Blending resistant and susceptible winter wheat for wheat stem sawfly (Cephus cinctus Norton) management

by Debra Kay Waters

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Entomology
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Abstract:
The wheat stems sawfly (Cephas cinctus Norton) has been a recurring pest of winter and spring wheat in the Northern Great Plains. Solid stem is the only host plant resistance factor that has been identified in wheat for wheat stem sawfly (WSS) management. Resistant (solid stem) winter and spring wheat varieties are available but are not widely accepted by producers because of reduced yield and protein, reduced disease resistance, and lower winter survival (winter wheat) compared with the susceptible (hollow stems) varieties. Blending of resistant and susceptible wheat cultivars may be a useful tool in managing losses from wheat stem sawfly yield losses due to feeding and cutting of the stem yet improving agronomic traits. Rampart released in 1997, was blended with two susceptible varieties of winter wheat, Rocky and Norstar, at two field locations in 1997 and three locations in 1998. Wheat stem sawfly populations were relatively low for both sites in 1997 and ranged from low to extremely high for the 3 sites in 1998 allowing for a comparison of blend treatments under varying degrees of WSS pressure. In the Rocky: Rampart and Norstar: Rampart blends there were no differences detected among the treatments for egg deposition preference. There were no consistent differences in larval numbers between blend treatments by the last sample date for Rocky: Rampart and Norstar: Rampart blends at all sites. Yields were not different for the Rocky: Rampart blend treatments for all sites except one site where 100% Rampart yielded higher than all other blends. There were no significant differences in yield across all blend treatments for Norstar: Rampart blends at all sites. Protein varied among treatments across sites. There was no definitive pattern for protein differences for the Rocky: Rampart blends. Predicting for the WSS infestation were positively related and correlated highly to the peak number of WSS per sweep indicating the importance of a regular WSS monitoring program that included adult WSS flight duration and peak number of adults which could provide valuable information about later WSS larval infestation.

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Debra Kay Waters

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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ABSTRACT

The wheat stems sawfly (*Cephus cinctus* Norton) has been a recurring pest of winter and spring wheat in the Northern Great Plains. Solid stem is the only host plant resistance factor that has been identified in wheat for wheat stem sawfly (WSS) management. Resistant (solid stem) winter and spring wheat varieties are available but are not widely accepted by producers because of reduced yield and protein, reduced disease resistance, and lower winter survival (winter wheat) compared with the susceptible (hollow stems) varieties. Blending of resistant and susceptible wheat cultivars may be a useful tool in managing losses from wheat stem sawfly yield losses due to feeding and cutting of the stem yet improving agronomic traits. Rampart released in 1997, was blended with two susceptible varieties of winter wheat, Rocky and Norstar, at two field locations in 1997 and three locations in 1998. Wheat stem sawfly populations were relatively low for both sites in 1997 and ranged from low to extremely high for the 3 sites in 1998 allowing for a comparison of blend treatments under varying degrees of WSS pressure. In the Rocky: Rampart and Norstar: Rampart blends there were no differences detected among the treatments for egg deposition preference. There were no consistent differences in larval numbers between blend treatments by the last sample date for Rocky: Rampart and Norstar: Rampart blends at all sites. Yields were not different for the Rocky: Rampart blend treatments for all sites except one site where 100% Rampart yielded higher than all other blends. There were no significant differences in yield across all blend treatments for Norstar: Rampart blends at all sites. Protein varied among treatments across sites. There was no definitive pattern for protein differences for the Rocky: Rampart blends. Predicting for the WSS infestation were positively related and correlated highly to the peak number of WSS per sweep indicating the importance of a regular WSS monitoring program that included adult WSS flight duration and peak number of adults which could provide valuable information about later WSS larval infestation.

CHAPTER 1

INTRODUCTION

The establishment of the Homestead Act in 1862, allowed large numbers of acres to be plowed and planted to spring wheat in the Northern Great Plains. Wheat and grasses have a similar growth cycle and both remain green during wheat stem sawfly (WSS) larval development. This provided conditions favorable for the transfer of WSS from grasses to wheat.

The WSS was first found in the United States in native and resident grass species in Colorado, Nevada, and California, although the primary hosts at the beginning of the century were native grasses. An interest in the wheat stem sawfly as a potential agricultural pest in cereal grains occurred around 1900. With the introduction and expansion of cereal grains into the range of WSS, wheat was suitable, abundant, and offered an accessible alternative host. Spring wheat was the primary cereal grain to be impacted by the WSS but recently winter wheat has sustained increased damage and infestation. The wheat stem sawfly, has become a major recurring wheat pest in Montana and the Northern Great Plains causing loss of quality and yield. Larvae feeding within the stem, can cause 10.8-22.3% grain yield loss and 0.6-1.2% protein reduction of the grain head (Holmes 1977). Additionally, larvae cutting lower portions of the stems following feeding caused stems to break prior to harvest and grain heads to be lost. Montana producers have estimated direct grain yield losses at $25-30 million per year due to sawfly cutting (Blodgett 1996, Montana State University Extension Service 1997).

These losses do not include an increase in custom harvest cost or equipment damage and modifications resulting from harvesting a WSS infested field.

The wheat stem sawfly has been the subject of major studies because of the damage it causes and ineffective control measures. Since the early 1900's many farm management practices were introduced, tried and discarded and have been reexamined in recent years. In the 1920's recommendations for control of WSS was burning stubble, mowing ditches and field edge grasses, deep tillage, use of trap strips and rotating to certain resistant crops (Ainslie 1920, 1929). Burning stubble had no effect on larval mortality because stems cut near ground level were protected and insulated by the soil. Mowing grasses on field edges and ditches eliminated potentially infested grass stems, but also reduced the number of natural parasites of WSS that utilize native grass species. Deep tillage of the stubble (min. of 15.2 cm) and compaction of the soil reduced sawfly populations by 35%, but is not a practice recommended for Montana, the Dakotas, and Canada because of the high potential for soil erosion (Ainslie 1920, 1929). Trap strips of susceptible crops were utilized as a sink for sawfly oviposition. The strips were then cut for hay following sawfly oviposition to destroy the eggs and larvae. The disadvantage of this method of control was expense in time, labor, loss of crop and yield acreage, and difficulty in marketing forage from trap crops such as oats, flax, and barley (Anonymous 1946). Shallow tillage after harvest from late summer to early fall (Farstad 1942), or spring using one-way disk or duck-foot cultivators (Holmes and Farstad 1956) was dependent on exposure of stubs to extreme weather condition causing desiccation and mortality. The drawbacks of shallow tillage in fall and spring was added time, labor and machinery costs, reduction of soil moisture from cultivation, loss of surface residue due to incorporation, and limited success if timing of tillage operation did not expose stems. A recommended practice in fields prone to high infestation was delaying spring wheat seeding until after May 20th, thus avoiding WSS infestation due to immature wheat development (Callenbach and Hansmeier 1944). The results confirmed that planting after May 18 was not economical and resulted in reduced wheat yields. A study was conducted using swathing as a method of minimizing cutting damage to wheat and reducing overwintering populations of the WSS while preventing grain yield and quality losses (Goosey 1999). Swathing at 40-48% moisture level used with other management methods could reduce overwintering larval population. The disadvantage is added labor, machinery, and time involved in incorporating this technique. However, in addition to benefit in minimizing WSS cutting damage, this technique also aids in uniform drying of the crop and has found favor with some producers. Insecticides have been examined as a possible control measure since the 1940's. From the 1940 to 1960's various insecticides have been applied as dusts, sprays, and granular applications, in seed, furrow, broadcast, and foliar treatments, however, no insecticide has been effective in consistently controlling the WSS (Holmes and Hurtig 1952, Wallace 1962, Blodgett, MSU, personal observation).

The management technique which has been the most effective, has been the identification of a resistant solid stem characteristic, parenchyma filled wheat stems, which offered a possible means of controlling the WSS. This characteristic was bred into the spring wheat varieties, "Rescue" and "Chinook", in 1938 (Platt and Farstad 1953, Taylor 1976). These and other solid stem spring wheat varieties have allowed producers to grow resistant spring wheat in WSS infested areas. However with the relatively recent shift of WSS into winter wheat, producers have sustained significant damage due to WSS. In 1995 and 1996 two resistant winter wheat varieties 'Vanguard' and 'Rampart' were released which integrated the solid stem characteristic from spring wheat (Bruckner et al. 1997, Carlson et al. 1997).

The wheat stem sawfly, (*Cephus cinctus* Norton) [Hymenoptera: Cephidae] is a holometabolous insect with one complete generation a year. The life cycle of the WSS is synchronized with the physiological development of the host plants. All the developmental stages occur within the confines of a grass stem except the adult stage. WSS adults emerge from previous years infested wheat in late May through the third week in July for most areas in Montana, Northwestern North Dakota and Canada (Criddle 1915, 1923, Wallace and McNeal 1966, Weiss et al. 1990, Weiss and Morrill 1992, Morrill and Kushnak 1996, Shanower unpublished data 2000). This adult emergence interval coincides with wheat development stages ranging from stem elongation through anthesis. The female WSS insert eggs within the grass stems with egg hatch occurring within 5-7 days. Larvae feed near the oviposition site, eventually working up and down the inside of the stem chewing through the nodes. When the plant begins to mature and dry, the surviving larva descends toward the base of the stem to prepare a site for diapause. The larva overwinter in the base of the grass stem protected from adverse conditions such as desiccation, light and exposure. Pupal development is initiated in the spring with adult emergence following shortly.

LITERATURE REVIEW

Wheat Stem Sawfly Taxonomy

Cephus cinctus Norton, wheat stem sawfly (WSS), is in the Order Hymenoptera, Family Cephidae. Hymenoptera have four membranous wings with the front wings larger than the hind wings. A row of tiny hooks (hamuli) attaches the hind wing to a fold on the front wings. The wings have relatively few or no veins at all. There is a well-developed ovipositor sometimes modified into a stinging organ. An abdomen that is broadly joined at the thorax, two-segmented trochanter, and three submarginal cells in hind wings characterizes the suborder Symphyta. Nearly all the Symphyta are phytophagous and have a single generation a year including *C. cinctus* (Borror et al. 1992).

The Family Cephidae contains stem sawflies in which the larvae bore and feed in grass stems, or stems and twigs of trees and shrubs. The adults are slender, laterally compressed sawflies and the larvae overwinter in a cocoon within the plant host. The thorax has two pairs of spiracles near wing bases. Antennae are near the middle of the face above the base of the eyes and the front tibia has one apical spur. There are 13 genera and about 100 species known in the world. *Cephus cinctus* feeds within grass stems and is a serious pest of cultivated grains (Wallace and McNeal 1966, Smith 1979, Borror et al. 1992). There are 25-30 world species in the Genus *Cephus* but only two are found in North America, *C. cinctus* Norton found in western United States and Canada and *C. pygmaeus* (L.) eastern United States and Canada (Smith 1979).

Both *C. cinctus* Norton (wheat stem sawfly) and *C. pygmaeus* (L.) (European wheat stem sawfly) are important wheat pests in the United States. They are similar in appearance and life cycles but differ in areas of habitat. *Cephus cinctus* was first described in 1872 by Edward Norton based on male specimens collected in Colorado and cotypes in Nevada and California. *Cephus cinctus* is found in grasses west of the Mississippi and north of the 36° parallel. WSS causes major economic losses in wheat (*Triticum* spp.) in the Northern Great Plains region that includes Montana, North and South Dakota, Wyoming, Nebraska, and neighboring provinces in Canada (Webster and Reeves 1910, Ainslie 1920 1929, Davis 1957, Wallace and McNeal 1966). *Cephus pygmaeus* was found in Ontario and New York in the 1880's, an unintentional introduction from Europe and Eurasia. *Cephus pygmaeus* inhabits the northeastern United States and eastern Canada but is not a major economic pest due to successful introduction of parasitoids in the 1930's (Udine 1941, Wallace and McNeal 1966, Smith 1979). There are two other synonyms for *Cephus cinctus*, *Cephus occidentalis* Riley and Marlatt, 1891 and *Cephus graenicheri* Ashmead, 1898 (Wallace and McNeal 1966, Smith 1979).

Wheat Stem Sawfly Description

The original description of 24 females and 14 males from California, Nevada and Montana of *Cephus occidentalis* synonym of *C. cinctus* by Riley and Marlatt (1891) is as follows:

"The adult insect agrees almost exactly with *Cephus pygmaeus* in coloration, coming much closer to it in this respect than to any other American species, but is in every way more slender and graceful and would never be mistaken for the European species. The head is narrower in proportion to the body and is more globular when viewed from the side. Viewed from above it narrows more posteriorly from the eyes than pygmaeus.

Female: Black; basal joints of the maxillary palpi, large yellow spot on mandibles, two spots beneath anterior wings, membranous regions of thorax, small spot on lower posterior edge of dorsum of first segment, larger one on second segment. Band dentate on basal margin on apical half of dorsum of third, fifth and sixth segments, and more less of the lower and apical margin of the remaining segments lemon yellow. Legs black, slender; spot on posterior coxae above upper side and tip of femora yellow; tibiae and tarsi reddish yellow except tips of posterior tibiae and their tarsi, which are brownish; last joint and claws of middle and anterior tarsi also brownish. Antennae 20-21 jointed, longer than head and thorax, slender to joint 7 beyond which the articles are shorter and thickened. Wings slightly smoky; veins brown except costal and margin of sigma which are yellowish; a small infuscated spot at base of discoidal vein; second recurrent vein joins the third submarginal cell near the base of the cell; cross veins of lanceolate cell slightly curved and oblique. Abdomen not much longer than head and thorax, strongly compressed laterally. Length, 9-11 mm.

Male: smaller and more slender than the female; abdomen less compressed; antennae 18-21 jointed. Coloration as in female except a large spot on the clypeus, one just below the eyes in front, the entire pectal region of the thorax and the posterior margin of the third, fifth, and remaining ventral segments which are lemon yellow. The under side of the coxae, trochanter, and femora, including the apex of the latter above are lemon yellow; the tibiae and tarsi are as in the case of the female. In some specimens the femora are entirely yellow or with a narrow black line on the anterior pair above, and the yellow band on the third ventral segment is occasionally obsolete. Length, 8-9 mm."

Additional descriptive identification of the adult WSS includes the following; the dorsal view of the pronotum is trapezoidal in shape, as wide as long. The front tibia has one apical spur without pectination on inner margin (Borror et al. 1992). The female ovipositor is well-developed and composed of two pairs of laterally compressed appendages with serrated teeth at tip on dorsal side and two rows on ventral side. The ovipositor is enclosed in a sheath and protrudes from the eighth and ninth sternites (Ainslie 1920,1929, Wallace and McNeal 1966).

Differences in adult body color distinguish *C. cinctus* and *C. pygmaeus*. *C. cinctus* has a more pronounced yellow markings on the black body compared to *C. pygmaeus*. Taxonomic key to adult stem sawflies of United States by Ries (1926), describes differences between the two species:

"Abdomen with dorsal, transverse, yellow bands; ovipositor sheaths when viewed dorsally, not swollen or laterally enlarged toward their apices; males without horseshoe-shaped depressions on last two apical ventral segments-- 2

Sigma and costa dark brown, of uniform color; mesepisternum black; femora black; apical tergite and venter black; face and scutellum black (face of male with yellow spots)--- *Cephus pygmaeus* (L.)

Stigma in greater part and costa yellow; mesepisternum with upper angle yellow; femora mostly yellow; apical tergite and usually venter in part yellow; face and scutellum of female usually black but occasionally with yellow spots--------*Cephus cinctus* Norton"

The distinguishing larval characteristics of C. *cinctus* and C. *pygmaeus* are more difficult. The following taxonomic key by Gahan, (1920) distinguishes between the larvae of the two species:

"Dorsal anal lobe of 10th tergite, viewed from side, triangular, sloping gradually from base to apex, and anterior end of lobe much thicker than posterior end, which is more or less acute. Spines on anal prong each arising from small, more or less chitinized tubercle and closely grouped about apex of enlarged fleshy part just basad of short chitinized apical ring. Eighth and ninth tergites apparently glabrous------------------------ 2

Anal prong terminating in short chitinized ring, which is not as long as broad. Spines basad of chitinized ring few in number, confined to single transverse row on dorsal surface. Dorsal, lateral, and ventral lobes sparsely hairy----*Cephus pygmaeus* (L.)

Anal prong terminating in chitinized tube-like process, which is distinctly longer than broad. Spines basad of apical tube-like process numerous, arranged in two irregular contiguous series completely encircling base of tube. Anal lobes distinctly hairy---*Cephus cinctus* Norton"

Wheat Stem Sawfly Life Cycle

The wheat stem sawfly is a holometabolous insect with one complete generation a year. The life cycle of the WSS is synchronized with the physiological development of the host plants. All the developmental stages occur within the confines of a grass stem except the adult stage.

Adult

WSS adults emerge late May to late June and may continue until the third week in July for areas in Montana, northwestern North Dakota and Canada (Criddle 1915, 1923, Wallace and McNeal 1966, Weiss et al. 1990, Weiss and Morrill 1992, Morrill and Kushnak 1996, Shanower unpublished data 2000). Adult emergence is synchronous with the physiological development of the grass hosts because female WSS choose to oviposit in developing stems of certain diameter, during certain plant growth stages. Plant developmental stages that are suitable for WSS oviposition begin at stem elongation through anthesis (Zadoks 32-69). Ovipositing WSS females require the presence of an internode or the stem will be rejected for a more suitable host. Anthesis usually marks the end of the oviposition period due to the increasing maturity of the tissue preventing insertion of the ovipositor. Younger more succulent stem tissue is desirable for the insertion of the ovipositor for egg deposition (Criddle 1923).

Weather, soil temperature, and soil moisture has an effect on adult emergence, longevity, and duration of flight (Seamans 1945, Wallace and McNeal 1966). The WSS adult chews through the frass that plugs the overwintering chamber and emerges in late

May to late June. Ideal conditions for emergence are a warm moist May, hot June with sufficient moisture for plant growth and dry weather for flight (Seamans 1945).

Adults are most active on calm, sunny days at temperatures that range from 17°C to 32°C. Activity declines or terminates during cloudy, windy, wet and rainy conditions and at temperatures less than 17°C (Seamans 1945). Duration of WSS flight is also effected by weather, soil moisture and soil temperature. Excessive hot windy conditions shorten the emergence period while moderate environmental conditions allow emergence to continue until late July (Wallace and McNeal 1966). The average lifespan of the WSS adult is 5-8 days with maximum lifespan of 12-16 days, depending upon available moisture and climatic conditions (Criddle 1923, Wallace and McNeal 1966).

Male WSS generally emerge first and congregate on grass stems near field edges waiting to mate with emerging females (Weiss and Morrill 1985). Females take flight soon after emerging in search of suitable hosts to oviposit eggs. Mating is not required for the production of viable eggs or egg development; the WSS female reproduces by a type of parthenogenesis, arrhenotoky (haplo-diploid), in which fertilization determines the sex of the developing WSS. In arrhenotokous population, unfertilized eggs develop into haploid males and fertilized eggs mostly produce diploid females however, infrequently azygous diploid females occur. The diploid female has 18 chromosomes and the haploid male has 9 chromosomes (MacKay 1955). A thelyotokous population was reported among areas of infestation with bisexual populations, near Lethbridge, Canada in 1936-37. In the thelyotokous population, unfertilized eggs produced diploid females, no males were found and diploid males were rare (Farstad 1938, MacKay 1955).

Mutations from a bisexual race or natural selection of diploid azygote isolates arising from haploid parthenogenesis may be responsible for this phenomenon (MacKay 1955).

The female WSS reproductive organs consist of paired ovaries containing seven polytrophic ovarioles in each ovary. Embryonic development of seven eggs can be seen in each ovariole but only three reach maturity in the adult female. The female WSS on average has an egg laying potential of forty eggs during her lifetime (MacKay 1955).

The female prefers the uppermost internode of an elongating stem with a diameter of 2.8-3.4 mm to deposit her eggs (Holmes and Peterson 1960). Grasses are susceptible to WSS oviposition at growth stages ranging from Zadoks 32 (stem elongation) through 69 (anthesis) (Holmes and Peterson 1960, Zadoks et al. 1974). The female WSS tests the suitability of a grass stem by moving, in a head down position, down the stem locating a suitable spot to insert the ovipositor. Once a site has been chosen, the female abdomen is drawn up under the body and an attempt is made to insert the saw-like ovipositor. The ovipositor is forced between the cells of the stem tissue causing a minutely visible oviposition scar. If the spot is suitable the ovipositor is inserted and withdrawn several times before one egg is inserted (Wallace and McNeal 1966). Each female lay only one egg per stem (Ainslie 1920) but egg lay by more than one female is common.

Egg

Newly laid eggs are an opaque, milky white color with tapered, rounded ends. The nearly symmetrical eggs range in size from 1-1.25 mm long and 0.33-0.42 mm wide (Ainslie 1920, 1929).

The egg stage is 5-7 days in length. During the first day the milky white content shrinks within the thin egg sac leaving a space or vacuole. Cells are visibly arranging along a central axis during the second day. By the third day the form of the larva is visible and abdominal segments well defined. The transparent head fills one end of the egg sac with the body looped or folded beneath the abdomen. An intermittent heartbeat is detectable in the fourth day of development. The heart becomes more regular with about 120 impulses per minute and the mandibles and eyespots began to darken during the fifth day. The fifth, sixth and seventh days show an increase of activity within the egg sac with subsequent escape from the egg sac by a series of convulsive movements (Ainslie 1920, Wallace and McNeal 1966).

Larvae

Shortly after emerging from the egg casing the head capsule, mandibles and eyespots sclerotize and darken resulting in a light brown head capsule and dark brown mandibles and eyespots. The remaining body is transparent and colorless developing from milky white to yellow color as feeding begins. The mandibles have well-developed molar and incisors for chewing and biting (Ainslie 1920, 1929, Wallace and McNeal 1966, Holmes 1954, Maxwell 1955). The larval type is eruciform, soft-bodied, cylindrical, and resembles Lepidoptera caterpillars but do not have the specialized crochets on the prolegs (Borror et al. 1992). The first two segments of the abdomen are swollen, with a short blunt point at the posterior end of the body (Criddle 1915). The pygidium also has stiff bristles that aid in movement up and down within the stem. The head and last thoracic segment are sparsely covered with hairs (Ainslie 1920, 1929, Wallace and McNeal 1966). Ainslie (1920) noted that larvae size is variable but recorded an average length of 2.24 mm and width of 0.54 mm.

Feeding begins as soon as the mandibles harden and are capable of chewing. The larvae begin feeding initially near the oviposition site, eventually working up and down the stem chewing through the nodes. The pygidium aids in the ability to turn and move in the stem and also supports the body when feeding. As the larvae feeds upon the stem pith, comprised of parenchyma and vascular tissue, it fills the stem with excreted partially digested plant tissue called 'frass' (Holmes 1954). The larvae exhibit cannibalistic behavior resulting in direct competition between earlier emerging larvae and later laid eggs and emerging larvae. The outcome is the survival of one larva per stem (Wallace and McNeal 1966).

Larval development includes at least four and possibly five instars, but instars are difficult to determine due to ingestion of skin castings and frass within the stem (Ainslie 1920, Taylor 1931, Farstad 1940).

When the plant begins to mature and dry, the surviving larva descends toward the base of the stem to prepare a site for diapause. Holmes (1975) found that movement toward the base of the stem is in response to infrared and visible light emitted through the mature drying stem. The larva chews around the inside of the stem cutting almost through existing stem tissue, resulting in 'girdling'. The lower three to six millimeters of the stem termed a 'stub', is plugged with 'frass' just below the girdled notch. This rigid plug prevents the stem from bending, breaking, or collapsing below the girdled notch which would compromise the integrity of the larva, and influence its mortality. After girdling and plugging the stem, the larva constructs a cocoon like sac within the hollow stem. The sac is a clear thin cellophane-like material that is secreted by the labium, drying to a transparent brown casing. It is attached to the frass plug and fills the stub, forming a free hanging sac. The sac protects the larval and pupal stages from desiccation and excessive moisture conditions (Wallace and McNeal 1966). The cocoon allows some freedom of movement within the stub and serves as a hibernaculum for the obligatory diapause stage (Wallace and McNeal 1966).

Cutting of the stem and subsequent diapause occurs in response to stem moisture loss as tissues mature, which can result in desiccation of the larvae (Holmes 1975). Any condition that delays the maturing or ripening of the stem such as delayed planting date, excess soil moisture, and/or lower temperatures result in the delay of stem cutting (Holmes et al. 1963). Excess soil moisture can result in a cut higher than ground level because of residual stem moisture in lower internodes (Holmes 1975). Overwintering in the base of the grass stem ensures the larva is protected from adverse conditions such as desiccation, light and exposure.

Diapause is initiated shortly after the cocoon is formed, lasting for a period of about ten months extending from harvest through spring. Development is arrested and metabolic processes are reduced during this time. Diapause is terminated in the spring when temperature conditions 10°C or greater are attained (Salt 1946, 1947).

<u>Pupae</u>

A cold period is required for initiation of pupal development. Salt (1947) concluded that 10°C for 90 days is the minimum cold period requirement. Pupal development according to Criddle (1923) is estimated to last 16 days depending on climatic and environmental conditions. For example, weather, soil temperature and moisture effects pupal development. Exposure of stubs to continuous light and high temperatures (35°C) results in malformed pupae and adults, diapause reinitiation in postdiapause larvae, and mortality of prepupae and pupal stages (Church 1955, Holmes and Farstad 1956, Villacorta et al. 1971). There must be adequate moisture in the spring for pupal development and to prevent mortality due to desiccation (Wallace and McNeal 1966).

The pupae are pale, milky white in color and exarate in form, appearing motionless but capable of movement within the cocoon. As pupal development progresses wings develop fully, eyes darken and gradual pigmentation of the body takes place resulting in a fully formed adult (Wallace and McNeal 1966).

Wheat Stem Sawfly History of Importance

Cephus cinctus was first described in 1872 by Norton based on male specimens collected from grasses in Colorado and co-types in Nevada and California (Wallace and McNeal 1966). In 1890, Koebele found larvae in grass stems near Alameda, California that were reared to adults and identified by Riley and Marlatt in 1891 along with specimens form Nevada and Montana as *C. occidentalis* a synonym of *C. cinctus*. A prediction made at this time, was based on the feeding habits and potential for host shifting of the grass-stem sawfly, stating: "The economic importance of this species arises from the fact that it may be expected at anytime to abandon its natural food-plant in favor of the small grains, on which it can doubtless successfully develop." (Ainslie 1920). Less than five years later, in 1895, *C. cinctus* adults and larvae were found infesting spring wheat in Souris, Manitoba (Ainslie 1920, 1929) and Moosejaw, Saskatchewan Canada (Wallace and McNeal 1966). In 1900 WSS was found infesting grasses in Bozeman, Montana. From 1902-1906 WSS was reportedly found in grass plants, primarily *Agropyron* spp., from the Northwest Territories as far south as the Dakotas and Wyoming (Ainslie 1920).

United States

The establishment of the Homestead Act in 1862, allowed large numbers of acres to be plowed and planted to spring wheat in the Northern Great Plains. Between 1900 and 1925 wheat acreage increased from 116,640 to 2,691,630 million hectares

(Hargreaves 1993). This resulted in large tracts of land, devoted to wheat production, providing an opportunity for WSS to shift hosts from grasses to cultivated small grains.

In 1906, *C. cinctus* larvae were found in spring wheat at Kulm, North Dakota (Ainslie 1920). In 1907 larvae and stem damaged spring wheat stems were found in central Manitoba, Southeastern Saskatchewan, Canada, and Minot, North Dakota (Ainslie 1920). Larvae were found in grasses in Oregon in 1908 (Ainslie 1920). WSS damage to spring wheat crops averaged 5-25% to as high as 66% from Minot, North Dakota and north into Canada in 1909. In 1910, total devastation of most of the spring wheat crop was reported in Bainville, Montana (Wallace and McNeal 1966).

Ainslie began determining the WSS distribution in the United States in 1911 (Wallace and McNeal 1966). From 1913-1915 Ainslie (1920) surveyed WSS infestation in grass species throughout the Dakotas and Minnesota. Ainslie found that the larger stemmed grasses were the preferred hosts of WSS, this included *Elymus* sp., timothy (*Phleum pratense*), *Agropyron* spp., and *Bromus* spp. Slender stemmed species such as bluegrass (*Poa* sp.) appeared to have immunity to WSS infestation (Ainslie 1920, 1929). In 1916 Ainslie (1920), found larvae in spring wheat stems in North Dakota counties, Bottineau, Benson, Pierce, McHenry and Rolette expanding to Hettinger, Towner and Cavalier in 1917. In Bottineau County, the percentage of cut spring wheat stems from WSS was greater than 60%, an estimate of 294,030 to 526,500 WSS infested stubs per hectare. By 1920, the distribution of *C. cinctus*, in wheat, had expanded north into neighboring provinces of Canada, east to the Mississippi River, south to the 36° parallel and west to the Pacific Ocean (Ainslie 1920, 1929).

From 1923 to 1943 almost all areas east of the Rockies including North Dakota reported infestations in spring wheat. Forty counties in South Dakota and a large number of counties in Wyoming also experienced crop damage. The heaviest infestation occurred in northern Montana, as much as 80% damage was reported (Anonymous 1946). Sawfly damage in Montana and North Dakota increased from 1943 to 1952. A damage survey conducted in 1952 estimated spring wheat losses in North Dakota and Montana at $17 million (Davis 1955).

The WSS has historically been successful in shifting from grass hosts to spring wheat in the hard red spring wheat growing areas, Canada, Montana, North Dakota, northern Wyoming and northern South Dakota with economic damage recorded in Montana and North Dakota (Ainslie 1920, 1929, Davis 1955). In southern Wyoming and South Dakota, Davis (1955) found the WSS had been less successful in shifting to infesting winter wheat, possibly due to lack of host/insect synchronization. In South Dakota WSS infested winter wheat plants matured before larval growth and development was completed causing considerable mortality of the WSS (Davis 1955). Further south in the central Great Plains, (southern Wyoming, Nebraska, Colorado, Kansas), winter wheat escaped infestation due to the early maturing of the wheat plant (Painter 1953, Wallace and McNeal 1966).

Until the 1960's, spring wheat was the dominant wheat grown in Montana. From 1960 to present, winter wheat acres have increased to equal that of spring wheat. With the increase of winter wheat acreage widespread losses due to WSS became more evident, beginning in 1985 (Morrill 1985). In 1997, infestation levels in winter wheat ranged from 33-96% in areas of Montana (Morrill 1997). Morrill and Kushnak (1996) determined that the wheat stem sawfly adapted to and synchronized with winter wheat development in Montana. The mean reported date of emergence of the WSS before 1970 was June 20, (Morrill and Kushnak 1996) compared to the more recent (1990-1995) mean emergence date of May 31. The difference of 21 days enabled the WSS to utilize winter wheat by synchronizing with elongation (Zadoks 31) through anthesis (Zadoks 69), susceptible developmental stages of winter wheat. Recently, the WSS has been able to utilize and cause more damage to winter wheat than to spring wheat in some areas (Morrill and Kushnak 1996).

The increased planting of susceptible wheat lines with more desired agronomic characteristics and higher yields has resulted in an increase or resurgence of the WSS in Montana and North Dakota (Byers and May 1991). Western North Dakota reported an average cutting of 5.2 to 11% and 50 to 90% for 1986 and 1992 respectively (McBride 1987, 1992). A survey of economic losses in spring and winter wheat was conducted in 1995 and 1996 in Montana. Results of the survey reported loss estimates of 15 million bushel at a cost of $25-30 million per year due to sawfly cutting (Blodgett 1996).

Canada

Between 1907 and 1922, Criddle studied the life habits, life cycle synchronization of the WSS with its host plants, observed alternative host adaptation to cultivated crops and recommended methods of control. Criddle observed the movement of the WSS from the grass hosts to cultivated wheat and rye in 1907 (Criddle 1911, Bird 1961). He also observed that oviposition was a function of stem diameter which in turn is dependent on soil moisture and noted that sunshine and warm temperatures were important for oviposition and activity of the WSS (Criddle 1915, Bird 1961). Criddle also recorded preferred grass hosts (*Agropyron* sp., *Elymus* sp., *Calamagrostis* sp., *Deschampsia* sp., *Hordeum jubatum*, *Bromus inermis*), susceptible cultivated crops (hard spring wheat, winter wheat, spring rye, spelt), and resistant cultivated crops (durum, barley, fall rye, oats) for Canadian districts (Criddle 1915, 1922, Bird 1961).

In 1926, Saskatchewan, Canada suffered severe economic losses estimated at $12 million attributed to WSS infestation. Between 1938 and 1948 grain losses ranged from 560,000 to 700,000 tons in Canada (Farstad et al. 1945, Platt and Farstad 1946). In 1929, at Dominion Experiment Station, Swift Current, it was observed that solid and semi-solid wheat was not seriously damaged by WSS. The solid stemmed wheat had limited feeding on the pith tissue resulting in limited damage from the WSS (Kemp 1934). It was believed that a solid stem offered a possible means of controlling the WSS and a cooperative breeding program was implemented, in 1932, to develop solid stemmed resistant varieties of spring wheat at Dominion Experiment Station, Swift Current and Dominion Entomological Laboratory, Lethbridge, Canada (Platt and Farstad 1946). This research resulted in two solid stemmed WSS resistant varieties 'Rescue' and 'Chinook' in 1938. Rescue was produced from a cross between solid stemmed variety from Portugal 'S-615' (*Triticum vulgare)* and 'Apex' a hollow stemmed spring wheat (*Triticum aestivum)* and Chinook resulted from a cross between a hollow stemmed spring wheat 'Thatcher' and the solid stemmed Portugal wheat 'S-615 (Taylor 1976). Rescue was released in 1946 and over 405,000 hectares were seeded in 1948 (Platt et al. 1948), however damage from WSS continued to remain high. Rescue and solid stemmed varieties of *T. vulgare* exhibited variability in the degree of sawfly resistance. Platt (1941) and Holmes (1984) determined environmental factors, such as light intensity and duration during stem development (Zadoks 32-45) influenced the expression of the solid stem characteristic therefore resulting in variable resistance from year to year.

In 1952, a second solid stemmed resistant spring wheat variety Chinook was released. In 1954 a combination of factors including weather conditions favorable for wheat stem rust, high parasitism in 1956 and the extensive use of resistant solid stemmed wheat varieties resulted in a decline of WSS populations from 1955 and 1959 (Holmes 1982). WSS populations have remained low in Canada for about 30 years possibly due to a variety of factors including the extensive cultural practice of early swathing to dry grain in preparation for harvest (Byers and May 1991).

Wheat Stem Sawfly Management

The conventional wheat crop-fallow system was developed by a farmer in Canada about 1885, and became an established cropping system practice in the northern Great Plains (Howard 1959). Soil moisture was allowed to accumulate for the next growing season in the fallow area left idle from crop or vegetation for one growing season, providing adequate moisture for plant growth with later senescence and increased wheat yields (Black 1983). However, fallow acres contained stubble from the previous year served as a source of overwintering WSS for infestation of adjacent wheat strips.

The extensive use of crop-fallow systems resulted in an increase in soil erosion due to wind and water. To decrease the damaging effects of wind erosion, fields were cultivated in narrow alternating strips of crop and fallow arranged perpendicular to the prevailing wind (Howard 1959). The crop-fallow system of farming amplified sawfly populations by alternating strips suitable for larval overwintering sites (stubble) with wheat host. Current minimum tillage farming practices which replaces soil tillage with chemical weed control (chem.–fallow), decreases tillage and favors WSS survival by reducing larval mortality due to tillage (Holmes and Farstad 1956, Weiss et al. 1987, Weiss and Morrill 1992). A recent study (Runyon et al. 2002) observed that minimum tillage practices should not increase WSS damage but increase in WSS parasitism overtime.

The difficulty in identifying economic and effective means of control spurred research on WSS management. A search for methods of controlling the WSS began in the early 1900's by Criddle in Canada and Ainslie in the U.S. Many WSS management techniques encompassing cultural, biological, and chemical controls have been evaluated, modified, or abandoned. At present the use of solid stemmed varieties is the only effective management technique recommended for control of WSS.

Cultural control

In the 1920's recommendations for control of WSS included burning stubble, mowing ditches and field edge grasses, deep tillage, use of trap strips with certain resistant crops. Other management practices considered were shallow tillage, delayed seeding of wheat, and insecticides. However these recommendations were not widely adopted because of added costs for equipment, management and lack of consistent effectiveness.

Burning stubble in the autumn or spring to kill the larvae in the cut stem stub was suggested as a means of controlling WSS (Ainslie 1920, 1929, Farstad 1942). It was thought that burning the stubble or grass would create enough heat to damage the overwintering chamber or kill the larvae. In highly infested fields the amount of wheat stubble standing, available to fuel the fire is reduced because cut stems are at ground level. Following a burn, exposed WSS stubs are fire-damaged but not sufficient to be an effective or consistent control (Goosey and Johnson 1998 unpub. data). Even in fields with low infestation and a greater proportion of standing stubble, the resulting fire is quick and hot but not uniform or sustained to cause damage to overwintering larvae in stubs (Ainslie 1920, 1929, Farstad 1942). Criddle (1922) used an additional layer of straw spread on an infested field as added fuel for burning. The ground was reported hot to the touch from the fire but no larval mortality was found in stubs sampled. Cut stubs are well insulated from temperature extremes by the soil attached to the crowns. Larvae have the ability to retreat to the lower end of the cocoon in the stub, further insulation themselves from excessive heat (Ainslie 1920, 1929, Criddle 1922, Farstad 1942). Negative effects of burning were an increased risk of erosion and loss of soil organic matter needed to improve soil characteristics and plant growth.

Mowing grasses near roadways and fields was initially a suggested practice for reducing sawfly larvae in the 1920's. However, this practice was not recommended because grasses are a source for parasitoids of the wheat stem sawfly and mowing would reduce the sawfly larval populations as well as the beneficial parasitoid populations (Ainslie 1920, Criddle 1922).

From 1917-1940's deep tillage using a moldboard plow was a recommended control practice. The practice of turning the stubble, burying it at least 15.2 cm and packing with a harrow between harvest and spring of the following year impeded the emergence of the sawfly adults. Ainslie (1920) found that stubs buried at a 15.2 cm depth resulted in a 35% reduction of emerging adults but is not a practice recommended for Montana, the Dakotas, and Canada because of the high potential for soil and wind erosion (Ainslie 1920, 1929).

The utilization of trap crops as a sink for sawfly oviposition has been recommended based on the assumption that adults are weak flyers and seldom fly further from the emergence point than is necessary to find a suitable host plant (Farstad 1942). The trap crop was typically a narrow strip the width of a seeder, 3-6 meters, planted between the previously infested field and new crop. The trap crop was then cut for hay between July 10-20 following sawfly oviposition to destroy the eggs and larvae (Criddle 1917, Callenbach and Hansmeier 1944). Planting resistant crops such as oats, barley, and winter rye in the trap strip before planting the susceptible crop was suggested as a means of lessening damage to the susceptible crop (Criddle 1917). The use of susceptible varieties in the trap strip (spring and winter wheat, spring rye, oats, barley, durum wheat, and flax) was also recommended. Modifying planting dates of trap crop by 10 to 14 days before and 2 to 3 days after planting main crop was required for spring wheat and spring rye, respectively (Farstad 1942, Farstad et al. 1945). The drawbacks of this method of control was expense in time, labor, cost, loss of crop acreage, and lower yields and market prices with use of alternative susceptible or resistant crops (Anonymous 1946, Morrill et al. 2001).

Shallow tillage was conducted shortly after harvest in late summer/early fall (Farstad 1942), or spring using one-way disk or duck-foot cultivators (Holmes and Farstad 1956). The purpose was to bring the crowns of the wheat stubble to the surface, while removing excess insulating soil from crowns, exposing the stubs to extreme environmental conditions. Success of fall tillage was dependent on exposure of stubs to hot and dry weather conditions causing desiccation that resulted in 35 to 60 % control (Callenbach and Hansmeier 1944, Holmes and Farstad 1956). Holmes and Farstad (1956) reported greater than 90% mortality by spring tillage exposing prepupal and early pupal stages by heat and cold conditions. Weiss et al. (1987) concluded that shallow spring tillage decreased sawfly survival but not enough to be economical. Morrill et al. (1993) found that overwinter survival of exposed WSS stubs by shallow fall tillage was 7.3 to 8.0% in 1990-1992. Greatest mortality occurred between April and May. Desiccation was a factor in the mortality increase during this time. The drawback of shallow spring or fall tillage was added time, labor and machinery costs, loss of soil moisture from cultivation, and loss of surface residue due to incorporation and increase potential for soil erosion.

In 1997 a study was conducted combining the use of a rotary harrow following spring shallow tillage applications to expose a greater number of soil-free crowns on the soil surface. Crown exposure was increased by 27.93% to 83.53% during 1997. In 1998 the rotary harrow application had a greater percentage of soil-free crowns (55.4% to 69.4%) compared to plots tilled with shovel and rod (27.9% to 44.77%) (Goosey 1999).

Delaying seeding spring wheat until after May 20th in fields expected to have high WSS infestations resulted in immature developmental stages of the wheat therefore avoiding WSS infestation (Farstad 1942, Callenbach and Hansmeier 1944, Farstad et al. 1945). McNeal et al. (1955) found that seeding would have to be delayed until after June 1 to avoid serious sawfly damage, however late seeding would result in yield losses due to a shortened growing season. In 1987, Weiss et al. conducted a study on the influence of planting dates. The results confirmed that planting after May 18 was not economical and resulted in reduced wheat yields.

Goosey (1999) looked at the effect of swathing wheat to minimize WSS larval cutting damage and reduce overwintering populations of the WSS while preventing grain yield and quality losses. Although larval survival was less than 20%, grain test weight decreased and protein increased at grain moisture levels above 40 to 48%. Swathing at crop moisture levels of 40-48% could reduce overwintering larval population. However, the disadvantage is added labor, machinery, and time is needed to incorporate this technique (Goosey 1999).

Insecticides have been examined as a possible control measure since the 1940's. From 1940 to 1960's chemicals have been applied as dusts, sprays, and granular applications, in seed, furrow, broadcast, and foliar treatments. In the 1950's parathion applied as a foliar treatment for control of WSS adults was ineffective and because of its short residual activity did not prevent oviposition due to the extended flight period

(Holmes and Hurtig 1952). Wallace (1962) found seed, broadcast, and furrow chemical treatments with a systemic mode of action did not control adults. Only heptachlor applied as seed and furrow treatments offered some control during the larval development stage. Most of the organochlorine, long residual insecticide chemicals tested such as DDT, dieldrin, heptachlor, and aldrin are now banned from use in the U.S. due primarily to environmental persistence and non-target effects. Few chemicals offer the residual activity needed to control WSS eggs and larvae, however, insecticides with new modes of action or range of activities are continually tested, as they become available.

<u>Biological control</u>

There are nine established parasitoids that have been recorded to attack *C. cinctus* in resident and native grasses in the northern Great Plains. They are: *Bracon cephi* (Gahan), *Bracon lissogaster* Muesebeck, *Eupelmella vesicularis* (Retzuis), *Eupelmus allynii* (French), *Eurytoma atripes* Gahan, *Pediobius utahensis* (Crawford), *Pediobius nigritarsis* (Thomson), and *Scambus detritus* (Holmgren), and *Eurytoma parva* Phillips (Holmes 1953, Holmes et al. 1963, Davis et al. 1955, Wallace and McNeal 1966, Morrill 1997). Only *Bracon cephi* and *Bracon lissogaster* have been successful in parasitizing WSS in wheat hosts (Morrill et al. 1998, Runyon et al. 2001).

Bracon cephi and *B. lissogaster* are both specialists on *C. cinctus*. *Bracon cephi* has been instrumental in reducing WSS populations in areas of Canada (Nelson and Farstad 1953, Holmes et al. 1963) and Montana. Morrill et al. (1994, 1998) reported levels of parasitism in Pondera County, Montana averaging 70-79% in 1992-93 and 15-98% between 1994 -1997.

Pediobius utahensis is a generalist native to North America with two known hosts (Ivie 2001). *Pediobius utahensis* has a wide geographic range, parasitizing WSS in grass hosts and was reported parasitizing WSS wheat in Utah in 1918 (Gahan 1921) and 1948 in North Dakota (Munro et al. 1949). *Eupelmus allynii* and *E. vesicularis* are both generalists with over thirty hosts, including *B. cephi* (Nelson 1953, Wallace and McNeal 1966, Ivie 2001). *Pediobius nigritarsis* and *E. atripes* are both generalist parasitoids that use the Hessian fly (*Mayetiola destructor*) as their primary host (Wallace and McNeal 1966, Ivie 2001). *Scambus detritus* is a generalist that was identified in Montana as a parasitoid of *C. cinctus* in 1952 (Holmes 1953) but is a parasitoid of *C. pygmaeus* in Europe (Salt 1931). *Eurytoma parva* is a primary parasitoid of the wheat joint worm (*Harmolita tritici*) but also attacks *C. cinctus*.

Collyria calcitrator (Gravenhorst) and *Bracon terebella* Wesmael both parasitoids of *C. pygmaeus* were introduced for possible control of *C. cinctus* in Montana, North Dakota and Canada. *Collyria calcitrator* was released in the Prairie Provinces in Canada from 1930-39 (Smith 1959), in North Dakota and Montana from 1952-55 (Davis et al. 1955, Davis 1959), in Alberta Canada in 1960 (Smith 1961). *Bracon terebella* was released from 1952-55 in North Dakota and Montana (Davis et al. 1955, 1957). Both parasitoids were unsuccessful in establishing in the Northern Great Plains on WSS. In 1937, *Heterospilus cephi* Rohwer a parasitoid of *C. pygmaeus* was released in Canada but was unsuccessful in establishing (Clausen 1977).

Host Pant Resistance

In 1932 a breeding program was implemented at Swift Current, Canada to develop resistant varieties of spring wheat to WSS (Taylor 1976). This research resulted in two solid stemmed varieties 'Rescue' and 'Chinook' in 1938. Rescue was produced from a cross between solid stemmed variety from Portugal 'S-615' and 'Apex' a hollow stemmed spring wheat (Platt and Farstad 1953) and Chinook resulted from a cross between a hollow stemmed spring wheat 'Thatcher' and the solid stemmed Portugal wheat 'S-615' (Taylor 1976). Rescue successfully reduced sawfly infestation to less than 1% in some areas. Agronomically, Rescue was not adapted to a wide growing area and exhibited average yield potential and low baking quality (Stoa 1947, Platt and Farstad 1953). In 1952 the solid stemmed resistant variety Chinook was released. Cypress, a cross between two solid stemmed wheat varieties Rescue and Chinook, was released in 1962 (Taylor 1976).

United States wheat breeding programs have resulted in additional solid stemmed spring wheat cultivars adapted to a wider area. 'Fortuna' a solid stemmed spring wheat was developed and released from North Dakota Agricultural Experiment Station in 1966 and was adapted to eastern Montana dryland districts. Fortuna was the first solid stemmed variety to combine resistance of leaf and stem rust with sawfly resistance. Fortuna was developed by crossing 'Rescue-Chinook' / 'Frontana' // 'Kenya 58-Newthatch'. The source of sawfly resistance is from Rescue and Chinook. Fortuna was superior in flour quality, yield and protein to previous solid stemmed varieties (Lebsock et al. 1967).

'Lew', a solid stem spring wheat variety was released in 1977 with resistant to stripe rust, leaf rust, and stem rust and had superior milling and baking qualities (McNeal and Berg 1977). Lew was selected from the cross of 'Fortuna'/ 'S6285'. S6285 is a hollow stemmed selection with Rescue and Chinook in its pedigree.

The MSU Winter Wheat Breeding Program has recently released two resistant solid stemmed, hard red winter wheat cultivars 'Vanguard' and 'Rampart'. Vanguard was released as a sawfly resistant cultivar in 1995 as an emergency measure to reduce losses by the WSS. Vanguard is a cross of 'Lew' / 'Tiber' // 'Redwin' (Carlson et al. 1997). Rampart was released in 1996 and is a sister line to Vanguard sharing the same parentage (Bruckner et al. 1997). Lew is the source of solid stemmed resistant characteristics for both cultivars. Although Vanguard and Rampart yield lower than hollow stemmed cultivars in the absence of WSS they are equivalent or superior to most hollow stemmed varieties under heavy sawfly pressure. Both Rampart and Vanguard meet domestic quality standards for high quality bread flour and protein content (Carlson et al. 1997, Bruckner et al. 1997).

Acceptance of solid stemmed WSS cultivars by producers has been slow due to less favorable agronomic characteristics such as variable expression of the resistant character stem solidness resulting in inconsistent WSS protection. Other less favorable characteristics include reduced disease resistance, and with some cultivars lower protein content and lower yield compared to hollow stemmed WSS susceptible varieties. Producers in northeastern Montana and northwestern North Dakota, to improve yield and reduce WSS damage, have in the past used resistant and susceptible spring wheat cultivar blends as a management practice (Weiss et al. 1999).

Cultivar mixtures or blends are frequently used in the United States and numerous other countries to control disease and pathogens with some success. A wheat cultivar mixture to study the effect on control of spot blotch (*Bipolaris sorokiniana*) and yield was conducted at Nepal, Mexico from 1990-1993 (Sharma and Dubin 1996). The mixtures reduced spot blotch development and increased yields compared to single cultivars. In California, USA 1991-1993, diverse spring wheat cultivar blends of high and low susceptibility were used to control septoria tritici blotch and leaf rust (Jackson and Wennig 1997). During high to moderate disease pressure blends had less leaf rust and septoria tritici blotch than the high susceptible cultivar. Yield and grain qualities were equivalent or better than single cultivars. Other successful cultivar mixtures or blends have been reported (Castro 2001) including the German Democratic Republic from 1984-1990, disease control in barley production (Wolfe 1997) and China, using susceptible and resistant rice cultivars to control rice blast severity (Zhu et al. 2000). In Switzerland 1992, cultivar mixtures were used as an alternative to fungicides, insecticides and growth regulators use for disease suppression in cereal crops (Mertz and Valenghi 1997). In 1997, Denmark successfully marketed winter barley mixtures with powdery mildew resistance (Munck 1997). Poland has used barley cultivar mixtures for disease suppression since the early 1990's (Gacek 1997) and in Kansas, wheat variety blends occupied 7% of fields in 2000 to stabilize yields, another advantage of blends (Bowden et al. 2001).

Wheat cultivar mixtures or blends have been used to control insects with mixed results. In 1991, Greenbug (*Schizaphis graminum*) biotype C and E resistant and susceptible wheat cultivars blends resulted in a recommendation of 75 resistant/ 25 susceptible ratio for management of both greenbug biotypes (Bush et al. 1991). A study was conducted from 1990-1992 (Sij et al. 1999) with seven arthropod insects on soybean (*Glycine max*). The results indicted that blending insect resistant and susceptible cultivars was not an alternative management tool in soybean. Blends have been demonstrated in some systems to provide benefit to producers in yield and quality while providing protection from insect and disease problems, however, benefits are specific for sites, cultivar use and pest situations.

CHAPTER 2

INTRODUCTION

The first North American observation of *Cephus cinctus* Norton, wheat stem sawfly (WSS), was reported as a note at the beginning of 1890 as a WSS infestation of native and resident grasses in Montana, Nevada, and California (Riley and Marlatt, 1891). Riley and Marlatt suggested that wheat stem sawfly might be a potential agricultural pest in cereal grains. With the introduction and expansion of cereal grain cultivation into the intermountain west wheat represented a suitable, abundant alternative host for the WSS. By 1920, the distribution area of *C. cinctus* had expanded north into neighboring provinces of Canada, east to the Mississippi River, south to the 36° parallel and west to the Pacific Ocean (Ainslie 1920, 1929, Davis 1955).

The WSS has historically been successful in shifting from non-cultivated grass hosts to spring wheat (Ainslie 1920, 1929). More recently, with the shift to winter wheat, WSS has become of concern to winter wheat producers in, Canada, Montana, North Dakota, northern Wyoming and northern South Dakota. Economic damage has been recorded in Montana and North Dakota (Davis 1955, Morrill 1985, Blodgett 1996). In the traditional winter wheat belt of the northern Great Plains (southern Wyoming, South Dakota) WSS had been less successful in shifting and infesting winter wheat possibly due to host/insect synchronization.

The wheat stem sawfly, has become a major recurring wheat pest in Montana and the northern Great Plains causing loss of quality and yield. Larvae feeding within the stem can cause 10.8-22.3% in yield loss and 0.6-1.2% protein reduction in the grain (Holmes 1977). Additionally, larval cutting following feeding causes stem breakage and loss of grain heads prior to harvest. Montana producers have estimated direct grain yield losses at $25-30 million per year due to sawfly cutting (Blodgett 1996). These losses do `not include an increase in custom harvest cost, equipment damage and modifications resulting from WSS infestation.

A search for methods of controlling the WSS began in the early 1900's in Canada and United States. A breeding program was implemented in Canada in 1932 to develop WSS resistant spring wheat varieties (Platt and Farstad 1946). This research resulted in the development of two solid stemmed spring wheat varieties 'Rescue' and 'Chinook' in 1938 (Stoa 1947, Taylor 1976). Rescue was successful in reducing sawfly infestation to less than 1% in some areas but was not widely adapted because it had low baking quality, and only average yield potential (Platt and Farstad 1953). United States wheat breeding programs have subsequently resulted in additional solid stemmed spring wheat cultivars such as 'Fortuna' (Lebsock et al. 1967) and 'Lew' (McNeal and Berg 1977), developed with 'Rescue' and 'Chinook' pedigree and most recently, 'Ernest'. These varieties were adapted to a wider growing area, superior in milling and baking quality and had improved yield and protein over previously developed solid stemmed varieties. In addition to plant breeding for WSS resistance cultural, biological, and chemical controls have been tested, evaluated, modified, or abandoned. These methods have provided inconsistent control and therefore, have not been widely adopted.

The winter wheat breeding program at Montana State University has recently released two WSS resistant solid stemmed hard red winter wheat, 'Vanguard' in 1995 and 'Rampart' in 1996. Although Vanguard and Rampart yield lower than hollow stemmed cultivars in the absence of WSS they are equivalent or superior to most hollow stemmed varieties under heavy sawfly pressure. Both Rampart and Vanguard meet domestic quality standards for high quality bread flour and protein content (Carlson et al. 1997, Bruckner et al. 1997).

Acceptance of solid stemmed, WSS cultivars by producers has been slow due to less favorable agronomic characteristics such as variable expression of the resistant characteristic stem solidness, reduced disease resistance, and with some cultivars lower protein content and lower yield compared to hollow stem WSS susceptible varieties. Variability in the expression of stem solidness results in inconsistent WSS protection. The use of resistant and susceptible spring wheat cultivars blends has been used over the years by producers in northeastern Montana and northwestern North Dakota to improve yields and reduce WSS damage (Weiss et al. 1999).

Cereal variety mixtures or blends are frequently used in the United States and Europe. Blending generally stabilizes yield and quality, reduces management inputs for control of pathogens and disease, and manipulates spatially the density of susceptible hosts and the barrier effect of resistant hosts (Newton and Swanston 1998, Habernicht and Blake 1999).

A recent study in the northern Great Plains blended WSS resistant solid stem and susceptible hollow stem spring wheat cultivars over a 3 year period from 1986 to 1988

(Weiss et al. 1990). The study objectives were to determine if cultivar blends were superior or equal to plantings of single cultivars for use in managing WSS. Wheat stem sawfly damage by cutting was inconsistent with the blends used. The differences between the blends and monocultures were not significant. The study suggested that delaying planting of resistant and susceptible blends would be effective by interrupting the synchronization of plant development and the WSS life cycle. It is also suggested that using the resistant and susceptible blends would be more advantageous when WSS population were low to moderate (Weiss et al. 1990).

The objectives for this project were to determine if blending resistant and susceptible winter wheat influenced WSS infestation, grain yield and protein and oviposition preference in relation to the resistant/susceptible blends.

MATERIAL AND METHODS

Site Descriptions and Locations

The four sites, Big Sandy, Loma, Broadview and Molt were located in areas with a history of moderate to high infestation levels of wheat stem sawfly (WSS) on privately owned and operated dryland wheat farms using conventional wheat fallow rotation systems. The Big Sandy site, used in both 1997 and 1998, was located in Chouteau County 20.9km west of Big Sandy, Montana (latitude: 48.225°N, longitude: 110.375°W). The elevation was 853m; soil texture was primarily sandy clay loam and an average soil pH of 7.1. The 1997 Broadview site was located in Stillwater County 10.5km west and 12.9km south of Broadview, Montana (latitude: 46.025°N, longitude: -109.025°W). The elevation was 1280m; soil texture was primarily loam/silt loam and an average soil pH of 7.3. The 1998 Loma site was located in Chouteau County 11.3 km south and 24.1 km west of Big Sandy, Montana (latitude: 48.075°N, longitude: 110.475°W). The elevation was 914m; soil texture was primarily clay loam and an average soil pH of 7.1. The 1998 Molt site was located in Stillwater County 1.6 km south of Molt, Montana (latitude: 45.875°N, longitude: 108.925°W). The elevation was 1158m; soil texture was primarily loam/silt loam and an average soil pH of 7.3.

Wheat Cultivar Selection for Experimental Blends

The winter wheat variety 'Rampart' was selected for its solid stem characteristic, which provides resistance to WSS damage, and yield improvement compared to an earlier released winter wheat solid stem variety 'Vanguard'. The selection criteria for the hollow stemmed (susceptible) cultivar were based on four specific desirable agronomic characteristics: plant maturity, milling and baking qualities, chaff color, and yield.

Plant Maturity

Early and late plant maturity differences were important in selecting two hollow stemmed varieties with respect to the medium maturing solid stemmed Rampart and WSS emergence. Plant maturity was based on comparative head emergence dates of the three wheat varieties in June. Wheat stem sawfly emergence occurs from late May until early July, coinciding with the beginning of wheat stem elongation through anthesis. Theoretically, selecting an early maturing hollow stemmed variety could avoid egg deposition by developing early and completing anthesis prior to the peak WSS flight. A medium maturing solid stemmed variety (Rampart) would be selected by WSS because the susceptible developmental plant growth stages coincide with female WSS flight and egg lay. A late maturing hollow stemmed variety could avoid egg deposition by developing late and completing susceptible growth stages after the peak WSS flight.