

## Imazapyr seed dressings for *Striga* control on acetolactate synthase target-site resistant maize

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### Abstract

High herbicide levels can be localized on or near seed of acetolactate synthase (ALS) resistant maize (*Zea mays*). The magnesium salt of imazapyr was optimal for seed dressings (drenching, priming, and coating), for preventing field damage from parasitic *Striga hermonthica* (witchweed) in three seasons. *Striga* emerged on untreated maize from 6 to 12 weeks after planting. There was almost no *Striga* emergence for 3 months on imazapyr-dressed homozygous ALS-R 3245IR maize seeds. Occasional *Striga* that emerged and flowered formed no seed by harvest. Dust or polyvinylpyrrolidone adhesive coatings were safer in maize and as effective in *Striga* control as priming. Seed dressing coupled with pulling *Striga* escapes reduces infestation and can be used to deplete the *Striga* seed bank until genetic crop resistance becomes available. © 2001 Elsevier Science Ltd. All rights reserved.

**Keywords:** Maize; *Striga*; Herbicide seed dressings; Imazapyr; Acetolactate synthase resistance

### 1. Introduction

The witchweeds (*Striga* spp.) are pernicious, root-attaching parasitic weeds found mainly in Africa. Grain and legume crops are attacked by different species of these parasites. Roots emerging from germinating *Striga* seeds attach to crop roots, and the parasite becomes a major sink for crop photosynthate, debilitating crop growth and yield, up to total loss. Tens of such attachments can occur on each host plant. The parasites later send up flower stalks, each bearing tens of thousands of seeds. The seeds remain dormant until a host root chemically stimulates their germination. *Striga* damage to the crop is first seen before anthesis on heavily infested plants as a sudden chlorosis of the maize (*Zea mays* L.) whorl due to a phytotoxic effect (Ransom et al., 1996). This “bewitching” (thus the common name) occurs long before the emergence of the *Striga* flower stalks. Pulling or cutting flower stalks can reduce reinfestation, but is deemed uneconomical because so

much damage has already been inflicted on the current crop (Parker and Riches, 1993). Crop seed becomes contaminated with *Striga* seed when manually dehusked maize ears are put on the ground for drying and later carried to the homestead. Contaminated crop seed is probably the major form of *Striga* dispersal in Africa (Berner et al., 1994b). Mechanical harvesting equipment would be expected to enhance seed spread within fields (Gressel et al., 1996b).

*Striga hermonthica* and *S. asiatica* are serious constraints to all cereal production in sub-Saharan Africa except for wheat (*Triticum aestivum* L.), barley (*Hordeum vulgare* L.) and paddy (*Oryza sativa* L.). Heavy witchweed infestations led to a stoppage of fertilizer use because it becomes uneconomic, and eventually to abandonment of farms (Doggett, 1984), often leading to encroachment on nature reserves and other undeveloped lands. The area infested by *Striga* is increasing (Frost, 1995). Small-scale farmers are the hardest hit, as they mainly produce maize, sorghum [*Sorghum bicolor* (L.) Moench], upland rice, and millets, all hosts of *Striga hermonthica*. The yield potential of maize without *Striga* (and without fertilizer) would be 2 t ha<sup>-1</sup>, double the current yield. Using fertilizers could double the yield again (Hassan et al., 1995). Berner et al. (1995) cite evidence that in western Africa “about 40

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million ha in cereal production are severely and 70 million ha are moderately infested by *Striga* spp., with \$7 billion lost yield, detrimental to the lives of over 100 million people". Where *Striga* species are indigenous, the best that can be hoped for is a partial control and lowering the levels of infestation by a substantial depletion of the *Striga* seedbank.

Much of the *Striga*-infested area of Africa has ultra-high levels of *Striga* seeds in the soil due to years of neglect. Thus, there is an immediate need for cost-effective mechanisms meeting two criteria: controlling *Striga* itself, so that adequate crop yields can be achieved; and depleting the *Striga* seedbank in the soil, to allow cultivation of crops such as sorghum. Such technologies are needed as a stopgap until crop varieties with adequate genetic resistance become available.

Herbicides that inhibit acetolactate synthase (ALS) activity control parasitic weeds (Garcia-Torres and Lopez-Granados, 1991). These herbicides specifically inhibit the biosynthesis of branch-chained amino acids (Saari et al., 1994). It has been claimed that these parasites rely on the host for provision of organic nitrogen (Press, 1995), but clearly they must produce the branch-chained amino acids wholly by themselves for this group of herbicides to be active. Adu-Tutu and Drennan (1991) achieved some control of *Striga* in normal sorghum and maize with some sulfonylurea herbicides affecting ALS, although crop growth was sensitive to the higher rates, leaving little margin for farmer error. Foliar treatment of systemic, metabolically selective herbicides would be ineffective against *Striga*, as the parasite would receive degraded, inactive herbicide from the crop's vascular system.

It was hypothesized that biotechnologically derived crops with resistance due to a modification of the target site of the herbicide could be used for parasitic weed control (c.f. Gressel, 1996). Such crop/herbicide combinations would allow using the amounts of herbicide needed for residual activity. A more limited hypothesis based on extrapolation from field experience was proposed for glyphosate-resistant crops (Foy et al., 1989). This target site resistance concept was borne out with broomrape (*Orobanche* spp.) using model transgenic crops. Such crops contain transgenes for resistance to chlorsulfuron (an inhibitor of ALS), glyphosate (an inhibitor of enol-phosphate-shikimate phosphate (EPSP) synthase leading to the synthesis of aromatic amino acids and other aromatic compounds), and asulam (an inhibitor of dihydropteroate synthase, leading to folic acid) (Gressel, 1995; Gressel et al., 1994, 1996a; Joel et al., 1995; Surov et al., 1998).

The use of the above herbicides to uniformly cover the fields of resistant crops would be too expensive for most African farmers and would not fit their cropping systems, which include intercropping. As the herbicides described above are all systemically translocated within

plants, and as other weeds are less pernicious and can be controlled by conventional means, we considered a point application that might allow less total herbicide use, but at very high local concentrations, just for *Striga* control. Such high concentrations could only be possible as dressings to crop seeds possessing target site resistance, as only these have a sufficient magnitude of resistance, and will not degrade the herbicides.

Seed dressings with herbicides have only rarely been tested. Years ago, EPTC was applied to maize seed as a method of soil incorporation (Dawson, 1987), which was never commercialized. Seed dressings have been tested for parasitic weed control of *Orobanche* spp. on beans having metabolic resistance, but repeated postemergence treatments were required for season-long control (Jurado-Exposito et al., 1996). Berner et al. (1994a) showed that *Striga gesnerioides* could be controlled in metabolically resistant cowpeas [*Vigna unguiculata* (L.) Walp.] by pre-soaking the seed in aqueous imazaquin, but the duration of soaking and concentrations were critical to prevent crop phytotoxicity.

Postemergence (whole field) applications of ALS-inhibitors delayed *Striga asiatica* emergence on ALS resistant maize in the USA (Abayo et al., 1998). Additionally, further experiments indicated that ALS inhibitors provided early-season *Striga hermonthica* control when herbicide was applied to maize seed as a drench at planting (Ransom et al., 1995; Abayo et al., 1996, 1998). Seed priming (soaking) with glyphosate or with ALS inhibitors, and seed coating with ALS inhibitors as well as asulam have been shown to control parasitic weeds on target-site resistant crops (Joel et al., 1997, 2000; Berner et al., 1997; Gressel and Joel, 2000).

There are currently a large number of ALS-inhibiting herbicides in the market, with varying persistence in the soil. In a previous study nine imidazolinone and sulfonylurea herbicides were screened as seed drenches in the planting hole. A maize hybrid with homozygous ALS target site resistance was used to identify those herbicides that could safely be used while having long-term effectiveness in controlling *Striga* (Abayo et al., 1998). Imazapyr had the least crop phytotoxicity with the longest duration of *Striga* control. Dressing with low rates of imazapyr could yield more than double in moderately infested conditions, which could be ca. 20 times more valuable than the cost of the herbicide. As the crop seed is dressed, there is no need for spray equipment, with the concomitant ecological advantage that no herbicide is applied off-target.

Many small-scale African farmers already have experience in applying pesticides, often in novel manners; maize stalk borer is commonly controlled with a pinch of insecticide dust or low-analysis granules applied directly into the whorl.

Maize with ALS target-site resistance developed from a tissue culture mutation (Newhouse et al., 1991), which bears a mutation of tryptophan 552 to leucine (Bernasconi et al., 1995) is marketed in the USA in homozygous form as IR (imidazolinone-resistant) maize. Maize with ALS target site resistance developed by pollen mutagenesis, which bears a mutation of alanine 133 to threonine is marketed in the USA in heterozygous form as IT (imidazolinone-tolerant) maize (Greaves et al., 1993). IR maize can withstand much higher levels of imidazolinone herbicides than IT maize (Siehl et al., 1996; Wright and Penner, 1998). Recent studies carried out in Africa with ALS inhibitors dressed as a drench (Ransom et al., 1995; Abayo et al., 1996, 1998) or as a coating (Berner et al., 1997) to maize seed bearing ALS resistance have demonstrated that low doses of herbicide can provide effective *Striga* control on IR maize. There are no previous reports on using imazapyr as a seed prime to IR maize.

The objectives of this study were to compare salts of imazapyr, to develop formulations, and to compare different methodologies of seed dressing with imazapyr for effective *Striga hermonthica* control on IR maize hybrids with ALS target site resistances. The application technologies must be readied, while the IR gene is being backcrossed into tropical African maize varieties that are able to cope with indigenous diseases and insect pests.

## 2. Materials and methods

### 2.1. Plant material

Maize hybrid 3245IR (Pioneer) was mainly used in this study, while hybrid 8326IT (Zeneca, Garst) was used in preliminary experiments. Both were commercial hybrids from the USA.

### 2.2. Preparation of imazapyr acid and its salts

As the surfactant in commercial imazapyr could adversely affect seed priming and coating, pure salts were prepared from imazapyr acid by crystallizing imazapyr acid from commercially formulated herbicide (containing detergent). The salts were prepared by dissolving the precipitated acid in the proper bases.

Surfactant-formulated isopropylamine salt of imazapyr (Arsenal™) was diluted with an equal volume of acetone and the pH of the solution decreased with concentrated HCl to the pKa of imazapyr (3.6). Imazapyr crystals formed, while the surfactant was retained in solution by the acetone. The crystals were poured onto filter paper in a Buchner funnel and vacuum was applied. The crystals were washed with acetone until no blue color of the formulant remained.

The crystals were air-dried in the fume hood. Comparison of the UV adsorption spectrum of this material against that of an analytical standard (Riedel-de Haën, Pestanal grade) showed >98% purity.

Ammonium, potassium, calcium, and magnesium salts were prepared by first dispersing solid imazapyr acid in distilled water and increasing its solubility by gradually adding ammonium hydroxide, potassium hydroxide, calcium hydroxide, or magnesium hydroxide, respectively, to raise the pH to be between 6 and 8.

### 2.3. Seed dressing optimization

The effect of a range of concentrations of the various salts on the emergence of maize was conducted in pot experiments to determine the least phytotoxic imazapyr salt for priming maize seeds. Single maize seeds of 3245IR and 8326IT were primed by soaking them for 24 h in vials containing 0.125-ml of 0, 10, 20, 30, 40, 50, 60 and 70 mM solutions of ammonium, potassium, calcium, and magnesium salts of imazapyr. Seeds imbibed all the 0.125-ml, which resulted in the imbibition of 0, 0.3, 0.7, 1.0, 1.3, 1.7, 2.0 and 2.3 mg a.e. of imazapyr seed<sup>-1</sup>, respectively. Four treated seeds were planted per pot in 30 cm deep, 15 cm diameter plastic pots containing sandy clay loam soil. The pots were then watered to field capacity and placed in full sunlight. Maize emergence was quantified after 3 weeks. Each treatment was with two replicates. Data were subjected to a probit analysis and the rate of imazapyr at which 50% of the maize seedlings failed to emerge (ED<sub>50</sub>) was calculated for each salt.

### 2.4. Field experiments

All field experiments were conducted at the National Sugar Research Center (NRSC) of the Kenya Agricultural Research Institute (KARI) near Kibos (0°04'S, 34°48', elevation 1214 m) in western Kenya. The soil is classified as a retro-eutic planosol according to the FAO/UNESCO (1974) system. The fields used had previously been cropped with maize that was heavily infested with *Striga*, which matured and seeded the area. All experiments were carried either during the 1997 or 1998 season A (April–July) as well as the 1997/1998 season B (October–January). Seasonal precipitation during the 1997 season A, 1997/98 season B and 1998 season A was 397, 1304 and 434 mm, respectively. In the 1997/98 season B rains were of 4 weeks late but the rainfall exceeded the multi-year average for the season by 880 mm. This delayed both maize growth and *Striga* emergence. Treatments were arranged in a randomized complete block design with three replicates for each experiment. Experimental units consisted of four 3-m long rows with 75 cm between rows. Two maize seeds were planted per hill within these rows, with hills spaced

at 50 cm. *Striga* seeds were added to each plot to ensure that each maize plant was exposed to a minimum of 2000 viable *Striga* seeds. These seeds were added in a sand/seed mixture and placed in an enlarged planting hole at a depth of 7–10 cm (directly below the maize seed) as well as in a 7–10 cm deep furrow parallel to the planting holes.

No fertilizer was applied during 1997 season A, as nitrogenous fertilizers reduce *Striga* emergence (Pieterse and Verkleij, 1991). In subsequent seasons, however, 50 and 128 kg N and  $P_2O_5$  ha<sup>-1</sup>, respectively, were applied at planting in the form of di-ammonium phosphate (18-46-0) to ensure reasonable maize development.

The maize hybrid used in the field is highly susceptible to pest problems in tropical Africa. Thus, maize was treated to preclude insect and disease problems with 100 mg a.i. carbofuran insecticide hill<sup>-1</sup> (2.65 kg a.i. carbofuran ha<sup>-1</sup>) at planting, and sprayed with 770 g a.i. ha<sup>-1</sup> endosulfan, and a mixture of the 225 g a.i. ha<sup>-1</sup> metalaxyl and 1.68 kg a.i. ha<sup>-1</sup> mancozeb fungicides at 2 and 8 weeks after planting.

Data were collected from the two inside rows excluding the end plants. Maize stand counts were determined 6 weeks after planting. *Striga* counts were made every 2 weeks beginning 6 weeks after planting when *Striga* began to emerge, and ending at harvest 14 weeks after planting. The number of flowering *Striga* plants and *Striga* seed capsules at 12 and 14 weeks; adjusted grain yield to 15% moisture; and total maize shoot dry weight were all measured. No yield data were collected during the 1997/98 season B, as heavy rains caused excessive late season fungal damage to the crop.

The collected data were subjected to an analysis of variance. The variances of the treatments were found to be heterogeneous due to the high proportion of zero *Striga* counts in some of the herbicide treatments. Therefore, *Striga* count data were transformed using the formula:  $Y = \log(X + 1)$ , where  $X$  is the original data value. Treatment variances were found to be homogeneous according to the Levene test for homogeneity. Preplanned single degree of freedom comparisons were performed for each experiment. Protected LSD (0.05) values based on analysis of variance were also calculated to allow pair-wise multiple comparisons among means.

### 2.5. Seed priming experiments

Experiments were conducted during 1997 season A and 1997/98 season B. Maize seeds were primed by soaking them in varying concentrations of magnesium imazapyr for 24 h. Each seed imbibed about 0.125-ml of imazapyr solution. The seeds were either planted immediately (wet), or were air-dried for 24 h before

planting. In previous preliminary work in the laboratory (data not shown) we found that imbibed imazapyr was more phytotoxic to seeds that were redried before planting than to seed planted wet. Therefore, a lower range of imazapyr concentrations was used on seeds that were dried than on seeds that were directly planted. The rates of seed priming used in the 1997 season A were 0.3, 0.75 and 1.0 mg imazapyr seed<sup>-1</sup> for primed and planted directly (wet), while 0.3, 0.5 and 0.7 mg imazapyr seed<sup>-1</sup> were tested in the 1997/98 season B. The rates of seed priming used for seeds that were dried after priming were 0.20, 0.26 and 0.33 mg imazapyr seed<sup>-1</sup> in the 1997 season A and 0.2, 0.3 and 0.4 mg imazapyr seed<sup>-1</sup> in the 1997/98 season B. Seed priming and coating with imazapyr was compared with spray applications of imazapyr, and with herbicide-free controls. The above treatments were also compared with seed drenching with imazapyr, as it previously was the best method for *Striga* control (Abayo et al., 1998). Drenching treatments consisted of applying a 1 ml aqueous herbicide solution (commercial formulation) above just-planted seed. The rates used were 0.3 mg hill<sup>-1</sup> in 1997 season A and 0.3 and 0.5 mg hill<sup>-1</sup> in 1997/98 season B. The spray treatments with commercial formulation were applied 14 days after maize emergence at 0.3 mg plant<sup>-1</sup> (15 g ha<sup>-1</sup>) in season A 1997, and 0.3 and 0.5 mg plant<sup>-1</sup> (15 and 25 g ha<sup>-1</sup>) in season B 1997/98. The two herbicide-free checks used consisted of priming maize seed in water and planting it immediately (wet) or after air-drying it for 24 h.

The seed priming data were analyzed separately for each season as the treatment levels varied (but overlapped) between seasons.

### 2.6. Seed coating experiments

Experiments were conducted during the 1997/98 season B and season A 1998 rainy seasons. A commercial seed dust Murtano<sup>TM</sup> containing 20% a.i. lindane and 26% a.i. thiram, or a solid coat of polyvinylpyrrolidone (PVP) (avg. MW 90 Kd) were used to bind the imazapyr to the maize seed. The seed dust at 0.1 g or 90 mg of PVP were combined with 2.9 ml of 53, 106 or 160 mM of Mg-imazapyr and mixed thoroughly with 144 maize seeds (to give a imazapyr coating of 0.3, 0.6, or 0.8 mg a.e. imazapyr seed<sup>-1</sup>). This is the equivalent of 15, 30 or 45 g a.e. ha<sup>-1</sup>, respectively, when planted in the field at 53,300 seeds ha<sup>-1</sup>. The treated seeds were then planted in the field within 2 days of coating. Seed coating with imazapyr was compared to imazapyr seed drenches spray applications of imazapyr and herbicide-free controls, as described above.

Seed coating data from two seasons were combined for the analysis of variance.

### 3. Results and discussion

#### 3.1. Salt optimization

The highest rates of all mineral salts of imazapyr tested reduced the emergence of '3245IR' maize. The Mg salt of imazapyr was the least phytotoxic at these rates and had a calculated ED<sub>50</sub> value double that of the other salts (Table 1). Based on these results, all further priming and coating research was conducted using the Mg salt of imazapyr. The heterozygous 8326IT hybrid variety succumbed at all herbicide rates (data not shown), and was thus considered insufficiently resistant for further testing.

#### 3.2. Field experiments

##### 3.2.1. Seed priming experiments (1997 season A and 1997/98 season B)

*Stand count.* Maize emergence was significantly reduced on imazapyr-treated maize seeds planted wet in the 1997 season A (Tables 2 and 3). There was a linear

decrease in maize emergence with increasing rates with this primed, wet-planted treatment in the 1997 season A (Table 3). Even at the rate of 0.3 mg imazapyr seed<sup>-1</sup>, priming and planting while wet reduced maize emergence compared to the priming at the same rate and drying before planting. No treatment during season B (the highest was 0.7 mg a.e. seed<sup>-1</sup>) significantly reduced maize stand establishment (Tables 3 and 4). Imazapyr sprayed postemergence or drenched to the hills, did not reduce stand in either season (Tables 2 and 4).

Previous preliminary greenhouse work in pots (data not shown) demonstrated that seeds primed and planted wet could withstand higher imazapyr rates than seeds that were treated and planted dry, which was not the case in the field. Those 5 days without rain that followed planting during the 1997 season A probably abetted phytotoxicity to germinating maize seeds that had been imbibed with the higher rates of imazapyr. These results show that we are near the upper limits for imazapyr use in field conditions, and sub-optimal environmental conditions might negatively interact with higher herbicide levels. Based on the results from these two seasons, we conclude that priming rates should be kept at 0.3 mg a.e. imazapyr seed<sup>-1</sup> or lower if phytotoxicity to maize is to be avoided. This conclusion was validated in later work, both with the hybrid and with back-crossed material (data not shown).

*Striga emergence.* All seed priming treatments during the 1997 season A provided early season *Striga* control compared to the controls. The higher rates provided near complete control for 8 weeks after planting (Fig. 1, Tables 2 and 3). Even the maize seed primed at very low rates hardly had any *Striga* emergence for the most

Table 1

Variable effect of imazapyr salts on maize. The concentration of imazapyr salts required to reduce 3245 IR maize emergence by 50% (ED<sub>50</sub>) was estimated by probit analysis

Imazapyr salt	ED <sub>50</sub> (mg seed <sup>-1</sup> )	Log ED <sub>50</sub> <sup>a</sup> (mg seed <sup>-1</sup> )
Calcium (Ca <sup>2+</sup> )	0.47	-0.332 ± 0.057
Ammonium (NH <sub>4</sub> <sup>+</sup> )	0.52	-0.285 ± 0.013
Potassium (K <sup>+</sup> )	0.65	-0.188 ± 0.040
Magnesium (Mg <sup>2+</sup> )	1.28	0.107 ± 0.043

<sup>a</sup> ± 95% confidence limits based on methods of Agresti (1990).

Table 2

Effect of imazapyr priming '3245 IR' seed on maize development and on *Striga* control (1997 season A). Data in ( ) are log transformed as described in materials and methods

Imazapyr (a.e. mg seed <sup>-1</sup> )	Formulation	Application method	Stand <sup>a</sup> No. ha <sup>-1</sup>	Maize production		<i>Striga</i> emergence (m <sup>-2</sup> )		<i>Striga</i>	
				Grain (kg ha <sup>-1</sup> )	Total (kg ha <sup>-1</sup> )	Weeks after planting		Flowering <sup>b</sup> (m <sup>-2</sup> )	Capsules ( <i>Striga</i> plant <sup>-1c</sup> )
						8	12		
0	Control	Planted dry	53,330	4210	9110	22.1 (1.3)	64.3 (1.8)	9.7 (1.0)	19.2 (1.3)
0	Control	Planted wet	52,220	4330	8810	28.8 (1.5)	76.4 (1.9)	10.2 (1.0)	28.8 (1.5)
0.3	Commercial	Drench in hills	51,110	5630	10,960	0.0 (0.0)	10.1 (1.0)	0.0 (0.0)	0.0 (0.0)
0.3	Commercial	Post spray	53,330	4950	9440	8.2 (0.9)	50.3 (1.7)	2.9 (0.5)	11.7 (1.1)
0.20	Mg-salt	Seed primed; redry	46,670	5480	10,690	1.2 (0.3)	20.6 (1.3)	0.0 (0.0)	0.6 (0.2)
0.25	Mg-salt	Seed primed; redry	46,670	5060	9830	0.1 (0.0)	14.8 (1.1)	0.1 (0.0)	2.7 (0.6)
0.3	Mg-salt	Seed primed; redry	50,000	4490	9270	0.2 (0.1)	15.4 (1.1)	0.0 (0.0)	0.0 (0.0)
0.3	Mg-salt	Seed primed; wet	35,560	3100	7870	0.0 (0.0)	4.2 (0.7)	0.0 (0.0)	0.0 (0.0)
0.7	Mg-salt	Seed primed; wet	33,330	3130	6370	0.0 (0.0)	1.2 (0.3)	0.0 (0.0)	0.0 (0.0)
1.0	Mg-salt	Seed primed; wet	27,780	3860	7860	0.0 (0.0)	0.2 (0.1)	0.0 (0.0)	0.0 (0.0)
LSD (0.05)			7290	NS <sup>d</sup>	NS <sup>d</sup>	(0.2)	(0.4)	(0.2)	(0.3)

<sup>a</sup> Measured 6 weeks after planting.

<sup>b</sup> Measured 12 weeks after planting

<sup>c</sup> Measured 14 weeks after planting and average of five plants

<sup>d</sup> NS—not significant at 0.05 probability level.

Table 3  
Single degree of freedom contrasts for maize and *Striga* variables measured in the seed priming experiments

Contrasts	Stand <sup>a</sup> No. ha <sup>-1</sup>	Maize production		<i>Striga</i> emergence		<i>Striga</i>	
		Grain (kg ha <sup>-1</sup> )	Total (kg ha <sup>-1</sup> )	Weeks after planting		Flowering <sup>b</sup> (m <sup>-2</sup> )	Capsules <sup>c</sup> (m <sup>-2</sup> )
				8	12		
<i>1997 Season A</i>							
Herbicide application vs controls	d	NS <sup>e</sup>	NS	d	d	d	d
Spray vs primed	d	NS	NS	d	d	d	d
Primed; redry 0.3 mg vs. primed; wet 0.3 mg	d	NS	NS	NS	NS	NS	NS
Primed; redry linear	NS	NS	NS	NS	NS	NS	NS
Primed; redry quadratic	NS	NS	NS	NS	NS	NS	NS
Primed; wet linear	f	NS	NS	NS	d	d	NS
Primed; wet quadratic	NS	NS	NS	NS	NS	NS	NS
<i>1997 Season B</i>							
Herbicide application vs. controls	NS	—	—	d	d	d	d
Spray 0.3 mg vs. primed; redry and wet 0.3 mg	NS	—	—	d	f	d	f
Drenched 0.3 mg vs. primed; redry and wet 0.3 mg	NS	—	—	NS	NS	NS	NS
Primed; redry 0.3 mg vs. primed; wet 0.3 mg	NS	—	—	NS	NS	NS	NS
Primed; redry linear	NS	—	—	NS	NS	NS	NS
Primed; redry quadratic	NS	—	—	NS	NS	NS	NS
Primed; wet linear	NS	—	—	NS	d	NS	f
Primed; wet quadratic	NS	—	—	NS	NS	NS	NS

<sup>a</sup> Measured 6 weeks after planting.

<sup>b</sup> Measured 12 weeks after planting.

<sup>c</sup> Measured 14 weeks after planting.

<sup>d</sup> Significant at the 0.01 probability level.

<sup>e</sup> NS—not significant at 0.05 probability level.

<sup>f</sup> Significant at the 0.05 probability levels.

Table 4  
Effect of seed priming '3245 IR' with imazapyr on maize development and on *Striga* control, 1997/98 season B. Data in ( ) are log transformed as described in materials and methods

Imazapyr (a.e. mg seed <sup>-1</sup> )	Formulation	Applicaion method	Stand <sup>a</sup> No. ha <sup>-1</sup>	<i>Striga</i> emergence		<i>Striga</i>	
				Weeks after planting		Flowering <sup>b</sup> (m <sup>-2</sup> )	Capsules <sup>c</sup> (m <sup>-2</sup> )
				8	12		
0	Control	Planted dry	45,190	7.7 (0.9)	42.6 (1.6)	3.8 (0.7)	47.7 (1.7)
0	Control	Planted wet	43,700	7.2 (0.9)	38.0 (1.5)	2.9 (0.6)	38.9 (1.5)
0.3	Commercial	Drenched into hills	42,220	2.3 (0.3)	26.8 (1.1)	1.4 (0.2)	24.0 (1.0)
0.5	Commercial	Drenched into hills	47,410	5.1 (0.6)	41.4 (1.4)	2.2 (0.4)	25.3 (1.1)
0.3	Commercial	Post emergence spray	43,700	0.8 (0.2)	19.3 (1.2)	0.3 (0.1)	16.4 (1.0)
0.5	Commercial	Post emergence spray	42,220	2.0 (0.3)	7.1 (0.9)	0.0 (0.0)	2.0 (0.4)
0.2	Mg-salt	Seed primed; redry	41,480	3.3 (0.6)	21.5 (1.3)	0.6 (0.2)	17.1 (1.2)
0.3	Mg-salt	Seed primed; redry	39,260	4.0 (0.6)	24.0 (1.3)	0.7 (0.2)	8.1 (0.9)
0.4	Mg-salt	Seed primed; redry	40,740	2.7 (0.5)	25.4 (1.3)	0.6 (0.1)	19.3 (1.2)
0.3	Mg-salt	Seed primed; wet	41,480	2.1 (0.3)	18.0 (1.1)	0.7 (0.2)	22.9 (0.7)
0.5	Mg-salt	Seed primed; wet	41,480	0.6 (0.2)	6.7 (0.9)	0.1 (0.0)	4.0 (0.4)
0.7	Mg-salt	Seed primed; wet	36,300	0.0 (0.0)	0.8 (0.2)	0.0 (0.0)	0.0 (0.0)
LSD (0.05)			NS <sup>d</sup>	(0.5)	(0.4)	(0.3)	(0.6)

<sup>a</sup> Measured 6 weeks after planting.

<sup>b</sup> Measured 12 weeks after planting.

<sup>c</sup> Measured 14 weeks after planting.

<sup>d</sup> NS—not significant at 0.05 probability level.

critical 2 months after planting. After this, the density of *Striga* generally increased to 12 weeks after planting, by which time *Striga* emergence was maximum as the crop

approached maturity. All seed priming treatments exerted very good *Striga* control for up to 12 weeks after planting during this season. There was a linear

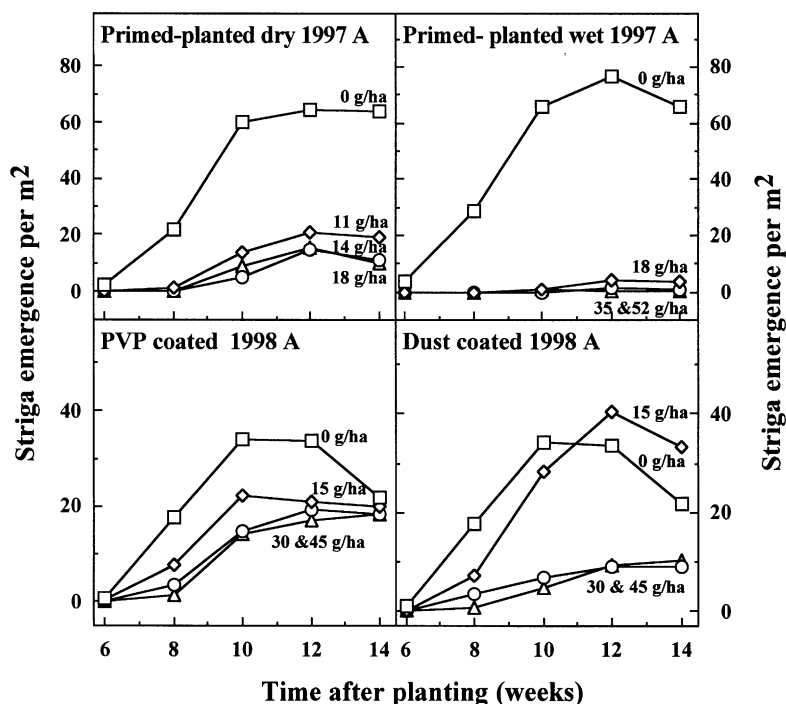


Fig. 1. Effect of imazapyr priming (1997 season A) and coating (1998 season A) '3245 IR' maize seed on *Striga* control.

decrease in *Striga* emergence at 12 weeks after planting with increasing rates of imazapyr with this priming, wet planting treatment (Table 3). There were no significant differences in *Striga* stand between the two highest wet-planted priming treatments at 12 weeks after planting during this season probably due to the higher rate of imazapyr used with this treatment method, which provided near season long control.

In the 1997/98 season B, however, only the highest rates of priming with imazapyr reduced *Striga* emergence at 8 weeks after planting (Table 4). Furthermore, by 12 weeks, only the higher rates of 0.5 and 0.7 mg a.e. seed<sup>-1</sup> bore less-emerged *Striga* than the controls. The late-emerged *Striga* on the imazapyr-treated maize was far smaller than that on the untreated controls. As in season A, there was a linear decrease in *Striga* emergence at 12 weeks after planting with increasing rates of imazapyr with this primed, wet planted treatment (Table 3). The poorer control obtained in the season B was probably related to the heavy rains experienced during this season, which possibly leached the herbicide beyond the zone in which it could be effective in controlling *Striga*.

Drenching imazapyr in hills was more effective in *Striga* control than postemergence spray during 1997 season A (Table 2). The opposite effect was observed during season B for a higher imazapyr rate (Table 4). The heavy leaching in the 1997/98 season B may have washed the herbicide beyond the *Striga* zone while the sprayed herbicide may have been washed into this *Striga* zone. Postemergence spraying during the 1997/98 season

B gave adequate *Striga* control for the higher imazapyr rate (Table 4). This was not the case during season A 1997 (Table 2), so spraying at this low rate seems unreliable. From both the practical point of view (cost, ease of application, and the lack of need for spray equipment), and from environmental considerations, application by seed dressing should be a better option than spraying for subsistence farmers.

*Striga* flowering and capsule formation. All priming treatments in the 1997 season A reduced the amount of flowering *Striga* at 12 weeks, and almost totally suppressed the formation of *Striga* seed capsules by harvest time at 14 weeks (Table 2). *Striga* on maize plants treated with the lowest rate of imazapyr seed dressings bore less than 1 seed capsule plant<sup>-1</sup> during season A. Similarly, *Striga* flowering was reduced by imazapyr at 12 weeks in the 1997/98 season B. Capsule formation was significantly reduced, however, only on those treatments where the maize seeds were primed and planted wet (Table 4).

Postemergence imazapyr spray was the least effective herbicide treatment in reducing *Striga* flowering and seed capsule formation during the 1997 season A. However, seed drenches to the hills at higher imazapyr rates allowed a higher density of flowering *Striga* plants with capsule formation than a postemergence spray at a similar rate during season B (Tables 2 and 4). Some *Striga* stalks emerged near harvest (14 weeks after planting), however, this was too late both to reduce maize yield and for the parasite to set seed.

**Grain yield.** Generally, maize grain yield from this study was high (Table 2) due to less than anticipated *Striga* parasitism during season A 1997. This was probably due to the high inherent soil fertility in the experiment station fields and favorable moisture conditions for maize growth. Yield on an area basis, did not differ significantly among herbicide treatments (Tables 2 and 3). The lack of a strong yield increase was probably due to the fact that the treatments that were most effective controlling *Striga* were also somewhat phytotoxic to the maize. A rate must be determined that is without crop phytotoxicity problems, even if this means occasional *Striga* appearing late, which must be rogued. No yield data were collected during season B due to the unusually high and prolonged rainfall during this season that caused massive preharvest fungal infection to these temperate maize hybrids, which are not suited to the tropics.

### 3.2.2. Seed coating experiments (1997/98 season B and 1998 season A)

There was no treatment by year interaction for all the seed coating data collected during season B 1997/98 and season A 1998. Therefore, all data are presented as a mean of the two growing seasons.

**Stand count.** Dust or adhesive seed coating with imazapyr did not adversely affect the emergence of maize when compared to the control (Table 5). As the rates used in the seed coating experiments were similar to those used in the seed priming experiments, it appears that seed coating is less phytotoxic to the maize seed than priming.

**Striga emergence.** The higher rates of dust and hard coatings of herbicide were significantly better than the lower rates at reducing the emergence of *Striga* through the 8 week count (Fig. 1 and Table 5). While all the herbicide treatments were significantly better than the untreated controls, there were no significant differences among the herbicide treatments by the 12 week count. There was a linear decrease in *Striga* emergence at 8 and 12 weeks after planting with increasing rates of imazapyr for hard coated treatments (Table 6). Similar observations were made at 8 weeks after planting for dust coated treatments.

**Striga flowering and capsule formation.** All the coating treatments had less than one flowering *Striga* plant  $m^{-2}$ , and only a few of those bore capsules at 14 weeks after planting (Table 5). There was a linear decrease in *Striga* flowering and capsules with increasing imazapyr rates, for both hard and dust coatings (Table 6).

**Grain yield.** Seeds coated with 0.6 mg a.e. Mg-imazapyr  $seed^{-1}$  gave significantly higher (ca. 75%) grain yield than the control during the 1998 season A (Tables 5 and 6 season A). There was a quadratic response to herbicide rate for grain yield with the 0.6 mg imazapyr  $seed^{-1}$  treatment producing the highest yield (Table 6). No yield data were collected during season B for reasons described above. Still, the growth responses seen were indicative of the positive effect exerted by the herbicide in both seasons.

There was no preanthesis chlorosis of the whorl in any of the imazapyr seed dressing treatments of the 3245IR maize, although this was prevalent in the untreated controls. This indicates that there was no massive early

Table 5

Effects of seed coating with imazapyr on '3245 IR' maize development and on *Striga* control, combined for the both seasons (1997/98 season B and 1998 season A) Data in ( ) are log transformed as described in materials and methods

Imazapyr rate		Application method	Stand <sup>a</sup> No $ha^{-1}$	Maize production <sup>b</sup>		<i>Striga</i> emergence ( $m^{-2}$ )		<i>Striga</i>	
(a.e. mg $seed^{-1}$ )	Formulation			Grain (kg $ha^{-1}$ )	Total biomass (kg $ha^{-1}$ )	Weeks after planting		Flowering <sup>c</sup> ( $m^{-2}$ )	Capsules <sup>d</sup> ( $m^{-2}$ )
						8	12		
0	Control	Planted dry	43,520	2290	5430	13.9 (1.1)	38.9 (1.6)	1.7 (0.4)	26.3 (1.3)
0.3	Commercial	Drenched in hills	38,890	3630	6370	3.2 (0.6)	22.0 (1.3)	0.7 (0.2)	18.1 (0.8)
0.5	Commercial	Drenched in hills	43,700	4330	7940	1.3 (0.3)	19.2 (1.2)	0.2 (0.1)	9.8 (0.6)
0.3	Commercial	Post spray	41,300	2720	6190	2.1 (0.4)	13.6 (1.1)	0.3 (0.1)	6.9 (0.7)
0.3	Mg-salt	PVP coat	34,330	3160	5000	4.3 (0.6)	28.8 (1.4)	0.7 (0.2)	16.7 (0.9)
0.6	Mg-salt	PVP coat	41,480	3850	7260	1.9 (0.3)	12.0 (1.1)	0.1 (0.0)	2.6 (0.5)
0.8	Mg-salt	PVP coat	40,370	3310	6920	0.4 (0.1)	11.3 (1.0)	0.0 (0.0)	3.7 (0.4)
0.3	Mg-salt	Dust coat	38,150	3490	6050	5.3 (0.7)	20.9 (1.3)	0.4 (0.1)	14.4 (1.1)
0.6	Mg-salt	Dust coat	40,740	4210	7450	2.2 (0.3)	13.4 (1.0)	0.0 (0.0)	0.8 (0.2)
0.8	Mg-salt	Dust coat	39,450	2810	5490	0.8 (0.2)	14.6 (1.1)	0.0 (0.0)	1.2 (0.2)
LSD (0.05)			NS <sup>e</sup>	1120	NS <sup>e</sup>	(0.3)	(0.3)	(0.1)	(0.5)

<sup>a</sup> Measured 6 weeks after planting.

<sup>b</sup> Maize yield only for season A, 1998.

<sup>c</sup> Measured 12 weeks after planting.

<sup>d</sup> Measured 14 weeks after planting.

<sup>e</sup> NS—not significant at 0.05 probability level.

Table 6

Single degree of freedom contrasts for corn and *Striga* variables measured in the seed coating experiments, combined for the both seasons (1997/98 season A and 1998 season B)

Contrasts	Maize production <sup>a</sup> Grain (kg ha <sup>-1</sup> )	<i>Striga</i>			
		Emergence (m <sup>-2</sup> )		Flowering <sup>b</sup> (m <sup>-2</sup> )	Capsules (m <sup>-2</sup> ) <sup>c</sup>
		Weeks after planting			
		8	12		
Herbicide vs. control	d	d	d	d	d
Spray 0.3 mg vs. PVP 0.3 mg	NS <sup>e</sup>	NS <sup>e</sup>	NS	NS	NS
Spray 0.3 mg vs. dust 0.3 mg	NS	NS	NS	NS	NS
Drench vs. dust coat	NS	NS	NS	f	NS
PVP coat vs. dust	NS	NS	NS	NS	NS
PVP coat, linear	NS	d	f	d	NS
PVP coat, quadratic	NS	NS	NS	NS	NS
Dust coat, linear	NS	d	NS	NS	f
Dust coat, quadratic	f	NS	NS	NS	f

<sup>a</sup>Maize yield only for 1998 season A. No significant differences were found in stand number, grain yield per plant and total maize biomass per hectare.

<sup>b</sup>Measured at 12 weeks after planting.

<sup>c</sup>Measured at 14 weeks after planting.

<sup>d</sup>Significant at the 0.01 probability level.

<sup>e</sup>NS—not significant at 0.05 probability level.

<sup>f</sup>Significant at the 0.05 probability level.

viable *Striga* infestation of the dressed maize seed by this critical period, and there were only a few late attachments with parasite emergence, which had little effect on the crop. The lack of a consistent statistically significant yield response to the various treatments that were effective in controlling *Striga* may be related to the fact that the genotype used was poorly adapted to the area where the experiment was conducted. This was further complicated by the inherent variability of *Striga* seeds in the soil, which was only partially alleviated by artificial inoculation. Well-adapted genotypes are being bred to develop effectively and test this technology for economic viability to farmers.

### 3.3. Implementation and management

Generally, maize seed that has had imazapyr dressings bore very few seed capsules per *Striga* plant. These few *Striga* plants could be quickly removed from a field before they set seed. This would require hand pulling less than 1000 *Striga* stalks ha<sup>-1</sup>. This roguing of late flowering plants would be a very effective way to deplete the *Striga* seedbank while preventing *Striga* damage to the crop and limiting reinfestation, as well as delaying the evolution of herbicide resistance.

Seed coating has been less damaging to the maize than priming, yet has been effective in *Striga* control. Thus, seed coating with ALS inhibitors has been the focus of further development of this technology.

The improved yields achieved by suppressing or delaying parasitism provides farmers with more resources and incentives to control the reproduction of

*Striga* later in the season. As farmers will not need to purchase and calibrate sprayers, seed dressing of herbicides should be readily adopted. Many African farmers purchase certified (varietal) maize seeds treated against other pests. The seed dressing treatments for *Striga* control described herein could be inexpensive with new, better-adapted IR maize varieties that are being bred by crossing and backcrossing to local open pollinated varieties using marker-assisted selection to generate tropically adapted material. This will allow us to further confirm the value of seed-dressed herbicide for *Striga* control in farmers fields with low fertility and high infestation levels.

An additional advantage is that this technology will still allow maize to exude germination stimulants into the rhizosphere, thereby inducing germination of *Striga* seeds, further depleting the *Striga* seedbanks. This stimulation and killing of *Striga* coupled with a program of suppressing *Striga* reproduction, while stopping the introduction of new *Striga* seed in crop seed and from off-farm sources can reduce the seedbank such that herbicide-resistant maize could be rotated occasionally with *Striga*-sensitive crops, in an integrated management system.

There has been activity in developing strategies for delaying herbicide resistance in *Striga*. Given the known high frequency of mutations conferring resistance to ALS-inhibiting herbicides, models predict that about five resistant *Striga* plants ha<sup>-1</sup> will emerge in the first year of treatment with herbicide (Gressel et al., 1996b). A strict regime of roguing by hand pulling before seed-

set will be needed to preclude the rapid build-up of resistance. Otherwise, resistant *Striga* will cover fields in 3–5 y according to the model. Such roguing will also assist in depleting the seedbank by preventing replenishment. Transgenic maize with other genes for target-site herbicide resistance should also be useful for controlling *Striga*, and as part of an integrated program to delay the evolution of herbicide resistance in *Striga*.

Already some crosses have been made and preliminary results show that the heterozygotes with the mutation in the 3245IR maize can withstand higher imazapyr doses than the 8326IT heterozygotic material, as expected with this type of resistance. The heterozygotes are less resistant than homozygotic 3245IR, as also reported by Wright and Penner (1998). These and previous findings (Abayo et al., 1996, 1998; Berner et al., 1997) show that even with modest application of herbicide, farmers are able to control *Striga* and allow adequate maize yields while depleting the *Striga* in the soil seedbank. As very few *Striga* plants reach the flowering stage in treated plots, herbicide treatment coupled with other cultural control methods such as hand pulling *Striga* will go a long way in controlling the parasite problem in small-scale farms in Africa.

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