2) 250 seeds m^{-2}, 3) 350 seeds m^{-2}, and 4) 450 seed m^{-2}.

Plots were seeded at Coalhurst and in year one and at Nobleford with a modified commercial zero tillage air drill manufactured by Vale Farms (Conserva Pak Model CP 129A, Indian Head, SK, Canada) and equipped with a Valmar air delivery system (Valmar Airflo Inc., Elie, MB, Canada). In all other years plots at Nobleford were seeded with a 13 m wide Morris air drill configured with single-shoot knife openers spaced 26 cm apart (Morris Industries, Saskatoon, SK, Canada). Treatment combinations were replicated four times with subplot experimental unit dimensions that measured 3.3 m wide x 5 m long at Coalhurst and 13 m wide x 50 m long at Nobleford. Each study area was treated with glyphosate (RoundUp®, Monsanto, St. Louis, MO, USA) a few days prior to seeding at a rate of 900 g a.i. ha^{-1} using a motorized sprayer calibrated to deliver a carrier volume of 45 L water ha^{-1} at 275 kPa pressure. In-crop herbicides were chosen based on the weed spectrum present at each site-year, and applied in early June at label rates. No insecticides were used at any site during the study period.

Temperature and light intensity data collection was initiated in 2007 at each site using Hobo Pendant temperature and light loggers (Onset Computer Corporation, Bourne, MA, USA; part no. UA-002-XX). The data loggers were attached near the top of 1m fibreglass'whisker stakes' (Imagine That Signs and Designs, Saskatoon, AB, Canada) and positioned at the center of each of the three ranges.

Plant counts were performed in mid- to late-May by staking a 1-m section in two randomly selected areas of the plot. The staked sections were counted again in mid- to late-July to assess spike density. To ensure an adequate estimate of stem solidness (Cárcamo et al., 2007), a 0.50 m section of row was collected in late-July or early-August in two random locations in each plot to determine stem diameter and pith expression or degree of stem solidness in the culm of the main stem. Mean stem diameter was determined by measuring the outside diameter of the first three internodes using a digital caliper. To determine mean pith expression, each stem was then split lengthwise from crown to neck, and starting from the crown, each internode was assessed visually for pith development. Ratings were as follows: 1 - Hollow stem - no pith development; 2 - Some degree of pith development - may appear ‘cotton like’; 3 - Large hollow tunnel in the stem, or, a huge cavity at a particular point in the internode; 4 - Size of hollow equivalent to a pencil lead, or, some cavitation has occurred at a particular point in the internode; and 5 - Solid stem (DePauw and Read, 1982). The samples were also used to determine infestation rates by WSS (live/dead larva, frass or evidence of stem boring) and parasitism of WSS (parasitized WSS larva, parasitoid, parasitoid cocoon, or exit holes) by *Bracon cephi* (Gahan) (Hymenoptera: Braconidae).

Plots were harvested at crop maturity using a Wintersteiger Expert (Wintersteiger AG, Salt Lake City, UT, USA) plot combine equipped with a straight cut header, pickup reel and crop lifters. Grain yield was calculated from the entire plot area at Coalhurst and from a 1.5 m x 50 m subsample of the plot in Nobleford. All grain collected from plots at Coalhurst and a 5 kg subsample from Nobleford were retained post-harvest to characterize seed weight (g 1000^{-1}), grain bulk density (kg hL^{-1}) and grain protein. Grain protein concentration was determined from whole grain using near infrared reflectance spectroscopy technology (Foss Decater GrainSpec, Foss Food Technology Inc, Eden Prairie, MN).

Data were analyzed with the MIXED procedure of SAS (Littell et al., 2006). Homogeneity of error variances was tested using the UNIVARIATE procedure of SAS; and any outlier observations were removed before a combined analysis over years and environments (site-years) was performed. Normality assumptions were also tested on the categorical data ‘pith expression’ and observational ‘Infestation by WSS (%)’ and ‘Parasitism of WSS (%)’ data as multiple categories were used for rating pith expression; and infestation and parasitism were expressed as percentages with a value distribution that was generally not extreme (Cochran, 1954). For analyses by environments, replicate was considered random and treatment effects were considered fixed; and significant if $P \leq 0.05$. Results by environment indicated similar treatment response patterns among environments; therefore, a combined analysis was performed with replicate, years, environments and their interactions considered random effects and treatment effects fixed and significant if $P \leq 0.05$. Pearson partial correlation coefficients were performed using the CORR procedure of SAS on raw data to determine the contribution of each yield component to overall yield performance. Response variable least square means generated for each site-year were used to create a Pearson correlation coefficient matrix of insect-related variables, stem diameter, stem solidness, grain yield, yield components, and grain protein data using the CORR procedure of SAS.

A grouping methodology previously described by Francis and Kannenberg (1978) and later adapted to agronomy studies (Beres et al., 2010b; Gan et al., 2009; May et al., 2010) was used to further explore treatment responses. The mean and coefficient of variation (CV) were estimated for each level of the treatment and plotted against each other. The overall mean of the treatment means and CVs was included in the plot to categorize the biplot ordination area into four quadrats/categories: Group I: High mean, low variability (optimal); Group II: High mean, high variability; Group III: Low mean, high variability (poor); and Group IV: Low mean, low variability.

4.2.2 Harvest management

A split-split-plot, 3x2x3 factorial was imposed on the 350 seeds m^{-2} level of sowing density with main plots assigned to the cultivar treatments AC Avonlea, Lillian, and CDC Go. The plots were split at harvest to create 2 levels of straw management, 1) Chopped straw, created by running all threshed material through a chopper installed at the rear of the threshing case of the plot combine, 2) Not chopped, which was performed by disengaging the chopper, which allowed the straw to be deposited directly on the ground after threshing. The straw management effects were sub-divided into 3 harvesting heights 1) **Low,** the table and cutter bar height of the pickup on the combine was lowered to ground level to cut and thresh all material above the soil surface, 2) **15 cm,** the table height and cutter bar height was set at 15 cm above ground level, and 3) **Spikes only,** the table height and cutter bar height was raised to a maximum height so that only the grain spikes were harvested from the stem.

The straw deposited by the combine harvester for each sub-sub-plot (6 experimental units per main plot) was covered with a 1 m^2 mesh screen and secured to the ground using washers and metal spikes (www.smallparts.com). This ensured the *Bracon cephi* parasitoid population housed within the harvested straw could overwinter in the natural environment. In mid- to late-May, prior to emergence of the parasitoid and WSS populations, a 1 m x 1 m-base triangular emergence cage (Dosdall et al., 1996) was placed over the mesh screen. The primary collection device consisted of a 700 mL glass jar with a funnel-shaped, amber lumite 530 micron mesh screen (BioQuip Products, Rancho Dominquez, CA, USA) inserted into the jar and secured by a ring-lid. The jar was inverted and placed through a circular opening on top of the cage cut wide enough to accommodate the outside diameter of the ring-lid. Sticky cards (Contech Inc, Delta, B.C. Product No. 611 – bright yellow) measuring 7.6 cm x 12.7 cm were mounted on wooden stakes and placed inside the emergence cage to act as a secondary trap. To prevent any escapes, the screen on the cages received an application of 3M (3M Automotive, St. Paul, MN) automotive coating (part #08964) applied with a 3M Schutz^{tm} applicator gun (part # 08801), which reduced the opening but did not completely seal the mesh. Three times weekly, newly eclosed *Bracon cephi* adults emerging from the straw were collected from the cage jars and sticky cards, and grouped by gender.

Four site-years were determined to have acceptable levels of parasitoid emergence (Nobleford in 2007 and 2009; Coalhurst in 2008 and 2010). Convergence criteria was met when data were collapsed into a one-way analysis for each of the three main effects using the GLIMMIX procedure of SAS (SAS Institute, 2005) . For analyses by environments, replicate was considered random and the treatment main effects were considered fixed and significant if $P \leq 0.05$. Results by environment indicated similar treatment response patterns among the four environments; therefore, a combined analysis was performed with replicate, years, environments and their interactions considered random effects and treatment main effects treated as fixed effects and significant if $P \leq 0.05$.

4.3 Results and discussion

Average annual and growing season precipitation during the study period was below average in two of five years at Coalhurst and two of three years at Nobleford (Table 4-1). However, the 2006 season at both sites benefitted from above average rainfall and subsequent soil moisture reserves experienced in 2005. The 2007 sites were most adversely affected by low rainfall during critical periods of crop growth. Nobleford received above average precipitation in 2008, and the final two years at Coalhurst received average to above-average precipitation. The precipitation patterns for 2008 are also evident in the temperature and light intensity data summarized in Table 4-1. Temperatures and light intensity generally peaked in July for all other years but declined sharply after June in 2008. Trends in light intensity and temperature were similar at both sites, with the notable exceptions of greater decline of light intensity at Nobleford in 2007, and higher overall temperature and light intensity in Nobleford in 2008 (Table 4-1). Temperature peaked in 2007 at both sites, which was the hottest month of the entire study period and corresponds to the arid conditions experienced at both sites; however, light intensity was lower in 2007 than in other years (Table 4-1).

4.3.1 Variety selection and sowing density effects.

Infestation rates by WSS on wheat cultivars differed between the hard red spring wheat class and the durum cultivar AC Avonlea, but did not differ between hard red spring wheat cultivars within the hard red spring wheat class (Table 4-2). The use of AC Avonlea durum reduced infestation rates by around 40% compared to CDC Go or the blend of CDC Go and Lillian. The relationship between infestation rates by WSS and the rate of parasitism on WSS by the parasitoid *B. cephi* is apparent as both variables displayed similar trends among the cultivar treatments. However, the downward linear trend for WSS infestation with increased seeding rates ($P=0.02$) was not evident in the rate of WSS parasitism (Fig. 4-1; Table 4-2).

As expected, pith expression was greatest in the solid-stemmed hard red spring wheat variety Lillian, lowest in the hollow-stemmed CDC Go, and intermediate in the blend treatment (Table 4-2). Compared to the other hollow treatments, a higher pith rating was recorded for AC Avonlea and is likely due to the thicker stem wall of durum wheat compared to most bread wheat cultivars, which creates a smaller observed cavity in the lumen of the stem (Damania et al., 1997). Reduced pith expression and stem diameter was observed as seeding rates increased over the low rate of 150 seeds m^{-2} (Table 4-2; Fig. 4-1). Single degree of freedom contrast results indicate that the best fit of the response was linear but the significant quadratic response for both traits may indicate that the downward trend was not strictly linear. Wallace et al. (1973) reported that a mean pith expression of 3.75 would be required to achieve consistent high tolerance to wheat stem sawfly infestations. We did not observe this degree of stem solidness in Lillian (3.0), which indicates that the weather parameters or the genetic potential of Lillian prevented maximum resistance to wheat stem sawfly infestation. The results reinforce the concept that cultivars with tolerant attributes cannot be relied upon in the absence of other management tactics.

The interaction of variety and seeding rate (P=0.003) was explored further and is summarized in Fig. 4-2. Increasing seeding rates from 150 to 450 seeds m^{-2} generally reduced rates of infestation by 25% in the bread wheat blend and CDC Go treatments. However, the non-significant downward trend for the solid-stemmed variety Lillian and the observed reduction in pith expression at higher seeding rates reinforces recommendations that planting densities for solid-stemmed varieties should not exceed a range of 250 to 300 seeds m^{-2} (Beres et al., 2011b; Chapter 5). Host preference by WSS for bread wheat treatments over the durum variety AC Avonlea resulted in low infestation rates in AC Avonlea irrespective of plant density (Fig. 4-2).

The most attractive host for WSS is a cereal plant that is succulent, in the boot or early anthesis stage, and has a suitable stem diameter that can be readily grasped by an ovipositing female (Holmes and Peterson, 1960). The preference for larger stems was not supported in the cultivar effect as AC Avonlea had the largest stem diameter but lowest infestation rate. However, the preference does correspond to the sowing density results as increased sowing density reduced stem diameter and infestation rates (Fig. 4-2). The low infestation we report for the durum cultivar has been observed in other studies (Goosey et al., 2007), but the rate of infestation could change if host choice is removed, which would be the case in large monoculture fields of durum wheat (Holmes and Peterson, 1960). Therefore, the adoption of durum cultivars over hard red spring wheat would not necessarily reduce WSS damage.

Average yield, yield component and grain quality responses were affected by variety selection (Table 4-3). Grain yield was greatest for the durum variety AC Avonlea (0.2 to 0.4 Mg ha^{-1} greater than the average of other varieties) and least for the solid-stemmed variety Lillian, with intermediate yields observed for CDC Go and the blend of CDC Go and Lillian (Table 4-3). Stand establishment response did not differ between varieties but spikes per plant and spike density was low for AC Avonlea compared to the averages of the bread wheat treatments (Table 4-3). Thus, the large kernel weight and fewer tillers per plant likely accounted for AC Avonlea's greater grain yield.

All yield, yield component and grain quality variables, except seed mass, responded to the effect of seeding rate (Table 4-3). High grain yield, stand establishment, spike density, and grain bulk density were associated with the highest seeding rate of 450 seeds m^{-2} (Figs. 4-3 and 4-4), but the increase generally diminished after 250 seeds m^{-2} (yield) or 350 seeds m^{-2} (stand establishment, spike density, and bulk density) (Table 4-3). When averaged over all varieties, plants responded to higher seeding rates and subsequent greater plant density by aborting tillers and partitioning more resources to the main stem (Table 4-3; Fig. 4-3). This response generally produced more grain (+0.6 Mg ha^{-1} from lowest to highest seeding rate) and suggests that production of more than a single tiller would compromise grain yield optimization. This is apparent in the grain yield results of AC Avonlea where it produced the highest grain yield with the fewest spikes per plant.

The interaction between variety and sowing density (P=0.0003) for grain yield indicates a similar positive response by the variety treatments when seeding rates increase from 150 to 450 seeds m^{-2} (Fig. 4-5). The pattern is most evident in the AC Avonlea results and indicates that benefits at the highest sowing density level may be best when a cultivar and/or the agroecological zone in which the cultivar is grown, is selected that has greater yield potential. The results for the bread wheat variety treatment suggest that the decision to increase seeding rates beyond 250 seeds m^{-2} would need to be based on factors other than just yield performance. In a weed competition study, Beres et al. (2010a) reported high yield response for the durum variety AC Avonlea when planted at 400 seeds m^{-2} (5.3 Mg ha^{-1}). Increased competitive ability with weeds and positive yield response at higher sowing densities has been reported in several studies involving winter wheat (Beres et al., 2010b), canola (Harker et al., 2003), and barley (Harker et al., 2009; O'Donovan et al., 2000; O'Donovan et al., 2009). Increased sowing densities may also reduce the reliance on herbicides for weed control or increase the efficacy when herbicide rates are reduced (O'Donovan et al., 2006). However, the rationale for higher seeding rates to enhance crop performance and competitive ability for wheat would not apply to solid-stemmed cultivars as pith expression is reduced when sowing density is increased.

Grain protein accumulation did not differ between the bread wheat varieties CDC Go (13.2%) and Lillian (13.4%) when planted in monoculture or blended together (Table 4-3). Protein averaged 1% lower in AC Avonlea durum compared to the bread wheat variety treatments. All variety treatments produced sufficient protein to meet the minimum #1 grade criteria (≥11.5%) set by the Canadian Wheat Board, but were all lower than the uppermost protein premium of 14.5%. The inverse relationship between grain yield and protein content is apparent in Table 4-2 and Fig. 4-4 as increasing sowing densities from the lowest to the highest seeding rate reduced grain protein by 5%.

We conducted partial correlation analyses between each yield component and final yield (Littell et al., 2006). These analyses were conducted to examine the direct effect of a given yield component upon final yield, where the effect of all other yield components are held constant. Averaged over all seeding rates and cultivars, Pearson partial correlation coefficients indicate that seed mass and spike density were primarily responsible for differences in grain yield (Table 4-4). This makes agronomic sense as the highest kernel weight was observed in the variety with the highest yield potential (AC Avonlea), and the single degree of freedom contrasts indicate a strong linear response in both stand establishment and grain yield with increasing seeding rates (Table 4-3; Fig. 4-3).

Biplots were constructed (Figs. 4-6 and 4-7) to study the stability of insect- and crop-related variable responses and to determine which variety x seeding combinations offer the best integrated system for WSS management. Optimum pith expression over a range of environments is necessary for a solid-stemmed cultivar to effectively reduce the negative effects of WSS. Higher pith expression in Lillian was observed in the 150 seeds m^{-2} treatment but the result was not as consistent as it was for the 250 or 350 seeds m^{-2} treatments (Fig. 4-6). Poor pith expression in CDC Go is expected as it is a hollow-stemmed cultivar, and the most consistent rating for AC Avonlea occurred at the highest seeding rate. Infestation rates were consistently highest for CDC Go and Lillian in monoculture and when blended together at the lowest seeding rate. Infestation dropped at the higher seeding rates for these treatments but with higher variability. Infestation for AC Avonlea was low and variable at all sowing densities (Fig. 4-6). Rates of parasitism on WSS followed a similar pattern to WSS infestation but the results for Lillian were more variable than any other treatment. For hollow-stemmed treatments, sowing densities of 350 seeds m^{-2} generally produced above average yield and stability. A sowing density of 450 seeds m^{-2} often increased yield in the hollow-stemmed treatments but with greater instability (Fig. 4-7). Yield of Lillian was generally below average at all seeding rates but produced consistently stable yields at the 350 seeds m^{-2} rate. The lowest rate produced inferior grain yields with poor overall stability. The inverse of the yield results were generally observed in the protein biplot (Fig. 4-7).

Correlation coefficients were generated to further explore relationships between insect-related parameters, yield, and yield component parameters (Table 4-5). Positive correlations were observed between rates of parasitism on WSS and the crop parameters grain yield and spikes per plant. The positive effect of parasitism on crop yield or mitigation of crop yield losses caused by WSS has been reported in a Montana study (Buteler et al., 2008), however, the relationship has not been observed in studies in southern Alberta (Wu et al., 2011). Negative correlations were observed between infestation rates by WSS and stand establishment, spike density and grain protein content. Larger stem diameter appears to positively affect the yield components spike density and spikes per plant but a negative relationship was observed for stand establishment. A negative relationship between grain yield and stand establishment was also observed. The negative association with stand establishment does not agree with a previous finding that reports a positive association (Chapter 3), which may be more plausible given that yield potential is dependant upon optimum plant stand or a high degree of tillers per plant. The result may indicate some of the treatment combinations in this study had a higher tillering capacity than what was observed in Chapter 3.

4.3.2 Harvest management effects

Responses for total and male *Bracon cephi* emergence in the main effects variety, straw management and cutting height at harvest were highly significant when averaged over all site-years (data not shown). Female *Bracon cephi* populations were altered by variety but emergence patterns were not altered by straw management or harvesting heights (data not shown). Parasitoid emergence was lower for AC Avonlea (Fig. 4-8). Infestation by WSS and subsequent parasitism rates were also low for AC Avonlea in the main experiment. There was no difference in parasitoid emergence between the hollow-stemmed variety CDC Go and the solid-stemmed Lillian. Processing straw through a chopper at harvest prior to returning the straw to the ground did reduce total parasitoid emergence by around 20% (Fig. 4-8). Most commercial combines are equipped with a straw chopper as straw is usually retained in the field, and the effect of chopping promotes rapid decomposition of the straw back into soil organic matter, which is critical in rainfed wheat production systems (Tarkalson et al., 2011). This also enhances residue management and increases the efficiency of re-cropping into standing stubble the following year. Therefore, the level of conservation of beneficial insects from not chopping straw at harvest is likely inadequate to justify removal of the straw chopping system since it did retain 80% of the parasitoid population. The reduction of parasitoid populations from chopping straw has been reported previously in a study that simulated chopping by shredding straw samples with a string trimmer (Meers, 2005). However, the negative effects from simulated straw chopping created a 100% reduction in parasitoids (Meers, 2005), whereas, we elected to use a combine chopper and left the straw samples in the field to expose them to the natural overwintering conditions. Therefore, the reduction of parasitoids in the simulated chopping methodology may have been overstated; and the incremental reduction we observed in the *Bracon cephi* population would not justify removal of the chopping step at harvest.

Alternatively, the focus at harvest may be better served by altering the stubble height, as increased cutting heights conserved *Bracon cephi* male and total populations (Fig 4-8). Compared to a low cutting height, increasing harvesting heights to 15 cm or higher to remove only the grain spikes increased total emergence of *Bracon cephi* by 40% and 60%, respectively (Fig. 4-8). The benefits of increasing harvesting heights to conserve beneficial parasitoids of WSS was also observed in a Montana study (Meers, 2005).

4.4 Conclusions

The differential response between hollow- and solid-stemmed cultivars and varying rates of sowing density suggest that a management package for wheat stem sawfly must take into account the stem type. The solid-stemmed cultivar Lillian generally had optimized grain yield and high and stable pith at the 250 to 350 seeds m^{-2} sowing densities. A higher sowing density for hollow-stemmed treatment is warranted based on the findings that infestation rates tended to decrease with increased seeding rates, and parasitism of WSS was also high at the higher seeding rates. There may also be other benefits related to enhanced competitive ability that were not part of this study. For wheat produced in regions prone to wheat stem sawfly infestation we encourage seeding rates of ≤ 300 seeds m^{-2} for solid-stemmed cultivars and recommend increasing the rate into the range of 400 to 450 seeds m^{-2} for hollow-stemmed cultivars.

The harvest management results underscore the need to integrate cultural practices as the ability to increase heights will only be accomplished if most of the wheat is still standing and has not lodged as a result of WSS infestation. Therefore, the use of solid-stemmed cultivars is encouraged if the market class is for bread wheat. If an alternative market is desired that requires the use of a hollow-stemmed cultivar, a higher seeding rate would be encouraged. Irrespective of stem type or market class of wheat, swathing prior to harvest can also increase the height of standing stubble and would ensure all infested stems are windrowed before toppling to the ground. However, swathing heights could not be raised sufficiently to accomplish the removal of only the spikes. This would require a straight-cutting operation at harvest and may necessitate the use of a stripper-header.

4.5 Summary

The wheat stem sawfly (*Cephus cinctus* Norton (Hymenoptera: Cephidae)) has been a serious pest of wheat (*Triticum aestivum* L.) since widespread production of the crop began in the late 19th century. Adoption of solid-stemmed cultivars, which are available only in the spring bread wheat class in Canada, can help to mitigate damage but the mechanism of resistance tends to be variable. Solid-stemmed cultivars have pith in the stem which protects the plant from the stem boring activity of a sawfly larva. Five other classes of wheat are grown within the geographical range of *C. cinctus* and are vulnerable to WSS infestation, and the entire production area for durum (*Triticum turgidum* L.) in western Canada, Montana, and western North Dakota lies within the geographic range of *C. cinctus*. Our objectives were to: 1) determine if changes to cultivar selection and sowing density (150, 250, 350, or 450 seeds m^{-2}) would alter wheat stem sawfly infestation patterns, and 2) to study responses by WSS endemic parasitoids to variety, stubble height and straw management at harvest. Thus, the following hypotheses were established: 1) the response of hollow- and solid-stemmed cultivars to sowing density may differ and subsequently affect WSS infestation patterns 2) harvesting methods may affect overwinter population of WSS endemic parasitoids. The lowest rates of infestation occurred in the hollow-stemmed durum cultivar AC Avonlea and declined with increased sowing density. Wheat pith expression was optimized at the lowest sowing density but the same level produced low and variable grain yield. In the solid-stemmed cultivar Lillian, pith expression was most stable at 250 or 350 seeds m^{-2}. Grain yield was optimized at the higher seeding rates of 350 or 450 seeds m^{-2}. Solid-stemmed wheat should be seeded at low to moderate density to maximize resistance to wheat stem sawfly, but hollow-stemmed cultivars should be seeded at higher seeding rates to optimize yield, lower WSS infestation, and to increase overall crop competitiveness.

At harvest, parasitism emergence rates were low for AC Avonlea, which is not a surprise as WSS infestation rates in AC Avonlea were also low. There was no difference in parasitoid emergence between the hollow-stemmed variety CDC Go and the solid-stemmed Lillian. Increased cutting heights conserved *Bracon cephi* male and total populations. The incremental benefit in parasitoid conservation through not chopping straw at harvest would not justify elimination of the chopping operation at harvest as this is a critical step in straw management. Compared to a low cutting height, increasing harvesting heights to 15 cm or higher to remove only the grain spikes increased total emergence of *Bracon cephi* by 40% and 60%, respectively. Optimal conservation of parasitoids would therefore occur when harvest cutting stubble heights are adjusted to 15 cm or greater; and later harvests would ensure the 2nd generation of *B. cephi* has emerged.

4.6 Acknowledgements

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4.7 Tables

Table 4-1. Description of test sites at Coalhurst and Nobleford, Alberta, Canada, and summary of agronomic practices performed during the study period 2006-09.

Variable												
Location	**Coalhurst, Alberta, Canada**							**Nobleford, Alberta, Canada**				
Latitude and Longitude	49°44′N, 112°57′W							49°54′N, 112°58′W				
Soil Zone/Series/Texture	Orthic Dark Brown Chernozemic Clay Loam (Typic Boroll)							Orthic Dark Brown Chernozemic Clay Loam (Typic Boroll)				
Crop Year	**2006**	**2007**		**2008**		**2009**		**2006**	**2007**		**2008**	
Sowing Date	6 May	25 April		30 April		4 May		17 May	17 April		30 May	
Harvest Date	1 September	5 September		9 September		11 September		12 September	28 August		30 September	
Mean Temperature and Light Intensity (Lm m^{-2}) x 1000	---	**°C**	**Lux**	**°C**	**Lux**	**°C**	**Lux**	---	**°C**	**Lux**	**°C**	**Lux**
June	---	19.3	26.8	21.9	26.4	---	---	---	20.5	28.4	22.1	49.7
July	---	25.2	29.3	20.8	27.2	20.8	30.6	---	26.2	28.8	20.9	42.7
August	---	21.3	28.4	20.8	20.4	19.4	25.0	---	20.7	24.8	20.9	37.1
Precipitation (mm)												
May 1 to Sept. 15 Long Term average = 251	150	164		380		241		150	164		380	
Annual Long Term average = 398	331	342		525		417		331	342		525	

Table 4-2. Insect data summary of least square means for main effects variety and seeding rate, collected from sites near Nobleford and Coalhurst, Alberta, Canada 2006-10.

Factor	Treatment	WSS Infestation (%)	Parasitism of WSS (%)	Pith Rating (1=hollow; 5=solid)	Stem Diameter (mm)
Variety (main plot)	AC Avonlea	30	8	2.4	2.62
	Lillian	43	16	3.0	2.46
	1: 1 Blend of Lillian:Go	51	22	2.1	2.52
	CDC Go	52	28	1.4	2.65
	SED†	5.02	4.58	0.182	0.043
	Pr > F	0.002	0.003	<0.0001	0.0011
	$LSD_{0.05}$‡	10	9	0.38	0.09
Seed Rate (subplot)	150 seeds m^{-2}	49	21	2.4	2.69
	250 seeds m^{-2}	44	18	2.2	2.57
	350 seeds m^{-2}	42	18	2.2	2.51
	450 seeds m^{-2}	41	18	2.2	2.49
	SED	3.62	1.54	0.054	0.026
	Pr > F	0.109	0.224	0.006	<0.0001
	$LSD_{0.05}$	--	--	0.12	0.05
Contrasts (Pr > F)	Linear	0.021	0.162	0.002	<0.0001
	Quadratic	0.449	0.138	0.046	0.026
	Cubic	0.949	0.616	0.811	0.934
Var. x Seed Rate	Pr > F	0.003	0.261	0.391	0.353

† SED, Standard error of the difference.

‡ LSD, Fisher's protected least significant difference.

Table 4-3. Agronomic summary of least square mean responses for main effects of variety and seeding rate, collected from sites near Nobleford and Coalhurst, Alberta, Canada 2006-09.

Factor	Treatment	Grain Yield (Mg ha^{-1})	Stand Establishment (plants m^{-2})	Spike Density (heads m^{-2})	Seed Mass (g 1000^{-1})	Grain Bulk Density (kg hL^{-1})	Grain Protein (%)	Spikes per plant
Variety (main plot)	AC Avonlea	3.15	163	281	39.9	76.7	12.2	2.1
	Lillian	2.75	183	367	30.1	75.7	13.4	2.5
	1:1 Blend of Lillian:Go	2.93	169	344	32.5	76.2	13.4	2.5
	CDC Go	2.90	169	335	34.5	76.7	13.2	2.5
	SED†	0.107	7.57	11.80	0.713	0.392	0.254	0.117
	Pr > F	0.0138	0.109	<0.0001	<0.0001	0.044	0.0004	0.011
	$LSD_{0.05}$‡	0.23	--	26	1.50	0.82	0.53	0.26
Seed Rate (subplot)	150 seeds m^{-2}	2.56	115	288	34.3	75.3	13.5	2.8
	250 seeds^{-2}	2.98	157	323	34.3	76.4	13.0	2.5
	350 seeds m^{-2}	3.02	196	354	33.9	76.6	12.9	2.2
	450 seeds m^{-2}	3.16	214	362	34.1	76.9	12.8	2.1
	SED	0.118	10.87	10.69	0.226	0.176	0.121	0.097
	Pr > F	0.0005	<0.0001	<0.0001	0.207	<0.0001	0.0002	<0.0001
	$LSD_{0.05}$	0.24	24	21	--	0.37	0.25	0.21
Contrasts (Pr > F)	Linear	0.0001	<0.0001	<0.0001	0.107	<0.0001	<0.0001	<0.0001
	Quadratic	0.099	0.133	0.068	0.651	0.003	0.058	0.277
	Cubic	0.205	0.608	0.581	0.179	0.080	0.517	0.506
Var. x Seed Rate	Pr > F	0.0003	0.399	0.082	0.011	0.310	0.496	0.183

† SED, Standard error of the difference.

‡ LSD, Fisher's protected least significant difference.

Table 4-4. Pearson partial correlation coefficients of spring wheat yield components grown in a semi-arid agroecosystem commonly prone to wheat stem sawfly attack.

Pearson Partial Correlation Coefficients				
	Stand Establishment	**Spike Density**	**Spikes per plant**	**Seed Mass**
Grain Yield	-0.13	0.64	-	0.66

† '-' = P >0.05; all other r values presented at P ≤0.05.

Table 4-5. Correlation matrix of insect-related variables, grain yield, yield components, and grain protein in spring wheat grown in areas prone to wheat stem sawfly attack.

Pearson Correlation Coefficients								
	Stem Solidness	**Rate of Parasitism on WSS**	**Stems Infested by WSS**	**Grain Yield**	**Stand Establishment**	**Spike Density**	**Spikes per Plant**	**Grain Protein**
Stem Diameter	-	-	-	-	-0.53	0.27	0.49	-
Stem Solidness	1	-0.42	-	-0.22	-	-	-	-
Rate of Parasitism		1	0.77	0.23	-0.53	-	0.42	-
Stems Infested by WSS			1	-	-0.42	-0.26	-	-0.26
Grain Yield				1	-0.48	0.71	0.70	-0.23
Stand Establishment					1	-0.22	-0.82	0.25
Spike Density						1	0.56	-
Spikes per Plant							1	-
Grain Protein								1

† '-' = $P > 0.05$; all other r values presented at $P \leq 0.05$.

4.8 Figures

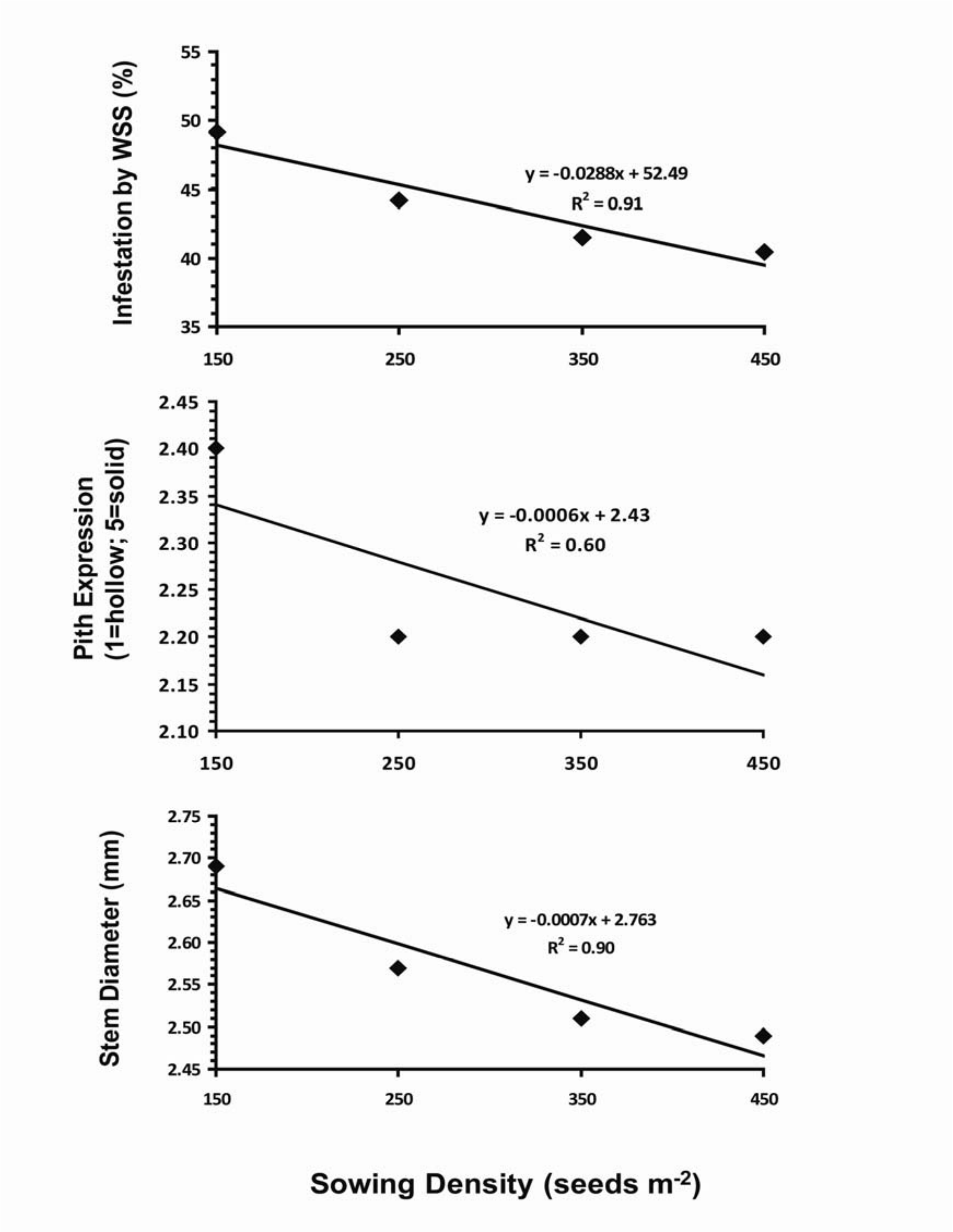
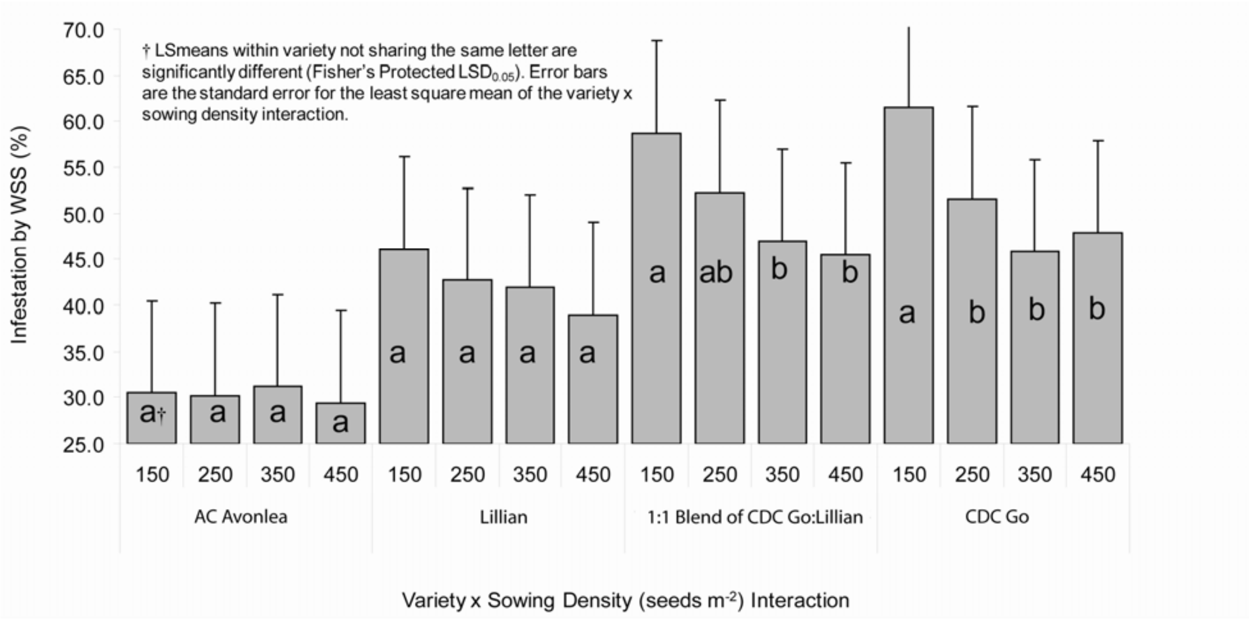


Figure 4-1. Summary of sowing density effects on the response of insect-related parameters. Regression lines are presented when P ≤0.05.



† LSmeans within variety not sharing the same letter are significantly different (Fisher's Protected $LSD_{0.05}$). Error bars are the standard error for the least square mean of the variety x sowing density interaction.

Figure 4-2. Response of WSS infestation rates to the interaction of variety selection and sowing density.

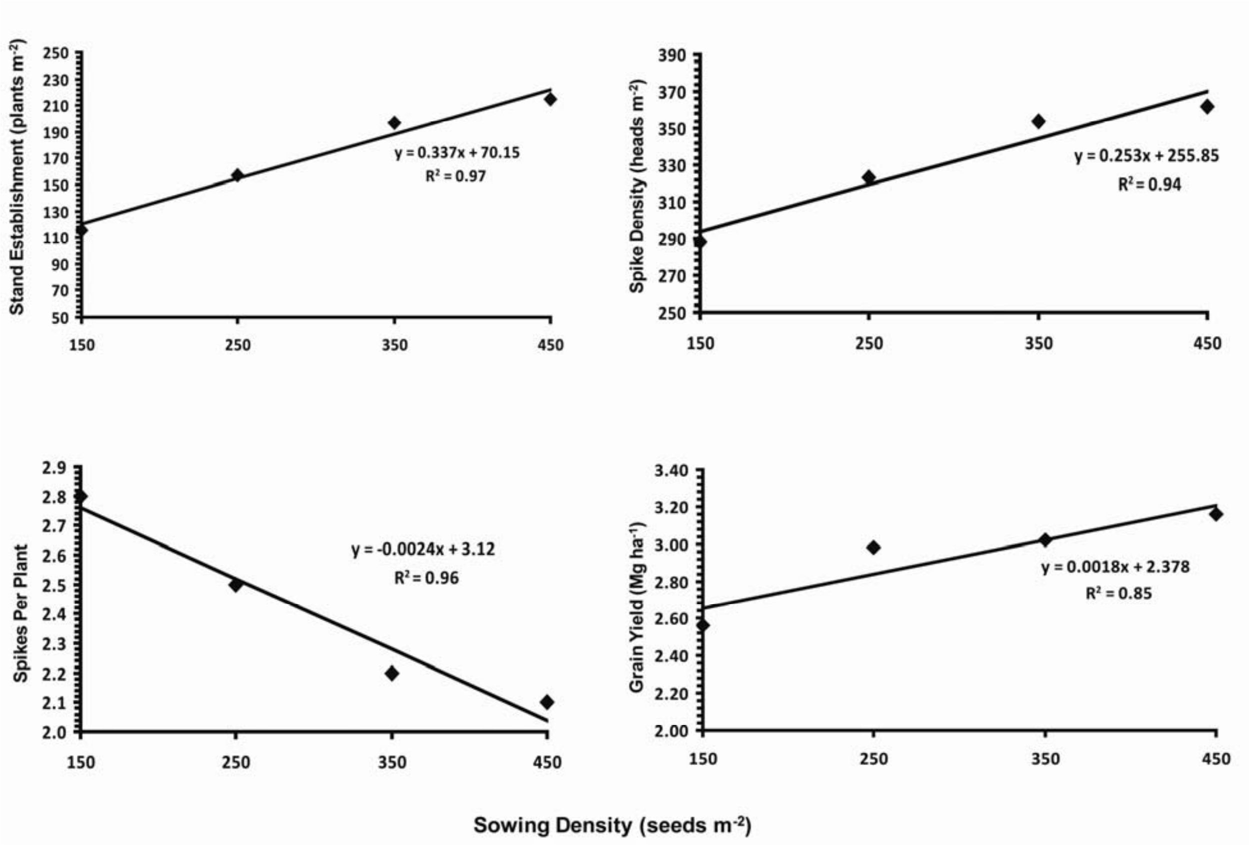


Figure 4-3. Summary of yield and yield component parameter responses to sowing density. Regression lines are presented when P ≤0.05.

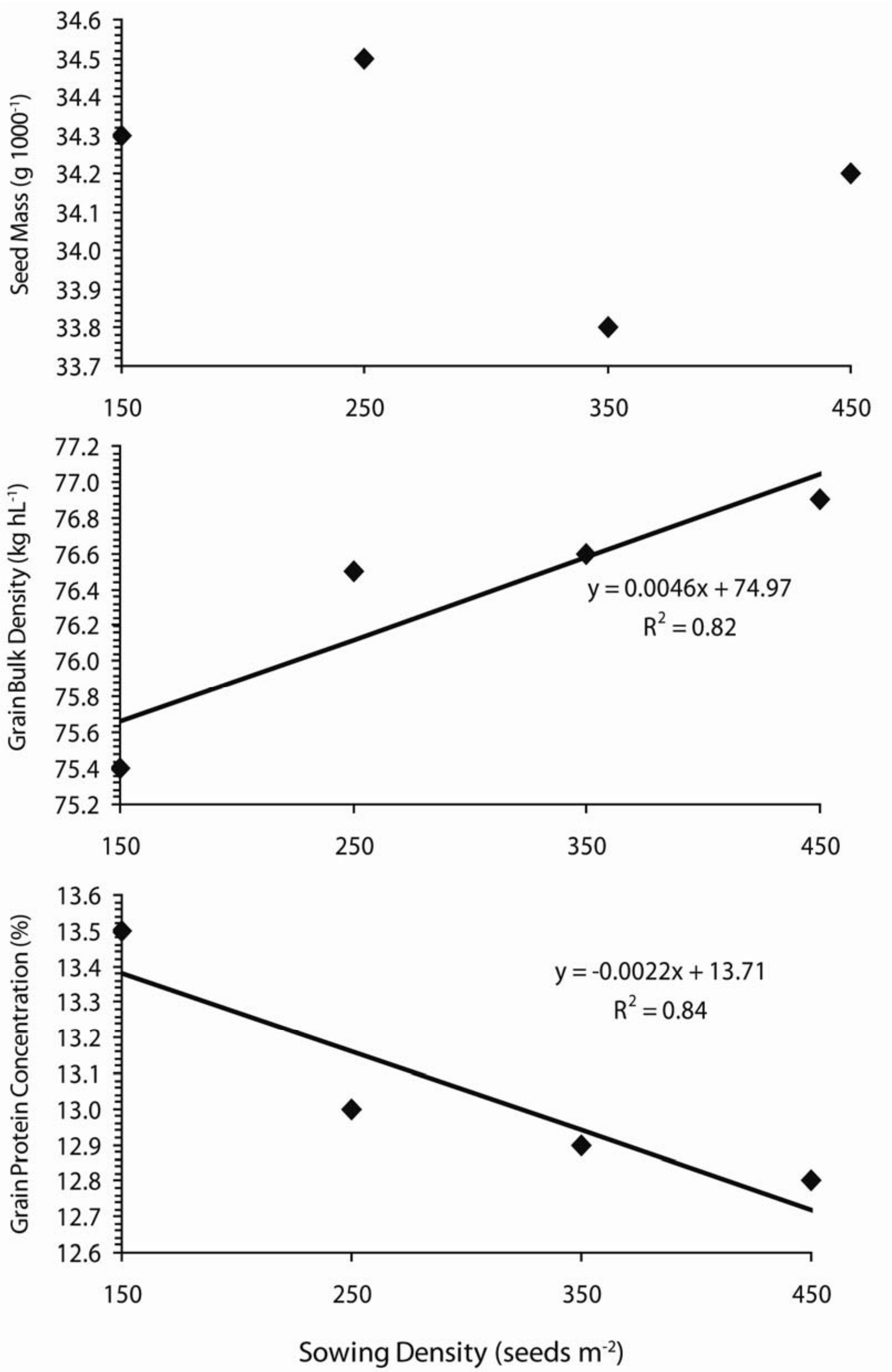


Figure 4-4. Summary of grain quality parameter responses to sowing density. Regression lines are presented when P ≤0.05.

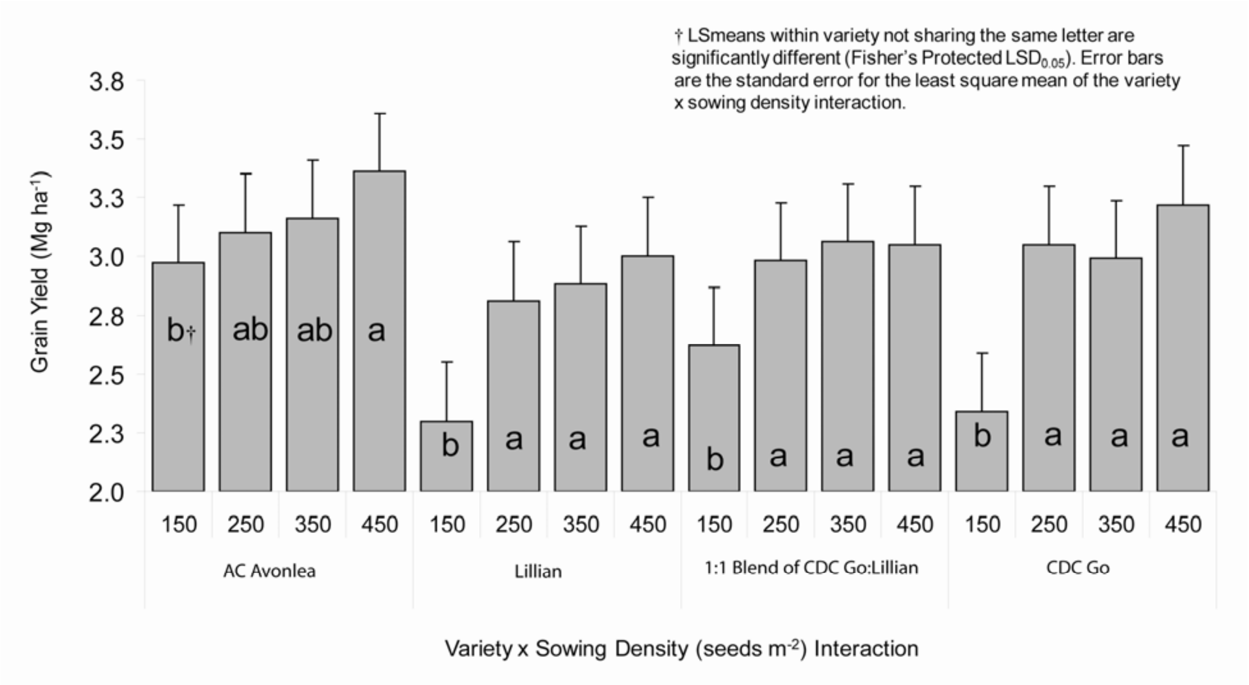


Figure 4-5. Grain yield responses of durum and hard red spring wheat cultivars to varying sowing densities.

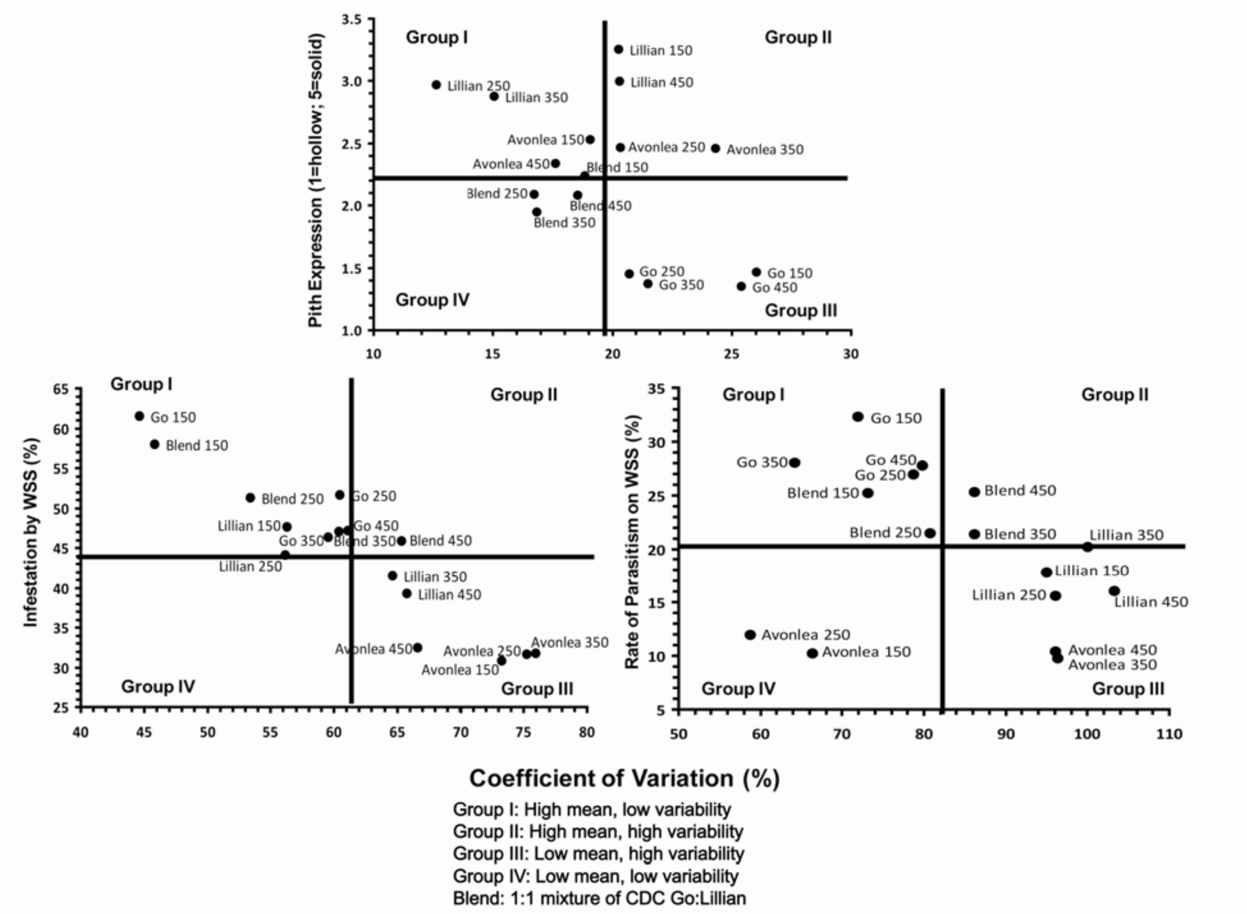


Figure 4-6. Biplot (mean vs. CV) of variety and sowing density combinations for data from insect-related variables collected at Coalhurst and Nobleford, Alberta, Canada, 2006–2009. The prefix of the labels indicates the variety selected followed by the planting density (150, 250, 350, or 450 seeds m^{-2}).

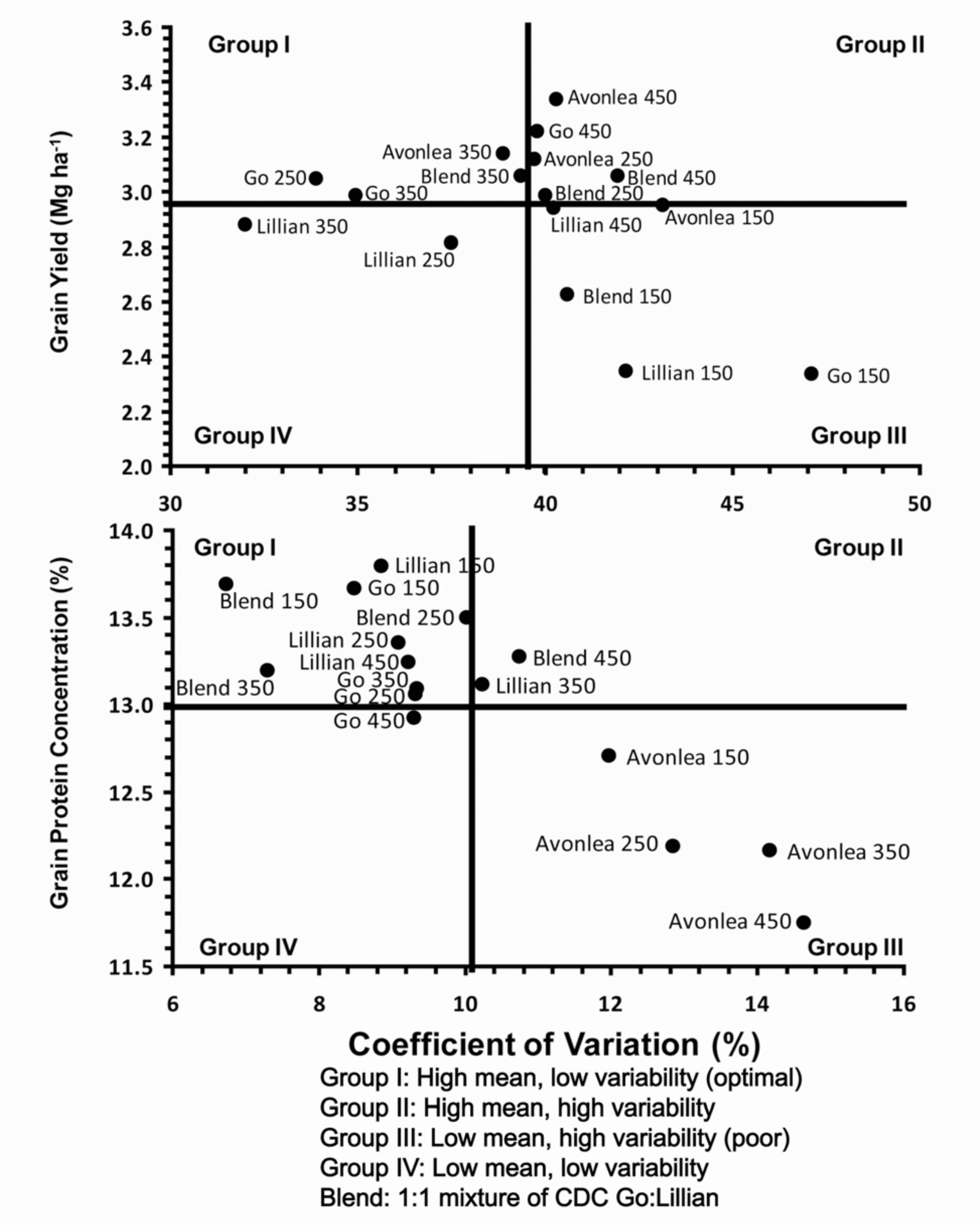


Figure 4-7. Biplot (mean vs. CV) of variety and sowing density combinations for grain yield and protein concentration data collected at Coalhurst and Nobleford, Alberta, Canada, 2006–2009. The prefix of the labels indicates the variety selected followed by the planting density (150, 250, 350, or 450 seeds m^{-2}).

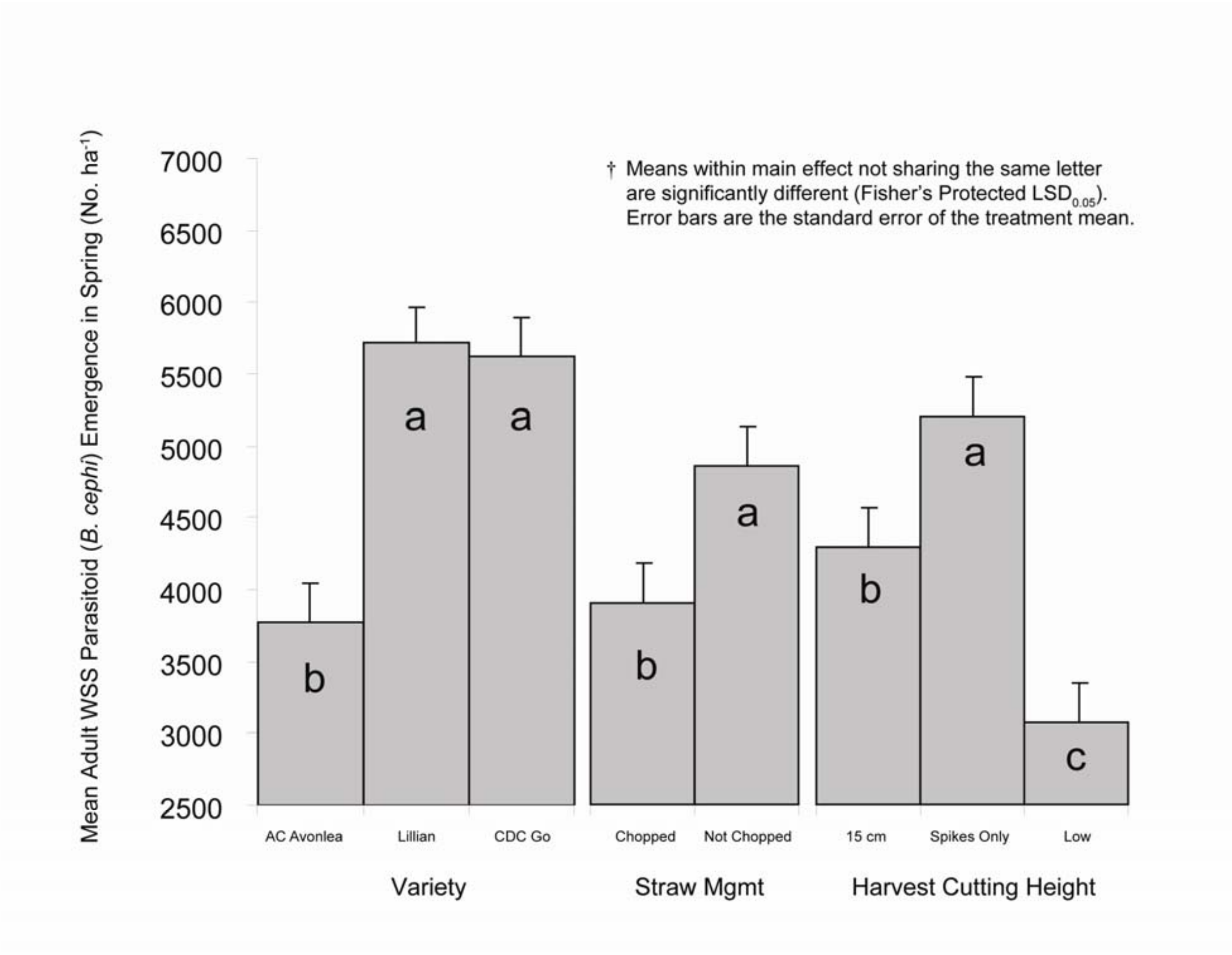


Figure 4-8. Harvest management effects to parasitism rates on wheat stem sawfly by endemic parasitoids.

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5.0 Integrating the building blocks of agronomy and biocontrol into an IPM strategy for wheat stem sawfly.[5]

5.1 Synthesis

The following is a summary of thesis findings based on the original research reported in chapters 2 to 4.

5.2 Background and status

One of the most economically important insect pests of wheat in the northern Great Plains is the wheat stem sawfly (WSS), (Beres et al., 2007; Beres et al., 2011a; Weiss and Morrill, 1992; Chapter 1) (Fig. 5-1). WSS has been a serious pest of wheat since widespread production of the crop began in the late 19th century (Comstock, 1889). Adults emerge from the previous year's crop stubble in late spring to early summer and, following mating, the adult female seeks out a suitable host plant to oviposit, usually an adjacent wheat field (Criddle, 1922). A healthy female can successfully lay up to 50 eggs, therefore, the population and subsequent damage to wheat can increase exponentially in a single generation (Ainslie, 1920). Shortly after an egg is deposited into a stem of wheat, a larva will hatch and begin boring the stem (Criddle, 1923). This activity continues throughout the growing season until the host plant reaches physiological maturity (Fig. 5-2a). Chlorosis associated with plant ripening and the reduction of whole plant moisture cues the larva to begin preparation to overwinter (Holmes, 1979). The larva moves to the base of the stem, notches a v-shaped groove around the stem, fills the region with frass, and encases itself in a cocoon below the groove. The groove weakens the stem and causes it to easily lodge or topple over, which proves difficult to recover at harvest (Ainslie, 1929). The injury caused by stem boring reduces photosynthetic rates (Macedo et al., 2007) and results in grain weight losses ranging from 10 to 17% (Holmes, 1977; Morrill et al., 1992; Seamans et al., 1944). An additional loss in yield potential occurs when toppled stems are not recovered at harvest (Ainslie, 1920; Beres et al., 2007). Thus, overall yield potential in wheat infested by WSS can be reduced by >25% (Beres et al., 2011; Chapter 1) and the loss of anchored residue leaves fields at risk to soil erosion (Lafond et al., 1996).

There are multiple factors that contributed to a resurgence of the WSS (Fig. 5-2b). Monoculture wheat production provides the sawfly with an abundance of nearby hosts each spring when the pest emerges from the previous year's infested wheat stubble. Many producers are reluctant to rotate into immune broad leaf crops as continuous wheat provides relatively low economic risk and higher returns compared to other cropping systems in semi arid regions (Zentner et al., 2006). Continuous or wheat-

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[5] *This chapter has been published in:* B.L. Beres, H.A. Cárcamo, D.K. Weaver, L.M. Dosdall, M.L. Evenden B.D. Hill, R.H. McKenzie, R-C Yang and D.M Spaner. 2011. Prairie Soils & Crops: Scientific Perspectives for Innovative Management 4: 54-65 [http://www.prairiesoilsandcrops.ca].

fallow systems in association with dry weather cycles further enhance WSS populations while wet weather patterns tend to inhibit reproduction and egg deposition (Wallace and McNeal, 1966).

These underlying issues favouring a wheat stem sawfly outbreak are exacerbated in situations where control practices are either absent or used inappropriately. Solid-stemmed cultivars can help to reduce damage caused by stem-boring larvae (Beres et al., 2007; Beres et al., 2011a; Platt and Farstad, 1949; Chapter 1), can negatively affect female sawflies (Cárcamo et al., 2005) and cause egg mortality (Holmes and Peterson, 1961); but these cultivars are only available in the bread wheat class. For example, the entire production area of durum wheat (*Triticum turgidum* L.) in Canada falls within the distribution area for wheat stem sawfly, but no solid-stemmed cultivars are available in this class. Each market class of wheat grown in sawfly-affected areas should have a solid-stemmed option as cultivation of susceptible cultivars perpetuates the cycle that leads to a WSS buildup (Fig. 5-2b).

Insecticides are generally ineffective management tools to control wheat stem sawfly. Seed-applied insecticides do not provide adequate residual activity to kill larvae, and foliar applications will not completely kill all females before egg deposition. In addition, insecticides will destroy beneficial insect populations (Beres et al., 2011a; Chapter 1). The parasitic wasp *Bracon cephi* (Gahan) (Hymenoptera: Braconidae) is the primary natural enemy of the WSS throughout its range. A closely related species, *B. lissogaster* (Muesebeck), is also quite abundant in a more restricted area centered in the major wheat producing counties of Montana. Both wasps produce two generations per year and overwinter above ground in the second or third internode of the wheat stem (Nelson and Farstad, 1953; Somsen and Luginbill, 1956). Lodged stems of wheat caused by stem cutting of the sawfly require lower cutting heights at harvest, which leads to higher mortality of *B. cephi.* Thus, in addition to continuous wheat or wheat-fallow systems as underlying causes of sawfly resurgence, planting susceptible cultivars and a lack of natural enemies exacerbate sawfly problems (Fig. 5-2b).

5.3 Assessment of Control Strategies

5.3.1 Cultivar development

All commercially available solid-stemmed spring and winter wheat cultivars developed to date derive resistance from the line S-615, but two other sources exist (Beres et al., 2011a; Chapter 1). The second resistance source is derived from a durum cultivar, Golden Ball, and all studies show that resistance in Golden Ball is more stable and 'solid' across a range of environments than cultivars derived from S-615 (Platt and Farstad, 1949). The third source is derived from *Agropyron elongatum* L., but attempts to transfer this resistance to common wheat have failed (Platt and Farstad, 1949). The recessive nature of the genes controlling resistance derived from S-615 leads to inconsistent pith expression in the field (Hayat et al., 1995). This was acknowledged shortly after the spring bread wheat cultivar Rescue was released, when observations of high susceptibility to stem cutting were noted at Regina, SK (Platt and Farstad, 1949). It was later determined that up-regulation of genes conferring pith development in the culm of a stem is influenced by photoperiod. Intense sunlight results in maximum expression and pith development, whereas shading or cloudy conditions inhibit pith development (Eckroth and McNeal, 1953; Holmes, 1984). An attempt to overcome this issue was made by first crossing Golden Ball x *Aegilops squarrosa* L. to create a synthetic hexaploid, then backcrossing the offspring to the hexaploid wheat cultivar, 'AC Elsa' (Clarke et al., 1998; Clarke et al., 2002). Two germplasm lines were recently released that were developed using this method (Clarke et al., 2005).

Solid-stemmed cultivars currently available in the Canada Red Western Spring class are 'AC Eatonia' (DePauw et al., 1994), 'AC Abbey' (DePauw et al., 2000), and 'Lillian' (DePauw et al., 2005). Solid-stemmed spring wheat cultivars available in Montana include 'Fortuna' and 'Choteau'. Resistance in winter wheat is also important as Montana has a biotype of WSS that has gradually adapted to become synchronous to winter wheat growth phenology by emerging 10 to 20 days earlier than normal. The adaptation seems to have occurred as a response to a shift in acreage away from spring to winter wheat production (Morrill and Kushnak, 1996). Solid-stemmed winter wheat cultivars available to Montana producers include 'Vanguard' (Carlson et al., 1997), 'Rampart' and 'Genou' (Bruckner et al., 1997; Bruckner et al., 2006).

5.3.2 Tillage

In addition to the use of tolerant cultivars, seeding and cultivation strategies used in wheat production can impact insect pest populations (Weaver et al., 2004). Tillage was one of the first control methods advocated to manage WSS populations. Although considered effective, plowing does not kill all sawflies (Ainslie, 1920), and it can destroy beneficial insects that attack WSS (Runyon et al., 2002). The plow was eventually replaced with low disturbance implements such as the Noble blade (Mathews, 1945), and concomitant with large blocks of fallow, this change in farming practice likely enhanced WSS populations (McGinnis, 1950; Weaver et al., 2004). Other studies investigating tillage as a management tool reported that burial of stubs was not necessary, but removal of soil from the crown was necessary so that overwintering stubs are exposed to lethal temperatures (Holmes and Farstad, 1956). Similar numbers of larvae emerged from tillage operations that did not remove soil from the crown compared to undisturbed stubble (Goosey, 1999). However, there is disagreement over the efficacy of tillage as a management tool (Weiss et al., 1987), and concern that tillage negatively impacts soil health (Beres et al., 2011a; Chapter 1). For Chapter 2, a study was conducted in southern Alberta to assess effects of implements commonly used in modern conservation farming on sawfly populations. Compared to a wheat-chemical fallow system, the authors report a direct-seeding system that consists of a pre-seed heavy tine harrow operation followed by an air drill equipped with knife openers spaced 30 cm apart reduced WSS adult emergence in spring by 50 – 70% (Beres et al., 2011b).

5.3.3 Planting strategies

Row spacing and seeding rates can influence WSS infestation rates, but this response varies between solid- and hollow-stemmed wheat cultivars. Luginbill and McNeal (1958) reported that narrow row spacing and high seeding rates reduced cutting by sawfly in the hollow-stemmed cultivar, Thatcher, but the same treatments reduced pith expression and led to increased cutting levels in the solid-stemmed cultivar, Rescue. Wider row spacing and lower plant densities create more opportunity for light to penetrate the canopy, which leads to greater pith expression (Beres et al., 2011c; Beres et al., 2011d; Chapters 3 & 4), and a resultant increase in water soluble carbohydrates and drought tolerance (Saint Pierre et al., 2010). For hollow-stemmed cultivars, high seeding rates and narrow row spacing resulted in lower whole-plant moisture, which is less attractive to ovipositing females than plants with higher moisture content (Luginbill and McNeal, 1958).

Seeding date can also influence WSS infestations. An early recommendation was to delay seeding wheat and to plant immune crops such as oats or non-cereals first (Criddle, 1922; Farstad et al., 1945). Jacobsen and Farstad (1952) reported that seeding near Lethbridge, Alberta after 21 May reduced high infestation levels to as low as 13%, and also produced significantly more males, which could disrupt mating habits in successive years (Holmes and Peterson, 1963). Studies in Montana reported that consistently lower infestation levels were only realized with planting dates after 1 June, which seriously erodes the yield potential of the crop (McNeal et al., 1955; Morrill and Kushnak, 1999). Therefore, a realistic approach for "safe" planting dates is to plant fields prone to attack last (Morrill and Kushnak, 1999).

5.3.4 Alternative planting strategies

An early approach to minimize dispersal beyond field edges involved the use of trap crops or border management (Beres et al., 2011a; Chapter 1). An updated approach to trap strips involves within-field border management; i.e., sowing the perimeter of a wheat field to an immune or resistant crop and then planting the interior of the field to a hollow-stemmed wheat cultivar. The goal of this strategy is to intercept incoming sawflies from adjacent infested stubble so that most of the infestation occurs within the trap (Beres et al., 2009; Morrill et al., 2001). Blending hollow- and solid-stemmed cultivars may be feasible (Beres et al., 2011d; Chapters 1 & 4). A Montana study blended hollow- and solid-stemmed cultivars and reported that the strategy was successful for minimizing damage at low to moderate levels of sawfly pressure, but was not feasible if pressure was high (Weiss et al., 1990). Two Alberta studies reported similar results and noted an 11% increase in yield potential with a 1:1 blend of solid-stemmed

‘AC Eatonia’ versus the monoculture system of hollow-stemmed cultivar ‘AC Barrie’ (Beres et al., 2007; Beres et al., 2009). Grain quality was also improved by blending cultivars with contrasting protein accumulation potential (Beres et al., 2007). Similar results were observed in the experiment summarized in Chapter 4 (Beres et al., 2011d), however, the trend of improved grain yield in the blend was not significant. There was also no improvement to grain protein, which is not a surprise as ‘Lillian’ carries the trait for high protein accumulation so an improvement through blending would not likely be achieved. There may be additional benefits by blending cultivars with ‘Lilllian’, however, as this cultivar also has excellent strip rust resistance and could be used in a cropping strategy to mitigate stripe rust infection.

5.3.5 Nutrient management

Crop nutrient management can significantly change crop canopy architecture and influence overall plant health, which in turn could influence WSS infestation rates. Luginbill and McNeal (1954) observed that when a blend of nitrogen and phosphorous was applied to wheat there was generally an increase in stem cutting. Nitrogen applied separately did not influence cutting whereas a slight increase in cutting was observed when phosphorous was applied alone. In contrast, a recent Montana greenhouse study reported that phosphorous-deficient wheat plants were most susceptible to sawfly damage (Delaney et al., 2010). In a Saskatchewan study, no effects of nitrogen or phosphorous could be detected due to the strong influence of environmental factors (DePauw and Read, 1982), which is similar to a North Dakota study that reported significantly more sawfly cutting occurred in fertilized plots in only one of eight experiments (O'Keeffe et al., 1960). The study summarized in Chapter 3 (Beres et al., 2011c) indicates there were no direct nutrient management effects on pith expression in solid-stemmed wheat that was attributed to anything other than shading effects. Fertilization did not influence pith expression but nitrogen did influence cutting susceptibility, which is not a surprise as increasing rates of nitrogen increased biomass and subsequent shading reduced stem solidity. The results of Chapter 3 indicate that low plant populations were often most effective at maximizing pith expression in solid-stemmed wheat and reducing sawfly cutting damage. However, this usually required the highest rates of N fertilizer, and a system of low seeding rates and high nitrogen may not be economical based on current fertilizer input costs and the generally lower grain yield response.

Micronutrient blends have been recommended as a means to improve crop productivity. There is also interest in micronutrient effects on pith expression in solid-stemmed wheat (M. Dolinski, personal communication). This was explored in the Chapter 3 study and reported in Beres et al. (2011c). At 5x the recommended rate, there was no improvement observed to either grain yield or pith expression with in-crop foliar applications performed at the 3 to 5 leaf stage and repeated at the boot stage (Chapter 3).

5.4 Biological control

Nine species of Hymenoptera are known to parasitize WSS and are summarized in Meers (2005) and Morrill et al. (1998). *Bracon cephi* (Gahan) (Hymenoptera: Braconidae) is the most important parasitoid of WSS in Canada (Nelson and Farstad, 1953) and North Dakota (Meers, 2005). *Bracon cephi* is bivoltine. The first (overwintered) generation emerges near the time that sawflies appear in mid-May to mid-June. The female wasp immobilizes a host larva with venom and deposits an egg nearby. The larval parasitoid consumes the host larva in about 10 days. The fully developed parasitoid larva spins a cylindrical cocoon and pupates within the stem. New adults emerge in August by chewing circular holes through the stem (Nelson and Farstad, 1953), seek new hosts, and produce another generation that will overwinter as pupae. Successful parasitism by this generation is dependent on crop maturity, which cues the host larva to prepare to overwinter at the base of the wheat plant (Holmes et al., 1963). If the wheat crop is delayed and crop maturity is not reached until mid-August, the rates of parasitism of the second generation can be very high. If the crop matures early, the host larva usually cuts the stem and is relatively safely housed within its overwintering chamber before the second generation of *B. cephi* has completely emerged (Holmes et al., 1963). Later seeding would enhance *B. cephi* success, but seeding is now more common in April than May in many parts of southern Alberta. This is partially offset by the adoption of later maturing, high yielding cultivars. Success of *B. cephi* is therefore variable. Mortality of the first generation can be high during harvest because the parasitoid overwinters in the upper internodes of the wheat crop where it is more susceptible to loss from cutting and threshing operations (Holmes, 1979). Low efficacy of *B. cephi* also occurs when activity of the second generation is low.

The second major parasitoid of WSS in wheat is *Bracon lissogaster* (Muesebeck) (Hymenoptera: Braconidae). Like *B. cephi*, *B. lissogaster* was slow to shift to wheat but is now active in Montana and North Dakota (Meers, 2005) and was recently found in southern Alberta (Cárcamo et al., unpublished). The life cycle is similar to *B. cephi* but it can more readily complete a second generation, which is attributed to immediate oviposition of adult females when they emerge (Somsen and Luginbill, 1956).

Crop management practices can significantly influence the abundance and efficacy of WSS parasitoids. Reduced tillage resulted in higher rates of parasitism and less stem-cutting than aggressive tillage (Runyon et al., 2002). Zero tillage cropping systems conserved parasitoids which helped to reduce sawfly populations (Weaver et al., 2004). Solid-stemmed cultivars also have high levels of parasitism that are comparable to or even higher than hollow-stemmed cultivars (Holmes et al., 1963; Morrill et al., 1994; Weaver et al., 2004). However, the actual number of parasitoids was not reported in the above published studies. Under high sawfly pressure, there can be a reduction of sawfly cannibalism in solid stems that could lead to multiple larvae in a stem, and would therefore benefit the parasitoid (Holmes et al., 1963). Conversely, overall numbers of the parasitoid will be lower if the solid-stemmed cultivar drastically reduces the number of available hosts as observed for a synthetic hexaploid line in a recent study near Lethbridge (Wu et al., 2011). Blends of susceptible and resistant cultivars may assist to maintain high levels of *B. cephi* over the long term. Conservation of parasitoids can also be accomplished by increasing stubble height at harvest (Meers et al., unpublished; Chapter 4) and by avoiding insecticide spraying for grasshoppers along grass ditches where natural enemies of WSS can be abundant.

5.5 A decision support strategy to manage wheat stem sawfly

Successful management of the wheat stem sawfly requires the distillation of information compiled over the past century into a decision support strategy (Fig. 5-3). Unlike other serious cereal pests such as orange wheat blossom midge, *Sitodiplosis mosellana* (Géhin) (Diptera: Cecidomyiidae), or the clear-winged grasshopper, *Camnula pellucida* (Scudder) (Orthoptera: Acrididae), insecticidal control has proven ineffective for sawfly control. Therefore, successful management requires a more complex approach (Beres et al., 2011a; Chapter 1).

5.5.1 Pest surveillance and monitoring

Critically important to the management of wheat stem sawfly are tools that provide an accurate risk assessment of the pest threat (Fig. 5-3). Large areas of similar cropping ecosystems in the Canadian prairies make the following approach very useful. Risk maps are available and can be reviewed prior to spring sowing (Meers and Tames, 2010), which allows producers to make informed decisions regarding cultivar selection, wheat field selection and crop phases. In-crop surveillance is recommended to assess site-specific risk and to determine the need for action based on the level of sawfly infestation (Fig. 5-3). Predicted risk of cutting damage by wheat stem sawfly can be categorized as low, medium, or high, based on infested stems observed in the ranges of 0-20%, 20-40%, and >40% stems infested, respectively (Fig. 5-3). A neural network model to predict pith expression in solid-stemmed cultivars has been developed (Beres et al., unpublished; available online at **ftp://ftp.agr.gc.ca/pub/outgoing/rb-bh**) based on precipitation-related weather data and should be used in conjunction with the risk map. Producers growing a solid-stemmed cultivar can use the model to determine if any action is warranted based on the cutting damage predicted by the model, and the level of threat identified in the risk map. For example, if the neural network model predicts cutting damage in a solid-stemmed cultivar to be >20% in a region where the risk to sawfly is moderate to high, swathing all or a portion of infested fields prior to harvest is recommended so that stems are collected into a windrow before they topple.

5.5.2 Crop management

A moderate to high threat identified in the risk map would warrant the use of solid-stemmed cultivars or modifications to field selection so that wheat is planted in areas of reduced risk (Fig. 5-3).

Pre-seed harrowing and recropping infested stubble may help to reduce damage in spring wheat and to optimize grain yield (Beres et al., 2011b; Chapter 2). To balance yield potential and pith expression in solid-stemmed wheat, seeding rates should not exceed 300 seeds m^{-2} as canopy shading at higher plant populations inhibits pith expression (Beres et al., 2011c; Beres et al., 2011d; Chapters 3 & 4). However, if the producer's business marketing strategy requires cultivars other than bread wheat cultivars, the only class with solid-stemmed cultivars, adjustments to seeding rate is recommended. Hollow-stemmed cultivars should be sown at a density of at least 400 seeds m^{-2} as high yield potential, weed competitiveness, and reduced sawfly damage can be achieved (Beres et al., 2011d; Luginbill and McNeal, 1958; Chapter 4) (Fig. 5-3).

The decision to use an alternative planting strategy should also be based on the predicted sawfly threat (Fig. 5-3). Trap crops at the field perimeter could be used in low to moderate threat situations because infestation is generally limited to those areas. Therefore, a border of a resistant cultivar or an immune crop such as oats could help reduce sawfly populations (Weaver et al., unpublished). However, the trap strategy may not be effective if the threat is high, as infestations could extend well beyond the field perimeter. The current recommendation is to plant either 1) a non-cereal, 2) a solid-stemmed wheat cultivar, or 3) a blend of solid and hollow stems so that there is a degree of protection throughout the field instead of just along the perimeter (Fig. 5-3).

Nitrogen management and the use of micronutrient blends will alter canopy architecture in a similar fashion as seeding rates. Since there was no direct effect on pith expression observed in solid-stemmed wheat that was attributed to anything other than shading effects, nutrient management should focus on plant health and thus standard amendments are recommended: i.e. 30 – 60 kg N ha^{-1} (Chapter 3; Fig. 5-3).

Harvest management methods should be carefully considered if fields are infested with wheat stem sawfly. The typical harvesting method is to straight-cut standing wheat in a single pass operation using a combine equipped with a straight-cut header and pick up reel. This is acceptable if there is a low cutting threat by WSS. However, if the cutting threat increases to moderate or high, swathing the wheat ahead of the combining operation is necessary to ensure that the stems are gathered into a windrow before they topple. A high threat would require that the entire field be swathed, but swathing of field perimeters may be all that is required if the threat is moderate (Chapter 4; Fig. 5-3).

Harvest management will also significantly affect sawfly parasitoid populations (Meers et al., unpublished). Cutting bar heights >15 cm will help conserve beneficial insect populations (Chapter 4). However, this will require an integration of management techniques to minimize cutting by sawfly; low cutting heights are required if too many stems have been toppled over prior to harvest.

In summary, an agronomic strategy to manage wheat stem sawfly consists of diligent pest surveillance, solid-stemmed cultivars, continuous cropping with appropriate pre-seed residue management, seeding rates no greater than 300 seeds m^{-2}, 30 to 60 kg N ha^{-1}, and harvest cutting heights of at least 15 cm.

5.6 Figures

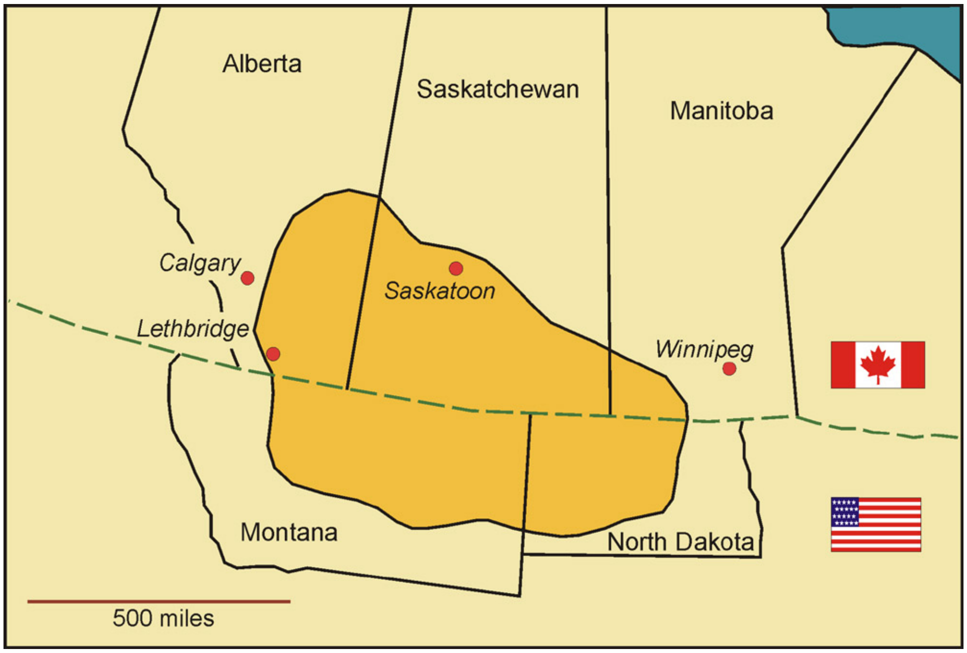


Figure 5-1. Area (shaded) historically most affected by wheat stem sawfly.

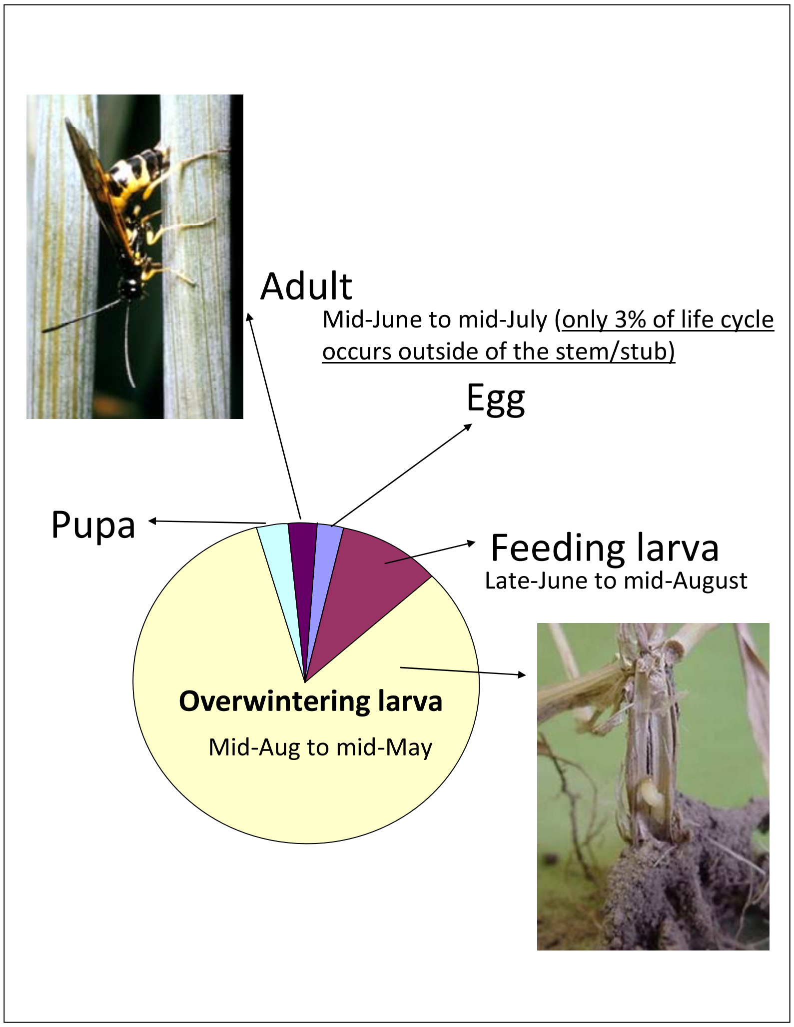


Figure 5-2a. Life cycle of the wheat stem sawfly *Cephus cinctus* Norton

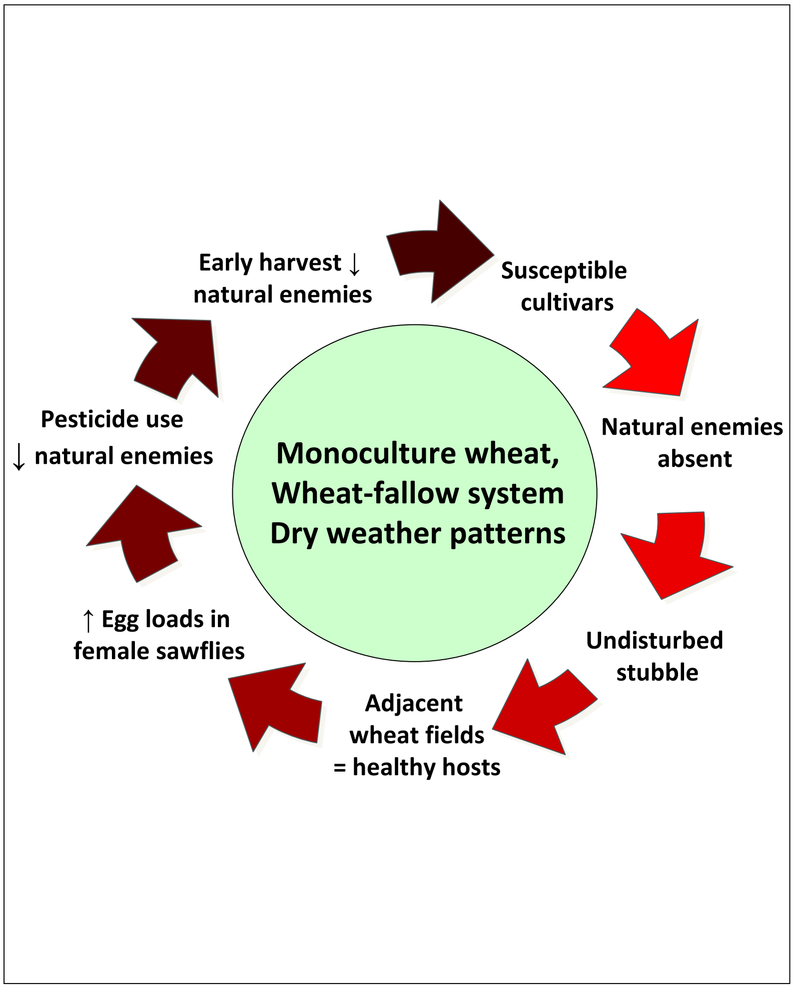
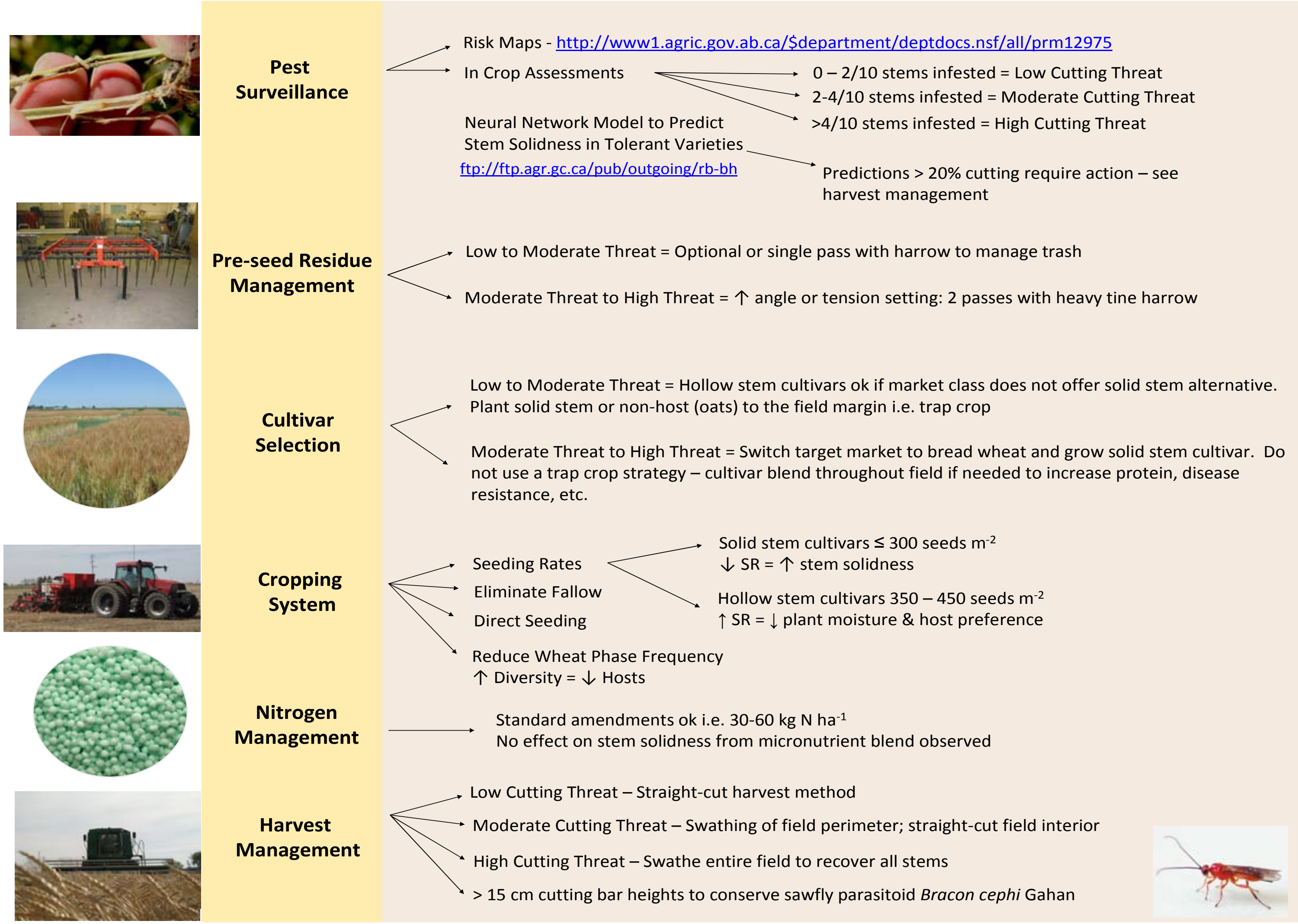


Figure 5-2b. Cycle of biological and environmental interactions that facilitated resurgence of the wheat stem sawfly *Cephus cinctus* Norton. Initiated with susceptible cultivars used in monoculture wheat systems, which worsens (represented by shade of arrow) when additional factors that favor wheat stem sawfly are present.



Pest Surveillance

- Risk Maps - http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/prm12975
- In Crop Assessments
  - 0 – 2/10 stems infested = Low Cutting Threat
  - 2-4/10 stems infested = Moderate Cutting Threat
  - >4/10 stems infested = High Cutting Threat

Neural Network Model to Predict Stem Solidness in Tolerant Varieties
ftp://ftp.agr.gc.ca/pub/outgoing/rb-bh
- Predictions > 20% cutting require action – see harvest management

Pre-seed Residue Management

- Low to Moderate Threat = Optional or single pass with harrow to manage trash
- Moderate Threat to High Threat = ↑ angle or tension setting: 2 passes with heavy tine harrow

Cultivar Selection

- Low to Moderate Threat = Hollow stem cultivars ok if market class does not offer solid stem alternative. Plant solid stem or non-host (oats) to the field margin i.e. trap crop
- Moderate Threat to High Threat = Switch target market to bread wheat and grow solid stem cultivar. Do not use a trap crop strategy – cultivar blend throughout field if needed to increase protein, disease resistance, etc.

Cropping System

- Seeding Rates
  - Solid stem cultivars ≤ 300 seeds m^{-2}
    ↓ SR = ↑ stem solidness
  - Hollow stem cultivars 350 – 450 seeds m^{-2}
    ↑ SR = ↓ plant moisture & host preference
- Eliminate Fallow
- Direct Seeding
- Reduce Wheat Phase Frequency
  ↑ Diversity = ↓ Hosts

Nitrogen Management

- Standard amendments ok i.e. 30-60 kg N ha^{-1}
  No effect on stem solidness from micronutrient blend observed

Harvest Management

- Low Cutting Threat – Straight-cut harvest method
- Moderate Cutting Threat – Swathing of field perimeter; straight-cut field interior
- High Cutting Threat – Swathe entire field to recover all stems
- > 15 cm cutting bar heights to conserve sawfly parasitoid *Bracon cephi* Gahan

Figure 5-3. Decision support schematic for the management of wheat stem sawfly *Cephus cinctus* Norton.

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6.0 Future research directions and original contributions to knowledge.

6.1 Future research directions

A research gap not yet fully addressed for areas prone to WSS attack relates to the instability of pith expression in solid-stemmed wheat. This could lead to catastrophic losses in the fall if the grower mistakenly assumes that a field sown to solid stems will be consistently resistant to WSS infestation and damage. Pith expression in wheat is highly dependent on precipitation-related environmental factors, and no tool exists that could be used by producers to accurately predict the degree of pith expression in wheat based on the observed precipitation weather variables. In collaboration with AAFC-LRC scientist, Dr. Bernie Hill, we established an objective to use Neural Network (NN) modeling to predict the in-season tolerance level of solid-stemmed wheat cultivars to wheat stem sawfly, expressed as '% stems cut by the sawfly'. Neural network models are used to make predictions for complex, non-linear systems with many co-related variables. Agricultural systems usually involve many variables including weather which makes NN models particularly applicable for predicting agricultural outcomes. Three generations of deployed neural network models have been developed to date that utilize Visual Basic® as an input/output user-interface. The user-interface permits the entry of different weather scenarios and the exported NN model runs seamlessly in the background once the user requests the calculation. The program has been compiled into an executable file to facilitate predictions for unknown cases of % stems cut and is available at **ftp://ftp.agr.gc.ca/pub/outgoing/rb-bh**. The value of the NN model is reflected in years like 2010 when pith expression in solid-stemmed wheat was less than ideal due to the precipitation patterns experienced across most of the Canadian prairies. Wallace et al. (1973) noted that the minimum level of stem solidness rating required in solid-stemmed wheat should be 3.75; none of the sites we sampled in 2010 achieved this level of pith expression. Producers would then have the option well in advance of harvest to scout fields to determine the presence of wheat stem sawfly and implement management strategies (swathing) as necessary to mitigate losses. For a thorough pest monitoring and surveillance strategy, the NN model should be used in conjunction with risk forecast maps, which are available in Canada for wheat stem sawfly.

We have also initiated a collaborative study this year with breeders and entomologists at AAFC-Swift Current, Montana State University, and North Dakota State University. Sites have been established in Alberta, Saskatchewan, Montana, and North Dakota that will generate pertinent data that will be used to create a NN model specific to the environments of Montana and North Dakota. Those data may also be used to improve the accuracy in a fourth generation model for Alberta and Saskatchewan.

The collaborations established during the development of the thesis studies should be enhanced in the future. The group contains world class scientists with diverse backgrounds. The skills could be devoted to integrated studies that successfully combine the latest biological control efforts with superior cultivars and agronomics. For example, the emergence data plotted with growing degree days (GDD) in Chapter 2 (Fig. 2-3a) indicates that the GDD requirements to initiate the onset of adult WSS emergence is relatively precise if calculated from 1 May using a base temperature of 5^{o} C (Beres et al., 2011). This finding as well as the data set from Chapter 2 has been shared with colleagues at Montana State University in an effort to validate a WSS emergence model developed for Montana. North Dakota State University is also collaborating with Montana State University on a similar model specific to North Dakota. The findings and subsequent collaborations may well lead to the successful deployment of pheromone bait traps and targeted pesticide applications synchronized to a GDD emergence model.

6.2 Original contributions to knowledge

The subject of WSS biology and management has been studied for as long as the insect first adapted to wheat at the turn of the 20th century; however, the resilience of this insect is evident over 100 yrs later as it still remains an important economic insect pest of wheat. Many management practices to minimize crop damage are either outdated or jeopardize sustainable crop and soil health. Therefore, a management package for WSS control that is compatible with modern farming practices was needed. Chapter 1 of the thesis is a review of the literature pertaining to WSS biology, management and the need for continuing research. The original contributions to the knowledge of WSS biology and management are discussed in the following paragraphs.

Historically, cultural practices to manage WSS often involved aggressive forms of tillage such as the plough or a heavy disc that turned over the infested stubble. No studies to date have integrated no-till residue management and direct seeding systems to measure the impact of the system on WSS populations. Therefore, my first study summarized in Chapter 2 was developed in response to the need for an updated alternative to tillage as a management practice for WSS. The results indicate that residue management and direct seeding systems will reduce emerging populations of WSS, but it would only be a sustainable practice in spring wheat production systems. Moreover, I emphasize the need to integrate the system with solid-stemmed cultivars to maximize the control strategy.

There is growing interest in the use of micronutrient blends for cereal production in the northern Great Plains. Research to date on fertilizer management for improved stem solidity in wheat has been restricted to macronutrients. Moreover, the conclusions have often been site-specific or environmental conditions during the study masked plant responses to fertilizers. Furthermore, studies involving fertility management have always been conducted in isolation of other agronomic factors such as sowing density. The goal of Chapter 3 was to integrate nutrient management and sowing density and determine if micronutrient blends would elicit a plant response unique from conventional urea nitrogen. There is no study to my knowledge that has integrated the two factors, nor is there any known study that addressed the influence of micronutrient blends on pith expression in spring wheat. Thus, the motivation for Chapter 3 was that research was needed to better define target plant populations when integrated with nutrient management so an appropriate balance between yield potential, WSS management, and overall crop competitiveness is achieved. The findings suggest that micronutrients do not influence pith expression, nor did it contribute to yield or any yield component responses. The results also start to define the upper limit for seeding rates in solid-stemmed wheat as rates above 300 seeds m^{-2} reduced pith expression; and that yield potential at this sowing density would be optimized with 60 kg N ha^{-1}.

The first two data chapters of the thesis focused primarily on the management of WSS and enhancing pith expression in wheat to minimize the stem boring activity of the WSS larvae. In the final data chapter (Chapter 4), my goal was to shift focus to include the preservation of endemic parasitoids of wheat stem sawfly. In addition to refining the optimum target plant populations for solid-stemmed spring wheat first initiated in Chapter 3, I was interested to see if the optimization would be different for current hollow-stemmed bread wheat and durum cultivars. There was no information I was aware of that quantified optimum seeding rate recommendations for hollow-stemmed wheat using modern farming practices in an area prone to sawfly attack. It was also not fully known if responses to WSS and parasitoid populations would be observed when variety selection was integrated with 4 levels of sowing density. I was equally interested to determine if modifications to harvest practices could preserve beneficial parasitoids. To date, there is only one study that has addressed harvest management, but those results have yet to be published, and components of the study involved simulation of harvest practices such as the effect of straw chopping on endemic parasitoids (Meers, 2005). Therefore, my goal was to determine effects on endemic parasitoids when exposed to the integrated harvest management factors of variety, stubble height, and chopping straw. There was no variety effect observed but our findings did support an unpublished report that increased cutting heights at harvest preserved endemic parasitoids. Our findings related to chopping straw differ from simulated studies and observation data (Meers, 2005) as the reduction in endemic parasitoids in our study was incremental and would not warrant removal of this step at harvest given the benefits derived for effective straw management.

My main goal was to develop a body of work that would contribute to WSS biology and management. The literature review will serve as a ‘one-stop’ reference for sawfly workers; and the agronomic package developed from the 3 data chapters and summarized in the synthesis chapter will benefit entomologists, agronomists and wheat producers in regions prone to WSS attack.

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7.0 Appendices

Appendix 7-1. Effect of residue management and direct seeding of winter and spring wheat planted into infested spring wheat stubble on parasitoid *Bracon cephi* population emergence near Coalhurst, Alberta, Canada 2004-06.

		2004-2006	
		Spring wheat	**Winter wheat**
Factor	Treatment	No. adults m^{-2}	
Harrow (main plot)	Control-no harrow	3 a	2 a
	Heavy tine 20°	2 b	2 bc
	Heavy tine 5°	3 a	1 c
	Rotary harrow 25°	3 a	2 ab
	Rotary harrow 45°	2 a	1 bc
Seed Drill (subplot)	Chemical fallow – no seeding	4 a	2 a
	Disc opener	2 b	2 b
	Knife opener 30 cm row spacing	2 b	1 b
	Knife opener 23 cm row spacing	2 bc	2 b
	Sweep opener 23 cm row spacing	2 c	2 b
Pr > F	Harrow (H)	0.006	0.023
	Drill (D)	<0.0001	0.0008
	HxD	0.038	0.048

† In main effect, means within columns sharing the same letter are not significantly different (P>0.05; Fisher's Protected LSD).

Appendix 7-2. Mean responses summarizing the harrow by seed drill interaction for parasitoid emergence (adults m^{-2}) in winter and spring wheat systems planted into infested spring wheat stubble at Coalhurst, Alberta, Canada, 2004–2006.

Effect		**Harrow (Main Plot)**											
	Treatments	Control No Harrowing		Heavy Tine 20° Setting		Heavy Tine 5° Setting		Rotary Harrow 25° Setting		Rotary Harrow 45° Setting		Mean over all harrow treatments	
		sw†	ww	sw	ww	sw	ww	sw	ww	sw	ww	sw	ww
Seed Drill (Subplot)	Chemical Fallow No recropping	4 a‡	4 a	2 a	2 ab	2 ab	5 a	2 a	7 a	1 a	5 a	2 a	5 a
	Disc Opener 18cm row spacing	2 abc	3 ab	2 ab	3 a	1 ab	3 b	2 ab	2 b	1 a	2 b	2 b	3 b
	Knife Opener 30cm row spacing	1 c	3 ab	1 b	1 bc	1 b	2 b	2 a	3 b	1 a	2 ab	1 b	2 b
	Knife Opener 23cm row spacing	3 ab	3 ab	1 b	3 abc	1 b	1 b	2 ab	2 b	2 a	2 b	2 b	2 bc
	Sweep Opener 23cm row spacing	2 bc	2 b	2 b	1 c	1 a	2 b	1 b	2 b	2 a	2 b	2 b	2 c
	Mean over all seed drill treatments	2 a	3 a	1 bc	2 b	1 c	3 a	2 ab	3 a	1 bc	3 a	--	

† Abbreviations: sw, spring wheat; ww, winter wheat.

‡ Values for treatments within columns followed by the same letter are not significantly different (P<0.05; Fisher's Protected LSD). Raw means presented with ANOVA and mean separation tests performed on transformed means [log10(x+1)].