Response of Asparagus to Repeated Application of Residual Herbicides

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SUMMARY. Asparagus (*Asparagus officinalis*) is a perennial crop that has a 12- to 20-year production life in the field. Herbicides are applied in the spring each year and again after final harvest in early summer. Asparagus yield declines with age, and herbicides may contribute to yield decline. An experiment was established in 2004 and maintained for seven years with the same herbicide treatments applied each spring to determine herbicide effects on marketable spear yield. Spring-applied diuron, metribuzin, terbacil, sulfentrazone, halosulfuron, mesotrione, and clomazone had no adverse effect on yield or quality over the seven years of the experiment. Flumioxazin reduced yearly average marketable yield compared with standard treatments, and some spears developed lesions early in the season after rainfall. Asparagus yield from most treatments declined more than 50% from 2004 to 2010.

Asparagus is a perennial crop that normally is established from one-year-old crowns and maintained for 12 to 20 years until the yield declines beyond profitability (Zandstra et al., 1992). Before introduction of all-male hybrids, volunteer asparagus was a serious weed problem. Traditional asparagus production included one or two tillings of asparagus fields each year for weed control and to incorporate previous year crop residue. However, it has been demonstrated that tillage reduces yield (Wilcox-Lee and Drost, 1991). In the 1970s, most Michigan growers converted to nontillage production of asparagus (Putnam, 1972; Putnam and Lacy, 1977).

Perennial weeds such as canada thistle (*Cirsium arvense*) and field bindweed (*Convolvulus arvensis*) often become serious problems in asparagus (Ogg, 1975). Other common biennial and perennial weeds in asparagus are quackgrass (*Elytrigia repens*), dandelion (*Taraxacum officinale*), common milkweed (*Asclepias syriaca*), spotted knapweed (*Centaurea maculosa*), and wild carrot (*Daucus carota*). Herbicide resistance in annual weeds is always a potential problem, and resistance to herbicides targeting photosystem II (PS II) has been confirmed for redroot pigweed (*Amaranthus retroflexus*) and

powell amaranth (*Amaranthus powellii*) in Michigan asparagus fields (Heap, 2012). Other common annual weeds found in asparagus fields include field sandbur (*Cenchrus incertus*), large crabgrass (*Digitaria sanguinalis*), fall panicum (*Panicum dichotomiflorum*), common lambsquarters (*Chenopodium album*), russian thistle (*Salsola iberica*), horseweed (*Conyza canadensis*), hairy vetch (*Vicia villosa*), and common groundsel (*Senecio vulgaris*) (Zandstra et al., 2010).

Asparagus weed control programs have been based on herbicides that inhibit PS II for over 50 years. Simazine and monuron were registered for asparagus in the 1960s, followed by diuron, linuron, metribuzin, and terbacil (Boydston, 1995; Welker and Brogdon, 1972). Now, most fields in Michigan are treated with one or more PS II inhibitors each year (Zandstra, 2011). Several other preemergence herbicides have

been registered for asparagus in recent years, including flumioxazin, halosulfuron, S-metolachlor, mesotrione, sulfentrazone, and pendimethalin.

In the past several decades, the life span of asparagus fields has been shortened by five to eight years (Morrison et al., 2011). This shortened life span has been largely attributed to the effects of the fungal pathogens *Fusarium proliferatum* and *Fusarium oxysporum*, which infect asparagus and produce soil toxins that inhibit asparagus growth (Keulder, 1999; Morrison et al., 2011). The application of herbicides has been suggested as a stressor that may facilitate *Fusarium* infection (Morrison et al., 2011) potentially leading to decreased yields. In addition, growers in Michigan have reported the development of lesions on spears from fields treated with flumioxazin that may be related to yield decline (J. Bakker, personal communication).

Welker and Brogdon (1972) conducted research on long-term effects of repeated herbicide applications on asparagus production and quality over a seven-year period. At the time of their research, there were few herbicides registered for weed control in asparagus. They concluded that some of the herbicides might have an adverse effect on spear quality but did not affect total yield.

Because the primary mechanism of preemergence herbicide selectivity in asparagus is differential placement (Monaco et al., 2002), there is a potential for crop injury if the herbicides leach into the crop root zone after heavy rainfall or flooding. This is a serious potential problem on light sandy soils, which are typical of Michigan asparagus growing regions. Several of the preemergence herbicides labeled for asparagus fields are moderately or highly soluble, so there is

Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.3048	ft	m	3.2808
9.3540	gal/acre	L·ha ⁻¹	0.1069
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
1.6093	mph	km·h ⁻¹	0.6214
28,350	oz	mg	3.5274 × 10 ⁻⁵
1	ppm	mg·L ⁻¹	1
6.8948	psi	kPa	0.1450
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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potential for crop injury after repeated use of these herbicides.

This experiment was established to determine if there are adverse effects on asparagus yield from single spring applications of the same pre-emergence herbicides repeated for seven years.

Materials and methods

Asparagus was planted at the Michigan State University Horticulture Teaching and Research Center in Holt, MI on 20 Apr. 1999. The soil was a Riddles sandy loam (fine-loamy, mixed, mesic Typic Hapludalfs), with 83% sand, 6% silt, 8% clay, 1% organic matter, pH 8.1, and cation exchange capacity of 13.7. The field was established with one-year-old 'Jersey Giant' crowns, which were obtained from a commercial grower in Oceana County, MI. The crowns were planted 12 inches apart at the bottom of 10-inch-deep furrows in rows 6 ft apart. After planting, the field was cultivated twice during Summer 1999 to control weeds and to fill the furrows. Diuron at 3 lb/acre was broadcast over the field preemergence in Spring 2000 to 2003 for weed control.

The experiment was established in 2004 when the field had reached optimum yield. Preemergence herbicide treatments were applied each year before spear emergence between 15 and 30 Apr. Herbicide treatments are listed in Table 1. The diuron and the diuron plus metribuzin treatments were considered to be grower-standard treatments for weed control and crop yield because they have been

common commercial treatments for many years. An untreated, hand-weeded control was not included in the study because of the difficulty of maintaining sufficient weed control to avoid reduced yield from weed competition. Welker and Brogdon (1972) reported no yield loss from herbicide treatments but significant loss from weed competition. Each experimental plot was 5.3 ft wide by 50 ft long. The experimental design was randomized complete block with three replications. Herbicides were applied with a carbon dioxide–pressurized backpack sprayer at 20 gal/acre volume and 30 psi pressure and a walking speed of 3.2 mph. The boom had four flat fan 8002 nozzles (Spraying Systems, Wheaton, IL) to provide a 64-inch spray band over each row. Percent weed control was rated by species once or twice per season on a scale of 1 = no control to 100 = complete control. Weed density, stand, and vigor were included in the assignment of control values.

The crop was harvested 20 to 22 times each year from 2004 to 2010, a total of seven years. Six- to 10-inch spears were snapped at the soil surface two to four times per week as needed to obtain commercial-size spears. Spears longer than 10 inches were snapped again and the butts discarded. Spears less than 0.25 inch in diameter were discarded and not included in the yield evaluation.

The spears were graded as marketable or unmarketable. Marketable spears are 0.25 inch or more in diameter, 6 to 10 inches long, relatively

straight, with no evidence of insect, disease, or physical damage. Spears that were misshapen, scarred, scored, bent, or had other defects were graded out as unmarketable. The spears in each category were counted and weighed. The harvest season lasted 6 to 7 weeks from early May through mid-June. Harvest ended each year when spear diameter declined after at least 20 harvests.

Immediately after the final harvest in each season, the entire field was treated with 0.25 lb/acre dicamba plus 0.19 lb/acre sethoxydim, or 1 lb/acre glyphosate to suppress perennial weeds. During the final harvest, all spears that had emerged were snapped off at soil level to reduce exposure to these herbicides. The asparagus fern and weeds were allowed to grow for the rest of the season. Infestations of common asparagus beetle (*Crioceris asparagi*) were controlled with 1 lb/acre carbaryl as needed. The field was mowed in the spring each year before weeds emerged to clear dead fern, but the field was not tilled during the experiment. Following standard grower practices, 50 lb/acre of nitrogen was applied after harvest each year in the form of ammonium nitrate, and 51 lb/acre of potassium was applied every other year in the form of potassium chloride (Zandstra et al., 1992).

All data were analyzed with PROC GLIMMIX in SAS (version 9.2; SAS Institute, Cary, NC). Repeated measures analysis of variance was used to determine differences among means between treatments for yield, spear counts, and weed control

Table 1. Marketable spear yields and percent decline from asparagus treated with preemergence herbicides from 2004 to 2010 at the Horticulture Teaching and Research Center, Michigan State University, Holt, MI. The field was established in 1999 with one-year-old 'Jersey Giant' crowns. Data were analyzed using a repeated measure generalized linear mixed effects analysis and significant differences within years were determined using Tukey's post hoc test ($P \leq 0.05$).

Herbicide	Rate (lb/acre) ^z	Asparagus marketable spears (kg/50-ft row) ^z								Decline (%) 2004–10
		2004 ^y	2005 ^y	2006 ^y	2007 ^y	2008 ^y	2009 ^y	2010 ^y	Yearly avg ^x	
Diuron	1.2	7.56	6.32	5.54	4.68	3.18	4.78	3.04	4.86 ab	59.8
Metribuzin	0.5	8.93	6.06	7.15	6.27	4.23	5.78	3.74	5.87 a	58.1
Diuron + metribuzin	1.2	8.79	6.19	6.50	5.65	4.27	6.20	3.76	5.72 a	57.2
Terbacil	1.2	6.66	5.59	6.50	5.42	4.18	6.32	3.33	5.32 ab	50.0
Flumioxazin	0.192	7.78	5.23	5.95	5.12	3.19	3.83	2.31	4.56 b	70.3
Sulfentrazone	0.375	8.98	6.35	6.92	6.14	4.17	6.02	3.74	5.86 a	58.4
Halosulfuron	0.047	7.41	5.14	5.26	5.37	3.94	5.33	3.08	4.97 ab	58.4
Mesotrione	0.094	8.95	6.24	6.68	5.11	3.96	5.39	3.82	5.60 ab	57.3
Diuron + S-metolachlor	1.2	8.02	4.86	5.54	4.94	3.57	5.73	4.66	5.21 ab	41.9
Clomazone	1.0	8.36	4.97	5.66	5.93	4.23	5.46	3.76	5.36 ab	55.0

^z1 kg/50-ft row = 0.0441 lb/ft = 0.0656 kg·m⁻¹, 1 lb/acre = 1.1209 kg·ha⁻¹.

^yNo statistical differences observed for this year.

^xModeled averages using a repeated measures generalized linear mixed effects model.

data (Ott and Longnecker, 2001). We attempted to perform a repeated measures analysis of covariance on the data (Ott and Longnecker, 2001); however, the data did not conform to model assumptions and, therefore, is not presented. For all other analyses, marketable yield weights were analyzed with a Gaussian distribution, whereas marketable spear counts and weed control data were modeled with Poisson distributions (Ott and Longnecker, 2001). Diagnostic plots of residuals and variances were used to assess Gaussian assumptions. Overdispersed Poisson models were corrected using a multiplicative overdispersion factor (SAS Institute, 2008). Akaike's information criterion was used to compare correlation structures (Akaike, 1974). A standard variance components correlation structure was used for all models (SAS Institute, 2008). Significant differences were obtained using a post hoc Tukey's test with a threshold of $P = 0.05$ (Ott and Longnecker, 2001). Square root transformations were used for yield data to conform to normality assumptions. Data presented in this article have been back-transformed for interpretation purposes.

Results and discussion

The weed control data presented (Fig. 1) is the modeled average rating taken 6 to 8 weeks after treatment each year. Differences among treatments did not vary through time (i.e., there was no statistically significant interaction between year and treatment); therefore, the treatments were compared for the entire study rather than for each year individually. When harvest concluded each year in late June, quackgrass, spotted knapweed, and wild carrot were present in most plots. The herbicide treatments provided various levels of control of the weeds present for ≈ 8 weeks. None of the herbicide treatments provided complete weed control throughout the harvest season. Some weeds were present throughout the study area but are not reported because there was a lack of statistical difference between treatments or because the weed was not consistently present throughout the study.

The 1.2-lb/acre terbacil treatment consistently provided the best overall weed control (Fig. 1) for quackgrass, spotted knapweed, and wild carrot. Clomazone at 1 lb/acre

suppressed quackgrass and spotted knapweed but did not control wild carrot sufficiently. Flumioxazin at 0.192 lb/acre did not control quackgrass, wild carrot, or spotted knapweed. Sulfentrazone at 0.375 lb/acre suppressed quackgrass by 64% but did not provide sufficient control of spotted knapweed or wild carrot. Halosulfuron at 0.047 lb/acre provided adequate control of wild carrot and spotted knapweed but did not provide sufficient overall weed control. Mesotrione at 0.094 lb/acre suppressed wild carrot by 63%. The combination of 1.2 lb/acre diuron plus 1.3 lb/acre

S-metolachlor did not provide sufficient control of any of the weeds. Diuron at 1.2 lb/acre provided $<50\%$ control of all these weeds. Metribuzin at 0.5 lb/acre provided $\approx 75\%$ control of spotted knotweed and 50% to 60% control of quackgrass and wild carrot. The combination of diuron plus metribuzin provided 80% control of spotted knapweed and wild carrot and 60% control of quackgrass.

Trends were similar between the weight of spears and the number of spears harvested (Table 1 and Fig. 2). Again, differences among treatments did not vary through time; therefore,

Fig. 1. Average yearly weed control with standard errors for 2004–10 at the Horticulture Teaching and Research Center, Michigan State University, Holt, MI. Data depicts control for the three most common weeds for this study: quackgrass, spotted knapweed, and wild carrot. Data were modeled with repeated measures analysis of variance. Tukey's post hoc test was used to determine statistical significance between treatments for each weed individually. Bars sharing the same letter for a single weed are not statistically different from each other ($P \leq 0.05$).

Fig. 2. Average number of marketable asparagus spears per plot with SE for 2004–10 at the Horticulture Teaching and Research Center, Michigan State University, Holt, MI. Data were modeled through repeated measures analysis of variance. Tukey's post hoc test was used to determine statistical significance between treatments. Bars sharing the same letter are not statistically different from each other ($P \leq 0.05$); 1 spear/50-ft row = 0.0656 spear/m.

Table 2. Average high and low temperatures and total precipitation for May and June 2004–10, Horticulture Teaching and Research Center, Holt, MI (Michigan State University, 2012).

	2004		2005		2006		2007		2008		2009		2010	
	May	June	May	June	May	June	May	June	May	June	May	June	May	June
Avg high temp (°F) ^z	70	75	65	83	70	78	73	80	67	79	69	77	71	78
Avg low temp (°F)	48	54	42	61	47	54	47	56	42	57	46	56	50	59
Total precipitation (inches) ^z	8.07	3.51	1.31	4.28	4.36	2.79	3.82	3.51	1.16	4.43	4.29	4.97	5.07	4.19

^z(°F – 32) ÷ 1.8 = °C, 1 inch = 25.4 mm.

the treatments were compared against each other for the entire study rather than for each year individually. Generally, metribuzin, diuron plus metribuzin, and sulfentrazone were the best treatments for yearly average marketable yield and number of spears. The marketable spears and marketable yield of the diuron plus metribuzin treatment (5.72 kg, 326 spears) were more similar to the metribuzin treatment (5.87 kg, 345 spears) than to the diuron treatment (4.86 kg, 271 spears). This difference may be a result of increased weed competition in the diuron treatment since it was not as effective at controlling weeds as the other two treatments. Although small and sometimes not statistically significant, flumioxazin had the lowest average marketable yields and number of spears among all other treatments.

Yearly variability in asparagus yields was somewhat correlated to early growing season precipitation (Table 2); however, the marketable yield for all treatments generally declined through time (Table 1). Yield in diuron plus S-metolachlor and terbacil treatments decreased the least over time, 41.9% and 50.0% decline respectively. Flumioxazin, however, had the greatest decrease in marketable yield (70.3%) over the seven-year study. Average yields were lower and decreased more over time in flumioxazin-treated asparagus indicating that some of the reduction in asparagus yields may result from specific herbicide applications.

Flumioxazin-treated asparagus had the greatest weight of unmarketable spears in 2004 (1.49 kg) compared with all other treatments (≤ 1.01 kg). Much of the damage in 2004 consisted of small vertical lesions on the lower to mid part of the spears, 2- to 3-mm wide and 1- to 2-cm long (Fig. 3). These lesions also appeared early in the season for subsequent years for the asparagus in the flumioxazin treatment. To determine

if precipitation was involved in the increase in lesions, the weight of unmarketable spears from the flumioxazin plots was plotted against precipitation events for the period of the 2004 harvest (Fig. 4). Rainfall in the first 2 weeks of harvest seemed to cause an increase in the number of damaged spears in the flumioxazin plots at the next harvest. As the season progressed, there was less response to rain, and the number of unmarketable spears from the flumioxazin plots declined. The relationship between precipitation and flumioxazin was not statistically significant in our study, but may be responsible for some minor asparagus loss.

The reduced yield within flumioxazin-treated plots could be the result of several factors. Flumioxazin did not control quackgrass, spotted knapweed, or wild carrot. Weed competition could have played a role in reducing yields in the flumioxazin plots. However, since weeds did not become established in plots until after the fifth week of harvesting, weed competition likely contributed little to the differences in yields. It has been suggested that herbicides may play a role in facilitating the infection of *Fusarium* in asparagus (Morrison et al., 2011), thereby reducing yields from increased pest pressure. Flumioxazin may have stunted the asparagus directly, as evidenced by the small lesions observed early in the season. It is likely that some combination of these factors is contributing to the decline in yield observed for flumioxazin in this study.

Flumioxazin should still be considered within a weed management program despite the potential yield loss and lesions it may cause. Spears with small lesions would still be acceptable for processing cuts and tips. Flumioxazin has a broad weed spectrum and long residual activity against many annual grasses and broadleaf weeds and may be an effective herbicide

Fig. 3. Lesion that developed on asparagus spears after preemergence treatment with flumioxazin. Study was conducted at Michigan State University Teaching and Research Center, Holt, MI from 2004 to 2010.

for weed control in asparagus. Preemergence application of flumioxazin, a protoporphyrinogen oxidase inhibitor, with a PS II inhibiting herbicide such as diuron or terbacil, will extend the duration of weed control and expand the weed control spectrum. It will also help control weeds resistant to PS II inhibiting herbicides and delay future development of resistance to these herbicides. However, since the flumioxazin treatment had a lower yield, we recommend that asparagus growers limit the use of this herbicide in their fields to every other year.

All of the herbicides used in this experiment are labeled for use on asparagus, except clomazone. A tolerance for clomazone is being developed for asparagus through Inter

Fig. 4. Unmarketable asparagus spear production after preemergence treatment with diuron or flumioxazin followed by precipitation in 2004. Study was conducted at Michigan State University Teaching and Research Center, Holt, MI; 1 g/50-ft row = 0.0656 g·m⁻¹; 1 inch = 25.4 mm.

Regional Project No. 4 (IR-4). Use of clomazone will improve control of annual grasses, common lambsquarters, russian thistle, spotted knapweed, and quackgrass in asparagus.

An effective and safe weed control program for asparagus includes several residual herbicides applied in combination and rotation over several years. Selecting preemergence herbicides for the specific weeds they control and their longevity in the soil will help reduce weed populations. Growers have several herbicide options and should not use preemergence herbicides with the same mode of action more than once per year. There are 11 herbicides registered for preemergence application in asparagus (Zandstra, 2011). Even with a choice of several herbicides, some weeds remain difficult to control, e.g., field bindweed, common milkweed, and wild carrot. During the four months of asparagus fern growth (July to October), most preemergence herbicides, including those applied after harvest, dissipate and various annual and winter annual weeds germinate; so, asparagus is seldom completely weed free. In fact, many growers want the preemergence herbicides to lose activity by about 1 Sept. because they scatter rye (*Secale cereale*) as a cover crop to help hold the sandy soil over the winter and in the spring. If the

herbicides remain active too long, the rye does not germinate.

Growers producing asparagus on light sandy soil should avoid repeated use of highly soluble residual herbicides. For example, metribuzin has water solubility of 1100 mg·L⁻¹ and terbacil has solubility of 710 mg·L⁻¹ (Senseman, 2007). Herbicide leaching into the root zone over several years may contribute to decline in vigor and productivity of the crop. By rotating herbicides and modes of action, development of weed resistance will be reduced greatly, and there will be less potential for crop injury and better overall weed control.

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