Available online at www.sciencedirect.com
SCIENCE DIRECT®
Crop Protection 22 (2003) 697–706
Crop Protection
www.elsevier.com/locate/cropro

Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls *Striga* spp. and increases yields in several African countries

Fred K. Kanampiu[a], Vernon Kabambe[b], Cornel Massawe[c], Lawrence Jasi[d], Dennis Friesen[a,e], Joel K. Ransom[a,1], Jonathan Gressel[f,*]

[a] *International Maize and Wheat Improvement Center (CIMMYT), Nairobi, Kenya*
[b] *Chitedze Research Station, Lilongwe, Malawi*
[c] *Agricultural Research Institute, Kilosa, Tanzania*
[d] *Mlezu Research Center, Zimbabwe*
[e] *International Fertilizer Development Center (IFDC), USA*
[f] *Department of Plant Sciences, Weizmann Institute of Science, Rehovot 76100, Israel*

Received 2 January 2003; received in revised form 13 January 2003; accepted 14 January 2003

Abstract

Plant parasitic *Striga* (witchweed) species have not been controlled in susceptible host crops prior to exerting damage. High dose, localized herbicide levels can be applied on or near maize seed bearing acetolactate synthase (ALS) target-site resistance. Such seed coating was cost-effective in preventing damage from parasitic witchweeds *Striga hermonthica* and *S. asiatica* in Kenya, Malawi, Tanzania, and Zimbabwe. Imazapyr at 30–45 $g\,ha^{-1}$ and pyrithiobac at 11–21 $g\,ha^{-1}$ were used at 3 experiment stations and in 93 farmers' fields over six seasons to further evaluate the effectiveness of this technology. Seed coating with imazapyr and pyrithiobac gave season-long *Striga* control in most cases resulting in a 3–4-fold increased maize yield when *Striga* density was high. Once herbicide resistant maize has been produced using locally adapted varieties, this technology should greatly benefit small-scale farmers in sub-Sahara Africa.

Keywords: *Striga*; Seed coating; Maize; Imazapyr; Pyrithiobac

1. Introduction

The witchweeds *Striga hermonthica* (Del.) Benth. and *S. asiatica* (L.) Kunze decimate maize (*Zea mays* L.), millets (*Pennisetum spp*), sorghum (*Sorghum bicolor* (L.) Moench]), and upland rice (*Oryza sativa*) throughout sub-Sahara Africa. From the high plateau of East Africa where peasant farmers struggle to survive on tiny fields of maize, to the arid savannas of northern Nigeria where they rely on sorghum, African farmers are fighting a losing battle against the spreading scourge of *Striga*. According to FAO studies, over 100 million Africans lose half their crop production to these flowering, root-attaching parasites (Berner et al., 1995a, b). In addition to draining photosynthates, minerals and water (Press and Graves, 1995), *Striga* does most of its damage to its host, partly through phytotoxins, before the weed emerges from the soil (Gurney et al., 1995). Above ground, the crop withers, and grain production is reduced.

Much of the *Striga*-infested area of Africa has ultra-high levels of *Striga* seed in the soil after years of monocropping with host crops, declining soil fertility, and using *Striga* contaminated crop seed for planting (Berner et al., 1995a, b). The ability of a single *Striga* flower stalk to produce hundreds of thousands of tiny, dust-like seeds means that a minor infestation can lead to devastating levels of damage in only a few seasons. Dormant *Striga* seeds continue to germinate for many years as only a portion of the seeds breaks dormancy

*Corresponding author. Tel.: +972-8-934-3481; fax: +972-8-934-4181.
E-mail address: jonathan.gressel@weizmann.ac.il (J. Gressel).
[1] Present address: Department of Plant Sciences, North Dakota State University, Fargo, ND, USA.

0261-2194/03/$ - see front matter © 2003 Elsevier Science Ltd. All rights reserved.
doi:10.1016/S0261-2194(03)00007-3

when stimulated by the exudates of a receptive crop growing in the vicinity. The *Striga* seed density can be so great that mechanisms conferring partial tolerance, such as crops with greatly reduced *Striga* germination stimulant production are overcome by the overwhelming density of *Striga* seed in the soil.

As a result of lack of control, the *Striga* problem continues to increase. In some areas of Africa, farmers are abandoning their fields in search of *Striga*-free land. As human populations grow and small, hand-plowed farms must support more people, soil nutrients are depleted and soils retain less moisture. *Striga* thrives best in poor soils in areas prone to drought, conditions often associated with poverty and poor nutrition, contributing to the downward spiral of poverty that in bad years in Africa can lead to starvation.

Crop rotation (Berner et al., 1995a, b; Oswald and Ransom, 2001), intercropping (Oswald et al., 2002), and organic (Combari et al., 1990) and inorganic (Mumera and Below, 1993) fertilizers can partially allay the problem. However, no control measure has been developed that subsistence farmers find within their financial means, or that fit well into their cropping systems. Moreover, the above measures require several seasons of repeated use before they begin to produce yield benefits (Ransom, 2000). Thus, despite widespread extension efforts, none of these strategies have been widely adopted. Years of conventional breeding and variety testing for resistance have not produced crop varieties that have proven themselves in heavily infested fields.

African subsistence farmers typically cultivate maize with judiciously used, small inputs of fungicide and insecticide, when they can see their value. For example, they use seed dressings of insecticide and fungicide at planting, and then weeks later, put a few granules of insecticide to control stem borers into the funnel formed by the whorl of maize leaves. It was reasoned that they would similarly use small affordable amounts of a herbicide if it would control the parasitic *Striga* before the weed damages the crop, that is, while it is still underground (Abayo et al., 1998; Kanampiu et al., 2001, 2002a, b). Many subsistence farmers in *Striga*-free areas purchase hybrid maize when the cost-benefit ratio renders hybrids superior to saved seed of open pollinated varieties. These practices (seed treatment, whorl pesticide applications, seed purchase) demonstrate that economically viable technologies would be accepted, if they give control of the parasite prior to crop damage. The yield and profit margins must be much greater in the developing world for the acceptance of new technologies. Considering that on farm yields are exceedingly low, such large profit margins are not hard to obtain with novel technologies, especially with biotechnology-derived crops (Gressel, 2002).

Abayo et al. (1996, 1998), Kanampiu et al. (2001, 2002a, b) and others (Berner et al., 1997) have developed methods of applying herbicide to biotechnologically produced (but in this case, non-transgenic) imidazolinone-resistant (IR) maize seed (Newhouse et al., 1991). Two herbicides, imazapyr (Abayo et al., 1998) and pyrithiobac (Kanampiu et al., 2001) were found to have sufficient residual activity. Imazapyr is used as a general herbicide at a rate of 0.6–1.7 kg ha^{-1} (Ahrens, 1994). The seed application lowers this rate more than 20-fold, and precludes the need for spray equipment. This renders the technology relatively economical to the farmer. Nevertheless, the herbicide concentration is very high in the vicinity of the seed, necessitating the high level of resistance conferred by the mutation in the acetolactate synthase gene present in this material (Bernasconi et al., 1995). We have tested this as a model system for *Striga* control in experiment station studies, using commercial herbicide-resistant maize varieties (that were not adapted to African conditions) in combination with traces of the herbicides imazapyr and pyrithiobac coated on the seed (Kanampiu et al., 2001, 2002a, b). Any *Striga* that attaches to the roots early in the season of such varieties dies before emerging from the soil. Yield could not be adequately measured in the previous studies because the maize succumbed to disease and insect damage, despite the use of fungicide and insecticide.

The herbicides dissipate from the soil before the next planting season, as evidenced by lysimeter studies (Kanampiu et al., 2002b) and the absence of any residual effect in subsequent crops. The herbicide dissipating from the treated maize seeds does not enter the root zone of legume intercrops planted at least 15 cm from the treated maize seed, so traditional intercropping need not be abandoned with this new technology (Kanampiu et al., 2002b). When *Striga* infestations are moderate, maize yield from treated seed is more than doubled; when the *Striga* infestations are severe, the potential yield benefit can be very large indeed because there is near total crop loss without seed treatment. This technique, coupled with other control methods such as normal weeding could go a long way toward containing the *Striga* problem in small-scale farms in most of sub-Sahara Africa.

2. Materials and methods

2.1. Plant material

2.1.1. IR-maize varieties used in the different seasons

A partially to more fully tropical adapted open-pollinated synthetic maize variety, 'CIMMYT Tropical-IR' was used in all experiments in all the countries. This variety, used during the final stages of selection breeding, was advanced from a BC_0F_3 cross of IR donor Pioneer hybrid 3245IR and ZM503 (INT-A/INT-B) initially made in 1996 in Zimbabwe. ZM503 is a full vigor varietal cross, developed by CIMMYT in Zimbabwe with good adaptation for the mid-altitude environments of eastern and southern Africa. The best initial BC_0F_1's were sprayed with herbicide and selfed to obtain S_1 ears. The S_1 seeds were planted ear-to-row, sprayed with herbicide and resistant plants were self-pollinated to obtain S_2s. The S_2 seeds were planted ear-to-row. Imazapyr (75 g ae ha^{-1}) as 25% Arsenal^{TM}, was applied over the top to maize plants at 8–10 leaf stage for selecting homozygous families. The remaining resistant plants were self-pollinated to obtain S_3 ears. Seeds from the best 151 S_3 ears were planted ear-to-row and recombined by half-sib pollinations to form the F_1 generation of 'CIMMYT Tropical-IR' in 1998. The F_2 and subsequent variety maintenance has been by bulking hand-pollinated, full-sib ears.

2.1.2. Other varieties used

Local commercial hybrid H513 (from Kenya Seed Company) was used as a farmers' benchmark variety during the 1998 short rainy season in Kenya. H513 is a medium maturing variety (about 3.5 months) similar to in maturity to the IR maize being used. During 2000/2001 season in Tanzania and 2001/2002 in Malawi, local commercial varieties TMV-1 and SC627 (135 d maturity) were used as local checks, respectively. TMV-1 has similar maturity length to that of the IR variety and is well adapted to the mid-altitude environments of Africa.

During the long rainy season of 2001, a putatively *Striga*-tolerant hybrid (STR) (from the Africa Maize Stress Project) was included in our tests for comparison with other treatments. The STR material is a 3-way hybrid formed with 3 inbred lines including CML442, CML444 and a segregating line, and is streak virus resistant and *Striga* tolerant at low *Striga* infestation levels. The hybrid has pre-release status in Kenya under the name of HB502 (Western Seed Co. Ltd., Kisumu, Kenya).

2.2. Chemicals

The magnesium salt of imazapyr initially used in this study was prepared by reacting solid imazapyr acid (precipitated from a commercial detergent formulation of isopropylamine imazapyr) with a magnesium hydroxide solution, as described by Kanampiu et al. (2001). However, starting with the short rainy season of 2001, technical grade 93% imazapyr acid supplied by BASF was directly used without forming a salt. Kumiai Chemicals, USA, kindly supplied unformulated sodium pyrithiobac.

2.3. Herbicide seed coating

Maize seeds were coated with the herbicide by mixing 100 mg of 20% a.i. lindane and 26% a.i. thiram-containing commercial seed-dressing powder (Murtano^{TM}) to bind the imazapyr or pyrithiobac to the seed with various amounts of an aqueous solution containing either 22 mg ml^{-1} of Na-pyrithiobac or 42 mg ml^{-1} of Mg-imazapyr. Maize seeds (144) were added to this slurry and mixed thoroughly to give coatings of 0.21, 0.40 and 0.60 mg a.i. pyrithiobac and 0.57, 0.85 and 1.13 mg a.i. imazapyr seed^{-1}, respectively (equivalent to 11, 21 and 32 g a.i. pyrithiobac and 30, 45 and 60 g a.i. imazapyr ha^{-1}, at 53,300 maize plants ha^{-1}), and dried. For large-scale field trials, equivalent wetted slurries were thoroughly mixed with Murtano^{TM} dust in a seed-mixer with known weights of maize seeds, further mixed to obtain a uniform herbicide coat at the required rates. Small amounts of water were added to help stick the mixture to the seed. The treated seeds were then dried, packaged, distributed to participating countries and planted in the field.

2.4. Herbicide seed priming and drenching

In experiments conducted on-station in Malawi during the 1998-season, 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 rates of seed priming were 0.28, 0.57 and 0.84 mg a.i. imazapyr seed^{-1} for primed and planted directly (wet). Drenching treatments consisted of applying a 1 ml aqueous herbicide solution (commercial formulation) above just-planted seed. The rates used were similar to those of priming.

2.5. Field trials

Field trials were conducted at experiment stations and in farmers' fields near Kibos Kenya, (where *S. hermonthica* is found) and Mwele Tanzania, Chitedze Malawi, and Henderson Zimbabwe (where *S. asiatica* is found). Supplemental infestations of *Striga* were used on-station (as per Kanampiu et al., 2001), and infested *Striga* "hot spot" sites were chosen (where possible) in farmers' fields based on the farmers' experience during previous seasons. Still, even in hot spots *Striga* infestation and damage levels are not the same every year. Studies were conducted for 6 seasons in western Kenya commencing with the short rainy season (September–January) of 1998 and ending with the long rainy season (March–August) of 2001. In other countries with single mode rainfall distribution, only one crop was planted per year, that is, in 2000 and 2001 (April–September) at Mwele, Tanzania and Zimbabwe (October–March). In Malawi, studies were conducted in 1998 to 2001 (November–May). Different treatments in various countries and seasons were used with imazapyr rates varying between 0 and 60 g ha^{-1} and pyrithiobac between 0 to 32 g ha^{-1}. All treatments were arranged randomly, with each farm being a replicate. On-station trials were replicated 3 or 4 times in randomized blocks. Experimental plots (both on-station and farmers' fields) consisted of 3-m long rows with 75 cm between rows. Maize seeds were planted two seeds per hill within these rows, with hills spaced 50 cm apart. Fertilizer was applied at 50 kg N ha^{-1} and 128 kg P_2O_5 ha^{-1} at planting in the form of di-ammonium phosphate (18-46-0) to ensure reasonable maize development. Plots were kept clean by regular hand weeding of all weeds other than *Striga*. The study was conducted on a total of 93 farms and 3 experiment stations, over six seasons in the four countries.

Data were collected from the inside rows excluding the end plants. *Striga* counts were made every 2 weeks beginning 6 or 7 weeks after planting when *Striga* began to emerge, and ended at 14 weeks. Maize yield at harvest was determined where possible. In some cases the yields could not be obtained due to disease or environmental problems. In some of the cases where the yield enhancement was reported, the data are underestimates, e.g. due to pilferage by neighboring farmers who thought that the *Striga* resistance was genetic, and the progeny would be resistant. The variances for *Striga* counts of the treatments were found to be heterogeneous. Therefore, *Striga* count data were transformed using the formula: $Y = \log(X + 1)$, where X represents the original values. Preplanned single degree of freedom comparisons were performed for each experiment and significance tested at confidence levels of $p < 0.05$ and 0.01.

3. Results and discussion

Two rates of the herbicide imazapyr were chosen for the regional farmers' field study: 30 g ha^{-1} (0.57 mg $seed^{-1}$), which was the optimal rate in experiment station studies in Kenya, and 45 g ha^{-1} as a higher rate to ascertain whether there may be phytotoxicity problems from the herbicide under any one of the more stressful situations developing in farmers' fields.

The maize used in these studies is not yet the final varietal material that will be released to farmers; it was material progressively being backcrossed and selected for resistance to maize streak virus and to turcicum blight. Thus, in each season the disease resistance was slightly better. The ALS gene in all the material is identical and invariate, and the objective of this study was to ascertain the utility of material bearing this gene for *Striga* control, and thus the comparative magnitude of yield enhancement due to the presence of the ALS gene and the herbicide seed coating.

We describe below the extensive farmers' field experiments in four countries of the region having intense problems with two *Striga* spp, as well as the experiment station results in the countries outside of Kenya. Some experiment station results in Kenya were previously reported (Kanampiu et al., 2001; Kanampiu et al., 2002b), and were the basis for this large-scale regional test.

3.1. Kenya

3.1.1. Short rainy season 1998

Hybrid H513, a commercial hybrid used as farmers' check elicited higher *Striga* emergence than the herbicide-resistant maize both treated and untreated (Table 1A). H513 was better adapted to local diseases than the herbicide-resistant maize at that time, and thus was more vigorous and hence stimulated more *Striga hermonthica* to germinate than the untreated herbicide resistant variety. *Striga* emergence was much lower on herbicide-resistant treated maize (30/45 g imazapyr ha^{-1}) than on the untreated check (Table 1A). Any *Striga* that emerges after 10 weeks does not produce seed by harvest with these short season varieties.

3.1.2. Short rainy season 1999

During this season, the low nitrogen rate application of 20 kg ha^{-1} gave lower maize grain yields compared to the higher rate of 60 kg (Table 1B). Herbicide application only reduced early *Striga* emergence. This demonstrates the potential benefits from using both fertilizer and herbicide where farms contain *Striga*.

3.1.3. Long and short rainy seasons 2000

During these seasons, plots with herbicide-treated maize seed had much lower *Striga* emergence and higher grain yield than the untreated controls (Table 2A and B). The higher imazapyr rate did not provide better *Striga* control nor increase grain yield over the lower rate, nor were there signs of phytotoxicity. Both rates provided season-long control preventing *Striga* seed capsule formation up to harvest (not shown). Maize seed coating resulted in increased grain yield by about 4-fold in the short rainy season, but could not be measured in the long rainy season due to pilferage.

3.1.4. Long and short rain seasons 2001

In the long rainy season 8 farms had rainfall below 400 mm and 15 others above 600 mm and thus the farms were grouped separately. *Striga hermonthica* emerged similarly at 8 weeks on the putative STR variety and on untreated control IR maize in both rainfall regimes (Table 2C). However, there was more *Striga* emergence on the putative STR than on the untreated controls at 12 weeks. As the putative STR variety seemed not to have any additional tolerance to *Striga* than the

Table 1
Suppression of *Striga hermonthica* emergence by herbicides and enhanced maize yields using herbicide-coated, partially adapted IR-maize seeds in farmers' fields in Kenya

Herbicide (g ha^{-1})	*Striga* emergence (m^{-2}) Weeks after planting			Grain (kg ha^{-1})
	8	10	12	16 weeks
A. Short rainy season 1998—average of 4 farms				
H513	15.6		19.5	1118
Untreated-IR	6.6		9.8	1273
+Imazapyr				
30	3.7		5.9	1470
45	3.5		5.1	1640
Contrasts				
H513 vs. untreated IR-	ns		ns	ns
H513 vs. IR30/50 g	*		*	ns
IR-control vs. IR-30/45 g	**		**	ns
IR-30 vs. IR-45 g	ns		ns	ns
B. Long rainy season 1999-average of 10 farms				
20 Kg N				
Untreated	33.9	72.1		3857
Imazapyr-30	19.6	59.3		5000
60 kg N				
Untreated	21.8	56.5		7119
Imazapyr-30	14.4	54.4		7619
Contrasts				
20 vs. 60 kg N	ns	ns		*
IR 0 vs. IR 30 at 20 kg N	ns	ns		ns
IR 0 vs. IR 30 at 60 kg N	ns	ns		ns
0 vs. 30 g imazapyr	ns	ns		ns

Contrasts calculated on transformed data. In some cases data were not collected due to inaccessibility of fields or to heavy disease on the crop.

conventional IR lines, the putative STR was dropped from further study. *Striga* emergence was severely suppressed by both herbicides compared to the untreated control at 8 and 12 weeks after planting in both rainfall regimes. Imazapyr and pyrithiobac rates above 30 and 11 g a.i. ha^{-1} gave almost total *Striga* control before 12 weeks after planting (Table 2C) and no late emerging *Striga* plants produced seed. Imazapyr appeared to be more effective than pyrithiobac in *Striga* control, probably due to the vastly different rates used. However, as in previous seasons, seed coating with both herbicides gave effective season-long *Striga* control and increased grain yields compared to the control both on-farm and on-station during short rainy season of 2001 (Table 2D).

3.2. Tanzania

At Mwele, Tanzania, 516 mm of rainfall was received during the growing season with most (60%) falling during the first 2 months (April and May) and 79 mm (15%) falling within 3 days after planting. There was a probability that much of the herbicide was washed beneath the maize root zone by this high rainfall in April and May.

The local variety (TMV-1) elicited sparse *Striga asiatica* emergence on-station and considerably more in the farmers' fields. Almost no *Striga asiatica* appeared on the herbicide-resistant treated maize (Table 3A and B). The tested IR-maize germplasm does not have the same yield potential of the local longer season variety, but demonstrates the potential of this technology to control *S. asiatic*a. No control of IR-maize without herbicide was included in this experiment, which would have allowed comparing the levels of *Striga* infestation with other treatments.

3.3. Zimbabwe 2000/2001

Both herbicides effectively delayed *Striga asiatica* emergence at all rates, and at the higher rates provided season-long control, promoting greater grain yields than the untreated control (Table 4).

3.4. Malawi

3.4.1. 1998

A substantial reduction in the number of emerged *Striga* plants was observed in the treated plots through 12 weeks after planting (Table 5A and B), with the few

Table 2
Suppression of *Striga hermonthica* emergence by herbicides and enhanced maize yields using herbicide-coated, partially adapted IR-maize seeds in farmers' fields in Kenya

Herbicide (g ha^{-1})	Striga emergence (m^{-2}) Weeks after planting		Grain yield (kg ha^{-1})
	8	12	16
A. Long rainy season* 2000*—average of* 18 *farms			
Imazapyr			
Untreated	1.0	14.8	
30	0.1	7.6	
45	0.1	5.2	
Contrasts			
Untreated vs. treated	**	**	
IR-30 vs. IR-45	ns	ns	
B. Short rainy season* 2000*—average of* 7 *farms			
Imazapyr			
Untreated	19.4	28.7	551
30	1.3	6.5	2498
45	2.8	6.0	2721
Contrasts			
Untreated vs. treated	**	**	**
IR-30 vs. IR-45	ns	ns	ns
C. Long rainy season* 2001*-average of* 23 *farms			
Low rainfall (*8 farms*)			
STR	0.4	32.7	
Untreated	1.3	23.1	
Imazapyr			
30	0.2	8.3	
Pyrithiobac			
21	0.1	12.1	
Contrasts			
STR vs. IR	ns	ns	
IR-0 vs. IR-herbicide	ns	**	
IR-imazapyr vs. IR-pyrithiobac	ns	**	
High rainfall (*15 farms*)			
STR	2.4	65.2	
Untreated			
Imazapyr	3.1	25.3	
45	0.3	4.5	
Pyrithiobac			
21	0.6	18.2	
Contrasts			
STR vs. IR	**	**	
IR-0 vs. IR-herbicide	**	**	
IR-imazapyr vs. IR-pyrithiobac	**	**	
D. Short rainy season* 2001*—average of* 14 *farms			
Untreated			
Imazapyr	2.7	11.2	1888
30	0.0	0.5	2651
45	0.0	0.3	2675
Pyrithiobac			
21	0.1	2.1	2118
Contrasts			
IR-0 vs. IR-herbicide	**	**	*
Imazapyr vs. pyrithiobac	ns	*	ns
Imazapyr-30 vs. imazapyr-45	ns	ns	ns

Contrasts calculated on transformed data. In some cases data were not collected due to inaccessibility of fields or to heavy disease on the crop. STR—putative *Striga* tolerant hybrid.

Table 3
Suppression of *Striga asiatica* emergence by herbicides using herbicide-coated, partially adapted IR-maize seeds on-station and in farmers' fields in Mwele, Tanzania 2000/2001

Herbicide	Rate (g ha^{-1})	*Striga* emergence (m^{-2}) Weeks after planting		Grain yield (kg ha^{-1})
		11	15	16 weeks
A: On-one station with 3 replications				
Local check (TMV-1)	0	0.31	0.55	1580
Imazapyr	30	0.0	0.0	1250
Imazapyr	45	0.0	0.0	1100
Imazapyr	60	0.04	0.1	1220
Pyrithiobac	11	0.2	0.2	2000
Pyrithiobac	21	0.0	0.0	1210
Pyrithiobac	32	0.0	0.0	1210
Contrast				
Local check vs. IR		*	**	ns
Imazapyr vs. pyrithiobac		ns	ns	ns
Herbicide rate linear		ns	ns	*
Herbicide rate quadratic		ns	ns	ns
B: Farmers field—average of 2 farms				
Local check (TMV-1)	0	10.0	5.07	1580
Imazapyr	30	2.1	4.83	1270
Imazapyr	45	0.4	0.0	1910
Imazapyr	60	0.0	0.0	1590
Pyrithiobac	11	0.73	0.67	2030
Pyrithiobac	21	0.04	0.0	2190
Pyrithiobac	32	0.0	0.0	2220
Contrast				
Local check vs. IR		**	**	ns
Imazapyr vs. pyrithiobac		ns	ns	ns
Herbicide rate linear		*	*	ns
Herbicide rate quadratic		ns	ns	ns

Contrasts calculated on transformed data.

Table 4
Suppression of *Striga asiatica* emergence by herbicides and enhanced maize yields using herbicide-coated, partially adapted IR-maize seeds in farmers' fields in Zimbabwe, 2000/01

Herbicide	Rate (g ha^{-1})	*Striga* emergence (m^{-2}) Weeks after planting		Grain yield (kg ha^{-1})
		10	14	16 weeks
Untreated (IR-maize)	0	5.4	13.5	1650
Imazapyr	30	0.0	1.0	2153
Imazapyr	45	0.0	0.0	3240
Imazapyr	60	0.0	0.0	3100
Pyrithiobac	11	1.3	2.5	1770
Pyrithiobac	21	0.0	0.6	2292
Pyrithiobac	32	0.8	1.9	3491
Contrast				
IR-0 vs. IR-herbicide		ns	**	**
Imazapyr vs. pyrithiobac		ns	ns	ns
Herbicide linear		ns	ns	ns
Herbicide quadratic		ns	ns	ns

Average of 4 farms Contrasts calculated on transformed data.

Table 5
Suppression of *Striga asiatica* emergence by herbicides using herbicide-coated, partially adapted IR-maize seeds on-station and in farmers' fields in Chitedze, Malawi

Herbicide	Rate (g ha^{-1})	*Striga* emergence (m^{-2}) Weeks after planting		*Striga* flowering (m^{-2})	Grain yield kg ha^{-1}
		10	12	15 weeks	16 weeks
A: 1998 On-station (3 replicates)					
Untreated	0	4.8	14.7	6.2	4305
Imazapyr-Drench	15	0.1	4.9	0.1	4464
Imazapyr-D	30	0.9	1.0	0.1	4175
Imazapyr-D	45	0.0	0.7	0.0	4633
Imazapyr-Prime	15	0.7	6.6	0.7	4644
Imazapyr-P	30	0.1	1.8	0.2	5220
Imazapyr -P	45	0.2	1.3	0.3	3420
Imazapyr-Coat	15	0.0	1.3	0.3	4521
Imazapyr-C	30	0.1	2.0	0.3	4617
Imazapyr-C	45	0.1	1.4	0.4	5898
Contrast					
IR-0 vs. IR-herbicide		**	**	**	ns
Drenching vs. priming		ns	ns	ns	ns
Drenching vs coating		ns	ns	ns	ns
Priming vs. coating		ns	ns	ns	ns
Herbicide linear		ns	*	ns	ns
Herbicide quadratic		ns	ns	ns	ns
B: 1998 Farmers field—average of 2 farms					
		9	*13*		
Untreated	0	0.93	37.4	7.90	1471
Imazapyr	30	0.0	4.9	0.25	2345
Contrast					
IR-0 vs. IR-herbicide		ns	**	**	*
C. 1999 Farmers field—average of 6 farms					
			12		
No nitrogen					
Untreated	0		7.7		1026
Imazapyr	45		0.98		1245
60 kg N					
Untreated	0		10.5		2696
Imazapyr	45		1.01		2547
Contrast					
No N vs. N-60			**		**
IR-0 vs. IR-45			ns		ns

Contrasts calculated on transformed data.

late emerging *Striga* plants not flowering. The infestation was much higher in the farmers' fields near Mponela, Malawi in 1998 (Table 5B) resulting in more *Striga* damage and lower grain yield. There was some phytotoxicity at 45 g ha^{-1} primed, which reduced the stand count (not shown) and hence the low yields. The maize variety used was not well adapted to southern African region and was susceptible to turcicum leaf blight. The demonstration plots in farmers' fields successfully illustrated the benefit that could be obtained in Malawi for control of *S. asiatica*. Few *S. asiatica* plants flowered in the treated plots compared to untreated control but did not set seed. There is an obvious need to combine the seed treatment protocol with an integrated program of suppressing *Striga* reproduction to reduce the seed bank in the soil.

3.4.2. 1999

The herbicide reduced *Striga* emergence but had no effect on grain yield (Table 5C) in this season when *Striga* infestation happened to be sparse. Nitrogen application increased maize grain yields but had no effect on *Striga* emergence. An imazapyr rate of 45 g a.i. ha^{-1} gave almost total *Striga* control up to 12 weeks after planting. *Striga* emergence was very delayed during

Table 6
Suppression of *Striga asiatica* emergence by herbicides using herbicide-coated, partially adapted IR-maize seeds on-station and in farmers' fields in Chitedze, Malawi

Herbicide	On-station 2001—3 replications					Farmers field—average of 3 farms, 3 replications each		
	Rate ($g\,ha^{-1}$)	*Striga* emergence (m^{-2}) Weeks after planting			Grain ($kg\,ha^{-1}$)	*Striga* emergence (m^{-2}) Weeks after planting		Grain ($kg\,ha^{-1}$)
		9	11	flowers (m^{-2})[a]	16 weeks	9	11	16 weeks
Local check (SC627)	0	0.46	3.49	95.2	5777	5.05	10.9	4061
Untreated	0	0.21	0.53	17.6	2621	0.30	1.2	1924
Imazapyr	15	0.04	1.13	21.5	4011	0.0	0.7	2547
Imazapyr	30	0.0	0.71	12.2	3226	0.0	0.1	1372
Imazapyr	45	0.0	0.81	24.1	4408	0.0	0.8	1641
Imazapyr	60	0.0	0.07	2.8	2477	0.0	0.8	607
Imazapyr	75	0.0	0.07	0.7	1994	0.1	1.0	1349
Contrast								
Local check vs. IR-maize		**	**	**	**	***	***	***
IR-0 vs. IR-herbicide		*	ns	*	ns	ns	**	ns
Herbicide linear		ns	*	**	ns	ns	ns	*
Herbicide quadratic		ns	ns	**	*	ns	ns	**

Contrasts calculated on transformed data.
[a] Measured 15 weeks after planting.

this season, and *Striga* did not measurably affect maize yield.

3.4.3. 2001

The herbicide treatment had no effect on the late emerging *Striga* at 9 and 11 weeks after planting and grain yield both at on-station and farmers fields (Table 6). Due to better adaptation, the local check SC627 had higher *Striga* emergence, capsules and grain yield than the herbicide-resistant maize both treated and untreated (Table 6). Grain yield responded to herbicide rate in a quadratic and linear manner on-station and on-farmers' fields, respectively.

4. Discussion

The results presented indicate that imazapyr and pyrithiobac can offer season-long *Striga* control. When the IR gene is incorporated into locally adapted varieties as in Kenya, this can result in improvements in maize growth and hence high maize yield benefits to small-scale farmers. This is in sharp contrast to the devastating effect of uncontrolled infections on maize as exhibited by the untreated controls when there are heavy, early emerging infestations. There were very few *S. hermonthica* plants in the treated plots with hardly any reaching flowering in any of the countries. This considerably reduces any *Striga* seed bank build-up except in Malawi, where the growing season is long. There is an obvious need to combine the seed treatment protocol with an integrated programme of suppressing *Striga* reproduction to reduce the seed bank in the soil when the season is that long.

Much of the variability among experiments can be attributed to two factors: (1) the time of *Striga* germination; and (2) the distribution of rainfall. Early germinating *Striga* has the greatest inhibitory effect on maize. In seasons where overall germination is late, there is far less effect on yield. This observation led to experimental transplanting of maize and sorghum (Oswald et al., 2001) where the transplants were started in *Striga*-free soil. The extra few weeks without *Striga* vastly improved yields. Though it is not yet impossible to predict when *Striga* will germinate within a field or geographic area, in seasons and fields where it is consistently problematic, it does emerge early.

The two herbicides found to have the greatest protective effect (Kanampiu et al., 2001; Abayo et al., 1998) are both highly water soluble and mobile in the soil (Kanampiu et al., 2002b). Heavy early rains can wash the herbicides out of the rhizosphere of the crop, slightly decreasing their effectiveness as seen in some seasons. Conversely, exceedingly low rainfall could result in too high local concentrations, resulting in phytotoxicity. Thus, there is a clear variation in the optimal rate from season to season and site to site. There is a good possibility that controlled release formulations might allow the use of lower doses and/or extend the herbicide effect or reduce phytotoxicity. Such formulations are presently being tested.

Farmers who no longer lose their maize to *Striga* will certainly see the benefit of buying coated seed each season, and can easily achieve $3.0\,t\,ha^{-1}$ with well adapted IR varieties. Maize imports can be reduced, and the cost of distribution cut down. The herbicide seed treatment is also compatible with legume intercrops as long as the legume is not planted within a few centimeters of the treated seed (Kanampiu et al., 2002b). These results of a very low cost and environmentally friendly herbicide intervention are very exciting and indicate that one more tool for the control of *Striga* is nearing readiness for application. This technology coupled with pulling rare *Striga* escapes or evolved resistant individuals can deplete the *Striga* seedbank, reducing infestation of susceptible rotation crops, delay the evolution of resistant populations (Gressel et al., 1996) and be used as a stopgap until sufficiently strong genetic crop resistance becomes available, if such can be found within the species, or genetically engineered from other species. This study verifies that the herbicide seed coating technology is successful in multi-site on-station studies and especially in farmers' fields in different conditions and environments where there are infestations of either *Striga hermonthica* or *S. asiatica*.

Acknowledgements

The excellent technical assistance of Peter Mbogo in Kenya; Charles Komba, in Tanzania; and others in Malawi and Zimbabwe is gratefully acknowledged. Drs. David Jewell, Kevin Pixley and Stephen Mugo developed the synthetic IR maize variety used in this study; while Dr. Alpha Diallo developed the STR. Dr. Peter Porpiglia of Kumiai Chemicals, USA, kindly supplied pyrithiobac and Mr. Charles Okuthe of BASF the imazapyr acid. This research is supported in part by the Kenya Agricultural Research Institute, Canadian International Development Agency and the Rockefeller Foundation *Striga* Program. J. Gressel is the Gilbert de Botton Professor of Plant Sciences.

References

Abayo, G.O., Ransom, J.K., Gressel, J., Odhiambo, G.D., 1996. *Striga hermonthica* control with acetolactate synthase inhibiting herbicides seed-dressed to corn with target site resistance. In: Moreno, M.T, Cubero, J.I., Berner, D., Joel, D.M., Musselman, L.J., Parker, C. (Eds.), Advances in Parasitic Weed Research. Junta de Andalucia, Cordoba, Spain, pp. 762–768.

Abayo, G.O., English, T., Eplee, R.E., Kanampiu, F.K., Ransom, J.K., Gressel, J., 1998. Control of parasitic witchweeds (*Striga* spp) on corn (*Zea mays* L) resistant to acetolactate synthase inhibitors. Weed Sci. 46, 459–466.

Ahrens, W.H. (Ed.), 1994. Herbicide Handbook, 7th Edition. Weed Science Society of America, Champagn IL, pp. 161–163.

Bernasconi, P., Woodworth, A.R., Rosen, B.A., Subramanian, M.V., Siehl, D.L., 1995. A naturally occurring point mutation confers broad range tolerance to herbicides that target acetolactate synthase. J. Biol. Chem. 270, 17381–17385.

Berner, D.K., Kling, B.B., Singh, B.B., 1995a. *Striga* research and control: a perspective from Africa. Plant Dis. 79, 652–660.

Berner, D.K., Cardwell, K.F., Faturoti, B.O., Ikie, F.O., Williams, O.A., 1995b. Relative roles of wind, crop seeds, and cattle in the dispersal of *Striga* species. Plant Dis. 78, 402–406.

Berner, D.K., Ikie, B.B., Green, B.B., 1997. ALS-inhibiting herbicide seed treatments control *Striga hermonthica* in ALS-modified corn (*Zea mays* L.). Weed Technol. 11, 704–707.

Combari, A., Pineau, R., Schiavon, M., 1990. Influence du degree de decomposition de produits organic sur la germination de graines de *Striga hermonthica* (Del.) Benth. Weed Res. 30, 29–34.

Gressel, J., 2002. Molecular Biology of Weed Control. Taylor & Francis, London, 520pp.

Gressel, J., Segel, L.E., Ransom, J.K., 1996. Managing the delay of evolution of herbicide resistance in parasitic weed. Int. J. Pest Manage. 42, 113–129.

Gurney, A.L., Press, M.C., Ransom, J.K., 1995. The parasitic angiosperm *Striga hermonthica* can reduce photosynthesis of its sorghum and corn hosts in the field. J. Exp. Bot. 46, 1817–1823.

Kanampiu, F.K., Ransom, J.K., Gressel, J., 2001. Imazapyr seed dressing for *Striga* control on acetolactate synthase target-site resistant maize. Crop Prot. 20, 885–895.

Kanampiu, F.K., Ransom, J.K., Gressel, J., Jewell, D., Friesen, D., Grimanelli, D., Hoisington, D., 2002a. Appropriateness of biotechnology to African agriculture: *Striga* and maize as paradigms. Plant Cell Tissue Organ Culture. 69, 105–110.

Kanampiu, F.K., Ransom, J.K., Gressel, J., 2002b. Imazapyr and pyrithiobac movement in soil and from maize seed coats controls *Striga* in legume intercropping. Crop Prot. 21, 611–619.

Mumera, L.M., Below, F.E., 1993. Role of nitrogen in resistance to *Striga* parasitism in maize. Crop Sci. 33, 758–763.

Newhouse, K.E., Wang, T., Anderson, P.C., 1991. Imidazolinone resistant crops. In: Shaner, D.L., O'Connor, S.L. (Eds.), The Imdazolinone Herbicides. CRC Press, Boca Raton, FL, pp. 139–150.

Oswald, A., Ransom, J.K., 2001. *Striga* control and improved farm productivity using rotation. Crop Prot. 20, 113–120.

Oswald, A., Ransom, J.K., Kroschel, J., Sauerborn, J., 2001. Transplanting maize (*Zea mays*) and sorghum (*Sorghum bicolor*) reduces *Striga hermonthica* damage. Weed Sci. 49, 346–353.

Oswald, A., Ransom, J.K., Kroschel, J., Sauerborn, J., 2002. Intercropping controls *Striga* in maize based farming systems. Crop Prot. 21, 367–374.

Press, M.C., Graves, J.D. (Eds.), 1995. Parasitic Plants. Chapman & Hall, London, 292pp.

Ransom, J.K., 2000. Long term approaches for the control of *Striga* in cereals: field management. Crop Prot 19, 759–763.