Pest Management of Wheat Stem Maggot (Diptera: Chloropidae) and Wheat Stem Sawfly (Hymenoptera: Cephidae) Using Insecticides in Spring Wheat

Janet J. Knodel, Patrick B. Beauzay, Eric D. Eriksmoen, and Jeremy D. Pederson


ABSTRACT The effectiveness and timing of foliar insecticides and insecticidal seed treatments were evaluated for pest management of the wheat stem maggot, *Meromyza americana* Fitch (Diptera: Chloropidae), and the wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), in hard red spring wheat in North Dakota. Treatments included: 1) untreated check, 2) foliar application of lambda-cyhalothrin at the 4–6 leaf stage, 3) foliar application of lambda-cyhalothrin at the flag-leaf stage, 4) low rate of thiamethoxam seed treatment, 5) high rate of thiamethoxam seed treatment, and 6) low rate of thiamethoxam seed treatment plus a foliar application of lambda-cyhalothrin at the 4–6 leaf stage. A foliar application of lambda-cyhalothrin at either leaf stage significantly reduced the number of white heads caused by wheat stem maggot. The combination of a low rate of thiamethoxam seed treatment plus a foliar application of lambda-cyhalothrin at the 4–6 leaf stage also resulted in a significantly lower number of white heads. However, the low and high rates of thiamethoxam seed treatment alone were not effective at reducing the number of white heads. None of the treatments reduced the percentage of damaged stems from wheat stem sawfly. No yield differences were observed among treatments for either wheat stem maggot or wheat stem sawfly.

KEY WORDS spring wheat, wheat stem maggot, *Meromyza americana*, wheat stem sawfly, *Cephus cinctus*, foliar applied insecticide, insecticide seed treatment, application timing

More than 59.2 million acres (24 million hectares) of wheat (*Tricticum aestivum* L.) are planted annually in the United States, and the crop is valued at 10 billion in U.S. dollars (NASS 2009). North Dakota ranks as one of the top two states in wheat production (hard red spring wheat and durum wheat) with 8.7 million acres (3.5 million hectares) valued at 1.8 billion dollars (ND NASS 2009). There are a number of insects that feed within wheat stems, the most economically important being wheat stem sawfly, *Cephus cinctus* Norton (Hymenoptera: Cephidae), wheat stem maggot, *Meromyza americana* Fitch (Diptera: Chloropidae), Hessian fly, *Mayetiola destructor* (Say) (Diptera: 

1Accepted for publication 22 April 2011.
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Cecidomyiidae), wheat jointworm, *Tetramesa tritici* (Fitch) (Hymenoptera: Eurytomidae), and wheat strawworm, *Tetramesa grandis* (Riley) (Hymenoptera: Eurytomidae) (Morrill 1995). In a recent survey of stem-feeding insect pests of wheat in the northern Great Plains including North Dakota, Shanower & Waters (2006) found that wheat stem sawfly, wheat stem maggot, and Hessian fly were the most commonly encountered insects. Wheat stem sawfly and wheat stem maggot were present in more than one-half of the fields surveyed (Shanower & Waters 2006).

Wheat stem maggot is found throughout the wheat-producing area from eastern North America across the prairie provinces of Canada and south to Mexico, where it is considered an occasional insect pest of wheat (Gilbertson 1925, Morrill 1995, Hesler & Kieckhefer 2000). A survey of stem-infesting insect pests of wheat in eastern Montana, western North Dakota, northwest South Dakota, eastern Wyoming, and western Nebraska indicated that wheat stem maggot infestation levels were low and averaged 3.2% in infested fields (Shanower & Waters 2006). These levels were comparable to the 1–3% infestations reported in eastern South Dakota by Gilbertson (1925), Kieckhefer & Morrill (1970), and Hesler & Kieckhefer (2000). However, recent pest surveys in North Dakota have detected higher levels of wheat stem maggot in wheat. Field scouts recorded the following average infestation levels from 2007 to 2010: 17.0% in 2007, 5.8% in 2008, 4.6% in 2009, and 7.0% in 2010 (JJK, unpublished data).

The principal cultivated crop hosts of wheat stem maggot are wheat (hard red spring and durum), rye (*Secale cereal* L.), and barley (*Hordeum vulgare* L.), with wheat being preferred (Gilbertson 1925). In the spring, larvae pupate and adults emerge in early to mid-June (Kieckhefer 1974, Morrill 1995). After mating, females deposit their eggs on the leaves or stems of host plants. Larvae crawl down beneath the leaf sheath, tunnel into the stem, and feed there (Allen & Painter 1937). Stems become partially severed, causing the developing wheat head to turn white. The heads and terminal stems of infested plants pull out easily due to the internal chewing damage by larvae (Morrill 1991). Adults emerge about midsummer and lay their eggs on wild grasses or volunteer grain, and overwinter in the stems. There are typically two generations a year, but Gilbertson (1925) reported that there may be three generations a year.

Maggot-infested stems produce characteristic white heads, which do not produce kernels (Gilbertson 1925, Allen & Painter 1937). Crop losses based on the number of white heads is usually less than 10% (Kieckhefer & Morrill 1970). Maggots also can infest young tillers before the boot stage, causing affected tillers to abort (Branson et al. 1967). Yield losses from these aborted tillers are difficult to estimate. Literature indicates that there are no control practices available for wheat stem maggots other than crop rotation to non-hosts, late planting date, and natural biological control (Morrill & Keickhefer 1971, Morrill 1991, 1995).

Wheat stem sawfly is a major pest of spring and winter wheat in the northern Great Plains of the United States (Morrill et al. 1992, Weiss & Morrill 1992, Morrill 1995). The resurgence of wheat stem sawfly in Montana, southern Alberta, and southern Saskatchewan, Canada has been attributed to increased use of susceptible cultivars, continuous wheat cropping, conservation tillage practices, and widespread drought in some regions (Kappel & Blodgett 1996, J. Agric. Urban Entomol. Vol. 26, No. 4 (2009).
Beres et al. 2007). In western North Dakota, populations of wheat stem sawfly have also been increasing over the past several years (Knodel et al. 2010).

Adult wheat stem sawflies emerge from mid-June to early July and females lay eggs inside plant stems, primarily during stem elongation (Wallace & McNeal 1966). Larvae emerge from the eggs and feed inside the stems, reducing kernel weight by 5–30% (Seamans et al. 1945, Wallace & McNeal 1966, Holmes 1977). As the crop matures, larvae move to the bases of the stems and cut them to construct a pupation chamber (Holmes 1975). Weakened stems break and the plants lodge, making harvest difficult and adding to yield losses (Weiss & Morrill 1992). Sawfly infestation can also reduce grain protein content (Holmes 1977, Beres et al. 2007). Field infestation levels of 80% have been reported, with yield losses of 20 to 100% being recorded in recent years in North Dakota (Knodel et al. 2010). Annual grain losses caused to wheat by wheat stem sawfly has been estimated to be between $50 and $144 million for the northern Great Plains (Berzonsky et al. 2003, Weaver et al. 2009), with losses between $25 and $70 million being recorded for North Dakota (Knodel et al. 2010).

Some common pest management strategies for the wheat stem sawfly include cultural control, biological control, and host plant resistance. Criddle (1922) reported that spring and fall tillage can kill some overwintering larvae. However, tillage is ineffective unless soil is separated from the bases of stems, which can lead to serious soil erosion (Weiss et al. 1987, Morrill et al. 1993). A late planting date (after May 20) also reduces damage significantly (Jacobson & Farstad 1952, Morrill et al. 1999). However, in temperate regions with short growing seasons, this is not practical for wheat producers. Biological control of wheat stem sawfly has had variable levels of success, and interests in managing cereal stem sawflies using natural enemies has increased (Morrill et al. 1998, Shanower & Hoelmer 2004). However, the preferred pest management strategy for control of wheat stem sawfly is the use of resistant solid-stemmed wheat varieties (Kemp 1934, Berzonsky et al. 2003). Wheat varieties with dense pith within the lumen have increased larval mortality and sustain less damage from cutting (Wallace et al. 1973). Female fecundity is also reduced through the use of solid-stemmed varieties (Holmes & Peterson 1961, 1962, Morrill et al. 2000, Cárcamo et al. 2005). Historically, widespread adoption of resistant varieties has been low, because solid-stemmed varieties have lower yield and protein content in the absence of wheat stem sawfly, and they provide inconsistent control depending on environmental conditions (Holmes 1984, Beres et al. 2009).

Despite research on other pest management strategies of wheat stem maggot and wheat stem sawfly, there is limited publicly available information on the use of insecticides for pest management of either insect pest. The published literature on chemical control of wheat stem maggot and wheat stem sawfly is outdated, and it contains information about insecticides that have been removed by the U.S. Environmental Protection Agency (such as heptachlor and parathion) and are no longer labeled for use in wheat. Most researchers report that systemic and contact insecticides are generally ineffective because wheat stem larvae are well-protected inside the stems (Wallace & McNeal 1966). Therefore, our objective was to evaluate current insecticides registered for wheat that are applied as either a seed treatment or foliar broadcast spray for management of wheat stem maggot and wheat stem sawfly at several locations in western North Dakota. We also assessed two different application timings of foliar insecticides; one at the 4–6
leaf stage when early season herbicides or fungicide may be applied for weed or disease control, and another at the flag-leaf stage when insecticides may be needed for control of other insect pests, such as cereal aphids.

**Materials and Methods**

Combinations of insecticide seed treatments and foliar insecticide applications were evaluated for control of wheat stem maggot and wheat stem sawfly. In 2008, experiments were conducted at the North Dakota State University (NSDU) Agronomy Farm in Fargo, ND, at the Hettinger Research and Extension Center in Hettinger, ND, at the North Central Research and Extension Center in Minot, ND, and at a cooperator site near Makoti, ND. In 2009, experiments were conducted at Fargo, and at cooperator sites near Hettinger and Makoti. The hollow-stemmed hard red spring wheat variety ‘Steele ND’ (Mergoum et al. 2005) was used for all treatments at all locations in 2008 and 2009. The Fargo experiment had no wheat stem maggot present in 2009, and the Hettinger experiment was destroyed by hail before anthesis in 2009. Consequently, Makoti was the only location assessed in 2009.

All experiments were arranged in a randomized complete block design with four replications. Plots at Fargo were 1.25 m wide by 6.1 m long, plots at Hettinger were 1.25 m wide by 7.0 m long, and plots at Minot and Makoti were 1.25 m wide by 5.0 m long. Plots at all locations consisted of seven rows with 18 cm row spacing. Untreated “guard” plots were positioned between treatment plots and on each end of the experiments to prevent spray overlap and to provide untreated wheat for sampling wheat stem maggot and wheat stem sawfly. Seeding rate was 3.95 million live seeds/ha (1.6 million live seeds/acre) at Fargo and 2.96 million live seeds/ha (1.2 million live seeds/acre) at Hettinger, Minot, and Makoti. Seeding rates reflect common commercial seeding rates for these locations. Planting dates were 5 May 2008 at Hettinger, 12 May 2008 at Fargo, 19 May 2008 at Minot and Makoti, and 18 May 2009 at Makoti.

The following treatments were evaluated: 1) untreated check, 2) foliar insecticide at the 4–6 leaf stage, 3) foliar insecticide at the flag-leaf stage, 4) low rate of insecticide seed treatment, 5) high rate of insecticide seed treatment and 6) low rate of insecticide seed treatment plus foliar insecticide at the 4–6 leaf stage. Difenoconazole + mefenoxam (Dividend Extreme®, Syngenta Crop Protection, Greensboro, NC) fungicide was applied to all treatments as a seed treatment [15 g ai/100 kg (2 fl oz product/cwt)] to prevent early season fungal diseases. Thiamethoxam (Cruiser 5FS®, Syngenta Crop Protection, Greensboro, NC), a neonicotinoid insecticide, was used as the insecticide seed treatment. All seed treatments were applied commercially. The low-rate seed treatment was 39 g ai/100 kg (1 fl oz product/cwt) and the high-rate seed treatment was 50 g ai/100 kg (1.33 fl oz product/cwt). Thiamethoxam is a second generation neonicotinoid that has systemic properties when absorbed by the root system and the active ingredient is translocated to actively growing parts of the plants (Elbert et al. 2008, Maienfisch et al. 2001). Lambda-cyhalothrin (Warrior® with Zeon Technology™, Syngenta Crop Protection, Greensboro, NC), a pyrethroid insecticide, was used for foliar insecticide applications at a rate of 22 g ai/ha (2.56 fl oz product/acre). At Fargo, foliar applications were made with a CO2 pressurized backpack sprayer using TeeJet 80015 nozzles (TeeJet Technologies,
Wheaton, IL) at 275.8 KPa (40 psi) and a spray volume of 187.1 L/ha (20 gal/acre). At Hettinger, foliar applications were made with a tractor mounted CO₂ pressurized sprayer using PK-01E80 nozzles at 206.9 KPa (30 psi) and a spray volume of 187.1 L/ha (20 gal/acre). At Minot and Makoti, foliar applications were made with a CO₂ pressurized backpack sprayer using TeeJet 8001 nozzles at 275.8 KPa (40 psi) and a spray volume of 93.6 L/ha (10 gal/acre). Dates of foliar insecticide application for the 4–6 leaf and flag-leaf timings are listed in Table 1.

Wheat stem maggot and wheat stem sawfly adults were sampled biweekly from early June through the end of August in 2008 and 2009 by combining 20 sweeps at five sites within the guard plots. A standard 38.1 cm (15 in) sweep net was used, and each sweep encompassed 180 degrees. The total number of each species for each sampling date was recorded. Sampling for wheat stem maggot adults was conducted at Fargo and Hettinger in 2008, and at Makoti in 2008 and 2009. Sampling for wheat stem sawfly adults was conducted at Hettinger and at Makoti in 2008 and 2009. There was no sampling for wheat stem maggot or wheat stem sawfly at Minot in 2008.

Incidence of wheat stem maggot injury was determined by recording the number of wheat stem maggot-induced white heads per plot. White heads were counted at each location within one week after anthesis was complete. White head count data were converted to number of white heads per m² to standardize counts across locations with different plot sizes.

Wheat stem sawfly damage was assessed by splitting 25 randomly selected central stems from each plot sample and counting the number of larvae in the lower four internodes of each stem. A stem was considered damaged if one larva was found in any of the lower four internodes. The total number of damaged stems per 25 stems was recorded and converted to percentage of damaged stems. Wheat plants were collected from one meter of row in each plot two weeks before harvest at each location. Samples were brought back to NDSU and stored in a cool, dry environment until larval counts could be made.

All plots were harvested with a small-plot combine, and grain yield was determined. Grain yield was adjusted to 11.5 percent grain moisture (Hellevang 1995). Grain yield, wheat stem maggot white head count data, and wheat stem sawfly damaged stem data were subjected to analysis of variance (PROC GLM, SAS Institute 2008). Treatment means were separated using Tukey’s HSD test at $P < 0.05$. All data were tested for normality using the Kolmogorov-Smirnov test in PROC UNIVARIATE, and for homogeneity of variance using O’Brien’s test (O’Brien 1979) in PROC GLM. Wheat stem maggot white head count data that did not show a normal distribution were transformed using the square root transformation. Wheat stem sawfly damaged stem data that did not show a normal distribution were transformed using the arcsine square root transformation. Wheat stem maggot and wheat stem sawfly voucher specimens were deposited in the North Dakota Insect Reference Collection, Entomology Department, NDSU, Fargo, ND.

**Results**

At Hettinger in 2008, first generation wheat stem maggot adults peaked in early June and were present throughout the month (Table 1). Sampling on 9 and 12 June was hampered by windy conditions, resulting in zero counts for those
Table 1. Dates of insecticide spray applications of lambda-cyhalothrin, first emergence and peak emergence of wheat stem maggot and wheat stem sawfly, and cumulative number of adults captured in sweep net samples per season in 2008 and 2009.

<table>
<thead>
<tr>
<th>Location</th>
<th>Year</th>
<th>Spray Dates</th>
<th>Wheat stem maggot</th>
<th>Wheat stem sawfly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4–6 leaf</td>
<td>Flag-leaf</td>
<td>First emergence</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fargo</td>
<td>2008</td>
<td>18 June</td>
<td>27 June</td>
<td>12 June</td>
</tr>
<tr>
<td>Hettinger</td>
<td>2008</td>
<td>16 June</td>
<td>25 June</td>
<td>4 June</td>
</tr>
<tr>
<td>Minot</td>
<td>2008</td>
<td>29 June</td>
<td>9 July</td>
<td>—</td>
</tr>
<tr>
<td>Makoti</td>
<td>2008</td>
<td>25 June</td>
<td>3 July</td>
<td>19 June</td>
</tr>
<tr>
<td>Makoti</td>
<td>2009</td>
<td>18 June</td>
<td>8 July</td>
<td>19 June</td>
</tr>
</tbody>
</table>

1In 2009, the Hettinger site was destroyed by hail, and Fargo had no wheat stem maggots. No sampling was conducted at Minot in 2008.
dates. All foliar insecticide treatments were applied when adults were present in the experiment. At Fargo in 2008, adults were first detected on 12 June; they peaked on 16 June, and were observed in the experiment through 26 June (Table 1). All foliar insecticide treatments were applied when adults were present in the experiment. The peak emergence of adults occurred between the 4–6 leaf foliar and the flag-leaf insecticide application. At Makoti in 2008, adults were first detected on 19 June and peaked on 30 June (Table 1). All foliar insecticide treatments were applied when adults were present in the experiment. The peak emergence of adults occurred between the 4–6 leaf foliar and the flag-leaf insecticide application. At Makoti in 2009, adults were first detected on 19 June and peaked on 25 June. Although sampling continued until 10 August, no adult wheat stem maggots were collected in sweep samples from the end of June through August. All foliar insecticide treatments were applied when adults were present in the experiment. The peak emergence of adults occurred between the 4–6 leaf foliar and the flag-leaf insecticide application. The cumulative number of adult flies captured in the sweep-net samples per season was low, and ranged from only three adults at Makoti in 2009 to 28 at Hettinger in 2008 (Table 1).

At Fargo in 2008, insecticide treatment had a significant effect on white heads per m$^2$ ($F = 19.22; \text{df} = 5, 15; P < 0.0001$) (Table 2). The 4–6 leaf foliar treatment, the flag-leaf foliar treatment, and the low seed-treatment rate + 4–6 leaf foliar treatment had significantly fewer white heads per m$^2$ than the untreated check and the low seed-treatment rate. The flag-leaf foliar treatment was not significantly different from the high seed-treatment rate. There were no significant differences among the foliar treatments. The low and high rates of seed treatments were not significantly different from the untreated check, and there was no significant difference between the low and high seed-treatment rates.

At Hettinger in 2008, insecticide treatment had a significant effect on white heads per m$^2$ ($F = 22.19; \text{df} = 5, 15; P < 0.0001$) (Table 2). The 4–6 leaf foliar treatment, the flag-leaf foliar treatment, and the low-rate seed treatment + 4–6 leaf foliar treatment had significantly fewer white heads per m$^2$ than the untreated check. The flag-leaf foliar treatment was not significantly different from the low seed-treatment rate. There were no significant differences among the foliar treatments. The low and high rates of seed treatments were not significantly different from the untreated check, and there was no significant difference between the low and high seed-treatment rates.

At Minot in 2008, insecticide treatment had a significant effect on white heads per m$^2$ ($F = 25.72; \text{df} = 5, 15; P < 0.0001$) (Table 2). The 4–6 leaf foliar treatment, the flag-leaf foliar treatment, and the low seed-treatment rate + 4–6 leaf foliar treatment had significantly fewer white heads per m$^2$ than the untreated check and the low and high seed-treatment rates. There were no significant differences among the foliar treatments. The low and high rates of seed treatments were not significantly different from the untreated check, and there was no significant difference between the low and high seed-treatment rates.

At Makoti in 2008, insecticide treatment had a significant effect on white heads per m$^2$ ($F = 12.76; \text{df} = 5, 15; P < 0.0001$) (Table 2). The 4–6 leaf foliar treatment, the flag-leaf foliar treatment, and the low seed-treatment rate + 4–6 leaf foliar treatment had significantly fewer white heads per m$^2$ than the
Table 2. Treatment means (mean ± SE) for wheat stem maggot white heads per m² and wheat stem sawfly percentage of damaged stems at each location in 2008 and 2009.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Wheat stem maggot – white heads/m²</th>
<th>Wheat stem sawfly – % damaged stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>Untreated check</td>
<td>2.9 ± 0.3a</td>
<td>0.8 ± 0.2a</td>
</tr>
<tr>
<td>Low seed treatment</td>
<td>2.7 ± 0.3a</td>
<td>0.5 ± 0.06ab</td>
</tr>
<tr>
<td>High seed treatment</td>
<td>1.9 ± 0.4ab</td>
<td>0.9 ± 0.2a</td>
</tr>
<tr>
<td>4–6 leaf foliar treatment</td>
<td>0.4 ± 0.3c</td>
<td>0.01 ± 0.01c</td>
</tr>
<tr>
<td>Flag-leaf foliar treatment</td>
<td>0.6 ± 0.2bc</td>
<td>0.2 ± 0.1bc</td>
</tr>
<tr>
<td>Low seed treatment + 4–6 leaf foliar treatment</td>
<td>0.03 ± 0.03c</td>
<td>0.01 ± 0.01c</td>
</tr>
</tbody>
</table>

Means within a column followed by the same letter are not significantly different (Tukey’s HSD, $P < 0.05$).

¹Data transformed using square root transformation prior to analysis. Actual means are presented in the table.

²Data transformed using arcsine square root transformation prior to analysis. Actual means are presented in the table.
untreated check and the low and high seed-treatment rates. There were no significant differences among the foliar treatments. The low and high seed-treatment rates were not significantly different from the untreated check, and there was no significant difference between the low and high seed-treatment rates.

At Makoti in 2009, insecticide treatment had a significant effect on white heads per m$^2$ ($F = 4.18; \text{df} = 5, 15; P = 0.014$) (Table 2). The 4–6 leaf foliar treatment, the flag-leaf foliar treatment, and the low seed-treatment rate + 4–6 leaf foliar treatment had significantly fewer white heads per m$^2$ than the untreated check, but were not significantly different from the low or high seed-treatment rates. There were no significant differences among the foliar treatments. Both seed-treatment rates were not significantly different from the untreated check.

Wheat stem sawfly was present at Hettinger in 2008 and at Makoti in 2008 and 2009. At Hettinger in 2008, wheat stem sawfly adults were first detected in the experiment on 30 June; they peaked on 3 July, and were present through 10 July (Table 1). The flag-leaf foliar insecticide treatment was applied at the beginning of adult emergence. At Makoti in 2008, adults were first detected in the experiment on 26 June; they peaked on 9 July, and were present through 21 July (Table 1). The 4–6 leaf foliar insecticide treatments were applied at the beginning of adult emergence, and the flag-leaf foliar insecticide treatment was applied six days before peak adult flight. At Makoti in 2009, adults were first detected in the experiment on 25 June; they peaked on 4 July, and were present through 23 July (Table 1). The 4–6 leaf foliar insecticide treatments were applied one week before adult emergence, and the flag-leaf foliar insecticide treatment was applied four days after peak adult flight. The cumulative number of adult wheat stem sawflies captured in the sweep net samples per season varied by location and year, and ranged from a low of 49 adults at Hettinger in 2008 to 1277 adults at Makoti in 2009 (Table 1).

There were no significant differences for the percentage of damaged stems by wheat stem sawfly among insecticide treatments at Hettinger in 2008 ($F = 0.28; \text{df} = 5, 15; P = 0.9143$), at Makoti in 2008 ($F = 1.18; \text{df} = 5, 15; P = 0.3647$), or at Makoti in 2009 ($F = 1.74; \text{df} = 5, 15; P = 0.1861$) (Table 2).

At Fargo in 2008, there were no significant differences for grain yield among all treatments ($F = 1.37; \text{df} = 5, 15; P = 0.2907$) (Table 3). At Hettinger in 2008, there were significant differences among treatments for grain yield ($F = 3.35; \text{df} = 5, 15; P = 0.0314$) (Table 3). The 4–6 leaf foliar treatment had a significantly lower grain yield than the low seed-treatment rate + 4–6 leaf foliar treatment. The high seed-treatment rate had a significantly lower grain yield than the untreated check and other insecticide treatments except for the 4–6 leaf foliar treatment. The Hettinger location suffered severe drought and heat stress in 2008. Differences in grain yield at Hettinger in 2008 are likely due to these effects. At Minot in 2008, there were no significant differences for grain yield among all treatments ($F = 2.23; \text{df} = 5, 15; P = 0.1051$) (Table 3). At Makoti in 2008, there were no significant differences for grain yield among treatments ($F = 0.10; \text{df} = 5, 15; P = 0.9914$) (Table 3). At Makoti in 2009, there were no significant differences for grain yield among all treatments ($F = 0.29; \text{df} = 5, 15; P = 0.9131$) (Table 3).
Table 3. Treatment means for grain yield (mean ± SE) in kg/ha and bu/acre at all locations in 2008 and 2009.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fargo</td>
<td>Hettinger REC</td>
</tr>
<tr>
<td>Grain yield (kg/ha)</td>
<td>5421 ± 233a</td>
<td>1286 ± 62ab</td>
</tr>
<tr>
<td>Grain yield (bu/acre)</td>
<td>80.5 ± 3.5a</td>
<td>19.1 ± 0.9ab</td>
</tr>
<tr>
<td>Low seed treatment</td>
<td>5037 ± 311a</td>
<td>1313 ± 34ab</td>
</tr>
<tr>
<td>High seed treatment</td>
<td>4988 ± 285a</td>
<td>1150 ± 34c</td>
</tr>
<tr>
<td>4–6 leaf foliar treatment</td>
<td>5310 ± 384a</td>
<td>1209 ± 58bc</td>
</tr>
<tr>
<td>Flag-leaf foliar treatment</td>
<td>5548 ± 81a</td>
<td>1325 ± 50ab</td>
</tr>
<tr>
<td>Low seed treatment + 4–6 leaf foliar treatment</td>
<td>5078 ± 215a</td>
<td>1356 ± 60a</td>
</tr>
</tbody>
</table>

Means within a column followed by the same letter are not significantly different (Tukey’s HSD, P < 0.05).
Morill (1991, 1995) and Gilbertson (1925) reported that the primary pest management strategies for wheat stem maggot include crop rotation with a non-host, late planting date, and biological control with parasitoids. Literature indicates that chemical control practices are not available or provide minimal control of wheat stem maggot (Gilbertson 1925, Morrill 1991).

Results of our insecticide study indicated that the foliar applications of a pyrethroid (lambda-cyhalothrin) applied at the early (4–6 leaf stage) or late (flag-leaf stage) spray timing effectively suppressed white head damage caused by wheat stem maggot. However, wheat stem maggot populations were not high enough (<4% white heads) to cause detectable yield loss at any location sampled in 2008 or 2009. The peak emergence of adults typically occurred between the 4–6 leaf foliar and the flag-leaf insecticide application of lambda-cyhalothrin. Because larvae hatch from eggs laid on the leaves and stems and then crawl and chew into the stems (Allen & Painter 1937), they were probably sprayed directly or exposed to residual foliar insecticide on wheat leaves. Because lambda-cyhalothrin insecticide has activity as a contact and stomach poison, and residual toxicity of about 7–21 days (Yu 2008), foliar applications of this insecticide should kill both adult flies and larvae that are exposed to it. Although thiamethoxam is systemic (Maienfisch et al. 2001, Elbert et al. 2008), the low and high rates of thiamethoxam were not effective in reducing the number of white heads per m², except when the foliar application of lambda-cyhalothrin was included in the treatment. The residual of thiamethoxam is typically 30 to 40 days depending on the insect, rate, and crop (Maienfisch et al. 2001). On spring wheat, adult flies lay eggs during late June, and larvae hatch from the eggs within an average of 6.8 days and then tunnel into the stem (Allen & Painter 1937). Because larvae are active about six weeks after planting, the residual of thiamethoxam was probably not lethal enough for stem-mining larvae. This research represents the first publicly available paper on an effective foliar-applied pyrethroid insecticide against wheat stem maggot, and two efficacious application timings using crop staging. However, wheat stem maggot populations are typically low in wheat and the economic value of reducing such low numbers with insecticide will not be justified in most cases. Further research is needed to develop a sampling protocol, an economic injury level, and an economic threshold for wheat stem maggot based on adult counts, which would help determine the need for insecticide. In addition, there is no degree-day model available for predicting the emergence of wheat stem maggot, which would help time sampling.

For wheat stem sawfly, there are several old publications that contain outdated chemical control information. Wallace (1962) tested 19 insecticides for control of wheat stem sawfly as in-furrow and foliar broadcast treatments and directed control at the larvae within the wheat stem. However, Wallace (1962) found that only granular heptachlor as an in-furrow treatment significantly reduced wheat stem sawfly damage. Holmes & Peterson (1963) further studied heptachlor and found heptachlor was effective only in the lower internodes and required light infestations of wheat stem sawfly to be effective in reducing populations. Under heavy infestations of wheat stem sawfly, Holmes & Peterson (1963) found little or no control from heptachlor. Parathion was reported as providing good control against wheat stem sawfly (Holmes & Hurtig 1952).
Munro et al. (1949) tested six insecticidal dusts, chlordane, DDT, toxaphene, parathion, gamma benzene heaxchloride (BHC), and DDD, and found that none of them produced satisfactory control of wheat stem sawfly.

Although we tested two new chemistries of insecticides that have unique modes of action against insect pests, our results indicated that wheat stem sawfly was not effectively controlled with either the low or high rates of thiamethoxam seed treatment or the foliar applications of lambda-cyhalothrin, regardless of application timing. Adult wheat stem sawflies prefer to oviposit into the stems of spring wheat during stem elongation (Criddle 1923), which typically occurs about 60–70 days after planting. Because the residual toxicity of thiamethoxam is less than 30–40 days depending on the insect, rate and crop (Maienfisch et al. 2001, Elbert et al. 2008), wheat plants probably did not contain a high enough residual toxicity level to kill immature stages (eggs and larvae) of wheat stem sawfly. Other possible reasons why insecticides are ineffective for pest management of wheat stem sawfly include: 1) the emergence period of adults is long (up to one month); 2) the short life span of adult wheat stem sawflies makes it difficult to target insecticide application(s) for adults to prevent oviposition; 3) adults spend little time feeding or imbibing water (Wallace & McNeal 1966), which may minimize oral exposure to insecticides; and 4) eggs, larvae, and pupae are protected within the plant, making them inaccessible to foliar insecticides (Weaver et al. 2009). Regardless of the new insecticide chemistries tested, these results continue to support previous research findings that insecticide control is ineffective and is not a recommended pest management strategy for wheat stem sawfly. Furthermore, crop staging was not useful for timing of insecticide applications for management of wheat stem sawfly. Additional research is needed to develop degree-day models for predicting the emergence of wheat stem sawfly for timing of alternative pest management strategies, such as the augmentative releases of biological control agents.

In terms of economics, insecticides can often be too costly for production management practices in low-value and large-acreage crops, such as wheat, depending on the market value of the crop (Berzonsky et al. 2003). A recent field demonstration plot near Mott in southwestern North Dakota resulted in a net loss of $13.50 per acre ($33.36/ha.) when three applications of a pyrethroid insecticide (zeta-cypermethrin) were applied at the beginning, peak, and end of wheat stem sawfly adult flight (Knodel et al. 2010). Use of solid-stemmed resistant wheat varieties will continue to be the primary pest management strategy for wheat stem sawfly in the future (Kemp 1934, Berzonsky et al. 2003). Results of this study will be useful for educating growers, extension specialists, crop consultants, field scouts, industry agricultural representatives, and commodity groups against the unnecessary use of insecticides.

Acknowledgments

We thank Denise Markle and Kayla Hutzenbiler for their field sampling and data collection. We are indebted to the land cooperators, Steve Petrick at Makoti and Alfred Rose at Hettinger. The North Dakota Wheat Commission, North Dakota Crop Improvement & Seed Association, and the North Dakota SBARE (State Board of Agricultural Research and Education) Wheat Committee provided financial support for this project.
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