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INTEGRATING HERBICIDE RESISTANT CORN (*Zea mays*)
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By

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ABSTRACT

INTEGRATING HERBICIDE RESISTANT CORN (*Zea mays*) INTO WEED MANAGEMENT SYSTEMS FOR MICHIGAN

By

Brent Edward Tharp

The recent introductions of glufosinate-resistant and glyphosate-resistant corn have created new opportunities for weed management. Field trials were conducted from 1996 to 1999 to determine how these herbicide resistant corn hybrids could be integrated into weed control systems for Michigan. Glufosinate and glyphosate have similar use characteristics, but they are distinctly different compounds with unique modes of action. In dose-response greenhouse trials, glufosinate and glyphosate were equally effective on barnyardgrass (*Echinochloa crus-galli*), common ragweed (*Ambrosia artemisiifolia*), fall panicum (*Panicum dichotomiflorum*), giant foxtail (*Setaria faberi*), and large crabgrass (*Digitaria sanguinalis*). Common lambsquarters (*Chenopodium album*) 4- to 8-cm in height was more sensitive to glufosinate than glyphosate. In contrast, 15- to 20-cm velvetleaf (*Abutilon theophrasti*) was more sensitive to glyphosate than glufosinate.

Glufosinate and glyphosate do not control weeds that emerge following application. Late postemergence (LPOST) (13-cm average weed height) applications of these herbicides adequately controlled many weed species, but reduced corn yields in a 1997 glyphosate-resistant corn trial. Cultivation after early postemergence (EPOST) (5-cm average weed height) applications of glufosinate or glyphosate applications increased weed control. Weed control was often increased when glufosinate or glyphosate were used with residual herbicides. Consistency of weed control was reduced if the application rate of the residual

herbicide partner was reduced. A single EPOST application of glufosinate in corn planted in reduced row spacings and at high populations did not provide adequate season-long weed control. Corn yields were not affected by row spacing, but were increased when corn populations exceeded 72,900 plants/ha. Other weed management strategies need to be used with glufosinate or glyphosate to obtain season-long weed control without reducing corn yields.

In no-tillage corn trials, glyphosate burndown timings can be delayed to enhance weed control in the absence of a cover crop. Delayed burndown timings in an actively growing wheat cover crop resulted in reduced corn populations and yields due to competition from the cover crop.

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INTRODUCTION

The methods used to control weeds today are dramatically different from the methods used fifty years ago. Prior to 1945, weeds were primarily controlled by tillage, crop rotation, and manual labor. Since 1945, numerous synthetic herbicides have been developed and have replaced dependency on other weed control methods. More effective weed management practices need to be developed to meet future weed control needs.

Recent advances in science have allowed scientists to develop agricultural systems which potentially provide effective, economical, and environmentally safe weed control. Agronomists, plant breeders, and molecular biologists have been using biotechnology to develop agronomic crops that are resistant to certain herbicides. Herbicide resistant crops are designed to be insensitive to herbicide exposure, which would normally be lethal to the crop. Herbicide resistant corn is a relatively new technology. Corn hybrids resistant to glufosinate and glyphosate have recently been introduced into the market. Glufosinate and glyphosate are classified as non-selective, foliar applied herbicides. A non-selective herbicide is generally toxic to all treated plants. Although these herbicides have similar use characteristics, they are distinctly different compounds with unique modes of action. Very little public information exists regarding the use of these herbicides in a production system with corn resistant to these herbicides. Weed species differ in sensitivity to these herbicides with some weeds more difficult to control than others. Research is needed to determine the relative effectiveness of glufosinate and glyphosate on summer annual weed species, and how these herbicides will perform in a row crop environment.

One of the major characteristics of glufosinate and glyphosate is the lack of herbicidal activity in the soil. These herbicides will not control weeds that emerge after application. Weed management systems that do not control weeds up to crop canopy closure will not readily be adopted by farmers. Research is needed to identify weed management systems in glufosinate- and glyphosate-resistant corn that consistently provide season-long weed control.

Greenhouse trials were conducted to compare the relative effectiveness of glufosinate and glyphosate on several annual weed species common to Michigan. Field trials were conducted to determine effective application timings and rates. Additional field trials were conducted to identify weed management strategies that could be used with glufosinate or glyphosate to provide consistent weed control. The strategies that were investigated included: i.) cultivation following an application of glufosinate or glyphosate; ii.) residual herbicides in combination with glufosinate or glyphosate; and iii.) planting high populations of corn in reduced row spacings. In no-tillage glyphosate-resistant corn, the effect of delayed burndown timings on weed control and corn yield was also investigated.

CHAPTER 1

RESPONSE OF ANNUAL WEED SPECIES TO GLUFOSINATE AND GLYPHOSATE

Abstract. The recent introduction of glufosinate-resistant and glyphosate-resistant crops provide growers with new options for weed management. Information is needed to compare the effectiveness of glufosinate and glyphosate on annual weeds. Greenhouse trials were conducted to determine the response of barnyardgrass, common lambsquarters, common ragweed, fall panicum, giant foxtail, large crabgrass, and velvetleaf to glufosinate and glyphosate. The response of velvetleaf and common lambsquarters was investigated at multiple stages of growth. Glufosinate and glyphosate were applied to each weed species at logarithmically incremented rates. The glufosinate and glyphosate rates which provided a 50 percent reduction in aboveground weed biomass, commonly referred to as GR_{50} values, were compared using nonlinear regression techniques. Barnyardgrass, common ragweed, fall panicum, giant foxtail, and large crabgrass responded similarly to glufosinate and glyphosate. Common lambsquarters 4 to 8 cm in height was more sensitive to glufosinate than glyphosate. In contrast, 15- to 20-cm velvetleaf was more sensitive to glyphosate than glufosinate.

Nomenclature: Glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; glyphosate, *N*-(phosphonomethyl)glycine; barnyardgrass, *Echinochloa crus-galli* L. Beauv.

#[1] ECHCG; common lambsquarters, *Chenopodium album* L. # CHEAL; common ragweed, *Ambrosia artemisiifolia* L. # AMBEL; fall panicum, *Panicum dichotomiflorum* Michx. # PANDI; giant foxtail, *Setaria faberi* Herrm. # SETFA; large crabgrass, *Digitaria sanguinalis* L. Scop. # DIGSA; velvetleaf, *Abutilon theophrasti* Medicus. # ABUTH.

Additional index words: dose response, GR_{50}, *Abutilon theophrasti*, *Ambrosia artemisiifolia*, *Chenopodium album*, *Digitaria sanguinalis*, *Echinochloa crus-galli*, *Panicum dichotomiflorum*, *Setaria faberi*, ABUTH, AMBEL, CHEAL, DIGSA, ECHCG, PANDI, SETFA.

Abbreviations: GR_{50}, rate causing 50% growth reduction.

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[1] The letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds*, revised 1989. Available from WSSA.

INTRODUCTION

Glufosinate and glyphosate are nonselective, foliar-applied herbicides that have been used for vegetative management in non-crop environments for several years (Wilson et al. 1985; Blackshaw 1989; Lanie et al. 1994). In a fallow system of volunteer hard red winter wheat (*Triticum aestivum* L. 'Centurk 78'), Carlson and Burnside (1984) found that glufosinate toxicity was less than glyphosate at equal rates, and four times the application rate of glufosinate was required to achieve equivalent control of winter wheat as compared to glyphosate. Before the advent of crops modified to resist glufosinate and glyphosate, the herbicides could only be applied in cropping systems using controlled application systems (Schweizer and Bridge 1982; Eberlein et al. 1993). The recent introduction of glufosinate- and glyphosate-resistant crops has created new opportunities for use of these herbicides for selective weed control in crop production. The performance of glufosinate and glyphosate has been evaluated on summer annual weeds in resistant crops (Lich et al. 1996; Tharp and Kells 1997). Steckel et al. (1997a) reported that weed control using glufosinate was influenced by application rate and weed growth stage. Similarly, Jordan et al. (1997) concluded that application rate and timing were critical factors in the effectiveness of glyphosate. Differential herbicide effectiveness is often associated with environmental effects on herbicide absorption, translocation, and metabolism within a plant (Schultz and Burnside 1980; Mersey et al. 1990; Steckel et al. 1997b). Although the effectiveness of glufosinate or glyphosate on weeds has been explored, more information is needed for direct comparison of the effectiveness of these herbicides on annual weeds.

Dose-response experiments are widely used to evaluate the effectiveness or activity of herbicides (Heap and Morrison 1996; Sprague et al. 1997). The results of these trials are often analyzed and reported using dose-response curves (Streibig 1980; Seefeldt et al. 1995). Seefeldt et al. (1995) referred to the comparison of two or more dose-response curves as differential dose-response relationships. Values describing the growth response of a weed to a herbicide are often estimated from the dose-response curves, and the values are used to compare the effect being tested (Lærke and Streibig 1995; Steckel et al. 1997b). One such value is GR_{50}, the herbicide rate that decreases plant growth by 50%. Sandral et al. (1997) used log-logistic dose response curves to estimate and compare GR_{50} values of five herbicide treatments applied to subterranean clover (*Trifolium subterraneum* L.). Carey et al. (1997) also compared GR_{50} estimates to determine the relative sensitivity of five plant species to two herbicides.

The introduction of glufosinate-resistant and glyphosate-resistant crops will place these two herbicides in competition with each other in the herbicide market, and growers need more information regarding their efficacy. Greenhouse trials were designed to compare the relative effectiveness of glufosinate and glyphosate on annual weed species. The statistical analysis used in these trials enable direct comparisons of glufosinate and glyphosate GR_{50} values on several annual weeds and on weeds growing at various stages of growth.

MATERIALS AND METHODS

Single growth stage experiments. Greenhouse trials were conducted to determine the relative sensitivity of seven annual weed species to glufosinate and glyphosate at one growth stage. Barnyardgrass, common lambsquarters, common ragweed, fall panicum, giant foxtail, large crabgrass, and velvetleaf were grown in a commercial potting mixture[2] in 1L plastic pots. Plants were grown in a 16 h photoperiod of natural lighting supplemented with sodium halide lights providing a midday photosynthetic photon flux density of 1000 μmol/m^2/s. Air temperature was maintained at 27°C ± 5°C. Plants were watered and fertilized as needed to insure maximum growth.

Commercial formulations of glufosinate and glyphosate were applied to weeds using a continuous link belt sprayer equipped with an 8001E flat fan nozzle[3] calibrated to deliver 234 L/ha at an operating pressure of 214 kPa. Grass weeds were thinned to five plants and broadleaf weeds were thinned to one plant at least 7 days before treatment. The height of barnyardgrass at application was 15 to 20 cm, common lambsquarters was 5 to 8 cm, common ragweed was 8 to 10 cm, fall panicum was 5 to 10 cm, giant foxtail was 5 to 10 cm, large crabgrass was 18 to 25 cm, and velvetleaf was 5 to 6 cm. Each weed species was managed as an independent greenhouse trial. Each trial was a two-factor factorial designed as a randomized complete block with four replications. Each trial was repeated in time. The factors were herbicide and application rate. A commercial formulation of glufosinate ammonium or isopropylamine salt of glyphosate was applied to the seven weed species. Herbicide application rates were logarithmically increased from a rate that caused no herbicide injury to a rate that caused plant death in preliminary greenhouse screens for each weed species (unpublished data). The application rates used on common ragweed were 0,

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[2]Baccto professional planting mix, Michigan Peat Co., P.O. Box 980129, Houston, TX. 77098.

[3]Spraying Systems Co., P.O. Box 7900, Wheaton IL 60189.

0.020, 0.040, 0.080, 0.16, and 0.32 kg ae/ha for glufosinate and 0, 0.053, 0.11, 0.21, 0.42, and 0.84 kg ae/ha for glyphosate. These rates in addition to 0.641 kg ae/ha glufosinate and 1.68 kg ae/ha glyphosate were applied to barnyardgrass, common lambsquarters, large crabgrass, and velvetleaf. The lowest rate of 0.020 kg/ha glufosinate was dropped from the preceding rates and 1.28 kg/ha glufosinate was added for the giant foxtail and fall panicum trials. Spray grade ammonium sulfate was added to all herbicide mixtures at a rate of 2% w/w. Above-ground biomass was harvested 14 d after treatment for all weed species except common ragweed, which was harvested 21 d after treatment. The harvested plants were oven dried at 110 C for 72 h and weighed. The response of each weed was expressed as dry weight relative to the untreated plants and calculated by taking the dry weight of a treated plant and dividing it by the mean dry weight of the untreated plants and multiplying this value by 100.

Multiple growth stage experiments. Common lambsquarters were grown in the greenhouse to 4 to 8 cm, 10 to 15 cm, and 20 to 30 cm in height, and velvetleaf was grown to 5 to 6 cm, 8 to 13 cm, and 15 to 20 cm in height. The weeds were treated with glufosinate or glyphosate in order to determine the effect of weed size on the sensitivity of the weeds to the herbicides. The environmental conditions used for growing and treating these weeds were identical to the conditions in the single stage experiment.

Common lambsquarters and velvetleaf were managed as independent greenhouse trials and were repeated in time. Each trial was a three-factor factorial designed as a randomized complete block with four replications. The factors consisted of herbicide, herbicide application rates, and weed growth stage. Glufosinate and glyphosate were applied to common lambsquarters and velvetleaf using rates in logarithmic increments of 0, 0.0044, 0.017, 0.070, 0.28, 1.12, 4.48 kg/ha. Spray grade ammonium sulfate was included in the herbicide mixture at a rate of 2% w/w. The above-ground biomass of the plants was harvested 14 d after treatment and oven dried. The response of each weed was expressed as dry weight reduction relative to the untreated plants.

Statistical analysis. Nonlinear dose-response curves were fitted, as described in Schabenberger et al. (1999), to the data obtained on the various weed species (Figures 1 and 2). The log-logistic dose-response model properly represented the trends in growth reduction for each weed species tested except barnyardgrass and common lambsquarters. As noted by Brain and Cousens (1989), some species exhibit a hormetic growth increase at low rates of applications. The term "hormesis" was coined by Southman and Ehrlich (1943) to describe the stimulatory effect of an organism when exposed to subinhibitory concentrations of a toxic substance. Ignoring this effect can bias the GR_{50} estimate as demonstrated by Schabenberger et al. (1999). Hormetic response was found in barnyardgrass. Therefore, the log-logistic model:

$$y = \delta + \frac{\alpha - \delta}{1 + \exp\{\beta \ln(x / GR_{50})\}} + e \qquad [1]$$

where x is rate of application, δ is the lower asymptote of relative growth, α is the upper asymptote, and β relates to the rate of change near the inflection point, was modified to:

$$y = \delta + \frac{\alpha - \delta + \gamma x}{1 + \omega \exp\{\beta \ln(x / GR_{50})\}} + e \qquad [2]$$

The variable, γ, in equation [2] measures the hormetic effect and allows the dose-response to grow beyond the upper asymptote and $\omega = 1 + 2\gamma GR_{50}/(\alpha - \delta)$. This version of the Brain-

Cousens model (Brain and Cousens 1998), which allows estimation of GR_{50} directly, is derived in Schabenberger et al. (1999). Notice that for $\gamma = 0$, equation [2] reduces to a log-logistic model.

The sigmoidal shape of the log-logistic model was not supported by the common lambsquarters data for which relative growth decreased with increasing rate of application without inflection. Instead, a modified version of the Langmuir model (Seber and Wild 1989) was chosen to depict dose-response in common lambsquarters. The model in terms of GR_{50} is:

$$y = \alpha \frac{\left(x / GR_{50}\right)^{\beta}}{1 + \left(x / GR_{50}\right)^{\beta}} + e \qquad [3]$$

where again α is the upper asymptote.

Differences in GR_{50} values among herbicides or growth stages for a given species were tested for significance with the sum of squares reduction test or "lack-of-fit F-test". The appropriate full model was fit to data combined across herbicides in the single growth stage experiment or to data combined across herbicides and growth-stages in the multiple growth stage experiment varying all parameters by treatments. Schabenberger et al. (1999) provides a more detailed description of the method used analyze GR_{50} values and lists the SAS code and assumptions of nonlinear model parameters used in the analyses. The models used for each weed species and the resulting R^2 and mean square error values are summarized in Table 1.

RESULTS AND DISCUSSION

Single growth stage experiments. The GR_{50} values for glufosinate and glyphosate were similar for barnyardgrass, common ragweed, fall panicum, giant foxtail, and large crabgrass (Table 2). Similarity in GR_{50} values indicates that the effectiveness of glufosinate and glyphosate are similar for these weed species. Contrary to our findings, Wilson et al. (1985) reported greater common ragweed control from 1.1 kg ai/ha of glufosinate than from 1.1 kg ai/ha of glyphosate. Common ragweed control was similar when they increased the glyphosate rate to 1.7 kg/ha. The same study also reported that fall panicum control was similar following early applications of glufosinate and glyphosate; however, later applications of 1.7 kg/ha glyphosate provided greater fall panicum control than the same rate of glufosinate. In field trials, Lanie et al. (1994) showed similar control of barnyardgrass after early applications of glufosinate and glyphosate, which was in agreement with the results of our greenhouse trials (Table 2). However, later applications of 0.84 kg/ha glyphosate provided greater barnyardgrass control than 0.84 kg/ha glufosinate suggesting barnyardgrass growth stage influences herbicide effectiveness (Lanie et al. 1994).

The GR_{50} values of glufosinate and glyphosate differed for common lambsquarters and velvetleaf (Table 2). More glyphosate was needed to reduce common lambsquarters biomass by 50% when compared to glufosinate, suggesting that common lambsquarters is more susceptible to glufosinate than glyphosate. Our results agree with those of Wilson et al. (1985) and Higgins et al. (1991), who reported that glufosinate provided equal or greater control of common lambsquarters than glyphosate applied at similar rates. The response of velvetleaf was opposite to that of common lambsquarters. More glufosinate was needed to reduce velvetleaf biomass by 50% when compared to glyphosate, suggesting that velvetleaf is more susceptible to glyphosate than glufosinate (Table 2). However, at higher application rates velvetleaf responded similarly to both herbicides (Figure 1).

Multiple growth stage experiments. *Common Lambsquarters.* Common lambsquarters was more susceptible to glufosinate than glyphosate in the single growth stage experiment. Therefore, the influence of common lambsquarters growth stage on herbicide effectiveness was examined. Glufosinate GR_{50} values were similar among the three growth stages of common lambsquarters (Table 3). The GR_{50} values for glyphosate were also similar among the growth stages. The response of common lambsquarters to glufosinate or glyphosate is not strongly influenced by the size of common lambsquarters in controlled environmental conditions. However, the size of common lambsquarters has been shown to influence herbicide efficacy in field experiments (Higgins et al. 1991; Krausz et al. 1996, Steckel et al.1997a). Glufosinate and glyphosate activity are also affected by environmental conditions (Anderson et al. 1993a, 1993b; Devine et al. 1983; McWhorter and Azlin 1978). Plants growing in typical greenhouse conditions of supplemented artificial light, constant temperatures, and ample moisture tend to develop differently than plants growing in natural environments. Differences in results from greenhouse and field experiments could be attributed to differences in conditions of the two environments.

The GR_{50} value of glyphosate was greater than the glufosinate GR_{50} value for 4- to 8-cm tall common lambsquarters (Table 3). Glufosinate and glyphosate GR_{50} values were not significantly different for 10- to 15-cm common lambsquarters. The glyphosate GR_{50} value was more than twice as large as the glufosinate GR_{50} value for 20- to 30-cm tall common lambsquarters, but this difference was not statistically significant (Table 3). This discrepancy may be related to variability of the common lambsquarters data as expressed by a large mean square error (Table 1), which results in imprecise estimates of the GR_{50} parameter. The wide range in common lambsquarters size may have contributed to the variability.

Velvetleaf. Since velvetleaf was found to be more susceptible to glyphosate than glufosinate in the single growth stage experiments, the influence of the growth stage of velvetleaf on herbicide effectiveness was examined. Figure 2 shows growth response curves for velvetleaf at three growth stages to glyphosate. Although the shape of the curves are similar for each growth stage, higher rates of glyphosate were required to induce a similar response on larger velvetleaf (Figure 2). The GR_{50} values of glufosinate and glyphosate increased at the later velvetleaf growth stages (Table 3). The 15- to 20-cm velvetleaf required more glufosinate and glyphosate for control than the 5- to 6-cm velvetleaf (Table 3). Smaller velvetleaf were more sensitive to both herbicides than larger velvetleaf. Jordan et al. (1997) and Krausz et al. (1996) concluded that application timing was important for velvetleaf control with glyphosate. Lich et al. (1997) suggested that environmental conditions influence glyphosate activity on velvetleaf. Similar conclusions were reported when glufosinate was used for velvetleaf control (Steckel et al. 1997a).

Glufosinate GR_{50} values were similar to glyphosate GR_{50} values for 5- to 6-cm and 8- to 13-cm velvetleaf, while glufosinate GR_{50} values for 15- to 20-cm velvetleaf were greater than glyphosate GR_{50} values (Table 3). The sensitivity of velvetleaf to glyphosate and glufosinate decreased as velvetleaf grew, and 15- to 20-cm velvetleaf was more sensitive to glyphosate. The large overlapping leaves of velvetleaf makes entire coverage of the plant with spray solution more difficult as the plant grows. Incomplete spray coverage would favor an easily translocated herbicide such as glyphosate over a contact herbicide such as glufosinate. The difference in velvetleaf sensitivity to glufosinate and glyphosate for the larger velvetleaf could be related to the differences in the translocation patterns of these herbicides.

In conclusion, the response of various weed species to glufosinate and glyphosate were compared by fitting a nonlinear dose-response curve to each weed species. Appropriate nonlinear models were chosen for statistical comparison of GR_{50} values. Based on our results the relative effectiveness of glufosinate and glyphosate were similar for five of the seven weed species tested. However, common lambsquarters was more sensitive to glufosinate than glyphosate, and velvetleaf was more sensitive to glyphosate than glufosinate under controlled environmental conditions. With regard to the velvetleaf and common lambsquarters experiments, glufosinate and glyphosate activity was influenced by the growth stage of velvetleaf but not common lambsquarters. The environmental conditions in which a weed is growing may influence the degree by which herbicide efficacy is affected by growth stage. Further research is needed to study the efficacy of glyphosate and glufosinate under various environmental conditions and to determine how these herbicides can be more effectively used for annual weed control in herbicide resistant crops.

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Table 1. Statistical models fit to weed species and measures of quality of fit.

Single growth stage experiments		Quality of Fit Measures	
	Model	R^2	Mean Square Error
Barnyardgrass	Brain Cousens	0.86	442
Common lambsquarters	Langmuir	0.89	185
Common ragweed	Log-logistic	0.89	172
Fall panicum	Log-logistic	0.80	307
Giant foxtail	Log-logistic	0.84	318
Large crabgrass	Log-logistic	0.85	227
Velvetleaf	Log-logistic	0.95	78
Multiple growth stage experiments			
Common lambsquarters	Langmuir	0.79	414
Velvetleaf	Log-logistic	0.90	181

Table 2. GR_{50} values for weeds treated at a single growth stage.

Weed species	Height	Growth stage	GR_{50} values[a]	
			Glufosinate	Glyphosate
	cm	true leaves	kg/ha	
Barnyardgrass	15-20	2-3	0.15 a	0.16 a
Common lambsquarters	5-8	5-6	0.069 b	0.12 a
Common ragweed	8-10	6-7	0.063 a	0.064 a
Fall panicum	5-10	2-3	0.080 a	0.064 a
Giant foxtail	5-10	2-3	0.097 a	0.096 a
Large crabgrass	18-25	4-6	0.11 a	0.12 a
Velvetleaf	5-6	2-3	0.16 a	0.12 b

[a]GR_{50} values, within each weed and measurement, followed by the same lower case letter are not significantly different at the 0.05 probability level.

Table 3. GR_{50} values for weeds treated at multiple growth stages.

	Height[a]	Growth stage[a]	GR_{50} values[bc]	
			Glufosinate	Glyphosate
	cm	true leaves	kg/ha	
Common lambsquarters				
	4-8	4-6	0.14 B a	0.24 A a
	10-15	8-10	0.20 A a	0.20 A a
	20-30	10-12	0.16 A a	0.34 A a
Velvetleaf				
	5-6	2-3	0.037 A b	0.028 A c
	8-13	3-4	0.056 A ab	0.037 A b
	15-20	5-6	0.12 A a	0.080 B a

[a]Growth stage at application

[b]GR_{50} values, within each growth stage of each weed, followed by the same upper case letter are not significantly different at the 0.05 probability level. (comparison within a row)

[c]GR_{50} values, within each herbicide for each weed, followed by the same lower case letter are not significantly different at the 0.05 probability level. (comparison within a column)

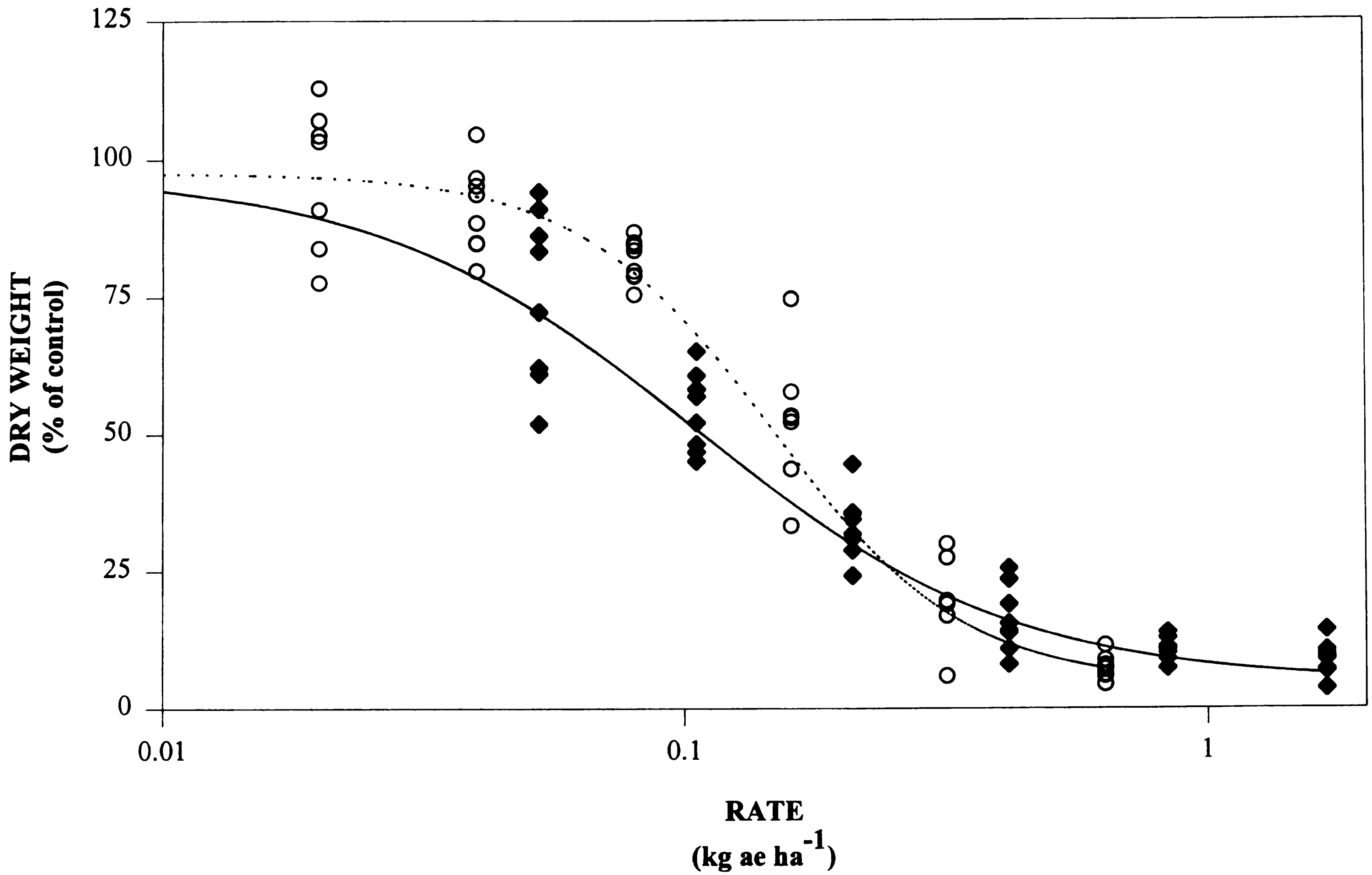

Figure 1. Example of log-logistic dose response curves for 5- to 6-cm velvetleaf treated with glyphosate (—◆—) and glufosinate (···○···).

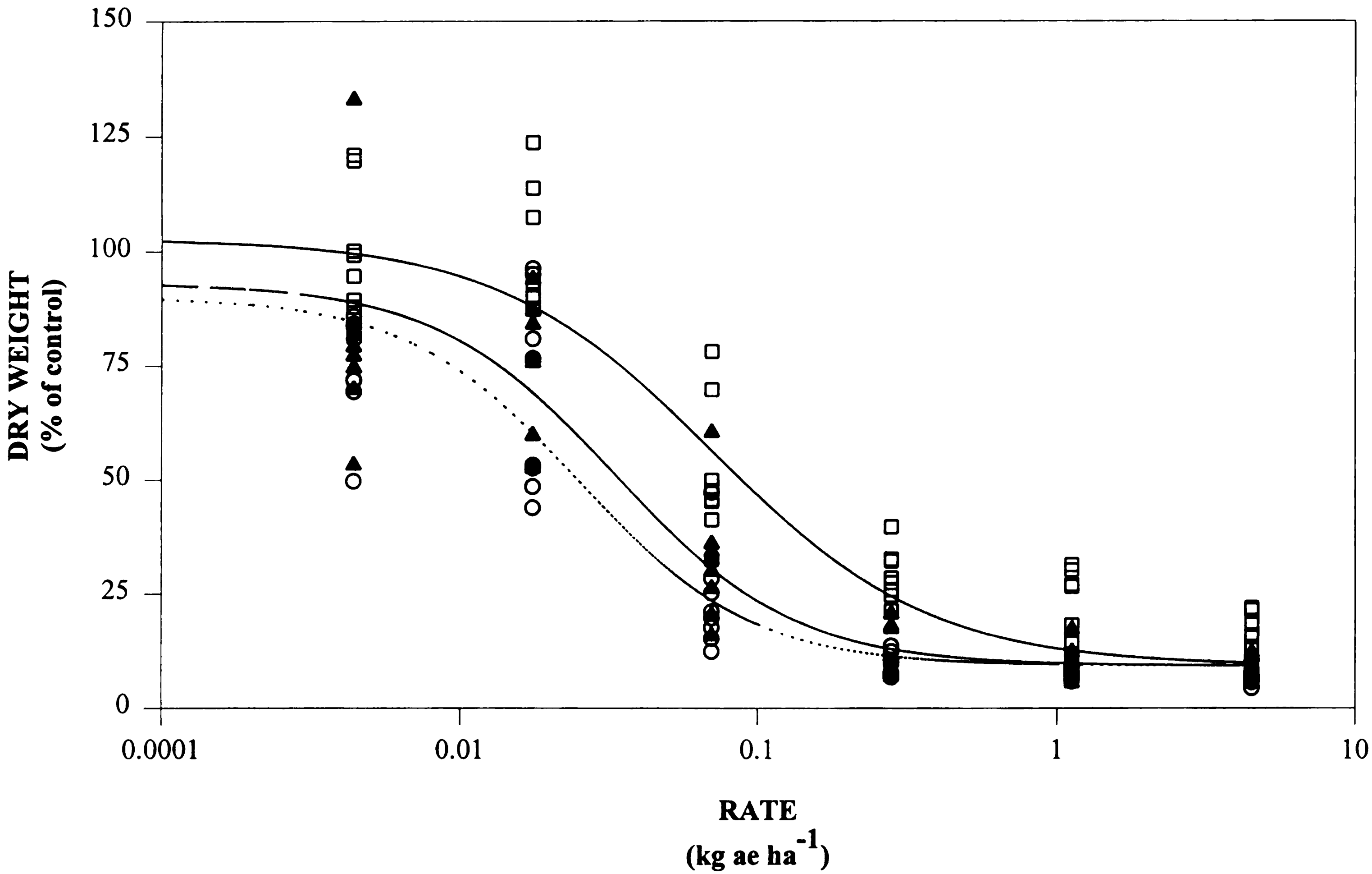

Figure 2. Example of log-logistic dose response curves for 5- to 6-cm (···○···), 8- to 13-cm (- - ▲- -), and 15- to 20-cm (—□—) velvetleaf treated with glyphosate.

CHAPTER 2

INFLUENCE OF HERBICIDE APPLICATION RATE, TIMING, AND INTERROW CULTIVATION ON WEED CONTROL, CORN (*Zea mays*) YIELD, AND PROFITABILITY IN GLUFOSINATE-RESISTANT AND GLYPHOSATE-RESISTANT CORN

Abstract: Field trials were conducted in 1996 and 1997 to determine the influence of glufosinate and glyphosate application rates, application timings, and interrow cultivation on weed control, corn yield, and profitability. Glufosinate-ammonium rates ranged from 0.18 to 0.41 kg ai/ha, while rates for the isopropylamine salt of glyphosate ranged from 0.21 to 0.84 kg ae/ha. These herbicides were applied to weeds averaging 5-cm in height (EPOST) and to weeds averaging 13-cm in height (LPOST). Increasing rates of glufosinate and glyphosate often increased weed control. Control of many of the weed species was enhanced by delaying herbicide application timing. Weed control was most consistent from LPOST applications of glufosinate at 0.41 kg ai/ha or glyphosate at 0.84 kg ae/ha. Application rates and timings did not influence gross margins for glufosinate or glyphosate treatments. Corn yields were reduced due to incomplete weed control when the lowest rate of glufosinate was applied. Weed control from EPOST glufosinate and glyphosate applications followed by cultivation was similar to weed control from LPOST glufosinate and glyphosate applications without cultivation. Interrow cultivation following glufosinate or glyphosate application did not affect corn yield, but did reduce gross margin over weed control costs with an assumption of low corn price in the glyphosate trial.

Nomenclature: Glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; glyphosate, *N*-(phosphonomethyl)glycine; corn, *Zea mays* L. 'DK 493GR'.

Additional index words: herbicide-tolerant crops, *Abutilon theophrasti, Amaranthus retroflexus*, *Chenopodium album*, *Setaria faberi*, *Zea mays*, ABUTH, AMARE, CHEAL, SETFA.

Abbreviations: EPOST, early postemergence; LPOST, late postemergence.

INTRODUCTION

The recent introduction of herbicide-resistant crops has created new opportunities for postemergence (POST) applications of herbicides traditionally considered non-selective, such as glufosinate and glyphosate. Glufosinate and glyphosate have been used for vegetation management in the absence of a crop (Carlson and Burnside 1984; Wilson et al. 1985), but these herbicides are currently being used for weed control in herbicide resistant corn hybrids and soybean varieties (Bertges et al. 1997; Probst et al. 1997; Scott et al. 1998).

Performance of glufosinate and glyphosate is often influenced by environmental factors (Anderson et al. 1993a, 1993b; McWhorter et al. 1980; Whitwell et al. 1980). Herbicide performance can also be affected by timing of herbicide application as well as rate of herbicide applied (Grichar 1997; O'Sullivan and Bouw 1997). Jordan et al. (1997) evaluated efficacy of glyphosate applied at four rates and three timings in a fallow environment. They found that glyphosate at earlier timings controlled weeds more consistently than when applied at later timings, and increased glyphosate rates increased control of large weeds. Krausz et al. (1996) reported similar findings for glyphosate rates and timings. Steckel et al. (1997) showed that rates and timing of application influenced the performance of glufosinate on several annual weed species.

In addition to managing herbicide rates and application timings, growers can incorporate cultivation into management systems to enhance weed control (Buhler et al. 1992). Newsom and Shaw (1994) found that a timely cultivation following an herbicide application in soybean (*Glycine max*) was beneficial for sicklepod (*Cassia obtusifolia*) and pitted morningglory (*Ipomoea lacunosa*) control. One or two cultivations following herbicide applications in no-tillage and chisel-plowed corn production systems has also been demonstrated to control weeds adequately (Buhler et al. 1995).

Much of the previous research investigating glufosinate and glyphosate activity has been conducted in non-crop environments. With the development of herbicide resistant crops, information is needed on application rates of glufosinate and glyphosate, the time these herbicides should be applied, and how other weed control methods can be integrated with glufosinate and glyphosate for effective season long weed control. The objectives of our research were to evaluate the influence of application rates, application timings, and interrow cultivation on annual weed control, profitability, and corn yields in glufosinate-resistant and glyphosate-resistant corn.

MATERIALS AND METHODS

Experimental Description. Field trials were conducted in 1996 and 1997 at separate locations on the Crop and Soil Sciences Research Farm at Michigan State University in East Lansing, MI. The soil was a Capac loam (fine-loamy, mixed mesic Aeric Ochraqualf) with a pH of 7.0 and 3.5% organic matter in 1996 and a Capac sandy loam with a pH of 6.4 and 2.6% organic matter in 1997. Both locations were moldboard plowed in the fall; secondary tillage consisted of disking and field cultivation in the spring. Prior to field cultivation, a 46-0-0 (N-P-K) fertilizer was broadcast at 305 kg/ha. A 6-24-24 fertilizer at 320 kg/ha in 1996 or 134 kg/ha in 1997 was banded 5 cm below and 5 cm to the side of the corn seed during the planting operation. An experimental glufosinate-resistant corn hybrid at 61,750 seed/ha and an experimental glyphosate-resistant corn hybrid at 54,340 seed/ha were planted on May

17,1996. 'Dekalb 493GR' and an experimental glyphosate-resistant corn hybrid were planted at 58,045 seed/ha and 50,635 seed/ha, respectively, on May 13, 1997. Plots consisted of four rows spaced 76 cm apart with lengths of 10.7 m in 1996 and 9.1 m in 1997.

Glufosinate-resistant and glyphosate-resistant corn were planted as separate trials. Treatments included glufosinate at 0.18, 0.30, and 0.41 kg ai/ha or glyphosate 0.21, 0.42, and 0.84 kg ae/ha applied early postemergence (EPOST) or late postemergence (LPOST). Weeds averaged 5-cm in height at the EPOST timing, while the weeds were 13-cm in height, 7 d later, at the LPOST timing (Table 1). Additional treatments included glufosinate at 0.30 kg/ha or glyphosate at 0.42 kg/ha applied EPOST or LPOST followed by cultivation. Ammonium sulfate at 2% (w/w) was included with all glufosinate and glyphosate applications. Untreated and weed-free plots were included. Weed-free plots were treated with a PRE application of metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide] at 2.24 kg/ha plus atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 1.12 kg/ha followed by hand-weeding as needed. A POST standard consisted of nicosulfuron {2-[[[[(4,6-dimethoxy-2-pyrimidinyl)amino]carbonyl] amino]sulfonyl]-*N,N*-dimethyl-3-pyridinecarboxamide} at 0.035 kg/ha plus dicamba (3,6-dichloro-2-methoxybenzoic acid) at 0.28 kg/ha plus non-ionic surfactant[4] at 0.25% (v/v) plus urea ammonium nitrate at 4.67 L/ha. Herbicides were applied with a tractor-mounted compressed-air sprayer equipped with flat-fan nozzles[5] and calibrated to deliver 187 L/ha at

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[4]Activator-90, a mixture of alkyl polyoxyethylene ether and free fatty acids, from Loveland Industries, Inc., P.O. Box 1289, Greeley, CO 80632.

[5]TeeJet XR 8003. Spraying Systems Co., North Ave., Wheaton, IL 60188.

a pressure of 207 kPa. Cultivation was performed with a four-row C-shank cultivator operated at a depth of 10 cm. Corn growth stages and weed densities were recorded in untreated plots at each herbicide application in the study (Table 1). Weed densities at cultivation were not recorded in untreated control plots because grasses were forming tillers which made accurate densities difficult to determine. Visual estimates of weed control were recorded 21 d after the LPOST herbicide application. Weed control was compared against an untreated control using a scale of 0 (no control) to 100 (all plants dead).

Two 1900-cm^2 quadrats per plot were established prior to EPOST and LPOST applications of 0.30 kg/ha glufosinate or 0.42 kg/ha glyphosate. Giant foxtail (*Setaria faberi*) were thinned by hand to 10 plants/quadrat in 1996 and 20 plants/quadrat in 1997, because high native populations of giant foxtail in these trials (Table 1) could interfere with broadleaf weed populations. Within each quadrat, wooden toothpicks were placed in the soil adjacent to the thinned grass and native broadleaf weeds. The toothpicks were used to distinguish between weeds present at the time of application and weeds which emerged following application. Weeds emerging after postemergence herbicide applications were recorded 18 d after herbicide application (Table 3).

Corn grain yield was determined by harvesting the center two rows of each plot with a mechanical plot harvester. Corn grain yield was corrected to 15.5% moisture. Glyphosate-resistant corn was not harvested in 1996 because it was destroyed prior to corn pollination in compliance with federal regulatory restrictions.

Statistical Analysis. The glufosinate-resistant corn trial and the glyphosate-resistant corn trial were designed as randomized complete blocks with three replications. Visual estimates of weed control were arcsine transformed prior to statistical analysis and subjected to ANOVA procedures. Means of the transformed weed control data and corn yields were separated using Fisher's protected LSD at the P= 0.05 level of probability. Nontransformed means are presented for clarity. Visual estimates of weed control and corn yields were subjected to F-Max tests to test for homogeneity of variance among years (Kuehl 1994). Data found to be homogenous were pooled over years.

Profitability analysis. The profitability analysis was based on gross margins over weed control costs for each treatment. Weed control costs included herbicide treatment, application, seed technology fee, and cultivation. These costs were added together as total weed control costs. All other production costs were assumed to be fixed across treatments. Gross margins over weed control costs were calculated by multiplying corn yield by corn price and subtracting total weed control costs. Gross margins were not calculated for weed free treatments because weed control costs could not be estimated due to the difficulty of assessing the value of handweeding. Gross margins over weed control costs for each replication of each treatment were statistically analyzed using ANOVA, and means were compared using Fisher's protected LSD at the P= 0.05 level of probability.

A sensitivity analysis for corn prices of $60/Mg, $100/Mg, and $140/Mg were included in the partial budget analyses. A technology fee is often assessed on herbicide resistant seed. The technology fee for 80,000 seed of 'DK 493RR' was $18.00, while the technology fee for 80,000 seed of 'DK 493GR' was $12.50. Prices for herbicides and custom application fees were obtained from a custom pesticide applicator service[6]. Doanes 1996

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[6] Dougherty Fertilizer Service. Franklin, IN 46131.

Agriculture Report[7] was used to estimate cost for owning and operating a six row cultivator on 76 cm row spacings and a trailer sprayer with 15 m booms. Operating costs included fuel, maintenance, and labor. All costs are summarized in Table 2.

RESULTS AND DISCUSSION

Effect of herbicide application timing on weed density. Weed emergence typically occurs during certain periods in a season (Ogg and Dawson 1984; Egley and Williams 1991; Anderson and Nielsen 1996). Weed species that exhibit extended emergence patterns will continue to emerge following an application of a non-residual POST herbicide such as glufosinate or glyphosate. More giant foxtail ($p=0.028$) and velvetleaf (*Abutilon theophrasti*) ($p=0.124$) emerged following an EPOST application of glufosinate than the LPOST application (Table 3). Similar trends were apparent for glyphosate. Giant foxtail ($p=0.167$), common lambsquarters (*Chenopodium album*) ($p=0.158$), and velvetleaf ($p=0.116$) emergence was greater following glyphosate EPOST compared to the LPOST timing (Table 3). The density of redroot pigweed (*Amaranthus retroflexus*) were low and were not affected by application timing. Glufosinate and glyphosate do not control weeds that emerge following application. The lack of residual activity of glufosinate and glyphosate makes timing of herbicide application critical for optimum weed control.

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[7] 1996. Estimated Machinery Operating Costs. Doanes Agriculture Report. 59:5-8.

Effect of herbicide rate and application timing on weed control. *Glufosinate trial.* Control of giant foxtail, redroot pigweed, and velvetleaf was not affected by glufosinate rates at the EPOST timing (Table 4). However, control of all weeds except common lambsquarters in 1996 was improved when increased rates of glufosinate were applied at the LPOST timing. Eberlien et al. (1993) and Steckel et al. (1997) similarly reported increased control of giant foxtail and common lambsquarters as the rates of glufosinate were increased. The rate response could be attributed to weed size at application. Weeds were larger at the LPOST timing compared to the EPOST timing (Table 1). The 0.18 kg/ha rate of glufosinate was too low to consistently control the larger weeds at the LPOST timing. Blackshaw (1989) reported that growth stage influenced glufosinate activity on two of six plant species. Under greenhouse conditions, large velvetleaf required more glufosinate to reduce plant biomass by 50% than small velvetleaf (Tharp et al. 1999).

With the exception of common lambsquarters in 1996, LPOST applications of 0.30 kg/ha glufosinate improved control of all weeds compared to EPOST timings (Table 4). Control of common lambsquarters in 1997 and giant foxtail in both years from LPOST applications of 0.41 kg/ha glufosinate was greater than EPOST timings. Steckel et al. (1997) showed that weed control from glufosinate was most effective when applied to 10-cm tall weeds compared to 5-cm and 15-cm tall weeds. They attributed erratic control of 15-cm tall weeds to incomplete spray coverage. In our trials, reduced weed control from early applications was likely due to emergence of weeds following application (Table 3).

Corn grain yields in plots treated with 0.18 kg/ha of glufosinate were reduced compared to the yield of the weed-free treatment (Table 4). Reduction in corn yields from lower herbicide rates is likely due to inadequate control of weeds that were present at herbicide application. Corn yields were not affected by application timing, indicating that competition from weeds which emerged following the EPOST timings was minimal. All glufosinate treated plots yielded similar to the POST standard (Table 4).

Although differences in weed control were apparent among glufosinate treatments, gross margins among glufosinate treatments were not statistically different (Table 4). The trends that occurred for gross margins were similar to trends among corn yields, demonstrating the importance of yields in determining profitability. Differences in gross margins were not sensitive to corn price. Gross margins for the untreated plots were severely lowered despite the lack of weed control costs. A weed control program including herbicides is essential for high gross margins. Glufosinate-based weed control systems were as profitable as the POST standard.

Glyphosate trials. Common lambsquarters control was improved when glyphosate rates were increased from 0.21 kg/ha to 0.84 kg/ha at the EPOST timing (Table 5). Control of all other weeds at the EPOST timing were not significantly influenced by glyphosate rates. Increasing the rate of glyphosate from 0.21 kg/ha to 0.84 kg/ha improved common lambsquarters and redroot pigweed control at the LPOST timing. Giant foxtail control was not influenced by glyphosate rates at either application timing. Increasing the rate of glyphosate has been shown to improve control of broadleaf weeds, while not affecting giant foxtail control (Krausz et al. 1996).

Common lambsquarters control in 1997 and giant foxtail control in both years was greater for LPOST applications than EPOST applications at each rate of glyphosate (Table

5). Control of redroot pigweed and velvetleaf from LPOST applications of 0.84 kg/ha glyphosate was improved compared to EPOST applications. Krausz et al. (1996) reported that application timings did not influence giant foxtail and redroot pigweed control, but they did not account for weeds that emerged following application in their visual ratings. As with the glufosinate trials, lower weed control from the EPOST timing could be attributed to weeds which emerged following glyphosate application.

Corn yields were not significantly affected by glyphosate rates or application timings compared with yields of weed-free plots (Table 5). However, yields in plots treated with an EPOST application of 0.84 kg/ha glyphosate were significantly higher than yields of plots treated with a LPOST application of glyphosate at the same rate. This yield reduction might be attributed to early season competition from weeds that were not treated until the LPOST timing. Carey and Kells (1995) and Tapia et al. (1997) reported that the duration of weed interference with a corn crop is a critical factor in the determination of corn yield. As herbicide timings are delayed the potential for yield reductions due to weed interference increases. In these trials, weeds were always less than 10 cm tall at the EPOST timing, while the highest density weed, giant foxtail, was 13 cm and 20 cm tall at the LPOST timing in 1996 and 1997, respectively (Table 1). Loux et al. (1998) reported that corn yield loss is likely when weeds reach 15-cm in height before treatment.

Gross margins among glyphosate rates at each application timing were similar (Table 5). However, as with corn yields, gross margins were higher for 0.84 kg/ha of glyphosate applied at the EPOST timing compared to the LPOST timing. Since the weed control costs among these treatments are equal, the difference was due to lower corn yields from the

LPOST timing. The profitability of plots lacking weed control treatments was severely reduced. Gross margins for many of the glyphosate based weed control programs exceeded the gross margins for the POST standard at lower corn prices. However, the gross margins of the POST standard were similar to the gross margins of the glyphosate treatments at higher corn prices (Table 5). As the price of corn increased, the revenue for each treatment increased while the weed control cost per treatment remained constant. Increased revenues at constant costs resulted in increased gross margins across treatments, and a higher overall mean square error when comparing differences in gross margins across treatments. A high mean square error resulted in a large LSD value. Therefore, the gross margins of the POST standard were not statistically different than the gross margins of the glyphosate treatments as corn price increased.

Control of each weed species was enhanced when applications of glufosinate and glyphosate were delayed. LPOST applications of glufosinate at 0.30 kg/ha or 0.41 kg/ha and glyphosate at 0.42 kg/ha or 0.84 kg/ha provided at least 89% control of all weeds. Weed control from glufosinate never exceeded the EPOST standard of nicosulfuron plus dicamba. Giant foxtail and velvetleaf control was greater from LPOST applications of 0.42 kg/ha of glyphosate compared to the POST standard. In the absence of weed control, corn yields were severely reduced in both trials, indicating a high amount of weed competition.

Effect of cultivation and application timing on weed control. *Glufosinate trial.* Buhler et al. (1995) demonstrated that annual grass control could be increased by following reduced rates of preemergence applied herbicides with cultivation. Nearly all weeds which emerged or recovered following an EPOST application of glufosinate were effectively removed by cultivation (Table 6). Cultivation following EPOST glufosinate applications increased control of redroot pigweed and velvetleaf compared to a LPOST glufosinate application alone. Velvetleaf that emerged or recovered following a LPOST glufosinate application was effectively removed by cultivation. LPOST applications of glufosinate controlled all weed species other than velvetleaf ≥92% and cultivation following the LPOST glufosinate application only increased velvetleaf control. Cultivation alone did not adequately control any of the weed species.

Mulder and Doll (1993) showed that cultivation increased weed control and did not affect corn yields. Within an application timing, cultivation did not affect yield (Table 6). Corn yields in weed free cultivated plots were higher than plots that were cultivated following glufosinate applications, indicating that weed control from the glufosinate plus cultivation was not complete. The remaining weeds competed with the corn enough to reduce yields. At low corn prices, the cost of cultivation reduced gross margins over weed control costs within the LPOST timings of glufosinate (Table 6). However this difference was not apparent at higher corn prices, because weed control costs remained constant as corn price increased. Cultivation was more economically feasible as corn price increased. Using cultivation as the only method of weed control resulted in severely reduced corn yields and gross margins that were equivalent to untreated plots. In the absence of weeds, cultivation did not affect yield.

Glyphosate trials. With the exception of velvetleaf, cultivation enhanced control of weeds following an EPOST application of glyphosate (Table 7). Cultivation increased redroot pigweed control following a LPOST application of glyphosate, but did not affect control of other weed species at this timing. Cultivation following EPOST glyphosate applications controlled all weeds ≥91%. Cultivation alone did not sufficiently control weeds.

Cultivation did not influence corn yields or gross margins in plots previously treated with glyphosate (Table 7). Cultivation in the absence of weeds did not influence yield. Corn yields in plots that received cultivation only were higher than the untreated plots but were severely reduced compared with treatments that included a glyphosate application with or without cultivation. At higher corn prices, cultivating without herbicide application increased gross margins compared to untreated plots, but gross margins were much lower than plots that were treated with glyphosate.

Weeds that emerge following application of glufosinate or glyphosate influence the efficacy of these herbicides. Giant foxtail emergence following EPOST applications of glufosinate or glyphosate was often greater than giant foxtail emergence following LPOST timings. Differences in weed emergence generally resulted in greater weed control from the LPOST timings compared to the EPOST timings. Weed control was most consistent in plots that were treated with LPOST applications of glufosinate at 0.41 kg/ha or glyphosate at 0.84 kg/ha, the highest rates tested in these studies. Although weed control was often enhanced from later timings of glufosinate and glyphosate, the later timings can reduce corn yields by extending the duration of weed interference with the corn. Since the risk of corn yield loss increases as glufosinate and glyphosate application timings are delayed, these herbicides should be applied to weeds at the EPOST timing. Weed control from an EPOST timing is often reduced from weed emergence following application. Cultivation following glufosinate and glyphosate applied at the EPOST timing is a cost effective weed management strategy to increase weed control from early glufosinate or glyphosate applications.

The EPOST and LPOST timings were only separated by an average of 7 d in which time corn had developed 2 collars and weed heights doubled. The proper timing for POST herbicide applications can occur within a short period. Therefore, a timely herbicide application is a critical component of a successful POST weed control program. The profitability of glufosinate based weed control programs were similar to the POST standard, and glyphosate based weed control programs often exceeded that of a POST standard. Corn yield strongly influences the profitability of weed control programs. Further research is needed to identify additional weed management strategies that will provide adequate weed control from timely glufosinate and glyphosate applications in corn without reducing yields or profits.

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Table 1. Corn growth stages, weed heights, and weed densities at time of herbicide application and cultivation.[a]

	Glufosinate trials						Glyphosate trials					
	1996			1997			1996			1997		
	EPOST	LPOST	Culti.	EPOST	LPOST	Culti.	EPOST	LPOST	Culti.	EPOST	LPOST	Culti.
Days after corn planting	27	35	37	29	35	42	27	35	37	29	35	42
Corn growth stage												
Visible collars	3	5	5	2	4	6	3	3	5	2	4	6
Height (cm)	15	36	38	17	23	58	15	25	38	14	33	58
Weed height	cm											
Giant foxtail	6	20	33	5	13	44	6	20	33	5	13	44
Common lambsquarters	5	10	13	3	7	30	5	10	13	3	7	30
Redroot pigweed	4	8	20	2	9	36	4	8	20	2	9	36
Velvetleaf	5	15	23	4	8	25	5	15	23	4	8	25
Weed density	plants/m^2											
Giant foxtail	613	742		1,130	710		1,173	710		893	538	
Common lambsquarters	22	11		97	75		32	32		129	172	
Redroot pigweed	22	22		32	11		32	22		11	11	
Velvetleaf	22	11		11	11		32	22		32	43	

[a] EPOST = early postemergence, LPOST = late postemergence, Culti.= interrow cultivation.

Table 2. Assumption of costs used in profitability analysis.

Custom application costs	
PRE	$10/ha
POST	$12/ha
Herbicide costs	
ammonium sulfate	$0.50/kg
dicamba	$303/L
glufosinate	$356/L
glyphosate	$189/L
nicosulfuron	$1/kg
Operating costs	
Cultivator (6-row 76-cm row spacing)	$8/ha
Sprayer (15-m boom)	$0.60/ha
Technology fee	
'DK 493GR'[b]	$12.50/unit[a]
'DK 493RR'[c]	$18/unit

[a] A unit of seed is estimated at 80,000 seed

[b] resistant to glufosinate

[c] resistant to glyphosate

Table 3. Weed densities 18 d after glufosinate and glyphosate applications.

	Weed density[a]			
	SETFA	CHEAL	AMARE	ABUTH
Glufosinate[b]	plants/m^2			
EPOST	55.9	5.6	1.3	2.9
LPOST	20.2	3.9	1.3	0.0
p-value	0.028	0.707	1.00	0.124
Glyphosate[c]				
EPOST	25.7	6.0	3.4	3.4
LPOST	9.8	2.2	3.4	0.9
p-value	0.167	0.158	0.993	0.116

[a] SETFA, giant foxtail; CHEAL, common lambsquarters; AMARE, redroot pigweed; ABUTH, velvetleaf. All data are pooled over 1996 and 1997.

[b] Application rate of 0.30 kg/ha. Ammonium sulfate was added at 2% (w/w).

[c] Application rate of 0.42 kg/ha. Ammonium sulfate was added at 2% (w/w).

Table 4. Weed control, corn yield, and gross margins as affected by glufosinate application rate and timing, 1996 and 1997.[a]

			Weed control[b]									
				CHEAL				Grain	Weed control	Gross margins over weed control costs[c]		
Treatment	Rate	Timing	SETFA	1996	1997	AMARE	ABUTH	yield	costs	$60/Mg[d]	$100/Mg	$140/Mg
	kg/ha		%					Mg/ha	$/ha	$/ha		
Glufosinate[e]	0.18	EPOST	84 b	84 b	50 e	86 c	82 bcd	8.06 b	45.77	414 a	720 a	1027 a
		LPOST	85 b	93 ab	84 cd	85 c	75 d	8.09 b	45.77	416 a	723 a	1031 a
	0.30	EPOST	80 b	93 ab	76 d	86 c	79 cd	8.81 ab	59.68	443 a	778 a	1112 a
		LPOST	92 a	95 ab	90 bc	94 b	90 ab	8.82 ab	59.68	443 a	778 a	1113 a
	0.41	EPOST	84 b	96 a	82 d	86 c	85 abc	9.20 a	73.58	451 a	701 a	1150 a
		LPOST	92 a	96 ab	93 b	91 bc	92 a	9.14 ab	73.58	448 a	795 a	1142 a
Nicosulfuron + dicamba[f]	0.035 + 0.28	EPOST	94 a	98 a	99 a	99 a	89 ab	9.02 ab	92.92	421 a	764 a	1107 a
Untreated			0	0	0	0	0	2.82 c	9.46	152 b	259 b	366 b
Weed-free			100	100	100	100	100	9.71 a				

[a] Means within a column followed by the same letter are not significantly different according to an LSD test (P=0.05).
[b] SETFA, giant foxtail; CHEAL, common lambsquarters; AMARE, redroot pigweed; ABUTH, velvetleaf. SETFA, AMARE and ABUTH data pooled over years.
[c] Gross margins over weed control costs were from 1997 only and were calculated by multiplying corn yield by corn price and subtracting total weed control costs.
[d] $60/Mg equivalent to $1.50/Bu, $100/Mg equivalent to $2.50/Bu, $140/Mg equivalent to $3.50/Bu.
[e] Glufosinate treatments included ammonium sulfate at 2 % (w/w).
[f] Included NIS at 0.25% (v/v) and urea- ammonium nitrate at 4.67 L/ha.

Table 5. Weed control, corn yield, and gross margins as affected by glyphosate application rate and timing, 1996 and 1997.[a]

			Weed control[b]									
				CHEAL				Grain	Weed control	Gross margins over weed control costs[d]		
Treatment	Rate	Timing	SETFA	1996	1997	AMARE	ABUTH	yield[c]	costs	\$60/Mg[e]	\$100/Mg	\$140/Mg
	kg/ha		%					Mg/ha	\$/ha	\$/ha		
Glyphosate[f]	0.21	EPOST	87 cd	92 bcd	52 e	85 d	83 bc	11.59 ab	33.86	627 ab	1067 ab	1507 ab
		LPOST	95 b	91 d	81 cd	88 cd	84 bc	10.78 b	33.86	581 abc	991 bc	1400 b
	0.42	EPOST	85 d	93 cd	74 d	88 cd	86 ab	11.72 ab	41.67	626 ab	1071 ab	1516 a
		LPOST	97 a	99 ab	93 ab	92 bc	91 a	11.61 ab	41.67	620 ab	1061 abc	1502 ab
	0.84	EPOST	86 d	100 a	86 bc	89 cd	76 c	12.28 a	56.91	643 a	1109 a	1576 a
		LPOST	96 ab	99 ab	97 a	94 b	89 ab	10.89 b	56.91	564 bc	978 bc	1392 b
Nicosulfuron + dicamba[g]	0.035 + 0.28	EPOST	90 c	98 abc	98 a	99 a	82 bc	11.09 ab	95.42	537 c	958 c	1379 b
Untreated			0	0	0	0	0	5.09 c	11.95	278 d	472 d	665 c
Weed-free			100	100	100	100	100	11.94 ab				

[a] Means within a column followed by the same letter are not significantly different according to an LSD test (P=0.05).
[b] SETFA, giant foxtail; CHEAL, common lambsquarters; AMARE, redroot pigweed; ABUTH, velvetleaf. SETFA, AMARE and ABUTH data pooled over years.
[c] Corn yield data from 1997 only.
[d] Gross margins over weed control costs were from 1997 only and were calculated by multiplying corn yield by corn price and subtracting total weed control costs.
[e] \$60/Mg equivalent to \$1.50/Bu, \$100/Mg equivalent to \$2.50/Bu, \$140/Mg equivalent to \$3.50/Bu.
[f] Glyphosate treatments included ammonium sulfate at 2 % (w/w).
[g] Included NIS at 0.25% (v/v) and urea- ammonium nitrate at 4.67 L/ha.

Table 6. Weed control, corn yield, and gross margins as affected by glufosinate application timing and cultivation, 1996 and 1997.[a]

Glufosinate application timing[c]	Cultivation	Weed control[b] SETFA	CHEAL	AMARE	ABUTH	Grain yield	Weed control costs	Gross margins over weed control costs[d] $60/Mg[e]	$100/Mg	$140/Mg
		%				Mg/ha	$/ha	$/ha		
EPOST	Yes	93 a	93 a	98 a	93 b	8.75 c	67.80	431 ab	764 a	1096 a
	No	80 b	85 b	86 c	79 d	8.81 bc	59.68	443 a	778 a	1112 a
LPOST	Yes	96 a	94 ab	95 ab	99 a	8.08 c	67.80	393 b	700 a	1007 a
	No	92 a	93 ab	94 b	90 c	8.82 bc	59.68	443 a	778 a	1113 a
Untreated	Yes	25 c	22 c	23 d	21 e	3.56 d	17.59	185 c	320 b	455 b
	No[d]	0	0	0	0	2.82 d	9.46	152 c	259 b	366 b
Weed-free	Yes	100	100	100	100	9.94 a				
	No	100	100	100	100	9.71 ab				

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).

[b] SETFA, giant foxtail; CHEAL, common lambsquarters; AMARE, redroot pigweed; ABUTH, velvetleaf. All data are pooled over years.

[c] Glufosinate application rate was 0.30 kg/ha. Ammonium sulfate was added at 2% (w/w).

[d] Gross margins over weed control costs were from 1997 only and were calculated by multiplying corn yield by corn price and subtracting total weed control costs.

[e] $60/Mg equivalent to $1.50/Bu, $100/Mg equivalent to $2.50/Bu, $140/Mg equivalent to $3.50/Bu.

Table 7. Weed control, corn yield, and gross margins as affected by glyphosate application timing and cultivation, 1996 and 1997.[a]

Glyphosate application timing[c]	Cultivation	Weed control[b]				Grain yield[d]	Weed control costs	Gross margins over weed control costs[e]		
		SETFA	CHEAL	AMARE	ABUTH			$60/Mg[f]	$100/Mg	$140/Mg
		%				Mg/ha	$/ha	$/ha		
EPOST	Yes	93 b	91 b	96 ab	92 ab	11.53 a	49.80	607 a	1046 a	1484 a
	No	85 c	84 c	88 c	86 b	11.72 a	41.67	626 a	1071 a	1516 a
LPOST	Yes	97 a	97 a	97 a	95 a	10.79 a	49.80	565 a	975 a	1385 a
	No	97 a	96 a	92 bc	91 ab	11.61 a	41.67	620 a	1061 a	1502 a
Untreated	Yes	28 d	27 d	25 d	25 c	6.46 b	20.08	348 b	593 b	639 b
	No[e]	0	0	0	0	5.09 c	11.95	278 b	472 c	665 c
Weed-free	Yes	100	100	100	100	11.57 a				
	No	100	100	100	100	11.94 a				

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).
[b] SETFA, giant foxtail; CHEAL, common lambsquarters; AMARE, redroot pigweed; ABUTH, velvetleaf. All data are pooled over years.
[c] Glyphosate application rate was 0.42 kg/ha. Ammonium sulfate was added at 2% (w/w).
[d] Corn yield data from 1997 only.
[e] Gross margins over weed control costs were from 1997 only and were calculated by multiplying corn yield by corn price and subtracting total weed control costs.
[f] $60/Mg equivalent to $1.50/Bu, $100/Mg equivalent to $2.50/Bu, $140/Mg equivalent to $3.50/Bu.

CHAPTER 3

WEED CONTROL AND CORN (*Zea mays*) YIELD FROM RESIDUAL HERBICIDE COMBINATIONS WITH GLYPHOSATE AND GLUFOSINATE IN CORN

Abstract: Weed management strategies are needed to control weeds that emerge following application of glyphosate or glufosinate. Field trials were conducted from 1996 to 1999 to determine if residual herbicides could be used with glyphosate or glufosinate to provide season-long weed control in glyphosate-resistant or glufosinate-resistant corn. Preemergence (PRE) applications of the residual herbicides, acetochlor, atrazine, metolachlor, and pendimethalin, followed by postemergence (POST) applications of glyphosate or glufosinate were compared with POST tank mixtures of glyphosate or glufosinate with the residual herbicides. In general, weed control was similar for total POST compared to PRE followed by POST systems. Residual herbicides used in combination with glyphosate or glufosinate increased control of most weed species. Reducing the rate of residual herbicides reduced the consistency of weed control. Tank mixtures with reduced rates of acetochlor plus atrazine provided the most consistent weed control. Corn yields were not affected by application timing, rates of the residual herbicides, or by whether residual herbicides were used. Using reduced rates of residual herbicides with glyphosate or glufosinate is a viable weed management system in glyphosate-resistant and glufosinate-resistant corn.

Nomenclature: acetochlor, 2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl)acetamide plus MON 4660; atrazine, 6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-

1,3,5-triazine-2,4-diamine; CGA-154281, 4-(dichloroacetyl)-3,4-dihydro-3-methyl-2*H*-1,4-benzoxazine; flumetsulam, [*N*-(2,6-diflourophenyl)-5-(1,3,4,5,6,7-hexahydro-1,3-dioxo-2*H*-isoindol-2-yl)phenoxy] acetic acid; glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; glyphosate, *N*-(phosphonomethyl)glycine; metolachlor, 2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide; pendimethalin, *N*-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine; corn, *Zea mays* L. 'DK 493GR', 'DK 493RR'.

Additional index words: acetochlor, atrazine, flumetsulam, glufosinate-resistant corn, glyphosate-resistant corn, herbicide tolerant crops, metolachlor, pendimethalin, soil-applied herbicides.

Abbreviations: DAT, days after treatment; POST, postemergence; PRE, preemergence.

INTRODUCTION

Glyphosate and glufosinate have traditionally been used to control a wide spectrum of weeds in non-crop environments. Recent advancements in biotechnology have resulted in the development of crops that are resistant to POST applications of glufosinate or glyphosate. These herbicides are currently used in resistant corn hybrids without crop injury (Ateh and Harvey 1995; Culpepper and York 1999; Gower and Loux 1999).

Glufosinate is readily degraded by soil microorganisms (Smith 1989; Tebbe and Reber 1991), and glyphosate is rapidly adsorbed to soil components (Sprankle et al. 1975a; 1975b). These characteristics typically eliminate herbicidal activity of glyphosate or glufosinate in the soil. Therefore, weeds that emerge following herbicide application are not controlled. Late emerging weeds can be controlled by various weed management strategies. Buhler et al. (1993) reported that interrow cultivation following a POST application of herbicides at reduced rates increased control of common cocklebur (*Xanthium strumarium*). Cultivation following a timely application of glufosinate and glyphosate can also enhance weed control (Tharp and Kells 1999). Watts et al. (1997) reported that PRE followed by POST applications of herbicides increased control of sicklepod (*Senna obtusifolia*). Similar sequential application methods were shown to consistently control annual grasses (Rabaey and Harvey 1997). In glyphosate resistant soybeans, soil-applied herbicides are often applied prior to POST glyphosate applications to provide residual weed control (Gonzini et al. 1999). Van Wychen et al. (1999) reported that in glufosinate-resistant sweet corn, weed management strategies that included residual herbicides or cultivation increased weed control compared to glufosinate applied alone. Weed control can be increased by delaying glufosinate or glyphosate applications (Tharp and Kells 1999). However, delayed applications can result in soybean (*Glycine max*) and corn yield reductions from increased weed competition (Carey and Kells 1995; Horak et al. 1998).

As the use of glyphosate or glufosinate for weed control in corn increases, weed management strategies that provide season-long weed control without reducing yields are needed. In these trials, residual herbicides were used in combination with glufosinate and glyphosate. Weed control from PRE applications of residual herbicides followed by POST glufosinate or glyphosate applications were compared with POST tank mixtures of glufosinate or glyphosate with the residual herbicides. The effect of reduced rates of the residual herbicide tank mix partners on weed control and corn yield was also investigated.

MATERIALS AND METHODS

Field trials were conducted in 1996, 1997, 1998, and 1999 at separate locations on the Michigan State University Crop and Soil Sciences Research Farm in East Lansing. In 1996 and 1998, the soil was a Capac loam (fine-loamy, mixed mesic Aeric Ochraqualf) with a pH of 7.0 and 3.5% organic matter, and in 1997 and 1999 the soil was a Capac sandy loam with a pH of 6.5 and 2.6% organic matter. Research sites were moldboard plowed in the fall of each year; secondary tillage consisted of disking and field cultivation in the spring of each year. Prior to field cultivation, a 46-0-0 (N,P,K) fertilizer was broadcast and a 6-24-24 fertilizer was banded 5 cm below and 5 cm to the side of the corn seed during the planting operation. Fertilizer rates were determined from results of soil analysis. All herbicides were applied with a tractor-mounted compressed-air sprayer equipped with flat-fan nozzles[8] and calibrated to deliver 187 kg/ha at a pressure of 207 kPa. Experimental glyphosate-resistant and glufosinate-resistant hybrids were planted on May 17, 1996. An experimental glyphosate-resistant hybrid and 'Dekalb 493GR' were planted on May 13, 1997. 'Dekalb 493RR' and 'Dekalb 493GR' were planted on May 11, 1998 and May 3, 1999. Plots consisted of four rows spaced 76 cm apart with lengths of 10.7 in 1996 and 1998 and 9.1 m in 1997 and 1999. Glufosinate-resistant and glyphosate-resistant corn were treated as separate trials, and each trial was designed as a randomized complete block with three replications. Corn growth stages and weed densities were recorded in untreated plots at the POST timing (Table 1). The average height of giant foxtail from 1996 to 1999 ranged from 5 to 8 cm and the average broadleaf weed height ranged from 3 to 6 cm at the POST timing.

Application timing of residual herbicide combinations. *Glyphosate field trials.* In 1996 to 1999, treatments in glyphosate-resistant corn consisted of POST tank mixtures of glyphosate with residual herbicides and PRE applications of residual herbicides followed by a sequential POST application of glyphosate. The residual herbicides included acetochlor at 1.8 kg/ha with MON 4660 (safener), atrazine at 1.1 kg/ha, metolachlor at 1.4 kg/ha with CGA-154281 (safener), and pendimethalin at 1.7 kg/ha. Additional treatments included a single POST application of glyphosate, untreated, and weed-free plots. Weed-free plots were treated with a PRE application of a premix[9] of metolachlor at 2.24 kg/ha plus atrazine at 1.12

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[8]TeeJet XR 8003. Spraying Systems Co., North Ave., Wheaton, IL 60188.

[9]Bicep Lite II, Novartis, Crop Protection Division, PO Box 18300, Greensboro, NC 27419.

kg/ha followed by hand-weeding as needed. The glyphosate rate in 1996 and 1997 was 0.43 kg ae/ha, and in 1998 the rate was 0.63 kg/ha for the sequential and tank mixture treatments and 0.43 kg/ha when glyphosate was applied alone. In 1999 all glyphosate rates were 0.63 kg/ha. Ammonium sulfate at 2% (w/w) was added to all treatments containing glyphosate.

Glufosinate field trials. In 1996 and 1997, POST tank mixtures of residual herbicides with glufosinate at 0.29 kg ai/ha and PRE applications of residual herbicides followed by sequential POST applications of glufosinate at 0.29 kg/ha were investigated. The residual herbicides included acetochlor at 1.8 kg/ha with MON 4660 (safener), atrazine at 1.1 kg/ha, metolachlor at 1.4 kg/ha with CGA-154281 (safener), and pendimethalin at 1.7 kg/ha. Additional treatments included glufosinate at 0.29 kg/ha applied alone, untreated, and weed-free plots. All treatments containing glufosinate included ammonium sulfate at 2% (w/w).

Reduced application rates of residual herbicides. *Glyphosate field trials.* Tank mixtures of full and reduced rates of residual herbicides with glyphosate were tested in 1998 and 1999. The full rates of the residual herbicides were acetochlor at 1.8 kg/ha with MON 4660 (safener), a pre-mix[10] of acetochlor at 1.8 kg/ha with MON 4660 (safener) plus atrazine at 1.4 kg/ha, atrazine at 1.1 kg/ha, flumetsulam at 0.056 kg/ha, metolachlor at 1.4 kg/ha with CGA-15428 (safener), and pendimethalin at 1.7 kg/ha. The reduced rates of the residual herbicides were half the full rate. In 1998, the glyphosate rate was 0.63 kg/ha for the tank mixture treatments and 0.43 kg/ha when glyphosate was applied alone. In 1999, all glyphosate rates were 0.63 kg/ha. Ammonium sulfate at 2% (w/w) was added to all treatments containing glyphosate.

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[10]Harness Xtra 5.6L, Monsanto, St. Louis, MO 63167

Glufosinate field trials. In 1998 and 1999, glufosinate at 0.29 kg/ha was applied in POST tank mixtures with full and reduced rates of the residual herbicides. The full rates of the residual herbicides were acetochlor at 1.8 kg/ha with MON 4660 (safener), a pre-mix[5] of acetochlor at 1.8 kg/ha with MON 4660 (safener) plus atrazine at 1.4 kg/ha, atrazine at 1.1 kg/ha, flumetsulam at 0.056 kg/ha, metolachlor at 1.4 kg/ha with CGA-15428 (safener), and pendimethalin at 1.7 kg/ha. The reduced rates of the residual herbicides were half the full rate. All treatments containing glufosinate included ammonium sulfate at 2% (w/w).

Data collection and statistical analysis. Visual estimates of weed control were recorded 28 d after the POST application in all trials. Weed control was compared against an untreated control using a scale of (0 no control) to 100 (all plants dead). Corn grain yield was determined by harvesting the center two rows of each plot with a mechanical plot harvester. Corn grain yield was corrected to 15.5% moisture. Glyphosate-resistant corn was destroyed prior to corn pollination in 1996 to comply with federal regulatory restrictions.

Visual estimates of weed control were arcsine transformed prior to statistical analysis and subjected to ANOVA procedures. Means of the transformed weed control data and corn yields were separated using Fishers protected LSD at the P= 0.05 level of probability. Nontransformed means are presented for clarity. Visual estimates of weed control and corn yield were subjected to F-Max tests to test for homogeneity of variance among years (Kuehl 1994). Data found to be homogenous were pooled over years. Differences in herbicide performance among years are likely due to differences in environmental conditions.

RESULTS AND DISCUSSION

Application timing of residual herbicide combinations. *Glyphosate field trials.* Control of each weed species in the trial except velvetleaf in 1996 and 1999 generally increased when a residual herbicide was used in combination with glyphosate (Table 2). The effect of atrazine application timing on velvetleaf control varied each year. In 1997 and 1998, POST tank mixtures of glyphosate and atrazine provided more complete velvetleaf control than sequential applications. However, in 1996 and 1999, timing of atrazine application had no effect on velvetleaf control. Control of velvetleaf was 90% or greater every year from combinations of glyphosate and pendimethalin, and control was always less than 90% from combinations of glyphosate and metolachlor and acetochlor. Control of redroot pigweed and giant foxtail was not affected by the timing of residual herbicide applications. Common lambsquarters and redroot pigweed were controlled ≥90% regardless of the timing of residual herbicide application. Likewise, common lambsquarters control was similar from PRE applications of residual herbicides followed by glyphosate compared to POST glyphosate tank mixtures in soybean trials conducted by Gonzini et al. (1999). When metolachlor and pendimethalin were tank mixed with glyphosate, common ragweed control was increased compared to sequential applications in 1997, but was not affected by application timing in other years. POST tank mixtures increased weed control compared to sequential applications in five instances. In contrast, using sequential applications increased weed control over tank mixtures in two instances.

Despite some differences in weed control between application timings, differences in corn yields were not apparent (Table 2). Corn yields in plots treated with residual herbicide combinations were similar to weed-free plots. Plots treated with glyphosate alone yielded similar to plots treated with residual herbicides and weed-free plots, suggesting that weeds that emerged after the glyphosate application did not compete with corn enough to reduce yields. Dalley et al. (In Press) showed that weeds that emerged following POST glyphosate applications did not reduce corn yields. Bosnic and Swanton (1997) reported that the time of weed emergence relative to corn emergence is critical in determining the competitive effects of weeds to corn. They showed that barnyardgrass seedlings that emerged after the 4-leaf corn stage reduced corn yields less than 6% (Bosnic and Swanton 1997). Weeds that emerge after crop emergence are less likely to cause yield reductions than weeds that emerge with the crop (Knake and Slife 1965; Murphy et al. 1996). Corn yields in untreated plots were severely reduced from intense weed competition.

Glufosinate field trials. The addition of residual herbicides increased control of each weed species in the trial except common lambsquarters in 1996 (Table 3). Velvetleaf control was not affected by application method for any of the residual herbicide combinations. Van Wychen et al. (1999) similarly showed that the application timing of atrazine combinations with glufosinate did not influence common lambsquarters, common ragweed, or velvetleaf control. Control of redroot pigweed and common ragweed exceeded 90% for all residual herbicide combinations (Table 3). Similar levels of common ragweed control were reported by Culpepper and York (1999). Sequential applications of acetochlor or metolachlor followed by glufosinate controlled common lambsquarters in 1997 greater than the POST tank mix combinations of these herbicides (Table 3). This difference in control could be attributed to poor common lambsquarters control from glufosinate. Although glufosinate applied alone in 1996 controlled common lambsquarters 93%, glufosinate applied alone in 1997 controlled common lambsquarters only 76%. In 1997, the density of common lambsquarters at application was more than five time higher than in 1996 (Table 1). The high density of common lambsquarters plants in 1997 might have resulted in incomplete herbicide exposure which would decrease the effectiveness of glufosinate. Steckel et al. (1997) attributed reduced glufosinate activity on giant foxtail to inadequate herbicide coverage. The residual tank mix partners likely prevented new emergence of common lambsquarters. Unlike the other residual herbicide partners, atrazine has foliar activity on common lambsquarters. Therefore, common lambsquarters control was complete and not affected by the application timing of atrazine. Giant foxtail control was greater when glufosinate was applied as a POST tank mixture with atrazine compared to a sequential application (Table 3). Giant foxtail control was increased when a PRE application of pendimethalin was followed by a POST application of glufosinate compared to a POST tank mixture of these herbicides. A PRE application of a herbicide with residual grass activity followed by a POST application of glufosinate has been shown to increase the consistency of annual grass control (Van Wychen et al. 1999; Culpepper and York 1999). Glufosinate tank mixtures with residual herbicides provided more complete control of weeds than sequential applications in two instances. Weed control was greater from sequential applications compared to tank mixtures in three instances. In most cases, the timing of the residual herbicide combinations did not affect weed control (Table 3). In cases where weed control was increased by application timing, corn yields were not affected.

Corn yields in plots treated with residual herbicide combinations with glufosinate were similar to the yields of the weed-free plots (Table 3). Corn in plots treated with glufosinate applied alone also yielded similar to weed-free plots. As with the glyphosate field trial, weeds emerging after herbicide application did not reduce corn yield. Corn yields in untreated plots were severely reduced as a result of intense weed competition.

Reduced application rates of residual herbicides. *Glyphosate field trials.* Velvetleaf control was not increased when acetochlor, metolachlor, or the reduced rate of atrazine were tank mixed with glyphosate (Table 4). Reduced rates of acetochlor plus atrazine and atrazine resulted in reduced control of velvetleaf compared to the full rates. Control of redroot pigweed was increased by tank mixing the residual herbicides with glyphosate, and reduced rates of all residual herbicide tank mix partners controlled redroot pigweed similar to full rates. Tank mixing glufosinate with each of the residual herbicides, except metolachlor or pendimethalin, increased common ragweed control in 1998. Common ragweed control was lower when application rates of acetochlor and atrazine were reduced in 1998, and when rates of flumetsulam and metolachlor were reduced in 1999. Common lambsquarters control was increased when each of the residual herbicides were included with glyphosate compared to glyphosate applied alone. Weed control is often increased when residual herbicides are applied in combination with glyphosate compared to glyphosate applied alone (Gonzini et al.1999; Wilson et al. 1985). Reducing the application rate of acetochlor and flumetsulam decreased common lambsquarters control. In 1998, giant foxtail control was increased when glyphosate was tank mixed with each of the residual herbicides compared to glyphosate applied alone, except for the reduced rate of atrazine (Table 4). In 1999, glyphosate tank mixtures with acetochlor, acetochlor + atrazine, and metolachlor increased control of giant foxtail compared to glyphosate applied alone. Control of giant foxtail in 1998 decreased when the rate of atrazine was reduced. Otherwise, giant foxtail control was not affected by application rate of residual herbicide combinations. O'Sullivan and Bouw (1993) reported consistent grass control from reduced rates of metolachlor plus cyanazine, but grass control was lower from reduced rates of cyanazine plus atrazine. Previous research showed potential antagonism when glyphosate is tank mixed with other herbicides (Lich et al. 1997; Selleck and Baird 1981). Although glyphosate tank mixtures with atrazine delayed the development of injury symptoms (data not shown), tank mixing residual herbicides with glyphosate did not reduce the overall control of any of the weed species in these trials. Weed control was often increased when a residual herbicide was included with glyphosate, and was less consistent when rates of the residual herbicides were reduced. Weed control was reduced in nine of 60 instances when residual herbicide application rates were reduced. Corn yields were similar among full and reduced rates of all residual herbicide combinations and were comparable to yields in the weed-free plots (Table 4). Corn yields in the untreated plots were significantly reduced indicating high weed competition.

Glufosinate field trials. Velvetleaf control was increased by tank mixing glufosinate with acetochlor plus atrazine, flumetsulam, pendimethalin, and the full rate of atrazine (Table 5). Previous research has also shown increased weed control when glufosinate is applied in combination with residual herbicides (Culpepper and York 1999; Wilson et al. 1985). Reduced rates of acetochlor plus atrazine, flumetsulam, and pendimethalin reduced velvetleaf control. Common ragweed control was increased when acetochlor, acetochlor plus atrazine, atrazine, or full rates of flumetsulam and metolachlor was added to glufosinate. Control of common ragweed decreased when application rates of acetochlor and flumetsulam were reduced. Reduced application rates of residual herbicide combinations did not affect control of redroot pigweed compared to full rates. When the application rate of acetochlor was reduced, common lambsquarters control decreased. All residual herbicide combinations, except the reduced rate of metolachlor, increased common lambsquarters control in 1998 and redroot pigweed control compared in both years to glufosinate applied alone. Herbicide combinations which included atrazine provided greater than 96% control of common lambsquarters and redroot pigweed. Culpepper and York (1999) similarly reported increased common lambsquarters and smooth pigweed (*Amaranthus hybridus*) control when glufosinate was tank mixed with atrazine. In 1998, giant foxtail control was increased when each of the residual herbicide combinations were used, and control was lower when application rates of metolachlor and pendimethalin were reduced (Table 5). In 1999, giant foxtail control was increased when each of the residual herbicides except atrazine were used with glufosinate, but was not influenced by application rate of the residual herbicides. Weed control was often increased when residual herbicides were used with glufosinate. Reducing the rates of residual herbicides reduced weed control in eight of 60 instances. As with glyphosate, none of the residual herbicides tank mixed with glufosinate reduced control of any weed species, and corn yield was not affected.

Large differences in weed control were not apparent when residual herbicides were applied PRE and followed by a POST timing of glyphosate or glufosinate compared to POST tank mixtures of the residual herbicides with the glyphosate or glufosinate. Of the residual tank mix partners evaluated in this research, the acetochlor plus atrazine tank mixture with glyphosate or glufosinate provided the most consistent control of all weed species, except velvetleaf. Reducing the application rates of the residual herbicides often decreases the consistency of weed control.

Many factors need to be considered when deciding whether or not to use residual herbicides with glyphosate or glufosinate. Weeds that emerge following glyphosate or glufosinate applied alone will not likely reduce corn yields. However, weed control from single POST applications of these herbicides alone is often less than 90%. Residual herbicide combinations with glyphosate or glufosinate increase season-long weed control and should minimize weed seed production, but corn yields will not likely be increased. Growers will need to assess the value of maintaining a high level of weed control throughout the season with no apparent corn yield increases when deciding if a residual herbicide is needed with glyphosate or glufosinate.

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Table 1. Corn growth stage and weed density at POST, 1996-1999.

	Glyphosate field trials				Glufosinate field trials			
	1996	1997	1998	1999	1996	1997	1998	1999
Corn growth stage								
Visible collars	3	2	4	3	3	2	4	3
Height (cm)	15	15	20	13	15	18	20	13
Weed Density	---------- plants/m^2 ----------							
Giant foxtail	1173	689	323	549	614	797	312	226
Common lambsquarters	37	46	3	6	26	136	5	34
Redroot pigweed	29	11	8	2	24	17	11	8
Common ragweed	20	6	2	2	8	10	9	6
Velvetleaf	28	49	7	31	27	40	15	23

Table 2. Effect of application timing of residual herbicide combinations with glyphosate on weed control and corn yield.[a]

Herbicide partner with glyphosate[b]:	Application timing[c]	Weed control[d]											Corn yield[e]
		ABUTH					AMBEL						
		1996	1997	1998	1999	AMARE	1996	1997	1998	1999	CHEAL	SETFA	
		% control											– Mg/ha –
acetochlor	sequential	71 c	80 b	85 cd	86 a	99 ab	91 ab	97 abc	98 a	96 ab	99 a	98 a	11.87 a
	tank mix	85 bc	82 b	75 e	87 a	99 ab	89 ab	100 a	95 a	98 a	96 b	99 a	11.71 a
atrazine	sequential	95 ab	84 b	81 de	93 a	99 ab	98 a	100 a	92 a	95 ab	100 a	84 c	11.69 a
	tank mix	97 a	95 a	97 b	88 a	100 a	98 a	100 a	100 a	99 a	100 a	87 c	11.63 a
metolachlor	sequential	87 bc	75 b	74 e	87 a	98 b	78 b	91 cd	52 b	88 bc	91 c	99 a	11.73 a
	tank mix	75 c	80 b	68 e	85 a	97 b	82 b	98 ab	67 b	95 ab	90 c	99 a	11.77 a
pendimethalin	sequential	95 ab	93 a	92 bc	90 a	98 b	82 b	86 d	54 b	91 bc	98 a	96 b	11.55 a
	tank mix	95 ab	96 a	100 a	93 a	98 b	81 b	96 abc	59 b	93 abc	99 a	95 b	11.89 a
glyphosate alone		93 ab	79 b	68 e	81 a	79 c	78 b	92 bcd	55 b	86 c	77 d	80 d	11.92 a
untreated[f]		0	0	0	0	0	0	0	0	0	0	0	7.75 b
weed free[f]		100	100	100	100	100	100	100	100	100	100	100	12.21 a

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).

[b] The glyphosate rate in 1996 and 1997 was 0.43 kg ae/ha, and in 1998 the rate was 0.63 kg/ha for the sequential and tank mix treatments and 0.43 kg/ha when glyphosate was applied alone. In 1999 all glyphosate rates were 0.63 kg/ha. Ammonium sulfate at 2% (w/w) was added to all treatments containing glyphosate.

[c] Sequential, PRE application of the herbicide partner followed by POST application of glyphosate; tank mix, POST tank mixture of glyphosate with herbicide partner.
[d] Visual ratings recorded 28 d after the POST application. ABUTH, velvetleaf; AMARE, redroot pigweed; AMBEL, common ragweed; CHEAL, common lambsquarters; SETFA, giant foxtail. AMARE, CHEAL, and SETFA pooled over years, 1996 - 1999.
[e] Corn yields pooled over years, 1997 - 1999.
[f] Weed control data for untreated and weed-free plots were not included in ANOVA because values have no variance.

Table 3. Effect of application timing of residual herbicide combinations with glufosinate on weed control and corn yield.[a]

Herbicide partner with glufosinate[b]:	Application timing[c]	Weed control[d] ABUTH	AMARE	AMBEL	CHEAL 1996	CHEAL 1997	SETFA	Corn yield[e]
		% control						Mg/ha
acetochlor	sequential	85 c	98 ab	98 ab	98 a	100 a	98 ab	8.37 c
	tank mix	86 c	98 ab	99 a	98 a	78 d	98 ab	8.42 c
atrazine	sequential	92 ab	100 a	99 a	100 a	100 a	82 d	9.16 ab
	tank mix	97 a	100 a	100 a	100 a	100 a	90 c	9.31 a
metolachlor	sequential	78 c	98 ab	92 bc	98 a	93 c	99 a	8.87 abc
	tank mix	79 c	97 b	100 a	100 a	64 e	97 ab	8.52 bc
pendimethalin	sequential	92 ab	97 b	95 bc	98 a	97 b	94 b	8.41 c
	tank mix	97 a	98 ab	98 ab	95 a	94 bc	90 c	8.53 bc
glufosinate alone		81 c	87 b	89 c	93 a	76 d	82 d	8.77 abc
untreated[f]		0	0	0	0	0	0	2.61 d
weed free[f]		100	100	100	100	100	100	9.04 abc

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).
[b] Glufosinate rates were 0.29 kg/ha. All treatments containing glufosinate included ammonium sulfate at 2% (w/w).

[c] Sequential, PRE application of the herbicide partner followed by POST application of glyphosate; tank mix, POST tank mixture of glyphosate with herbicide partner.
[d] Visual ratings recorded 28 d after the POST application. ABUTH, velvetleaf; AMARE, redroot pigweed; AMBEL, common ragweed; CHEAL, common lambsquarters; SETFA, giant foxtail. ABUTH, AMARE, AMBEL, and SETFA pooled over years, 1996 - 1997.
[e] Corn yields pooled over years, 1996 - 1997.
[f] Weed control data for untreated and weed-free plots were not included in ANOVA because values have no variance.

Table 4. Effect of reduced rates of residual herbicides in glyphosate tank mixtures on weed control and corn yield.[a]

		Weed Control[b]							
	Application			AMBEL			SETFA		
Tank mix partner	rate[c]	ABUTH	AMARE	1998	1999	CHEAL	1998	1999	Corn Yield
		% control							Mg/ha
acetochlor	full	81 d	100 a	95 a	98 abc	99 ab	100 a	98 a	12.00 ab
	reduced	79 d	97 ab	78 cd	99 ab	86 d	99 ab	96 abc	11.67 ab
acetochlor+atrazine	full	99 a	100 a	97 ab	100 a	100 a	100 a	98 a	11.79 ab
	reduced	91 bc	100 a	100 a	100 a	100 a	100 a	97 ab	11.88 ab
atrazine	full	93 c	100 a	100 a	99 ab	100 a	81 d	87 d	11.84 ab
	reduced	81 d	99 a	81 cd	96 bc	99 ab	65 e	91 cd	12.11 ab
flumetsulam	full	96 abc	84 b	89 bc	100 a	97 b	85 d	93 bcd	11.73 ab
	reduced	91 bc	96 ab	80 cd	96 bc	93 c	78 d	92 cd	12.43 a
metolachlor	full	76 d	96 ab	67 de	95 bc	86 d	99 ab	97 ab	11.84 ab
	reduced	74 d	94 ab	60 e	84 d	82 d	98 abc	95 abc	11.47 b
pendimethalin	full	97 ab	98 ab	59 e	93 c	100 a	96 c	92 cd	12.28 ab
	reduced	96 abc	99 a	55 e	95 bc	100 a	95 bc	91 cd	12.18 ab
glyphosate alone		75 d	74 c	55 e	86 d	68 e	64 e	87 d	12.07 ab
untreated[d]		0	0	0	0	0	0	0	9.09 c
weed free[d]		100	100	100	100	100	100	100	12.53 a

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).

[b] Visual ratings recorded 28 d after the POST application. ABUTH, velvetleaf; AMARE, redroot pigweed; AMBEL, common ragweed; CHEAL, common lambsquarters; SETFA, giant foxtail. ABUTH, AMARE, and CHEAL pooled over years, 1998 - 1999.

[c] The full rates were acetochlor at 1.8 kg/ha, acetochlor at 1.8 kg/ha plus atrazine at 1.4 kg/ha, atrazine at 1.1 kg/ha, flumetsulam at 0.056 kg/ha, metolachlor at 1.4 kg/ha, and pendimethalin at 1.7 kg/ha. The reduced rates of the residual herbicides were half the full rate. In 1998 the glyphosate rate was 0.63 kg/ha for the tank mixture treatments and 0.43 kg/ha when glyphosate was applied alone. In 1999 all glyphosate rates were 0.63 kg/ha. Ammonium sulfate at 2% (w/w) was added to all treatments containing glyphosate.

[d] Weed control data for untreated and weed-free plots were not included in ANOVA because values have no variance.

Table 5. Effect of reduced rates of residual herbicides in glufosinate tank mixtures on weed control and corn yield.[a]

		Weed Control[b]							
	Application		AMARE				SETFA		
Tank mix partner	rate[c]	ABUTH	1998	1999	AMBEL	CHEAL	1998	1999	Corn Yield
		% control							Mg/ha
acetochlor	full	79 ef	95 ab	100 a	99 a	87 c	100 a	94 ab	11.84 ab
	reduced	81 def	86 bc	100 a	94 bcd	78 de	98 a	94 ab	12.31 a
acetochlor+atrazine	full	99 a	100 a	100 a	100 a	100 a	99 a	96 a	11.85 ab
	reduced	86 c	100 a	100 a	100 a	100 a	99 a	94 ab	11.70 ab
atrazine	full	86 cde	100 a	100 a	98 ab	99 ab	77 cd	86 de	12.09 ab
	reduced	79 ef	100 a	99 a	95 bc	97 ab	70 d	85 de	12.08 ab
flumetsulam	full	92 b	82 cd	100 a	92 bcd	90 c	68 d	87 d	11.46 b
	reduced	87 cd	85 cd	100 a	81 ef	89 cd	68 d	86 de	11.57 ab
metolachlor	full	75 f	72 de	100 a	87 def	73 ef	99 a	93 abc	11.67 ab
	reduced	73 f	58 ef	100 a	81 ef	65 fg	92 b	93 abc	12.02 ab
pendimethalin	full	97 a	90 bc	99 a	87 def	99 ab	92 b	92 bc	12.16 ab
	reduced	93 b	84 bc	97 a	86 def	96 b	83 c	89 cd	12.19 ab
glufosinate alone		73 f	52 f	90 a	75 f	61 g	52 e	82 e	12.35 a
untreated[d]		0	0	0	0	0	0	0	7.33 c
weed free[d]		100	100	100	100	100	100	100	11.99 ab

[a] Means within a column followed by the same letter were not significantly different according to an LSD test (P=0.05).

[b] Visual ratings recorded 28 d after the POST application. ABUTH, velvetleaf; AMARE, redroot pigweed; AMBEL, common ragweed; CHEAL, common lambsquarters; SETFA, giant foxtail. ABUTH, AMBEL, and CHEAL pooled over years, 1998 - 1999.
[c] The full rates were acetochlor at 1.8 kg/ha, acetochlor at 1.8 kg/ha plus atrazine at 1.4 kg/ha, atrazine at 1.1 kg/ha, flumetsulam at 0.056 kg/ha, metolachlor at 1.4 kg/ha, and pendimethalin at 1.7 kg/ha. The reduced rates of the residual herbicides were half the full rate. Glufosinate was applied at 0.26 kg/ha. All treatments containing glufosinate included ammonium sulfate at 2% (w/w).
[d] Weed control data for untreated and weed-free plots were not included in ANOVA because values have no variance.

CHAPTER 4

EFFECT OF CORN (*Zea mays*) POPULATION AND ROW SPACING ON LIGHT INTERCEPTION, WEED GROWTH, AND CORN YIELD IN GLUFOSINATE-RESISTANT CORN

Abstract: Management of corn row spacings and populations have been used for many years to increase corn (*Zea mays*) productivity. In 1998 and 1999, corn was grown in 38-, 56-, and 76-cm row spacings at populations averaging 59,300, 72,900, and 83,900 plants/ha. Glufosinate at 0.29 kg/ha was applied to common lambsquarters (*Chenopodium album*) averaging 5 cm in height in each plot. Weed emergence following herbicide application was monitored and no differences were found among row spacings or corn populations. Common lambsquarters biomass and seed production were reduced when grown under canopies of corn planted in populations exceeding 72,900 plants/ha. Row spacing did not influence the growth or seed production of common lambsquarters. Early season interception of photosynthetic active radiation (PAR) by corn canopies increased as row spacings decreased, but differences were not apparent later in the season. Interception of PAR among corn populations were similar throughout the season. Corn yields were not affected by row spacing, but were increased when corn populations exceeded 72,900 plants/ha. When averaged over row spacings and populations, corn yields were reduced by weeds not

controlled by glufosinate. Planting corn in reduced row spacings at high populations did not significantly increase weed control following a POST application of a non-residual herbicide.

Nomenclature: glufosinate, 2-amino-4-(hydroxymethylphosphinyl)butanoic acid; common lambsquarters, *Chenopodium album* L.#[11] CHEAL; corn, *Zea mays* L. 'DK 493GR'.

Additional index words: crop density; herbicide tolerant crops; narrow row corn.

Abbreviations: DAP, days after planting; DAT, days after treatment; PAR, photosynthetic active radiation; POST, postemergence; PRE, preemergence.

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[11] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

INTRODUCTION

Corn yields have dramatically increased since the beginning of the 20th century (Warren et al. 1998). Cardwell (1982) reported how changes in production practices contributed to corn yield increases from 1930 to 1980 in Minnesota. He estimated that the adoption of hybrid corn contributed to 58% of the yield increase, and 23% of the yield increase was attributed to increasements in weed control. The adoption of new technologies has also contributed to corn yield increases. For instance, the advancement of power driven equipment over horse-drawn equipment has allowed farmers to reduce corn row spacings and increase plant densities. Cardwell (1982) attributed a 25% yield increase to increased plant densities and reduced row spacings. Other factors such as soil erosion and occurrences of new insect pests have had negative effects on corn yields.

The effects of row spacing on corn grain yield is quite variable throughout the literature. Some researchers have reported yield increases when row spacings were reduced (Lutz et al. 1971; Murphy et al. 1996; Ottman and Welch 1989; Porter et al. 1997) while others have reported no effect on yields (Alessi and Power 1974; Johnson et al. 1998; Nunez and Kamprath 1969; Westgate et al. 1997). Increased corn populations have consistently resulted in yield increases (Cox 1997; Nunez and Kamprath 1969; Westgate et al. 1997). Fulton (1970) reported yield increases from corn planted in a 50 cm row spacing at 54,000 plants/ha when soil moisture levels were high. Polito and Voss (1991) cautioned that adoption of techniques such as reduced row spacing and higher populations for higher yields pose greater risks to producers who cannot control water availability.

Managing row spacings and plant populations alter the spacing of plants between and within rows. These changes influence corn growth and development. Seedlings grown in close proximity to each other express phytochrome mediated responses by developing narrow leaves, long stems, and less massive roots (Kasperbauer and Karlen 1994). Planting corn in a pattern that equalizes the spacing of plants within and between rows can increase plant biomass and leaf area index (Bullock et al. 1988). These types of spatial changes affect the architecture and light dynamics of a corn canopy. Reduced row spacings increased the total interception of photosynthetic active radiation (PAR) by the corn canopy and redistributed the radiation towards the top of the canopy (Ottman and Welch 1989). Tetio-Kagho and Gardner (1988) reported a similar trend of light distribution as plant density was increased. Photosynthetic efficiency, corn growth, and ultimately grain yield is influenced by the distribution and interception of PAR within a corn canopy.

Reduced row spacings and increased corn populations are thought to increase weed control by increasing the competitiveness of a crop with the weeds and by reducing the light transmittance to the soil surface. Teasdale (1995) showed that reduced row spacing and increased populations decreased weed growth in the absence of herbicides and shortened the time to canopy closure by one week. Many research trials have been conducted to investigate the potential for reducing herbicide use by reducing the row spacing or increasing the population of corn. Forcella et al. (1992) and Teasdale (1995) found that weed control from reduced herbicide rates was increased in narrow row compared to wide row environments. In contrast, Johnson et al. (1998) showed little benefit to reduced row spacings as a method for reducing herbicide inputs. Other trials have been conducted to determine the influence of row spacing and corn populations on weeds that emerge later in the season. Weed biomass was reduced when corn populations were increased (Tollenaar et al. 1994) and row spacings were reduced (Murphy et al. 1996).

The emergence of weeds following application of non-residual herbicides, such as glufosinate, is a potential weakness of weed management systems that include these herbicides. Glufosinate controls early-season weeds in corn, but additional weed management strategies are needed for season-long weed control. The objectives of this research was to determine if glufosinate-resistant corn planted in reduced row spacings and at increased populations would increase weed control following a timely application of glufosinate. Data evaluated in this trial include PAR interception, weed emergence, weed growth, and corn yield.

MATERIALS AND METHODS

Field trials were conducted in 1998 and 1999 on the Crop and Soil Sciences Research Farm at Michigan State University in East Lansing, MI. The soil was a Capac sandy loam (fine-loamy, mixed mesic Aeric Ochraqualf) with a pH of 7.1 and 3.5% organic matter in 1998, and a pH of 5.9 and 1.4% organic matter in 1999. A 46-0-0 (N-P-K) fertilizer was broadcast prior to corn planting each year. Fertilizer rates were determined from the results of soil analysis. A custom built toolbar equipped with John Deere planter units was used to plant 'DK 493GR' corn in row spacings of 38 cm, 56 cm, and 76 cm on May 27, 1998 and

May 14, 1999. The corn was planted at low, medium, and high population regimes for each row spacing. The number of emerged corn plants in the center rows of each plot were counted to determine actual populations (Table 1).

Two weed control treatments were applied within each row spacing and corn population. Glufosinate at 0.29 kg/ha plus ammonium sulfate at 2% (w/w) was applied when weeds averaged 5 cm in height 36 days after planting (DAP) in 1998 and 28 DAP in 1999. Weed-free plots were included at all row spacing and corn population combinations. Weed-free plots were treated with a PRE application of a premix[12] of *S*-metolachlor at 2.24 kg/ha plus atrazine at 1.12 kg/ha followed by hand-weeding as needed. Herbicides were applied with a tractor-mounted compressed-air sprayer equipped with flat-fan nozzles[13] and calibrated to deliver 187 L/ha at a pressure of 207 kPa. Plots were 3 m wide and 10.7 m long in 1998 and 9.1 m long in 1999.

The amount of photosynthetic active radiation (PAR) transmitted through the corn canopy to the soil surface was measured in 1998 and 1999 on a weekly basis beginning when corn had developed 5 to 6 collars and ending at corn silking, at which time it was assumed that canopy closure was complete. A SunScan[14] canopy analysis system was used for these

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[12]Bicep Lite II Magnum, Novartis, Crop Protection Division, PO Box 18300, Greensboro, NC 27419.

[13]TeeJet XR 8003VS. Spraying Systems Co., North Ave., Wheaton, IL 60188.

[14] Delta-T Devices Ltd. 128 Low Road, Burwell, Cambridge CB5 OEJ, England.

measurements, and was comprised of a 1 m long probe used to detect the amount of PAR transmitted to the soil surface below the corn canopy, and a beam fraction sensor used to detect direct and diffuse PAR outside the canopy. The probe was aligned down the center of adjacent corn rows in each weed-free plot. The beam fraction sensor was situated on a tripod and placed outside of the corn canopy. The two devices were used to record simultaneous PAR measurements. Three measurements were recorded in each plot near solar noon at each weekly interval. The percent PAR intercepted by the canopy was determined by dividing the transmitted PAR by the incident PAR and multiplying by 100. In 1998, the 63 DAP light measurement date was discarded because corn in all plots were showing symptoms of moisture stress (rolled leaves) which skewed PAR readings.

Common lambsquarters was the dominant weed species present each year. Three 1060 cm^2 quadrats were randomly established between the center two rows of each plot previously treated with glufosinate. Ten days following glufosinate application common lambsquarters that showed symptoms of potential recovery from herbicide application were marked with toothpicks within each quadrat. The marked weeds enabled us to distinguish between common lambsquarters that emerged following herbicide application from those that recovered from the glufosinate application 21 days after treatment (DAT).

In 1998 two common lambsquarters plants in the center of the plots were covered with an inverted 10 cm clay pot prior to application of glufosinate to protect the plants from exposure to the herbicide. The clay pots were removed within an hour following herbicide application and the common lambsquarters remained undisturbed until seed drop. In 1999, the number of common lambsquarters plants were increased to three per plot to reduce variability. The aboveground shoots of these plants were harvested at the initiation of seed drop on September 29, 1998 and September 28, 1999. The harvested shoots were dried in a 100°C oven for at least 5 d and dry weights were determined. Achenes containing seed, referred to as seed from this point forward, were separated from the harvested shoots and weighed. The number of seed per plant was estimated by multiplying the weight of seed per plant by the average weight of ten random samples of 100 seed.

Corn grain yield was determined by harvesting the center five rows of the 38-cm row spacing plots, the center three rows of the 56-cm row spacing plots, and the center two rows of the 76-cm row spacing plots with a mechanical plot harvester. Corn grain yield was corrected to 15.5% moisture.

Each trial was designed as a split-split-plot with four replications. The whole-plot was row spacing, the sub-plot was corn population, and the sub-sub-plot was weed control treatments. All data were subjected to ANOVA procedures. Data were pooled over main effects when the p-values of the interactions were greater than 0.05. PAR and yield data were separated using Fisher's protected LSD at the P= 0.05 level of significance. Common lambsquarters emergence, biomass, and seed production data were variable. Therefore, means were separated using Fisher's protected LSD at the P= 0.10 level of significance. All data were subjected to F-Max tests to test for homogeneity of variance among years (Kuehl 1994). Data found to be homogenous were pooled over years.

RESULTS AND DISCUSSIONS

Light interception. The amount of light intercepted by a corn canopy typically increases as row spacing is decreased (Bullock et al. 1988; Murphy et al. 1996; Ottman and Welch 1989). Averaged over populations, corn grown in 38-cm row spacings intercepted more PAR than 76-cm spacings up to 50 DAP in 1998 and 42 DAP in 1999 (Figure 1). The difference in PAR interception among row spacings never exceeded 20%. The maximum level of intercepted PAR never exceeded 95%. Differences in the levels of PAR interception among row spacings were not apparent later in the season (Figure 1). Westgate et al. (1997) also reported no differences in maximum PAR levels as row spacings were decreased.

Averaged over row spacings, corn planted at low populations intercepted similar amounts of PAR than corn planted at higher populations (Figure 2). In contrast, previous researchers have reported an increase in light interception when corn populations were increased (Murphy et al. 1996; Tollenaar 1994; Westgate et al. 1997). This contradiction could be due to differences in the range of populations investigated. The average difference between the low and high populations in our trials was 24,600 plants/ha, which was less than the range tested by others.

Weed growth. Smith (1988) reported that glufosinate is rapidly degraded by soil microorganisms. Therefore, the herbicidal activity of glufosinate in most soils is severely diminished, and weeds that emerge following application are not controlled. Corn grown in reduced row spacings and at increased populations did not affect weed emergence following application of glufosinate (Table 2). Johnson et al. (1998) similarly reported that row spacing has little impact on mid-season weed densities. Peak time and periodicity of weed emergence was similarly not affected by row spacing in soybeans (Mulugeta and Boerboom 1999). Tollenaar et al. (1994) reported that in both high (144 plants/m^2) and medium (79 plants/m^2) weed pressures the number of weeds at corn silking did not differ among corn populations.

Biomass of untreated common lambsquarters was reduced in 38-cm and 56-cm row spacings compared to 76-cm row spacing (Table 3). Common lambsquarters biomass was also reduced as corn populations increased. McLachlan et al. (1993) showed that as light interception by a corn canopy increased, the total dry matter accumulation of redroot pigweed (*Amaranthus retroflexus*) decreased. Tollenaar et al. (1994) and Murphy et al. (1996) also reported a reduction in weed biomass from increased corn densities or reduced row spacings, while Johnson et al. (1998) reported no effect of row spacing on weed biomass. McLachlan et al. (1993) and Murphy et al. (1996) showed that increased light interception by corn canopies decreased weed growth. In our trials, differences in common lambsquarters biomass and seed production were most pronounced among corn populations. However, light interception among corn populations were similar throughout the season, suggesting that factors other than light interception were contributing to the differences in weed growth. In addition to light, corn and weeds compete for water and nutrients. Tollenaar et al. (1994) suggested that increased corn populations enhanced the competitive effects of corn with weeds. Such a shift in competitive balance would result in decreased weed growth. Since high soil fertility levels were maintained in both years and large differences in light interception were not apparent, competition for moisture would have most likely contributed to decreased weed growth.

The number of seed produced by each common lambsquarters plant was also reduced as corn populations increased, but was not affected by row spacings (Table 3). McLachlan et al. (1993) similarly found that redroot pigweed inflorescence was reduced as corn populations increased. There was a strong correlation (r^2=0.93) between the number of seed produced by each common lambsquarters plant and shoot biomass (Figure 3). Crook and Renner (1990) also reported a correlation between common lambsquarters seed production and shoot biomass.

Corn yield. Johnson et al. (1998) and Teasdale (1995) showed that, regardless of the level of weed control, yields were similar for corn planted in 76-cm row spacings to corn planted in 38-cm row spacings. In our trials, corn yields were also similar among row spacings (Table 4). In contrast, Murphy et al. (1996) and Porter et al. (1997) reported yield advantages as row spacings were reduced. Hybrid selection and environmental conditions could attribute to the differences in yield results. In our trials, corn yields were highest at 73,000 plants/ha and 84,000 plants/ha (Table 4). Porter et al. (1997) reported that corn yields were higher at populations of 79,000 and 86,000 plants/ha in some years, but were unaffected by populations in other years. Cox (1997) reported optimum corn yields from populations averaging 75,300 plants/ha in dry environmental conditions and populations exceeding 88,900 plants/ha in favorable environmental conditions, indicating a strong environmental influence to yield determination.

Corn yields were reduced in plots that were treated with glufosinate compared to weed-free plots (Table 4). This difference was may be due to weed competition from weeds that were not controlled by glufosinate.

Murphy et al. (1996) stressed the importance of early-season weed control, and suggested that cultivation and corn planted in narrow rows might be a potential integrated weed management system that could be used to control late-season weeds. A timely application of glufosinate will provide adequate early-season weed control, but other weed control measures are needed for weeds that emerge later in the season. Weed emergence following an application of glufosinate was not affected by planting corn in narrow row spacings and at high populations. Weed growth was reduced under a canopy of corn planted in 38-cm and 56-cm row spacings and at populations exceeding 73,000 plants/ha. Corn yields were not increased by narrow row spacing but were increased when populations were increased. The results of this research suggest that increasing corn populations to 73,000 plants/ha may reduce weed growth and increase corn yields under the environment where these studies were conducted. However, weed emergence following an application of glufosinate was not affected by increased corn populations. Our research does not support the hypothesis that corn planted in narrow rows at high populations reduces weed emergence. Further research is needed to identify other weed management strategies that can be used to increase weed control following application of a non-residual herbicide, such as glufosinate.

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Table 1. Actual corn populations for each year of the study.

Population regime	Actual populations[a]		
	1998	1999	Average
	plants/ha		
High	84,800	83,000	83,900
Medium	72,000	73,800	72,900
Low	59,000	59,700	59,300

[a] populations averaged over row spacings

Table 2. Effect of row spacing and corn population on emergence of common lambsquarters following an application of glufosinate, 1998 -1999.

	Common lambsquarters emergence
	— plants/m^2 —
Row spacing[a]	
38 cm	21.5 a
56 cm	17.4 a
76 cm	21.5 a
Average corn population[b]	
59,300 plants/ha	20.6 a
72,900 plants/ha	17.1 a
83,900 plants/ha	21.2 a

[a] Means are pooled over corn populations and represent a main effect. Means for row spacing followed by the same letter within a column are not significantly different according to an LSD test (P=0.10).

[b] Means are pooled over row spacings and represent a main effect. Means for corn population followed by the same letter within a column are not significantly different according to an LSD test (P=0.10).

Table 3. Effect of row spacing and corn population on untreated common lambsquarters biomass and seed production, 1998-1999.[a]

	Biomass	Seed production
	— grams —	— no. of seed/plant —
Row spacing[b]		
38 cm	28.0 b	26,770 a
56 cm	29.4 b	26,990 a
76 cm	38.4 a	34,860 a
Average corn population[c]		
59,300 plants/ha	48.4 a	47,740 a
72,900 plants/ha	27.2 b	24,090 b
83,900 plants/ha	20.2 b	16,910 b

[a] Common lambsquarters plants were not exposed to glufosinate application.

[b] Means are pooled over corn populations and represent a main effect. Means for row spacing followed by the same letter within a column are not significantly different according to an LSD test (P=0.10).

[c] Means are pooled over row spacings and represent a main effect. Means for corn population followed by the same letter within a column are not significantly different according to an LSD test (P=0.10).

Table 4. Effect of row spacing, corn population, and weed control treatments on corn grain yields, 1998-1999.

	Corn yield
	— Mg/ha —
Row spacing[a]	
38 cm	10.61 a
56 cm	10.64 a
76 cm	10.56 a
Average corn population[b]	
59,300 plants/ha	10.22 b
72,900 plants/ha	10.75 a
83,900 plants/ha	10.86 a
Weed control[c]	
Glufosinate treated plots	10.42 b
Weed-free plots	10.80 a

[a] Means are pooled over corn populations and weed control treatments and represent a main effect. Means for row spacing followed by the same letter within a column are not significantly different according to an LSD test (P=0.05).
[b] Means are pooled over row spacings and weed control treatments and represent a main effect. Means for corn population followed by the same letter within a column are not significantly different according to an LSD test (P=0.05).
[c] Means are pooled over corn populations and row spacings and represent a main effect. Means for weed control treatments followed by the same letter within a column are not significantly different according to an LSD test (P=0.05).

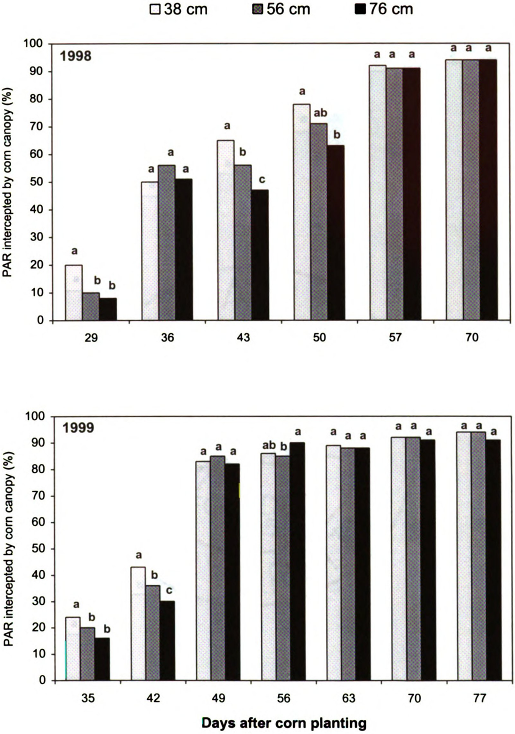

Figure 1. Photosynthetic active radiation (PAR) intercepted by corn canopies among row spacings at weekly intervals in 1998 and 1999. Data is averaged over corn populations and represents whole-plot effects. Bars that are followed by the same letter within weekly light measurement dates were not significantly different according to an LSD test (P=0.05).

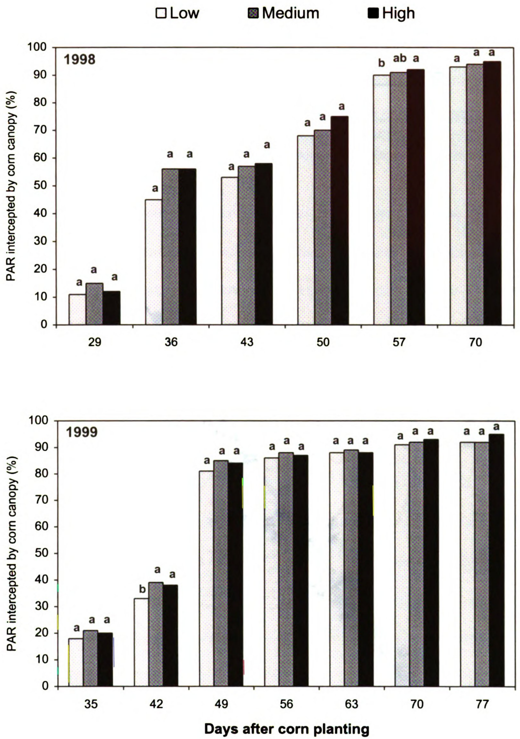

Figure 2. Photosynthetic active radiation (PAR) intercepted by corn canopies among corn populations at weekly intervals in 1998 and 1999. Data is averaged over row spacings and represents sub-plot effects. Bars that are followed by the same letter within weekly light measurement dates were not significantly different according to an LSD test (P=0.05).

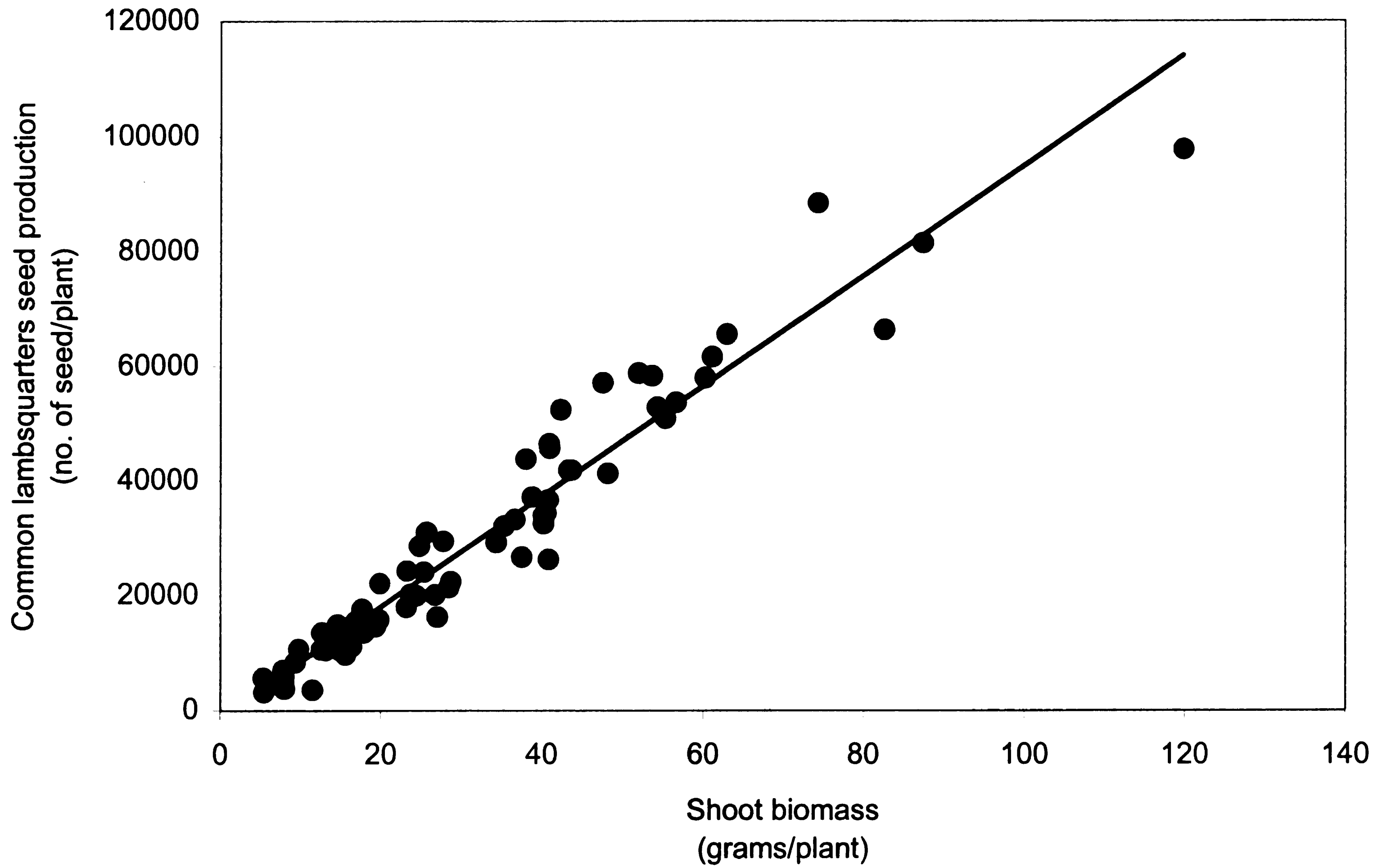

Figure 3. Relationship of common lambsquarters seed production to shoot biomass. Equation of the best-fit line is $Y = 963X - 1188$ ($r^2 = 0.93$).

CHAPTER 5

DELAYED BURNDOWN TIMINGS IN NO-TILLAGE GLYPHOSATE-RESISTANT CORN (*Zea mays*) PLANTED INTO SOYBEAN (*Glycine max*) RESIDUE AND INTO A WHEAT (*Triticum aestivum*) COVER CROP

Abstract: Field trials were conducted in 1998 and 1999 to determine the effect of delayed burndown timings on weed control and yield of no-tillage glyphosate-resistant corn planted into soybean residue or into a wheat cover crop. Burndown treatments containing glyphosate were applied to both trials when the corn was planted (PRE), when the corn began to emerge (SPIKE), or when the corn had developed three leaves (3-LEAF). When corn was planted into soybean residue, glyphosate applied at SPIKE or 3-LEAF followed by a sequential glyphosate application controlled velvetleaf ≥91% and corn yields were similar to the weed-free plots. Glyphosate tank mixtures with residual herbicides provided less than 60% velvetleaf control. Corn yields among the burndown treatments were directly related to velvetleaf control. In the wheat cover crop trial, wheat treated at the PRE timing was completely controlled and corn yields were similar to the weed-free plots. As burndown timings were delayed, corn emergence and yields were severely reduced. Applying glyphosate to 25-cm wide strips of wheat over the corn row at corn planting and following with delayed burndown timings increased corn emergence and yield.

Nomenclature: glyphosate, *N*-(phosphonomethyl)glycine; velvetleaf, *Abutilon theophrasti* Medicus #[15] ABUTH; corn, *Zea mays* L. 'DK 493RR'; winter wheat, *Triticum aestivum* L.

Additional index words: herbicide tolerant crops; acetochlor, atrazine, *Abutilon theophrasti*, ABUTH.

Abbreviations: POST, postemergence; PRE, preemergence; SPIKE, at corn emergence; 3-LEAF, corn with three developed leaves.

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[15] Letters following this symbol are a WSSA-approved computer code from Composite List of Weeds, Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

INTRODUCTION

Tillage has been an integral part of corn production since corn was first produced. However, advancements in farm machinery, adoption of herbicides, and concerns about soil erosion have reduced the reliance of tillage. Many factors associated with corn production are affected when tillage is reduced. Fortin (1993) reported that corn development was delayed and soil temperatures were reduced within the seed zone in no-tillage systems compared to conventional tillage systems. In Indiana, reduced tillage systems are adequately adapted to well-drained soils, but are not adapted to poorly drained, fine-textured soils (Griffith et al. 1973). No-tillage systems also affect weed control. Some weeds are more difficult to control in reduced tillage systems (Buhler 1992). Larger densities of green foxtail and redroot pigweed were reported in no-tillage compared to conventional tillage systems, and horseweed appeared only in no-tillage systems (Buhler 1992; Wrucke and Arnold 1985). The mean depth of weed emergence was found to be more shallow in no-tillage systems than conventional (Buhler and Mester 1991). Mulugeta and Stoltenberg (1997) found that 74% of the total viable weed seed in no- tillage systems were in the top 10-cm of the soil profile compared to 43% in conventional tillage. Differences in weed control have caused farmers to develop weed management strategies that are unique to no-tillage systems.

Cover cropping systems can be easily integrated into no-tillage corn production. Proper management of the cover crop is needed to obtain the beneficial aspects of a cover cropping system. When managed appropriately, cover crops can reduce water and wind erosion (Frye et al. 1983; Smith et al. 1987), sequester excess nitrates (Jackson et al. 1993; Shipley et al. 1992), provide nitrogen to succeeding crops (Mitchell and Teel 1977; Wagger

1989a), increase soil properties (Benoit et al. 1962), provide a favorable environment for predatory insects (Bugg 1991; Clark et al. 1993; Kaakeh and Dutcher 1993), and suppress weeds (Lal et al. 1991; Weston 1996).

Cover crops are often desiccated prior to corn planting to provide non-living surface residues, but can be managed to provide living surface residues, as in living mulch systems (Echtenkamp and Moomaw 1989; Eberlien et al. 1992). Delaying the timing of cover crop dessication will increase the biomass of the cover crop and ultimately result in higher surface residues and accumulated nitrogen (Smith et al. 1992; Clark et al. 1997a). Wagger (1998b) cautioned that managing a cover crop for additional growth and nitrogen accumulation should not delay corn planting.

Reports on the influence of cover crop dessication timing on corn growth and yield are mixed. Munawar et al. (1990) and Raimbault et al. (1991) reported yield reductions from cover crops desiccated later in the season, while others reported yield reductions from early timings of dessication (Moschler 1967; Clark et al. 1995; Clark et al. 1997b). These differences were attributed to differences in soil moisture and potential allelopathic effects. Munawar et al. (1990) stated that early season cover crop growth depleted soil moisture, but that during years of high spring rainfall the removal of soil moisture might be advantageous. Clark et al. (1997b) concluded that soil moisture conservation by cover crop residues was more important than spring water depletion in determining corn yield. Rainfall patterns are important factors to consider in cover crop management. Weston (1996) reported allelopathic effects of many plant species used as cover crops on other plant species. Tollenaar et al.

(1993) and Raimbault et al. (1991) suggested that reductions in corn development and yield could be caused by allelopathic interactions.

In no-tillage corn production, non-selective herbicides with no soil residual activity, such as glyphosate or paraquat, are often applied before planting to remove existing vegetation that would have been removed by tillage in conventional systems. These applications are commonly referred to as burndown applications. Herbicides with residual herbicidal activity in the soil are often combined with the non-selective herbicides to provide season long weed control (Wilson et al. 1985; Blackshaw 1989). The availability of glyphosate-resistant corn hybrids provides the opportunity to effectively remove vegetation after corn emergence. The objective of this research was to determine if glyphosate applied alone and in tank mixtures with residual herbicides could be delayed to increase weed control and crop yield in no-tillage corn planted into soybean residue. Delayed glyphosate burndown applications were also examined in no-tillage corn planted into a wheat cover crop to determine the effect of the cover crop on corn yield.

MATERIALS AND METHODS

No-tillage corn into soybean residue. Field trials were conducted in 1998 and 1999 on the Crop and Soil Sciences Research Farm at Michigan State University in East Lansing, MI. The soil was a Capac sandy loam (fine-loamy, mixed mesic Aeric Ochraqualf) with a pH of 6.2 and 3.1% organic matter in 1998 and a Capac sandy clay loam with a pH of 6.9 and 2.9% organic matter in 1999. A 34-0-0 (N-P-K) fertilizer was broadcast prior to corn planting and a 6-24-24 fertilizer was banded 5 cm below and 5 cm to the side of the corn seed during the planting operation. Fertilizer rates were determined from the results of a soil analysis. 'DK 493RR' hybrid corn was no-till planted into soybean residue on May 14, 1998 at a population of 53,100 seeds/ha and on May 10, 1999 at a population of 71,600 seeds/ha. Plots consisted of four rows spaced 76 cm apart with lengths of 10.7 m. The trials were not irrigated. Weekly rainfall amounts are listed in Table 1.

Four burndown herbicide treatments were applied at three timings. The burndown herbicide treatments included glyphosate at 0.84 kg ae/ha applied alone, glyphosate at 0.84 kg/ha tank mixed with atrazine [6-chloro-*N*-ethyl-*N'*-(1-methylethyl)-1,3,5-triazine-2,4-diamine] at 1.12 kg ai/ha, glyphosate at 0.84 kg/ha tank mixed with a premix[16] of acetochlor at 0.88 kg ai/ha plus atrazine at 0.7 kg/ha, and an initial application of 0.84 kg/ha glyphosate applied alone followed by a sequential application of glyphosate at 0.84 kg/ha. Each of the burndown herbicide treatments were applied before corn emergence (PRE), when corn in the weed free plots was beginning to emerge (SPIKE), and when corn in the weed free plots had three visible leaves (3-LEAF). The average height of velvetleaf was 1.3 cm at the PRE timing in both years, 3.8 cm in 1998 and 2.5 cm in 1999 at the SPIKE timing, and 3.8 cm at the 3-LEAF timing in both years. Velvetleaf in plots receiving sequential treatments were 2.5 to 5 cm tall. Sequential treatments were applied 25 and 24 days following the PRE application, 28 and 27 days following the SPIKE application, and 27 and 19 days following the 3-LEAF application in 1998 and 1999, respectively. Ammonium sulfate at 2% (w/w) was included with all glyphosate applications. Weed-free plots were treated with a PRE

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[16]Premix of acetochlor [2-chloro-*N*-(ethoxymethyl)-*N*-(2-ethyl-6-methylphenyl) acetamide] plus atrazine plus MON 4660 (safener)

application of a premix[17] of metolachlor at 2.24 kg/ha plus atrazine at 1.12 kg/ha followed by hand-weeding as needed. Herbicides were applied with a tractor-mounted compressed-air sprayer equipped with flat-fan nozzles[18] and calibrated to deliver 187 L/ha at a pressure of 207 kPa.

Velvetleaf was the dominant weed species present in both years. Visual estimates of velvetleaf control were compared against untreated velvetleaf using a scale of 0 (no control) to 100 (all plants dead) 28 d after the final POST sequential application. Aboveground shoots of velvetleaf within a 930-cm^2 quadrat in 1998 and a 1900-cm^2 quadrat in 1999 were harvested from each plot 80 days after corn planting. The harvested shoots were oven dried for at least 5 d and dry weights were determined. Corn grain yield was determined by harvesting the center two rows of each plot with a mechanical plot harvester. Corn grain yield was corrected to 15.5% moisture.

The trial was a two-factor factorial designed as a randomized complete block with three replications. The factors were burndown herbicide treatments and burndown application timings. Visual estimates of weed control were subjected to ANOVA procedures. Weed free plots were not included in the statistical analysis of the weed control data since the values contained no variance. Means of the weed control data and corn yield were separated using Fisher's protected LSD at the P= 0.05 level of probability. Visual estimates

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[17]Premix of *S*-metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide, *S*-enantiomer] plus atrazine plus CGA-154281 [4-(dichloroacetyl)-3,4-dihydro-3-methyl-2*H*-1,4-benzoxazine]

[18]TeeJet XR 8003VS. Spraying Systems Co., North Ave., Wheaton, IL 60188.

of weed control and corn yields were subjected to F-Max tests to test for homogeneity of variance among years (Kuehl 1994). Data found to be homogenous were pooled over years.

No-tillage corn into a wheat cover crop. Field trials were conducted in 1998 and 1999 on the Crop and Soil Sciences Research Farm at Michigan State University in East Lansing, MI. The soil was a Capac sandy loam (fine-loamy, mixed mesic Aeric Ochraqualf) with a pH of 6.2 and 3.1% organic matter in 1998 and a pH of 6.1 and 1.0% organic matter in 1999. A 34-0-0 (N-P-K) fertilizer was broadcast prior to corn planting and a 6-24-24 fertilizer was banded 5 cm below and 5 cm to the side of the corn seed during the planting operation. Fertilizer rates were determined from the results of a soil analysis. 'DK 493RR' was no-till planted into an actively growing winter wheat cover crop on May 13, 1998 at a population of 70,400 seeds/ha and on May 10, 1999 at a population of 71,600 seeds/ha. Plots consisted of four rows spaced 76 cm apart with lengths of 10.7 m. The wheat cover crop was drilled the previous fall of each year. The wheat was 30 to 40-cm tall when corn was planted in 1998 and 25 to 48 cm tall in 1999. Permethrin at 0.11 kg ai/ha was broadcast over the entire study on June 27, 1998 and June 15, 1999 to minimize corn damage from armyworms (*Pseudaletia unipuncta*).

Four burndown herbicide treatments were applied at three timings. The burndown herbicide treatments included glyphosate at 0.84 kg ae/ha applied alone, glyphosate at 0.84 kg/ha tank mixed with atrazine at 1.12 kg ai/ha, glyphosate at 0.84 kg/ha tank mixed with a premix of acetochlor at 0.88 kg ai/ha plus atrazine at 0.7 kg/ha, and an initial application of 0.84 kg/ha glyphosate applied alone followed by a sequential application of glyphosate at 0.84 kg/ha. Each of the burndown herbicide treatments were applied before corn emergence (PRE), when corn in the weed free plots was beginning to emerge (SPIKE), and when corn in the weed free plots had three visible leaves (3-LEAF). The height of the wheat averaged 38 cm and 33 cm at the PRE timing, 53 cm and 36 cm at the SPIKE timing, and 61 cm and 46 cm at the 3-LEAF timing in 1998 and 1999, respectively. The sequential glyphosate applications were applied 26 and 24 days following the initial application of glyphosate at the PRE timing, 32 and 34 days following the initial SPIKE glyphosate application, and 27 and 19 days following the initial 3-LEAF glyphosate application in 1998 and 1999, respectively. Weed-free plots were treated with a PRE application of glyphosate at 0.84 kg/ha plus a formulated premix of metolachlor at 2.24 kg/ha plus atrazine at 1.12 kg/ha followed by hand-weeding as needed. An additional treatment was glyphosate at 0.84 kg/ha applied in 25-cm wide bands directly over the corn row. The banded glyphosate was applied immediately following corn planting with a tractor-mounted compressed-air sprayer equipped with even flat-fan nozzles[19] and calibrated to deliver 187 L/ha at a pressure of 207 kPa. Plots previously treated with the PRE banded glyphosate applications were treated with the four burndown herbicide treatments broadcast at the SPIKE timing and at the 3-LEAF timing.

Weed populations were negligible both years. Visual estimates of wheat control was compared against untreated wheat plants using a scale of 0 (no control) to 100 (all plants dead) 28 d after the 3-LEAF burndown timing. The emergence and height of corn plants were recorded 45 days after planting from the center two rows of each plot in both years.

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[19]TeeJet 80015EVS. Spraying Systems Co., North Ave., Wheaton, IL 60188.

Corn grain yield was determined by harvesting the center two rows of each plot with a mechanical plot harvester. Corn grain yield was corrected to 15.5% moisture.

The trial was a two-factor factorial designed as a randomized complete block with four replications. The factors were burndown herbicide treatments and burndown application timings. In addition, a factorial arrangement of burndown herbicide treatments at the SPIKE and 3-LEAF burndown timings were applied where glyphosate had been applied PRE in bands. Since most of the wheat control data was between 80 and 100%, the data were arcsine transformed prior to statistical analysis and subjected to ANOVA procedures. Means of the transformed wheat control data, corn emergence, height, and yield data were separated using Fishers protected LSD at the P= 0.05 level of probability. Nontransformed means are presented for clarity. All data were subjected to F-Max tests to test for homogeneity of variance among years (Kuehl 1994). Data found to be homogenous were pooled over years.

RESULTS AND DISCUSSION

No-tillage corn into soybean residue. Glyphosate has negligible herbicidal activity in most soils. Therefore, weeds that emerge after a glyphosate application will not be controlled unless a residual herbicide is also applied. Glyphosate applied once did not provide season-long control of velvetleaf (Table 2). However, sequential applications of glyphosate provided the greatest control of velvetleaf, and dramatically increased velvetleaf control at each timing compared to a single application of glyphosate. Gonzini et al. (1999) also reported increased weed control in soybeans from sequential applications of glyphosate compared to glyphosate applied once. When the initial applications of glyphosate were delayed the sequential applications were subsequently delayed resulting in increased velvetleaf control.

A tank mixed residual herbicide or a sequential application of glyphosate generally increased velvetleaf control compared to glyphosate applied once. Velvetleaf control was increased and velvetleaf biomass was reduced as the burndown application timings were delayed (Table 2). The 3-LEAF timing resulted in greater control of velvetleaf by glyphosate than the PRE timing because less velvetleaf emerged following the 3-LEAF application compared to the PRE timing. Glyphosate plus atrazine applied at the 3-LEAF timing controlled velvetleaf greater than when applied at the PRE timing. In addition, velvetleaf control increased and velvetleaf biomass decreased as applications of glyphosate plus acetochlor/atrazine were delayed. Control of broadleaf weed species is often increased when herbicides are tank mixed with atrazine (Culpepper and York 1999; Wilson et al. 1985).

Corn yield trends were similar to the trends of velvetleaf control. Carey and Kells (1995) showed that weeds emerging with corn can potentially reduce yield if the weeds are not removed before they reach 10 cm in height. In our trials, velvetleaf height never exceeded 10 cm when burndown applications were applied, and yields were increased as burndown timings were delayed (Table 2). Therefore, yield reductions in our trials were likely caused by competition from weeds that emerged after application. Sequential applications of glyphosate and delayed applications of burndown treatments that included residual herbicides resulted in corn yields that were similar to the weed-free plots (Table 2). Corn yields in plots treated with glyphosate applied once at all burndown timings were lower than yields of weed-free plots. Sequential glyphosate applications and residual herbicide treatments controlled velvetleaf long enough to prevent corn yield reductions from velvetleaf competition.

No-tillage corn into a wheat cover crop. All of the burndown herbicide treatments applied at the PRE timing completely controlled the wheat cover crop (Table 3). Control was reduced as the application timings were delayed. As herbicide timings are delayed, plants grow larger and become increasingly difficult to control. Tank mixtures of glyphosate with atrazine reduced cover crop control, compared to glyphosate applied alone, when applications were delayed. Antagonism of the herbicidal activity of glyphosate plus atrazine tank mixtures has been reported on other plant species (Selleck and Baird 1981). Sequential applications of glyphosate did not increase control of the wheat cover crop compared to a single application of glyphosate.

Residual herbicides or sequential applications of glyphosate did not affect the emergence and height of corn compared to glyphosate applied alone (Table 3). The emergence and height of corn were significantly reduced as burndown timings were delayed.

Within each herbicide treatment, corn emergence and height at the PRE timing were similar to corn in the weed-free plots. However, corn emergence and height were reduced in treatments where herbicide application was delayed beyond the PRE timing. Reductions in corn emergence are likely attributed to soil moisture depletion by the competing wheat cover crop. Less than 3 cm of rainfall occurred within 4 weeks of corn planting in 1998, and less than 4 cm of rain fell between 3 and 6 weeks after planting in 1999 (Table 1). In addition to moisture stress, differences in corn height could be due to competition for available nitrogen between the corn and the wheat cover crop.

Corn yields were similar among burndown herbicide treatments within each burndown timing (Table 3). Within each burndown herbicide treatment, delayed applications resulted in reduced yields compared to the PRE timing and compared to the yields of the weed-free plots. The reductions in yield are likely due to reduced corn emergence and moisture stress from the competing wheat cover crop. In plots where the cover crop was controlled at planting, corn yields were similar to the yields in weed-free plots.

Plots previously treated with banded applications of glyphosate contained a larger number of corn plants that grew taller and yielded more than corn in plots that were not treated with banded applications of glyphosate (Table 4). Eberlein et al. (1992) reported reduced soil moisture availability and reduced yields of corn planted into a partially suppressed alfalfa sod. Corn yields were not reduced by the presence of a living crimson clover mulch (*Trifolium incarnatum*), as long as the clover was dessicated in strips greater than 60% of the total area (Kumwenda et al. 1993). When burndown treatments were applied at the SPIKE and 3-LEAF timing, the glyphosate treated strips of wheat provided an environment that was conducive to corn germination, but the plants that emerged in the 3-LEAF timing plots were stunted from competition with wheat that remained in the interrow. Corn yields were also reduced when burndown treatments were delayed to 3-LEAF compared to SPIKE timings.

Results of this research suggest that burndown herbicide application can be delayed to increase weed control in glyphosate-resistant no-tillage corn in the absence of a cover crop. The addition of residual herbicides with glyphosate increased velvetleaf control but did not provide adequate control with a single treatment weed management system. Sequential applications of glyphosate provided the greatest weed control and corn yields. Corn yields increased when velvetleaf control increased. In our trials, very few winter annuals were present at corn planting. Corn yields would likely be reduced if large populations of weeds were present at corn planting.

The presence of an actively growing cover crop at the time of corn planting will strongly influence the success of delayed burndown timings. Delayed burndown timings in an actively growing wheat cover crop resulted in reduced corn populations and yields. The wheat competed with the corn for moisture and nutrients. This data suggests that burndown of a wheat cover crop should occur no later than the time non-irrigated corn is planted to avoid yield loss from competition.

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Table 1. Weekly rainfall amounts, 1998 and 1999.

Weeks after corn planting	1998	1999
	cm	
1	0	1.1
2	0.4	2.6
3	1.5	0.9
4	0.9	1.9
5	2.3	0.1
6	0	0.4
7	3.6	1.8
8	5.0	6.0
9	0	2.0
10	1.8	0
11	0	3.6
12	0.4	1.4

Table 2. Effect of delayed glyphosate burndown applications on velvetleaf control, velvetleaf biomass, and corn yield, 1998 and 1999.[a]

Variable	Velvetleaf control[b]	Velvetleaf biomass[c]		Corn yield
		1998	1999	
	— % —	— g/m^2 —		— Mg/ha —
Burndown herbicide treatment (main effect)[d]				
Glyphosate alone	14 c	816 a	112 a	7.54 c
Glyphosate plus atrazine	39 b	167 c	42 bc	10.01 b
Glyphosate plus acetochlor/atrazine	34 b	395 b	71 ab	9.63 b
Glyphosate sequential	76 a	63 c	7 c	10.78 a
Burndown timing (main effect)[e]				
PRE	21 c	817 a	94 a	8.26 b
SPIKE	45 b	127 b	50 ab	10.14 a
3-LEAF	56 a	144 b	30 b	10.34 a

Table 2 (cont'd).

Burndown herbicide treatment × Burndown timing (interaction)[f]					
Glyphosate alone	PRE	0 g	1850 a	162 a	5.00 e
	SPIKE	15 fg	210 cd	116 abc	8.12 d
	3-LEAF	28 ef	390 c	58 bcd	9.48 bc
Glyphosate plus atrazine	PRE	27 ef	300 cd	47 cd	8.92 cd
	SPIKE	40 cde	169 cd	33 cd	10.61 a
	3-LEAF	50 bc	32 d	47 cd	10.61 a
Glyphosate plus acetochlor/atrazine	PRE	12 fg	977 b	153 ab	8.28 d
	SPIKE	33 de	115 cd	50 cd	10.44 ab
	3-LEAF	58 b	94 d	10 d	10.17 ab
Glyphosate sequential	PRE	48 bcd	143 cd	14 d	10.29 ab
	SPIKE	91 a	13 d	1 d	11.04 a
	3-LEAF	90 a	17 d	6 d	11.01 a
Weed free		100	0	0	10.87 a

[a] All treatments included ammonium sulfate at 2% (w/w).

[b] Visual ratings recorded 28 d after the final POST sequential application.

[c] Velvetleaf was harvested 80 days after corn planting.

[d] Means are pooled over burndown timings and represent a main effect. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

[e] Means are pooled over burndown herbicide treatment and represent a main effect. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

[f] Means represent the interaction of burndown timings and burndown herbicide treatments. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

Table 3. Effect of delayed glyphosate burndown applications on wheat cover crop control and corn emergence, height, and yield, 1998 and 1999.[a]

	Wheat Cover Crop	Corn		
Variable	Control[b]	Emergence[c]	Height[c]	Yield
	—— % ——	- plants/m row -	— cm —	— Mg/ha —
Burndown herbicide treatment (main effect)[d]				
Glyphosate alone	93 a	3.7 a	48 a	7.45 ab
Glyphosate plus atrazine	81 b	3.7 a	45 a	7.65 ab
Glyphosate plus acetochlor/atrazine	81 b	3.6 a	45 a	7.35 b
Glyphosate sequential	94 a	3.7 a	45 a	8.24 a
Burndown timing (main effect)[e]				
PRE	100 a	4.4 a	60 a	9.64 a
SPIKE	90 b	3.6 b	43 b	7.44 b
3-LEAF	72 c	3.1 c	35 c	5.94 c

Table 3 (cont'd)

Burndown herbicide treatment × Burndown timing (interaction)[f]					
Glyphosate alone	PRE	100 a	4.4 a	64.7 a	9.45 a
	SPIKE	96 b	3.7 bc	43.3 c	7.25 cde
	3-LEAF	83 c	3.2 cde	36.8 d	5.97 ef
Glyphosate + atrazine	PRE	100 a	4.3 a	56.5 b	9.45 a
	SPIKE	87 c	3.5 cd	43 c	7.38 cd
	3-LEAF	58 d	3.3 cde	36.8 d	6.11 def
Glyphosate + acetochlor/atrazine	PRE	100 a	4.5 a	60.6 ab	9.92 a
	SPIKE	83 c	3.4 cd	43.2 c	7.02 cde
	3-LEAF	61 d	2.8 e	32.6 d	5.10 f
Glyphosate sequential	PRE	100 a	4.4 a	59.1 b	10.05 a
	SPIKE	96 b	3.6 bcd	42.6 c	8.10 bc
	3-LEAF	85 c	3.1 de	33.8 d	6.56 de
Weed free		100 a	4.1 ab	57.5 b	9.64 a

[a] All treatments included ammonium sulfate at 2% (w/w).

[b] Visual ratings recorded 28 d after the 3-LEAF burndown timing.

[c] Measurements recorded 45 days after corn planting.

[d] Means are pooled over burndown timings and represent a main effect. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

[e] Means are pooled over burndown herbicide treatment and represent a main effect. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

[f] Means represent the interaction of burndown timings and burndown herbicide treatments. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

Table 4. Effect of banded applications of glyphosate on corn emergence, height, and yield at delayed burndown timings, 1998 and 1999.

		Corn		
Variable	Banded glyphosate[a]	Emergence[b]	Height[b]	Yield
		plants/m row	— cm —	— Mg/ha —
Banded glyphosate (main effect)[c]				
	Yes	4.0 a	50 a	8.27 a
	No	3.3 b	39 b	6.69 b
Burndown timing × Banded glyphosate (interaction)[d]				
SPIKE	Yes	4.0 a	51 a	8.70 a
	No	3.6 b	43 c	7.44 b
3-LEAF	Yes	4.0 a	48 b	7.83 b
	No	3.1 c	35 d	5.94 c

[a] Glyphosate plus ammonium sulfate applied in 25-cm bands directly over corn row at planting.

[b] Measurements recorded 45 days after corn planting.

[c] Means are pooled over burndown timings and burndown herbicide treatments and represent a main effect. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05).

[d] Means are pooled over burndown herbicide treatments and represent the interaction of burndown timing and banded glyphosate. Means that are followed by the same letter are not significantly different according to an LSD test (P=0.05). Abbreviations: SPIKE, burndown treatments broadcast at corn emergence; 3-LEAF, burndown treatments broadcast when corn had developed three leaves.