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# Influence of Stem-Boring Insects on Common Lambsquarters (*Chenopodium album*) Control in Soybean with Glyphosate

Dana B. Harder, Christy L. Sprague, Christina D. Difonzo, Karen A. Renner, Eric J. Ott, and William G. Johnson*

Control of common lambsquarters with glyphosate in Michigan soybean fields has been inconsistent. Stem-boring insects and evidence of insect tunneling were found inside the stems of common lambsquarters plants not controlled with glyphosate. In 2004 and 2005, field surveys and studies were conducted to identify and evaluate the prevalence of stem-boring insects in common lambsquarters in Michigan and Indiana soybean fields to determine whether tunneling by insects occurred before or following POST glyphosate applications and to evaluate the effect of glyphosate rate, application timing, and insect tunneling on the control of common lambsquarters with glyphosate. Two insect species, the beet petiole borer (*Cosmobaris americana*) from the Curculionidae family and an unidentified leafminer fly larvae from the Agromyzidae family were found inside common lambsquarters stems. Leafminer larvae were present in Michigan soybean fields in mid- to late-June, when most POST glyphosate applications are made in Michigan and Indiana; however, beet petiole borer larvae were not found in common lambsquarters stems until mid-July and would only be present in common lambsquarters plants if glyphosate applications occurred at that time. Results from three field experiments in East Lansing, MI, demonstrated the variability in common lambsquarters control. Control ranged from 79 to 98%, 75 to 99%, and 49 to 97% from glyphosate applied at 0.84 kg ae/ha to 10-, 25-, and 46-cm common lambsquarters, respectively. In general, applying glyphosate to common lambsquarters plants 10 cm or less, or increasing the glyphosate rate beyond 0.84 kg ae/ha, improved common lambsquarters control. Insect tunneling by leafminer and beet petiole borer larvae did not contribute to reduced common lambsquarters control with glyphosate applied to 10- and 25-cm common lambsquarters.
**Nomenclature:** Glyphosate potassium salt; common lambsquarters, *Chenopodium album* (L.) CHEAL; soybean, *Glycine max* (L.) Merr. 'AG 2701'; Coleoptera: Curculionidae, beet petiole borer, *Cosmobaris americana* (Casey); Diptera: Agromyzidae, unidentified leafminer fly.
**Key words:** Insect–weed–herbicide interactions, application timings, inconsistent common lambsquarters control.

Common lambsquarters is a successful colonizing species and one of the most widely distributed weeds in the world (Holm et al. 1977). Ranked as the most problematic weed by Michigan soybean producers (Sprague 2004), common lambsquarters is found in 47 countries in 40 different crops and is considered a principal weed pest in corn (*Zea mays* L.), potato (*Solanum tuberosum* L.), soybean, and sugarbeet (*Beta vulgaris* L.) (Holm et al. 1977; Mitich 1988). Common lambsquarters is competitive with many of these crops and can reduce soybean yields by 15% (Shurtleff and Coble 1985) and 28% (Harrison 1990) from season-long competition at population densities of 16 and 10 plants/m row, respectively. The success of common lambsquarters as a problematic weed is attributable to many factors, including seed germination in a wide range of environments (Henson 1970), early emergence during the crop-growing season (Ogg and Dawson 1984), plasticity of growth (Ervio 1971), prolific seed production (Harrison 1990), and seed longevity (Lewis 1973).

Glyphosate-resistant soybean varieties are planted in 87% of the soybean hectares in the United States (NASS 2005b). Growers adopted this technology because glyphosate offers greater flexibility in application timing and weed control than conventional herbicides and tillage provided in the past (McKinley et al. 1999; VanGessel et al. 2000). Ateh and Harvey (1999) reported that glyphosate at 0.31 kg ae/ha controlled common lambsquarters plants that were less than 15 cm in height, and the standard rate of 0.84 kg ae/ha controlled plants greater than 15 cm in height. Krausz et al. (1996) observed that common lambsquarters control was 100% when glyphosate was applied at 0.56 kg ae/ha to 10-cm plants. Recently, there have been several reports of poor common lambsquarters control with glyphosate (Kniss et al. 2004; Loux et al. 2005; Schuster et al. 2004). In some cases of poor control with glyphosate of common lambsquarters (C. L. Sprague, personal observation) and other weeds, including giant ragweed (*Ambrosia trifida* L.) (Maertens 2003: Ott et al. 2005), and quackgrass [*Elytrigia repens* (L.) Nev.] (Westra et al. 1981), insect larvae were found tunneling in the vascular tissue of the plants. Because glyphosate is a systemic herbicide, it was hypothesized that weed control with glyphosate might be reduced if insect larval tunneling is present in the plant stems at the time of the herbicide application.

There are many reports of the use of insects as biological weed control agents (Bacher and Schwab 2000; Julien 1998; Sheldon and Creed 1995). However, there is limited research on the effect of insect feeding on weeds and the subsequent control by herbicides. Westra et al. (1981) observed that a weevil (*Notaris bimaculatus* Fabricius) reduced the effectiveness of glyphosate on quackgrass. Recently, Ott et al. (2007) reported that European corn borer (*Ostrinia nubilalis* Hubner) tunneling had a negative impact on giant ragweed control with glyphosate. In contrast, Williams et al. (2004) reported that Colorado potato beetle (*Leptinotarsa decemli-*

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* Former Graduate Research Assistant, Assistant Professor, Associate Professor, and Professor, Michigan State University, East Lansing, MI 48824; Graduate Research Assistant and Associate Professor, Purdue University, West Lafayette, IN 47907. Corresponding author's E-mail: sprague1@msu.edu

*neata* Say) feeding in combination with reduced fluroxypyr rates enhanced volunteer potato control compared with either strategy alone.

In 2003, tunneling was found throughout the vascular system of common lambsquarters that survived applications of glyphosate in Michigan. The larvae were identified as the beet petiole borer. Landis et al. (1970) published an extensive study on the life cycle of the beet petiole borer after discovering it in sugarbeet in the western United States. Beet petiole borer larvae overwinter in feeding galleries of dead host plants, pupate in May, and emerge as adult weevils within 1 to 2 wk. Adult weevils feed primarily at nodes or on stems of host plants, and mated females deposit a single egg inside feeding pits. Larvae are often found near the oviposition site, and weed hosts generally do not appear stressed despite having as many as 30 larvae tunneling per plant. Beet petiole borer was more commonly found in weedy hosts than sugarbeet in Washington (Landis et al. 1970). In California, Gilbert (1964) reported that the most frequent host for beet petiole borer was common lambsquarters.

Because the majority of U.S. soybean acres are planted with glyphosate-resistant soybeans, reduced common lambsquarters control with glyphosate is a major concern. Therefore, the objectives of this study were to (1) identify and evaluate the prevalence of stem-boring insects in common lambsquarters plants in southern Michigan and northern Indiana soybean fields, (2) determine if insect tunneling occurred before or following POST glyphosate applications, and (3) evaluate the effect of glyphosate rate, application timing, and insect tunneling on common lambsquarters control.

## Materials and Methods

**Presence of Tunneling and Stem-Boring Insects in Common Lambsquarters.** *Temporal distribution.* Plants were sampled every 2 wk from a natural population of common lambsquarters in East Lansing, MI, in 2004 and 2005. Sampling began May 1 and ended on July 29 and August 5 in 2004 and 2005, respectively. At each sampling period, 40 representative common lambsquarters plants were arbitrarily selected and dissected longitudinally. The number of plants with insect tunneling was recorded. Insect larvae were collected and, when possible, were identified to species. Weather data from the Michigan Automated Weather Network[1] was used to calculate growing–degree days (GDD) for each sampling date by averaging the maximum and minimum daily temperatures and subtracting the base temperature of 4 C. A base temperature of 4 C was chosen to track insect development in relation to common lambsquarters germination (Harvey and Forcella 1993).

*Spatial Distribution.* In 2004, four regions in the southern half of Michigan's Lower Peninsula and one region in northern Indiana were surveyed for stem-boring insects. The regions surveyed in Michigan represented 94% of Michigan's soybean acres (NASS 2005a) and were designated as the northeast, northwest, southeast, and southwest regions of Michigan's soybean production area. The northern region of Indiana consisted of the northern third of the state. In each region, seven soybean fields, each in a different county, were sampled. The regions were surveyed from July 28 to August 9 to target common lambsquarters plants that presumably were not controlled from an initial glyphosate application. Field selection was based on the presence of common lambsquarters plants above the soybean canopy. Common lambsquarters' heights and overall control of common lambsquarters and other weed species were taken into consideration in determining whether the field was treated glyphosate. Coordinates for each field location were marked with a global positioning system (GPS) unit[2] and recorded. Ten representative common lambsquarters plants from each field were arbitrarily selected and dissected. Plant height, stem diameter, insect tunnel-length, and the number of live larvae present were recorded for each plant. Insect specimens were collected and preserved in vials containing 70% isopropyl alcohol for later identification.

Using procedures similar to the 2004 survey, the same four regions in Michigan and three regions in Indiana were surveyed in 2005. The three regions in Indiana included the central region and splitting the northern region surveyed in 2004 into two regions, the northeast and northwest regions. Each region was surveyed three times: June 23 to 24, August 8 to 12, and September 14 to 17. The June sampling period was added to determine the presence and distribution of insect tunneling at the time of typical POST glyphosate application in soybeans. The September sampling period was added to determine the temporal distribution of the insects found in earlier surveys. At each survey date, five soybean fields were sampled per region. Field coordinates, the number of plants with tunneling, and the number of live larvae present in each sample were recorded in 2005. Insect specimens were collected and preserved in vials containing 70% isopropyl alcohol for later identification. Common lambsquarters height, stem diameter, and insect tunnel-length data were not collected in 2005 because there were no strong correlations found among these parameters in the 2004 data.

In 2004, the PROC CORR procedure in SAS 8.02[3] was used to determine whether there were correlations between insect tunneling and common lambsquarters height or stem diameter. All other survey data were subjected to ANOVA, using the PROC MIXED procedure in SAS, to determine whether significant differences in insect tunneling and larvae existed among regions and 2005 survey dates. Fields in each region were considered replicates and were treated as random effects in the model. LSDs were calculated and used to separate mean values when the $F$ values were statistically significant at the $P \geq 0.05$ level.

**Factors Influencing Common Lambsquarters Control.** *Field Studies Planted to Soybean.* Field studies were established on May 6 and June 4, 2004, and May 4, 2005, in East Lansing, MI, to evaluate the effect of glyphosate rate, application timing, and insect tunneling on common lambsquarters control. 'AG 2107' soybeans[4] were planted in 76-cm rows at 395,000 seeds/ha. The experimental design was a randomized complete block in a factorial arrangement with four replications. Plot size was 9.1 m long by 3.1 m wide. In 2004, the experiment was a two-factor (three by four) factorial. The first factor was glyphosate application timing

Table 1. Environmental conditions at the time of herbicide application for field studies established in 2004 and 2005 in East Lansing, MI.

| Application information | Field studies planted to soybean | | | | | | | | | Cage study |
|---|---|---|---|---|---|---|---|---|---|---|
| | May 6, 2004 | | | June 4, 2004 | | | May 4, 2005 | | | May 15, 2005 |
| C. lambsquarters ht. (cm) | 10 | 25 | 46 | 10 | 25 | 46 | 10 | 25 | 46 | 25 |
| Application date | May 26 | June 16 | July 13 | July 13 | July 23 | July 29 | June 8 | June 17 | June 21 | June 24 |
| Time of day (h) | 5:00 P.M. | 9:00 A.M. | 3:00 P.M. | 3:00 P.M. | 12:00 P.M. | 6:00 P.M. | 5:00 P.M. | 7:00 P.M. | 5:00 P.M. | 8:00 A.M. |
| Growing degree days (4 C)[a] | 551 | 841 | 1,245 | 1,245 | 1,411 | 1,492 | 632 | 787 | 827 | 876 |
| Soybean stage | VC | V2 | V4 | V2 | V6 | V8 | V2 | V3 | V4 | — |
| Soil temperature (C) | 16 | 19 | 28 | 28 | 24 | 28 | 27 | 19 | 24 | 21 |
| Air temperature (C) | 22 | 21 | 29 | 29 | 27 | 24 | 32 | 17 | 29 | 23 |
| Relative humidity (%) | 46 | 76 | 57 | 57 | 37 | 57 | 40 | 58 | 46 | 69 |

[a] Growing–degree days (GDD) were calculated by averaging the maximum and minimum daily temperatures and subtracting the base temperature of 4 C. A base temperature of 4 C was chosen to track insect development with common lambsquarters germination.

based on common lambsquarters heights of 10, 25, and 46 cm; the second factor was glyphosate rates of 0, 0.63, 0.84, and 1.68 kg ae/ha. The 2005 experiment was a three-factor (two by three by four) factorial. The additional factor of a biweekly application of the insecticide λ-cyhalothrin[5] at 21 g ai/ha was added to reduce insect tunneling in half of the plots.

Before each glyphosate application, 10 representative common lambsquarters plants per treatment (2004) or per plot (2005) were arbitrarily selected, dissected, and examined for insect tunneling. Glyphosate[6] plus ammonium sulfate (AMS) at 2% (wt/wt) was applied using a tractor-mounted compressed-air sprayer calibrated to deliver 178 L/ha at 207 kPa using Airmix 11003[7] nozzles at the appropriate common lambsquarters heights. Environmental conditions at the different application timings are presented in Table 1. Common lambsquarters control was visually evaluated 14, 21, and 28 d after treatment (DAT) on a 0 (no control) to 100% (complete death) scale. Although three different evaluations were made, data were similar across all dates; therefore, only data from 28 DAT are presented. Additionally, at 28 DAT, common lambsquarters plants that survived the glyphosate application were dissected and examined for insect tunneling.

*Cage Study.* In 2005, an additional field study was established on May 15 in East Lansing, MI, to examine the effect of insect tunneling on common lambsquarters control with glyphosate. The experiment was a completely randomized design with nine replications. Insect-proof, 1-$m^3$ screen cages were constructed of polyvinyl chloride (PVC) pipe and no-see-um mesh.[8] Eighteen sample sites were arbitrarily placed in a conventionally tilled field. Nine sites were caged immediately after tillage to keep common lambsquarters free of insects. The remaining sites were not caged to allow for natural insect infestation. Glyphosate at 0.84 kg ae/ha plus AMS at 2% (wt/wt) was applied to 25-cm plants with a $CO_2$ backpack sprayer calibrated to deliver 187 L/ha at 207 kPa using 8003[9] flat-fan nozzles on June 24 (Table 1). Before glyphosate application, three common lambsquarters plants in each caged and cage-free area were dissected to determine the presence and extent of insect tunneling. Common lambsquarters control was visually evaluated 21 and 28 DAT.

*Statistical Analysis.* All data from the field studies were subjected to ANOVA, using the PROC MIXED procedure in SAS. Main effects and all possible interactions were tested using the appropriate mean square values as recommended by McIntosh (1983). Because of treatment-by-environment interactions, field experiments are presented separately. In field studies, replications were declared random effects in the model; glyphosate rate and application timing in 2004 and glyphosate rate, application timing, and insecticide treatment in 2005 and the interactions among them were designated as fixed effects. The effects of glyphosate rate and application timing were evaluated using the SLICE option in SAS when main effects were significant. LSDs were calculated and used to separate mean values when $F$ values were statistically significant at the $P \leq 0.05$ level. Single degree-of-freedom contrasts were used to compare the effect of λ-cyhalothrin treatments on insect tunneling and common lambsquarters control with glyphosate (2005). Single degree-of-freedom contrasts were also used to compare treatment differences in the cage study.

## Results and Discussion

**Presence of Tunneling and Stem-Boring Insects in Common Lambsquarters.** *Temporal Distribution.* The larvae of beet petiole borer (confirmed by the U.S. Department of Agriculture Systematic Entomology Laboratory[10]) and a leaf-miner fly (Diptera: Agromyzidae; confirmed by H. Russell, Michigan State University Diagnostic Services[11]), which could not be identified to the species level were the only insects found tunneling in common lambsquarters stems in 2004 and 2005 in East Lansing, MI. Observations from the fall and winter of 2003 indicated that beet petiole borer larvae overwintered in common lambsquarters stems. Based on preliminary growth chamber research, overwintering larvae of beet petiole borer pupated, and adults emerged from, stems at an average of 470 GDD at a base temperature of 4 C (data not shown). In the field, adult beet petiole borer were found inside common lambsquarters stems from the previous year on May 15 (418 GDD) and May 24 (412 GDD) in 2004 and 2005, respectively. These observations on the life cycle of beet petiole borer in Michigan agree with those of Landis et al. (1970), who reported that beet petiole borer larvae overwintered in the feeding galleries of dead host plants, and that adults emerged in mid-May in the western United States.

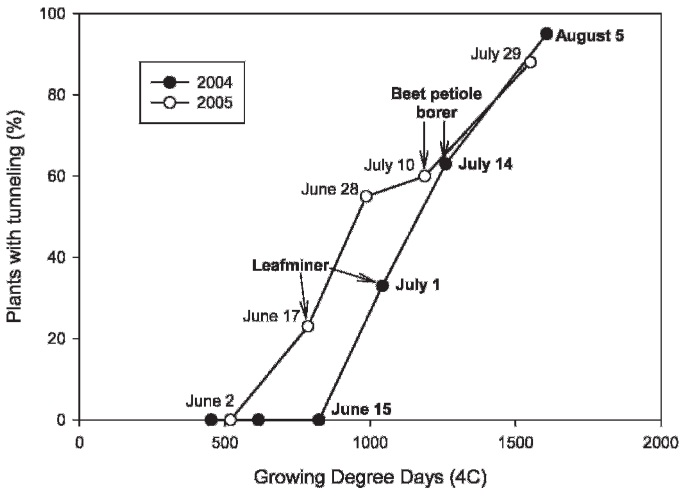


Figure 1. Percentage of common lambsquarters plants tunneled over time in East Lansing, MI, in 2004 and 2005. Growing–degree day information was calculated by averaging the maximum and minimum daily temperatures and subtracting the base temperature of 4 C. A base temperature of 4 C was chosen to track insect development with common lambsquarters germination.

Leafminer larvae were found inside the stems of live common lambsquarters plants on July 1, 2004, and June 17, 2005, at 992 and 786 GDD, respectively (Figure 1). Tunneling by leafminer larvae was narrow and limited to the center portion of the stem, causing little damage to vascular tissue. Furthermore, common lambsquarters infested with leafminer larvae were not visually stressed.

Beet petiole borer larvae were found inside common lambsquarters stems on July 14 and July 10 in 2004 and 2005, respectively, corresponding to 1,260 and 1,189 GDD (Figure 1). Common lambsquarters height in mid-July ranged from 25 to 65 cm. Beet petiole borer tunneling was more extensive than that of leafminer larvae, and the beet petiole borer tunneling destroyed the pith tissue of common lambsquarters plants.

In 2004, the proportion of common lambsquarters plants with tunnels increased steadily from July 1 (33%) to August 5 (95%) (Figure 1). The percentage of plants with insect tunneling also increased steadily in 2005 from June 17 (23%) to July 29 (88%). Not all common lambsquarters stems with tunneling had insect larvae present. Tunneling in common lambsquarters plants that lacked insect larvae more closely resembled that of the leafminer larvae, which probably completed development and emerged as adult flies during the field season.

POST glyphosate applications for annual weed control in glyphosate-resistant soybeans in Michigan are typically made between June 15 and July 3. In East Lansing, MI, tunneling in 2004 and 2005 occurred during this application window (July 1, 2004, and June 17, 2005). However, only the leafminer was present during this period. Therefore, leafminer tunneling caused little damage to the vascular tissue of common lambsquarters when typical POST glyphosate applications are made for common lambsquarters control. However, if glyphosate applications are delayed past 1,189 GDD (mid-July), beet petiole borer larvae, which caused greater damage to the vascular tissue of common lambsquarters, can be present.

Table 2. Insect tunneling and leafminer (Diptera: Agromyzidae) and beet petiole borer larvae present in common lambsquarters from selected soybean fields in Michigan and Indiana in August 2004.

| | | Plants with larvae, by species[c] | |
|---|---|---|---|
| Region[a] | Plants with tunnels[b] | Leafminer | BPB |
| | —— % —— | | |
| Northeast MI | 82 | 23 | 5 |
| Northwest MI | 77 | 16 | 11 |
| Southeast MI | 63 | 6 | 19 |
| Southwest MI | 53 | 3 | 9 |
| Indiana | 75 | 0 | 36 |
| $LSD_{0.05}$ | 20 | 11 | 15 |

[a] Fields sampled in Michigan were from the northeast, northwest, southeast, and southwest regions of Michigan's soybean production area (the southern half of Michigan's Lower Peninsula), and fields sampled in Indiana were from the northern third of the state.

[b] Ten common lambsquarters plants per field were sampled from seven different soybean fields in each region for a total of 70 plants sampled per region.

[c] Not all common lambsquarters plants with tunnels contained insect larvae.

*Spatial Distribution.* In August 2004, tunneling in stems of common lambsquarters was widespread throughout the soybean production region in Michigan and northern Indiana. The frequency of tunneled plants ranged from 53 to 82% (Table 2), and both leafminer and beet petiole borer were collected. As previously described, tunneling damage by the beet petiole borer was more extensive then that of leafminer larvae. Tunneling by leafminer or beet petiole borer larvae did not correlate with common lambsquarters height ($P \geq 0.6625$) or stem diameter ($P \geq 0.7656$). Thus, leafminer or beet petiole borer adults may have no preference in regard to plant size when selecting a host. Tunneling by leafminer or beet petiole borer larvae did not appear to reduce common lambsquarters height or stem diameter.

Although a large portion of the common lambsquarters plants were tunneled, less than 30 and 40% of plants sampled in Michigan and Indiana, respectively, contained larvae (Table 2). Infested common lambsquarters stems averaged 1.3 leafminer and 2.9 beet petiole borer larvae per plant. The ratio of leafminer to beet petiole borer larvae found in common lambsquarters stems varied from north to south. In the northeast and northwest regions of Michigan, the leafminer larvae was 1.5 and 4.6 times more prevalent than beet petiole borer larvae, respectively. However, in the southern regions of Michigan, beet petiole borer larvae were three times more prevalent than the leafminer larvae. In northern Indiana, only beet petiole borer larvae were found inside common lambsquarters stems. The southern sample sites were further ahead in GDD accumulation compared with the northern Michigan sites. Thus, leafminer larvae (first observed between 786 and 992 GDD) had already emerged as adults in Indiana and much of southern Michigan.

*Temporal and Spatial Distribution.* Unlike the survey conducted in 2004, the 2005 survey had three sampling periods: June, August, and September. The June sampling period was added to determine the presence and distribution

Table 3. Insect tunneling and leafminer (Diptera: Agromyzidae) and beet petiole borer (BPB) larvae present in common lambsquarters from selected soybean fields in Michigan and Indiana in June, July, and August 2005.

| | | | | | Plants with larvae, by species[d] | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Plants with tunnels[b] | | | | Leafminer | | | | BPB | | | |
| Region[a] | June | August | September | $LSD_{0.05}$[c] | June | August | September | $LSD_{0.05}$ | June | August | September | $LSD_{0.05}$ |
| | % | | | | % | | | | % | | | |
| Northeast MI | 36 | 37 | 38 | NS | 20 | 11 | 0 | 8 | 0 | 13 | 14 | 6 |
| Northwest MI | 44 | 46 | 52 | NS | 22 | 0 | 0 | 10 | 0 | 28 | 26 | 7 |
| Southeast MI | 62 | 26 | 28 | 15 | 34 | 1 | 0 | 4 | 0 | 16 | 10 | 11 |
| Southwest MI | 46 | 39 | 50 | NS | 10 | 8 | 0 | 7 | 0 | 3 | 8 | 6 |
| Northeast IN | 34 | 48 | 34 | NS | 0 | 0 | 0 | NS | 0 | 15 | 0 | 11 |
| Northwest IN | 32 | 42 | 44 | NS | 0 | 0 | 0 | NS | 0 | 14 | 0 | 6 |
| Central IN | 34 | 44 | 52 | 17 | 0 | 0 | 0 | NS | 0 | 24 | 8 | 7 |
| $LSD_{0.05}$[e] | 19 | 18 | 15 | | 10 | 7 | NS | | NS | 13 | 10 | |

[a] Fields sampled in Michigan were from the northeast, northwest, southeast, and southwest regions of Michigan's soybean production area (the southern half of Michigan's Lower Peninsula), and fields sampled in Indiana were from the northern and central thirds of the state.

[b] Ten common lambsquarters plants per field were sampled from five different soybean fields in each region for a total of 50 plants sampled per region.

[c] Denotes values required for significance at $P \geq 0.05$ among sampling times.

[d] Not all common lambsquarters plants with tunnels contained insect larvae.

[e] Denotes values required for significance at $P \geq 0.05$ among regions.

of insect tunneling at the time of typical POST glyphosate application in soybeans. It was hypothesized that insect tunneling present at that time would have the greatest impact on common lambsquarters control with glyphosate. In July and early August, subsequent glyphosate applications may also be used to control weed escapes or weeds that germinate after the initial glyphosate application. Sampling in August and September was conducted to determine whether tunneling was present in common lambsquarters that presumably were not controlled with an initial glyphosate application.

In June 2005, the frequency of common lambsquarters that were tunneled by insect larvae ranged from 32 to 62% (Table 3). In all regions, tunneling was consistent with that from leafminers. Although no plants from Indiana contained larvae, 22 to 56% of common lambsquarters in Michigan were infested, and 100% of these larvae were leafminers (Table 3). Again, it was assumed that leafminer larvae had already completed development and emerged as adults in Indiana, which had accumulated more GDDs. Thus, in the June sampling, when initial POST glyphosate applications are typically made in Michigan and Indiana, leafminer was the only stem-boring insect present and creating tunnels.

In August 2005, tunneling and insect larvae were found in 26 to 48% and 11 to 28% of the common lambsquarters plants sampled, respectively (Table 3). Both leafminers and beet petiole borer larvae were present in Michigan, whereas only beet petiole borer larvae were found in Indiana (Table 3). In all regions, except southwest Michigan, a higher proportion of beet petiole borer larvae were found in common lambsquarters plants in August compared with leafminers. Thus, at this sampling time, when later POST glyphosate applications would likely be made to control weed escapes or late-emerging weeds, beet petiole borer was the primary stem-boring insect present and creating tunnels.

In September 2005, 28 to 52% of the common lambsquarters plants sampled were tunneled, and 0 to 26% contained insect larvae (Table 3). All of the larvae were beet petiole borer.

Across sampling periods, there were few differences in the frequency of plants with tunneling (Table 3). Common lambsquarters plants sampled in August and September presumably survived glyphosate application. If insect tunneling were an important cause of reduced control with glyphosate, then the proportion of common lambsquarters plants with tunneling should increase over time; however, the only region where there was an increase in the proportion of plants with tunneling was in central Indiana (Table 3).

**Factors Influencing Common Lambsquarters Control.** Before each glyphosate application, a subset of common lambsquarters plants was sampled for insect tunneling. Because of differences in soybean planting dates and environments, the temporal distribution of insect tunneling and common lambsquarters control with glyphosate differed; thus field experiments are presented separately.

*Soybean Planted in May 2004.* Common lambsquarters population densities were high (43 plants/$m^2$) at this location. Regardless of glyphosate application timing or rate, common lambsquarters control was less than 90% (Table 4). Control of 10-cm common lambsquarters was less than 81% and was not different across glyphosate rates, in contrast to previous reports of 100% control of 10-cm common lambsquarters at 0.56 kg ae/ha of glyphosate (Krausz et al. 1996). Control of 25- and 46-cm common lambsquarters was reduced by 14 to 21% when glyphosate was applied at 0.63 and 0.84 kg ae/ha compared with 1.68 lb ae/ha. There was no difference in common lambsquarters control between the 10- and 25-cm application timing, within each glyphosate rate. However, when glyphosate was applied to 46-cm common lambsquarters, control was reduced significantly (> 25%) compared with the 10- and 25-cm application timings.

Tunneling by leafminers was evident in 40% of the common lambsquarters plants sampled before the 46-cm

Table 4. Effects of glyphosate rate, common lambsquarters height, and insect tunneling on common lambsquarters control with glyphosate (28 DAT) for soybean planted in May and June of 2004 in E. Lansing, MI.

| Common lambsquarters height | May Planting | | | | | | June Planting | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Tunneling before:[a] | Glyphosate rate (kg ae/ha) 0.63 | 0.84 | 1.68 | | Tunneling 28 DAT[b] | Tunneling before: | Glyphosate rate (kg ae/ha) 0.63 | 0.84 | 1.68 | |
| cm | % plants[c] | ——% control—— | | | $LSD_{0.05}$[d] | % plants | % plants[e] | ——% control—— | | | $LSD_{0.05}$ |
| 10 | 0 | 75 | 79 | 81 | NS | 0 | 40 | 88 | 93 | 98 | 6 |
| 25 | 0 | 72 | 75 | 89 | 12 | 6 | 60 | 92 | 92 | 97 | NS |
| 46 | 40 | 42 | 49 | 63 | 12 | 60 | 70 | 83 | 88 | 93 | 6 |
| $LSD_{0.05}$[f] | — | 12 | 12 | 12 | — | 10 | — | 6 | NS | NS | — |

[a] Ten common lambsquarters plants per treatment were sampled before glyphosate application to determine whether stem-boring insect tunneling was present.

[b] Ten common lambsquarters plants not controlled by glyphosate were sampled for stem-boring insect tunneling 28 days after treatment (DAT).

[c] The insect larvae found tunneling in common lambsquarters before application was leafminer (Diptera: Agromyzidae) larvae.

[d] Denotes values required for significance at $P \geq 0.05$ among glyphosate rates.

[e] Beet petiole borer and leafminer (Diptera: Agromyzidae) larvae were found tunneling inside common lambsquarters plants.

[f] Denotes values required for significance at $P \geq 0.05$ among common lambsquarters heights.

application timing (Table 4). Glyphosate applications to 10- and 25-cm common lambsquarters occurred before 992 GDD, when leafminer larvae were already present in common lambsquarters stems in 2004 (Table 1; Figure 1). Plants not controlled by glyphosate were sampled for tunneling at 28 DAT. Tunneling was found in 0, 6, and 60% of the sampled plants from the 10-, 25-, and 46-cm common lambsquarters application timing, respectively (Table 4).

Several factors may have contributed to the overall unacceptable control of common lambsquarters at this location. Although only 60% of the plants surviving glyphosate applications to 46-cm common lambsquarters were tunneled, the tunneling by leafminer larvae before this timing may have contributed to reduced control of 46-cm common lambsquarters. However, because there was not a leafminer-free control for comparison, other factors, including large plant height and high common lambsquarters population densities, may have been more important for the reduced control of 46-cm common lambsquarters. High population densities of common lambsquarters at all application timings that resulted in dense canopies may have reduced glyphosate spray penetration and individual plant coverage, resulting in overall poor control at this location.

*Soybean Planted in June 2004.* Common lambsquarters population densities ranged from 15 to 20 plants/$m^2$. Tunneling by insect larvae in the June planting was evident in 40, 60, and 70% of common lambsquarters plants sampled before the 10-, 25-, and 46-cm glyphosate application timings, respectively (Table 4). Tunneling by leafminer larvae was present before all glyphosate application timings; tunneling by beet petiole borer larvae was evident before only the 25- and 46-cm applications. Appearance of tunneling by leafminer and beet petiole borer larvae corresponded to GDD accumulations previously discussed (Table 1; Figure 1).

Common lambsquarters control with glyphosate was greater than 80%, regardless of application rate, common lambsquarters height, or frequency of insect tunneling (Table 4). Control of 10-, 25- and 46-cm common lambsquarters was similar at 0.84 and 1.68 kg ae/ha of glyphosate; 0 to 4 common lambsquarters plants per plot (28 $m^2$) remained after these applications. Glyphosate at 0.63 kg ae/ha was not as effective as glyphosate at 1.68 kg ae/ha in controlling 10- and 46-cm common lambsquarters. Of the five common lambsquarters remaining per plot in treatments where 10- and 46-cm tall common lambsquarters were treated with 0.63 kg ae/ha of glyphosate, insect tunneling was present only in one plant in the 10-cm, and two plants in the 46-cm, application timings, suggesting that insect tunneling had little effect on common lambsquarters control. Glyphosate application rate was the predominant factor that influenced common lambsquarters control at this location.

*Soybean Planted in May 2005.* Biweekly applications of the insecticide λ-cyhalothrin were made to half of the plots to provide a direct comparison of common lambsquarters control with ambient and reduced levels of insect tunneling. Similar to soybean planted in May 2004, there was no insect tunneling at the time glyphosate was applied to 10-cm common lambsquarters (Table 5). Control of 10-cm common lambsquarters was excellent, regardless of glyphosate rate, which is consistent with previous reports of excellent common lambsquarters control with glyphosate at rates of 0.56 to 0.84 kg ae/ha (Ateh and Harvey 1999; Krausz et al. 1996).

There was tunneling by leafminer larvae before glyphosate applications to 25- and 46-cm common lambsquarters (Table 5). Evidence of tunneling by leafminer larvae corresponded to GDD accumulations previously discussed (Table 1; Figure 1). Regardless of insecticide treatment, a portion of the common lambsquarters plants treated at 25 and 46 cm was tunneled (Table 5). However, plots that received λ-cyhalothrin had significantly fewer common lambsquarters plants that were tunneled (by more than 60%) than plots that did not receive the insecticide treatment.

Control of 25- and 46-cm common lambsquarters at 0.63, 0.84, and 1.68 kg ae/ha of glyphosate was greater than 90%. Common lambsquarters control was similar between in-

Table 5. Effects of glyphosate rate, common lambsquarters height, and insect tunneling on common lambsquarters control with glyphosate (28 DAT) for soybean planted in May 2005 at East Lansing, MI.

| Common lambsquarters height | Insecticide treatment[a] | Tunneling before glyphosate application[b] | Glyphosate rate (kg ae/ha) | | | |
|---|---|---|---|---|---|---|
| | | | 0.63 | 0.84 | 1.68 | |
| cm | | % plants[c] | —— | % control | —— | $LSD_{0.05}$[d] |
| 10 | No Insecticide | 0 | 98 | 98 | 98 | NS |
| | Insecticide | 0 | 96 | 98 | 98 | NS |
| | $P > F$[e] | NS | NS | NS | NS | |
| 25 | No Insecticide | 64 | 98 | 99 | 99 | NS |
| | Insecticide | 26 | 98 | 98 | 99 | NS |
| | $P > F$ | 0.0002 | NS | NS | NS | |
| 46 | No Insecticide | 70 | 92 | 97 | 99 | 3 |
| | Insecticide | 13 | 93 | 96 | 99 | 2 |
| | $P > F$ | 0.0001 | NS | NS | NS | |

[a] Biweekly applications of the insecticide λ-cyhalothrin were made to half of the plots to provide a direct comparison of common lambsquarters control with ambient and reduced levels of insect tunneling.

[b] Ten common lambsquarters plants per plot were sampled before glyphosate application to determine whether stem-boring insect tunneling was present.

[c] Leafminer (Diptera: Agromyzidae) larvae were found tunneling inside common lambsquarters plants.

[d] Denotes values required for significance at $P \geq 0.05$ among glyphosate rates.

[e] Single degree-of-freedom contrasts compared the effect of λ-cyhalothrin treatments on stem-boring insect tunneling and common lambsquarters control with glyphosate.

secticide treated and untreated plots, indicating that tunneling by leafminer larvae did not affect common lambsquarters control with glyphosate.

*Cage Study.* Insect-proof cages kept common lambsquarters plants free of insect tunneling (Table 6). Tunneling by leafminer larvae was prevalent (94%) in uncaged common lambsquarters plants before glyphosate application. Glyphosate was applied on June 24 (876 GDD), when plants were 25 cm tall (Table 1). This application occurred before the appearance of tunneling by beet petiole borer larvae, which was present at 1,260 and 1,189 GDD in 2004 and 2005, respectively. Common lambsquarters control with glyphosate was similar between uncaged areas with tunneling and caged areas that were free of insects and tunnels (Table 6). Control of common lambsquarters with 0.84 kg ae/ha of glyphosate was 95% or greater at 28 DAT.

Table 6. Effect of insect tunneling on common lambsquarters control at 21 and 28 d after treatment (DAT) with glyphosate at 0.84 kg ae/ha. Tunneling by insects was controlled by placing 1-$m^3$ cages over areas in the field before common lambsquarters emergence.

| | Tunneling before glyphosate application[a] | Common lambsquarters control | |
|---|---|---|---|
| | | 21 DAT | 28 DAT |
| | % of plants[b] | —— % —— | |
| Uncaged | 94 | 92 | 97 |
| Caged (insect-free) | 0 | 89 | 95 |
| $P \geq F$[c] | 0.0001 | 0.0897 | 0.1972 |

[a] Three common lambsquarters plants per plot were sampled before glyphosate application to determine whether insect tunneling was present.

[b] Percentage of common lambsquarters plants in which leafminer (Diptera: Agromyzidae) larvae were found tunneling.

[c] Single degree-of-freedom contrasts compared the effect of cages on stem-boring insect tunneling and common lambsquarters control with glyphosate.

In conclusion, common lambsquarters served as a host for two different stem-boring insects in Michigan and Indiana soybean fields. These insects were the beet petiole borer and a leafminer fly larvae, which was not identified to the species level. Leafminer larvae were present in common lambsquarters stems in all regions of Michigan's soybean production area in June, in the northern portions of that area in August, and were not present in September, suggesting that the leafminer completed development and emerged as an adult sometime in August. Beet petiole borer larvae were first present in common lambsquarters stems in East Lansing, MI, in mid-July. By August, tunneling by beet petiole borer was widespread in all regions of Michigan and Indiana, indicating that beet petiole borer tunneling occurs later in the season. Most glyphosate applications in Michigan and Indiana are made in late-June and coincide with leafminer tunneling. Tunneling by the leafminer larvae caused little damage to vascular tissue of common lambsquarters. In field experiments, tunneling by leafminer larvae did not reduce common lambsquarters control with glyphosate. Beet petiole borer was only present in the field experiment where soybean was planted in June, and 25- and 46-cm common lambsquarters control with glyphosate was evaluated. Control of 25-cm common lambsquarters with glyphosate was greater than 90% at this application timing across all glyphosate rates, even with beet petiole borer tunneling present. However, control of 46-cm common lambsquarters was dependent on the glyphosate rate.

Control of common lambsquarters with glyphosate remains inconsistent; results from three field experiments in East Lansing, MI, demonstrated the variability in common lambsquarters control. Applications of glyphosate to common lambsquarters plants that are 10 cm or less in height increased control, as did increasing the glyphosate rate beyond 0.84 kg ae/ha. Larger common lambsquarters are more difficult to control, and mid-July or later glyphosate applications to 46-cm common lambsquarters can create other concerns.

## Sources of Materials

[1] Michigan Automated Weather Network, Michigan Climatological Resources Program 417 Natural Sciences Building, East Lansing, MI 48824.

[2] Garmin GPS 60, Garmin International Inc., 12100 East 51st Street, Olathe, KS 66062.

[3] SAS Institute Inc., 100 SAS Campus Drive, Cary, NC 27513.

[4] Asgrow Seed Co., Monsanto Co., 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[5] Warrior, Syngenta Crop Protection, Inc. P.O. Box 18300, Greensboro, NC 27409.

[6] RoundupWeatherMAX, Monsanto., 800 North Lindbergh Boulevard, St. Louis, MO 63167.

[7] TeeJet Airmix 11003, Spraying Systems Co., North Avenue, Wheaton, IL 60188.

[8] No-see-um mesh, Venture textiles, 115 Messina Drive, P.O. Box 850289, Braintree, MA 02185.

[9] TeeJet flat fan 8003, Spraying Systems Co., North Avenue, Wheaton, IL 60189.

[10] Systematic Entomology Laboratory, Agriculture Research Service, U.S. Department of Agriculture, Beltsville, MD 20705.

[11] Michigan State University Diagnostic Services. Howard Russell, Insect Diagnostician. Michigan State University, East Lansing MI 48824-1311.


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