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Timing of atrazine application for control of quackgrass (*Agropyron repens*)

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Résumé de l'article

L'application foliaire ou au sol de l'atrazine dans la lutte au chiendent (*Agropyron repens*) dans le maïs (*Zea mays*) a été étudiée. Les traitements d'atrazine pour la lutte au chiendent ont augmenté significativement le rendement du maïs. Le labour printanier sans atrazine a eu peu ou aucun effet à long terme sur la population de chiendent. Une seule application de 4,5 kg m.a. d'atrazine ha^{-1} à l'automne ou au printemps n'a pas procuré une meilleure lutte au chiendent qu'une application fractionnée de 2,25 kg m.a. d'atrazine ha^{-1} dans les expériences en application foliaire ou sur sol dénudé. La repousse du chiendent et le rendement en soya (*Glycine max*) ont été mesurés pendant 2 ans après la dernière application d'atrazine. Le chiendent ne s'est pas réimplanté de façon appréciable en-dedans de 2 ans après l'arrêt des traitements sur n'importe laquelle des parcelles traitées à l'atrazine. Les résidus d'atrazine des applications automnales antérieures ont réduit significativement le rendement en soya. Deux ans après le dernier traitement à l'atrazine, les rendements du soya étaient similaires, peu importe si les applications antérieures d'atrazine avaient été effectuées au printemps ou à l'automne.

Timing of atrazine application for control of quackgrass (*Agropyron repens*)

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The use of foliar or soil applied atrazine to control quackgrass (*Agropyron repens*) in corn (*Zea mays*) was investigated. Atrazine treatments to control quackgrass significantly increased corn yield. Spring tillage without atrazine had little or no long term effect on quackgrass stand. A single application of 4.5 kg a.i. atrazine ha^{-1} applied in the fall or spring provided no better control of quackgrass than a split application of 2.25 kg a.i. atrazine ha^{-1} in either the foliage or bare soil experiments. Quackgrass recovery and soybean (*Glycine max*) yield were measured for 2 yr after the last atrazine application. Quackgrass did not recover to any significant extent within 2 yr after the cessation of the treatments on any of the atrazine treated plots. Atrazine residues from the previous fall applications significantly reduced soybean yield. Two years after the last atrazine treatment, soybean yields were similar, regardless of former spring or fall atrazine application.

Gaynor, J.D. et A.S. Hamill. 1993. Période d'application de l'atrazine pour la lutte au chiendent (*Agropyron repens*). PHYTOPROTECTION 74: 89-99.

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INTRODUCTION

Quackgrass [*Agropyron repens* (L.) Beauv.; syn.: *Elytrigia repens* (L.) Desv.] is a perennial, rhizomatous grass which seriously infests agricultural land in the United States, Canada, Asia, and Europe (Mitich 1987; Werner and Rioux 1977). It is a troublesome weed in soybean [*Glycine max* (L.) Merr.] and corn [*Zea mays* L.]. Quackgrass is a vigorous, aggressive plant which can reduce corn and soybean yield by competition for moisture (Bandeen and Buchholtz 1967; Sikkema

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and Dekker 1987; Young *et al.* 1982) or from production of plant toxins such as a glycoside or ethylene by rhizomes (Gabor and Veatch 1981; Harvey and Linscott 1978; Weston and Putnam 1986). Inexpensive herbicide treatments are not available for control of quackgrass in soybeans but atrazine (6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4-diamine) controls this grass in corn (Schirman and Buchholtz 1966). Atrazine however, can limit the choice of subsequent crops because of the presence of triazine residues from previous applications.

Quackgrass rhizomes are high in carbohydrates and unsaturated fatty acids which contribute to its ability to overwinter in northern environments (Leakey *et al.* 1977a, 1977b; Steen and Larsson 1986; Stoller 1977). Tillage disrupts rhizome growth and aids in dissipation of carbohydrate reserves which can enhance winter kill (Majek *et al.* 1984; Schimming and Messersmith 1988; Stoller 1977; Vengris 1962). Also, seasonal distribution of carbohydrates in rhizomes vary so that control measures can be timed when carbohydrate reserves are lowest (Leakey *et al.* 1977a; Steen and Larsson 1986). Carbohydrate concentrations are highest in the fall and lowest in the spring after the plant emerges from winter dormancy.

Atrazine primarily inhibits photosynthesis which reduces the plants capability to produce necessary carbohydrates (Arntzen *et al.* 1982; Shimabukuro and Swanson 1969). Schirman and Buchholtz (1966) demonstrated that either a split spring/fall application of 2.2 kg a.i. atrazine ha^{-1} or a single spring application of 4.4 kg a.i. ha^{-1} effectively controlled quackgrass. They also indicated that late fall tillage after treatment may improve control.

In Ontario, there has been some concern as to the effect of environmental factors on quackgrass control with atrazine. The introduction of shorter season varieties of corn and soybean has permitted the production of these crops in Eastern Ontario. A split fall/spring application of 2.25 kg a.i atrazine ha^{-1} to quackgrass foliage was the standard recommendation in Ontario for quackgrass control in corn. The fall treatment was to be followed by plowing 7 to 14 d after application. The delay between harvest and plowing in many regions of the province is sometimes difficult because of the short season and weather conditions. This has led researchers and growers to question the need to specifically apply atrazine to quackgrass foliage.

Our objective was to determine the best time for quackgrass control with atrazine by comparing single and/or split applications of the herbicide applied in fall and/or spring. Quackgrass recovery in soybean and the effect of atrazine residues on soybean yield were followed for 2 yr after the last atrazine treatment. Two experiments were conducted, one where atrazine was applied to quackgrass foliage, the other where it was applied to bare ground.

Table 1. Atrazine rates and application times from 1983 to 1985

	Time and rate of application (kg a.i. ha^{-1})						
Treatment	Oct. 1983	May 1984	June 1984	Oct. 1984	May 1985	June 1985	Oct. 1985
Fall + spring preplant	2.25	2.25	—	2.25	2.25	—	2.25
Fall	4.5	—	—	4.5	—	—	4.5
Fall + postemergence	2.25	—	2.25	2.25	—	2.25	2.25
Spring preplant	—	4.5	—	—	4.5	—	—
Spring preplant + postemergence	—	2.25	2.25	—	2.25	2.25	—

MATERIALS AND METHODS

Treatments were begun in the fall of 1983 in a quackgrass infested field on Perth clay (o.m. 3.36%, pH 6.3, gleyed brunisolic grey brown luvisol) near Malden, Ontario. Plot size was 3 m X 12 m where atrazine was applied to quackgrass foliage or 3 m X 18 m where atrazine was applied to bare soil. A randomized complete block design with four replications was used for each of the bare soil and foliage experiments. Atrazine was applied in the fall and spring to quackgrass foliage in one experiment and on bare soil after the plots were disked in the other experiment at the times and rates indicated in Table 1. All plots were plowed 2 wk after herbicide application in the fall. Spring preplant treatments were applied 2 wk before seeding and postemergence treatments 2 wk after seeding. Atrazine was applied in 280 L ha^{-1} water at 210 kPa with a field plot sprayer. Oil concentrate at 15 L ha^{-1} was added to treatments where atrazine was applied to quackgrass foliage and in all postemergence applications to enhance uptake.

Corn cv. Pioneer 3707 or Pioneer 3901 was seeded at 55 328 seeds ha^{-1} in 1 m wide rows in the spring of 1984 and 1985 with a John Deere Flexi planter. Plots were fertilized according to soil test and 150 kg nitrogen ha^{-1} was sidedressed 3 wk after planting. Alachlor [2-chloro-*N*-(2,6-diethylphenyl)-*N*-(methoxymethyl) acetamide] plus dicamba [3,6-dichloro-2-methoxybenzoic acid] at 2.25 and 0.6 kg a.i. ha^{-1}, respectively were applied preemergence for annual grass and broadleaf weed control.

In 1986 and 1987, soybean cv. Northrup King B-152 was seeded at 100 kg ha^{-1} in 60 cm wide rows with a Maxi Merge planter. Fertilizer was applied according to soil test. Trifluralin [2,6-dinitro-*N,N'*-dipropyl-4-(trifluoromethyl)benzenamine] plus metribuzin [4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4H)-one] were applied preplant incorporated at 1.0 and 0.5 kg a.i. ha^{-1}, respectively for annual grass and broadleaf weed control.

Data analysis

Corn and soybean yield data were analyzed within experiments by analysis of variance as a randomized complete block with four replicates. The fall tillage management did not allow for a design that permitted statistical comparison between the two experiments but general trends were noted. Appropriate single degree of freedom contrasts within years were made between untreated and split or single atrazine applications, between single and split atrazine applications and between treatments which had received a fall atrazine application and those with no fall atrazine application.

Quackgrass was rated visually in spring and fall as percent cover of each plot area (0% = area free of quackgrass, 100% = entire area covered). Trends in percent quackgrass cover ratings in the fall were similar to spring and are not presented. The percent quackgrass cover data was tested for homogeneity of variance and no transformation was required. A polynomial regression model relating percent cover to year of rating was used to analyze the data for each replicate. After the appropriate degree of polynomial was selected as described by Légère and Schreiber (1989), the obtained regression coefficients were subjected to multivariate analysis of variance (MANOVA) to test the hypothesis. Wilks' criterion was used to calculate significance levels.

Triazine soil residues

Soil samples for atrazine and de-ethyl atrazine residue analyses were collected before and after each atrazine application. Additional soil samples were collected and analyzed each spring before seeding soybeans. Twenty core samples of 2.0 cm diam to a depth of 10 cm were collected with a soil auger. The samples were dried, ground and sieved to <2 mm and stored at -10°C until analyzed. A 40 g sample of soil was extracted for 1 h with 100 mL methanol, extracts were filtered, reduced to dryness on a rotary evaporator and the residue dissolved in an appropriate volume of 1:18 ethyl acetate:hexane. Samples were quantified on a gas chromatograph fitted with a thermionic nitrogen detector. Air, hydrogen and carrier gas flows were 175, 4.5 and 30 mL min^{-1}, respectively. Injector, column and detector temperatures were 220, 220 and 250°C, respectively. Analytes were separated on 10% DC-200 Gas Chromosorb W, HP in a 1.2 m X 6-mm diam glass column. The concentration of atrazine and de-ethyl atrazine in the extracts were summed and the results reported as total triazine.

The relationship between soybean yield and atrazine soil concentration was derived from a linear regression model by least squares fit for 1986 and 1987. The complete experiments were repeated in the fall 1984. Data from the repeat experiments were not combined because the experiments were initiated in different years and annual effects were significant ($P \leq 0.0001$). The experiment by treatment interaction terms were not significant ($P = 0.1512$) indicating that trends were similar to those reported herein.

RESULTS AND DISCUSSION

Quackgrass control

Quackgrass cover remained relatively unchanged in the untreated controls during the 4 yr of the study (Figs. 1 and 2). Quackgrass coverage in untreated controls averaged 63 and 66% in the foliage and bare soil experiments, respectively. Quackgrass stand varied from year to year depending upon the growing season but fall plowing and spring disking prior to planting the crops did not alter the weed stand in the long term. While timely tillage in the fall has been found to exhaust quackgrass food reserves thereby providing a measure of control (Werner and Rioux 1977), this response was not observed in this study.

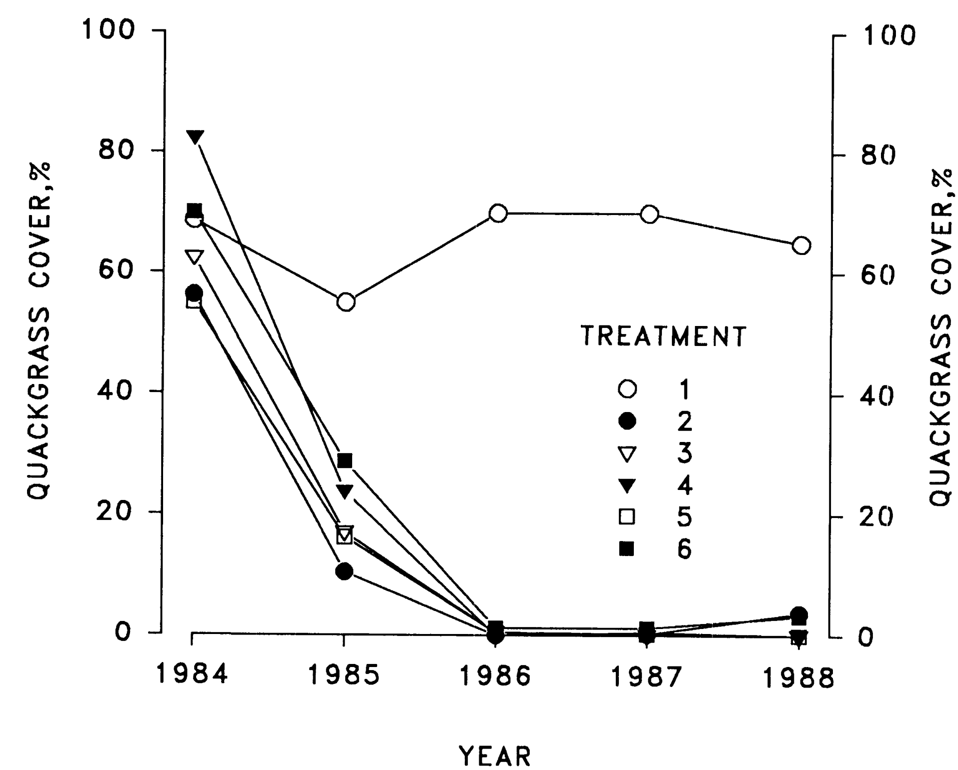

Figure 1. Percent quackgrass cover (spring evaluation) as a function of time. Atrazine treatments were applied to quackgrass foliage as follows: 1) untreated control; 2) split fall + spring preplant; 3) fall; 4) split fall + postemergence; 5) spring preplant; and 6) split spring preplant + postemergence. Refer to Table 1 for details on rates and time of applications.

Since the control treatment in both experiments was managed similarly, the difference observed between this treatment in Figures 1 and 2 can only be interpreted as variability present within the field and related to experimental error.

Second degree polynomial equations adequately described the quackgrass control data for each treatment in the two experiments (Tables 2 and 3). Quackgrass cover in the atrazine treated plots was significantly reduced from that in the untreated control. The polynomial equations describing quackgrass cover over 5 yr had similar regression coefficients whether atrazine was applied as a single or split treatment. Atrazine treatments that included a fall application were compared with those that had no fall application. No differences among regression coefficients were found between treatments with a fall application and those with no fall application (Tables 2 and 3).

Atrazine was last applied in the spring or fall of 1985 depending on the treatment (Table 1). Control of quackgrass in spring of 1986 was greater than 99% in the foliar experiment and 92% in the bare soil experiment. Quackgrass was still controlled 2 yr after the last atrazine application (Figs. 1 and 2). Over 94% of the quackgrass was controlled in the final spring evaluation where atrazine was foliarly applied and over 88% where atrazine was applied to bare soil. In either the foliage or bare soil experiments, long term quackgrass control from atrazine was similar whether applied as a split or

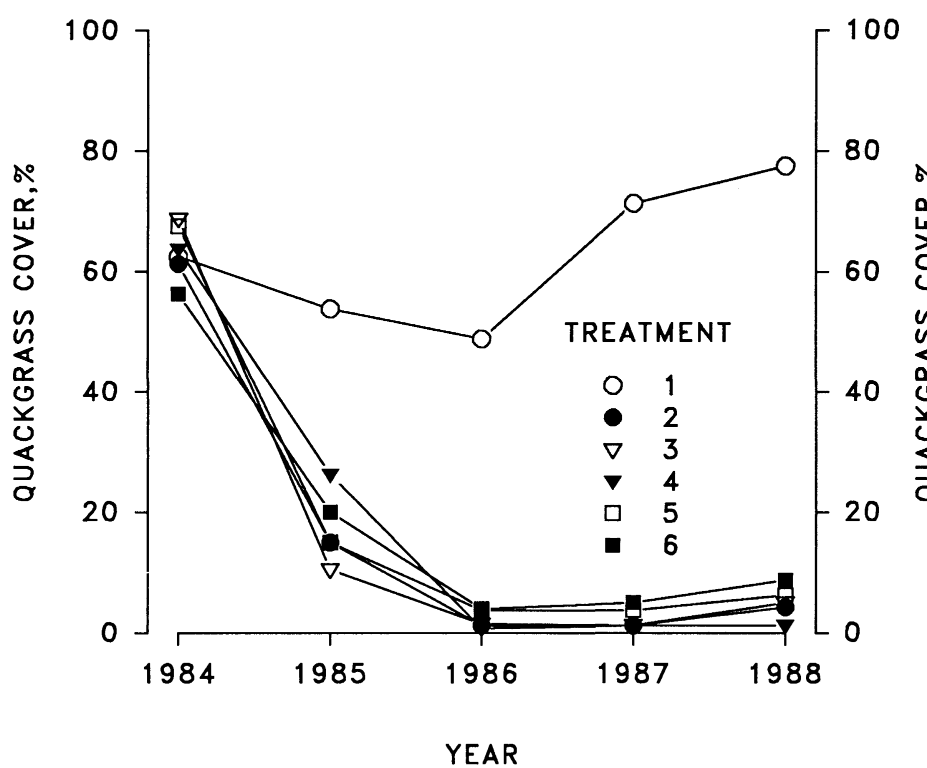

Figure 2. Percent quackgrass cover (spring evaluation) as a function of time. Atrazine treatments were applied to bare soil as follows: 1) untreated control; 2) split fall + spring preplant; 3) fall; 4) split fall + postemergence; 5) spring preplant; and 6) split spring preplant + postemergence. Refer to Table 1 for details on rates and time of applications.

as a single application (Tables 2 and 3). These results indicate that the corn producer has considerable flexibility in the timing and placement for atrazine to provide good control of quackgrass.

Since completion of this work, regulations in the United States and Canada now prohibit the use of atrazine in the fall and limit the rate of application in Ontario to less than 1.5 kg ha^{-1}. Thus, atrazine applied in spring may provide adequate quackgrass control but further research at the reduced rate is required.

Corn and soybean yield

Quackgrass infestation in the untreated control reduced corn yield in all years in either the foliar applied or bare soil experiment (Table 4, Figs. 3 and 4). Corn yield was lower in 1984 than 1985 which appeared to be related to the growing season. Atrazine treatment increased corn yield compared to the untreated control in both experiments in 1984 and 1985 (Table 4). In 1984 the yield increase was smaller in the foliar applied experiment than in the bare soil experiment. Grain yield for the control in the foliar applied experiment was higher, accounting for the smaller increase in yield from the atrazine treatments (Figs. 3 and 4). Corn yield was similar in all treatments where atrazine was applied either to foliage or to bare soil, within each of the 2 yr. In the bare soil experiment, higher grain yield was measured in 1984 where atrazine was applied in the fall compared to treatments where atrazine was applied in spring (Table 4, Fig. 4). This yield increase was not observed in the foliar experiment in 1984 or 1985 or in the bare soil experiment in 1985. In the absence of further experimental data it would be presumptuous to suggest atrazine applied in the fall to bare soil would provide greater grain yield than where atrazine was applied in spring. This data suggests that: 1) timing of atrazine application is not critical and 2) that foliar contact between quackgrass and atrazine is not essential to substantially reduce the influence of quackgrass on grain yield.

Table 2. Effect of atrazine applied to quackgrass foliage on the parameters of a second order polynomial regression ($y = b_0 + b_1 X + b_2 x^2$, where y = percent quackgrass cover and x = time) and results of a multivariate analysis of variance performed on those regression parameters

Factors	Mean b_0	Mean b_1	Mean b_2	Wilks' criterion, $P > F$
Treatment [a]				
Control	64.61	0.0357	0.1786	0.0001
Fall + spring preplant	52.81	-42.7393	7.8036	
Fall	59.69	-44.7714	7.6929	
Fall + postemergence	79.11	-59.0393	10.0536	
Spring preplant	52.81	-39.0286	6.6071	
Spring preplant + postemergence	69.39	-48.6714	8.1429	
Contrasts [b]				
Control vs. treated	—	—	—	0.0001
Fall vs. spring [c]	—	—	—	0.1707
Single vs. split [d]	—	—	—	0.8675

[a] Refer to Table 1 for details on rates and time of application.

[b] Single degree of freedom contrasts.

[c] Fall = treatments with a fall atrazine application; spring = treatments with only a spring application of atrazine.

[d] Single = treatments with one annual atrazine application; split = treatments with atrazine application in fall and spring or two applications in spring.

Table 3. Effect of atrazine applied to bare soil on the parameters of a second order polynomial regression ($y = b_0 + b_1 X + b_2 x^2$, where y = percent quackgrass cover and x = time) and results of a multivariate analysis of variance performed on those regression parameters

Factors	Mean b_0	Mean b_1	Mean b_2	Wilks' criterion, $P > F$
Treatment [a]				
Control	61.46	-11.6786	4.1071	0.0001
Fall + spring preplant	58.19	-44.8464	8.0179	
Fall	63.71	-51.6036	9.4821	
Fall + postemergence	63.08	-43.8571	7.2143	
Spring preplant	63.32	-48.0179	8.6607	
Spring preplant + postemergence	54.66	-38.7143	6.9286	
Contrasts [b]				
Control vs. treated	—	—	—	0.0001
Fall vs. spring [c]	—	—	—	0.7396
Single vs. split [d]	—	—	—	0.1064

[a] Refer to Table 1 for details on rates and time of application.

[b] Single degree of freedom contrasts.

[c] Fall = treatments with a fall atrazine application; spring = treatments with only a spring application of atrazine.

[d] Single = treatments with one annual atrazine application; split = treatments with atrazine application in fall and spring or two applications in spring.

Table 4. Contrast analysis for corn and soybean yield on plots treated with atrazine for quackgrass control

	$P > F$			
	Corn		Soybean	
Contrast [a]	1984	1985	1986	1987
Atrazine applied to foliage				
Control vs. single [b]	0.0131	0.0001	0.0056	0.0003
Control vs. split	0.0290	0.0001	0.0152	0.0032
Control vs. treated	0.0139	0.0001	0.0062	0.0006
Single vs. split	0.4812	0.3552	0.3959	0.0722
Fall vs. spring [c]	0.7463	0.4691	0.0055	0.2389
Atrazine applied to bare soil				
Control vs. single	0.0001	0.0001	0.0036	0.0151
Control vs. split	0.0001	0.0001	0.0573	0.0033
Control vs. treated	0.0001	0.0001	0.0124	0.0037
Single vs. split	0.5876	0.2117	0.0622	0.4686
Fall vs. spring	0.0262	0.2781	0.0001	0.4011

[a] Single degree of freedom contrasts.

[b] Single = treatments with one annual atrazine application; split = treatments with atrazine application in fall and spring or two applications in spring.

[c] Fall = treatments with a fall atrazine application; spring = treatments with no fall application.

Soybean yield, in the first year after corn, was severely reduced (Table 4, Figs. 3 and 4) in treatments which had received a single fall application of atrazine because of the triazine residue (Table 5). Fall application, whether single or split, reduced soybean yield compared to spring only application (Table 4). The lower yield measured in 1986 from the fall versus spring atrazine application is supported by the higher soil concentrations of atrazine from the fall treatments and occurred in each of the experiments involving atrazine application to foliage or to bare soil.

Soil triazine residues

Triazine residues in the fall of 1985 reflect the fall application and the residue from the spring application (Table 5). Triazine residues were greatly reduced over the winter of 1985 possibly because of leaching to greater than 10 cm or dissipation to products not detected in the analysis (Walker 1987). In the spring of 1986 before seeding soybean, triazine soil residues in the fall applied treatments averaged 301 ± 16 μg kg^{-1} in the foliar experiment and 334 ± 70 μg kg^{-1} in the bare soil experiment. Corresponding spring triazine residues on plots with no fall atrazine treatment averaged 204 ± 12 μg kg^{-1} in the foliar experiment and 174 ± 16 μg kg^{-1} in the bare soil experiment. Contrast analysis indicated residues in 1987 among all atrazine applications were not different. Frank *et al.* (1983) reported atrazine at 125 μg kg^{-1} reduced by 80% soybean fresh weight in a loam soil with 24% clay and 3.5% o. m. Therefore, soy-

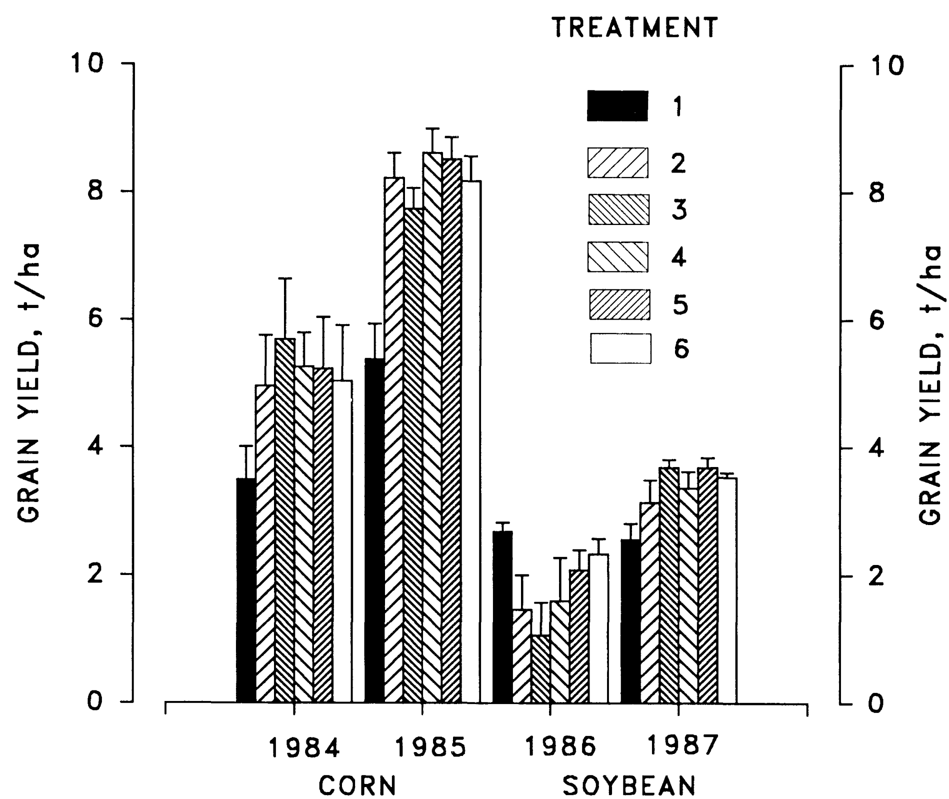

Figure 3. Corn and soybean yields on plots where atrazine was applied to quackgrass foliage. 1) untreated control; 2) split fall + spring preplant; 3) fall; 4) split fall + postemergence; 5) spring preplant; and 6) split spring preplant + postemergence. Vertical bars indicate standard error. Refer to Table 1 for details on rates and time of applications.

bean yield in 1986 may not have been maximized in any of the herbicide-treated plots because of triazine residues.

In 1987, soybean yields were higher on plots previously treated with atrazine than on those without atrazine treatment (Figs. 3 and 4). However, maximum soybean yield may still not have been achieved because of atrazine residue. The regression of 1986 and 1987 soybean yield on triazine residue was linear ($P \leq 0.0001$) with intercept 3.65 and regression coefficient -0.0065. From this regression, a triazine soil residue of 56 μg kg^{-1} could result in 10% yield reduction.

Quackgrass was, over a 2-yr period, controlled by atrazine applied to foliage either in a single application or split between a fall/spring or spring/spring application. Excellent control of quackgrass was obtained over the same period by similar treatments applied to bare soil. Although corn yield differed between years, there was no difference in corn yield between treatments which involved single application versus split application or fall versus spring atrazine application within the foliage treatment experiment. Soybean yield, in the first year after atrazine application ceased, was lower than or equal to the untreated quackgrass infested area; primarily as a result of the presence of atrazine residues. However, atrazine soil residues and quackgrass infestation 2 yr after the last application were sufficiently low that soybean yield from the previously treated areas was higher than from the untreated areas. To avoid soybean injury, a minimum of one

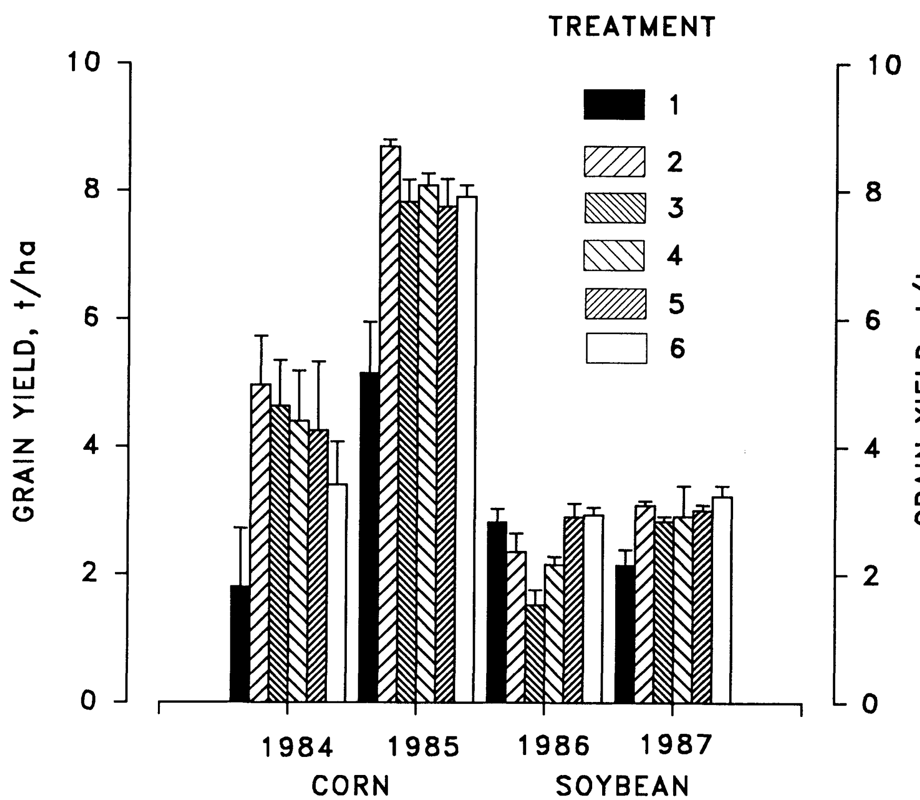

Figure 4. Corn and soybean yields on plots where atrazine was applied to bare soil. 1) untreated control; 2) split fall + spring preplant; 3) fall; 4) split fall + postemergence; 5) spring preplant; and 6) split spring preplant + postemergence. Vertical bars indicate standard error. Refer to Table 1 for details on rates and time of applications.

Table 5. Triazine (atrazine + de-ethyl atrazine) soil residue in fall 1985 after the last atrazine application and in the spring of 1986 and 1987 before planting soybeans

	Soil residue from atrazine application ($\mu g\ kg^{-1}$)					
	Foliage			Bare soil		
Factors	1985	1986	1987	1985	1986	1987
Treatment [a]						
Control	<4	<4	<4	<4	<4	<4
Fall + spring preplant	2041	307	90	685	328	94
Fall	3661	312	115	1591	406	109
Fall + postemergence	1905	283	92	1179	267	108
Spring preplant	588	212	125	375	162	83
Spring + postemergence	643	195	95	544	185	96
Contrasts [b]	$P > F$					
Control vs. single [c]	0.0001	0.0001	0.0002	0.0108	0.0001	0.0001
Control vs. split	0.0001	0.0001	0.0013	0.0237	0.0001	0.0001
Control vs. both	0.0001	0.0001	0.0003	0.0112	0.0001	0.0001
Fall vs. spring [d]	0.0001	0.0032	0.5339	0.0146	0.0001	0.2627

[a] Refer to Table 1 for details on rates and time of application.

[b] Single degree of freedom contrasts.

[c] Single = treatments with one annual atrazine application; split = treatments with atrazine application in fall and spring or two applications in spring.

[d] Fall = treatments with a fall atrazine application; spring = treatments with no fall application.

year delay should be considered between the last application of atrazine and the planting of soybeans. These results indicate that atrazine could be applied either as a single application or split application over a 2-yr period for good long lasting quackgrass control.

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