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EFFECT OF SOYBEAN [*Glycine max* (L.) Merr] ROW WIDTH AND PLANT POPULATION ON WEED COMPETITION AND SOYBEAN YIELD
AND
INFLUENCE OF STEM-BORING INSECTS ON COMMON LAMBSQUARTERS [*Chenopodium album* (L.)] CONTROL WITH GLYPHOSATE

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ABSTRACT

EFFECT OF SOYBEAN [*Glycine max* (L.) Merr] ROW WIDTH AND PLANT POPULATION ON WEED COMPETITION AND SOYBEAN YIELD
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Field studies were conducted to determine the effect of soybean row width and population on canopy closure, yield, yield components, weed biomass, weed emergence, and economic return. Weed biomass decreased as soybean population increased. Under weedy conditions, yield was greater in 19-cm rows compared with 76-cm rows, regardless of population in three of six site years. In weed-free conditions, yield was greater in 19-cm rows compared with 76-cm rows, regardless of population in five of six site years. Branch pod number increased as row width or population decreased; however, mainstem pod number only increased as population decreased. Field and greenhouse studies were conducted to evaluate the effect of glyphosate rate, application timing, and insect larval tunneling on common lambsquarters control. Insect larval tunneling in common lambsquarters was wide-spread throughout Michigan and northern Indiana. Two insect species, an unidentified larva from the order Diptera, family Agromyzidae, and the beet petiole borer (*Cosmobaris americana*) were found in common lambsquarters stems. Diptera:Agromyzidae was present prior to late-June glyphosate applications; however, the beet petiole borer was not found in common lambsquarters stems until mid-July. Common lambsquarters control with glyphosate was not influenced by insect larval tunneling. Increasing glyphosate rate or applying glyphosate to smaller plants improved control.

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CHAPTER 1

REVIEW OF LITERATURE

INTRODUCTION

The effect of row width and population on soybean (*Glycine max* (L.) Merr) growth, competitiveness with weeds, and yield has been researched extensively. Soybean can adjust to varying plant populations and row widths and still maintain yield; however, maximum seed yield is thought to be obtained when the arrangement of plants approach uniform distribution within and between rows (Wiggans 1939). In most studies, soybean yield increases as row width decreases when environmental conditions are favorable (Devlin et al. 1995; Taylor 1980; Yelverton and Coble 1991). Producers have utilized narrow rows and higher plant populations as a cultural method of weed control. Earlier canopy closure prevents weed development due to lower light quality (Burnside and Colville 1964; Carey and DeFelice 1991; Nelson and Renner 1999; Yelverton and Coble 1991). Increased seeding rates are required to maximize grain yields with narrow-row soybean (Devlin et al 1995); however, the drawbacks to increased soybean seeding rates include increased seed cost, increased plant mortality due to competition, and increased lodging (Costa et al. 1980). Increased yield has been attributed to improved distribution of soybean over the soil surface for the efficient use of available water, light, and nutrients (Bertram and Pedersen 2004).

The success of common lambsquarters (*Chenopodium album* L.) as a competitive weed is attributed to seed germination in a wide range of environments (Henson 1970), early emergence during the growing season (Ogg and Dawson 1984), plasticity of growth

(Ervio 1971), prolific seed production (Harrison 1990), and seed longevity (Lewis 1973). Common lambsquarters has been reported as an increasingly problematic weed in glyphosate resistant soybean (Schuster et al. 2004; Kniss et al. 2004). There is little research on the influence of larval tunneling on weed control with glyphosate.

SOYBEAN ROW WIDTH AND POPULATION

I. YIELD

Soybean has greater yield potential in narrow rows (< 25cm) than soybean planted in wide rows. Many researchers reported higher yields in narrow-compared with wide-row soybean (Bertram and Pedersen 2004; Costa et al. 1980; Kratochvil et al. 2004; Lehman and Lambert 1960). In Wisconsin, Costa et al. (1980) reported that soybean yield increased 21% in 27-cm rows compared with 76-cm rows. Kratochvil et al. (2004) reported that soybean drilled in 19-cm rows produced significantly better yields compared with 38-cm rows in 2 of 3 years in Maryland. Yields were greater in 20-cm rows compared with 76-cm rows, regardless of tillage system in Wisconsin (Oplinger and Philbrook 1992), and yields were 9 and 10% greater in 19- and 38-cm rows, respectively, compared with 76-cm rows (Bertram and Pedersen 2004).

Optimum soybean populations vary from 30 000 plants/ha to 500 000 plants/ha (Board 2000). Cooper (1977) reported that a seeding rate of 375 000 seeds/ha was the optimum seeding rate for 17-, 50-, and 75-cm row widths. There was a yield advantage of 10 and 20% from planting soybean in 17-cm rows compared with 50-cm and 75-cm rows, respectively. Norsworthy and Frederick (2002) reported that a seeding rate 40% below the current recommended standard of 620 000/ha for drilled soybean produced yields similar to the recommended standard in South Carolina. However, yield was significantly less when the seeding rate was 40% lower than the recommended seeding rate of 432 250 seeds/ha in Maryland, although seeding rates 20% less than the recommended seeding rate consistently produced yields similar to the standard and produced an additional profit of $14.30 to $27.72/ha (Kratochvil et al. 2004). In Wisconsin, seeding recommendations for 19-, 38-, and 76-cm rows are 556 000, 432 000, and 309 000 seeds/ha, respectively (Bertram and Pedersen 2004). When these seeding rates were increased 20%, no differences in yield were found between the recommended seeding rates and seeding rates 20% higher for each respective row width. Oplinger and Philbrook (1992) reported that seeding rates for drilled soybean need to be 32% greater in no–tillage and reduced-tillage systems than conventional tillage. The determination of optimal plant population (the minimum population for best yield) lowers seeding costs, reduces lodging, and prevents disease problems (Boquet and Walker 1980).

Excessive intraspecific competition can occur when soybean is planted at high populations. Increasing plant density decreases the number of branches per plant and increases lodging (Costa et al. 1980). Peters et al. (1965) observed excessive intraspecific competition when soybean was planted in 20- and 41-cm row widths; soybean had thin stems, delayed maturity, small seed, and lodging. Harvested plant populations were significantly lower in no- and reduced-tillage compared with conventional tillage at seeding rates greater than 247 000 seeds/ha (Oplinger and Philbrook 1992). Ethredge et al. (1989) noticed that the number of plants producing seed in 76-cm rows was only 77% of the initial population, whereas, the number of plants producing seed in 51- and 25- cm rows was 93 and 97%, respectively. Greater natural thinning occurred in wide rows compared with narrow rows when plant population was constant (Ethredge et al. 1989). Board (2000) also observed that soybean population declined 38% in 76-cm rows over the growing season.

Due to increased yields in narrow-row soybean, economic returns are generally greater than wide-row soybean when similar weed management systems are implemented. However, seeding rates and thus seeding costs are typically 20 to 45% greater in 19-cm compared with 76-cm rows (Bertram and Pedersen 2004; Kratochvil 2004; Nelson and Renner 1999; Norsworthy and Frederick 2002; Norsworthy and Oliver 2001). Nelson and Renner (1999) reported $45 to $64/ha greater gross margins when soybean were grown in 19-cm rows at 494 000 plants/ha rather than 76-cm rows at 360 000 plants/ha; however, seeding rates were higher for 19-cm rows. In other research, gross margins were $52/ha greater in drilled soybean seeded at 185 000 seed/ha compared with the recommended seeding rate of 432 000 seeds/ha in Arkansas (Norsworthy and Oliver 2001).

II. MOISTURE

In soybean, moisture is a critical factor for maximum yield. The amount and duration of seasonal rainfall are the two most important factors in determining soybean yield (Taylor 1980). Devlin et al. (1995) reported that under favorable environmental conditions, yield was greater when soybean was planted in 20-cm rows compared with 76-cm rows at 378 000 plants/ha. Wide-row yields were greater than narrow-row soybean when seeding rates were lower than 378 000 plants/ha. Devlin concluded that under favorable environmental condition, the optimal seeding rate for soybean planted in 20- and 76-cm rows was 501 000 and 274 000 seeds/ha, respectively. In poor environmental conditions, yields were greater in 76-cm rows than 20-cm at all seeding rates. In contrast, Taylor (1980) observed that in years when water was limiting, row width had no effect on soybean yield. Greater water use early in the growing season resulted in less moisture available during pod fill for narrow-row soybean. Norris et al. (2002) also observed that soybean yields were similar between row widths when growing conditions mid- and late-season were extremely dry.

III. YIELD COMPONENTS

Soybean can compensate for sparse plant populations resulting in similar yield per area compared with higher plant populations (Wells 1991). Plant populations for maximum yield depend on row width, cultivar, and planting date (Ethredge et al. 1989). Increases in plant population results in lower branch yield (Carpenter and Board 1997), yield per plant (Weber et al. 1966), fewer pods per plant (Ethredge et al. 1989), and in some cases lower seed weight (Costa et al. 1980; Etheredge et al. 1989). Moore (1991) and Wright et al. (1984) reported that seed size was responsible for yield compensation at lower populations; however, others have reported that yield compensation results from increased pod production associated with greater branch development (Herbert and Litchfield 1982; Hicks et al. 1969; Lehman and Lambert 1960). Pod number per plant is the most variable of seed yield components and the most likely to respond to changes in row width or plant population (Lehman and Lambert 1960; Herbert and Litchfield 1982; Pedersen and Lauer 2004; Weber et al. 1966). Changes in seed weight and number of seeds per pod due to changes in row width or soybean population has not been consistent (Board et al. 2000; Carpenter and Board 1997; Herbert and Litchfield 1982) Yield component response to increasing soybean populations may differ based on soybean row width. Ethredge et al. (1989) observed that the pod number and yield per area were similar across populations in 76-cm rows due to soybean at low populations producing more pods on branches than soybean planted at higher populations. In the same study, pod number and yield were greater at higher populations in 25- and 51-cm rows.

In general, row width influences soybean yield components; however, some report little response in yield components to row width. Ethredge et al. (1989) observed that the number of pods per plant was not affected by row width. Weber et al. (1966) observed that seed size was independent of row width. In contrast, seed weight and the number of seeds per pod were greater when soybean was planted in wide rows (Costa et al. 1980; Lehman and Lambert 1960).

The partitioning of soybean yield to branch or mainstem fractions is also influenced by row width and population. Mainstem yield is greater in narrow-row soybean than wide-row soybean and some soybean genotypes are capable of partitioning more resources to increase branch seed yields in response to row width (Norsworthy and Shipe 2005). Rigsby and Board (2003) also reported that there are genotypic differences in soybean branching and branch yield at low populations. Branches produce a greater proportion of seed yield at lower populations (Herbert and Litchfield 1982).

Partitioning of yield components to branch or mainstem fraction is also influenced by environmental conditions. The contribution of branch seed yield to total yield was greater in years of higher rainfall (Norsworthy and Frederick 2002). In dry environments, the mainstem portion of yield is greater and remains stable over environments (Board, 1987; Frederick et al. 2001). Yield was correlated to dry matter production, and total dry matter per plant was greater in narrow rows with a greater fraction being produced on branches (Board et al. 1990).

IV. WEED CONTROL

Soybean row width was traditionally limited to 76-cm rows to allow for late-season row cultivation. Technological advancements in herbicide development and equipment allow growers to plant narrow-row soybean and rely heavily on the use of herbicides as the primary means of controlling weeds. Studies indicate that as soybean row width decreases, weed control increases for a given herbicide treatment due to rapid canopy closure (Burnside and Colville 1964; Legere and Schreiber 1989; Mickelson and Renner 1997; Nelson and Renner 1999; Peters et al. 1965).

Narrow-row soybean is more competitive with weeds than wide-row soybean. Young et al. (2001) reported that weed control with a single glyphosate application in 19- and 38- cm rows was greater than 76-cm rows, and weed control in 38-cm rows was more similar to 19-cm rows than 76-cm rows. Common waterhemp (*Amaranthus rudis*) and velvetleaf (*Abutilon theophrasti*) control was less in 76-cm rows and was more variable compared with 19-cm rows. Chandler et al. (2001) reported that soybean planted at 400 000 seeds/ha in 19-cm rows reduced weed biomass by 56 and 47% compared with soybean planted in 76-cm and twin-rows, respectively. Soybean planted in narrow- or twin-rows reduced weed seed return compared with wide rows. In comparison to twin- and narrow-row soybean, weeds in wide-row soybean contributed an additional 2651 and 2960 seeds m^{-2}, respectively. Weeds that emerged after the 1- to 2- trifoliate stage did not increase the total number of seeds in the seedbank or reduce soybean yield when compared with the season-long weedy control.

Mickelson and Renner (1997) reported that soybean drilled in 19-cm rows at 469 300 seeds/ha reduced weed biomass by 30% compared with soybean planted at 358 150 seeds/ha in 76-cm rows. Soybean yield was 14% greater when soybean was drilled in narrow rows compared with soybean planted in wide rows when averaged across herbicide treatments. However, there was no difference in soybean yield in the weed-free control for both years between narrow- and wide-row soybean. Common lambsquarters and velvetleaf control in wide-row soybean was less than that in narrow rows.

Nice et al. (2001) conducted a study in Mississippi researching sicklepod (*Senna obtusifolia*) development when soybean was planted in 19- and 38-cm rows at seeding rates of 326 000, 652 000, and 976 000 seeds/ha, compared with a 'standard' soybean population of 326 000 seeds/ha planted in 76-cm rows. They observed that soybean had little effect on sicklepod density when planted in row widths less than 76-cm at 326 000 seeds/ha. However, high soybean populations in either 38- or 19-cm row widths produced significantly fewer sicklepod plants than the standard 76-cm soybean population. Furthermore, soybean planted in 19-cm rows at the high seeding rate of 976 000 seeds/ha reduced sicklepod populations up to 80%.

Patterson et al. (1988) conducted a study in Alabama in which soybean was planted in 15, 30, 45, and 90-cm rows at a single population of 430 000 plants/ha. Soybean biomass and seed yield was affected more by sicklepod and common cocklebur competition when soybean row width decreased. Soybean biomass and yield decreased 14 kg/ha and 12 kg/ha, respectively, for each centimeter increase in soybean row width in season-long competition with sicklepod. Furthermore, sicklepod biomass increased 12 kg/ha for each centimeter increase in soybean row width. Soybean biomass and yield decreased 10 kg/ha and 16 kg/ha, respectively, for each centimeter increase in row width in season-long competition with common cocklebur. Furthermore, common cocklebur biomass increased 10 kg/ha for each centimeter increase in soybean row width.

The time of weed removal in soybean is important in preventing unacceptable yield loss. This term is often referred to as the critical time of weed removal (CTWR). In Nebraska, the critical time of weed removal (CTWR) was delayed in narrow row widths at all locations (Knezevic et al. 2003). The CTWR for soybean planted in 19-, 38-, and 76-cm rows was V3-V4, V2, and V1 soybean growth stages, respectively. Furthermore, the CTWR was 9 to 30 days longer when soybean was planted in 18-cm rows compared with 76-cm rows (Mulugeta and Boerboom 2000). Glyphosate applied at the V2, V4, or R1 soybean growth stages provided season-long control of weeds in 18-cm rows (Mulugeta and Boerboom 2000). In wide-row soybean, broadleaves emerged when glyphosate was applied at the V2 soybean growth stage due to lack of complete canopy closure. Mulugeta and Boerboom (2000) reported that 85-90% of weeds emerged at the V4 soybean growth stage, and that only 55 to 65% of total weed emergence occurred prior to the V2 soybean growth stage. In contrast, Dalley et al. (2004a) concluded that narrow-row soybean was more susceptible to early-season weed interference than wide-row soybean. Weed interference reduced soybean yield when glyphosate application was delayed until weeds were 15-cm or more in 19- and 38-cm rows. Dalley et al. (2004b) found that weed biomass production decreased in 76-cm rows when glyphosate applications were delayed; however, there was no benefit of delaying glyphosate application in row widths less than 38-cm. Weed biomass production was similar across all application timings for 19- and 38-cm rows.

V. CANOPY DEVELOPMENT

Canopy development, which is a function of row width, seeding rate, and environmental conditions, is an effective weed control tool (Duncan 1986; Peters et al. 1965). Increased soybean densities promote a quicker canopy closure by increasing the leaf area index and light interception (Bertram and Pederson 2004). Benefits of drilled soybean include quicker canopy development and greater weed control (Mickelson and Renner 1997). As row width decreased, the number of weeds that emerged after herbicide application decreased linearly as a result of more light being intercepted by the canopy (Yelverton and Coble 1991). Weed resurgence following herbicide applications was less under irrigated conditions because of rapid soybean canopy formation; however, yield was not significantly affected. Yelverton and Coble (1991) stated that late emerging weeds could contribute to the soil weed seedbank.

Planting soybean in 19- or 38-cm rows resulted in higher levels of light interception compared with 76-cm rows (Dalley et al. 2004a). Maximum light interception occurred 64 d after soybean emergence and was greater than 98% when soybean was planted in row widths less than 38 cm, but when soybean was planted in 76-cm rows light interception never exceeded 84%. Norsworthy and Oliver (2001) observed that the time to reach 90% canopy closure decreased as soybean density increased; however, all densities intercepted 88-99% of available light 70 d after soybean emergence. Researchers in Nebraska and Illinois reported canopy closure of soybean in 25-cm rows at 35 to 36 d after planting and 58 to 65 d after planting in 76-cm rows (Burnside and Colville 1964; Wax and Pendleton 1968). Carey and Defelice (1991) reported that soybean planted in 19-cm rows formed a canopy on average of 20 days earlier than soybean grown in 76-cm rows. Nelson and

Renner (1999) reported soybean canopy closure occurred 45 and 80 days after planting for 19- and 76-cm rows, respectively. Burnside and Colville (1964) observed that soybean planted in 25-, 45-, 76-, and 90-cm rows completely shaded the ground in 36, 47, 68, and 67 days after emergence, respectively.

VI. CANOPY PHYSIOLOGY

Canopy physiology is dependent on plant density and row width. Decreased row widths at equal plant densities produced more equidistant plant distribution (Shibles and Weber, 1966). This equidistant plant distribution decreased plant-to-plant competition for available water, nutrients, and light and increased radiation interception and biomass production. Andrade et al. (2002) reported that as row width decreased, radiation interception by the crop canopy increased. Therefore, yield response to reductions in soybean row width can be partly attributed to an improvement in radiation interception at the critical-pod setting period.

The leaf area index (LAI) that correlates to 95% solar radiation interception has been adopted as the critical LAI (Gardner et al. 1985). Light interception approaches a maximum asymptotically making it impossible to measure 100% light interception. Furthermore, 95% light interception under maximum solar radiation of 2300 μmol photons m^{-2} sec^{-1} means that radiation level at the bottom of the canopy is 115 μmol photons m^{-2} sec^{-1} which is the light compensation point for many species. Crop growth rate (CGR) did not increase significantly when light interception was above 95% (Shibles and Weber 1965). Norsworthy and Oliver (2001) found that yields over a range of seeding rates were similar when 95% or greater of photosynthetically active radiation was intercepted, but yields were reduced when soybean intercepted less than 95% photosynthetically active radiation.

Soybean at low populations (80 000 plants/ha) can achieve the same yield as medium (145 000 plants/ha) and high (390 000 plants/ha) populations when planted in 75-cm rows (Board 2000). This was a result of greater net assimilation rate (NAR) during vegetative growth and greater relative leaf area growth rate (RLAGR) during late vegetative and early reproductive growth. Soybean planted at low populations had a similar CGR compared with medium and high populations during the emergence to R5 growth period. CGR was similar between populations 14 to 21 days after emergence, but after 21 days after emergence CGR was twice as great when soybean was planted at the lower populations. CGR was consistently greater at low populations through the reproductive growth stages of soybean. Light interception efficiency was also greater in the low population compared with the high population and this explains the greater CGR at the low population. At soybean growth stage of R1, LAI was greater at higher populations compared with lower populations; however, LAI was similar between populations at R5. Greater RLAGR in low populations was due to a greater number of leaves produced rather than greater area on a per leaf basis.

Wells (1991) reported that canopy photosynthesis was linearly related to light interception and LAI prior to canopy closure, but not afterwards. Soybean planted in 43-cm rows had greater canopy apparent photosynthesis (CAP) than soybean planted in 96-cm rows. CAP was not different for any treatment after R5; however, differences were present prior to R5. The late season reduction in CAP was greater than indicated by light interception alone. The loss of photosynthetically inactive leaves after canopy closure explained the inability to relate LAI to light interception. Wells stated that when LAI was above critical levels after canopy closure, factors other than photosynthesis were involved in the response of yield to plant density. Weber et al. (1966) reported that leaf loss increased with higher populations but was relatively constant across row widths. Higher populations also increased the rate of LAI accumulation and resulted in greater rates of dry weight accumulation. However, the greatest difference among the populations occurred in narrow rows.

COMMON LAMBSQUARTERS

I. BIOLOGY AND GROWTH

Common lambsquarters is a successful colonizing species, and is one of the most widely distributed weeds in the world (Holm et al. 1977). It is found in 47 different countries in 40 different crops, and considered the 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 native to Britain, but is found on all continents from 70° N to 50° S except in areas of extreme desert (Holm 1977). Common lambsquarters grow mainly in disturbed areas, particularly near concentrations of nitrogen or organic matter (Mitich 1988). It is a common weed in plant communities and seedbanks (Forcella et al. 1997). The success of common lambsquarters as a competitive, wide-spread weed is attributable to many factors including seed germination in a wide range of environmental conditions (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).

Common lambsquarters is an annual plant with succulent stems and leaves, with short alternate branches, that grows from 0.6 to 1.5 m tall (Mitich 1988). As plants mature, stems may appear reddish from anthocyanin accumulation (Williams 1963). The leaves and stems of common lambsquarters are powdered with a whitish-gray meal, and leaf shape can vary from narrow to wide-pointed, toothed oval, or triangular with wavy teeth (Mitich 1988).

II. SEED PRODUCTION AND GERMINATION

The seeds of common lambsquarters are polymorphic and although some are brown (<3%) most are black and are either smooth or reticulate with raised lines (Williams and Harper 1965). Brown seeds readily germinate while black seeds are more dormant. The testae of black seeds are thicker and provide a physical barrier to prevent germination. All of these seed types can be found on a single plant (Williams and Harper 1965). Progeny grow in close association to the mother plant (Williams 1963) because a seed dispersal mechanism is not present. Common lambsquarters is hexaploid (2n=6x=54), with 34 subspecies in North America that are minor variants of *C. album* (Bassett and Crompton 1978). Flowers are perfect and can be cross- or self-pollinated by wind.

Common lambsquarters is a prolific seed producer, as seed production can range from 30 000 to 176 000 seeds per plant (Harrison 1990); however, an average-sized plant produces 72 450 seeds (Stevens 1932). Seed production generally varies according to plant density and biomass, and is related to the distance between each plant and to the size of neighboring plants (Harrison 1990). Seed yield per area remained constant regardless of density since seed production per plant decreased as plant density increased (Ervio 1971). In addition, total seed production increased as soil nitrate concentrations increased

(Williams and Harper 1965). Early sensitivity to photoperiod enables common lambsquarters seedlings to adjust the duration of vegetative development according to the length of the photoperiod (Huang et al. 2001). Flowering is induced indeterminately by a 14 h photoperiod allowing the plant to produce seed, regardless of plant developmental stage (Huang et al. 2001).

Day length and fertility level have been shown to influence seed characteristics and dormancy. Wuff et al. (1999) studied the progeny of five seed families of common lambsquarters under different environmental conditions. Common lambsquarters grown under low fertility produced seed that germinated at a higher frequency and more readily than plants grown under high fertility. Seed polymorphism was not modified by nitrogen, but there was evidence that early seed shed contained a higher than normal proportion of brown seeds (Williams and Harper 1965). The amount of brown seed with a high seed weight and a thin seed coat was promoted by short days during seed formation. A high percentage of black dormant seed with thick testa were produced under long day lengths (Bouwmeester and Karssen 1993; Cumming 1963; Henson 1970). These maternal effects allow common lambsquarters to have a plastic response to environmental conditions and to successfully colonize an area.

Common lambsquarters has two germination peaks, the first in the autumn soon after seed ripening, and the second in the spring in April-May (Williams and Harper 1965). The first coincides with the ability of brown seeds to germinate immediately upon release and the latter follows a period of chilling. Harvey and Forcella (1993) observed that common lambsquarters did not germinate at temperatures below 4 C, and that the optimum temperature for germination was 24 C.

Common lambsquarters flourishes in conventional tillage systems. Clements et al. (1996) observed that the top 5 cm of soil contained the highest concentration of common lambsquarters seeds, regardless of tillage type. Among tillage systems, moldboard plowing allowed the greatest amount of common lambsquarters seed to remain in the seedbank; however, in no-tillage systems there is a decrease in the total amount of seed. Tillage allows exposes seed to light which promotes germination (Baskin and Baskin 1977). Seeds that are buried remain viable and germinate in subsequent years when returned to a suitable depth (Baskin and Baskin 1977). Seeds are small and have little endosperm making it difficult for seedlings to emerge from soil depths greater than 2.5 cm (Weaver et al. 1988). Two cultivations per year increased the rate of seed loss in the soil (Roberts and Dawkins 1967).

The number of viable seeds in the top 23 cm of soil follows a pattern of exponential decay of 22% per year. Therefore, 1% of the initial population would remain after 18 years (Roberts and Dawkins 1967). In one study, 6% of seed germinated after 39 years (Toole and Brown 1946). Furthermore, seed germinated 89, 76, and 32% after 1, 2, and 20 years, respectively, after being stored at a soil depth of 13 cm (Lewis 1973).

The conditions required to relieve seed dormancy in common lambsquarters are complex and involve alternating temperature, nitrate, seed after-ripening, seed age, and light. Seed germination is generally improved if a combination of these factors interact together, but a single factor can replace another to initiate germination (Henson 1970). Cumming (1963) demonstrated that common lambsquarters germinated over a wider range of conditions than the less weedy species of the genus. In addition, Cumming stated that dormancy factors contribute to the success of common lambsquarters as a weed. Nitrate largely determines the germination response of young common lambsquarters seed. Light will substitute for nitrate, but their dual effect is much more than additive at a constant temperature of 23 C (Henson 1970). Younger seeds were more sensitive to nitrate and light given together, but when applied separately germination was not initiated. Long photoperiods inhibited germination compared with short photoperiods; however, seeds became indifferent to light as they aged. Alternating temperatures of 10/30 C increased the sensitivity to light and nitrates when given separately or together (Henson 1970). Responsiveness to light exists or can be induced by nitrate, alternating temperatures, or ageing of the seed. Increased nitrate fertilization during seed formation results in seeds that are more likely to germinate due to increased endogenous nitrate levels (Bouwmeester and Karssen 1993). Germination was highest at temperatures between 10 and 20 C; however, when temperatures are above 30 C or below 10 C fluctuation in germination was observed. In addition, when common lambsquarters seeds were desiccated and then re-imbibed in nitrate, 80-90% of the seeds germinated. Incomplete germination often occurred when seeds were tested at 10 C. At alternating temperatures of 30/15 or 35/20 C, germination occurred in darkness. Bouwmeester and Karssen (1993) stated that when indicators of a position close to the surface such as desiccation or alternating temperatures were present light is no longer required for germination.

The seed forms of common lambsquarters differ in dormancy and/or conditions to relieve dormancy. Williams and Harper (1965) observed that brown seeds imbibed 76-78% of their weight in water, while black reticulate and black smooth seeds imbibed 43% and 6% of their weight in water in the first 12 h, respectively. Brown seeds germinated quickly when they were provided with water, even at temperatures of 0 C. Black-reticulate seeds exhibited dormancy broken by nitrate, but not by chilling. Black-smooth seeds exhibited dormancy that was broken by nitrate and partly replaceable by chilling. Furthermore, the black seeds had chemical inhibitors present in the testa that prevented germination. Mulugeta and Stoltenberg (1998) observed that germination was similar in late-season cohort timings compared with early-season cohort timings after the testa was removed.

Common lambsquarters seed germinate at a higher percentage in light with a high red to far-red ratio (Cumming 1963). Established plants can alter the ratio of red to far-red by filtering it with their leaves which prevents seed from germinating in an unfavorable environment. The germination of common lambsquarters can be reversibly controlled by red and far-red light (Cumming 1959). Seeds did not germinate with water in the dark, but when seeds were desiccated or placed in nitrate, 20% of the seeds germinated (Bouwmeester and Karssen 1993).

Incomplete germination and the ability to continue germination when conditions are favorable, allowed common lambsquarters the ability to adapt to a wide range of environmental conditions (Cumming 1963). Seed exhibited incomplete germination in soil with low moisture under a photoperiod of 16 h. In addition, incomplete germinated seed remained viable for prolonged periods in moist or dry conditions, and rapidly continued germination when transferred to optimum conditions. Low temperatures favored incomplete germination, but the alternating temperature of 10/30 C favored complete germination despite photoperiod length (Bouwmeester and Karssen 1993). After the seeds are imbibed, Pfr, gibberellins 4 and 7, and ethylene cause the splitting of the outer testa layer. However, ABA inhibits the extension of the radicle from the seed coat, resulting in incomplete germination. In addition, the seasonal changes in germination may be the result of a combination of changes in the level or sensitivity to ABA and GA. Baskin and Baskin (1987) observed that common lambsquarters required low temperatures to complete after-ripening. Common lambsquarters must receive 1to 3 months of low-temperature after-ripening for 50% or more germination in March (15/6 C) and April (20/10 C). Common lambsquarters is a C_3 plant that germinates, has increased growth, and a higher photosynthetic rate under temperatures that range from 20 to 25 C (Chu et al. 1978). The ability for optimum growth under cool conditions in combination with early germination allows common lambsquarters to establish earlier and have a competitive advantage over a C_4 weed species like redroot pigweed (*Amaranthus retroflexus*).

Huang et al. (2001) observed that the vegetative growth of common lambquarters occurs over a wide temperature range. Shoot height increased as alternating temperatures increased from 12/2 to 29/19 C, but declined when temperature increased to 45/35 C. Common lambsquarters completes its reproductive development and produces mature seeds at temperatures ranging from 23/13 to 35/25 C. The cardinal temperatures for shoot elongation and radicle elongation are 25 and 26 C, respectively (Roman et al. 1999). Juvenile plants were rapidly sensitive to photoperiod, allowing reproductive growth soon after emergence under long-day lengths (Huang et al. 2001). This allowed plants to produce seed at the end of the growing season, regardless of emergence date.

III. COMPETITION

Common lambsquarters is plastic in its response to intra- and interspecific competition. Rohrig and Stutzel (2000) observed that with increasing competition in taller crops, common lambsquarters allocated relatively more biomass to stems than to leaves to outgrow competing plants. Under conditions of limited light, biomass was allocated to increase leaf area and leaf biomass, and at low densities plants produced 20 to 30% less dry matter than those planted at a 2.5-fold higher rate (Rohrig and Stutzel 2000). When grown in monoculture, increased densities caused stem diameter and the number of branches to decrease (Ervio 1971). However, plant height was greater when common lambsquarters was grown at higher densities. Increased density had no effect on seed output per unit area (Ervio 1971). When plants were subjected to competition there was a decrease in size and/or number of plant parts, with a consequent decrease in weight per plant (Ervio 1971).

Colquhoun et al. (2001) observed that soybean was more competitive with common lambsquarters than corn. Common lambsquarters grown in monoculture produced early-season leaf area similar to that when grown in corn. Competition increased between common lambsquarters and soybean due to below normal soil temperatures that favored the continuous germination of common lambsquarters. Soybean height was not greatly affected by common lambsquarters because soybean plant height increased at a rate greater than soybean leaf area. This effect was due to soybean senescing lower leaves and new leaf tissue was produced near the apex of the plant. Plants increased in height after maximum leaf area was attained and was attributed to inter- and intraspecific competition for light due to a mediated red: far-red phytochrome response. Common lambsquarters height and conical canopy shape allow for increased light capture.

Common lambsquarters at densities of 32 plants/10 m row reduced soybean yield 20% when common lambsquarters was present all season (Crook and Renner 1987). In North Carolina, soybean yield was reduced 15% at weed densities of 16 plants/10 m row (Shurtleff and Coble 1985). Harrison (1990) observed that for each kg/ha of common lambsquarters biomass there was a 0.25 kg/ha reduction in soybean yield. Soybean yield was reduced 25% when common lambsquarters competed all season with soybean at 20 plants/10 m row. Corn yield was reduced 12% at weed densities of 49 plants/10 m row (Beckett et al. 1988). Sibuga and Bandeen (1980) observed that corn yield was reduced 13 and 7% at common lambsquarters densities of 46 and 109 plants/m^2, respectively. Sugar beet yield was reduced 48% when 8 plants/10 m row were present all season (Schweizer 1983). Marketable tomato (*Lycopersicon esculentum* Mill.) yield was reduced 36% at common lambsquarters densities of 640 plants/10 m row (Bhowmik and Reddy 1988). Barley (*Hordeum vulgare* L.) yield was reduced 23 and 36% at common lambsquarters densities of 150 and 300-400 plants/m^2, respectively (Conn and Thomas 1987).

IV. CONTROL WITH GLYPHOSATE

Taylor et al. (1981) reported that it is difficult for postemergence herbicides to control common lambsquarters due to limited absorption through the waxy surface of the leaf. The wax forms a homogeneous covering over the entire leaf surface, though platelets are less dense over the mid-ribs, large veins, and stomata vicinity. This wax contains a substantial proportion of aldehydes which presents a barrier to penetration of polar molecules through the cuticle. Furthermore, environmental factors influence herbicide efficacy.

Ateh and Harvey (1999) reported that glyphosate at 310 g ae/ha controlled common lambsquarters when weeds were small (>15 cm) and soybean was at the V2 growth stage. When glyphosate was applied to larger weeds (>15 cm) at 840 g ae/ha, common lambsquarters was also controlled. Weed control was also more consistent in narrow-row soybean than in wide-row soybean.

Krausz et al. (1996) observed that common lambsquarters control was 100% when glyphosate was applied to 10-cm tall plants, regardless of glyphosate rate or spray volume. When glyphosate was applied to 20-cm common lambsquarters, control increased as glyphosate rate increased. Control was reduced 44% when glyphosate was applied at 560 g ae/ha in 93 L/ha water compared with glyphosate at the same rate in 187 L/ha water; however, there was no difference in control due to spray volumes when glyphosate rates were greater than 560 g ae/ha.

Schuster et al. (2004) observed that the glyphosate rate to reduce common lambsquarters growth 40% (GR_{40}) varied between populations. Common lambsquarters collected from Ohio had the highest GR_{40} value when glyphosate was applied. The GR_{40} values were 0.27 and 3.97 times the suggested use rate for 2.5- and 15-cm tall plants, respectively. In the same study, there were no differences in absorption or translocation of glyphosate among growth stages in common lambsquarters collected from Nebraska. Radioactivity translocated equally to foliage above the treated leaf, foliage below the treated leaf, and roots. Kniss et al. (2004) observed that as common lambsquarters growth changed from 4-leaf to 10-leaf the GR_{50} values doubled. The addition of ammonium sulfate to glyphosate increased common lambsquarters control 73 to 91% and 80 to 89% when applied to 10- and 25-cm plants, respectively.

INSECT-WEED INTERACTIONS

I. BIOLOGY OF BEET PETIOLE BORER

In the first extensive study of the beet petiole borer (*Cosmobaris americana*), Landis (1970) observed that larvae overwintered, then pupated in May. The pupal stage lasted 1-2 weeks. Some adult beetles cut holes in stems and emerged within 1-2 days while others delayed emergence until July. Adults were found on May 17 at Grandview, Washington, and May 19 at Stanfield, Oregon. After emergence, the adults fed primarily at nodes or stems of host plants. Once a female weevil was several weeks old, it laid a single egg in one of the feeding pits it had made. On weed hosts, feeding and oviposition pits and the shallow lesions were most abundant a short distance above the stem node. However, lesions were not found on the small stems of weeds. Gall-like growths were reported to develop on sugarbeet and common lambsquarters, but not on other weeds that serve as hosts. Larvae were often found near the oviposition site and the stem was usually swollen. Weed hosts did not appear stressed despite larval tunneling, with as many as 30 larvae found within a single plant. Mature larvae entered diapause in the stems of saltbrush (*Atriplex polycarpa*) as early as August. The beet petiole borer is more commonly found in weedy hosts than sugarbeet. In California, Gilbert (1964) reported that the most common host for beet petiole borer was common lambsquarters.

II. INFLUENCE OF INSECTS ON WEED CONTROL

There are many reports of the use of insects for biological control of weeds; however, there is little research on the effects of insect feeding on weeds and subsequent control from herbicides. Westra et al (1981) observed that the weevil *Notaris bimaculatus* reduced the effectiveness of glyphosate on quackgrass. *N. bimaculatus* adults fed on the culms of quackgrass and deposited eggs later in old feeding galleries. When the soil-insecticide chlordane was applied, the number of quackgrass shoots produced after glyphosate application was reduced. Although 100% control of *N. bimaculatus* was not observed, shoot counts were reduced 30% by using chlordane. In cage studies, there were fewer shoots produced by insect-free quackgrass compared with insect-infested quackgrass after glyphosate application.

From greenhouse studies, Ott et al. (2003) concluded that when giant ragweed was sprayed at heights of 40-44 cm with glyphosate at rates of 0.76 and 1.52 kg ae/ha, control was similar between plants infested with European corn borer and non-infested plants. In contrast, giant ragweed control was lower in infested- compared with non-infested plants when glyphosate was applied at the lowest rate of 0.63 kg ae/ha.

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CHAPTER 2

EFFECT OF SOYBEAN ROW WIDTH AND POPULATION ON CANOPY DEVELOPMENT, WEED BIOMASS, WEED EMERGENCE, YIELD, AND ECONOMIC RETURN.

ABSTRACT

Field studies were conducted to determine the effect of soybean row width and population on soybean canopy closure and yield, as well as the effect of soybean population and row width on weed biomass and economic return. Canopy closure occurred earlier in 19- and 38-cm rows compared with 76-cm rows. Soybean LAI was greater in 19- and 38-cm rows compared with 76-cm rows, 43 to 58 days after planting. Increasing the soybean population in 19- or 38-cm rows from 123 500 to 308 750 plants/ha increased soybean LAI 71 to 74 DAP at Clarksville and East Lansing in 2004. Increasing the soybean population in 19-cm rows from 197 600 to 444 600 plants/ha increased soybean LAI 56 to 64 DAP at East Lansing in 2004 and St. Charles in 2004 and 2005. Canopy development was similar in 76-cm rows at peak canopy, regardless of the soybean population. Fewer weeds emerged in the 35 days following a single application of glyphosate in 19- and 38-cm rows compared with 76-cm rows. Higher soybean populations reduced weed biomass; however, there was a trend for reduced biomass in 19-cm row soybeans. Under weedy conditions, soybean yield was greater in 19- and 38-cm rows at populations of 296 400 to 444 600 plants/ha, and in 76-cm rows at populations of 185 250 to 308 750 plants/ha. In weed-free conditions, yield was greatest when soybean was planted at 308 750 to 444 600 in 19-cm rows and 296 400 to 308 750 in 38-and 76-cm rows. The greatest economic return was in 19-cm rows at 308 750 plants/ha at Clarksville and East Lansing in 2004. The greatest

economic return was in 19-cm rows at 444 600 plants/ha at East Lansing in 2005 and St. Charles in 2004 and 2005. Therefore, increased seeding rates in 19-cm rows resulted in greater yield, while relatively lower seeding rates are appropriate for 76-cm rows.

Nomenclature: Glyphosate, N-(phosphonomethyl) glycine, soybean 'AG 2701', *Glycine max* (L.) Merr.

Keywords: soybean populations, row spacing, weed emergence, canopy development, weed competition.

Abbreviations: CGR, crop growth rate; DAP, days after planting; DAT, days after treatment; POST, postemergence; LAI, leaf area index.

INTRODUCTION

Soybean row width has traditionally been limited to 76-cm rows to allow for late-season row cultivation (Wax et al. 1977). However, advances in herbicide development and equipment have allowed growers to plant soybean in narrow rows and rely heavily on the use of herbicides to control weeds. Weed control is generally better in narrow rows compared with wide rows (Chandler et al. 2001; Mickelson and Renner 1997, Mulugeta and Boerboom 2000; Nelson and Renner 1999; Peter et a. 1965), due to more rapid canopy closure (Burnside and Colville 1964; Burnside and Moomaw 1977; Legere and Schreiber 1989; Mickelson and Renner 1997; Peters et al. 1965, Yelverton and Coble 1991).

Canopy development, which is a function of row width, seeding rate, and environmental conditions, is an effective weed control tool (Duncan 1986; Peters et al. 1965). Increasing soybean density promotes quicker canopy closure by increasing leaf area index (LAI) and resulting light interception (Bertram and Pederson 2004). As row width decreases, the number of weeds that emerge after herbicide application decreases linearly because sunlight is intercepted by the crop canopy (Yelverton and Coble 1991). Researchers in Nebraska and Illinois reported soybean canopy closure in 25-and 76-cm rows 35 to 36 and 58 to 65 days after planting, respectively (Burnside and Colville, 1964; Wax and Pendleton, 1968). Similarly, Carey and Defelice (1991) reported that soybean planted in 19-cm rows formed a canopy an average of 20 days earlier than soybean grown in 76-cm rows, while Nelson and Renner (1999) reported soybean canopy closure 45 and 80 days after planting for 19- and 76-cm rows, respectively.

When row width is narrowed, there is more equidistant plant distribution in the field (Shibles and Weber, 1966). Equisdistant plant distribution decreases intraspecific competition for water, nutrients, and light, and increases radiation interception and biomass production (Shibles and Weber, 1966). The LAI that correlates to 95% solar radiation interception has been adopted as the critical LAI (Gardner et al. 1985). Soybean crop growth rate (CGR) does not increase significantly when light interception is greater than 95% (Shibles and Weber 1965). Furthermore, soybean yield over a range of seeding rates was similar when 95% or more of photosynthetically active radiation was intercepted (Norsworthy and Oliver 2001).

Soybean yield is usually greater in narrow-row compared with wide-row soybean when water is not limited. This is partly due to better distribution of soybean plants over the soil surface for more efficient use available water, light, and mineral nutrients (Burnside and Colville 1964). Soybean seeding rate can also influence soybean yield. Bertram and Pedersen (2004) reported that there was no difference between the recommended seeding rates and seeding rates 20% higher for 19-, 38-, and 76-cm row widths. However, soybean yield decreased 6% when soybean populations were lowered 20% from the recommended seeding rates of 556 000, 432 000, and 309 000 for soybean planted in 19-, 38-, and 76-cm rows, respectively. In contrast, Kratochvil et al. (2004) observed that soybean seeding rates 20% less than the recommended seeding rate consistently produced yields similar to the standard soybean seeding rate of 432 250 seeds/ha in 19- and 38-cm rows. An additional profit of $14 to $28/ha was realized when soybean was planted at 20% less than the standard seeding rate. Soybean yield and economic returns were $45 to $65/ha greater in narrow-row compared with wide-row soybean when similar management systems were implemented (Nelson and Renner 1999).

The cost of seeding glyphosate resistant soybean is $20-25/ha more than non-glyphosate-resistant seed (Kratochvil et al. 2004). Seeding rates for narrow-row soybean are 20 to 45% greater than wide-row soybean (Bertram and Pedersen 2004; Kratochvil et al. 2004; Norsworthy and Frederick 2002). Lowering seeding rates is a strategy producers can utilize to lower production costs. However, the influence of lower than optimal seeding rates on soybean competitiveness with weeds has not been researched extensively. Therefore, the objectives of this study were to determine the effect of soybean row spacing and population on 1) soybean canopy closure and soybean yield, 2) weed biomass, and 3) the economic returns when seeding soybean at higher population and in narrow rows.

MATERIALS AND METHODS

Field experiments were conducted at three locations in Michigan in 2004 and 2005 (Table 1). An indeterminate group II soybean glyphosate-resistant cultivar, 'AG 2107[1]' was planted in plots measuring 3 m wide by 10.7 m long in 2004, and 3 m wide by 9.1 m long in 2005. Soybean was planted in three row widths (19-, 38-, and 76-cm) using a customized toolbar with John Deere planter units. Soybean populations were thinned to target populations of 197 600, 296 400, and 444 600 plants/ha prior to the V1 growth stage Due to heavy rains following planting that lowered initial populations soybeans were thinned to target population of 123 500, 185 250, and 308 750 plants/ha at East Lansing in 2004 and at Clarksville in 2004 and 2005.

Herbicide treatments at all locations included a POST application of glyphosate[2] at 0.84 kg ae/ha + ammonium sulfate at 2% w/w to 10-cm weeds, a weed-free control, and a weedy control. Weed-free plots were maintained with two POST glyphosate applications at V2 and V5. All herbicides were applied using a tractor-mounted compressed-air sprayer calibrated to deliver 178 L/ha at 207 kPa using Airmix 11003[3] nozzles. Soybean yield was determined by harvesting the center 1.52 m of each plot for seed yield and adjusting seed yield to 13% moisture.

Soybean Canopy Development

The amount of light transmitted through the soybean canopy was measured every 1 to 2 weeks at or near solar noon at each site beginning five weeks after soybean planting until the canopy began to senesce. Measurements were taken in weed-free plots using the

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[1] Asgrow Seed Co., Monsanto Co., 800 North Lindbergh Boulevard, St. Louis, MO 63167.
[2] Roundup WeatherMAX, Monsanto., 800 North Lindbergh Boulevard, St. Louis, MO 63167.
[3] Teejet Airmix 11003, Spraying Systems Co., North Avenue, Wheaton, IL 60188.

Sunscan Canopy Analysis System[4]. The SunScan system consisted of three components: 1) a wand that was 1 m long and 13 mm wide with sensors placed every 15.6 mm along the length of the wand with a spectral response of 400 to 700 nm to measure light beneath the crop canopy; 2) a tripod-mounted sensor that measured both incident and diffuse light above the crop canopy; and 3) a handheld Psion Workabout datalogger[5] that recorded simultaneous measurements of light above and beneath the crop canopy. Light transmission, as a percent of incident, was automatically calculated as each measurement was taken perpendicular to the soybean row from the weed-free plots.

Weed Emergence

Weed emergence was recorded at Clarksville and East Lansing in 2004 and at East Lansing and St. Charles in 2005. Weed emergence was not recorded at St. Charles in 2004 due to little or no weeds present following the glyphosate application. The number of weeds that emerged after the 10-cm POST glyphosate application was recorded from 15- by 150-cm quadrats (0.225 m^2) that were established at the time of application. Two quadrats were placed in the center of each plot, perpendicular to the crop row. Density of each weed species was recorded weekly beginning 14 DAT, and ending 42 DAT.

Weed Biomass

Weed biomass and density were measured in the weedy-control in mid-August. Aboveground weed biomass was also measured in two quadrats placed in the 10-cm glyphosate treatments at all locations except at St. Charles in 2004 where there was little or no weed biomass. Quadrats were randomly placed in the center of each plot, with length

[4] Delta-T Device LTC, 128 Low Road, Burwell, Cambridge CB5 0EJ, England.
[5] Psion Digital, 1810 Airport Exchange Boulevard, Suite 500, Erlanger KY 41018.

perpendicular to the crop row. Weeds were separated by species, dried in a forced-air oven at 60 C, and dry weights calculated (kg/ha).

Economic Analysis

An economic analysis determined the gross margin for the 10-cm glyphosate treatment, since this is a common weed management system. Seed and herbicide prices were obtained from local seed and agrichemical dealers. Weed management costs were the sum of seed and herbicide costs. Seed cost was $0.81/kg of seed with a $0.62/kg seed technology fee assessed for the glyphosate trait. Seed cost was based on a weight of 6600 seed/kg. Herbicide cost for glyphosate plus AMS was $25/ha, and application cost was $15/ha. Weed management input costs for herbicide treatments included herbicide, adjuvant, application, and seed costs. Gross receipts were the product of crop yield and the assumed market price. Market prices of $0.18, 0.22, and 0.26/kg of seed yield were used to determine gross receipts. Gross margin was the difference between the gross receipt and weed management costs.

Statistical Analysis

The experiment design was a split-split plot with four replications. The main plot was row width, the sub-plot was soybean population, and the sub-sub-plot was herbicide treatment. Data were subjected to ANOVA using the PROC MIXED procedure in SAS 8.02[6] software. Main effects and all possible interactions were tested using the appropriate expected mean square values as recommended by McIntosh (1983). Each location combination was considered an environment sample at random from a population as suggested by Carmer et al. (1989). Environments, replications (nested within

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

environments), and all interactions containing these effects were declared random effects in the model; row width, population, and herbicide were designated as fixed effects. Data from locations with similar populations were combined and mean separation performed using Fisher's Protected LSD at α=0.05.

RESULTS AND DISCUSSION

Growing Conditions

Rainfall in 2004 was greater than the 30 year average at all locations (Table 2). Soybean had difficulty emerging at Clarksville and East Lansing due to excessive May rains and soil crusting after planting. In 2005, total rainfall was slightly lower than the 30 year average at East Lansing and St. Charles, and rainfall was below normal in the month of August during the time of soybean pod fill in Michigan. At Clarksville in 2005, total rainfall was about half the 30 yr average; however, soil crusting occurred again at this location after planting and reduced soybean populations. Weed densities were slightly lower in 2004 (36 weeds/m^2) at Clarksville compared with 2005 (52 weeds/m^2) (Table 3). At East Lansing weed densities were similar both years. The biggest change in weed density between years occurred at St. Charles. In 2004, weed density at St. Charles was 13 weeds/m^2 compared to 71 weeds/m^2 in 2005.

Soybean Canopy Development

At Clarksville and East Lansing in 2004, LAI did not differ due to soybean row width or soybean population from 35-39 to 55-64 days after planting (DAP) (Table 4). At 55-64 DAP, LAI was greater in 19- and 38- cm rows compared with 76-cm rows at soybean populations of 185 250 and 308 750 plants/ha. Soybean LAI in 19- and 38-cm rows at the lowest population of 123 500 plants/ha was similar to soybean planted in 76-cm rows at the highest population of 308 750 plants/ha at 71-82 DAP. This indicates that a soybean populations of 123 500 plants/ha in 19- or 38-cm rows had greater LAI than soybean planted at 308 750 plants/ha in 76-cm rows. Canopy development was greatest at 88-90 DAP for soybeans planted at all populations in each row width and the canopy began to senesce shortly after. At 88-90 DAP, LAI was similar between 19- and 38-cm rows at 308 750 plants/ha. Soybean population had little influence on soybean canopy development in 76-cm rows despite a 2.5 fold difference between the low and high populations.

At East Lansing in 2005 and St. Charles in 2004 and 2005, soybean canopy development was similar between row widths at populations of 197 600 and 444 600 plants/ha at 39-48 DAP (Table 5). By 76-83 DAP, soybean in 19- and 38-cm rows had greater LAIs than soybean planted in 76-cm rows, regardless of soybean population. Furthermore, LAI was greater in 19-cm rows at 444 600 plants/ha compared with 197 600 plants/ha. By 85-93 DAP, soybean planted in 38-cm rows had greater LAIs a than 76-cm row soybean, regardless of population. Canopy senescence began at 98-103 DAP; leaf area at this time was similar among all row spacings and populations. From 70-103 DAP, canopy development was similar in 38- and 76-cm rows. These results indicate that row width influenced canopy development more than soybean population at East Lansing and St. Charles.

At Clarksville in 2005, LAI was greater in 19- and 38-cm rows compared with 76-cm rows at 185 250 plants/ha at 58 DAP; however, canopy development was similar between treatments 64 DAP (Table 6). At 76 and 90 DAP, LAI was greater in 19- and 38-cm rows compared with 76-cm rows, regardless of population. Canopy development was greatest at 96 DAP; LAI was similar among 19- and 38-cm rows, regardless of population.

These results show that at peak canopy development, LAI was greater in 19- and 38-cm rows compared with 76-cm rows in 5 of 6 site years. At Clarksville in 2005, LAI was similar at between row widths at 185 250 plants/ha, probably due to very low rainfall.

Furthermore, the high population of 185 250 at Clarksville is sub-optimal for 19-, 38, and 76-cm rows (Bertram and Pedersen 2004). At peak canopy development, LAI was greater in 19- and 38-cm rows at 308 750 plants/ha compared with 123 500 plants/ha at Clarksville and East Lansing in 2004. Soybean planted at 444 600 plants/ha had greater LAI compared with 197 600 plants/ha in 19-cm rows at East Lansing in 2005 and St. Charles in 2004 and 2005. Soybean population in 76-cm rows had no effect on soybean LAI in 5 of 6 site years.

The LAI that correlates to 95% solar radiation interception has been adopted as critical LAI (Gardner et al. 1985). When there is 95% light interception under maximum solar radiation of 2300 μmol photons m^{-2} sec^{-1} radiation at the bottom of the canopy is 115 μmol photons m^{-2} sec^{-1} which is the light compensation point for many species. For these studies, 95% light interception occurred when LAI was around 5.5 (data not shown). Canopy closure occurred approximately 16 d earlier in 19- and 38-cm rows at Clarksville and East Lansing and 6-12 d earlier at East Lansing and St. Charles compare with 76-cm rows. Other researchers have also shown earlier canopy closure in narrow rows (Burnside and Colville 1964; Carey and Defelice 1991; Nelson and Renner 1999; Wax and Pendleton 1968).

Weed Emergence

Weed emergence following the 10-cm glyphosate application was lower in narrow row soybeans; soybean population had no effect on weed emergence. Data are therefore combined across soybean populations. At Clarksville and East Lansing in 2004, weed emergence in 19- and 38-cm rows was reduced compared to emergence in 76-cm rows 21 DAT (Figure 1). Soybean canopy measured 55-64 DAP corresponds to weed emergence

14 DAT. Canopy closure occurred when LAI reached a value of 5.5 which first occurred in 19- and 38-cm rows at 308 750 plants/ha when weed emergence was recorded 21 DAT. Since the soybean canopy developed more slowly in 76-cm rows, weed emergence was greater 35 DAT.

At East Lansing in 2005 and St. Charles in 2004 and 2005, weed emergence in 38-cm rows was similar to emergence in 76-cm rows 14 and 21 DAT (Figure 2). By 35 DAT, weed emergence was greater in 76-cm rows compared with emergence in 19- and 38-cm rows. Soybean LAI was greater in 19- and 38-cm rows compared with 76-cm rows from 49-58 DAP until 76-83 DAP. Canopy closure occurred around 70-71 DAP which corresponds to weed emergence 28 DAT, thus explaining higher weed emergence early on at East Lansing in 2005 and St. Charles in 2004 and 2005 compared with Clarksville and East Lansing in 2004. At Clarksville and East Lansing in 2004, canopy closure occurred at weed emergence 21 DAT. The number of weeds continued to decline over time in 19- and 38-cm compared with 76-cm rows, because the light available was less than the light compensation point.

Soybean planted in 19- or 38-cm rows reduced weed emergence following herbicide application in 5 of 5 site years, resulting in better weed control in comparison to 76-cm rows. Other researchers have also reported better weed control in narrow-row soybean due to earlier canopy closure (Burnside and Collville 1964; Chandler et al. 2001; Mickelson and Renner 1997; Nelson and Renner 1999). Our results support those of Yelverton and Coble (1991) who observed low weed emergence after herbicide application in narrow-row soybean. Weeds that emerge later in season may not reduce yield, but contribute to the seed bank (Yelverton and Coble 1991).

Weed Biomass

Weed biomass in the weedy-control treatment was similar among row widths at each population at Clarksville and East Lansing in 2004 (Figure 3); however, weed biomass was reduced in soybean planted at higher populations in 19-cm rows. There was a trend for reduced weed biomass in 19- and 38-cm rows compared with 76-cm rows. A similar trend in regards to row width was observed at East Lansing in 2004 and St. Charles in 2004 and 2005 at 197 600 and 444 600 plants/ha (Figure 4). However, weed biomass was lower in 19-cm rows compared with 38- and 76-cm rows at 296 400 plants/ha. At Clarksville in 2005, weed biomass was similar among treatments (Figure 5).

There were few weeds following glyphosate application, and many of the harvested weeds were small in size. Weed biomass after the glyphosate application was similar among soybean row widths and populations at Clarksville and East Lansing in 2004 (Figure 6). Weed biomass was greatest in soybean planted at 197 600 plants/ha in 76-cm rows; however, weed biomass was similar between 19- and 38-cm rows, regardless of population in 76-cm rows at 296 400 and 444 600 plants/ha (Figure 7). At Clarksville in 2005, weed biomass was similar across treatments, but the only measurable biomass was produced in 76-cm rows (Figure 8).

Weed biomass in weedy control plots was reduced by increasing soybean population; however, there was a trend for greater weed biomass in 76-cm rows. Previous research has shown that narrow-row soybean reduces weed biomass when no herbicide is used (Burnside and Collville 1964; Dalley et al. 2004b; Nice et al. 2001; Patterson et al. 1988). Our research supports those results. At the lowest soybean population, biomass in the weedy-control was similar regardless of row width; however, increasing the soybean population in narrow rows provided a greater reduction of weed biomass. Nice et al. (2001) reported similar results with sicklepod (*Senna obtusifolia*) in soybean. Weed biomass after glyphosate application was variable but there was a trend for less biomass in narrow-row soybean at higher plant populations in 4 of 6 site years, supporting research in Wisconsin (Ateh and Harvey 1999), Illinois (Young et al. 2001), and Michigan research (Dalley et al. 2004b; Nelson and Renner 1999).

Soybean Yield

At Clarksville and East Lansing in 2004, soybean yield was greater in 19- and 38-cm rows compared with 76-cm rows at each population (Table 7); however, yields were similar between 19- and 38-cm rows. Yield was greater at the high population of 308 750 plants/ha compared with the low population of 123 500 plants/ha in each row width. The intermediate population of 185 250 plants/ha yielded similar to the high population in 38- and 76-cm rows. Yields were similar between weed-free and 10-cm glyphosate treatments, despite weed emergence following glyphosate application. Soybean yields in 10-cm glyphosate treatments were similar between 19- and 38-cm rows and were greater than 76-cm rows at 123 500 and 185 250 plants/ha. Yield of soybean planted at 308 750 plants/ha was similar for 38- and 76-cm rows. Soybean yield in the weedy-controls was much lower than yield in the 10-cm glyphosate and weed-free treatments. At 123 500 and 185 250 plants/ha, yields of soybean in the weedy-control treatment were similar across row width. At 308 750 plants/ha, yield was greater in 19- and 38-cm rows compared with 76-cm rows.

At St. Charles in 2004 and 2005 and East Lansing in 2005, which had higher populations, weed-free soybean yield was greater in 19- and 38-cm rows compared with 76-cm rows, regardless of population (Table 8). Increasing the soybean population did not increase soybean yield in 76-cm rows; however, yields were greater when soybean was planted at 444 600 plants/ha compared with 197 600 plants/ha in 19- and 38-cm rows. Yields were similar between 19- and 38-cm rows for each respective population. Yields were similar between weed-free and 10-cm glyphosate treatments. Yield of soybean treated with glyphosate was similar in the 19- and 38-cm rows and yield was greater than yield in 76-cm rows at each population. Soybean yields were greater at 444 600 plants/ha compared with 197 600 plants/ha in 19- and 38-cm rows, but were similar in 76-cm rows. Weedy-control yields were greater in 19-cm rows compared with 76-cm rows at each population. Yields were similar between populations in both 19- and 76-cm rows, but in 38-cm rows soybean at 444 600 plants/ha had greater yields than 197 600 plants/ha.

At Clarksville in 2005, soybean yield in the weed-free plots was greater in 19-cm rows compared with 76-cm rows at 185 250 plants/ha; however, yields were similar at 123 500 plants/ha (Table 7). Yields were similar in the 10-cm glyphosate and weed-free control treatments. Similar to weed-free yields, yield of soybean treated with glyphosate was greater at 185 250 plants/ha in 19-cm row compared with 76-cm rows.

Planting soybean in narrow rows increases soybean yield (Wiggans 1939; Etheredge et al. 1989; Ikeda 1992; Board and Harville 1993; Egli 1994). Our research supports those findings. Average weed-free soybean yield was 4139 kg/ha at Clarksville and East Lansing in 2004 and 3913 kg/ha at St. Charles and East Lansing in 2004 and 2005. Despite having lower soybean populations at Clarksville and East Lansing, weed-free yield was higher compared with St. Charles and East Lansing and was probably due to greater rainfall in 2004. Despite having studies with two different ranges of populations, yield was greater in 19-and 38-cm rows compared with 76-cm rows for each population.

Trends were similar between studies in regard to 19- and 38-cm rows, but differed in response to population in 76-cm rows. Yields were greater at higher populations in 76-cm rows at Clarksville and East Lansing, possibly due to both greater rainfall and lower populations. Seeding recommendations for 76-cm rows is 309 000 seeds/ha which corresponds to the high populations at Clarksville and East Lansing, Recommended seeding rates for 19- and 38-cm row are 556 000 and 432 000 seeds/ha (Bertram and Pedersen 2004), higher populations than the populations in our research.

Weed biomass after glyphosate application did not affect yield in comparison to weed-free plots. Similar results have also been reported (Dalley et al. 2004a; Yelverton and Coble 1991). Similar to weed-free yields, planting soybean at higher populations increased yield in each row width at Clarksville and East Lansing in 2004; however, this trend was also observed in 19- and 38-cm rows at East Lansing in 2004 and St. Charles in 2004 and 2005. Soybean yield in the weedy-control was greater at higher populations in 19-cm rows at Clarksville and East Lansing in 2004 and in 38-cm rows at East Lansing in 2005 and St. Charles in 2004 and 2005. Planting soybean in 19-cm compared with 76-cm rows increased soybean yield at East Lansing in 2004 and St. Charles and 2005 for each population; however, this was true at 308 750 plants/ha at Clarksville and East Lansing in 2004.

Economic Return

At Clarksville and East Lansing, soybean planted in 19-cm rows at 308 750 plants/ha had the greatest gross margin, regardless of grain price (Table 10). In 38-cm rows, gross margins were similar regardless of population; however, gross margins tended to be higher as soybean population increased. Gross margins were greater in 19-cm rows compared with 76-cm rows for each respective population. In 76-cm rows, gross margins were similar between 185 250 and 308 750 plants/ha, but were greater than 123 500 plants/ha. Furthermore, there was a trend for greater gross margins as population increased in 38- and 76-cm rows. At East Lansing and St. Charles, the gross margins were similar among populations in 19- and 38-cm rows(Table 11); however, gross margins increased as population increased in 19-cm rows. Gross margins were greater in 19- and 38-cm rows compared with 76-cm rows at 444 600 plants/ha. In 76-cm rows the highest return occurred at 296 400 plants/ha. At Clarksville in 2005, gross margins were similar among populations in 19- and 76-cm rows, but gross margins were greater at 185 250 compared with 123 500 plants/ha in 38-cm rows (Table 12). There was no difference in gross margins among row widths at 185 250 plants/ha.

In conclusion, soybean LAI was higher in 19- and 38-cm rows compared with 76-cm rows. Increasing population in 19- or 38-cm rows resulted in greater LAI; however, LAI was similar regardless of population in 76-cm rows at peak canopy development. Canopy closure occurred 15-22 days earlier in 19- and 38-cm rows compared with 76-cm rows. Weed emergence after a single application of glyphosate was lower in 19- and 38-cm rows than 76-cm rows 35 DAT; weed biomass was variable. Weed biomass was reduced in the weedy control treatment by planting higher soybean populations within a row width. There was a trend for a reduction in weed biomass as row width narrowed. Under weedy conditions, yields were greatest when soybean was planted at 296 400 to 444 600 plants/ha in 19- and 38-cm rows, and 185 250 to 308 750 plants/ha in 76-cm rows. In weed-free conditions, yield was greatest when soybean was planted at 308 750 to 444 600 in 19-cm rows and 296 400 to 308 750 in 38-and 76-cm rows. The greatest economic return was in 19-cm rows at 308 750 plants/ha at Clarksville and East Lansing in 2004. The greatest economic return was in 19-cm rows at 444 600 plants/ha at East Lansing in 2005 and St. Charles in 2004 and 2005.

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Table 1. Field characteristics for the three Michigan locations in 2004 and 2005.

	Clarksville	East Lansing	St. Charles
Soil series	Lapeer loam	Capac sandy clay loam	Misteguay silty clay loam
Soil family	coarse-loamy, mixed mesic Mollic Haplaquepts	fine-loamy, mixed mesic Aeric Ochraqualfs	fine-loamy, mixed, mesic Aeric Endoaquepts
Soil characteristics			
pH	6.1	7.0	8.1
OM, %	2.6	4.1	3.0
Planting date			
2004	19 May	29 May	19 May
2005	12 May	5 May	19 May
Population, plants/ha			
2004	123 500 185 250 308 750	123 500 185 250 308 750	197 600 296 400 444 600
2005	123 500 185 250	197 600 296 400 444 600	197 600 296 400 444 600
Harvest date			
2004	12 October	12 October	12 October
2005	21 October	13 October	29 September

Table 2. Monthly precipitation recorded at the Clarksville Horticulture Experiment Station in Clarksville, MI, at the Michigan State University Department of Horticulture and Research Center, East Lansing, MI, and at the Saginaw Valley Bean and Beet Farm, St. Charles, MI.

	Precipitation (cm)								
	Clarksville			East Lansing			St. Charles		
	2004	2005	30 yr.	2004	2005	30 yr.	2004	2005	30 yr.
May	21.8	4.5	7.4	20.5	3.3	6.9	16.5	4.4	6.3
June	7.6	4.1	9.7	8.9	10.9	9.0	6.9	12.6	7.8
July	12.2	5.2	6.0	10.2	11.6	7.7	5.1	8.1	7.2
Aug.	6.6	2.4	9.2	8.7	1.6	7.9	5.9	2.1	8.4
Total	48.2	16.2	32.3	48.3	27.4	31.5	34.4	27.2	29.7

Table 3. Weed densities at Clarksville, East Lansing, and St. Charles in 2004 and 2005.[a]

Year	ABUTH[b]	AMARE	AMBEL	ANGR	BARVU	BRAKA	CHEAL	Total
	weeds/m^2 at Clarksville							
2004	0	2	3	7	21	0	3	36
2005	1	1	2	18	8	0	22	52
	weeds/m^2 at East Lansing							
2004	3	4	8	80	0	6	1	102
2005	2	2	13	72	0	6	11	106
	weeds/m^2 at St. Charles							
2004	0	1	2	1	0	0	9	13
2005	0	16	0	12	0	0	43	71

[a] Reported weed densities were measured at time of weed harvest.

[b]ABUTH=velvetleaf, AMARE=redroot pigweed, AMBEL=common ragweed, ANGR=annual grass (including giant foxtail, green foxtail, yellow foxtail, and barnyardgrass), BARVU=yellow rocket, BRAKA=wild mustard, and CHEAL=common lambsquarters.

Table 4. Soybean canopy development at Clarksville and East Lansing in 2004. Leaf area index (LAI) was obtained by a non-destructive measurement using the SunScan Canopy Analysis System. Different letters within each column represent mean separation at $LSD_{0.05}$.

	Days after planting						
Population	35-39	43-48	55-64	71-74	81-82	88-90	96-98
19-cm	LAI						
123 500	0.53 cde	0.83 e	1.72 c	4.23 c	5.13 cd	5.99 d	4.89 c
185 250	0.53 b-e	1.17 bc	2.14 bc	4.83 c	5.74 b	6.68 cd	5.01 c
308 750	0.60 abc	1.39 a	2.94 a	6.77 b	6.21 ab	7.26 abc	6.32 ab
38-cm							
123 500	0.51 de	0.94 de	2.02 bc	4.86 c	5.49 bc	6.71 bcd	5.39 bc
185 250	0.52 de	1.05 cd	2.69 ab	5.90 b	6.70 a	7.46 ab	5.52 bc
308 750	0.65 a	1.30 ab	3.35 a	7.94 a	7.05 a	8.00 a	6.80 a
76-cm							
123 500	0.49 e	0.98 de	1.60 c	2.90 d	3.67 e	5.62 d	4.76 c
185 250	0.57 bcd	1.00 d	1.90 c	3.00 d	4.37 de	6.10 d	4.99 c
308 750	0.63 ab	1.21 abc	2.05 bc	3.90 cd	4.60 cd	6.42 cd	5.30 bc

Table 5. Soybean canopy development at East Lansing in 2004 and St. Charles in 2004 and 2005. Leaf area index (LAI) was obtained by a non-destructive measurement using the SunScan Canopy Analysis System. Different letters within each column represent mean separation at $LSD_{0.05}$.

	Days after planting						
Population	39-48	49-58	56-64	70-71	76-83	85-93	98-103
19-cm	LAI						
197 600	0.53 def	2.13 bcd	3.20 de	6.15 ab	7.50 a	7.71 bc	5.85 a
296 400	0.70 abc	2.20 bc	3.51 bcd	6.46 a	7.35 a	8.47 ab	5.85 a
444 600	0.84 a	2.84 a	3.98 ab	6.39 a	7.98 a	8.68 a	5.88 a
38-cm							
197 600	0.48 ef	1.87 cde	3.40 cd	6.04 ab	7.37 a	8.07 ab	5.49 a
296 400	0.73 abc	2.25 b	3.86 abc	6.19 ab	7.61 a	8.29 ab	5.92 a
444 600	0.78 ab	2.76 a	4.36 a	6.75 ab	7.94 a	8.27 ab	5.90 a
76-cm							
197 600	0.44 f	1.62 e	2.46 f	4.87 c	5.89 b	6.62 d	5.56 a
296 400	0.60 cde	1.80 de	2.83 ef	4.79 c	5.59 b	6.99 cd	5.34 a
444 600	0.66 bcd	1.82 de	3.14 de	5.22bc	6.04 b	7.20 cd	5.45 a

Table 6. Soybean canopy development at Clarksville in 2005. Leaf area index (LAI) was obtained by a non-destructive measurement using the SunScan Canopy Analysis System. Different letters within each column represent mean separation at $LSD_{0.05}$.

	Days after planting					
Population	58	64	76	90	96	106
19-cm	LAI					
123 500	1.7 ab	3.1 a	5.0 ab	5.8 a	6.5 a	5.0 a
185 250	2.0 a	3.3 a	4.8 b	6.3 a	5.9 a	3.9 b
38-cm						
123 500	1.6 bc	3.1 a	4.8 b	5.8 a	6.3 a	4.5 a
185 250	1.8 a	3.1 a	5.3 a	6.3 a	6.5 a	4.7 a
76-cm						
123 500	1.3 c	2.5 a	4.0 d	4.9 b	4.8 b	3.7 b
185 250	1.3 c	2.7 a	4.5 c	4.6 b	5.8 a	3.9 b

Table 7. Effect of soybean row width, population, and herbicide treatment on soybean yield at Clarksville and East Lansing in 2004.[ab]

	Soybean Yield (kg/ha)		
Population	Weed-free	Weedy-control	Glyphosate
19-cm			
123 500	3966 D(cde)	1250 D (jk)	3832 D(def)
185 250	4262 BC(a-d)	1660 BCD(hij)	4147 BC(b-e)
308 750	4598 A(ab)	2642 A(g)	4638 A(a)
38-cm			
123 500	3959 D(cde)	1479 BCD(ijk)	3939 CD(de)
185 250	4289 BC(a-d)	1909 BC(hi)	4060 BC(cde)
308 750	4423 AB(abc)	2077 AB(gh)	4215 B(a-d)
76-cm			
123 500	3677 E(ef)	1049 D(k)	3381 E(e)
185 250	3959 D(c-e)	1318 CD(jk)	3778 D(def)
308 750	4114 CD(b-e)	1398 CD(ijk)	4040 BC(cde)

[a]Mean separation ($LSD_{0.05}$) within herbicide treatment are denoted by capital letters.
[b]Mean separation ($LSD_{0.05}$) between herbicide treatments are denoted by lower case letters in parentheses.

Table 8. Effect of soybean row width, population, and herbicide treatment on soybean yield at East Lansing in 2005 and St. Charles in 2004 and 2005.[ab]

	Soybean Yield (kg/ha)		
Population	Weed-free	Weedy-control	Glyphosate
19-cm			
197 600	3986 AB(a-d)	2084 ABC(ef)	4087 BC(a-d)
296 400	4141 A(a-d)	2393 AB(e)	4255 AB(ab)
444 600	4255 A(ab)	2406 A(e)	4423 A(a)
38-cm			
197 600	3805 BC(bcd)	1721 CD(fg)	3959 CD(a-d)
296 400	4020 AB(a-d)	2057 ABC(ef)	4215 AB(abc)
444 600	4053 AB(a-d)	2285 AB(e)	4322 AB(ab)
76-cm			
197 600	3643 C(d)	1499 D(g)	3630 E(d)
296 400	3711 C(c)	1707 CD(fg)	3953 CD(a-d)
444 600	3610 C(d)	1882 BCD(efg)	3711 DE(cd)

[a]Mean separation ($LSD_{0.05}$) within herbicide treatment are denoted by capital letters.
[b]Mean separation ($LSD_{0.05}$) between herbicide treatments are denoted by lower case letters in parentheses.

Table 9. Effect of soybean row width, population, and herbicide treatment on soybean yield at Clarksville in 2005.[ab]

	Soybean Yield (kg/ha)		
Population	Weed-free	Weedy-control	Glyphosate
19-cm			
123 500	3756 AB(ab)	759 AB(fg)	3566 ABC(bcd)
185 250	3838 A(a)	502 C(h)	3742 A(ab)
38-cm			
123 500	3371 C(de)	613 BC(gh)	3281 D(e)
185 250	3613 ABC(a-d)	617 BC(gh)	3653 AB(abc)
76-cm			
123 500	3481 BC(cde)	952 A(f)	3396 CD(de)
185 250	3404 C(cde)	537 BC(gh)	3525 BC(b-e)

[a]Mean separation ($LSD_{0.05}$) within herbicide treatment are denoted by capital letters.
[b]Mean separation ($LSD_{0.05}$) between herbicide treatments are denoted by lower case letters in parentheses.

Table 10. Gross margins for 10-cm glyphosate application at Clarksville and East Lansing in 2004.

	Gross Margin		
Population	$0.18/kg	0.22/kg	0.26/kg
19-cm		($/ha)	
123 500	637	778	919
185 250	682	834	987
308 750	746	916	1087
38-cm			
123 500	657	802	947
185 250	666	815	964
308 750	668	823	978
76-cm			
123 500	555	679	803
185 250	614	753	892
308 750	636	784	933
$LSD_{(0.05)}$	42	52	59

Table 11. Gross margins for 10-cm glyphosate application at East Lansing in 2005 and St.Charles in 2004 and 2005.

	Gross Margin		
Population	\$0.18/kg	0.22/kg	0.26/kg
19-cm		(\$/ha)	
197 600	661	810	958
296 400	675	831	987
444 600	685	849	1014
38-cm			
197 600	644	790	936
296 400	670	825	980
444 600	657	816	976
76-cm			
197 600	583	716	849
296 400	627	773	920
444 600	548	685	822
$LSD_{(0.05)}$	45	54	62

Table 12. Gross margins for 10-cm glyphosate application at Clarksville in 2005.

Population	Gross margins		
	$0.18/kg	0.22/kg	0.26/kg
19-cm	($/ha)		
123 500	589	720	851
185 250	607	745	882
38-cm			
123 500	536	657	777
185 250	591	725	860
76-cm			
123 500	557	682	807
185 250	568	697	827
$LSD_{(0.05)}$	52	57	67

Figure 1. Weed emergence following glyphosate application at Clarksville and East Lansing in 2004. Vertical bars at each measurement indicate $LSD_{0.05}$. Dotted vertical line indicates canopy closure.

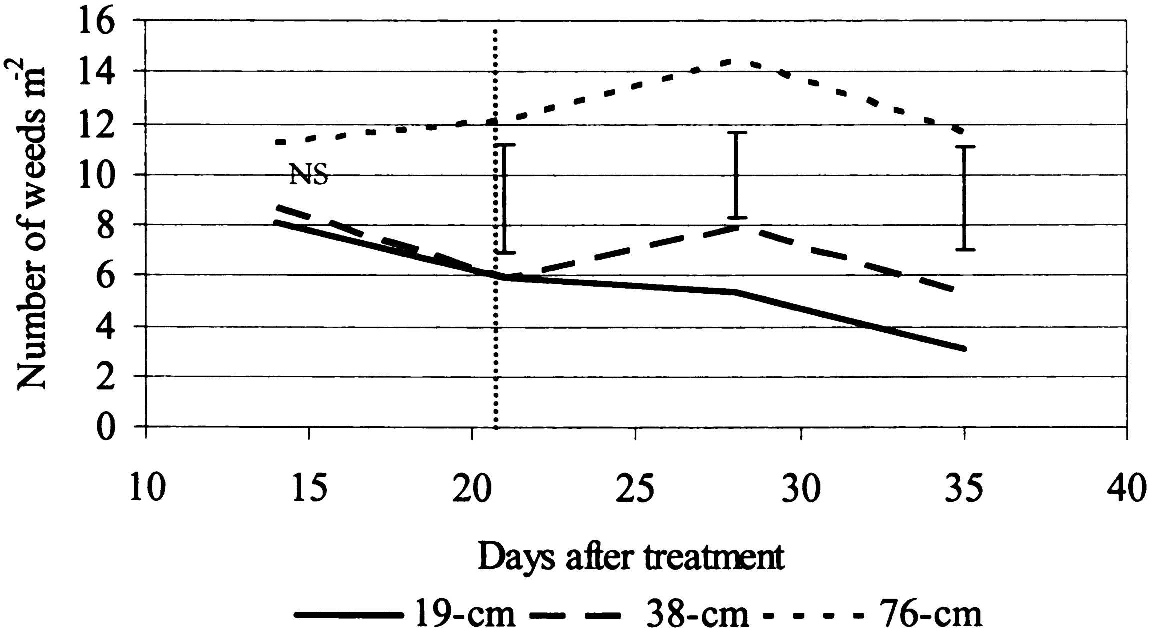


Figure 2. Weed emergence following glyphosate application at East Lansing and St. Charles in 2005. Vertical bars at each measurement indicate $LSD_{0.05}$. . Dotted vertical line indicates canopy closure.

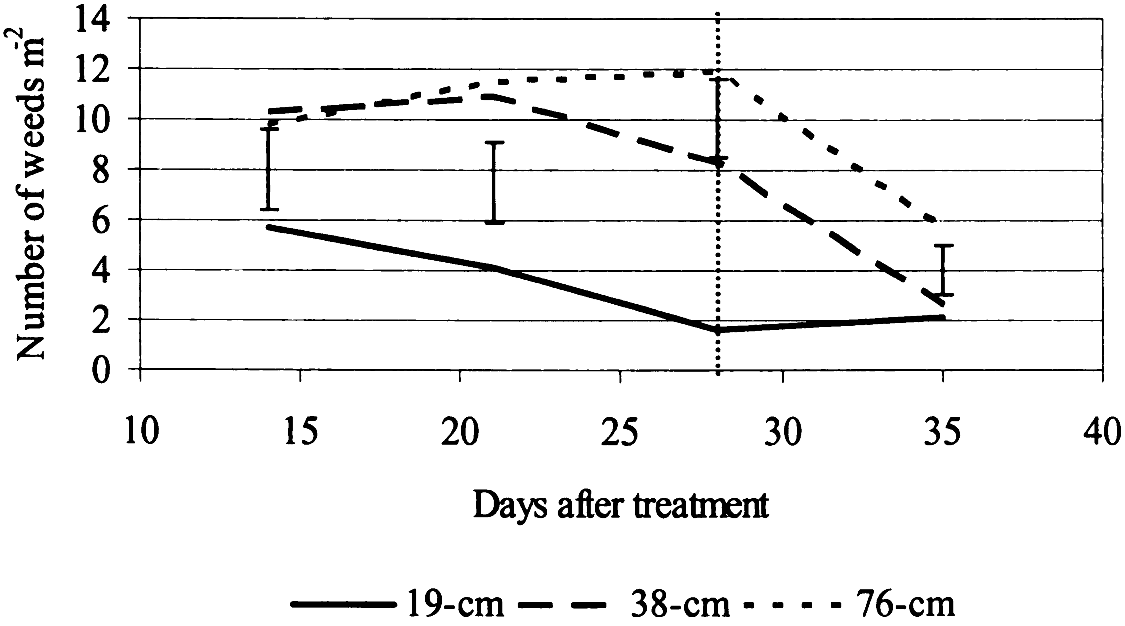


Figure 3. Effect of soybean row width and population on weed biomass at Clarksville and East Lansing in 2004. Different letters above each column indicate mean separation $LSD_{0.05}$.

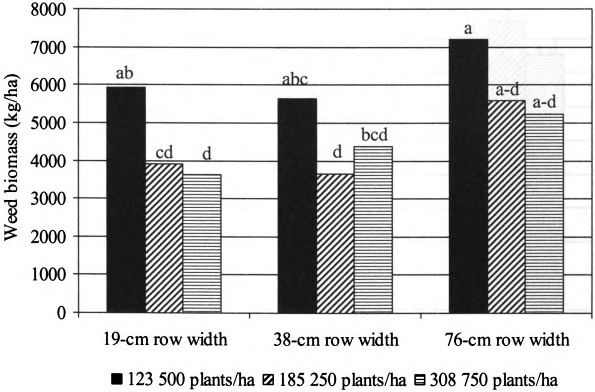


Figure 4. Effect of soybean row width and population on weed biomass at East Lansing in 2005 and St. Charles in 2004 and 2005. Different letters above each column indicate mean separation $LSD_{0.05}$.

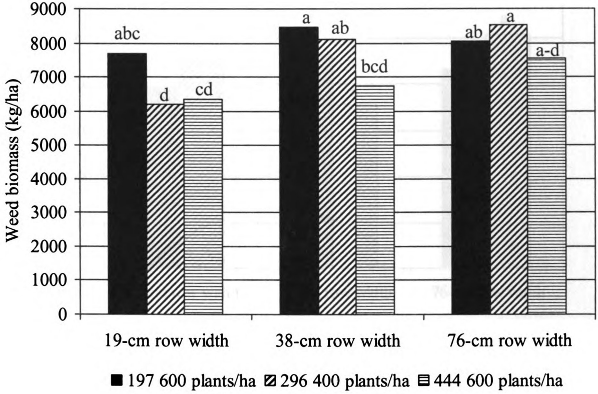


Figure 5. Effect of soybean row width and population on weed biomass at Clarksville in 2005. Different letters above each column indicate mean separation $LSD_{0.05}$.

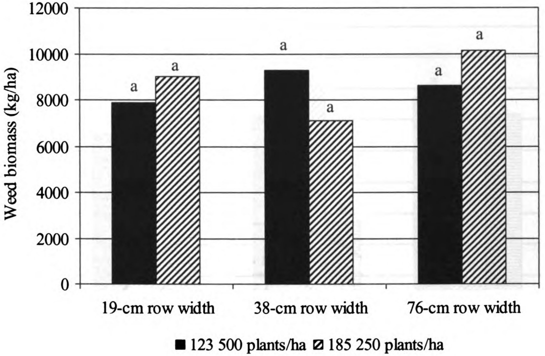


Figure 6. Effect of soybean row width and population on weed biomass in 10-cm glyphosate treatment at East Lansing and Clarksville in 2004. Different letters above each column indicate mean separation $LSD_{0.05}$.

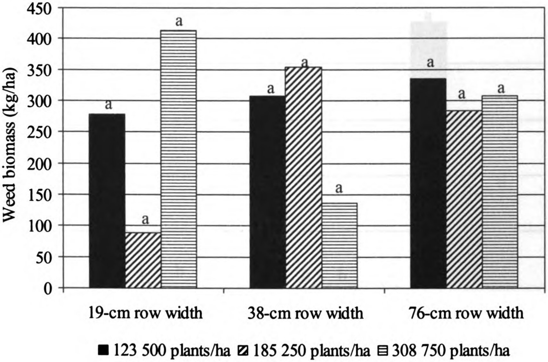


Figure 7. Effect of soybean row width and population on weed biomass in 10-cm glyphosate treatment at East Lansing and St. Charles in 2005. Different letters above each column indicate mean separation $LSD_{0.05}$.

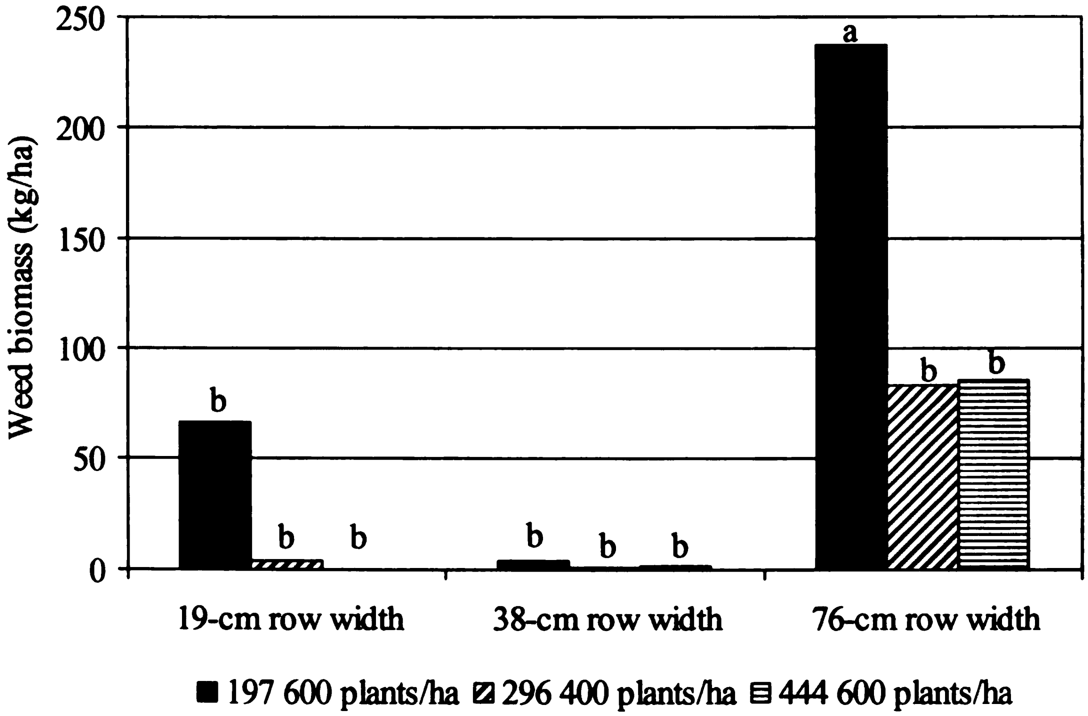
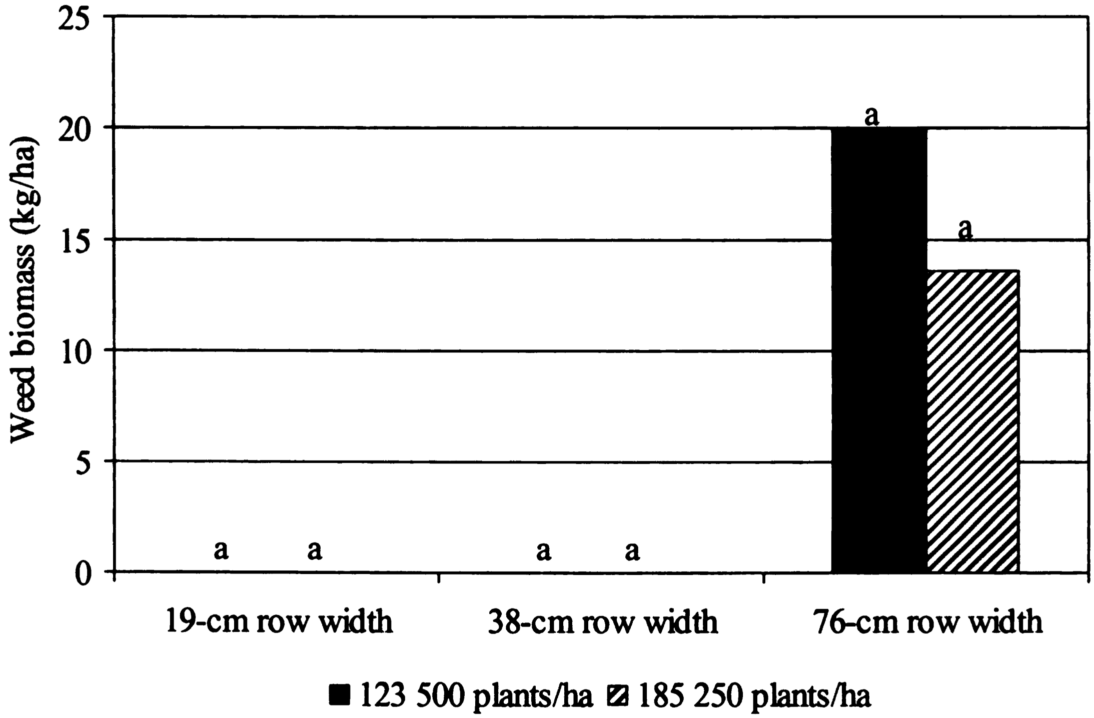


Figure 8. Effect of soybean row width and population on weed biomass in 10-cm glyphosate treatment at Clarksville in 2005. Different letters above each column indicate mean separation $LSD_{0.05}$.



CHAPTER 3

EFFECT OF ROW WIDTH AND POPULATION ON SOYBEAN YIELD COMPONENTS.

ABSTRACT

Understanding how soybean can compensate for changes in population and row width will help identify the optimal population for a particular row width. The objective of this study was to determine soybean yield and yield components of the mainstem and branch fraction of soybean grown in three different row widths at three different seeding rates. Soybean was planted in 19-, 38- and 76-cm rows at 123 500, 185 250, and 308 750 plants/ha at Clarksville and East Lansing in 2004, and 197 600, 296 400, 444 600 plants/ha at East Lansing in 2005 and St. Charles in 2004 and 2005. Optimal plant populations were 308 750 to 444 600 plants/ha for soybean planted in 19- or 38-cm rows, and 185 250 to 308 750 for soybean planted in 76-cm rows. Pod number per plant was the most responsive yield component to changes in population and row width. A greater proportion of yield was composed from branch yield components in narrow rows and at lower populations. Mainstem plant weight was responsive to changes in population but was similar across row widths at each population. Branch plant weight was responsive to changes in populations, but also responded to changes in row width at lower populations. In conclusion, branch pod number was responsive to changes in row width and population, while mainstem pod number was responsive to changes in population only.

Nomenclature: Glyphosate, N-(phosphonomethyl) glycine; soybean 'AG 2701', *Glycine max* (L.) Merr.

Keywords: soybean populations, row spacing, yield components, mainstem seed yield, branch seed yield.

Abbreviations: CGR, crop growth rate; LAI, leaf area index.

INTRODUCTION

Soybean yield is dependent on row width, cultivar, population, and planting date (Ethredge et al. 1989). The effect of row width on soybean growth and yield has been researched extensively. Generally, yield is greater in narrow-row soybean compared with wide-row soybean when environmental factors are favorable (Devlin et al. 1995; Taylor 1980; Yelverton and Coble 1991). Increased yield in narrow-row soybean is partly due to more efficient use of available water, light, and mineral nutrients by soybean plants spaced at a more equidistant spacing (Burnside and Colville 1964).

Yield response to reductions in row width can be partly attributed to an improvement in radiation interception during pod set (Andrade et al. 2002). However, canopy photosynthesis is linearly related to light interception and LAI prior to canopy closure, but not afterwards (Wells 1991). The leaf area index (LAI) that correlates to 95% solar radiation interception has been adopted as the critical LAI (Weber et al. 1966). Soybean crop growth rate (CGR) does not increase significantly when light interception is above 95% (Shibles and Weber 1965). Furthermore, yields over a range of seeding rates are similar when 95% of photosynthetically active radiation is intercepted (Norsworthy and Oliver 2001). Board (2000) observed that soybean at low populations (80 000 plants/ha) can yield the same as medium (145 000 plants/ha) and high (390 000 plants/ha) populations when planted in 75-cm rows due to greater CGR and light interception efficiency by soybean at lower populations.

The impact of row width on soybean yield components varies by study. Ethredge et al. (1989) observed that the number of pods per plant was not affected by row width. Weber et al. (1966) observed that seed size was independent of row width. In contrast, seed weight and the number of seeds per pod were greater when soybean was planted in wide rows (Costa et al. 1980; Lehman and Lambert 1960).

Soybean can compensate for sparse plant populations (Wells 1991). Increased pod production associated with greater branch development occurs at low soybean populations (Carpenter and Board 1997; Herbert and Litchfield 1982; Hicks et al. 1969; Lehman and Lambert 1960). Seed size has also been implicated as one factor in yield compensation due to larger seeds at lower populations (Moore 1991; Wright et al. 1984). However, the changes in seed weight and number of seeds per pod due to soybean population are inconsistent (Board 2000; Carpenter and Board 1997; Costa et al. 1980; Etheredge et al. 1989; Herbert and Litchfield 1982). Of the seed yield components, pod number per plant is the most responsive to changes in row width or plant population (Lehman and Lambert 1960; Herbert and Litchfield 1982; Pedersen and Lauer 2004; Weber et al. 1966). At higher soybean populations there are fewer pods per plant (Ethredge et al. 1989).

The partitioning of soybean yield to branch or mainstem fractions is influenced by both row width and population. Mainstem yield is greater in narrow-row soybean than wide-row soybean, and some soybean genotypes are capable of partitioning more resources to increased branch seed yields in response to row width (Norsworthy and Shipe 2005). Rigsby and Board (2003) reported genotypic differences in soybean branching and branch yield at low populations. Branches produce a greater proportion of seed yield at lower populations (Herbert and Litchfield 1982).

The partitioning of yield components to branch or mainstem fraction is also influenced by environmental conditions. When moisture is limiting there is often no yield benefit in planting narrow-row soybean (Devlin et al. 1995; Norris et al. 2002; Taylor 1980). One explanation for this is that the contribution of branch seed yield to total yield is greater in years of higher rainfall (Norsworthy and Frederick 2002). In dry conditions, the mainstem portion of yield is greater, indicating that mainstem yield is stable over environments (Board, 1987; Frederick et al. 2001). Furthermore, yield has been correlated to dry matter production, and total dry matter per plant is greater in narrow rows, with a greater fraction being produced on branches (Board et al. 1990).

The optimal seeding rate for soybean varies from 30 000 plants/ha to 500 000 plants/ha (Board 2000). Understanding how soybean compensated for changes in population and row width will help identify the optimal population for a particular row width. There are few studies comparing soybean yield and yield components across various row widths. Etheredge et al. (1989) studied yield component response to 25-, 51-, and 76-cm rows with seeding rates remaining constant across row widths. However, there are no studies comparing constant seeding rates across 19-, 38-, and 76-cm rows. Therefore, the objective of this study was to determine soybean yield and yield components of the mainstem and branch fraction of soybean grown in three different row widths at three different seeding rates.

MATERIALS AND METHODS

Field experiments were conducted in Michigan at three locations in 2004 and two locations in 2005 (Table 1). An indeterminate group II glyphosate-resistant soybean cultivar 'AG 2107[1]'was planted in plots measuring 3 m wide by 10.7 m long in 2004, and 3 m wide by 9.1 m long in 2005. Soybean was planted in three row widths (19-, 38-, and 76-cm) using a customized toolbar with John Deere planter units. Target populations were 197 600, 296 400, and 444 600 plants/ha at all locations; however, heavy rains following planting lowered populations at Clarksville and East Lansing in 2004. Populations were thinned prior to the V1 growth stage. Weed-control was accomplished by two postemergence glyphosate[2] applications at 0.84 kg ae/ha at the V2 and V5 growth stage of soybean using a tractor-mounted compressed-air sprayer calibrated to deliver 178 L/ha at 207 kPa with Airmix 11003[3] nozzles.

At physiological maturity, all soybean plants in 15- by 150-cm quadrats (0.225 m^2) were harvested at the soil surface from weed-free plots. Branches were separated from the mainstem fraction of the soybean plant and weighed and divided by the number of plants in each quadrat to report data on a per plant basis. From three randomly selected plants in each sampled quadrat, pod number and seed number per plant were counted. The number of seeds per pod was determined by dividing the number of seeds per plant by the number of pods per plant. Weight of 100 seed was recorded. Soybean yield was determined by harvesting the center rows of each plot. Seed yield was adjusted to 13% moisture and for soybean removal from quadrats in weed-free plots.

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[1] Asgrow Seed Co., Monsanto Co., 800 North Lindbergh Boulevard, St. Louis, MO 63167.
[2] Roundup WeatherMAX, Monsanto Co. 800 North Lindbergh Boulevard, St. Louis, MO 63167.
[3] Teejet Airmix 11003, Spraying Systems Co., North Avenue, Wheaton, IL 60188.

The experiment design was a split plot with four replications. The main plot was row width and the sub-plot was soybean population. Data were subjected to ANOVA using the PROC MIXED procedure in SAS 8.02[4] software. Main effects and all possible interactions were tested using the appropriate expected mean square values as recommended by McIntosh (1983). Each location combination was considered an environment sampled at random from a population as suggested by Carmer et al. (1989). Environments, replications (nested within environments), and all interactions containing these effects were declared random effects in the model. Data from locations with similar populations were combined and mean separation performed using Fisher's Protected LSD at $\alpha=0.05$.

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

RESULTS

Growing conditions

Rainfall in 2004 was greater than the 30 year average at all locations (Table 2). May rainfall was approximately three times greater than the 30 year average at Clarksville and East Lansing where soil crusting inhibited soybean emergence. Rainfall at St. Charles during May 2004 was approximately two times greater than the 30 year average as well. In 2005, total rainfall was slightly lower than the 30 year average at East Lansing and St. Charles. Rainfall was low in the month of August in 2005, which corresponds to the time of soybean pod fill in Michigan.

Soybean Yield

At Clarksville and East Lansing in 2004, soybean yield was greater in 19- and 38-cm rows compared with 76-cm rows at each population (Figure 1); yields were similar between 19- and 38-cm rows. Yield was greater at the high population of 308 750 plants/ha compared with the low population of 123 500 plants/ha in each row width. The medium population of 185 250 plants/ha yielded similar to the high population in 38- and 76-cm rows.

At St. Charles in 2004 and 2005 and East Lansing in 2005, soybean yield was greater in 19- and 38-cm rows compared with 76-cm rows, regardless of population (Figure 2). There was no difference in yield between populations in 76-cm rows; however, yields were greater when soybean was planted at 444 600 plants/ha compared with 197 600 plants/ha in 19- and 38-cm rows. Yields were similar between 19- and 38-cm rows at each population.

Plant Seed Yield

Total, mainstem, and branch seed yields were greater at the low population compared with the high population in each row width at Clarksville and East Lansing in 2004 (Table 3). At 185 250 and 308 750 plants/ha, total, mainstem, and branch seed yields were similar across row widths. At the low population, mainstem seed yield was similar across row widths; however, total and branch seed yields were greater in 19-cm rows compared with 38- and 76-cm rows. Mainstem seed yield was statistically similar across row width at each population, but a greater proportion of yield was produced on the mainstem in 76-cm rows compared with 19-cm rows. For example, soybean in 19-cm rows at 123 500 plants/ha produced 43% of seed yield on the mainstem fraction compared with 53% in 76-cm rows. As population increased, the mainstem proportion of seed yield also increased. Soybean planted in 38-cm rows at 123 500 plants/ha produced 48% of seed yield on the mainstem fraction compared with 67% at 308 750 plants/ha.

Total, mainstem, and branch seed yields per plant were greater at the low population compared with the high population in each row width at St. Charles in 2004 and 2005 and East Lansing in 2004 (Table 4). Total and mainstem seed yields were similar across row widths at each population. Branch seed yield was greater in 19-cm rows compared with 38- and 76-cm rows at 296 400 plants/ha and 76-cm rows at 197 600 plants/ha. A trend similar to Clarksville and East Lansing was observed in regards to the proportion of seed yield produced on the mainstem fraction; however, there was little change in the percentage of seed yield produced at 444 600 plants/ha across row width.

Pod Number

Total, mainstem, and branch pod production were greater at the low population compared with the high population in each row width at Clarksville and East Lansing in 2004 (Table 3). Total and mainstem pod number was similar across row widths at each population. Branch pod number was similar across row widths at 308 750 plants/ha; however, pod number was greater in 19-cm rows compared with 76-cm rows at 123 500 and 185 250 plants/ha.

Total, mainstem, and branch pod production were greater at the low population compared with the high population in each row width at St. Charles in 2004 and 2005 and East Lansing in 2005 (Table 4). Total and mainstem pod number were similar across row width at 296 400 and 444 600 plants/ha. Total pod number was greater in 19-cm compared with 76-cm rows at 197 600 plants/ha, but mainstem pod number was similar. Branch pod number was greater in 19-cm rows compared with 76-rows at 197 600 plants/ha. Furthermore, branch pod number in 19-cm rows was greater than 38- and 76-cm rows at 296 400 plants/ha, respectively.

Plant weight

Total plant weight was greater at the low population of 123 500 plants/ha compared with the high population of 308 750 plants/ha across row widths at Clarksville and East Lansing in 2004 (Figure 3). At the high and medium populations, plant weights were similar across row widths; however, at the low population plant weight was greater in 19-cm rows compared with 38- and 76-cm rows. Mainstem weight was greater in 19-cm rows compared with 76-cm rows at all populations. Branch weight was greater at the low populations compared with high population at all row widths. Branch weight was similar at the high and medium populations across row width. At the low population, branch weight was greater in 19- and 38-cm rows compared with 76-cm rows.

Total plant weight was greater at the low population of 197 600 plants/ha compared with the high population of 444 600 plants/ha across row widths at St. Charles in 2004 and 2005 and East Lansing in 2004 (Figure 4). Total plant weight was similar between row widths at the low and high population; however, plant weight was greater in 19-cm rows compared with 38- and 76-cm rows at the medium population. Mainstem plant weight was greater at the low population compared with the high population in each row width. Weights were similar across row width at each population. Branch weight was greater at the low population compared with the high population in each row width. At the high population, branch weight was similar across row widths; however, branch weight was greater in 19-cm rows compared with 38- and 76-cm rows at 197 600 and 296 400 plants/ha.

DISCUSSION

Planting soybean in narrow row widths increased soybean yield in agreement with previous research (Wiggans 1939; Etheredge et al. 1989; Ikeda 1992; Board and Harville 1993; Egli 1994). None of these studies compared the three row widths that were used in this study; however, Etheredge et al. (1989) used 25-, 51, and 76-cm row widths and concluded yield was greater and more consistent in 25-cm rows. Despite having lower populations at Clarksville and East Lansing in 2004, yield was greater compared with St. Charles in 2004 and 2005 and East Lansing in 2004, probably due to greater rainfall in 2004. Soybean yield was greater in 19-and 38-cm rows compared with 76-cm rows for each population, regardless of soybean population range. Trends were similar between studies in regard to population in 19- and 38-cm rows, but differed in response to population in 76-cm rows. Soybean yields were greater at higher populations in 76-cm rows at Clarksville and East Lansing, possibly due to both greater rainfall and lower overall soybean populations. The seeding recommendation for 76-cm rows is 309 000 seeds/ha (Bertram and Pedersen 2004) which corresponds to the high population at Clarksville and East Lansing in 2004. The optimal plant populations from our results were 308 750 to 444 600 plants/ha for soybean planted in 19- or 38-cm rows, and 185 250 to 308 750 for soybean planted in 76-cm rows.

Total seed yield per plant was influenced more by changes in plant population than changes in row width. Soybean compensated for lower populations by increasing branch seed yield. Total seed yield per plant was greater at lower populations and in narrow rows. The branch seed number comprised a larger proportion of total seed yield in narrow rows and at lower populations, while the mainstem seed yield comprised a higher percentage of total seed yield at higher populations and at wide row widths.

The number of seeds per pod did not change as row width or population changed at any location in either year, supporting previous research (Carpenter and Board 1997; Herbert and Litchfield 1982). Furthermore, seed weight did not change as row width or population changed at any location in either year, supporting previous research (Carpenter and Board 1997; Herbert and Litchfield 1982; Lehman and Lambert 1960; Moore 1991; Wright et al 1984). Seed weights were greater at Clarksville and East Lansing compared with St. Charles and East Lansing. This was probably due to differences in rainfall during August, the time of seed fill.

Pod number per plant was the most responsive yield component to changes in population and row width. Other researchers have reported pod production as the most responsive yield component to changes in row width or population (Board 1987; Carpenter and Board 1997; Etheredge et al. 1989; Herbert and Litchfield 1982). Our data supports results that pod production varies in response to changes in population. Previous research reported that adjustments in yield per plant to changing plant population were accounted for by changes in branch pod per plant (Carpenter and Board 1997; Board et al. 1990; Herbert and Litchfield 1982). While total pod production in 19-cm rows compared with 76-cm rows was not always statistically significant, trends showed that pod production was greater in 19-cm rows. Mainstem pod production was statistically similar across row width; however, branch pod number differed across row widths at lower populations. This suggests that branch pod production is more dynamic, while mainstem pod production is more stable in response to changes in row width.

Mainstem plant weight was responsive to changes in population but was similar across row widths at each population. Branch plant weight was also responsive to changes in population, but also responded to changes in row width at lower populations. Previous research reported that increased branch dry weight correlated to yield as row width and population changed (Board et al. 1980; Carpenter and Board 1997).

In conclusion, optimal plant populations were 308 750 to 444 600 plants/ha for soybean planted in 19- or 38-cm rows, and 185 250 to 308 750 for soybean planted in 76-cm rows. Pod number per plant was the most responsive yield component to changes in population and row width. The number of seeds per pod and seed weight was not influenced by changes in row width and population. A greater proportion of yield was composed from branch yield components in narrow rows and at lower populations. Mainstem plant weight was responsive to changes in population but was similar across row widths at each population. Branch plant weight was also responsive to changes in populations, but also responded to changes in row width at lower populations.

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1 **Table 1.** Field characteristics for three Michigan locations in 2004 and 2005.

	Clarksville	East Lansing	St. Charles
Soil series	Lapeer loam	Capac sandy clay loam	Misteguay silty clay loam
Soil family	coarse-loamy, mixed mesic Mollic Haplaquepts	fine-loamy, mixed mesic Aeric Ochraqualfs	fine-loamy, mixed, mesic Aeric Endoaquepts
Soil characteristics			
pH	6.1	7.0	8.1
OM, %	2.6	4.1	3.0
Planting date			
2004	19 May	29 May	19 May
2005	12 May	5 May	19 May
Population, plants ha^{-1}			
2004	123 500	123 500	197 600
	185 250	185 250	296 400
	308 750	308 750	444 600
2005		197 600	197 600
		296 400	296 400
		444 600	444 600
Harvest date			
2004	12 October	12 October	12 October
2005		13 October	30 September

Table 2. Monthly precipitation recorded at the Clarksville Horticulture Experiment Station, Clarksville, MI, at the Michigan State University Department of Horticulture and Research Center, East Lansing, MI, and at the Saginaw Valley Bean and Beet Farm, St. Charles, MI.

	Precipitation (cm)							
	Clarksville		East Lansing			St. Charles		
	2004	30 yr.	2004	2005	30 yr.	2004	2005	30 yr.
May	21.8	7.4	20.5	3.3	6.9	16.5	4.4	6.3
June	7.6	9.7	8.9	10.9	9.0	6.9	12.6	7.8
July	12.2	6.0	10.2	11.6	7.7	5.1	8.1	7.2
Aug.	6.6	9.2	8.7	1.6	7.9	5.9	2.1	8.4
Total	48.2	32.3	48.3	27.4	31.5	34.4	27.2	29.7

Table 3. Effect of soybean row width and population on total, mainstem, and branch plant yield and hundred seed weight at Clarksville and East Lansing in 2004. Numbers in parentheses indicates percentage of yield contributed by the mainstem fraction. Values at the bottom of each yield component section indicate $LSD_{0.05}$.

	Row width		
Population	19-cm	38-cm	76-cm
--------Total seed yield per plant--------			
123 500	163.2	143.4	131.0
185 250	111.4	117.9	103.8
308 750	81.1	74.1	76.0
		$LSD_{0.05}$ 18.5	
--------Mainstem seed yield per plant--------			
123 500	71.1 (43)	68.4 (48)	69.5 (53)
185 250	60.0 (52)	59.2 (50)	67.1 (65)
308 750	52.6 (64)	50.9 (67)	54.1 (72)
		$LSD_{0.05}$ 9.2	
--------Branch seed yield per plant--------			
123 500	94.4	75.0	61.5
185 250	51.4	58.7	36.7
308 750	28.5	23.6	21.9
		$LSD_{0.05}$ 15.6	
--------Seed weight g per 100 seed--------			
123 500	17.1	16.9	17.5
185 250	16.8	16.8	17.6
308 750	17.2	17.4	17.4
		$LSD_{0.05}$ NS	

Table 4. Effect of soybean row width and population on total, mainstem, and branch plant yield and hundred seed weight at East Lansing in 2005 and St. Charles in 2004 and 2005. Numbers in parentheses indicates percentage of yield contributed by the mainstem fraction. Values at the bottom of each yield component section indicate $LSD_{0.05}$.

	Row width		
Population	19-cm	38-cm	76-cm
--------------------------------------Total seed yield per plant----------------			
197 600	118.8	117.9	111.5
296 400	90.8	85.2	90.2
444 600	68.9	66.4	68.5
		$LSD_{0.05}$ 13.9	
--------------------------------------Mainstem seed yield per plant----------			
197 600	60.6 (51)	62.5 (53)	63.4 (57)
296 400	54.3 (60)	56.5 (66)	60.7 (67)
444 600	51.7 (75)	52.2 (79)	49.3 (72)
		$LSD_{0.05}$ 5.9	
--------------------------------------Branch seed yield per plant-------------			
197 600	58.5	55.5	47.7
296 400	43.4	28.8	29.7
444 600	19.4	14.5	19.3
		$LSD_{0.05}$ 9.1	
--------------------------------------Seed weight g per 100 seed-------------			
197 600	14.8	14.8	15.0
296 400	14.2	14.6	15.2
444 600	14.2	15.2	15.0
		$LSD_{0.05}$ NS	

Table 5. Effect of soybean row width and population on total, mainstem, and branch pod production and number of seed per pod at Clarksville and East Lansing in 2004. Values at the bottom of each yield component section indicate $LSD_{0.05}$.

	Row width		
Population	19-cm	38-cm	76-cm
	---Total pods per plant---		
123 500	82.8	73.3	67.4
185 250	56.6	62.7	50.6
308 750	43.0	38.1	38.0
	$LSD_{0.05}$ 10.7		
	---Mainstem pods per plant---		
123 500	35.8	34.6	35.5
185 250	30.0	31.0	32.3
308 750	27.9	25.8	26.9
	$LSD_{0.05}$ 3.9		
	---Branch pods per plant---		
123 500	47.0	38.7	31.9
185 250	26.6	31.8	18.3
308 750	15.2	12.5	11.1
	$LSD_{0.05}$ 8.1		
	---Seed number per pod---		
123 500	2.0	2.0	2.0
185 250	2.0	1.9	2.1
308 750	1.9	2.0	2.0
	$LSD_{0.05}$ NS		

Table 6. Effect of soybean row width and population on total, mainstem, and branch pod production and number of seed per pod at East Lansing in 2005 and St. Charles in 2004 and 2005. Values at the bottom of each yield component section indicate $LSD_{0.05}$.

	Row width		
Population	19-cm	38-cm	76-cm
	---Total pods per plant---		
197 600	62.3	59.8	55.3
296 400	50.5	44.0	45.0
444 600	34.8	32.8	34.6
		$LSD_{0.05}$ 5.9	
	---Mainstem pods per plant---		
197 600	31.7	31.6	31.5
296 400	31.0	29.3	30.2
444 600	26.8	25.4	24.9
		$LSD_{0.05}$ 2.4	
	---Branch pods per plant---		
197 600	30.8	28.5	23.8
296 400	23.0	15.0	15.0
444 600	10.0	7.6	9.8
		$LSD_{0.05}$ 4.3	
	---Seed number per pod---		
197 600	1.9	2.0	2.0
296 400	1.9	1.9	2.0
444 600	2.0	2.0	2.0
		$LSD_{0.05}$ NS	

Figure 1. Effect of row width and population on soybean yield at Clarksville and East Lansing in 2004. Different letters above each column represent significant differences at $LSD_{0.05}$.

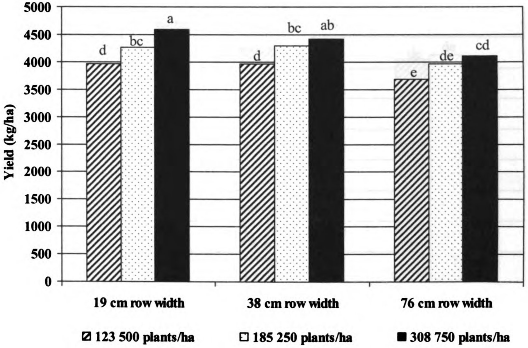


Figure 2. Effect of row width and population on soybean yield at East Lansing in 2005 and St. Charles in 2004 and 2005. Different letters above each column represent significant differences at $LSD_{0.05}$.

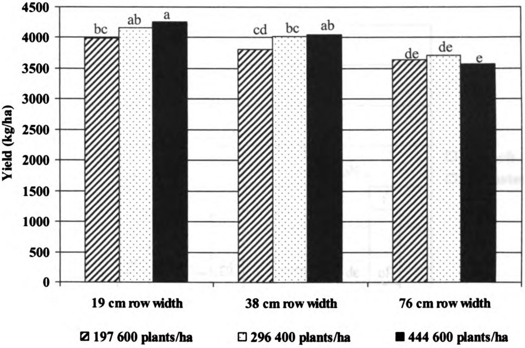


Figure 3. Effect of soybean row width and population on total, mainstem, and branch weights at Clarksville and East Lansing in 2004. Different letters above, between, and at the base of each column represent significant differences in total, mainstem, and branch weights, respectively, at $LSD_{0.05}$.

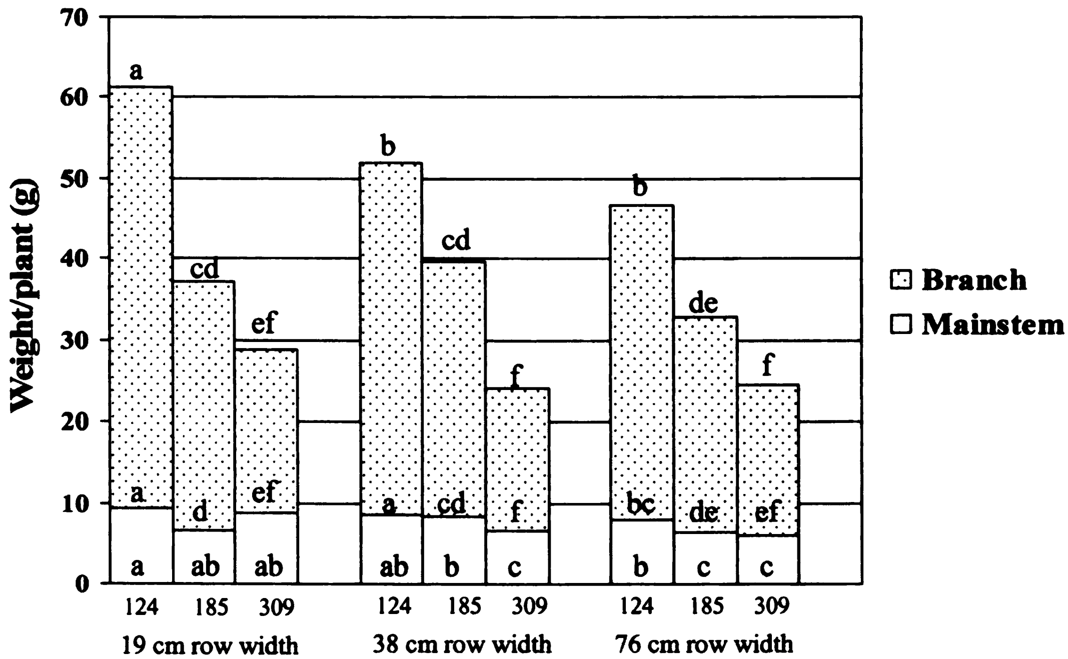
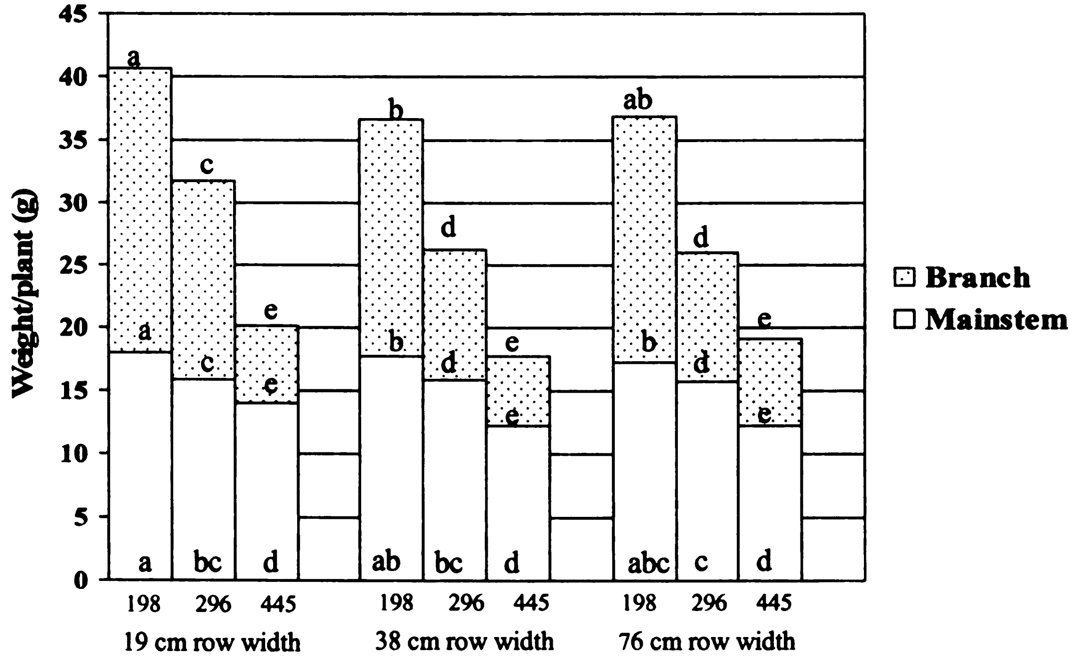


Figure 4. Effect of soybean row width and population on total, mainstem, and branch weights at East Lansing in 2005 and St. Charles in 2004 and 2005. Different letters above, between, and at the base of each column represent significant differences in total, mainstem, and branch weights, respectively, $LSD_{0.05}$.



CHAPTER 4

INFLUENCE OF STEM-BORING INSECTS ON COMMON LAMBSQUARTERS CONTROL WITH GLYPHOSATE

ABSTRACT

Common lambsquarters is the most problematic weed for soybean producers in Michigan. Recently, insect tunneling was found inside the stems of many plants that were not controlled with glyphosate. Field and greenhouse studies were conducted to identify insect larvae found tunneling in common lambsquarters; to determine if tunneling occurred prior to or following postemergence glyphosate applications, and to evaluate the effect of glyphosate rate, application timing, and insect larval tunneling on the control of common lambsquarters populations with glyphosate. Two insect species, the beet petiole borer (*Cosmobaris americana* Casey) and a leafminer fly larvae (Diptera:Agromyzidae) were found inside common lambsquarters stems. The leafminer fly larvae were present in late-June when most postemergence glyphosate applications are made in Michigan; however, the beet petiole borer was not found in common lambsquarters stems until mid-July and would only be present in common lambsquarters plants if glyphosate applications were delayed. Common lambsquarters control with glyphosate was not affected by leafminer fly larvae tunneling. Applying glyphosate to smaller plants or at rates greater than 0.84 kg ae/ha improved common lambsquarters control. Control of common lambsquarters with glyphosate varied between common lambsquarters populations, suggesting there may be a genetic basis for reduced control of some common lambsquarters populations.

Nomenclature: Soybean, 'AG 2701', *Glycine max* (L.) Merr.; common lambsquarters, *Chenopodium album*(L.); Glyphosate, *N*-(phosphonomethyl)glycine; beet petiole borer, *Cosmobaris americana*; fly maggot, Diptera:Agromyzidae

Additional index words: Insect-weed interactions, common lambsquarters, glyphosate, dose-response.

Abbreviations: AMS, ammonium sulfate; DAT, days after treatment; GR_{25}, rate causing 25% growth reduction; GR_{50}, rate causing 50% growth reduction; GR_{75}, rate causing 75% growth reduction

INTRODUCTION

Common lambsquarters is a successful colonizing species, and one of the most widely distributed weeds in the world (Holm et al. 1977). It is found in 47 different countries in 40 different crops, and considered the principal weed pest in corn (*Zea mays* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* (L.) Merr.), and sugarbeet (*Beta vulgaris* L.) (Holm et al. 1977; Mitich 1988). Common lambsquarters is ranked as the most problematic weed by soybean producers in Michigan (Sprague 2004). Soybean yield was reduced 15 (Shurtleff and Coble 1985) to 28% (Harrison 1990) from season-long competition at common lambsquarters densities of 16 and 10 plants/m row, respectively. The success of common lambsquarters as a competitive, wide-spread weed is attributable to many factors including seed germination in a wide range of environmental conditions (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 fields in the United States (NASS 2005). Growers have adopted this technology because glyphosate offers greater flexibility in application timing and weed control than conventional herbicides and tillage have provided in the past (Culpepper and York 1998; McKinley et al. 1999; VanGessel et al. 2000). Glyphosate has traditionally controlled common lambsquarters. Ateh and Harvey (1999) reported that glyphosate at 0.31 kg ae/ha controlled plants 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 reports of poor common lambsquarters control with glyphosate (Kniss et al. 2004; Schuster et al. 2004). Common lambsquarters has been difficult to control with other postemergence herbicides due to reduced herbicide absorption through epicuticular waxes on the leaf's surface (Taylor et al. 1981). The waxes form a homogeneous covering over the entire leaf surface and are a barrier to penetration of polar molecules through the cuticle. Furthermore, environmental factors influence the thickness of the epicuticular waxes leading to reduced herbicide efficacy.

In some cases of poor weed control with glyphosate, insect larvae were found tunneling or feeding in the vascular tissue (Maertens 2003, Ott et al. 2003; Westra et al. 1981). Since glyphosate is a systemic herbicide, it was hypothesized that weed control with glyphosate may be reduced if insect larval tunneling or feeding is present in the plant 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 from herbicides. Westra et al. (1981) observed that the weevil (*Notaris bimaculatus*) reduced the effectiveness of glyphosate on quackgrass (*Agropyron repens*). In contrast, Ott et al. (2003) reported that giant ragweed (*Ambrosia trifida*) control was similar in plants infested with European corn borer (*Ostrinia nubilalis*) and non-infested plants. In contrast, Williams et al. (2004) reported that Colorado potato beetle (*Leptinotarsa decemlineata*) feeding in combination with reduced fluroxypyr rates enhanced volunteer potato (*Solanum tuberosum* L.) 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 later identified as the beet petiole borer (*Cosmobaris americana* Casey). Landis et al. (1970) published an extensive study on the lifecycle of the beet petiole borer after discovering it on sugar beet in the western United States. Larvae of the beet petiole borer overwintered in feeding galleries of dead host plants. Larvae pupated in May and adult weevils emerged within 1-2 weeks. Soon after emergence, the weevils fed primarily at nodes or stems of host plants. Female weevils mated after emergence and deposited a single egg in feeding pits in the host plant. Larvae were often found near the oviposition site, and stems of host plants were usually swollen. Weed hosts did not appear stressed despite having as many as 30 larvae tunneling per plant. Mature larvae entered diapause in the stems of saltbrush (*Atriplex polycarpa*) as early as August in Washington. The beet petiole borer was more commonly found in weedy hosts than sugarbeet. In California, Gilbert (1964) reported that the most common host for beet petiole borer was common lambsquarters.

Many producers have readily adopted glyphosate-resistant crops, and with over 80% of soybean acres planted with glyphosate-resistant soybean incidents of reduced common lambsquarters control are a major concern. Therefore, the objectives of this study were to: 1) identify the insect larvae found tunneling common lambsquarters 2) determine if the tunneling of these insects occurred prior to of following postemergence glyphosate application timings in Michigan, 3) evaluate the effect of glyphosate rate, application timing, and insect larval tunneling on common lambsquarters control, and 4) determine if different Michigan common lambsquarters populations vary in control to glyphosate.

MATERIALS AND METHODS

Presence of Insect Larval Tunneling in Common Lambsquarters

A natural population of common lambsquarters was grown in monoculture in the field. Every two weeks, forty common lambsquarters plants were longitudinally dissected beginning May 15 and ending July 29 and August 5 in 2004 and 2005, respectively, to assess larval tunneling in common lambsquarters over the growing season. Weather data from the Michigan Automated Weather Network[1] was used to calculate growing degree days (GDD) for each sampling date. Corresponding growing degree days (GDD) were calculated using common lambsquarters base temperature of 4 C at each sampling date (Harvey and Forcella 1993). GDD were calculated by averaging the maximum and minimum daily temperatures and subtracting the base temperature of 4 C.

Factors Influencing Common Lambsquarters Control

Field Studies. Field studies were established at East Lansing on May 6 and June 4, 2004 and May 4, 2005 to evaluate the effect of glyphosate rate, application timing, and insect larval tunneling on common lambsquarters control. Soybean 'AG 2107[2]'was 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 3.1 m by 9.1 m. In 2004, the experiment was a 3x4 factorial. The first factor was glyphosate application timing based on common lambsquarters heights of 10-, 25-, and 46-cm; the second factor was glyphosate rates of 0, 0.63, 0.84, and 1.7 kg ae/ha. In 2005 the experiment was a 2 X 3

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

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

X 4 factorial. The additional factor of bi-weekly application of the insecticide lambda-cyhalothrin[3] at 21 g ai/ha were added to keep half of the study area insect-free.

Prior to each glyphosate application, 10 common lambsquarters plants per treatment (2004) or per plot (2005) were dissected and examined for insect larval tunneling. Glyphosate[4] plus ammonium sulfate (AMS) at 2% w/w was applied using a tractor-mounted compressed-air sprayer calibrated to deliver 178 L/ha at 207 kPa using Airmix 11003[5] nozzles at the appropriate common lambsquarters heights, with environmental conditions documented (Table 1). Common lambsquarters control was visually evaluated 28 DAT on 0 to 100% scale with 0 indicating no control and 100% indicating complete plant death.

In 2005, an additional field study was established on May 15 to examine the effect of insect larval tunneling on common lambsquarters control with glyphosate. Cages 1-m^3 in size were constructed of PVC pipe and no-see-um mesh[6]. Nine cages were randomly placed in a conventionally-tilled field with a known natural population of common lambsquarters. Cages were used to keep common lambsquarters plants insect-free, while nine areas were left cage-free to allow for insect-infestation. Glyphosate at 0.84 kg ae/ha plus AMS at 2% w/w was applied to 25-cm plants with a CO_2 backpack sprayer calibrated to deliver 187 L/ha at 207 kPa using 8003[7] flat fan nozzles. Prior to glyphosate application, three common lambsquarters plants in each caged and cage-free areas were dissected to determine the presence and extent of insect larval tunneling. Common lambsquarters

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[3] Warrior, Syngenta Crop Protection, Inc. P.O. Box 18300, Greensboro, North Carolina 27409
[4] Roundup WeatherMAX, Monsanto., 800 North Lindbergh Boulevard, St. Louis, MO 63167.
[5] Teejet Airmix 11003, Spraying Systems Co., North Avenue, Wheaton, IL 60188.
[6] No-see-um mesh, Venture textiles, 115 Messina Dr. P.O. Box 850289, Braintree, MA 02185.
[7] Teejet flat fan 8003, Spraying Systems Co., North Avenue, Wheaton, IL 60189

control was visually assessed 28 DAT. The experiment was a completely randomized design with nine replications.

Greenhouse Studies. A greenhouse experiment was designed to evaluate the effect of beet petiole borer feeding on common lambsquarters control with glyphosate. Common lambsquarters stems collected from the field in mid-October were sealed in nylon bags and placed in the greenhouse. Based on preliminary growth chamber research, beet petiole borer adults emerged around 470 growing degree days at a base temperature of 4 C. Greenhouse temperature was maintained at 25 ± 2 C. Once pupae of the beet petiole borer developed into adult weevils, common lambsquarters stems were split, and the adult weevils were removed. Concurrently, common lambsquarters seeds were planted at a depth of 1.5-cm into 1000 cm^3 pots filled with BACCTO[8] potting mix. Seedlings were grown in the greenhouse and natural sunlight was supplemented with sodium vapor lighting to provide a total midday intensity of 1000 µ/m/s photosynthetic photon flux at plant height in a 16 h day. Plants were watered daily and fertilized weekly with a complete fertilizer. Plants were thinned to one plant per pot 1 week after emergence. Plants were then placed in 0.9 m x 0.9 m x 1.2 m wood-framed cages covered with no-see-um netting. Half of the cages were infested when plants were 10-cm in height, with four beet petiole borer adults per pot were allowed to feed and mate on common lambsquarters plants for 30 d. Based on previous growth chamber research a minimum of 15 d provided enough GDD to ensure adult weevils; however, it was unknown how long it would take weevils to mate and lay eggs. New weevils were reared for each experimental run. When plants were 46-

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[8] BACCTO, Michigan Peat Co., P.O. Box 980129, Houston, TX 77098.

and 60-cm in height, herbicide treatments were applied with a single tip track-sprayer with a Teejet[9] 8003E flat-fan nozzle calibrated to deliver 187 L ha^{-1} at 207 kPa. Glyphosate rates of 0, 0.84, 1.7, and 3.4 kg ae/ha and AMS at 2% w/w was applied. At 28 DAT, all aboveground plant tissue was then harvested, oven-dried at 60 C for two days, and weighed to determine reduction of plant biomass. Data were then converted to percent of control for data presentation. The experimental design was a split-plot with sub-factors arranged in a completely randomized design with six replications and the experiment was repeated. The whole-plot was insect presence; sub-factors were common lambsquarters heights of 46- and 60-cm, and glyphosate rates of 0, 0.84, 1.7, and 3.4 kg ae/ha.

Response of Seven Common Lambsquarters Populations to Glyphosate

An experiment was designed to evaluate the response of six Michigan common lambsquarters populations from Eaton, Gratiot, Ingham, Montcalm, Saginaw, and Shiawassee Counties to glyphosate. These populations were compared with a control population from F&J seeds[10]. In mid-October of 2004, seed was collected from soybean fields in Eaton, Gratiot, Ingham, Montcalm, Saginaw, and Shiawassee Counties where common lambsquarters was not controlled with glyphosate. Following the same general experimental procedures as stated above, common lambsquarters plants were treated with glyphosate at rates of 0, 0.21, 0.42, 0.84, 1.68, 3.4, and 6.7 kg ae/ha + AMS at 2% w/w when plants were 8- to 10-cm tall. At 28 DAT, common lambsquarters were visually evaluated for control, dry plant biomass was determined, and then converted to percent of

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[9] Teejet flat fan 8003E, Spraying Systems Co., North Avenue, Wheaton, IL 60189
[10] F&J Seeds, P.O. Box 82, Woodstock, IL 60098.

control. The experiment was a two factor factorial in a completely randomized design with four replications and was repeated.

Statistical Analysis. All data were subjected to ANOVA using the PROC MIXED procedure in SAS 8.02[11] software. Field experiments are presented separately due to treatment by environment interactions. Greenhouse experiments were combined over runs since no interaction between repeated experiments was observed. Means were separated using Fisher's Protected LSD at $\alpha=0.05$. In the common lambsquarters populations response to glyphosate experiment, growth reduction (GR) values were calculated for plant dry weights using the dose-response curve equation $Y=A+B/[1+(X/C)^D]$, where Y is the herbicide activity as a percent control, X is the rate of application, A is the upper limit, B is the lower limit, C is the dose that causes the desired growth reduction, and D is the slope of the curve around the GR_{50}. TableCurve 2D[12] software was used to calculate regression curves and equations for each replication. Corresponding GR values were calculated using regression curves for each replication and subjected to ANOVA.

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

[12] TableCurve 2D v. 5.01. Jandel Stientific, 2591 Kerner Blvd., San Rafael, CA 94901.

RESULTS AND DISCUSSION

Presence of Insect Larval Tunneling in Common Lambsquarters

Beet petiole adults were found inside common lambsquarters stems from the previous year on May 15 in 2004 and May 24 in 2005. Based on preliminary growth chamber research, beet petiole borers emerge around 470 growing degree days at a base temperature of 4 C (data not shown). The beet petiole borer and leafminer fly larvae (Diptera:Agromyzidae) were the only insects found tunneling in common lambsquarters both years. The leafminer fly larvae were found on June 13 in 2004 and 2005 at 790 and 616 GDD, respectively. Tunneling by the leafminer fly larvae was narrow and contained to the center of stem, causing little damage to vascular tissue. Furthermore, plants with leafminer fly larvae were not visually stressed.

The beet petiole borer (BPB) larvae were found in plants on July 13 and July 8 in 2004 and 2005, respectively, corresponding to 1245 and 1036 GDD. Tunneling by the BPB was much greater than that of the leafminer fly larvae and the pith tissue of plants was destroyed. Plants that contained many beet petiole borer larvae had swollen stems and were slightly stunted in height.

In 2004, the proportion of common lambsquarters plants infested with insect larvae increased steadily from July 1 to August 5 where 90% of plants were infested (Figure 1). In 2005, insect tunneling increased steadily until July 29 when 88% of plants were infested. These observations on the life cycle of the beet petiole borer in Michigan agree with those of Landis (1970) who reported BPB adult emergence in mid-May in Washington and

Oregon, and larvae were full grown by August, and overwintering of larvae in the stems of weed hosts.

Based on Michigan State University research from the last 10 years, glyphosate applications in Michigan are typically made from June 20 to July 3. The leafminer fly larvae is present when glyphosate is applied for common lambsquarters control. However, the BPB larvae are only present in common lambsquarters plants if glyphosate applications are delayed past July 8 or 1053 GDD.

Factors influencing common lambsquarters control

Common lambsquarters control was similar across glyphosate rates at the 10-cm application timing (Table 2). However, control of 25-cm common lambsquarters decreased when glyphosate was applied at 0.63 kg ae/ha compared to 1.7 kg ae/ha. Leafminer larval tunneling was only present in the 46-cm application timing for the May planting, when 40% of plants were infested. Glyphosate applications were made on May 26, June 16, and July 13 when 552, 841, and 1245 GDD had accumulated, respectively. Tunneling found in plants prior to application corresponded to tunneling found in sampled plants grown in an adjacent area Common lambsquarters control was lower at the 46-cm application timing compared with earlier glyphosate applications. The higher glyphosate rate of 1.7 kg ae/ha improved control of 46-cm tall common lambsquarters; however control was still less than 64%. Reduced control may have been due to poor coverage since common lambsquarters density was high at 43 plants/m^2.

There was insect larval tunneling the by the leafminer in common lambsquarters prior to all glyphosate applications for the June planting (Table 3). Both the BPB and leafminer larvae were found in sampled plants. In the June 2004 planting, glyphosate applications were made on July 13, July 23, and July 29 when 1245, 1411, and 1492 GDD were accumulated, respectively. Unlike the May planting, common lambsquarters control was similar (>85%) when glyphosate was applied at 0.84 kg ae/ha and 1.7 kg ae/ha to 25- and 46-cm lambsquarters. Common lambsquarters density was 5 plants/m^2 and was 9.5 times greater in the May planting in comparison to the June planting (data not shown). Higher densities in the 2004 May planting may have reduced common lambsquarters control. Furthermore, cooler conditions present during the 2004 May planting could possibly explain lower common lambsquarters control compared with the 2004 June planting and 2005 May planting (Table 1).

In 2005, insect larval tunneling was evident at the 25- and 46-cm application timings (Table 4). The only insect present was the leafminer. In 2005, glyphosate applications were made on June 8, June 17, and June 21 when 516, 670, and 728 GDD were accumulated. Bi-weekly applications of lambda-cyhalothrin significantly reduced the number of plants infested prior to glyphosate application at the 25- and 46-cm applications. Of the plants sampled, 65 and 66% of common lambsquarters contained tunneling at these applications; however, insecticide treatment did not influence common lambsquarters control with glyphosate. Common lambsquarters control was similar when glyphosate was applied at 1.7 kg ae/ha, regardless of application timing; however, control was lower at the 46-cm timing at the low rate of 0.63 kg ae/ha. Common lambsquarters density was 9 plants/m^2 and control with glyphosate was greater than 92% indicating coverage was not an issue.

In the cage study, plants inside cages were completely insect-free and plants outside cages were completely infested with leafminer larvae at the time of glyphosate applications. Common lambsquarters control with glyphosate was 96 and 97% for caged and non-caged treatments indicating that insect tunneling did not influence control with glyphosate (Table 5).

Greenhouse studies. Plants infested with the BPB were stunted by adult feeding, and tended to produce branches after feeding. Due to differences in heights between infested and non-infested plants, glyphosate applications were made when non-infested plants were 46- and 60 cm in height. Furthermore, applications were made at these heights to allow time for larval development and tunneling inside of plants. Common lambsquarters control was greater when glyphosate was applied at 0.84 and 1.68 kg ae/ha to 46-cm plants compared to 0.63 kg ae/ha (Table 6). Control by 0.63 kg ae/ha glyphosate was less than 68%. Insect infestation did not affect control with glyphosate, regardless of application timing. In infested plants, there were no differences in larvae number between treatments indicating larval pressure was uniform, and plants averaged about 3 larvae per plant. There was no difference in control between glyphosate rates when applied to 60-cm plants; however, control was unusually low and ranged from 3 to 17%.

Response of 7 Common Lambsquarters Populations to Glyphosate

Common lambsquarters populations from Gratiot, Saginaw, and Shiawassee Counties required lower glyphosate rates in comparison the F&J biotype to reduce growth 25% (Table 7). Eaton, Montcalm, and Ingham County populations required 0.36 kg ae/ha to reduce growth by 25%, a rate comparable to that needed for the F&J biotype. Common lambsquarters collected from Shiawassee County was the only population that required a lower use rate than the F&J biotype to reduce growth 50%. The Eaton, Ingham, and Montcalm County populations required 1.4,1.5, and 1.8 times the F&J biotype use rate of 0.49 kg ae/ha, respectively, to reduce common lambsquarters growth by 50%.

Other researchers have also noted variability in control with glyphosate to certain weed biotypes. For example, Patzoldt et al. (2002) reported variability in the response of common waterhemp (*Amaranthus rudis*) to glyphosate rate of 0.21 and 0.84 kg ae/ha. Schuster et al. (2004) also found that common lambsquarters populations from different states vary in their tolerance to glyphosate. Our results show that there is significant variation in common lambsquarters populations collected between adjacent counties in Michigan.

The level of tolerance by common lambsquarters biotypes in our study was less than that of identified biotypes in common waterhemp (Zelaya and Owen 2005), horseweed (*Conyza canadensis*) (VanGessel 2001), goosegrass (*Eleusine indica*) (Lee and Ngim 2000), and rigid ryegrass (*Lolium rigidum*) (Powles et al. 1998). However, the continued use of glyphosate in glyphosate resistant crops increases the potential risk for the development of common lambsquarters that will not be controlled with normal field use rates.

In conclusion, common lambsquarters control with glyphosate does not appear to be influenced by leafminer tunneling. The leafminer was present when most glyphosate applications are made in Michigan; however, if glyphosate applications are made later in the season the BPB can be present in common lambsquarters plants at application. These two insects were the only species found inside plants in 2004 and 2005. Leafminer tunneling coincides with typical glyphosate applications made in late June or early July making it possible to assume escapes are due to tunneling. In general, applying glyphosate to smaller plants or at increased rates improved control. Tolerance to glyphosate appears to vary somewhat between common lambsquarters populations suggesting there maybe a genetic basis for plants escaping control with glyphosate.

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Table 1. Weather conditions before, during, and after glyphosate application for field studies in 2004 and 2005 at East Lansing.

	Date	Temperature at application	Relative Humidity	Precipitation after application		Temperature prior to application	
				0-7 d	8-14 d	3 d	1 d
		C	%	mm		C	
May 2004						High/Low	High/Low
10-cm	26 May	22	46	14	0	27/15	17/9
25-cm	16-June	21	76	9	10	17/10	27/14
46-cm	13 July	29	57	24	36	29/16	27/19
June 2004							
10-cm	13 July	29	57	24	36	29/16	24/10
25-cm	23 July	27	37	14	23	29/16	30/20
46-cm	29 July	24	57	1	2	22/12	27/11
May 2005							
10-cm	8 June	32	40	85	3	33/18	33/17
25-cm	17 June	17	58	3	0	28/19	21/11
46-cm	21 June	29	46	2	1	19/14	26/10

Table 2. Percent of common lambsquarters plants with insect larval tunneling prior to glyphosate application and common lambsquarters control (28 DAT) for soybean planted in May 2004 at East Lansing.

	Common lambsquarters application heights		
	10-cm	25-cm	46-cm
Plants with insect larval tunneling[a] (%)	0	0	40
Glyphosate rate[b]	control (%)		
0.63 kg ae/ha	75 abc[c]	72 bc	42 d
0.84 kg ae/ha	79 ab	76 abc	49 d
1.70 kg ae/ha	81 ab	88 a	64 c

[a] Insect identified tunneling in common lambsquarters was a leafminer fly larvae.
[b] All glyphosate applications included 2% w/w ammonium sulfate.
[c] Means followed by the same letter are not statistically different according to Fisher's Protected $LSD_{0.05}$

Table 3. Percent of common lambsquarters plants with insect larval tunneling prior to glyphosate application and common lambsquarters control (28 DAT) for soybean planted in June 2004 at East Lansing.

	Common lambsquarters application heights		
	10-cm	25-cm	46-cm
Plants with insect larval tunneling[a] (%)	40	60	70
Glyphosate rate[b]		control (%)	
0.63 kg ae/ha	88 bc[c]	92 ab	83 c
0.84 kg ae/ha	93 bc	92 ab	88 bc
1.70 kg ae/ha	98 a	97 ab	93 ab

[a] Insects identified tunneling in common lambsquarters were a leafminer fly larvae and the beet petiole borer (*Cosmobaris americana*).

[b] All glyphosate applications included 2% w/w ammonium sulfate.

[c] Means followed by the same letter are not statistically different according to Fisher's Protected $LSD_{0.05}$

Table 4. Percent of common lambsquarters plants with insect larval tunneling with and without insecticide treatments prior to glyphosate application and common lambsquarters control (28 DAT) for soybean planted in May 2005 at East Lansing.

	Common lambsquarters application heights					
	10-cm		25-cm		46-cm	
	No insecticide	Insecticide[a]	No insecticide	Insecticide	No insecticide	Insecticide
Plants with insect larval tunneling[b] (%)	0 D[c]	0 D	65 A	29 B	66 A	14 C
Glyphosate rate[d]	control (%)					
0.63 kg ae/ha	99 a[c]	99 a	99 a	99 a	92 c	93 c
0.84 kg ae/ha	98 a	98 a	99 a	98 a	97 a	96 ab
1.70 kg ae/ha	98 a	98 a	99 a	99 a	99 a	99 a

[a] Common lambsquarters plants were treated with lambda-cyhalothrin at 0.21 lb ai/ha bi-weekly.

[b] Insects identified tunneling in common lambsquarters was an unknown larvae in the order Diptera: family Agromyzidae.

[c] Means followed by the same letter are not statistically different according to Fisher's Protected $LSD_{0.05}$. Capital letters represent differences between insecticide treatment and lower case letters represent differences between herbicide treatments.

[d] All glyphosate applications included 2% w/w ammonium sulfate.

Table 5. The effect of glyphosate on caged and non-caged common lambsquarters control 28 DAT.[a]

	No Cage	Cage
Plants with insect larval tunneling[b] (%)	100 A[ac]	0 B
	—— control (%) ——	
	97 a[b]	96 a

[a] Insects identified tunneling in common lambsquarters was Diptera larvae in the family Agromyzidae.

[b] Means followed by the same letter are not statistically different according to Fisher's Protected $LSD_{0.05}$. Capital letters represent differences between insecticide treatment and lower case letters represent differences between herbicide treatments.

Table 6. Common lambsquarters control in cage and cage-free treatments (28 DAT) in the greenhouse.

	Common lambsquarters application heights			
	46-cm		60-cm	
	Infested[a]	Non-infested	Infested	Non-infested
Glyphosate rate[b]	control (%)			
0.63 kg ae/ha	9 cd[c]	22 c	8 cd	3 d
0.84 kg ae/ha	51 b	44 b	9 cd	11 cd
1.70 kg ae/ha	68 a	40 b	13 cd	17 cd

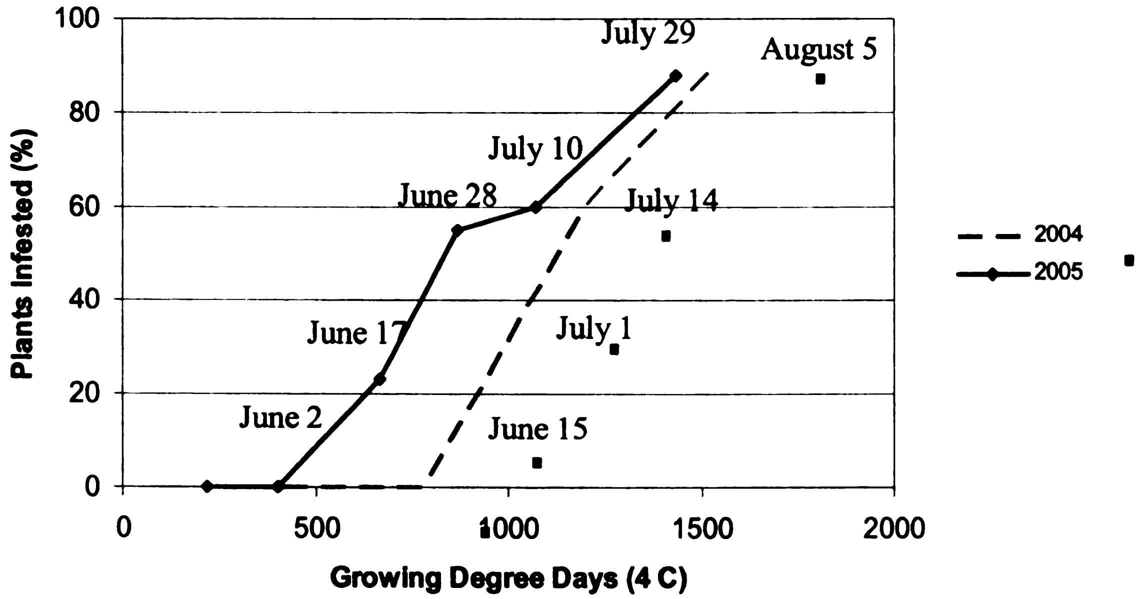
[a] Plants were infested with beet petiole borer (*Cosmobaris americana*).
[b] All glyphosate applications included 2% w/w ammonium sulfate.
[c] Means followed by the same letter are not statistically different according to Fisher's Protected $LSD_{0.05}$

Table 7. Glyphosate rates associated with each growth reduction value for six Michigan common lambsquarters biotypes. [a]

Biotypes	Biomass reduction		
	GR_{25}[a]	GR_{50}	GR_{75}
	kg ae/ha		
F&J	0.36 b[b]	0.49 c	0.74 a
Eaton Co.	0.57 b	0.67 ab	0.84 a
Gratiot Co.	0.28 c	0.52 c	1.13 a
Ingham Co.	0.46 b	0.74 a	1.39 a
Montcalm Co.	0.44 c	0.66 ab	1.23 a
Saginaw Co.	0.32 c	0.54 bc	1.60 a
Shiawassee Co.	0.31 c	0.45 c	0.82 a

[a]Biotypes collected from a single field from each county.
[b]Mean separation ($LSD_{0.05}$) between populations are denoted by lower case letters within columns.

Figure 1. Percent of common lambsquarters plants with insect larval tunneling over accumulated growing degree days.



CHAPTER 5

TEMPORAL AND SPATIAL DISTRIBUTION OF STEM-BORING INSECTS IN COMMON LAMBSQUARTERS IN MICHIGAN AND INDIANA

ABSTRACT

In 2004 and 2005, Michigan and northern Indiana soybean fields were surveyed for insect larval tunneling in common lambsquarters. Insect larval tunneling of common lambsquarters was found to be wide-spread throughout Michigan and northern Indiana. In June of 2005, leafminer larvae (Diptera:Agromyzidae) were found tunneling in common lambsquarters stems. Leafminer fly larvae were also found during the August sample time in Michigan, but not in Indiana. Beet petiole borer larvae were found in both states during the August sample timing. Most glyphosate is applied applications in late-June in Indiana and Michigan, coinciding with leafminer tunneling. Since glyphosate is a systemic herbicide, it was hypothesized that insect tunneling in common lambsquarters could reduce efficacy.

Nomenclature: Common lambsquarters, *Chenopodium album* L.; beet petiole borer, *Cosmobaris americana*; leafminer fly, *Diptera:Agromyzidae*.

Additional index words: Survey, insect weed-interactions, common lambsquarters.

INTRODUCTION

Few plants are immune to attack by insects and interactions between weeds and insects occur more often than what is recognized. Norris and Kogan (2000) reported that three outcomes occur from insect and weed interactions; these consist of energy/resource flow, habitat modification, and control tactics to mitigate pests. Therefore, Weber et al. (1990) suggested that weed scientists and entomologists need to work together to understand the effect of weed management on insect population dynamics; moreover we should understand what effect insect populations have on weed management.

Common lambsquarters is a successful colonizing species, and one of the most widely distributed weeds in the world (Holm et al. 1977). It is found in 47 different countries in 40 different crops, and considered the principal weed pest in corn (*Zea mays* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* (L.) Merr.), and sugarbeet (*Beta vulgaris* L.) (Holm et al. 1977; Mitich 1988). Common lambsquarters is ranked as the most problematic weed for soybean producers in Michigan (Sprague 2004). The success of common lambsquarters as a competitive, wide-spread weed is attributable to many factors, including seed germination in a wide range of environmental conditions (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).

In some cases where weed control was poor with glyphosate, insect larvae were found tunneling or feeding in the vascular tissue (Maertens et al. 2003, Ott et al 2003; Westra et al. 1981). Since glyphosate is a systemic herbicide, it is hypothesized that weed control with glyphosate may be reduced if insect larval tunneling or feeding is present in the plant at the time of the herbicide application. While there are many reports of using of insects as biological control agents for weeds (Bacher and Schwab 2000; Julien 1998; Sheldon and Creed 1995), there is limited research on the effects of insect feeding on weed control from herbicides. Westra et al. (1981) observed that the weevil (*Notaris bimaculatus*) reduced the effectiveness of glyphosate on quackgrass (*Elytrigia repens*). In contrast, Ott et al. (2003) reported that giant ragweed (*Ambrosia trifida*) control was not affected by infestation with the European corn borer (*Ostrinia nubilalis*). Furthermore, Williams et al. (2004) reported that Colorado potato beetle (*Leptinotarsa decemlineata*) feeding in combination with reduced fluroxypyr rates enhanced volunteer potato (*Solanum tuberosum* L.) control compared with either strategy alone.

In 2003, insect larval tunneling was found throughout the vascular system of common lambsquarters that survived applications of glyphosate in Michigan. The larvae were later identified as the beet petiole borer (*Cosmobaris americana* Casey). Gilbert (1964) reported that the most common host for this insect in California was common lambsquarters and as many as 30 larvae were found within a single plant (Landis et al. 1970). However, there is limited information on the biology of this insect in the Midwest.

Many producers readily adopted glyphosate-resistant crops, and with over 87% of soybean acres planted with glyphosate-resistant soybean (NASS 2005) incidents of reduced effectiveness are a major concern. Understanding the potential for interactions between insect damage and glyphosate effectiveness is important. Prior to this work, there was no information on the extent and distribution of insect larval tunneling in common lambsquarters in Michigan or Indiana. Therefore the objective of this study was to determine the temporal and spatial distribution of insect larval tunneling in common lambsquarters in Michigan and northern Indiana, in relation to glyphosate application timing.

MATERIALS AND METHODS

In 2004 and 2005, sampling was done in conjunction with Purdue University to examine the extent and distribution of insect larval tunneling in common lambsquarters in Michigan and northern Indiana. In 2004, random soybean fields in Michigan and Indiana were sampled between July 28 and August 9. Ten common lambsquarters plants were collected from 29 samples in 29 different counties in Michigan and 8 fields in 7 different counties in Indiana. Locations were marked with GPS, and plant height, stem diameter, insect tunnel-length, number of live larvae present, and insect specie were recorded.

In 2005, common lambsquarters plants were sampled at three different times throughout the growing season. The first sample period occurred June 23-24, when most glyphosate applications are made. The second and third sample periods occurred August 8-12 and September 14-17, respectively Four regions in Michigan (northeast, northwest, southeast, and southwest) and three regions in Indiana (northeast, northwest, and central) were sampled. Five fields per region were sampled, except for the August sampling period in Michigan were seven fields per region were sampled (Figure 1).

The survey data were treated as completely randomized, with each field in each region treated as a replication. Plant measurement data were subjected to correlation using the PROC CORR procedure in SAS 8.02[1] software. Survey data were subjected to ANOVA using the PROC MIXED procedure in SAS and since no interaction between repeated data for the Michigan August sample period occurred, data were combined over years. Indiana data from August 2005 was analyzed separately. Means were separated with Fisher's Protected LSD at α=0.1.

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RESULTS AND DISCUSSION

In 2004, insect tunneling of common lambsquarters stems was wide-spread throughout Michigan and northern Indiana. In August, 55% of the total larvae found tunneling in common lambsquarters were beet petiole borers (BPB) in Michigan (data not shown). In the Michigan Counties of Huron, Ingham, Jackson, Lenawee, Montcalm, Saginaw, and Tuscola 100% of common lambsquarters plants contained tunneling (Table 1). In Indiana, 100% of the total larvae found tunneling in common lambsquarters were BPB. In Caroll County, 100% of the common lambsquarters plants contained tunneling; however, Jasper County had the greatest percentage of plants with live larvae in Indiana. There were 2.9 and 1.3 larvae per plant that were BPB and leafminer, respectively. There were no strong correlations between stem diameter or plant height to tunnel length P=0.76 and 0.66 respectively. This indicates that either insect have little preference in regards to plant size or plant growth is unaffected by larval tunneling. Tunneling by the leafminer larvae was narrow and was contained to the center of stem causing little damage to vascular tissue. Tunneling by the beet BPB larvae was much greater than that by leafminer larvae and the pith tissue of plants was damaged. Plants that contained many BPB larvae appeared to have swollen stems and were slightly stunted in height. The common lambsquarters plants sampled during this time frame were presumed to have escaped control with glyphosate in glyphosate-resistant soybean. Since glyphosate is a systemic herbicide it was hypothesized that insect tunneling in common lambsquarters could reduce efficacy.

Insect tunneling for the June 2005 sampling time was quite variable; the percentage of plants with tunneling ranged from 10 to 100% in Michigan (Table 2).

Gratiot County had the most common lambsquarters plants with live leafminer larvae, and on average there were 1.4 larvae per plant for this sample period. In Indiana, tunneling ranged from 10 to 60% in Jasper and Boone Counties, respectively, however, there were no live larvae found in plants. There were no differences between regions in Michigan and Indiana in regards to the percentage of plants with tunneling and plants with live insects in June (Table 3). Of the plants sample, 47% contained tunneling, and the leafminer was the only insect found in 22% of dissected plants. At this sample period, the only larvae found inside of plants was the leafminer larvae indicating that this species is the first to tunnel in common lambsquarters plants. Most glyphosate applications in Michigan are made in late-June. This means that insect larval tunneling by the leafminer is most likely to be present in common lambsquarters during this timeframe.

In August 2005, Cass and St. Clair Counties had the highest percentage of plants with insect tunneling at 100 and 90%, respectively, in Michigan (Table 4). In Indiana, Noble, Pike, and White Counties had the greatest percentage of plants with tunneling. Tunneling was similar between regions in Michigan (Table 3). Tunneling was less in August 2005 compared with August 2004. Furthermore, tunneling in August was less than the June sample period. This may be due to control of common lambsquarters with glyphosate applied in June resulting in fewer plants with tunneling for the August sample period. Of the plants sampled, 9 to 27% of contained live larvae (Table 3). In Michigan and Indiana, 81 and 100% of total larvae found were BPB, respectively. There were 2.5 and 1.5 larvae per plant that were the BPB and leafminer, respectively. The northeast and southeast regions in Michigan contained plants with the most live larvae present. The northwest region of Indiana contained the most BPB larvae inside plants. The number of leafminer fly larvae was the greatest in northeast region of Michigan. In Indiana, the only insect found in plants was the BPB and was in 14 to 28% of the plants sampled. In studies conducted at a similar time, the first larvae found within common lambsquarters was the leaf-miner fly larvae on June 13 in 2004 and 2005. Furthermore, the BPB larvae were found within plants on July 13 and July 8 in 2004 and 2005. Our observations on the life cycle of the beet petiole borer in Michigan agree with those of Landis (1970) who reported that BPB adults emerged in May Washington and Oregon and larvae were full grown by August and then overwinter in the stems of weed hosts.

In September 2005, tunneling was similar between regions in which 42% of the plants contained tunneling (Table 5). The only live larvae found in plants at this time were the BPB, averaging 2.3 larvae per plant. The northwest region of Michigan had the greatest percent of infested plants. There were no insects found in the southeast region. Shiawassee and St. Joseph Counties had the greatest percentage of plants with tunneling. However, the counties with the greatest percentage of plants with live larvae were Gratiot, Ionia, and Jackson. Insect tunneling for this sample period was similar to August timing, but less than the June timing. In Indiana, tunneling ranged from 20 to 80%, and the BPB was the only insect larvae found. The central region was the only region which live BPB larvae were found.

In conclusion, the insect tunneling of common lambsquarters was wide-spread throughout Michigan and northern Indiana. The insects involved included the BPB as well as a still to be identified leafminer fly larvae. In June, the leafminer larvae were common in plants during the timeframe when glyphosate is first applied. In August, the leafminer fly larvae were still present in Michigan, but not in Indiana. BPB larvae were found in Indiana and Michigan in August indicating that BPB tunneling occurs later in the season. The lifecycle of the BPB coincided with earlier published reports from beet and weed host in the western U.S. Most glyphosate applications in Michigan and Indiana are made in late-June and coincide with leafminer tunneling. However, tunneling by leafminer fly larvae did not produce any visual damage to plants. BPB damage was more extensive, but occurred later in the season after most glyphosate applications are made. However, if glyphosate applications were delayed, BPB tunneling could interfere with translocation.

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Table 1. Frequency of insect larval tunneling in common lambsquarters collected in soybean fields in Indiana and Michigan, August 2004.

Region	County	Plants with tunneling[a]	Plants with live larvae	Plants with beet petiole borer larvae	Plants with Diptera larvae[b]
		(%)			
MI-NE	Huron	100	50	0	50
	Lapeer	90	30	0	30
	Saginaw	100	30	0	30
	Shiawassee	20	20	20	0
	Sanilac	90	20	0	20
	St. Clair	90	20	10	10
MI-NW	Allegan	60	20	20	0
	Barry	90	20	20	0
	Clinton	80	20	10	10
	Gratiot	90	20	10	10
	Ionia	90	30	20	10
	Kent	30	0	0	0
	Montcalm	100	80	0	80
MI-SE	Hillsdale	20	0	0	0
	Ingham	100	50	30	20
	Jackson	100	50	50	0
	Lenawee	100	50	50	0
	Livingston	80	0	0	0
	Monroe	40	20	0	20
	Washtenaw	0	0	0	0
MI-SW	Berrien	40	0	0	0
	Branch	60	20	20	0
	Calhoun	60	0	0	0
	Cass	30	20	10	10
	Eaton	40	0	0	0
	Kalamazoo	40	0	0	0
	St. Joseph	70	30	20	10
	Van Burren	80	20	20	0
Indiana	Blackford	80	60	60	0
	Carroll	100	80	80	0
	Grant	70	0	0	0
	Jasper	90	90	90	0
	Marshall-1	90	20	20	0
	Marshall-2	40	0	0	0
	Noble	60	20	20	0
	Whitley	70	20	20	0

[a]10 total plants sampled per location.
[b]Unidentified leafminer fly larvae (Diptera:Agromyzidae).

Table 2. Frequency of insect larval tunneling in common lambsquarters collected in soybean fields in Indiana and Michigan in June 2005.

Region	County	Plants with tunneling[a]	Plants with live larvae	Plants with beet petiole borer larvae	Plants with Diptera larvae[b]
		(%)			
MI-NE	Genesse	10	0	0	0
	Lapeer	40	10	0	10
	Saginaw	30	30	0	30
	Shiawassee	70	30	0	30
	Tuscola	30	30	0	20
MI-NW	Clinton	40	20	0	20
	Gratiot	70	60	0	60
	Ionia	20	0	0	0
	Montcalm-1	40	0	0	0
	Montcalm-2	50	30	0	30
MI-SE	Eaton	40	30	0	30
	Hillsdale	60	40	0	40
	Ingham	70	20	0	20
	Jackson	50	40	0	40
	Lenawee	90	40	0	40
MI-SW	Branch-1	60	20	0	20
	Branch-2	100	20	0	20
	Calhoun	30	10	0	10
	Kalamazoo-1	30	0	0	0
	Kalamazoo-2	10	0	0	0
IN-NE	Elkhart	50	0	0	0
	Marshall	40	0	0	0
	St. Joseph	10	0	0	0
	Whitley-1	30	0	0	0
	Whitley-2	40	0	0	0
IN-NW	Fountain	60	0	0	0
	Jasper	10	0	0	0
	Jasper	30	0	0	0
	Pulaski	40	0	0	0
	White	20	0	0	0
IN-C	Boone	60	0	0	0
	Hamilton	20	0	0	0
	Morgan	30	0	0	0
	Putnam-1	40	0	0	0
	Putnam-2	20	0	0	0

[a]10 total plants sampled per location.
[b]Unidentified leafminer fly larvae (Diptera:Agromyzidae).

Table 3. Frequency of insect larval tunneling in common lambsquarters in Indiana and Michigan in 2004 and 2005.

Region	Plants with tunneling[a]	Plants with live larvae	Plants with beet petiole borer larvae	Plants with Diptera larvae
	(%)			
June				
MI-NE	36	20	0	20
MI-NW	44	22	0	22
MI-SE	62	34	0	34
MI-SW	46	10	0	10
$LSD_{(0.1)}$	NS	NS	NS	NS
IN-NE	32	0	0	0
IN-NW	34	0	0	0
IN-C	34	0	0	0
$LSD_{(0.1)}$	NS	NS	NS	NS
August				
MI-NE	64	27	8	19
MI-NW	61	19	11	8
MI-SE	53	25	21	4
MI-SW	43	9	4	5
$LSD_{(0.1)}$	NS	11	9	10
IN-NE	44	24	24	0
IN-NW	48	28	28	0
IN-C	14	14	14	0
$LSD_{(0.1)}$	NS	NS	NS	NS
September				
MI-NE	38	14	14	0
MI-NW	52	26	26	0
MI-SE	30	0	0	0
MI-SW	48	18	18	0
$LSD_{(0.1)}$	NS	15	15	NS
IN-NE	44	0	0	0
IN-NW	34	0	0	0
IN-C	52	8	8	0
$LSD_{(0.1)}$	NS	6.3	6.3	NS

[a] Frequency was calculated form 50 plants per region for the June, August, and September sampling time in Indiana and 70 plants per region for the Michigan August sampling time.

Table 4. Frequency of insect larval tunneling in common lambsquarters collected in soybean fields in Indiana and Michigan, August 2005.

	County	Plants with tunneling[a]	Plants with live larvae	Plants with beet petiole borer larvae	Plants with Diptera larvae[b]
		(%)			
MI-NE	Huron	60	20	0	20
	Lapeer	10	0	0	0
	Saginaw	60	30	0	30
	Shiawassee	60	10	0	10
	Sanilac	10	10	0	10
	Tuscola	20	10	10	0
MI-NW	Allegan	40	10	10	0
	Barry	20	10	10	0
	Clinton	20	10	10	0
	Gratiot	50	30	30	0
	Ionia	60	10	10	0
	Kent	60	0	0	0
	Montcalm	70	0	0	0
MI-SE	Hillsdale	10	10	10	0
	Ingham	50	40	40	0
	Jackson	30	30	30	0
	Lenawee	60	20	10	10
	Livingston	10	10	10	0
	Monroe	10	10	10	0
	Washtenaw	10	0	0	0
MI-SW	Berrien	10	0	0	0
	Branch	30	0	0	0
	Calhoun	20	0	0	0
	Cass	100	40	0	40
	Eaton	30	20	0	20
	Kalamazoo	30	0	0	0
	St. Joseph	60	30	30	0
	Van Burren	30	0	0	0
IN-NE	Dekalb	30	20	20	0
	Miami-1	30	10	10	0
	Miami-2	30	10	10	0
	Noble	80	40	40	0
	Wells	70	60	60	0
IN-NW	Benton	0	0	0	0
	Cass	50	0	0	0
	Starke	60	10	10	0
	White-1	20	0	0	0
	White-2	80	60	60	0
IN-C	Hendricks	40	10	10	0
	Pike	80	80	80	0
	Putnam-1	40	20	20	0
	Putnam-2	30	10	10	0
	Sullivan	30	0	0	0

[a]10 total plants sampled per location.
[b]Unidentified leafminer fly larvae (Diptera:Agromyzidae).

Table 5. Frequency of insect larval tunneling in common lambsquarters collected in soybean bean fields in Indiana and Michigan, September 2005

Region	County	Plants with tunneling[a]	Plants with live larvae	Plants with beet petiole borer larvae	Plants with Diptera larvae[b]
MI-NE	Bay	20	0	0	0
	Lapeer	40	20	20	0
	Saginaw-1	30	0	0	0
	Saginaw-2	50	30	30	0
	Tuscola	50	20	20	0
MI-NW	Clinton	50	20	20	0
	Gratiot	50	40	40	0
	Ionia	50	40	40	0
	Ionia-2	40	10	10	0
	Montcalm	70	20	20	0
MI-SE	Ingham	30	0	0	0
	Jackson	60	50	50	0
	Lenawee	10	0	0	0
	Lenawee-2	30	0	0	0
	Lenawee-3	10	0	0	0
MI-SW	Branch	40	0	0	0
	Branch-2	40	20	20	0
	Calhoun	40	10	10	0
	Eaton	60	10	10	0
	St. Joseph	70	0	0	0
IN-NE	Miami	20	0	0	0
	Wabash-1	30	0	0	0
	Wabash-2	40	0	0	0
	Wells	50	0	0	0
	DeKalb	30	0	0	0
IN-NW	White	30	0	0	0
	Jasper-1	50	0	0	0
	Jasper-2	20	0	0	0
	Cass	80	0	0	0
	White-2	40	0	0	0
IN-C	Boone-2	50	20	20	0
	Hamilton	60	10	10	0
	Hancock	60	10	10	0
	Hendricks	70	0	0	0
	Boone-2	20	0	0	0

[a]10 total plants sampled per location.
[b]Unidentified leafminer fly larvae (Diptera:Agromyzidae).

Figure 1. Regions sampled in Michigan and Indiana in 2004 and 2005.