4-2016

DISPERSAL AND SAMPLING OF THE WHEAT STEM SAWFLY, Cephus cintus NORTON, (HYMENOPTERA: CEPHIDAE)

Christopher McCullough
University of Nebraska-Lincoln

Follow this and additional works at: http://digitalcommons.unl.edu/entomologydiss

Part of the Entomology Commons

http://digitalcommons.unl.edu/entomologydiss/41

This Article is brought to you for free and open access by the Entomology, Department of at DigitalCommons@University of Nebraska - Lincoln. It has been accepted for inclusion in Dissertations and Student Research in Entomology by an authorized administrator of DigitalCommons@University of Nebraska - Lincoln.
DISPERSAL AND SAMPLING OF THE WHEAT STEM SAWFLY, *CEPHUS CINTUS NORTON*, (HYMENOPTERA: CEPHIDAE)

By

Christopher T. McCullough

A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Entomology

Under the Supervision of Professors Jeffery D. Bradshaw and Gary L. Hein

Lincoln, Nebraska

May 2016
DISPERAL AND SAMPLING OF THE WHEAT STEM SAWFLY, *CEPHUS CINTUS NORTON*, (HYMENOPTERA: CEPHIDAE)

Christopher T. McCullough, M.S.

University of Nebraska, 2016

Advisors: Jeffery D. Bradshaw and Gary L. Hein

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), is a serious insect pest of wheat, *Triticum aestivum* L., in the northern central Great Plains. The sawfly has been a pest of wheat in Montana, North Dakota, and Canada since the early 20th century. It was first detected in Nebraska winter wheat in the early 1990s, in Scotts Bluff County. The sawfly has since spread throughout the Nebraska Panhandle region and become a pest of serious concern. To gain a better understanding of the sawfly in Nebraska, investigations on the emergence, dispersal, and sampling of the sawfly were conducted.

Observations on the emergence and dispersal of the adult sawfly were made in 2014 and 2015 in three winter wheat fields in the Nebraska Panhandle by using emergence cages, sticky traps, and sweep net sampling. Adult sawflies begin emerging in mid-May and are no longer found by the end of June. Adult sawfly densities decreased the farther into the wheat that was sampled. This edge effect was observed for both sexes of the sawfly, but it is more apparent with male sawflies.

The adult sawfly has an aggregated distribution when described by Taylor’s Power Law. By using Taylor’s Power Law, the number of sweep net samples required to maintain a desired precision level was determined. When sampling at early wheat
heading, five, 20-sweep sweep net samples are needed to maintain a 20% precision level. These sampling data were correlated to larval infestation rates and used to develop a sampling plan that predicts larval infestation rates based upon stem density and the number of adults sampled. Sampling adults gives wheat growers ample time to take management action, such as swathing, during the current growing season. It also allows time for growers to change their wheat variety to a more resistant, solid stem wheat variety, for the next growing season.
ACKNOWLEDGMENTS

An acknowledgment in my thesis isn’t enough to say thank you to my parents for getting me through the rehabilitation process to be well enough to begin this journey. For now though, it is all I have to offer. Your support then in trusting that I was well enough to make the drive to Scottsbluff, and your continued support throughout this process has been instrumental in getting me to where I am today. Hopefully the next chapter doesn’t start with a trip to the hospital.

Thank you to Jeff for providing me with this opportunity to pursue a Master’s degree. Three years ago I wouldn’t have known what a wheat stem sawfly was if it bit me; but, I can safely say today that they shouldn’t bite or sting me. You gave me a lot of freedom to pursue my ideas, even if in the end they didn’t work out or proved unreasonable. To you and Gary both, the patience you have had with me in making up my mind about future and in the continued process of improving my writing, has been great amount. Thank you both for your guidance through this process. Thank you to Dr. Heng-Moss for being on my committee and giving me the opportunity to teach ENTO 116.

To everyone at the PREC, you all have helped me a great deal in my research, for that I am truly grateful. Marissa, Rick, Susan, and Tevyn you all helped keep the summers fun. With inside jokes galore, I don’t think I could summarize it all in one paragraph, let alone a few sentences. Maybe a weather rock saying would do, but I don’t know whether or not if a weather rock saying is appropriate for this document. Sorry, no puns either.
Thank you to the faculty, staff, and my fellow graduate students in Lincoln. Everyone in the department makes this a great place to be. You all have been helpful in answering the many questions that I have had, regardless of how obvious the answer might have been. Hopefully the occasional baked good has been fair compensation for the questions that have crossed my mind. An exceeding large thank you to Francis at the statistics help desk. You made my analysis better than it was and showed me how important it is to make a friend in the statistics department.

Lastly, thank you Laura. You’ve supported me through this from afar. You put up with our dates getting side tracked by interesting insects that cross our path. You ask questions that I may not always give the best answers for, but you keep asking anyway. Maybe someday Cleopatra and Cinderella can become insect families.
# TABLE OF CONTENTS

ACKNOWLEDGMENTS .................................................................................................................. iv
LIST OF TABLES .......................................................................................................................... vii
LIST OF FIGURES ......................................................................................................................... viii

CHAPTER 1. Literature Review ........................................................................................................ 1
  Introduction ............................................................................................................................... 2
  Taxonomy and Description ...................................................................................................... 3
  Life Cycle ................................................................................................................................. 4
  Damage .................................................................................................................................. 10
  Detection ................................................................................................................................ 11
  Management ............................................................................................................................. 13

CHAPTER 2. Dispersal and emergence of the wheat stem sawfly, *Cephus cinctus* Norton, in Nebraska winter wheat fields ................................................................. 40
  Introduction ............................................................................................................................... 41
  Materials and Methods .......................................................................................................... 43
  Results .................................................................................................................................... 48
  Discussion ................................................................................................................................. 52
  References Cited ...................................................................................................................... 60
  Tables and Figures .................................................................................................................. 64

CHAPTER 3. Sampling adult wheat stem sawfly, *Cephus cinctus* Norton, populations to determine adult distribution and predict larval infestation rates in Nebraska winter wheat fields .................................................................................................................. 75
  Introduction ............................................................................................................................... 76
  Materials and Methods .......................................................................................................... 79
  Results .................................................................................................................................... 83
  Discussion ................................................................................................................................. 86
  Sampling Plan .......................................................................................................................... 89
  References Cited ...................................................................................................................... 93
  Tables and Figures .................................................................................................................. 97
LIST OF TABLES

Table 2.1 Distance (m) into the fallow, from the edge of the wheat field, emergence cages were placed at each field in 2014 and 2015. ................................................................. 64

Table 2.2 Dates (month/day) of sampling events used for analysis of the emergence of adult sawflies sampled by sweep net and emergence cages in 2014 (A), 2015 (B), and the dates of exposure for the sticky traps in 2014 (C). ........................................................................ 65

Table 2.3 Field level information including when sawflies were first caught, sampling blocks per field (n), the number of sawflies caught with each sampling method each year, and the sex ratio of male to female sawflies. ............................................................................. 66

Table 2.4 Average sticky trap catches (sawflies per trap ± std. error of mean) across sampling distances for female and male sawflies at Gurley (A), Hemingford (B), and McGrew (C) in 2014. ........................................................................................................ 67

Table 2.5 Comparisons of the male and female sawflies sweep net sampled (sawflies per 20 sweeps ± std. error of mean) across distances (m) into the wheat field in 2014 (A) and 2015 (B) for each field. ........................................................................................................ 68

Table 2.6 Average number of sawflies (sawflies per cage ± std. error of mean) sampled during the year at Hemingford and Gurley in 2014 and 2015. ........................................................... 69

Table 3.1 Calculated parameter b values for Taylor’s Power Law using log transformations and PROC NLIN for sawflies collected with sticky traps in 2014 ....... 97

Table 3.2 Parameter a and b of Taylor’s Power Law calculated using log transformations and PROC NLIN for sweep net sampled sawflies................................................................. 98

Table 3.3 Analysis of variance for Type I fixed effects on total sawflies sampled per 20 sweeps during early wheat heading, stems per row meter, and distance sampled using larvae per row meter as the response variable. (Distance = 0, 10, 20, 30, and 40m into the wheat field) ........................................................................................................ 99

Table 3.4 Regression equations, on the natural log scale, for predicting larval infestation rates (Y), larvae per row meter, using total adult sawflies sampled per 20 sweeps during early wheat heading (x), stems per row meter (z), and distance sampled into the wheat field. Correlation coefficients (r) between the observed and predicted value of larvae per row meter. ................................................................. 100
LIST OF FIGURES

Figure 2.1 Larvae per row meter of wheat stems (mean ± std. error of mean) across distances sampled into the wheat at each field sampled in 2015. ............................................ 70

Figure 2.2 Average number of male and female sawflies caught per 20 sweeps (mean ± std. error of mean) for each sampling date from all fields in 2014 (A) and 2015 (B). .... 71

Figure 2.3 Average number of sawflies (mean ± std. error of mean) collected per emergence cage in 2014 (A) and 2015 (B) from all fields. ................................................................. 72

Figure 2.4 Accumulated proportion of male and female sawflies collected via sweep net samples averaged across all fields and years. ................................................................. 73

Figure 2.5 Accumulated proportion of sawflies sampled for male and female sawflies collected by emergence cages averaged from Hemingford and Gurley from both year. 74

Figure 3.1 Predicted values plotted against observed values of larval infestation rates using sweep net samples of total sawflies as the predictor. The line is where predicted and observed values are equal. ........................................................................................................ 101
CHAPTER 1

Literature Review
Introduction

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), is a stem mining insect that is a major pest of wheat, *Triticum aestivum* L. The wheat stem sawfly is broadly distributed across North America, with records of the sawfly in every state west of the Mississippi River, as well as all the Canadian Prairie Provinces (Ivie 2001). Despite its broad range, the sawfly was only considered a pest of spring wheat in the northern Great Plains, in Montana, North Dakota, and the Canadian Prairie Provinces. (Beres et al. 2011). However, after adapting to the earlier maturation of winter wheat, the sawfly has expanded it pest presence into other winter wheat growing regions, including western Nebraska, southeastern Colorado, and eastern Wyoming. Whether this is the spread of a biotype or the slow adaptation to winter wheat remains unknown. Sawflies taken from wild grasses near Broken Bow, Nebraska in 1952 were able to complete development within winter wheat when their life cycle was artificially synchronized with winter wheat (Davis 1952); but a large amount of genetic variation does exist between sawfly populations in Montana, North Dakota, and Wyoming making it possible biotypes do exist (Lou et al. 1998). Primers were developed to continue the study of sawfly genetics (Hartel et al. 2003), but no additional work on the population genetics of the sawfly has been published.

The sawfly was first described and named by Edward Norton (1872) in Colorado, but was originally placed in Tenthredinidae. It was described again by Riley and Marlatt in 1891 under the name *Cephus occidentalis* (Riley and Marlatt 1891); and again in 1897 by Ashmead under the name *Cephus graenicheri* (Ashmead 1898). Both names are synonyms of *Cephus cinctus*, with this being the correct name due to priority. *Cephus*
hylinatus, a species of Asian origin, was proposed to be a synonym as well, as C. cinctus specimens are anatomically the same as C. hylinatus (Ivie and Zinojev 1996). In addition to describing a sawfly specimen in 1891, Charles Valentine Riley aptly predicted the future of the sawfly saying, “The economic importance of this species arise from that fact that it may be expected at any time to abandon its natural food-plant in favor of the small grains, on which it can doubtless successfully develop (Ainsile 1920).” In 1895 Riley’s prediction became true when sawfly larvae were found infesting wheat fields near Souris, Manitoba (Ainslie 1920). Two years later, sawfly larvae were found in wheat stems near Minot, North Dakota (Ainslie 1920). The pest status of the sawfly has fluctuated through the 20th century being mitigated by high levels of reported parasitism, the release of solid stem wheat varieties, or the loss of wheat by wheat stem rust outbreaks (Beres et al. 2011). Despite a long history of dealing with the sawfly, only partial success has been found in attempting to control it.

**Taxonomy and Description**

The sawfly is placed in the sub-Order Symphyta within the Hymenoptera. The family, Cephidae, is further divided into two subfamilies Cephinae and Athetocephinae (Middlekauff 1969). Within the subfamily, Cephinae, there are two tribes, Hartigiini and Cephini, members of Cephini are borers of plants within Poaceae (Middlekauff 1969). Of the 11 genera in Cephidae, the wheat stem sawfly is found within the genus Cephus (Middlekauff 1969). The members of Cephidae all lack cenchri, a characteristic that makes them unique within Symphyta (Middlekauff 1969).

Wheat stem sawfly adults are on average 10mm in length, females are typically larger than males (Ainslie 1920). Adults have a yellow and black banded abdomen,
yellow legs, smoky black wings, and slightly clavate antennae (Ainslie 1920). The presence of an ovipositor easily distinguishes females from males. From there, eggs are 1mm in length, milky white, and crescent shaped; the egg is found within the stem lumen or a small hole excavated by the female (Ainslie 1920). After hatching, larvae progress through five instars, with a fully developed larva being between 8-14mm in length (Ainslie 1920). Larvae have a milky white body with a brown head and caudal horn that is used to move within the stem. From here, the pupa averages 12 mm in length with white coloration until development commences when they turn begin to turn black (Ainslie 1920).

**Life Cycle**

In western Nebraska adult emergence begins in mid-May and continues until late June (Hein unpublished data). Sawflies exhibit protandry, with males emerging before females (Holmes and Peterson 1963). After emerging, females may mate provided that males are available for mating. The temporal dynamic of emergence leads to fewer males being available for mating late in the flight period (Holmes 1954). The mating system is some form of lekking. Males compete with each other as they nip off antennae and legs of other males (Ainslie 1920). When placed together, males begin fanning their wings and release phenylacetic acid, a volatile that attracts females (Cossé et al. 2002). A minimum concentration of phenylacetic acid needs to be created as females showed no attraction when phenylacetic acid was released from a single male (Cossé et al. 2002). There were 13 other compounds that stimulated sawfly antennae in an electroantennograph reading, with 9-acetyloxynonanal creating the strongest response (Cossé et al. 2002). Groups of males emitted the largest amounts of these volatiles (Cossé
et al. 2002). After mating, females disperse in search of a suitable host for oviposition. All cereal crops except for oats have been successfully utilized as a host by the sawfly (Ainslie 1920). Many wild grasses will also support sawfly development, particularly the member’s genus *Agropyron* and *Elymus* (Ainslie 1920, Youtie and Johnson 1988). It is believed before the cultivation of wheat, plants in the genus *Agropyron* were the preferred hosts (Wallace and McNeal 1966). An important host to note is the noxious weed *Bromus tectorum* L, as it is prevalent in wheat growing regions of the Great Plains (Perez-Mendoza et al. 2006).

Adults have a short lifespan of 7-10 days, and are believed not to feed (Wallace and McNeal 1966). They have been observed on the flowers of mustard plants and taking in moisture from puddles (Wallace and McNeal 1966). Adults are weak fliers and prefer to fly on sunny days, and are rarely seen flying on cloudy days (Ainslie 1920). The greatest distance recorded a sawfly has dispersed is approximately ½ mile (Wallace and McNeal 1966). In part because of their flight capabilities, sawfly populations display an edge effect with higher densities closer to the field edge (Weaver et al. 2004, Nansen et al. 2005ab). When not flying, adults often rest on the wheat stem facing down (Ainslie 1920).

Wheat is suitable for oviposition once it has more than two nodes (Morrill 2000). In finding a host, females are attracted to the volatile compounds (Z)-3-hexenyl acetate and (E)-β-ocimene (Weaver et al. 2009). Females also prefer taller wheat when selecting a host (Buteler and Weaver 2012). Stems need sufficient girth to allow the female to grasp it fully for oviposition (Holmes and Peterson 1960). After finding a suitable host, females will examine a stem by walking up and down while tapping it with their
antennae. Then the female inserts her ovipositor into the stem and lays an egg (Buteler et al. 2009). Females cannot discern if a host has been utilized (Buteler et al. 2009). Females contain 30-40 eggs, but that number is dependent on the quality of the host they were feeding upon (Holmes 1982, Cárcamo et al. 2005, Morrill et al. 2000). Once the early milk stage has been reached, wheat is no longer a suitable host as it does not allow for sufficient time for the larvae to complete development and reach the lower nodes (Morrill and Kushnak 1999). The node that receives the most eggs changes as wheat continues to grow during the flight period (Holmes and Peterson 1960).

Like other members of Hymenoptera, female sawflies are capable of arrhenotokous parthenogenesis where unfertilized eggs become males and fertilized eggs become females (Smith 1938). Females have 18 chromosomes, while the males only have nine (Mackay 1955). Farstad (1938) correctly stated the sawfly was capable of parthenogenesis, but incorrectly hypothesized that it was thelytokous parthenogenesis. Interestingly, a population of sawflies was monitored for eight years near Lethbridge, Alberta that was exclusively female with no males being sampled (Farstad 1938). All lab reared specimens from this population developed into females (Farstad 1938). Unmated females have been able to produce female progeny, giving some credibility to the report (Mackay 1955).

With the ability to determine the sex of their offspring, females have a preference for ovipositing fertilized eggs in larger stems and unfertilized eggs in smaller stems (Wall 1952, Morrill et al. 2000, Cárcamo et al. 2005). Larger stems produce more fecund females (Morrill et al. 2000). Male sawflies show no effects from differences in host quality (Morrill and Weaver 2000). Multiple eggs may be laid in a stem, but the first
larva to hatch, typically, is the only one to survive due to larval cannibalism (Ainslie 1920). The average incubation period for the egg is one week (Ainslie 1920). Larvae feed within the stem on the vascular tissue (Holmes 1954b). Larvae continue feeding within the stem until increasing light transmission through the stem wall and a drop in plant moisture content is sensed (Holmes 1975). Then, larvae move down the stem to prepare for diapause (Holmes 1975). When larvae no longer detect light through the stem, they girdle the inside of the stem above this location (Holmes 1975). This typically results in larvae preparing their hibernaculum below the soil surface. Larvae prepare for diapause as 5th instars (Beres et al. 2011). It is at this stage of development that sex determination of sawfly larvae is the easiest. The imaginal discs of the genitalia are apparent when larvae are injected with a 2% methylene blue solution in the posterior segments of the abdomen (Holmes 1970).

Larvae prepare a diapause chamber below the site of their cut. They plug the stem with frass, empty their gut contents, secrete a waxy layer, and enter diapause (Ainslie 1920). These preparations aid larvae in surviving freezing temperatures, the supercooling point of the larvae is around -24° C, although the deleterious effects of freezing become apparent at temperatures below -15° C (Morrill et al. 1993, Salt 1961). An additional physiological change larvae make during diapause is to reduce their respiratory rate. Larvae consume 0.003-0.005-mm³ of oxygen per mg of live weight compared to the active rate of 0.75-mm³ of oxygen per mg of live weight (Villacorta et al. 1972). Lower respiratory rates aid in limiting desiccation, as losing more than 40% of their moisture results in death for the larvae (Salt 1946a). However, larvae are able to absorb moisture come into contact with to offset any losses experienced (Salt 1946b). To
end diapause and resume development, larvae must meet cooling requirements. Some larvae terminate diapause with as little as 50 days of exposure to 10°C; however, over 95% of larvae terminate diapause after 90 days at 10°C (Salt 1947). Larvae that terminate diapause sooner require a greater amount of time for post-diapause development than larvae that terminated diapause later (Salt 1947).

If high temperatures are experienced shortly after ending diapause, larvae can reenter diapause (Perez-Mendoza and Weaver 2006). The exposure to high temperatures stops secretion of the growth and differentiation hormone from prothoracic gland interrupting post-diapause development and reverting the larvae into diapause (Church 1955b). Access to additional moisture is needed for proper post-diapause development (Church 1955a). Between high temperatures and desiccation, high temperatures have a greater ability to push larvae back into diapause (Church 1955). In lab conditions, Villacorta et al. (1971) found that continuous light pushed larvae towards reentering diapause instead of continuing development. Larvae collected in *Leymus condensatus* (J. Presl) Á. Löve, giant wildrye, were alive after 3 years and 5 months demonstrating the potential for larvae to endure prolonged periods of diapause (Ainslie 1920).

Under ideal conditions, 20-25°C, larvae pupate and finish development in approximately 3 weeks (Perez-Mendoza and Weaver 2006). For post-diapause development to initiate, growth and differentiation hormone must be secreted by the prothoracic glands, which has been stimulated by secretions from the brain (Church 1955b). Interestingly, when placed under the same developmental conditions, larvae from Montana emerged before larvae from North Dakota by 15 to 40 days (Lou et al. 1998). Once development is complete, adults remain within the stub until an unknown cue
stimulates them to chew their way out. Once out of the stub, the cycle starts again. Only one generation occurs per year, making rearing sawflies important for off-season research as opportunities to collect adults are limited.

Completing the lifecycle of the sawfly in the lab still presents challenges. Stubble can be collected to obtain adult sawflies for lab. The time of collection, pre or post-winter, of stubble is of little importance; but collectors need to be aware of the differences in the emerging sawflies by collection location (Delaney et al. 2006). Raising adults and getting eggs is easily accomplished as adults do not have an apparent need to feed and only occasionally take in moisture (Ainslie 1920). Female sawflies attempt to oviposit in many things it perceives to be a host, even glass rods (Holmes 1977). Straws filled with agar, sucrose, and green food coloring were oviposited in by females, and allowed for the easy collection of the egg (Villacorta et al. 1971). If given adequate moisture, eggs can be hatched when not in a host (Ainslie 1920).

Rearing sawfly larvae under artificial conditions proves the most difficult part of the process, larvae require contact to mimic the inside of a stem (McGinnis and Kasting 1962). One option for a container was to put small grooves across a plastic plate, fill in the grooves with diet, then cover it (McGinnis and Kasting 1962). Pushing diet into drinking straws works as well, but it is hard to locate the larvae within the straw (Kasting and McGinnis 1958). Additionally, the larvae required frequent transfers to fresh straws to prevent mold growth, which to leads to an increased levels of mortality (Kasting and McGinnis 1958). However, drinking straws were used by Macedo et al. (2005) and they experienced little larval mortality due to mold growth. Contamination by mold was not experienced with larvae that were transferred to new straws on a monthly basis (Macedo
et al. 2005). The different result is likely because of the better diets used (Macedo et al. 2005). Larvae have been reared for 60 days on commercially available Spodoptera frugiperda and Ostrinia nubilalis diets, which greatly exceeded the maximum survival of 14 days that had previously been recorded as well as the time required for proper development (Macedo et al. 2005, Kastings and McGinnis 1958).

**Damage**

Feeding on the vascular tissue by the larvae causes a physiological reduction in yield of 10-25% (Delany et al. 2010). Similar reductions in yield were found by Holmes (1977) with an average reduction of 17.3% with a range of 10.8%-22.3%. Yield reductions are further exacerbated when the plant is under nutrient and water stress. A phosphorous deficiency in combination with stem mining created a 35% reduction in head weight (Delany et al. 2010). Yield loss is caused by a reduction in kernel weight, not a reduction in kernels per head (Delany et al. 2010, Holmes 1977).

Sawfly infested wheat grown in a growth chamber experienced a reduction in stomatal conductance, CO₂ levels, and transpiration rates, but no significant reductions in these processes were detected on wheat grown in greenhouses or in the field (Macedo et al. 2005). Reductions in photosynthetic capability of the flag leaf where detected in greenhouse studies when the main stem was infested (Delany et al. 2010). However, wheat, in a greenhouse setting, does appear to compensate for some of this stem mining by increasing chlorophyll a and b levels which lead to increased efficiency in the photochemical processes of photosystem II (Macedo et al. 2006). A similar study conducted by the same authors found no compensation in photosystem II (Macedo et al. 2007). The authors did note they only measured photosynthetic capabilities during grain
fill and they used a different cultivar of wheat than in the previous study (Macedo et al. 2007). No compensation in photosynthetic activity was found by uninfested tillers (Delany et al. 2010). Abiotic stress magnifies the effects of the stem mining as wheat that was under water stress or had a phosphorous deficiency had larger decreases in photosynthetic activity compared to unstressed plants that were infested (Delany et al. 2010).

Stem mining is a constant source of loss, but stem lodging creates the most severe losses. Lodged stems are difficult to harvest creating the potential for stems to not be harvested. However, stem lodging is highly variable as an external force, such as high winds, is needed to lodge the stem. This makes it hard to estimate the potential loss due to stem lodging alone.

**Detection**

Detecting sawfly populations is important as low level infestations one year can lead to economically damaging ones the next (Holmes 1982). The only reliable way to confirm a sawfly infestation is by splitting stems and checking for larval presence. A sampling plan was developed that allows the sampler to only have to sample for larvae along the field edge to predict the infestation level up to 200-m into the field. The sampling plan proposed by Nansen et al. (2005c) requires collecting ten, 30-cm row samples of wheat along the field edge. All the stems in five of the samples are split to check for larval presence, and if the average infestation level is below 20%, sampling is stopped. If the average infestation is higher than 20%, the rest of the stems need to be split. With the average from the stems sampled, the following equation can be used to predict infestation levels up to 200-m into a wheat field.
Where $\text{Inf}_{M_I}$ is the infestation level predicted at a distance into the wheat field (M) based on infestation level at the edge (I). The coefficients $a$, $b$, $c$, $M_0$, and $I_0$ were fit from the data and have values of 1.39, 273.32, 0.36, -435.75, and 0.68 respectively (Nansen et al. 2005c). The utility of this sampling plan is limited, as it takes 9.5 hours to process all the samples from one field edge (Nansen et al. 2005c). Small improvements were made to this sampling plan by reducing the number of stems that need to be split to maintain the 20% precision level. At higher infestation levels, e.g. 40-50% of stems infested, only 50 stems need to be split in each sub-sample (Cárcamo et al. 2008). More novel methods have been developed to sample sawfly populations in a timelier manner. Each method reduces the sampling time required, but comes with a trade-off such as reduced accuracy or feasibility.

One method that does not require stem splitting is to use the presence of dark spots below the nodes as an indicator of infestation. Dark spots below the nodes can be a reliable indicator of larval presence depending on the time of sampling (Morrill 1992). During early dough stage, samples had 21.2% error rate, an error being spots present with no larva or no spots and a larva was present (Morrill 1992). In the soft and hard dough stages those error rates dropped to 4.7% and 7.1% respectively (Morrill 1992). This increase in accuracy later in the growing season is related to more larvae being present in the field as well as the increased likelihood of a larva chewing through the node (Morrill 1992). Other methods require the use of extra equipment and proper training to interpret the results.
Audio recordings of sawfly larvae feeding were profiled to allow the detection of larvae within the stem by clipping a microphone to the stem. This method did prove accurate, but excessive background noise can produce false positives (Mankin et al. 2004). This method requires extra equipment and software to listen to wheat steams, limiting its practicality.

Hyperspectral imaging has shown promise in detecting sawfly induced stress on wheat plants. Taking readings in longitudinal direction of the leaf and analyzing the red edge and near infrared bands gave the most reliable readings for detecting larvae (Nansen et al. 2009). Sawfly induced stress was detected in a lab setting, but a considerable amount of effort and technical knowledge is needed to minimize errors in data collection (Nansen et al. 2009). Having an effective means of detecting sawfly infestations is necessary to enable appropriate management actions.

**Management**

The biology of the sawfly creates challenges for finding effective management tactics. The extended emergence period of adults and the cryptic nature of the larvae are the two biggest challenges that limit the success of chemical control options. The herbicide 2-4D increases larval mortality when applied during oviposition, but is not as effective one week before or after oviposition (Gall and Dogger 1967). No differences were found in the extent of sawfly damage in spring wheat between foliar applications of lambda-cyhalothrin and seed treatments of thiamethoxam, the two treatments together, or untreated wheat (Knodel et al. 2009). Wallace (1962) tested the efficacy of 19 insecticide treatments and found that furrow application of heptachlor was the most effective. When used as a seed treatment, the effectiveness is limited to the lower nodes allowing larvae in
the upper nodes to escape (Holmes and Peterson 1963). Further investigation found applying heptachlor at rate of 1 pound per 43,560 row-ft resulted in 76% control of sawfly larvae (Wallace and Butler 1967). However, trace amounts of heptachlor are detected in the grains when applied at that rate (Wallace and Butler 1967). Heptachlor is no longer a registered pesticide due to environmental concerns (Knodel et al. 2009). The economics of chemical control also make it impractical as three treatments of zeta-cypermethrin during the adult flight period resulted in a net loss of $33.36/ha (Knodel et al. 2009).

Tillage of the stubble for sawfly control works best when it separates the stubble from the soil, exposing larvae to increased desiccation (Morrill et al. 1993). Sheep grazing works in a similar fashion as hoof action breaks open the stubble exposing larvae (Hatfield et al. 2005). Enough exposure is required to cause a 40% reduction in the larval weight, the point when mortality begins to occur (Salt 1946a). As sawflies progress from larvae to adults, they become more susceptible to desiccation (Salt 1946a). Burying the stubble is less effective as emerging adults are still able to reach the soil surface (Runyon et al. 2002). While fall and spring tillage both create high levels of mortality, > 90%, spring tillage needs to be properly timed to achieve high levels of mortality (Morrill et al. 1993, Holmes and Farstad 1956). In Canada, Holmes and Farstad (1956) found exposing stubs between May 25th and June 6th produced over 90% mortality. The date of tillage with the highest mortality in Montana was March 23rd (Morrill et al. 1993). This timing ensures that larvae had pupated and would be unable to reenter diapause, but before pupae can complete development (Holmes and Farstad 1956). If precipitation occurs after tillage, sawflies are able to absorb moisture and limit the effects of exposure (Salt 1946b).
The use of tillage for sawfly control can be effective, but is heavily influenced by timing and environmental conditions. Only one study reports no differences in the levels of sawfly infestation in wheat bordering fallow that was heavily tilled, minimally tilled, and untilled (Runyon et al. 2002). These findings must be viewed cautiously as there is no indication of when tillage was conducted nor how the soil was worked. Additionally, it was found that tillage resulted in lower rates of parasitism on the sawfly (Runyon et al. 2002). If tillage is done in the late summer or early fall while parasitoids are still active, larvae within the stubs will be less accessible to the parasitoids, and mortality can be reduced (Rand et al. 2011).

Parasitoids are an important source of mortality for the sawfly. Ten parasitoids have been recorded attacking the sawfly (Ivie 2001). Many of these parasitoids have little impact in wheat because they only attack the sawfly in wild grasses. The wasp *Pleurotropis utahensis* Crawford (Hymenoptera: Eulophidae) can attack the sawfly in wheat, but prefers to attack sawflies in native grasses (Neilson 1949). The parasitoid wasps *Eupelmella vesicularis* (Retz.) (Hymenoptera: Eupelmidae), *Eurytoma atripes* Gah. (Hymenoptera: Eurytomidae), and *Merisus febriculosus* Gir. (Hymenoptera: Pterimalidae) have been recorded parasitizing sawfly larvae, but they are actually hyperparasitoids of the wasp *Bracon cephi* (Gahan) (Hymenoptera: Braconidae), a parasitoid of the sawfly (Nelson 1953). The wasp *Scambus detritus* Holmg. (Hymenoptera: Ichneumonidae) is distributed throughout the range of the sawfly and attacks *Cephus pygmaeus* L. (Hymenoptera: Cephidae), but it has been unsuccessful in becoming established in wheat as it overwinters too high in the stem and gets cut out during harvest (Holmes 1953). The exotic wasp *Collyria catoptron* Wahl (Hymenoptera:
Ichneumonidae) is able to locate sawfly larvae in wheat, but it is unable to complete development on the sawfly (Rand et al. 2016).

There are two parasitoids that have had success in controlling the sawfly within wheat fields, *B. cephi* and *B. lissogaster* Muesebeck (Hymenoptera: Braconidae). Determining which wasp is present is difficult as both adult wasps resemble each other in appearance and life cycle. Four characteristics can be used to distinguish between the two wasps include: the origin of the radial cross vein in relation to the stigma, the size of the 2nd submarginal cell, the texture of the metasoma, and the appearance of the first metasomal suture (Runyon et al. 2001). Both species are bivoltine, larval ectoparasites of the sawfly (Nelson and Farstad 1953, Somsen and Luginbill 1956). The larvae of *B. cephi* are solitary, but *B. lissogaster* larvae can be gregarious or solitary (Nelson and Farstad 1953, Somsen and Luginbill 1956). The first generation of each parasitoid has a preovipositional period, three weeks for *B. cephi* and eight days for *B. lissogaster*, but the second generation does not (Nelson and Farstad 1953, Somsen and Luginbill 1956). In Canada, the first generation of *B. cephi* is present from late June to early August, and the second generation is present from August to September (Nelson and Farstad 1953). The first generation of *B. lissogaster* is active from late June to late July in Montana, with the second generation being present from August to September (Somsen and Luginbill 1956). The second generation of both parasitoids is usually larger than the first, indicating these parasitoids might be affected by overwintering mortality or harvest practices (Wu et al. 2013). The primary benefit from these parasitoids is in controlling sawfly populations, but parasitism of sawfly larvae reduces the yield loss incurred by larval feeding (Buteler et al. 2008). High levels of parasitism have been able to control sawfly infestations, but
parasitoid populations are temporally and geographically variable resulting in inconsistent control (Peterson et al. 2011).

Many factors influence the success of these two parasitoids. Higher densities of sawflies reduce the success of the parasitoids as parasitized larva can be eaten by other sawfly larvae within the stem (Holmes et al. 1963). The timing of the maturity of wheat plays a large role in the success of these parasitoids. If the wheat matures earlier, sawfly larvae move down the stem making them harder to locate; but, if maturity occurs later, sawfly larvae are easier for the parasitoids to locate (Holmes et al. 1963). Sawfly larvae are relatively safe from parasitism in wheat stubs. Holmes et al. (1963) reported 2% parasitism rates when sampling stub. However, rates of parasitism up to 45% have been observed at a fields when sampling stubs, with more than 75% of the fields sampled having rates greater than 20% (Rand et al. 2011). Wu et al (2012) reported 10-20% rates of parasitism at field locations when sampling stubs for parasitoids.

Harvest practices can conserve parasitoid populations. By leaving one-third of the stem standing at harvest or by using a stripper harvester, pupating parasitoids remain alive in the field (Peterson et al. 2011). These conservation efforts need to be directed throughout the wheat field as these wasps are randomly distributed throughout the field (Weaver et al. 2005). In field conservation is important to maintain populations of parasitoids as they are slow to respond to changes in the ecosystem. Increased areas of refuge outside of the wheat field does not enhance parasitism of the sawfly nor increase parasitoid abundance (Rand et al. 2014). Inoculative releases of B. cephi and B. lissogaster have had little success as populations fail to become established in new areas where sawflies hosts are available (Morrill et al. 1998). While B.cephi has been
previously documented in Canada, *B. lissogaster* has only been recently found in parasitizing sawflies in Canada (Cárcamo et al. 2012).

Other opportunities exist for the use of other biological control agents. The beetle, *Phyllobaenus dubius* (Wolcott) (Coleoptera: Cleridae), has been found feeding on sawfly larvae (Morrill et al. 2001). Both adult and larval stages of this beetle feed on sawfly larvae. No further investigations have been published on this beetle. Other control agents being investigated are *Fusarium* spp. that have been found on field collected larval cadavers (Wenda-Piesik et al. 2009). While these fungi kill sawfly larvae, their dual pathogenicity to wheat limits their usefulness (Wenda-Piesik et al. 2009). It is also difficult to determine if the fungi killed the larva or was feeding on the cadaver (Wenda-Piesik et al. 2009).

The primary management tactic recommended for the sawfly is the use of solid stem wheat varieties. The greater expression of pith within the stem is what makes a variety solid stemmed. A minimum solid stem score of 15 is needed to have an affect on sawfly populations (Wallace et al. 1973). This is calculated by cutting the middle of the top 4 internodes and rating the stem on a scale of 1-5 with one being no pith and 5 being completely solid (Wallace et al. 1973). Solid stem varieties work against the sawfly though various means. The pressure exerted by the stem on eggs laid in the pith is strong enough to destroy eggs (Holmes and Peterson 1961). The pith dries before other parts of the stem increasing desiccation (Holmes and Peterson 1961). Extra pith inhibits larval movement within the stem (Holmes and Peterson 1962). If a larva is able to complete development in a solid stem variety, the adult that is produced is lighter and less fecund than those produced by hollow stem varieties (Cárcamo et al. 2005). Larval weigh
reductions do not lead to increased overwintering mortality (Cárcamo et al. 2011). Solid stem varieties experience less yield loss compared to hollow stem varieties (Delaney et al. 2010).

The use of solid stem varieties for sawfly management has a long history. A landrace from Portugal, S-615, was found to have higher levels of pith expression, making it more resistant to the sawfly (Platt and Farstad 1946). S-615 was subsequently crossed with the variety ‘Apex’ to create ‘Rescue’, the first solid stemmed variety bred specifically for sawfly resistance, and it was released in 1947 (Platt et al. 1948). Upon release, Rescue had better resistance to the sawfly compared to its progenitors and the common hollow stem variety ‘Thatcher’ (Platt et al. 1948). In later tests, a total population of 2,000 sawflies was confined to a test plot, and after three years the sawfly population was reduced to one male (Holmes and Peterson 1957). Parasitoids were allowed access to the plots; therefore, the population reduction cannot solely be attributed to Rescue.

Locating the genes that control pith expression allows for the rapid transfer of these genes to create locally adapted varieties. It was believed the gene was located on the 3rd genome of *T. aestivum*, as prior attempts at hybridizing durum wheat and bread wheat failed to transfer the trait (Platt and Larson 1944). Pith expression in wheat was traced to the locus *Qss.ms*ub*-3BL* on the 3BL chromosome (Cook et al. 2004). This locus accounts for 76% of the total variation of pith expression in creating solid stem wheat varieties (Cook et al. 2004). Other loci have been found that control the expression of pith throughout the growing season (Varella et al. 2015).
Loci that control the amount of wheat volatiles released have also been mapped. Differences in the amount of volatiles released create the potential for trap cropping. In choice tests between the varieties ‘Reeder’ and ‘Conan’, Reeder received more eggs (Weaver et al. 2009). Reeder produces more (Z)-hexenyl acetate, a volatile attractive to ovipositing females, compared to Conan (Weaver et al. 2009). Quantitative trait loci mapping located these traits to chromosomes 2D and 4A in wheat (Sherman et al. 2010). In creating recombinant inbred lines with Conan and ‘Scholar’, it was seen that plants that had one or both of these traits at 3BL or 4A experienced reduced stem cutting (Talbert et al. 2014). The trait mapped to chromosome 2D was shown to have no effect on infestation by the sawfly (Talbert et al. 2014). While traits for a different form of resistance has been identified, solid stems will continue to be the primary breeding target for sawfly resistance due to the relative ease of selecting for this trait (Talbert et al. 2014). More novel forms of resistance have been detected within hollow stem varieties, but the mechanisms by which they act has yet to be identified (Varella et al. 2015).

Concerns of yield potential between solid stem and hollow stem varieties limit the adoption of solid stem varieties. In the Montana 2014 winter wheat variety trails, the hollow stem variety ‘Yellowstone’ out preformed most solid stem varieties in yield performance, even under sawfly pressure (Berg et al. 2015). The solid stem variety ‘Judee’ is not significantly different from Yellowstone in yield when grown under sawfly pressure (Berg et al. 2015). A test of Canadian spring wheat had solid stem varieties ‘AC Abbey’ and ‘AC Eatonia’ rank 2nd and 3rd in yield behind a semi-solid variety ‘McKenzie’ (Beres et al. 2007). These two varieties experienced half the losses that were incurred by the leading hollow stem varieties as well as having the lowest levels of stem
cutting (Beres et al. 2007). A similar study in South Dakota shows solid stem varieties experience less yield loss when grown under sawfly pressure (Szczepaniec et al. 2015). Subsequently, the perceived differences in yield may not be as large an issue as the solid stem variety Judee was the second most planted winter wheat variety in Montana in 2014, following the hollow stem variety Yellowstone (Berg et al. 2015). The solid stem variety ‘Genou’ was the third most planted winter wheat variety in Montana in 2014. It had previously been the most planted winter wheat variety from 2007-2011 (Berg et al. 2015, NASS 2013). Other solid stem varieties available in Montana include ‘Bearpaw’, ‘Rampart’, ‘Warhorse’, and ‘Quake’. Warhorse is the most recently released variety in (Berg et al. 2015). Continued breeding efforts have continued to narrow the yield gap between solid and hollow stem varieties. Six near iso-genic-lines of wheat with a common solid stem parent, resulted in only one line with lower yield than the hollow stem parent (Sherman et al. 2015).

Despite yield differences between hollow and solid stem varieties, variable expression of pith from year to year is another concern with solid stem varieties. S-615, the solid stem trait donor, exhibited variable pith expression in variety trials across Canada, and no increased pith expression when grown in greenhouses (Platt 1941). Pith expression is positively correlated to the number of sunny days during the growing season (Platt 1941). Pith expression can be suppressed by growing wheat under yellow or red light filters (Holmes 1984). The intensity of light also affects pith expression, leading to the conclusion that cloudy days can suppress pith expression as well (Holmes 1984). In 1953, 90% of infested Rescue stems were cut compared to 1961, when 4% of stems were cut (Holmes 1984). Seeding rates can also affect pith expression, due to shading by other
plants; therefore, higher seeding rates results in decreased pith expression (Beres et al. 2012). Row-width also affects pith expression, narrower rows results in less pith expression (Luginbill and McNeal 1958).

Nitrogen and phosphorous fertilizer applied at planting was found to have no effect on pith expression (Depauw and Read 1982). Nitrogen fertilizer applied at three to four leaf stage, at flag leaf stage, and at five times the recommended rate did not affect pith expression (Beres et al. 2012). Nitrogen and phosphorous applications resulted in more cut wheat stems, but this was not due to changes in pith expression (Luginbill and McNeal 1954). The authors believed increased host quality resulted in more vigorous larvae (Luginbill and McNeal 1954). Location and weather had a greater effect on pith expression than fertilizer regimen (Depauw and Read 1982). The durum wheat variety ‘Golden Ball’ has better resistance to these environmental factors, but early attempts to transfer the more robust pith expression of durum wheat into bread wheat via hybridization have failed (Platt and Larson 1944).

The expression of pith also varies from node to node. Differences in stem solidness were found between the 1st and 3rd internodes (Morrill et al. 1992). Within the internodes, the pith of the internode is denser in the middle than near the ends (O’Keeffe et al. 1960). Holmes and Peterson (1962) found the bottom three internodes of Rescue expressed more pith than the top internode. This allows for larvae to grow to a sufficient size in the upper internodes to be able to overcome the pith in the lower part of the stem (Holmes and Peterson 1962). However, modern solid stem varieties do not show significant variation in pith expression easing some concerns about variable pith expression (Berg et al. 2015). Additionally, genetic markers have been identified that
result in more even expression of pith throughout the growing season (Varella et al. 2015).

Higher rates of parasitism were seen in hollow stem varieties than solid stem ones; but, solid stemmed varieties should increase parasitism as it slows the movement of sawfly larvae (Holmes 1963). However, solid stem wheat varieties have a negative impact on parasitoid populations. Two ideas have been put forth for what is driving this interaction. Rand et al. (2012) postulated that the reduced efficacy is due to difficulty in locating and successfully parasitizing sawflies in solid stem hosts. The extra pith makes it harder for the parasitoids to sense the vibrations of the sawfly and/or successfully penetrate the stem to parasitize the host (Rand et al. 2012). In contrast, Wu et al. (2012) hypothesizes that the reduction in the parasitism is due to the lower population of sawflies available as a result of the use of the solid stem varieties. A possible way to mitigate the consequences of using solid stem varieties could be through trap cropping and border plantings of solid stem varieties.

By making border modifications, growers could benefit from planting a hollow stem variety with the protection offered by a solid stem variety. If adequate moisture is available, trap strips planted in the fallow can reduce sawfly cutting in fields protected by trap strips (Morrill et al. 2001). Planting a winter wheat trap strip next to spring wheat was found to be more effective than a trap strip of solid stemmed wheat (Morrill et al. 2001). Winter wheat develops ahead of spring wheat making it more attractive to ovipositing sawflies. When a 24-m winter wheat border was planted around all sides of spring wheat, a 70% reduction in stem cutting was observed in the interior spring wheat compared to the control (Morrill et al. 2001). The planting of a solid stem trap strip next
to a hollow stem stand saw a modest increase in yield over a field of hollow stem wheat, but it did little to control the sawfly population (Beres et al. 2009). Oats are considered resistant to sawflies; however, a border planting of oats offered no protection to the adjacent wheat (Beres et al. 2009).

Another strategy that incorporates solid stem varieties is planting a blend of hollow stem and solid stem varieties. A 1:1 blend of solid stem and hollow stem wheat was compared to plots of both varieties. The blend provided an 11% yield increase over the hollow stem plot; but the solid stem plot had 18% greater yield than the hollow stem plot (Beres et al. 2009). Blends also provide a small increase to sawfly parasitoid populations (Cárcamo et al. 2016). These results contradict an older study that found blends provided no benefits to sawfly control and yield (Weiss et al. 1990). This discrepancy was likely caused by the difference in plot sizes used. A plot size of 1.21 by 4.57-m was used by Weiss et al. (1990), while plots used by Beres et al. (2009) were 50 by 200-m. Regardless, blends are only beneficial when sawfly infestations are low to moderate (Beres et al. 2009, Weiss et al. 1990).

Solid stem wheat remains the primary management tactic for the sawfly, but a push-pull strategy with existing wheat varieties has shown potential for sawfly management. The two most important ones for management purposes are (Z)-3-hexenyl acetate and (E)-β-ocimene (Piesik et al. 2008). Although volatiles may play a role as transcriptome analysis of sawfly antennae found 28 complete odor receptor sequences, with 99 more to be completely sequenced (Gress et al. 2013). In a comparison of ‘Conan’ and ‘Reeder’, more eggs were oviposited in Reeder because of the greater amount of attractive volatiles released (Weaver et al. 2009). A broader screen of wheat varieties
identified ‘Norstar’, ‘Neely’, ‘Morgan’, and Rampart as good options for trap crops with wheat varieties (Buteler et al. 2010). These varieties received more sawfly eggs than other varieties because they release greater amounts of attractive volatiles, are taller, and remain in stem elongation longer (Buteler et al. 2010). Further analysis of these varieties revealed Norstar to be the best candidate to use as a trap crop as it has the best mix of these traits (Buteler and Weaver 2012). Rampart is a solid stem variety that exhibits these traits. If a solid stem variety is used as the trap crop, destruction of the trap crop may not be required (Buteler and Weaver 2012).

The noxious weed downy brome, *Bromus tectorum* L., is a concern for wheat growers as it outcompetes wheat. Management of this weed also has implications for sawfly management. The sawfly prefers downy brome over wheat when selecting a host (Perez-Mendoza 2006). However, larvae are less likely to complete development in downy brome (Perez-Mendoza 2006). Under high downy brome pressure, planting a competitive variety of wheat at a higher seeding rate is recommended to compete with the brome, as it is the primary source of yield loss (Keren et al. 2015). Higher planting rates alone can reduce sawfly cutting, but the rates needed are impractical (Luginbill and McNeal 1958). Since the sawfly preferentially lays eggs in downy brome, it is less of a concern when compared to the yield loss caused by the brome (Keren et al. 2015). When downy brome pressure is low, planting a solid stem variety of wheat at a lower seeding rate produced the greatest yield (Keren et al. 2015). Without downy brome, sawflies are the primary source of loss, and planting at a lower seeding rate results in better pith expression (Keren et al. 2015, Beres et al 2012, Luginbill and McNeal 1958).
Swathing is another management tactic that can be used to increase harvest efficiency. It is recommended to swath fields when 15% or more of stems are infested and when grain moisture content drops below 40% (Knodel 2009). While swathing before that mark can reduce the sawfly population, it comes at the expense of yield (Holmes and Peterson 1965). Following swathing guidelines in Alberta and Saskatchewan, cutting the wheat at a 20-25-cm stem height left enough stem for the larvae to survive below that point (Holmes and Peterson 1965). An alternative to swathing would be to use a harvester equipped with a stripper header. In addition to picking up lodged stems, it also leaves more stem standing which helps to conserve parasitoids (Knodel 2009).

Early swathing is not the only management option taken against sawfly populations at the expense of yield. Delayed planting of spring wheat has the potential to be a management tool (Morrill and Kushnak 1999). The trade off in yield for sawfly management was 30kg/ha, leading to the suggestion of planting the most heavily infested fields last and not delaying planting specifically for sawfly control (Morrill and Kushnak 1999). The alteration of planting dates also affects the sex ratio of the emerging sawflies. Spring wheat that is planted later results in a more male biased population since it becomes more suitable for ovipositioning later in the flight period when fewer males are available to mate with females (Jacobson and Farstad 1952, Holmes and Peterson 1963).

Despite a long history of dealing with the sawfly, controlling sawfly infestations has proven difficult. No one tactic truly controls the sawfly. To effectively manage sawfly infestations, an integrated approach is required that utilizes every management tool available. New management options need to be identified as well. Solid stem
varieties have been the primary management choice, but little work has been published on new forms of antibiosis. Newer, more effective, forms of antibiosis are needed if greater control is to be achieved through host plant resistance.
References Cited


Nansen, C., M. J. Grieshop, C. L. Shannon, M. L. Johnson, W. L. Morrill, D. K. Weaver, S. E. Sing, and J. B. Runyon. 2005. Within-field spatial distribution of


(Hymenoptera: Cephidae) damage and wheat quality parameters. J. Econ. Entomol. 83:255-259.


CHAPTER 2

Dispersal and emergence of the wheat stem sawfly, *Cephus cinctus* Norton, in Nebraska winter wheat fields
Introduction

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), was first described from a male specimen collected from wild grasses in Colorado (Norton 1872). Since that time, the wheat stem sawfly has grown to become a significant insect pest of wheat in the northern Great Plains. It was first found infesting spring wheat, *Triticum aestivum* L., near Souris, Manitoba in 1895 (Beres et al. 2011). After that, more incidents of the sawfly infesting wheat began occurring throughout the spring wheat growing regions of the northern Great Plains. Throughout most of the 20th century, winter wheat in the Great Plains escaped sawfly damage as the sawfly was not synchronized with winter wheat phenology. By the mid 1980’s, sawfly populations had synchronized their life cycle with winter wheat, rendering it susceptible to infestation as well (Morrill and Kushnak 1996). This adaptation coincided with increased reports of economic sawfly infestations occurring farther south than previously seen. Winter wheat growing areas where the sawfly is a pest now include southeast Wyoming, the Nebraska Panhandle, and northeastern Colorado.

In Nebraska, adult sawflies are active from mid-May to mid-June (Hein unpublished data). During that time females may mate, then seek out nearby hosts for oviposition (Ainslie 1920). Sawflies reproduce via arrhenotokous parthenogenesis where fertilized eggs become females and unfertilized eggs give rise to males (Mackay 1955). Females prefer to oviposit fertilized eggs in larger stems, and use smaller stems for unfertilized eggs (Cárcamo et al. 2005). After hatching, larvae begin feeding on vascular tissue within the stem. Other eggs and larvae within the stem are eaten by the first larvae to hatch (Ainslie 1920). Larvae continue feeding until increasing light penetrating the
stem wall and a drop in plant moisture signals them to move down the stem to prepare for diapause (Holmes 1975). The site of diapause is selected when a larva no longer detects light through the stem wall, and this usually is in the crown below the soil line (Holmes 1975). Above this site, larvae girdle the inside of the stem and plug the stub with frass. To terminate diapause, larvae must accumulate sufficient time at cool temperatures. Ninety days at 10°C terminates diapause in more than 90% of larvae (Salt 1947). When temperatures warm in the spring, larvae pupate and complete development in 21 days at 25°C (Perez-Mendoza and Weaver 2006). Adults emerge and start the cycle again.

Although adults are easily identifiable, it is the cryptic larvae that make the sawfly a pest.

Because of the damage potential, management tactics are directed against the larvae. The planting of solid stem wheat varieties is the primary management tactic for sawfly control. Solid stem varieties crush sawfly eggs, increase desiccation, inhibit larval movement, and make emerging females less fecund (Holmes and Peterson 1961, Holmes and Peterson 1962, Cárcamo et al. 2005). Solid stem varieties are only economical when grown in fields that are under medium to heavy sawfly pressure, because their yield is not comparable to hollow stem varieties in the absence of sawflies (Berg et al. 2015). Differences in yield potential and inconsistencies in the expression of pith have hampered the adoption of solid stem varieties (Holmes 1984). Border modifications or the use of seed blends to limit the amount of solid stem wheat planted have had limited success in limiting the sawfly (Beres et al. 2009).

To take management action against adult sawflies, knowledge of their emergence and dispersal into wheat fields is required. The low value of wheat and prolonged nature of the sawfly emergence make insecticide application uneconomical (Knodel et al. 2009).
Trap cropping with wheat varieties that emit different amounts of attractive volatiles has the potential to slow the movement of the sawfly into wheat and limit its spread (Buteler et al. 2010). For a tactic such as this, an appropriate amount of trap crop needs to be planted next to the crop it is protecting to ensure its effectiveness. Previous border modification and trap cropping studies give no basis for the area of the trap crop planted (Morrill et al. 2001, Beres et al. 2009).

Most of the knowledge on the dispersal of the adult sawfly is based on inferences made from the distribution of sawfly eggs and larvae. Mark recapture has been attempted with the sawfly, but there was little success in recapturing adults (Davis 1952). Inferences can be made from larval and egg distributions, but adult behavior is hard to discern as only one larva survives per stem. Sawfly infestations have an edge effect, with high densities near the field edge that taper off farther into the field (Nansen et al. 2005a). This is believed to be an artifact of its dispersal behavior when seeking wild grass hosts (Nansen et al. 2005a). However, it was inferred that adults move in a unidirectional fashion towards the field center based on observations from eggs and larvae (Nansen et al. 2005a). The edge effect has been observed with adult sawflies in dryland wheat fields in Montana, with males showing a more drastic edge effect than females (Goosey 1999). It is possible to discern some information about the dispersal of adults based on the location of the larvae. However, the differences between males and females would remain unknown if relying solely on larvae. The objective of this study was to describe the emergence and dispersal of the adult wheat stem sawfly into wheat fields.

**Materials and Methods**

Field Locations
Three winter wheat fields in the Nebraska Panhandle were each sampled in 2014 and 2015. All three fields were dryland fields that used a wheat-fallow rotation. The McGrew field was located six kilometers southwest of McGrew, NE in Scotts Bluff County. The variety ‘Goodstreak’ was grown here both years. Wheat and fallow alternated in 80-m wide by 500-m long strips at this location. The fallow was worked with a disc in the spring of 2014. No spring tillage was done in 2015 due to wet field conditions. The Gurley field was located six kilometers west of Gurley, NE in Cheyenne County. In 2014, Goodstreak was grown, and in 2015, the variety was ‘Settler CL’. Wheat and fallow were rotated between two 420-m wide by 800-m long blocks. No-till was practiced at this field with the grower using herbicide to manage the fallow. However, one, 10-m wide, pass at the edge of the fallow adjacent to the wheat was made with a disc in attempt to control sawflies. This was done in the spring of both years of sampling. The Hemingford field was located six kilometers southwest of Hemingford, NE in Box Butte County. Wheat and fallow sampled at this location were rotated between two blocks. The wheat sampled in 2014 was in a 200-m wide block and the 2015 wheat was in a 330-m wide block, both of which were 800-m long. Settler CL was grown at this field both years of sampling. The fallow at this field was managed with herbicide.

Sampling Methods

Phercon AM/NB (no bait) yellow sticky traps (Trécé Inc. Adair, OK) and a sweep net were used to sample adult sawflies. In 2014, samples were taken at the field edge and 5, 10, 20, and 30-m into the wheat. In 2015, the 5-m sample was dropped and a 40-m sample distance added. One set of the five sampling distances made a sampling block. Within each block, the order of placement of the distances was randomized. Sampling
locations were spaced 10-m apart, as measured along the field edge. Sampling blocks were repeated as many times as allowable by the field dimensions providing 14-18 sample blocks per field. Two sticky traps were placed at each sample location. Traps were opened approximately 120° to expose the entire sticky surface to only one side of the field. One trap faced towards the fallow and the other faced into the center of the wheat field. A square meter area was cleared out around the traps to prevent wheat from sticking to them. Traps were set 20-cm above the ground. Sticky traps were collected and changed weekly.

At each sample location, 20 sweeps were taken, while moving in the direction of the row, with a 38-cm sweep net through the upper third of the wheat canopy. The sweep sampler started at the location marker and continued along the row, covering an area of 13-m². The movement of the net across the body in a 180° arc across the rows was considered one sweep. Sampling began in early May and concluded in June, when sawflies were no longer found. Sweep net samples were taken biweekly at each field. All sawfly samples were returned to the lab for counting and sex determination.

Emergence cages were placed in the adjacent fallow at each field. Each emergence cage covered an 80 x 60-cm area of fallow. The base of each emergence cage was dug into the ground to prevent sawflies from crawling underneath the cage. Wire mesh was attached to the wooden base that funnels up to a glass collection jar. No killing agents were used within the collection jars of the emerge cages. A paper funnel was placed inside the jar to retain sawflies that entered the jar. In 2014, three repetitions of five distances were placed on the fallow at each field. In 2015, three repetitions of four distances were placed on the fallow ground at each field. Placement of the cages started
at the wheat fallow border and moved farther into the fallow. Cage distances were not standardized among fields due to differences in field layouts. The distances that cages were placed are listed in Table 2.1. Emergence cages were checked on a biweekly basis.

In 2015, sawfly larvae were sampled from the same sampling locations as those for sweep samples. Within the area covered by the sweep net sampling, two non-continuous 50-cm row samples were collected following the adult flight period, but before harvest. All stems from these samples were split to determine the presence or absence of sawfly larvae. Visual confirmation of a larva, a larval cadaver, pupation chamber of a parasitoid wasp, or the larval frass trail were counted as larval presence.

Statistical Analysis

A repeated measures analysis of variance was conducted using PROC GLIMMIX (SAS 2013) to analyze the effects of distance into the field and sex of the sawfly. The data were fit to a negative binomial distribution. Sampling blocks within fields and sampling dates were considered random effects. The autoregressive one structure was fit using Akaike’s Information Criterion. Mean comparisons among distances and between sexes were evaluated using Tukey’s Honestly Significant Differences. Separate analyses were done for each field for each year of sampling for sweep net, sticky trap, and emergence cage data.

Linear regression was used to test for a linear relationship between stem density and larval density. An analysis of covariance was performed (PROC GLIMMIX) to measure the change in larval density over sampling distances (SAS 2013). Sampling block within the field was treated as a random effect. The data were not normally
distributed and were fit to a negative binomial distribution. Tukey’s Honestly Significant Differences were used for mean comparisons of the number of larvae among sampling distances. This analysis was done separately for each field.

To standardize sampling dates among fields for analysis, the term sampling event is used. The date of peak adult activity was used to match the fields. Table 2.2 lists the date of each sampling event at each field for each method of sampling. To test the effects of sampling date and sex of the sawfly, a repeated measures analysis of variance was done using PROC GLIMMIX utilizing the negative binomial distribution. Sampling distance, sampling block, and field were treated as random effects. The autoregressive one covariance structure was fit to the data because the Pearson’s Correlation Coefficient divided by the degrees of freedom statistic was closest to one. Single degree of freedom contrasts were used to compare the population size of males and females. Tukey’s Honestly Significant Differences were used for mean comparisons among dates and between sexes. This was done for sweep net and emergence cage data. Further analysis of the sweep net data was done to compare the number of each sex of the sawfly that was sampled each year, treating year as a fixed effect and sampling date as a random effect.

Sawfly emergence and seasonality was characterized by calculating the total proportion of sawflies sampled to that date. A repeated measures analysis of variance was performed using PROC GLIMMIX to test for differences in the rate of emergence and between the sexes of the sawflies. Field and year were considered random effects in the model. A covariance structure was fit to the data by comparing the value of Akaike’s Information Criterion. The autoregressive one structure was used. A Gaussian distribution was fit to these data. Tukey’s Honestly Significant Differences and single
degree of freedom contrasts were used to compare the means of date and sex. This analysis was done for sweep net and emergence cage data.

**Results**

During both years of sampling, the first sawflies sampled were at McGrew, May 19\textsuperscript{th} in 2014 and May 14 in 2015. In 2014, peak emergence occurred on May 29\textsuperscript{th} at McGrew, June 3\textsuperscript{rd} at Gurley, and June 4\textsuperscript{th} at Hemingford. In 2015, peak emergence was recorded on May 28\textsuperscript{th} at McGrew, June 3\textsuperscript{rd} at Gurley, and June 8\textsuperscript{th} at Hemingford. The last sawflies caught each year came from Hemingford, June 27\textsuperscript{th} in 2014 and June 25\textsuperscript{th} in 2015. Hemingford had the most sawflies sampled for all methods from both years, and McGrew had the fewest sawflies sampled for all methods both years (Table 2.3).

A significant sex by distance interaction for sticky trap samples was detected at Gurley ($f_{4,1000} = 2.82, p = 0.02$), Hemingford ($f_{4,1432} = 7.57, p < 0.0001$), and McGrew ($f_{4,1288} = 4.83, p < 0.0001$). Female densities were not significantly different across the sampling distances at each field (Table 2.4). Male densities were greater than female densities at the field edge (Table 2.4). Only at Hemingford and McGrew is there a difference in male sawfly density between the field edge and the 30-m distance. The main effect of sex shows that more males than females were sampled, overall, at all fields. At Gurley, $0.27 \pm 0.04$ more males than females were caught, on average, per sticky trap. At Hemingford and McGrew $0.31 \pm 0.03$ and $0.72 \pm 0.11$, respectively, more males than females were sampled per sticky trap.

A significant sex by sampling distance interaction was detected for sweep net sampled sawflies at Gurley ($f_{4,776} = 16.53, p < 0.0001$), Hemingford ($f_{4,888} = 37.78 p <$
0.0001), and McGrew (t_{4,856} = 38.78, p < 0.0001) during the 2014 flight period. These interactions were significant in 2015 at Gurley (t_{4,832} = 11.21, p < 0.0001), Hemingford (t_{4,838} = 29.91, p < 0.0001), and McGrew (t_{4,888} = 8.95, p < 0.0001). Typically, the greatest densities of sawflies were found along the field edge, and densities decreased farther into the field (Table 2.5). There were two exceptions. No significant differences were detected among distances for females at Gurley in 2014 and McGrew in 2015. Males have a greater decrease in density compared to females the farther into the field that was sampled. The most interior sampling distance had a 70-90% reduction in male density compared to the field edge. This change in density for females, when present, was a 40-50% reduction in density from the field edge to the most interior sampling distance.

A significant linear relationship was detected between stem density and larval density (t_{1,187} = 19.5, p < 0.0001). Hemingford had the greatest stem density, averaging 196.6 ± 3.34 stems per row meter, followed by Gurley 138.2 ± 2.54, with McGrew having the fewest stems per row meter 121.34 ± 2.20. The 20-m sampling distance at Hemingford had the highest stem density, with an average of 240.31 ± 8.96 stems per row meter. Larval density was highest at the field edge for each field. The edge at McGrew had the lowest larval density of the field edges sampled, with 83.0 ± 6.82 larvae per row meter. Hemingford had the greatest density of larvae at the edge with 154.38 ± 6.82 larvae per row meter. All three fields showed a decline in larval density from the field edge to the 40-m sampling distance, a 60-40 % decrease (Figure 2.1). At Hemingford, the 20-m sampling distance had the second highest larval density in the field, 99.1 ± 6.84 larvae per row meter of wheat.
In observing the seasonality of the sawfly, a significant sex by sampling event interaction was detected for sweep net samples in 2014 ($f_{6, 2586} = 27.84, p < 0.0001$) and 2015 ($f_{6, 2532} = 26.84, p < 0.0001$). Peak activity for the adult sawfly occurred at the end of May and beginning of June both years (Figure 2.2). No differences were found between the number of males and females caught per 20 sweeps in 2014 ($t_{6396} = -1.6, p < 0.38$). In 2015, $4.56 \pm 1.1$ more females than males were sampled per 20 sweeps ($t_{6396} = 16.04, p < 0.0001$). In both years, male density was less than one male per 20 sweeps by sampling events 6 and 7 (Figure 2.2).

The main effect of the sex of the sawfly was significant for sawflies sampled by emergence cages in 2014 ($f_{1,25} = 6.02, p = 0.02$) and 2015 ($f_{1,47} = 12.55, p = 0.001$) with more females being sampled than males. On average, $2.32 \pm 1.40$ more females were collected than males in emergence cages in 2014. In 2015, $1.93 \pm 1.20$ more females than males were sampled for each date from emergence cages. Sampling event was significant in 2014 ($f_{5,180} = 5.67, p = 0.02$) and 2015 ($f_{1,27} = 5.67, p = 0.02$). The greatest number of sawflies sampled in 2014 ($0.84 \pm 0.43$) was on sampling event three (Figure 2.3). In 2015, the greatest number of sawflies sampled per cage was on event 2, $1.23 \pm 0.58$ (Figure 2.3). No sex by sampling date interaction was detected in 2014 ($f_{5,290} = 1.47, p = 0.20$) or 2015 ($f_{5,180} = 0.82, p = 0.54$).

The main effects of sex of the sawfly and sampling event for the rate of accumulation of sweep net sampled sawflies were significant ($f_{1,35} = 14.39, p = 0.0006; f_{6,6} = 103.18, p < 0.0001$). Males accumulated at a $4 \pm 1\%$ faster rate than females (Figure 2.4). The emergence rate was greatest from sampling event three to four, a $37\% \pm 6$
increase in the number of sawflies sampled. No event by sex interaction was detected 
\((f_{6,35} = 1.62, p = 0.17)\) for the rate of accumulation for sweep net sampled adult sawflies.

Emergence cage data from McGrew was excluded from the analysis due to the
low number of sawflies sampled. The main effects of sex of the sawfly and sampling date 
for the rate of accumulation of sawflies sampled by emergence cages were significant
\((f_{1,21} = 5.16, p = 0.03, f_{6,6} = 1.41.51, p <0.0001)\). Males accumulated at a 3 ± 1 % faster
rate than females. Significant changes in the total percent of sawflies sampled occur from 
event two to three \((t_6 = -5.4, p = 0.015)\), from three to four \((t_6 = -5.05, p = 0.021)\), and
four to five \((t_6 = -5.2, p = 0.018)\) (Figure 2.5). No date by sex interaction was detected
\((f_{6,21} = 0.69, p = 0.66)\).

One repetition of cages was lost at Hemingford in 2015 due to flooding. The main
effect of sex of the sawfly was significant in 2014 and 2015 \((F_{1,32} = 4.46, p = 0.04; F_{1,9} =
8.53, p = 0.018)\). In 2014, 2.91 ± 1.7 more females than males were collected from
emergence cages per sampling event. In 2015, 2.13 ± 1.3 more females than males were
collected per sampling event. Distance did not have a significant effect in 2014 \((F_{4, 208} =
2.12, p = 0.08)\) nor 2015 \((F_{3, 66} = 2.36, p = 0.08)\). No sex by sampling distance interaction
was detected at Hemingford in 2014 \((F_{4,112} = 1.25, p = 0.29)\) nor 2015 \((F_{3, 54} = 1.05, p =
0.38)\).

The main effect of distance was significant for sawflies sampled by emergence
cages at Gurley in 2014 \((F_{4,112} = 9.92, p < 0.0001)\) and 2015 \((F_{3, 54} = 3.36, p = 0.03)\). The
distance closest to the wheat field sampled fewer sawflies, 0.15 ± 0.07 per sampling
event, than the next distance farther into the fallow. Distance one and three captured
similar numbers of sawflies during the flight period (Table 2.6). In 2015, distance one and two caught equal numbers of sawflies, 1.33 ± 0.4 and 1.25 ± 0.4 respectively (Table 2.6). Sex was not significant in 2014 (F1, 16 = 0.79, p = 0.39), but was significant in 2015 (F1, 7 = 6.81, p = 0.03). On average, 2.09 ± 1.32 more females than males were collected each sampling date at Gurley in 2015. No sex by sampling distance interaction was detected at Gurley in 2014 (F4, 112 = 1.25, p = 0.29) nor 2015 (F3, 54 = 1.05, p = 0.38).

Discussion

Sticky trap sampling was not done in 2015 due to cost considerations. A total of 3,080 sticky traps were used during the 2014 season, with the cost of the 3,500 traps ordered being $4,926.25 (Great Lakes IPM, Vestaburg, MI). This does not include additional costs for materials to make holders for the traps. A total of 14 sticky trap sampling dates were used for analysis, compared to the 29 dates used from the sweep net sampling dates. A sweep net that costs $23.45, $70.10 if two replacement nets are included (Great Lakes IPM, Vestaburg, MI). However, a sticky trap sampling plan that uses 10 sticky traps per field for four weeks, has a more comparable cost to sweep net sampling plan with a cost of $73.75 per case of 50 traps (Great Lakes IPM, Vestaburg, MI). This makes sticky traps more practical for sampling. However, the low number of sawflies caught on sticky traps, 0.6-1.53 sawflies per sticky trap sampling point, makes it difficult to draw conclusions about sawfly population differences.

Although differences in sticky trap captures were detected among the distances sampled, mean comparisons showed there were no differences in female densities among sampling distances. However, these differences are small, as they are differences of less than one sawfly. The lower efficacy of the sticky traps, particularly in sampling females,
trapping data suggests that females have a similar density through the first 30-m of the wheat. The edge effect for adult sawflies has been previously observed, and it was seen here as well, but, previous observations were made with sweep net samples (Holmes 1982, Morrill et al. 2001, and Weaver et al. 2004). No adult sampling schemes with unbaited sticky traps has been published. The edge effect might be a density dependent phenomena for dispersing females, as low female densities sampled by sweep net did not demonstrate an edge effect at McGrew and Gurley. The lack of an edge effect for female sawflies could be in part to greater female dispersal or the poor sampling abilities of sticky traps for female sawflies. However, with the identification of sawfly volatiles, it could be possible to improve the efficacy of sticky traps, making them a useful sampling tool for sawflies (Piesik et al. 2008). Sticky traps have been used to sample adult corn rootworms to predict larval damage (Kuhar and Youngman 1998). It may be possible to develop a similar scheme for sawfly sampling. Sticky traps could be a useful sampling tool for the sawfly as they are easy to check, change, and sample continuously while in the field.

Sweep net sampling shows the edge effect in the dispersal of the sawfly, with the exception of females sampled at McGrew and Gurley in 2014. The edge effect is more apparent in males as there are fewer males at the interior sampling distances, with greater densities at the field edge. The greatest densities of females was at the field edge as well, but the decline into the field was not as great as males. A similar pattern was observed in Montana wheat fields over distances greater than the ones sampled here (Goosey 1999). The difference in dispersal pattern could be due to the needs of each sex. By congregating, males increase the concentration of 9-acetyloxynanal, a volatile used by
males to attract females (Cossé et al. 2002). Congregating along the field edge gives them the greatest potential to encounter females. Males may benefit by moving farther into the wheat to mate females again or mate with virgin females. However, it is not known if female sawflies only need to be mated once to fill their spermatheca. Females show greater dispersal into the wheat field than males. By plotting the proportion of infested wheat stem samples against the average infestation level, a dispersion relationship is described indicating that females disperse farther into the wheat (Nansen et al. 2005b). Nansen et al. (2005b) hypothesized that females move unidirectionally towards the field center, when they encounter wheat. From the female sweep net samples gathered here, the movement of the female sawfly into the wheat field would be better described as diffusion into the wheat. Dispersing farther into the field to oviposit will increase survival of their offspring, as females do not discriminate between infested and uninfested stems for oviposition (Buteler et al. 2009). Ovipositing in uninfested stems is important as larval cannibalism is the most probable cause of mortality for the larvae (Buteler et al. 2015).

An interesting anomaly is the uniformity of females across distances at McGrew. This may have been caused by the sampling environment at McGrew. Each field sampled had differing populations of downy brome, *Bromus tectorum* L., present. Hemingford had no downy brome, Gurley had downy brome near the field edge, and McGrew was heavily infested with downy brome, particularly the first 10-m of wheat from the field edge. Female sawflies prefer downy brome to wheat as a host, so it could be expected to find greater amounts of females in these areas (Perez-Mendoza et al. 2006); however, this was not observed. Downy brome can reach densities of 200 plants per row meter and
outcompetes wheat that was planted (Blackshaw 1993). The high density of downy brome at McGrew created a sampling environment that made it difficult to sweep net sample. The greater density of stems also provides more cover for the sawflies. The downy brome in this area also senesced before the wheat, reducing the number of acceptable hosts in the area. The combination of the dense downy brome stand and fewer wheat stems available, likely caused females to disperse farther into the wheat to find oviposition hosts.

The decline in larval density as sampling distance into the wheat field increases, matches the general trend of the adult density. The edge effect was observed within the 40-m of wheat sampled, but Nansen et al. (2005b) saw the decline in larval density up to 250-m into wheat fields. The edge effect with larvae is not always a uniform decline as sampling distance increases, as seen in Hemingford, as well as in Montana (Nansen et al. 2005b). Part of the increased larval density at 20-m at Hemingford resulted from greater stem density. Within-field and field-to-field variation in stem density affect the larval density gradient, but the edge effect is present. To limit variation, infestation curves have been standardized using non-linear regression, but even then, a consistent decrease in larval density is not always seen (Nansen et al. 2005b). While larval infestations mirror adult dispersal to an extent, the fluctuations in larval densities does not match that of the female sawfly.

More males than females were sweep net sampled in 2014, 2.32 males per female. In 2015, more females than males were sweep net sampled, 0.46 males per female. A combination of the vigor of wheat and availability of male sawflies may have caused this change in the population. Female sawflies prefer to oviposit fertilized eggs in larger
stems and oviposit unfertilized eggs in smaller stems (Cárcamo et al. 2005). The adults sampled in 2014 developed during the 2013 winter wheat growing season. That wheat was planted and developed during a drought that would eventually be alleviated by May 2014 (NOAA 2015). During the sawfly flight period of 2013, the wheat received 2.95-5.59 inches of rain depending on the field location (NOAA 2016). One response wheat has to growing in a water deficit is smaller stem diameters (Saint Pierre et al. 2010). More than a 1-mm change in stem diameter was observed under a difference of 150-mm of irrigation (Saint Pierre et al. 2010). As little as 0.15-mm change in stem diameter can influence the female to change the sex of the egg being oviposited (Cárcamo et al. 2005). Another response winter wheat has to drought conditions is to abort a greater number of tillers (Duggan et al. 2000). It is possible the drought conditions experienced during the 2013 growing season led to fewer stems being available for oviposition. Of those stems available, they may have had smaller diameters, leading to more unfertilized eggs being oviposited.

With a larger male population in 2014, male densities were higher farther into the wheat field. The greater abundance of males created more opportunities for females to be mated. If females need to be mated more than once to fill their spermatheca, then the higher densities of males farther in the field would allow for more opportunities for multiple mating events. It would also increase the chance that a female would encounter a males. With better moisture availability in 2014, 5.79-8.01 inches of precipitation depending on the field location (NOAA 2016), more vigorously growing wheat could result in females ovipositing more fertilized eggs. No differences were found between the number of male and female sawflies sweep net sampled in Montana wheat fields in 1996
and 1997 (Goosey 1999). The amount of precipitation received between those years was similar (NOAA 1996, NOAA 1997). The response of wheat to the growing conditions present could influence the ratio of males and females.

Emergence cage data produced a sex ratio that indicates more females were present both years of sampling. However, sweep net samples only show this for 2015. The sampling bias of emergence cages likely caused this result. Different sampling methods of spruce budworm, *Choristoneura fumiferana* Clemens (Lepidoptera: Tortricidae), resulted in different sex ratios being observed. Adult moths sampled by fogging resident trees produced an equal sex ratio, while light traps within the canopy were male biased, and light traps outside the canopy were female biased (Rhainds and Heard 2014). Only sawflies present in the collection jar were counted. Males confined to small areas will attack other males nipping off antennae and legs, while leaving females alone (Ainslie 1920). This competition could have prevented more males from entering the collection jar or driven males out of the jar, giving emergence cages a female bias.

The faster rate of emergence of the male sawflies creates the dynamic of having fewer males available later in the flight period to mate females. Protandry has been previously recorded in the emergence of the sawfly (Holmes and Peterson 1963). After seven days, 50% of males had emerged, but it took 13 days for 50% of females to emerge (Holmes and Peterson 1963). Protandry was more pronounced in 2015. The already low male densities declined to two or fewer males per 20 sweeps while more than double that number of females were still present. The protandry of the sawfly could be exploited in spring wheat systems. Delayed planting of spring wheat means the wheat is suitable for oviposition later in the flight period, exposing it to fewer female sawflies (Morrill and
Kushnak 1999). Additionally fewer males may be present, limiting the amount of fertilized eggs that are oviposited (Morrill and Kushnak 1999). Fewer females create the potential for fewer infested stems, but low densities of sawflies have the greatest population growth potential due to less intraspecific competition (Holmes 1982). A similar tactic for winter wheat could be achieved by planting later maturing varieties; however, later maturing winter wheat is at greater risk of exposure to higher temperatures that can reduce yields (Tashiro and Wardlaw 1990).

At Gurley in 2014, fewer sawflies were collected from the emergence cages nearest the wheat-fallow border. These cages were placed within the area that was tilled. While it is only one observation each year, tillage may have increased larval mortality within that area resulting in the lower adult densities sampled. Properly timed spring tillage can cause high levels of mortality of sawfly larvae and pupae in infested fields (Holmes and Farstad 1956). However, this reduction in sawflies from within this area did little to limit the overall infestation at Gurley. Similarly, management tactics used along the field edge reduced the infestation within that area, but did not limit the overall infestation at the field (Beres et al. 2009).

The equal number of sawflies sampled from the emergence cages closest to the wheat and the next distance at Hemingford may have been due to parasitism of the sawfly. *Bracon cephi* (Gahan) and *Bracon lissogaster* Muesebeck (Hymenoptera: Braconidae) are the only parasitoids that attack the sawfly in wheat (Morrill et al. 1998). Adult *B. cephi* were collected in sweep nets samples at all distances during both years of sampling at Hemingford. Densities as high as $16.5 \pm 8.98$ adult *B. cephi* per 20 sweeps were observed along the field edge in 2014, and $24.6 \pm 3.81$ adults per 20 sweeps in
2015. Wheat stem samples taken from the field edges, had rates of parasitism over 90% (Harvey unpublished data). This high mortality is reflective of the high densities adult *B. cephi* sampled along the field edge. Further investigations into the seasonality of this parasitoid in Nebraska is needed as these wasps can be an important source of mortality for sawfly (Buteler et al. 2015).

In describing the dispersal of the wheat stem sawfly, a decrease in adult density the farther into the field sampled was observed. Male densities are highest near the field edge, with few male sawflies dispersing farther into the field. Female densities are also highest along the field edge, but they can be more uniformly found across the 40-m sampled. Taking management actions along the field edges is a plausible tactic, the scale of these actions will likely need to extend greater than 40-m into the wheat field as female density has not significantly declined after 10-m into the wheat. Further research is need to understand, at a finer scale, how sawflies are moving within a wheat field. A better understanding of the mating system of the sawfly is needed, as there might be opportunities to exploit that for management purposes.
References Cited


Tables and Figures

Table 2.1 Distance (m) into the fallow, from the edge of the wheat field, emergence cages were placed at each field in 2014 and 2015.

<table>
<thead>
<tr>
<th>Field</th>
<th>McGrew</th>
<th>Gurley</th>
<th>Hemingford</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>20</td>
<td>17</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>40</td>
<td>31</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>44</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>58</td>
<td>71</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Distance (m)</td>
<td>-</td>
<td>22</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>40</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>56</td>
<td>57</td>
</tr>
</tbody>
</table>
Table 2.2 Dates (month/day) of sampling events used for analysis of the emergence of adult sawflies sampled by sweep net and emergence cages in 2014 (A), 2015 (B), and the dates of exposure for the sticky traps in 2014 (C).

<table>
<thead>
<tr>
<th>Sampling event</th>
<th>McGrew</th>
<th>Gurley</th>
<th>Hemingford</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5/20</td>
<td>5/26</td>
<td>5/27</td>
</tr>
<tr>
<td>2</td>
<td>5/24</td>
<td>5/28</td>
<td>6/1</td>
</tr>
<tr>
<td>3</td>
<td>5/26</td>
<td>6/3</td>
<td>6/4</td>
</tr>
<tr>
<td>4</td>
<td>5/28</td>
<td>6/5</td>
<td>6/8</td>
</tr>
<tr>
<td>5</td>
<td>6/2</td>
<td>6/9</td>
<td>6/11</td>
</tr>
<tr>
<td>6</td>
<td>6/5</td>
<td>6/12</td>
<td>6/15</td>
</tr>
<tr>
<td>7</td>
<td>6/10</td>
<td>6/17</td>
<td>6/18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling event</th>
<th>McGrew</th>
<th>Gurley</th>
<th>Hemingford</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>B</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5/22</td>
<td>5/27</td>
<td>5/28</td>
</tr>
<tr>
<td>2</td>
<td>5/26</td>
<td>5/29</td>
<td>5/31</td>
</tr>
<tr>
<td>3</td>
<td>5/29</td>
<td>6/3</td>
<td>6/4</td>
</tr>
<tr>
<td>4</td>
<td>6/2</td>
<td>6/5</td>
<td>6/6</td>
</tr>
<tr>
<td>5</td>
<td>6/5</td>
<td>6/10</td>
<td>6/11</td>
</tr>
<tr>
<td>6</td>
<td>6/9</td>
<td>6/12</td>
<td>6/13</td>
</tr>
<tr>
<td>7</td>
<td>6/12</td>
<td>6/17</td>
<td>6/18</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling event</th>
<th>McGrew</th>
<th>Gurley</th>
<th>Hemingford</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>C</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 2.3 Field level information including when sawflies were first caught, sampling blocks per field (n), the number of sawflies caught with each sampling method each year, and the sex ratio of male to female sawflies.

<table>
<thead>
<tr>
<th>Field</th>
<th>Year</th>
<th>Sampling method</th>
<th>First sawflies</th>
<th>Last sawflies</th>
<th>n</th>
<th>Sawflies</th>
<th>Ratio (M:F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>McGrew</td>
<td>14</td>
<td>Sticky Traps</td>
<td>May 26&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 23&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>18</td>
<td>269</td>
<td>1.61</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Sweep Nets</td>
<td>May 19&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 23&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>18</td>
<td>2,273</td>
<td>1.19</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Sweep Nets</td>
<td>May 12&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 17&lt;sup&gt;th&lt;/sup&gt;</td>
<td>16</td>
<td>1,983</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Emergence Cages</td>
<td>May 19&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 9&lt;sup&gt;th&lt;/sup&gt;</td>
<td></td>
<td>27</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Emergence Cages</td>
<td>May 20&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td></td>
<td>14</td>
<td>0.17</td>
</tr>
<tr>
<td>Gurley</td>
<td>14</td>
<td>Sticky Traps</td>
<td>May 27&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 24&lt;sup&gt;th&lt;/sup&gt;</td>
<td>14</td>
<td>652</td>
<td>4.17</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Sweep Nets</td>
<td>May 20&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 24&lt;sup&gt;th&lt;/sup&gt;</td>
<td>14</td>
<td>5,680</td>
<td>3.22</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Sweep Nets</td>
<td>May 21&lt;sup&gt;st&lt;/sup&gt;</td>
<td>June 19&lt;sup&gt;th&lt;/sup&gt;</td>
<td>15</td>
<td>4,283</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Emergence Cages</td>
<td>May 27&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 17&lt;sup&gt;th&lt;/sup&gt;</td>
<td>101</td>
<td>101</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Emergence Cages</td>
<td>May 21&lt;sup&gt;st&lt;/sup&gt;</td>
<td>June 19&lt;sup&gt;th&lt;/sup&gt;</td>
<td></td>
<td>48</td>
<td>0.5</td>
</tr>
<tr>
<td>Hemingford</td>
<td>14</td>
<td>Sticky Traps</td>
<td>May 28&lt;sup&gt;th&lt;/sup&gt;</td>
<td>July 1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>16</td>
<td>3,902</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Sweep Nets</td>
<td>May 28&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 27&lt;sup&gt;th&lt;/sup&gt;</td>
<td>16</td>
<td>18,475</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Sweep Nets</td>
<td>May 14&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 25&lt;sup&gt;th&lt;/sup&gt;</td>
<td>16</td>
<td>10,357</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>Emergence Cages</td>
<td>May 28&lt;sup&gt;th&lt;/sup&gt;</td>
<td>June 27&lt;sup&gt;th&lt;/sup&gt;</td>
<td>252</td>
<td>252</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Emergence Cages</td>
<td>June 1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>June 22&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>101</td>
<td>101</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Table 2.4 Average sticky trap catches (sawflies per trap ± std. error of mean) across sampling distances for female and male sawflies at Gurley (A), Hemingford (B), and McGrew (C) in 2014.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Females</th>
<th>Males</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.12 ± 0.03a</td>
<td>0.49 ± 0.08a**</td>
</tr>
<tr>
<td>5</td>
<td>0.14 ± 0.03a</td>
<td>0.75 ± 0.12a**</td>
</tr>
<tr>
<td>10</td>
<td>0.17 ± 0.04a</td>
<td>0.76 ± 0.12a**</td>
</tr>
<tr>
<td>20</td>
<td>0.19 ± 0.04a</td>
<td>0.59 ± 0.10a**</td>
</tr>
<tr>
<td>30</td>
<td>0.23 ± 0.05a</td>
<td>0.48 ± 0.08a</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.58 ± 0.10a</td>
<td>2.42 ± 0.39a**</td>
</tr>
<tr>
<td>5</td>
<td>0.73 ± 0.12a</td>
<td>2.77 ± 0.44a**</td>
</tr>
<tr>
<td>10</td>
<td>0.70 ± 0.12a</td>
<td>1.96 ± 0.32ab**</td>
</tr>
<tr>
<td>20</td>
<td>0.63 ± 0.11a</td>
<td>1.43 ± 0.23bc**</td>
</tr>
<tr>
<td>30</td>
<td>0.68 ± 0.11a</td>
<td>1.23 ± 0.20c**</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0.10 ± 0.02a</td>
<td>0.30 ± 0.05a*</td>
</tr>
<tr>
<td>5</td>
<td>0.11 ± 0.03a</td>
<td>0.15 ± 0.03b</td>
</tr>
<tr>
<td>10</td>
<td>0.05 ± 0.01a</td>
<td>0.12 ± 0.03b</td>
</tr>
<tr>
<td>20</td>
<td>0.11 ± 0.02a</td>
<td>0.13 ± 0.03b</td>
</tr>
<tr>
<td>30</td>
<td>0.12 ± 0.03a</td>
<td>0.06 ± 0.02b</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (p < 0.05) (Tukey’s Honestly Significant Difference)
Means followed by an asterisk are significantly different within the row for the field * p < 0.01 ** p <0.0001 (Tukey’s Honestly Significant Difference)
### Table 2.5 Comparisons of the male and female sawflies sweep net sampled (sawflies per 20 sweeps ± std. error of mean) across distances (m) into the wheat field in 2014 (A) and 2015 (B) for each field.

#### A

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Hemingford</th>
<th>McGrew</th>
<th>Gurley</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Females</td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>0</td>
<td>11.89 ± 1.40a</td>
<td>45.96 ± 4.96a**</td>
<td>1.05 ± 0.16ab</td>
</tr>
<tr>
<td>5</td>
<td>7.25 ± 0.91b</td>
<td>13.42 ± 1.57b**</td>
<td>0.97 ± 0.15ab</td>
</tr>
<tr>
<td>10</td>
<td>6.09 ± 0.79b</td>
<td>9.03 ± 1.10c</td>
<td>1.46 ± 0.23a</td>
</tr>
<tr>
<td>20</td>
<td>6.56 ± 0.84b</td>
<td>6.84 ± 0.87c</td>
<td>0.78 ± 0.12b</td>
</tr>
<tr>
<td>30</td>
<td>5.77 ± 0.75b</td>
<td>6.64 ± 0.84c</td>
<td>1.19 ± 0.19ab</td>
</tr>
</tbody>
</table>

#### B

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Hemingford</th>
<th>McGrew</th>
<th>Gurley</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Females</td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>0</td>
<td>9.40 ± 1.37a</td>
<td>5.40 ± 0.81a*</td>
<td>2.02 ± 0.27a</td>
</tr>
<tr>
<td>10</td>
<td>4.61 ± 0.70b</td>
<td>1.45 ± 0.24b**</td>
<td>1.63 ± 0.22a</td>
</tr>
<tr>
<td>20</td>
<td>4.57 ± 0.70b</td>
<td>0.79 ± 0.14bc**</td>
<td>1.40 ± 0.20a</td>
</tr>
<tr>
<td>30</td>
<td>4.11 ± 0.63b</td>
<td>0.56 ± 0.10c**</td>
<td>1.44 ± 0.20a</td>
</tr>
<tr>
<td>40</td>
<td>4.23 ± 0.64b</td>
<td>0.58 ± 0.10c**</td>
<td>1.53 ± 0.21a</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different within the column (p < 0.05) (Tukey’s Honestly Significant Difference)

Means followed by an asterisk are significantly different within the row for the field * p < 0.05, ** p < 0.0001 (Tukey’s Honestly Significant Difference)

n = 16 per distance at Hemingford in 2014 and 2015, n = 18 in 2014 and n = 16 in 2015 per distance at McGrew, n = 14 in 2014 and n = 15 in 2015 per distance at Gurley
Table 2.6 Average number of sawflies (sawflies per cage ± std. error of mean) sampled during the year at Hemingford and Gurley in 2014 and 2015.

<table>
<thead>
<tr>
<th>Distance</th>
<th>2014</th>
<th>2015</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.39 ± 1.01a</td>
<td>1.29 ± 0.44a</td>
<td>0.23 ± 0.10b</td>
<td>1.33 ± 0.40a</td>
</tr>
<tr>
<td>2</td>
<td>2.18 ± 1.27a</td>
<td>1.32 ± 0.45a</td>
<td>1.42 ± 0.37a</td>
<td>1.25 ± 0.38a</td>
</tr>
<tr>
<td>3</td>
<td>1.28 ± 0.96a</td>
<td>0.77 ± 0.30ab</td>
<td>0.28 ± 0.12b</td>
<td>0.79 ± 0.27ab</td>
</tr>
<tr>
<td>4</td>
<td>1.28 ± 0.95a</td>
<td>0.39 ± 0.17b</td>
<td>0.29 ± 0.11b</td>
<td>0.39 ± 0.15b</td>
</tr>
<tr>
<td>5</td>
<td>1.58 ± 1.08a</td>
<td>---</td>
<td>0.27 ± 0.10b</td>
<td>---</td>
</tr>
</tbody>
</table>

Means followed by the same letter within the column are not significantly different (p < 0.05) (Tukey’s Honestly Significant Difference)

Table 2.1 lists the distances that each cage was placed at in the fallow
Figure 2.1 Larvae per row meter of wheat stems (mean ± std. error of mean) across distances sampled into the wheat at each field sampled in 2015.

Means within the row followed by the same letter are not significantly different (p < 0.05) (Tukey’s Significantly Honest Differences)
Figure 2.2 Average number of male and female sawflies caught per 20 sweeps (mean ± std. error of mean) for each sampling date from all fields in 2014 (A) and 2015 (B).

Events with the same letter are not significantly different (p < 0.05) (Tukey’s Honestly Significant Difference). Uppercase letters specify differences among female densities, and lower case letters specify differences among male densities.

Refer to Table 2.2 for Julian date of the sampling event for each field.
Figure 2.3 Average number of sawflies (mean ± std. error of mean) collected per emergence cage in 2014 (A) and 2015 (B) from all fields.

Events followed by the same letter are not significantly different (p < 0.05) (Tukey’s Honestly Significant Difference).
Refer to Table 2.2 for the Julian date of the sampling event for each field.
Figure 2.4 Accumulated proportion of male and female sawflies collected via sweep net samples averaged across all fields and years.

Differences between the sampling event and the next event in the change of the proportion of the total sawfly population sampled * p < 0.01 (Tukey’s Honestly Significant Difference)
Refer to Table 2.2 for the Julian date of the sampling event for each field.
Figure 2.5 Accumulated proportion of sawflies sampled for male and female sawflies collected by emergence cages averaged from Hemingford and Gurley from both year.

Differences between the sampling event and the next event in the change of the proportion of the total sawfly population sampled * p < 0.01 (Tukey’s Honestly Significant Difference)
Refer to Table 2.2 for the Julian date of the sampling event for each field.
CHAPTER 3

Sampling adult wheat stem sawfly, *Cephus cinctus* Norton, populations to determine adult distribution and predict larval infestation rates in Nebraska winter wheat fields
Introduction

The wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), is a key pest of wheat, *Triticum aestivum* L., in the northern Great Plains (Beres et al. 2011). The wheat stem sawfly was traditionally only a pest of spring wheat in this region; however, by the 1980s the sawfly had synchronized its emergence such that winter wheat became a suitable host (Morrill and Kushnak 1996). Shortly thereafter, the sawfly began infesting winter wheat fields in the Nebraska Panhandle. Initial infestations were reported in Scotts Bluff County, but sawfly infestations have since been found throughout the Nebraska Panhandle (Hein unpublished data). The sawfly’s range as a pest continues to grow as economic infestations have been reported as far south as southeastern Colorado (Randolph personal communication).

Sawfly larvae can be a yield limiting factor. Stem mining interferes with nutrient and water transfer to the grain kernels, resulting in smaller kernels and reduced yield (Delaney et al. 2010). Stem mining results in a 10-25% physiological reduction in yield, but under water and/or phosphorus stress the loss is greater (Delaney et al. 2010). Additionally, stem girdling done by mature larvae weakens the stem, making it prone to lodging. Lodged stems are difficult for harvesters to recover. The sawfly causes an estimated annual loss of $350 million in the Great Plains (Beres et al. 2011).

Adult sawflies in Nebraska are active from mid-May to mid-June (Hein unpublished data). Sawflies are protandrous; therefore, females that emerge earlier during the flight period lay more fertilized eggs as more males are available for mating (Holmes and Peterson 1963). More unfertilized eggs are oviposited later in the season due to this dynamic, and because the sawfly is haplodiploid, these eggs give rise to males (Holmes
and Peterson 1963). Sawflies begin ovipositing once they encounter acceptable hosts. The sawfly can use many cereal grains and other wild grass species as hosts (Ainslie 1920). Females prefer to oviposit fertilized eggs in larger stems (Cárcamo et al. 2005). Larvae hatch in about one week and begin feeding on the vascular tissue within the stem (Ainslie 1920). Typically, only the first larvae to hatch survives due to larval cannibalism (Ainslie 1920). Larvae continue feeding until light transmission through the stem wall increases and a drop in plant moisture content are detected (Holmes 1975). Upon receiving these signals, larvae move down the stem to prepare a chamber where the larvae undergo diapause as prepupae (Holmes 1975). Above the diapause chamber, larvae girdle the inside of the stem and plug it with frass (Holmes 1975). After accumulating sufficient cold temperatures, larvae pupate and emerge in the spring as temperatures increase (Salt 1947).

The primary tactic for sawfly management is the use of solid stem wheat varieties. The extra pith expressed within the stem crushes eggs, limits larval mobility, and increases desiccation of the larvae (Holmes and Peterson 1961, Holmes and Peterson 1962). However, solid stem varieties have variable expression of pith between years and stem nodes (Holmes 1984, Platt 1941). Pith expression is positively related to the number of sunny days during wheat development (Holmes 1984). Additional concerns for solid stem varieties include, reduced yield relative to hollow stem varieties when sawfly pressure is low and the negative impact these varieties can have on sawfly parasitoids (Beres et al. 2007, Rand et al. 2012). Seed blends of hollow and solid wheat varieties as well as planting field edges with solid stem varieties have had moderate success in limiting sawfly damage while reducing the impact of solid stem wheat in the field (Beres
et al. 2009). However, planting the entire field to a solid stem variety is still the best strategy for sawfly management (Beres et al. 2009).

In Montana, Nansen et al. (2005a) found an aggregated distribution of larvae and eggs throughout the wheat growing season with higher densities at or near the field edge. A sampling plan for sawfly larvae was created using this information (Nansen et al. 2005c). The plan requires collecting ten, 30-cm row samples of wheat. The initial step requires the sampler to split the stems in five samples to determine if the infestation rate is sufficient to warrant continued stem splitting. If the infestation is less than 20\%, then sampling is stopped; otherwise, the stems in the remaining five samples are split (Nansen et al. 2005c). This plan is time consuming, requiring 9.5 hours to complete for one field edge (Nansen et al. 2005c). A sampling plan based on adult sawfly populations to predict larval infestation may require less time and effort to complete.

No sampling plan for the adult sawfly has been developed. However, adult sawflies have been sweep net sampled as part of other studies, and their change in density into a wheat field has been described. The decline in adult density was prevalent from the field edge to 30-m into the wheat (Weaver et al. 2004). Morrill et al. (2001) recorded a decline in adult density 90-m into a wheat field; and, after 90-m, adult densities did not decline further. A similar result was seen by Goosey (1999), that by 80-m into field the decline in adult density had stopped. By that distance, male density was less than one per sweep, but female density was between two to four per sweep (Goosey 1999).

The use of one life stage to predict the damage caused by another has successfully been used in other cropping systems. Adult western and northern corn rootworms,
Diabrotica virgifera virgifera LeConte and Diabrotica barberi Smith (Coleoptera: Chrysomelidae), catches on unbaited Phercon AM sticky card traps were significantly correlated with subsequent larval damage in continuous corn (Hein and Tollefson 1985). Larval damage of western corn rootworm has been predicted by sampling adults with unbaited Pherocon AM sticky card traps in a corn-soybean rotation (O’Neal et al. 2001). Sampling adult Listronotus maculicollis Kirby (Coleoptera: Curculionidae) during peak emergence was proven to be an accurate indicator of larval damage to turfgrass (McGraw and Koppenhöfer 2009). Counts of cereal leaf beetle, Oulema melanopus (L.) (Coleoptera: Chrysomelidae), eggs taken on wheat at the two node stage were highly correlated to 4th instar populations and subsequent yield loss (Ihrig et al. 2001). A sampling plan was devised that uses egg masses of the European corn borer, Ostrinia nubilalis (Hubner) (Lepidoptera: Pyralidae) to predict larval stalk tunneling in corn (Sorenson et al. 1995). The objective of this study was to determine the distribution pattern of the adult wheat stem sawfly in the field, establish the relationship between adult density and larval infestation, and create a sampling plan that uses sampled adult sawflies to the predicted larval infestation rate.

Materials and Methods

Sampling Locations

Three winter wheat fields in the Nebraska Panhandle were each sampled in 2014 and 2015. All three fields were dryland fields that used a wheat-fallow rotation. The McGrew field was located six kilometers southwest of McGrew, NE in Scotts Bluff County. The variety ‘Goodstreak’ was grown here both years. Wheat and fallow alternated in 80-m wide by 500-m long strips at this location. The fallow was worked
with a disc in the spring of 2014. No spring tillage was done in 2015 due to wet field conditions. The Gurley field was located six kilometers west of Gurley, NE in Cheyenne County. In 2014, Goodstreak was grown, and in 2015, the variety was ‘Settler CL’. Wheat and fallow were rotated between two 420-m wide by 800-m long blocks. No-till was practiced at this field with the grower using herbicide to manage the fallow. However, one, 10-m wide, pass at the edge of the fallow adjacent to the wheat was made with a disc in attempt to control sawflies. This was done in the spring of both years of sampling. The Hemingford field was located six kilometers southwest of Hemingford, NE in Box Butte County. Wheat and fallow sampled at this location were rotated between two blocks. The wheat sampled in 2014 was in a 200-m wide block and the 2015 wheat was in a 330-m wide block, both of which were 800-m long. Settler CL was grown at this field both years of sampling. The fallow at this field was managed with herbicide.

Sampling Methods

Phercon AM/NB (no bait) yellow sticky traps (Trécé Inc. Adair, OK) and a sweep net were used to sample adult sawflies. In 2014, samples were taken at the field edge and 5, 10, 20, and 30-m into the wheat. In 2015, the 5-m sample was dropped and a 40-m sample distance added. One set of the five sampling distances made a sampling block. Within each block, the order of placement of the distances was randomized. Sampling locations were spaced 10-m apart. Sampling blocks were repeated as many times as allowable by the field dimensions providing 14-18 sample blocks per field. Two sticky traps were placed at each sample location. Traps were opened at an, approximately, 120° to expose the entire sticky surface to only one side of the field. One trap faced towards the fallow and the other faced into the center of the wheat field. A square meter area was
cleared out around the traps to prevent wheat from sticking to them. Sticky traps were collected and changed weekly.

At each sample location, 20 sweeps were taken, moving in the direction of the row, with a 38-cm sweep net through the upper third of the wheat canopy. The sweep sampler started at the location marker and continued along the row, covering an area of 13-m². The movement of the net across the body in a 180° arc across the rows was considered one sweep. Sampling began in early May and concluded in June, when sawflies were no longer sampled. Sweep net samples were taken biweekly at each field. All sawfly samples were returned to the lab for counting and sex determination.

In 2015, sawfly larvae were sampled from the same sampling locations as the sweep samples. Within the area covered by the sweep net sampling, two non-continuous 50-cm row samples were collected following the adult flight period, but before harvest. All stems from these samples were split to determine the presence or absence of sawfly larvae. Visual confirmation of a larva, a larval cadaver, pupation chamber of a parasitoid wasp, or the larval frass trail were counted as larval presence.

Statistical Analysis

The distributions of the female, male, total adults, and larval sawfly populations were described using Taylor’s Power Law (Taylor 1961). This fractional power law can be used to describe the variance to mean relationship within a population. The power law uses the equation:

\[ s^2 = am^b. \]
Where $s^2$ is the sample variance, $m$ is the sample mean, parameter $b$ is an index of aggregation, and parameter $a$ is related to sample size (Taylor 1961). The mean and variance from each sampling date were transformed by $\log_{10}(x+1)$ to make the variance independent of the mean. The variance and mean were plotted, and a linear regression line was calculated. In this regression equation, parameter $a$ is the intercept and parameter $b$ is the slope of the line. If parameter $b = 1$, the distribution is random, if $b < 1$, the distribution is uniform, and when $b > 1$, the distribution is aggregated (Taylor 1961). The linear regression of the log transformed data was done using PROC GLIMMIX (SAS 2013). The parameters of Taylor’s Power Law were also estimated with non-linear regression using PROC NLIN allowing for the data to be analyzed without transformations. Non-linear methods have been used before in estimating parameters $a$ and $b$, because linear regression over estimates the variance at low densities (Reay-Jones 2010). T-tests $[t = (b - 1 / SE of b)]$ were used to test if parameter $b$ was significantly different from one (Zar 1999). An analysis of variance was done using PROC GLIMMIX to test the effects of the method of calculation and sex of the sawfly on parameters $a$ and $b$. The data were found to fit a Gaussian distribution, and this distribution was used in this analysis. Year and field were treated as random effects. Tukey’s Honesty Significant Differences was used for mean comparisons between sampled populations and methods.

Taylor’s Power Law can be used to determine the minimum sample size needed to maintain a desired precision level, by using the formula:

$$N = (am^{b-2})/(d^2).$$
\( N \) is the number of samples needed for the given precision level, variables \( a \) and \( b \) are obtained from the regression equation of Taylor’s Power Law, \( m \) is the sample mean, and \( d \) is the precision level desired, expressed as a standard error of the mean (Buntin 1994). A 0.2 precision level is often used when sampling to make pest management decisions, and was used for this study (Buntin 1994).

Regression analysis was conducted using PROC GLIMMIX to establish the relationship between the number of sawflies sampled per 20 sweeps, distance into the wheat field, stem density, and the larval infestation rate. These data were found to fit a negative binomial distribution, and this distribution was used for this analysis. Field and sampling block within the field were treated as random effects. A Type I fixed effects ANOVA was used to identify the significant terms in the model. Non-significant terms were dropped from the model. The values for each significant term were given by requesting the solutions for the Type III fixed effects ANOVA. Because coefficients of determination, \( r^2 \), are undefined in generalized linear mixed models, correlation coefficients between predicted and observed values were calculated with PROC CORR and used to evaluate model fit.

**Results**

In 2014, adult sawflies were sampled from May 19\(^{th}\) to June 27\(^{th}\). Adult sawflies were sampled from May 12\(^{th}\) to June 25\(^{th}\) in 2015. Hemingford had the largest number of sawflies sampled each year with 18,475 adults caught in 2014 and 10,375 adults caught in 2015. McGrew had the lowest number of adults sampled. In 2014, 2,273 adults were sampled, while in 2015, 1,983 adults were caught.
For sticky trap sampling, parameter $b$, estimated by the log transformation method, is significantly greater than one for females (1.12), males (1.43), and the total sampled population (1.43) (Table 3.1), indicating adult sawflies have an aggregated distribution. The PROC NLIN method of calculation for parameter $b$ indicates only males (1.44) and the total sampled population (1.45) have $b$ values significantly greater than one (Table 3.1). The $b$ value for females, 1.11, was not significantly different from one, indicating their distribution is random.

When sampled with sweep nets, adults have an aggregated distribution (Table 3.2). All log transformation method estimations of parameter $b$ are significantly greater than one with $b$ values ranging from 1.21-2.00. The PROC NLIN estimations have four estimates of parameter $b$ that are not significantly greater than one, the total sample population at McGrew in 2015 (1.25), males and the total sample population at Gurley in 2014 (1.21, 1.15), and males using both years of data at Gurley (1.09).

A significant interaction of sample population and method of estimating parameter $a$ was detected ($f_{2,33} = 3.85, p = 0.032$). Examining the simple effects shows the PROC NLIN method estimated a $0.937 \pm 0.4$ larger $a$ value than the log transformation method ($t_{33} = -2.37, p = 0.024$). There were no differences between the methods for females ($t_{33} = 1.56, p = 0.13$) or the total sample population ($t_{33} = -0.48, p = 0.64$). A significant interaction between sample population and method of estimating parameter $b$ was detected ($f_{2,33} = 8.3, p = 0.0012$). Looking at the simple effects, the methods of estimation are significantly different when estimating $b$ for females ($t_{33} = -6.05, p < 0.0001$). The log transformation method estimates $b$ for the females as $1.40 \pm 0.15$, compared to the PROC NLIN estimate of $2.55 \pm 0.15$. No differences were found
between the method of estimation for males \(t_{33} = -0.6, p = 0.55\) or the total sample population \(t_{33} = -1.65, p = 0.1\).

For larval sampling, the PROC NLIN estimation of parameter \(b\) was 2.14, and this value was significantly greater than one \(t_{13} = 3.95, p < 0.001\). The PROC NLIN method indicates the distribution of the larvae is aggregated. The log transformation estimation of parameter \(b\) for the larvae sampled was 1.61, but this was not significantly different from one \(t_{13} = 1.52, p = 0.08\).

The sampling dates used for designing a sampling plan to predict larval infestation rates from sampled adults were May 26th and 28th at McGrew, June 3rd and 5th at Gurley, June 6th and 8th at Hemingford. These dates coincide with early wheat heading, head emergence to soft dough, at each field. These dates also had the greatest densities of adults sampled, on average, 22.01 ± 1.44 sawflies per 20 sweeps. Using these data, parameters \(a\) and \(b\) of Taylor’s Power Law were 0.386 and 1.80, respectively. These values were estimated using the log transformation method. When sampling adult sawflies during this time, five samples are required to maintain a 20% precision level.

Sawflies sampled at the field edge during early wheat heading were significantly correlated to the larval infestation at all distances, \(r\)-values of 0.35-0.68 \(p < 0.0001\). In building the regression equation for this relationship, the analysis of variance of Type I fixed effects indicated that all terms needed to be included in the model to use total sawflies sampled to predict the number of larvae per row meter (Table 3.3) The lack of fit term was not significant \(f_{4,401} = 1.02, p = 0.39\), indicating the model adequately describes the data. Five regression equations were generated, one for each sampling
distance (Table 3.4). At each distance, predicted values were significantly correlated with observed values ($r = 0.64-0.95$, $p < 0.0001$). Overall, the predicted values are significantly correlated with the observed values ($r = 0.91$, $p < 0.0001$) (Figure 3.1). Correlation coefficients of sawflies sampled at the field edge are significantly correlated with the predicted larval density at all distances with $r$-values of $0.49-0.66$ ($p < 0.0001$).

**Discussion**

Using both methods of estimating parameter $b$ of Taylor’s Power Law, the adult wheat stem sawfly has an aggregated distribution within Nebraska winter wheat fields, $b$ having a range of $1.15-3.99$. While only the female $b$ values differed between the two methods of estimating Taylor’s Power Law, there are four instances where the two methods of estimation disagree on the distribution. The NLIN method indicates the distribution is random, but the log transformation method indicates it is aggregated. Wilson (1994) found that it is possible for parameter $b$ to be greater than one, and for the distribution to not be aggregated. This can occur when parameter $a$ and $b$ values are greater than one (Wilson 1994). All four estimations, using the NLIN method, have $a$ and $b$ values greater than one.

A similar result occurred in describing the distribution of stink bug species (Hemiptera: Pentatomidae) in wheat using multiple indices of aggregation (Reay-Jones 2010). Using more than one index of aggregation may help to detect more differences; however, choosing one index for further use is difficult, as every index has its limitations (Taylor 1984). Like the multiple methods used to calculate Taylor’s Power Law presented here, the use of multiple indices of aggregation creates differences in what the distribution of the stink bug was described as. There are four times when Iwao’s
regression indicates a non-random distribution, but Taylor’s Power Law does not (Reay-Jones 2010). However, using multiple indices of aggregation leaves the researcher to explain any differences that may occur. It is also up to the researcher to justify why they may have decided to use one index. A similar situation occurs when using different methods to calculate the same equation.

While there are limited statistical differences between the $a$ and $b$ estimates from each method of estimation, there is a practical difference that exists. Using the sweep net data collected for total sawflies sampled during early wheat heading in 2015, the log transformation method estimates parameters $a$ and $b$ to be 0.62 and 1.53. The PROC NLIN method estimates parameters $a$ and $b$ to be 0.0003 and 3.77. When calculating the minimum sample size needed to maintain a 0.2 precision level, the log transformation method results in five samples being needed while the PROC NLIN method suggests only one is required. From a practicality standpoint, a sample size of one does not provide a realistic sense of the population in the field, especially given the aggregated nature of the sawfly’s distribution. Without a more in depth investigation into the calculations themselves, it is difficult to suggest one method over the other. It is known that data transformations can introduce a bias into the data and alter error variance, particularly when used to linearize data sets (Schabenberger and Pierce 2002). The nonlinear calculations of parameters $a$ and $b$ limit the introduction of bias as done by transformations, but they require more advanced statistical software to calculate. Since the values generated by the log transformation offers a more conservative, but still a relatively small sample size, they will be used for designing a sampling plan.
When sampled by sweep net, all three sample populations, using all sampling events from all fields, show an aggregated distribution regardless the method used to estimate the parameters of Taylor’s Power Law. Sticky traps have a similar trend except for the female distribution as estimated by the PROC NLIN method. Sticky traps show a bias towards random distributions compared to the distributions determined from sweep net samples. The difference between the two methods likely comes from the efficacy of sampling method used. The passive nature of the sticky trap relies on the sawfly to land on the trap or be blown onto it. While many sawflies may have encountered the sticky traps, males appear more likely to land on them. Given the aggregation behavior observed in male sawflies (Cossé et al. 2002), the presence of males may lead to more males landing on the trap. Similarly, male *Pholetesor ornigis* Weed wasps (Hymenoptera: Braconidae), a parasitoid of the spotted tentiform leaminer, *Phyllonorcyter blancardella* (Fabr.) (Lepidoptera: Gracillariidae), were caught more frequently on sticky traps despite an equal number of males and females emerging (Trimble and Brach 1985). Female sawfly movement could be more influenced by plant volatiles within the wheat canopy.

The distribution of sawfly larvae reported in this paper is best described as aggregated. The log transformation method is approaching significance, but the variability prevents estimate from being significant. The $b$ value is $1.60 \pm 0.39$. However, the distribution of sawfly larvae and eggs has been previously described as aggregated (Nansen et al. 2005a). The larvae of the European wheat stem sawfly, *Cephus pygmaeus* L. (Hymenoptera: Cephidae), also have an aggregated distribution, even at low densities (Filipy et al. 1985). Nansen et al. (2005a) only sampled one wheat stem per sampling
location. This allowed for 132-187 samples per field, with 11 samples for each distance, with 12-17 sampling distances depending on the field (Nansen et al. 2005a). While Nansen et al. (2005a) calculated distribution using the software package SADIE, the greater number of sampling points would increase the precision of the estimates when using an index of aggregation. However, for an index of aggregation, like Taylor’s Power Law, more than one stem would need to be sampled to better capture changes in density. Up to four larvae were found in a wheat stem, but this only happened in 4% of stems sampled on that day (Nansen et al. 2005a).

**Sampling Plan**

Sampling plans that use adult counts as an indicator of larval densities have been developed for other pests, such as the corn rootworm, *Diabrotica* spp., in continuous corn and corn-soybean rotations. Adults rootworm beetles caught on unbaited sticky traps during the latter half of August were correlated with subsequent larval damage the next year in continuous corn, accounting for 26% of the total variation in damage (Hein and Tollefson 1985). A correlation between adult rootworms caught during late July to mid-August in soybeans and damage to corn planted the next year was observed, with sampled adults accounting for 27% of the variation in the damage caused by the larvae (O’Neal et al. 2001). Using the data gathered here, a sampling plan was developed that allows the prediction of larval infestation rates based on the number of adult sawflies sampled.

To begin this sampling plan, take five, 20-sweep samples, along the field edge at the wheat fallow border. The sampler will move in the direction of the primary axis of planting. These samples should be taken during early wheat heading. Count the sawflies
to get a sample average. Next take an estimate of stems per meter of row. These two parameters can be used to predict the infestation rates, larvae per row meter, up to 40-m into the field (Table 3.4). The resulting number is on the natural log scale and needs to be back-transformed to get an estimate on the data scale. This number scale can be compared to the stem density estimate to gain a better understanding of how infested the wheat is. From there, it is up to the grower to decide if the wheat is infested enough to warrant management action, as economic thresholds have not been developed for sawfly management.

Economic thresholds are used in both sampling plans for corn rootworm for when management action should be taken (Hein and Tollefson 1985, O’Neal et al. 2001). Without a better understanding of the economics of sawfly infestations, it is hard to set an economic threshold. A 20% infestation level was the threshold used by Nansen et al. (2005c), but that threshold is based on the minimum sample size needed to maintain their precision level. Although economic thresholds have not been developed, the economics of the loss caused by wheat stem sawflies has been studied. Using grain prices from 2005, Özberk et al. (2005) found when 10-15% stems were cut by *C. pygmaeus*, a loss of $68.60 ha\(^{-1}\) for bread wheat was incurred. Assuming 10% of stems are cut, *C. cinctus* infestations result in a loss of $11.13 ha\(^{-1}\) using 2002 grain prices (Beres et al. 2007). However, even with an economic threshold, no immediate management tactics, such as applying an insecticide, are available. Swathing, to increase harvest recovery, would be the most beneficial management action that could be taken during the growing season. Swathing to control sawfly larvae requires cutting when kernel moisture content is above 50%; however, this results in considerable yield loss potential (Holmes and Peterson
Lower thresholds may be necessary to get ahead of sawfly populations for management, as most management actions cannot be taken until the following growing season. Low levels of infestation one year can lead to economic infestations the next (Holmes 1982).

The plan presented here is faster than the current larval sampling plan. It takes approximately 9.5 hours to split the stems required for the larval sampling plan (Nansen et al. 2005c). Counting adults from one, 20-sweep, sweep net sample takes about four minutes. The total time for sample processing for the proposed adult sampling plan is approximately a half an hour. In sample processing alone, a 93% reduction in time is gained by sampling adults. This plan could be further improved by sampling farther into the wheat field, as the larval plan allows for the prediction of infestation rates up to 200 m into the field. An additional improvement could be to reduce the effort needed to conduct the sampling plan by excluding the stem density estimate. However, the analysis here proved that stem density has a significant effect on the infestation level. When creating the equations without the stem density estimates, the correlation coefficients between the observed and predicted values range from 0.33 to 0.87. Compared to the equations generated with the stem density estimates that have correlation coefficients ranging from 0.64 to 0.95. Additionally, without the stem density estimate, quadratic and cubic terms are needed for the equations. Stem density had a significant effect on larval infestation in Montana wheat fields as well (Nansen et al. 2005c). Stem density will always play a role in determining the sawfly population as, ultimately, the total number of available stems limits the population size (Holmes 1982).
As the wheat stem sawfly continues to affect more wheat growing regions, early detection of this insect pest is important since most management options cannot be taken until the following growing season. By establishing the relationship between adult densities and larval densities, sampling adult sawflies can be used as a tool to help make management decisions. With a better understanding of the economic impact of sawfly infestations, this sampling plan could be further improved.
References Cited


Hein, G. L., and J. J. Tollefson. 1985. Use of the Pherocon AM trap as a scouting tool for predicting damage by corn rootworm (Coleoptera: Chrysomelidae) larvae. J. Econ. Entomol. 78:200-203.


### Tables and Figures

**Table 3.1 Calculated parameter $b$ values for Taylor’s Power Law using log transformations and PROC NLIN for sawflies collected with sticky traps in 2014.**

<table>
<thead>
<tr>
<th>Field</th>
<th>n</th>
<th>Log Transformation</th>
<th>PROC NLIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Total</td>
<td>Female</td>
</tr>
<tr>
<td>McGrew</td>
<td>20</td>
<td>1.24*</td>
<td>1.05</td>
</tr>
<tr>
<td>Gurley</td>
<td>20</td>
<td>1.35*</td>
<td>0.90</td>
</tr>
<tr>
<td>Hemingford</td>
<td>30</td>
<td>1.44*</td>
<td>1.12*</td>
</tr>
<tr>
<td>All Fields</td>
<td>70</td>
<td>1.43*</td>
<td>1.12*</td>
</tr>
</tbody>
</table>

*Significantly different from one * $p < 0.05$
Table 3.2 Parameter $a$ and $b$ of Taylor’s Power Law calculated using log transformations and PROC NLIN for sweep net sampled sawflies.

<table>
<thead>
<tr>
<th>Year</th>
<th>Date</th>
<th>n</th>
<th>Log transformation</th>
<th>PROC NLIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total $b$ $a$</td>
<td>Total $b$ $a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female $b$ $a$</td>
<td>Female $b$ $a$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male $b$ $a$</td>
<td>Male $b$ $a$</td>
</tr>
<tr>
<td>McGrew</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>45</td>
<td>1.41*</td>
<td>0.74</td>
<td>1.34*</td>
</tr>
<tr>
<td>2015</td>
<td>35</td>
<td>1.45*</td>
<td>0.93</td>
<td>1.21*</td>
</tr>
<tr>
<td>Both</td>
<td>80</td>
<td>1.38*</td>
<td>0.90</td>
<td>1.21*</td>
</tr>
<tr>
<td>Gurley</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>40</td>
<td>1.53*</td>
<td>0.61</td>
<td>1.43*</td>
</tr>
<tr>
<td>2015</td>
<td>35</td>
<td>1.50*</td>
<td>0.82</td>
<td>1.52*</td>
</tr>
<tr>
<td>Both</td>
<td>75</td>
<td>1.49*</td>
<td>0.74</td>
<td>1.37*</td>
</tr>
<tr>
<td>Hemingford</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>50</td>
<td>1.73*</td>
<td>0.48</td>
<td>1.53*</td>
</tr>
<tr>
<td>2015</td>
<td>35</td>
<td>1.58*</td>
<td>0.80</td>
<td>1.40*</td>
</tr>
<tr>
<td>Both</td>
<td>85</td>
<td>1.62*</td>
<td>0.69</td>
<td>1.48*</td>
</tr>
<tr>
<td>All Fields</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>135</td>
<td>1.54*</td>
<td>0.53</td>
<td>1.46*</td>
</tr>
<tr>
<td>2015</td>
<td>105</td>
<td>1.52*</td>
<td>0.84</td>
<td>1.39*</td>
</tr>
<tr>
<td>Both</td>
<td>240</td>
<td>1.53*</td>
<td>0.73</td>
<td>1.42*</td>
</tr>
</tbody>
</table>

Significantly different from one * $p < 0.05$
Table 3.3 Analysis of variance for Type I fixed effects on total sawflies sampled per 20 sweeps during early wheat heading, stems per row meter, and distance sampled using larvae per row meter as the response variable. (Distance = 0, 10, 20, 30, and 40m into the wheat field)

<table>
<thead>
<tr>
<th>Effect</th>
<th>Num DF</th>
<th>Den DF</th>
<th>F Value</th>
<th>Pr &gt; F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawflies (distance)</td>
<td>5</td>
<td>401</td>
<td>84.54</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Stem density (distance)</td>
<td>5</td>
<td>401</td>
<td>95.84</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Sawflies*stem density (distance)</td>
<td>5</td>
<td>401</td>
<td>7.87</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Lack of fit</td>
<td>4</td>
<td>401</td>
<td>1.02</td>
<td>0.3941</td>
</tr>
</tbody>
</table>
Table 3.4 Regression equations, on the natural log scale, for predicting larval infestation rates (Y), larvae per row meter, using total adult sawflies sampled per 20 sweeps during early wheat heading (x), stems per row meter (z), and distance sampled into the wheat field. Correlation coefficients (r) between the observed and predicted value of larvae per row meter.

<table>
<thead>
<tr>
<th>Distance (m)</th>
<th>Equations</th>
<th>Correlation</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( Y = 3.328 + 0.0067x + 0.0093z - 0.00004xz )</td>
<td>0.945*</td>
<td>94</td>
</tr>
<tr>
<td>10</td>
<td>( Y = 3.328 + 0.0247x + 0.0071z - 0.00016xz )</td>
<td>0.640*</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>( Y = 3.328 + 0.0066x + 0.0054z - 0.00002xz )</td>
<td>0.923*</td>
<td>94</td>
</tr>
<tr>
<td>30</td>
<td>( Y = 3.328 + 0.0044x + 0.0039z + 0.00003xz )</td>
<td>0.782*</td>
<td>94</td>
</tr>
<tr>
<td>40</td>
<td>( Y = 3.328 + 0.0092x + 0.0032z + 0.00004xz )</td>
<td>0.818*</td>
<td>94</td>
</tr>
</tbody>
</table>

Significantly correlated *p < 0.0001
Figure 3.1 Predicted values plotted against observed values of larval infestation rates using sweep net samples of total sawflies as the predictor. The line is where predicted and observed values are equal.