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Crop Protection 21 (2002) 611–619

Crop Protection

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Imazapyr and pyrithiobac movement in soil and from maize seed coats to control *Striga* in legume intercropping

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Received 11 July 2001; received in revised form 2 December 2001; accepted 11 December 2001

Abstract

Imazapyr and pyrithiobac dressed to seeds of imidazolinone-resistant maize effectively control *Striga hermonthica* (witchweed). The effects of the movement of these herbicides in the soil and in maize plants was measured on *Striga* germination and on legumes intercropped with maize. *Striga* seeds were killed when high rates of either herbicide percolated through simulated soil columns; almost no viable *Striga* seeds remained in the upper 10 cm, and >80% were killed at 30 cm. The herbicides applied to maize leaf whorls moved systemically out of roots, killing attached and germinating *Striga*. Sensitive crops (beans, cowpea, and yellow gram) were unaffected when planted at >15 cm from maize coated with 0.4 mg a.i. pyrithiobac or 0.84 mg a.i. imazapyr seed^{-1}, but were severely inhibited when planted within 12 cm. Simple herbicide seed coatings are thus compatible with commonly used African intercropping systems, while facilitating maize growth and depleting the *Striga* seed bank. © 2002 Published by Elsevier Science Ltd.

Keywords: Herbicide movement; Intercropping distances; Beans; Cowpeas; Yellow gram; Witchweed

1. Introduction

Damage caused by *Striga* spp. (witchweeds) in sub-Saharan Africa is devastating to resource-poor farmers whose lives can be threatened by complete crop loss to this root-parasitic weed. *Striga* spp. damage often first appears before crop anthesis as chlorotic and twisted 'bewitched' whorls, before the emergence of the *Striga* flower stalk from the soil. *Striga* exerts a potent phytotoxic effect on its host (Ransom et al., 1996) by inducing enzyme and plant hormone changes, disrupting host–water relations, and reducing carbon fixation below that expected purely by competition for water, nutrients, and light (Gurney et al., 1995; Stewart and Press, 1990).

New technologies to deal with the exceedingly high levels of *Striga* in African soils must meet four criteria to be widely adopted by farmers (Ransom, 2000): (1) have the ability to control *Striga* early in its growing cycle in order to reduce yield loss; (2) deplete the *Striga* seed bank in the soil; (3) be cost effective; and (4) be compatible with existing cropping systems and technologies.

Many African farmers traditionally intercrop maize (*Zea mays* L.) or sorghum (*Sorghum bicolor* (L.) Moench) with legumes to increase crop production and reduce the risk of total crop failure. They thus achieve better returns on fertilizer, pesticide, energy and manpower resources (Willey, 1979). Intercrops that quickly cover the inter-row area of maize can reduce *Striga* emergence and impede its growth and flowering on maize (Carsky et al., 1994). Nitrogen fixation by legumes can overcome the low soil nitrogen generally associated with the build up of *Striga* (Pieterse and Verkleij, 1991). Additionally, legumes such as cowpea can act as trap crops; they stimulate *Striga* germination but the parasite cannot attach and eventually dies (Langston and English, 1990).

Point applications of acetolactate synthase (ALS)-inhibiting herbicides as dressings to seeds possessing target-site resistance have been found to effectively

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PII: S0261-2194(01)00151-X

control *Striga* early in the season (Abayo et al., 1996, 1998; Berner et al., 1997; Kanampiu et al., 2001). Imazapyr and pyrithiobac were safe to ALS-resistant maize as seed drenches, primings, and coatings in providing effective *Striga* control (Abayo et al., 1998; Kanampiu et al., 2001). The efficacy of *Striga* control is enhanced by its long soil persistence. Normal field applications of these herbicides at the commonly used rates can lead to carryover problems to crops grown in rotation with maize (Vizantinopoulos and Lolos, 1994) and they have the potential to contaminate ground water. The rates used as seed dressings are more than an order of magnitude lower (Abayo et al., 1998; Kanampiu et al., 2001), which should preclude carryover.

There is no information on the effect that point applications of these herbicides might have on susceptible intercrops. The behavior of ionic herbicides such as imazapyr and pyrithiobac in soil is strongly affected by soil pH, organic matter, and the surface charge of soil colloids (Pusino et al., 1997; El Azzouzi et al., 1998). Imazapyr is relatively mobile and yet is slowly degraded in the soil (Vizantinopoulos and Lolos, 1994; McDowell et al., 1997; El Azzouzi et al., 1998). Imazapyr exhibits different adsorption behaviors depending on pH (Pusino et al., 1997). Organic matter retains imazapyr at pH <5. Imazapyr can exist in cationic, neutral and anionic forms with pK_a values of 3.6 and 1.9, respectively (Pusino et al., 1997). Only the anionic form of imazapyr would be available in typical tropical soils where the pH values range between 5 and 7, precluding binding to the negatively charged soil colloids, facilitating imazapyr movement in the soil. There is no published information on pyrithiobac movement in soils. The pK_a value of 2.34 of pyrithiobac (USDA-ARS, 2001) is similar to that of imazapyr, suggesting that both would have similar mobility in most tropical soils.

Two contrasting characteristics are required for the use of a herbicide as a seed treatment: (a) rapid movement into the zone where weeds are to be controlled; and (b) sufficient adsorption and persistence to retain herbicide activity (Dawson, 1987). Imazapyr is absorbed by plant roots or leaves, moves systemically within the plant, and is also excreted by roots (Little and Shaner, 1991). These attributes are all important for the control of parasitic weeds. Attached parasitic weeds and those approaching the crop through the rhizosphere would be controlled by the moving herbicide. The movement of herbicide away from treated maize seed in soil water, and its systemic movement within the plant and excretion by roots, should theoretically result in herbicide distribution throughout the maize rhizosphere. Thus, herbicide movement could possibly kill *Striga* seed that it contacts as it moves, and could negatively affect intercropped plants should it come in contact with them.

The objective of this study was to determine whether point application of herbicide to herbicide-resistant maize was compatible with contemporary indigenous intercropping systems. This requires an understanding of the movement of imazapyr and pyrithiobac in the plant and the soil as well as their effects on *Striga* seeds as well as their phytotoxicity to intercropped legumes.

2. Materials and methods

2.1. Plant material

A tropically adapted, open pollinated synthetic maize variety, ‘CIMMYT Tropical-IR’, was used in all experiments. It was selected for this project because it has good adaptation (high yield, adequate resistance to prevalent diseases, etc.) for eastern and southern Africa. The variety is an advanced BC_0F_3 cross of IR donor Pioneer hybrid 3245IR and ZM503 (INTA/INTB) initially made in 1996 in Harare, Zimbabwe. ZM503 is a full vigor variety cross that was developed by CIMMYT in Zimbabwe with good adaptation for Eastern and Southern Africa. The best 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 were planted ear-to-row, sprayed with herbicide and resistant plants were self-pollinated to obtain S_3 ears. 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. Imazapyr (75 g ae ha^{-1}) as Arsenal 25%, was applied over the top to maize plants at 8–10 leaf stage for selecting homozygous families.

Beans (*Phaseolus vulgaris* L.), cowpea (*Vigna unguiculata* (L.) Walp.) and yellow gram (*Vigna radiata* L.) were used as the herbicide-sensitive intercrops. The *Striga hermonthica* seeds used were collected in the previous seasons from local farms near the experimental site, and were mixed to provide uniformity.

2.2. Chemicals

The magnesium salt of imazapyr 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). Kumiai Chemicals, USA, kindly supplied unformulated sodium (Na)-pyrithiobac.

2.3. Herbicide seed coating

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) with 2.88 ml of an aqueous solution containing either 22 mg ml^{-1} of aqueous Na-pyrithiobac or 42 mg ml^{-1} of Mg-imazapyr. Control seeds were treated with the insecticide/fungicide powder. Maize seeds (144) were added to this slurry and mixed thoroughly to give calculated coatings of 0.44 mg a.i. pyrithiobac and 0.84 mg a.i. imazapyr seed^{-1}, respectively (i.e. 21 and 45 g a.i. ha^{-1}, at 53,300 maize plants ha^{-1}), and dried. The treated seeds were then planted in the field.

2.4. Herbicide movement in soil

The effects of Mg-imazapyr and Na-pyrithiobac on *Striga* seed viability as they move through a soil column were determined as follows: field soil from the upper 15 cm was collected from the Kenya Agricultural Research Institute (KARI)—Kibos Center and passed through 2 mm mesh sieve. The soil used contained a layer of sediments from eroded adjacent hill areas and is classified as a vetro-eutic planosol (FAO/UNESCO, 1974). Other properties are pH (H_2O) 6.9, 0.71% organic matter, 0.31 g Mg^{+2} kg^{-1} soil, 0.45 g K^{+1} kg^{-1} soil, 4.25 g Ca^{+2} kg^{-1} soil, 13.9 g Na^{+1} kg^{-1} soil, 0.16% total nitrogen and 0.11% phosphorus. Underlying it were layers of a black cotton soil, imperfectly drained, very deep, very dark gray to black, subject to cracking when dried, gravelly clay to clay, with a calcareous deeper gravelly subsoil in places.

Striga seeds (8.2 mg) were thoroughly mixed in 1.5 kg soil to give a uniform soil/*Striga* seed mixture. Seed material contained about 25% extraneous material, and only 70% germinated. This resulted in about 480 viable *Striga* seeds kg^{-1} soil (1000 *Striga* seeds weigh about 6 mg). The soil/*Striga* mixture was placed in 30 cm tall and 7.3 cm diameter (1.3 L) polyethylene tubes. This mixture was added in 100 g increments and packed to a bulk density of 1.2 g ml^{-1} (every 5 cm of column contained 250 g mixture). A filter paper disc was placed on the soil surface in each column to prevent soil disturbance when adding solutions.

Water (500 ml) was added to each column in 100 ml increments at daily intervals (to allow equilibration) until some water began to trickle from the bottom of the columns. The columns were lightly sealed at the top with polyethylene paper between additions and during the 12 day *Striga* pre-conditioning (as per Berner et al., 1995) to prevent water loss by evaporation. This renders *Striga* seeds susceptible to the germination stimulants excreted by maize roots. Eighty mg of Mg-imazapyr or Na-pyrithiobac dissolved in 10 ml water or 10 ml of water alone as a control treatment were applied evenly on the soil surface. After 3 days, water (500 ml, equivalent to about 120 mm rainfall sufficient to move the herbicide band completely through the column) was added to the columns in 10 ml increments at intervals of 15 min.

All soil columns were then sectioned in 5 cm long segments, giving 250 g soil/*Striga* mixture per section. The *Striga* seeds were recovered from the soil/*Striga* mixture by elutrification (Eplee and Norris, 1990). Recovered seeds were placed on 9 cm diameter glass filter papers in petri-dishes and germination was stimulated by adding 0.5 ml of 1 μM GR24 (3[2,5-dihydro-3-methyl-2-oxo-5-furanyl]oxymethylene-3,3a,4,8b-tetrahydroindeno-{1,2-b}furan-2-one). The number of germinated *Striga* seeds in each sample was counted 72 h after stimulation. The experiment was repeated 3 times, each time with 2 replicates.

2.5. Herbicide movement out of the crop

2.5.1. Polyethylene bag method

Experiments were conducted to determine whether imazapyr and pyrithiobac kill *Striga* before or after attachment to maize roots. Glass fiber sheets (11×23 cm) were mounted in 31×48 cm polyethylene bags, wetted with water and about 100 cleaned *Striga* seeds were sprinkled over the surface of one side, basically as outlined in Parker and Dixon (1983). One IR maize seed that had not been treated with herbicides was placed on each glass fiber sheet. Two weeks after maize germination, the numbers of germinated and attached *Striga* were counted, then 0.5 ml of a solution containing 0, 0.2, 0.4 and 0.6 mg imazapyr ml^{-1} or 0, 0.2, 0.4, 0.6 and 0.8 mg pyrithiobac ml^{-1} was applied down the whorl of each plant. The numbers of healthy and dead *Striga* that germinated and attached were counted again 5 days after imazapyr and pyrithiobac application. The experiment had three replications.

A $\log_{10}(X + 1)$ transformation was applied to all data to normalize errors before analysis of variance. Means were separated using Duncan's Multiple Range Test at a confidence level of $p < 0.05$.

2.5.2. Petri-dish method

Conditioned *Striga* seeds were spread on glass fiber and then stimulated with GR24 before placing a pre-germinated maize seedling. Imazapyr was then applied after some *Striga* seeds had germinated and attached to maize roots. Imazapyr rates, data collection and analysis were as described above.

2.5.3. Whorl application of herbicide in the field

A field site at the KARI–Kibos Center was chosen to study the effect of whorl application of imazapyr and pyrithiobac on *Striga* emergence. The site had been previously planted to maize and was heavily infested with *Striga hermonthica* that had been allowed to produce seed. Experiments were conducted during the September, 1998–February, 1999, short rainy season, March–August, 1999, long rainy season and September, 1999–February, 2000, short rainy season during which 710, 695 and 550 mm of precipitation, respectively, were received.

The experimental design was a randomized complete block with three replications. Plots consisted of four 3 m long rows, with 75 cm spacing between rows. Maize was planted at two seeds hill^{-1} within rows with hills spaced at 50 cm. *Striga* seeds were added to each planting hill to ensure that each maize plant was exposed to a minimum of 2000 viable *Striga* seeds in addition to those already in the field. These seeds were added in a sand/seed mixture to an enlarged planting hole at a depth of 7–10 cm (directly below the maize) as well as in a furrow parallel to the planting holes (a 7 cm shift). Diammonium phosphate fertilizer (50 kg N and 128 kg P_2O_5 ha^{-1}) was applied at the time of planting. As the synthetic maize variety used was susceptible to turcicum blight (*Helminthosporium turcicum*), it was sprayed with 185 g a.i. ha^{-1} propiconazole every 4 weeks after germination to preclude damage.

Imazapyr was applied in the maize whorls at rates of 0.6 and 0.9 mg plant^{-1} in a 2 ml solution (corresponding to rates of 30 and 45 g ha^{-1}, respectively) at 2 (3–4 leaves), 4 (8–10 leaves) and 6 (14–16 leaves) weeks after planting (WAP) during the three seasons. Pyrithiobac was applied as above at the rate of 0.2 and 0.4 mg plant^{-1} (11 and 21 g ha^{-1}). Four weeks after herbicide application, five 250 g soil samples were randomly taken at 15 and 25 cm from the maize plants at depths of 0–5, 5–10, 10–15 and 15–20 cm from maize treated with the highest rates of imazapyr and pyrithiobac, as well as from untreated plots. Samples from each depth were bulked and air-dried. A 250 g sub-sample was then elutriated according to the procedure of Eplee and Norris (1990), to recover *Striga* seeds and the data expressed as the number of seeds kg^{-1} soil. The elutriated *Striga* seeds were pre-conditioned for 12 days, and GR24 was then added, as described above. Viable *Striga* seeds were counted 72 h later and the percent of viable *Striga* was calculated.

Data on *Striga* emergence were collected from the two inside rows of the plots, excluding the end plants. *Striga* counts were made at 2-week intervals beginning 6 WAP (when *Striga* began to emerge) until maize was harvested 14 WAP. A $\log_{10}(X+1)$ transformation was applied to the data prior to analysis of variance. Means were separated using Duncan's Multiple Range Test at $p<0.05$.

2.6. Intercropping experiments

Experiments were similarly conducted to determine the effect of imazapyr and pyrithiobac coating of IR maize seed on the growth of legumes intercropped at various distances from the maize hills. Plots consisted of four 3 m long rows with 75 cm spacing between rows. Maize was planted at two seeds hill^{-1} within these rows, with hills spaced 60 cm apart. Beans, cowpea, or yellow gram were planted at the same time as maize within the maize rows at 3 or 5 cm intervals (in different experiments) from the maize hills. The field site, experimental design, *Striga* seed preparation and addition to the planting hills, fertilizer, disease control, and data analyses were as discussed above.

All legume intercrop plants were rated for visual symptoms of herbicide injury and the percent of healthy plants was calculated. Analyses of variance and regression were performed on log-transformed data.

3. Results and discussion

3.1. Herbicide movement in the soil

The effects of herbicide leaching through the soil profile on the viability of *Striga* seed at various depths are shown in Fig. 1. These bioassays indicate that ungerminated *Striga* seeds at various depths imbibed imazapyr or pyrithiobac and were killed as the herbicides moved through the soil column. The herbicide effects were seen after the seeds were separated from the soil and artificially stimulated to germinate with GR24. More than 98% of seeds in the critical top 10 cm of soil were killed while <20% remained viable in the

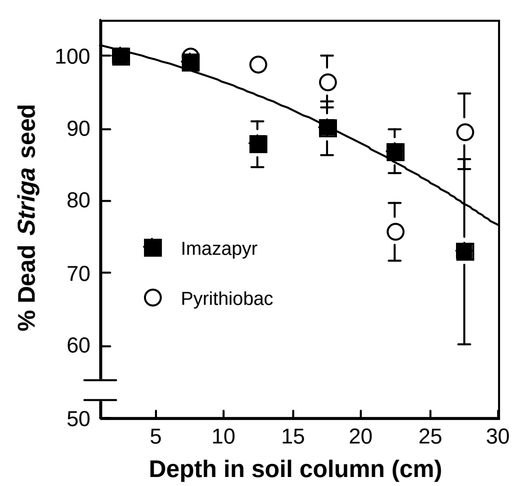

Fig. 1. *Striga hermonthica* mortality from leaching of imazapyr and pyrithiobac through a soil column. Standard error bars are shown when larger than the symbols. The line drawn is a best-fit average of the data for both herbicides. $y = -0.015x^2 - 0.400x + 101.911$; $r^2 = 0.908$.

lower profile. The *Striga* seeds in the top 10 cm are those that attach earliest and cause the most damage to the crop. Control soil columns, which were leached with water that did not contain herbicide, had between 120 and 190 viable *Striga* seeds kg^{-1} soil, i.e. 90% germinated. Only part of those seeds germinated by GR24 would have germinated in the rhizosphere of maize; the rest could remain dormant until the next seasons. The 10% ungerminated seeds could be alive and unreceptive to herbicide and GR24; they may also be viable and might break dormancy in a subsequent seasons. Whether GR24-treated seeds that did not germinate (but may be alive) are sensitive to the herbicides remains an open question. It is clear though that the herbicide had an irreversible effect on *Striga* seed germination, i.e. the herbicide was not removed from the seed by the intensive washing of elutriation, i.e. the ability to germinate was not restored.

The diffusion of imazapyr and pyrithiobac into the soil in the field around dressed maize seed should kill *Striga* seeds even before germination and help to reduce the *Striga* seed bank. However, the amount of *Striga* seed killed will depend on the amount of herbicide used. The herbicide rates used in the soil column leaching studies were about double those that will be recommended for field use, so much less control of ungerminated seed should be anticipated in the field. The herbicide would be distributed in a cone-shaped pattern in the field, and not in the constrained cylindrical pattern in the laboratory experiment. This would lead to a fan-shaped decrease in herbicide concentration, with a concomitant decrease in effectiveness at the edges.

3.2. Herbicide movement out of the crop

Both attached and nearby germinating *Striga* were measured in experiments with imazapyr and only attached *Striga* was measured in the experiments with pyrithiobac. *Striga* was killed within 5 days after application of imazapyr or pyrithiobac to the maize whorl in both in vitro methodologies (Table 1). Almost all the viable *Striga* (unattached and attached germlings) were killed by rates $\geqslant 0.1$ mg imazapyr $plant^{-1}$ (about 5 g ha^{-1}). All attached *Striga* were killed at whorl applications of pyrithiobac $\geqslant 0.2$ mg $plant^{-1}$ (10 g ha^{-1}). It is not clear whether the low effect of pyrithiobac on attached *Striga* compared to imazapyr at the same rates was due to its lower mobility than imazapyr in maize plants or to less pyrithiobac exudation, or if other mechanisms are involved. These data indicate that even at very young growth stages, enough herbicide disperses to the maize root system to kill attached *Striga* and is also sufficiently excreted to kill nearby, as yet unattached *Striga* seedlings. Thus, these herbicides are able to kill *Striga* both before attachment, when the germinated *Striga* is chemotactically growing towards

Table 1
Mortality of *Striga* from imazapyr and pyrithiobac applied to the whorl of maize seedlings and translocated to the roots and rhizosphere

Herbicide rate (mg/plant)	Number of *Striga* before herbicide application[a]		% *Striga* plants killed by foliar application to maize whorls	
	Germinated	Attached	Germinated	Attached
Polybag method				
Imazapyr				
0	4.7	2.7	0 a	0 a
0.1	8.0	3.3	100 b	86 b
0.2	4.7	2.0	100 b	100 b
0.3	4.3	2.7	100 b	100 b
Pyrithiobac				
0	12.0 a	5.5	dnc	0 a
0.1	10.0 ab	3.5	dnc	42 b
0.2	7.0 abc	4.0	dnc	75 c
0.3	4.5 bc	3.5	dnc	80 c
0.4	2.5 c	4.5	dnc	100 c
Petri-dish method				
Imazapyr				
0	11.7 a	5.7 a	0 a	0 a
0.1	12.7 a	5.3 a	100 b	94 b
0.2	6.7 b	4.7 a	100 b	100 b
0.3	10.0 ab	3.0 b	100 b	100 b

[a] Figures within a column and treatment followed by the same letter (or with no letters) are not significantly different according to Duncan's Multiple Range Test ($p < 0.05$). It is not clear whether the low effect of pyrithiobac on attached *Striga* compared to imazapyr at same rates was due to its less mobility than imazapyr in maize plants or less pyrithiobac exudation or if other mechanisms are involved.

Application to maize whorls was 2 weeks after germination (ca. 4–5 leaves).

dnc = data not collected.

the maize root, as well as after attachment. Foliar-applied imazapyr has been shown to be excreted by maize roots (Little and Shaner, 1991). To the best of our knowledge, this is the first demonstration that weed seeds in the maize rhizosphere are killed by excreted herbicide.

Imazapyr applied to maize whorls as early as 2 WAP significantly suppressed *Striga* emergence in the field at 10 WAP (Table 2). During the short rainy seasons of 1998/1999 and 1999/2000, emergence was suppressed by >90% whereas during the long rains of 1999, emergence was suppressed by >60%. *Striga* emergence increased on the treated plants at later enumerations 12 WAP, yet there still was a more than a 65% reduction in flower and seed capsule formation by harvest time at 14 WAP. Imazapyr applications at 4 WAP were relatively less effective in controlling *Striga* than application at 6 WAP in the long rainy season of 1999 (Table 2). Pyrithiobac was significantly more effective than imazapyr at controlling *Striga*, particularly at the 4 WAP application date during the long rainy season of 1999, but less effective during the short rainy season of 1999/2000. Whorl-applied imazapyr and pyrithiobac reduced viable *Striga* seeds in the soil to <30% of control levels at various depths (Table 3). There was no significant effect on viable *Striga* seeds in soil sampled at various distances from maize treated

Table 3
Suppression of *Striga* seed germination in the soil following whorl application of imazapyr and pyrithiobac

Depth (cm)	Percent of untreated control[a]	
	Imazapyr	Pyrithiobac
Control	100 a	100 a
0–5	29 b	30 b
5–10	25 b	15 b
10–15	18 b	23 b
15–20	12 b	26 b

[a] The 100% value is based on parallel samples from near untreated maize. The actual viability of the controls was 30%. The remaining seed was not stimulated to germinate by GR24, and may be dead or dormant.

Performed during the 1999 long rainy season.

Table 2
Suppression of *Striga* by imazapyr and pyrithiobac application to maize whorls as a function of time of application

Herbicide rate (g a.i. ha^{-1})	Time of application (WAP[a])	*Striga* emergence ([b] m^{-2})		No. of *Striga*[c]	
		10 WAP	12 WAP	Flowers m^{-2}	Capsules m^{-2}
Short rains 1998/1999					
0	Control	13.8 a	16.8 a	2.7 a	10.2 a
Imazapyr					
45	2	3.8 b	7.7 ab	0.9 b	2.3 b
45	4	0.9 b	3.8 b	0.9 b	2.3 b
45	6	1.1 b	3.0 b	0.9 b	2.3 b
Long rains 1999					
0	Control	34.6 a	41.4 a	9.3 a	33.1 a
Imazapyr					
45	2	10.3 b	21.2 bc	3.2 bc	4.2 bc
45	4	24.8 a	31.3 ab	4.7 b	19.3 b
45	6	7.8 b	7.5 c	0.0 c	0.0 c
Pyrithiobac					
21	2	5.7 b	16.5 bc	2.1 bc	2.9 bc
21	4	4.7 b	11.5 c	1.0 bc	2.6 bc
21	6	6.0 b	14.3 bc	1.2 bc	4.1 bc
Short rains 1999/2000					
0	Control	47.6 a	51.1 a	22.4 a	31.2 a
Imazapyr					
45	2	0.9 c	4.5 c	0.0 b	0.0 c
45	4	0.7 c	1.8 c	0.0 b	0.0 c
45	6	3.1 bc	3.2 c	0.0 b	0.0 c
Pyrithiobac					
21	2	5.1 bc	7.0 bc	0.7 b	0.0 c
21	4	7.1 bc	13.9 b	1.2 b	7.9 b
21	6	16.9 b	17.3 b	3.4 b	6.8 b

[a] Weeks after planting.
[b] Figures within a column and season followed by the same letter are not significantly different from each other according to Duncan's Multiple Range Test ($p<0.05$).
[c] Measured at 14 WAP.

with herbicide applications in the whorl at 4 WAP. This was probably due to herbicide being exuded by maize roots into the rhizosphere killing *Striga* seeds. The data further confirm that imazapyr and pyrithiobac applied to the whorls can move systemically to maize roots and kill attached *Striga,* and also be exuded and kill *Striga* seeds in the rhizosphere.

3.3. Lack of herbicide damage to normally planted intercropped legumes

Beans and cowpea intercropped with the herbicide-treated maize seed during the 1998/1999 short rainy season were unaffected when grown at distances of 15 cm or more from the maize hills. The legumes were killed when planted in the same hills and were killed or injured when planted at distances of <15 cm from the maize seeds (Fig. 2). Yellow gram and cowpea inter-planted with imazapyr- or pyrithiobac-treated maize seed were also unaffected by the herbicides when grown 15 cm or more from the maize seeds during the 1999 long rainy season. The legumes were killed or injured at distances of <9 and 12 cm from maize hills, respectively (Fig. 3a and b). Probably, the total amount of water received (supplemental irrigation and 710 mm rainfall) during the 1998/1999 short rainy season caused less herbicide injury to legumes closer to maize hills compared to 1999 long rainy season.

Yellow gram and cowpea interplanted at distances $\geqslant 15$ cm from imazapyr- or pyrithiobac-treated maize in the 1999/2000 short rainy season were unaffected by herbicide (Fig. 3c and d). Due to the low amounts of rainfall during this season (550 mm), an estimated

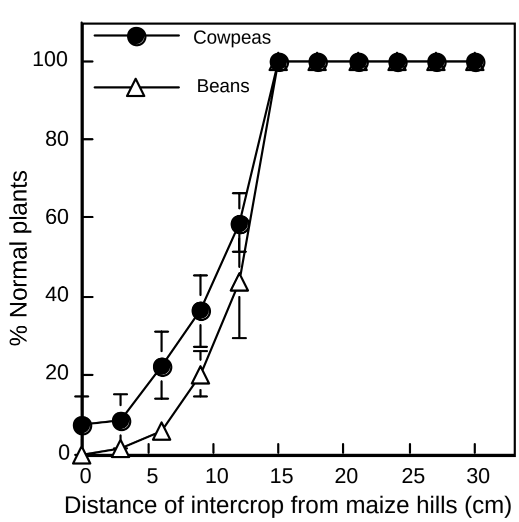

Fig. 2. Limited inhibition of legume growth by imazapyr leaching from maize seed as intercropping distances from the maize hills approach those normally used (short rainy season, 1998/1999). Standard error bars are shown when larger than the symbols.

150 mm supplemental irrigation was applied as required, and this total amount may have moved the herbicide further from the maize hills.

When coated maize seed is planted in moist soil, the herbicide coating begins to dissolve in the soil solution and move away from the seed by both diffusion and convection in leaching soil water. This results in a plume of herbicide that is increasingly dilute as it moves away from the maize seed point source of application. The shape and lateral extent of the plume will depend on the relative rates of diffusive and convectional movement, which in turn are governed by soil physical properties as well as incident rainfall. As intercropped legume roots spread vertically and laterally in the soil, they may encounter the plume of herbicide moving away from the treated maize seed and be injured or even killed as a consequence.

Our studies over three seasons of widely differing rainfall patterns as well as total rainfall demonstrate that sensitive legume crops can be safely intercropped with imazapyr- or pyrithiobac-treated maize seeds when sown between the maize hills or between maize rows. Farmers typically plant maize at a spacing of 75 cm between and 50 cm within rows. Intercropped legumes are usually sown in one or two rows spaced equidistant between maize rows. Thus, the intercrops are usually well outside the 15 cm maximum zone of influence of the herbicide moving away from the maize seed-coat, allowing this *Striga* control technology to be adopted with little risk to intercrops, without the need to modify traditional cropping practices. Those few farmers who randomly broadcast legume intercrops into maize would have to modify their practices and plant the legumes at least 15 cm from maize seeds, if they wish to use herbicide-treated maize.

The application rates of the two herbicides used in these field experiments were nearly double the rates that would normally be recommended for seed-coat treatment of maize for *Striga* control. These higher rates were used to accentuate any potential damage to intercropped legumes from the herbicides. Furthermore, the soil on which these studies were conducted is a sandy loam having both high soil-water diffusivity and hydraulic conductivity where one might expect the plume of herbicide dispersion to extend into the inter-row or inter-hill volume of soil more than in heavier textured soils. Thus, the conditions for herbicide injury to the intercrop in these experiments probably represent the worst case scenario for this methodology.

The effects of the treatments on maize or legume grain yield could not be realistically estimated in this experimental series. This is because the legume seeds were sown at all the 3 or 5 cm spacings between the maize hills, resulting in at least seven healthy legume plants between each maize hill instead of the one or two as in normal practice. These survivors were very

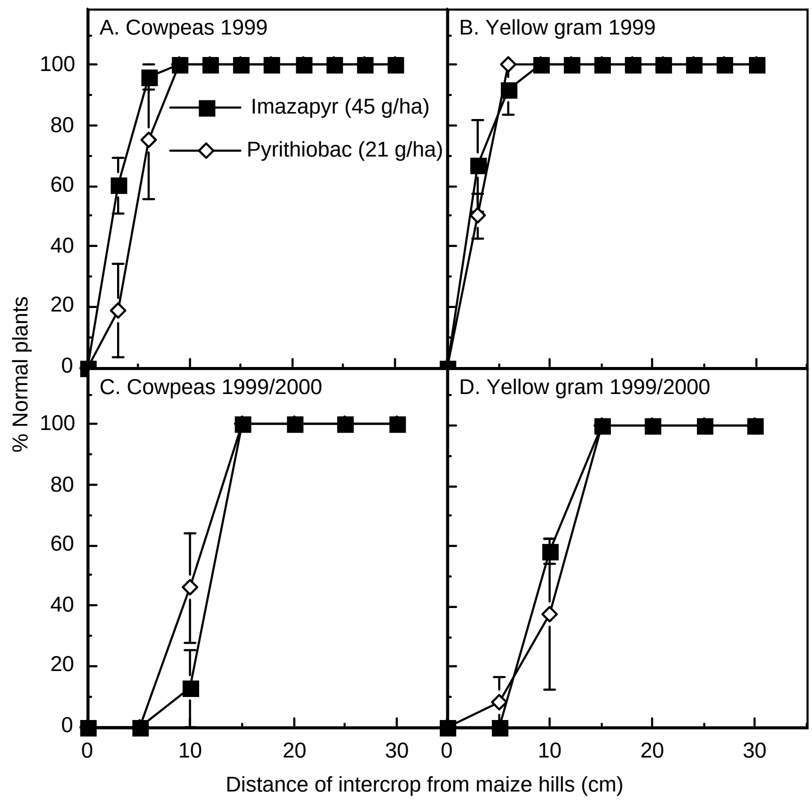

Fig. 3. Limited inhibition of legume growth by imazapyr and pyrithiobac leaching from maize seed as intercropping distances from the maize hills approach those normally used: (A) cowpeas, long rainy season 1999; (B) yellow gram, long rainy season, 1999; (C) cowpeas, short rainy season, 1999/2000; (D) yellow gram, short rainy season, 1999/2000). Standard error bars are shown when larger than the symbols.

successful competitors with each other and the maize, and yield measurements would have been irrelevant.

The intercropping of maize and legumes has multiple benefits to small-scale farmers. This system enables farmers to harvest two crops, reduce the *Striga* seed bank in the soil due to stimulation caused by the maize and the legume, and to improve soil fertility from the nitrogen fixed by the legumes. The decreased number of *Striga* escapes, achieved by intercropping herbicide-treated maize with legumes should make it easier to identify and rogue both the expected herbicide-resistant *Striga* plants (Gressel et al., 1996), as well as late emerging escapes, before the *Striga* plants set seeds.

We have not observed any carryover effects of herbicide to crops grown in rotation after planting imazapyr- and pyrithiobac-dressed maize seeds in 10 seasons of experimentation. This is probably due to the low dosages used per hectare, and/or the dissipation of the herbicides in soil, and/or their being leached below the root zone. The fact that *Striga* is no longer controlled 3 months after planting at even double the recommended rate (Abayo et al., 1996, 1998; Kanampiu et al., 2001) is further evidence for lack of herbicide carryover. Thus, it appears that rotation of maize with herbicide-susceptible crops is possible with this technology.

These results, as well as field studies in Malawi (Kabambe and Kanampiu, unpublished) clearly demonstrate that intercropping herbicide-sensitive legumes with herbicide-treated maize is feasible, rendering this technology appropriate for traditional intercropping systems used by small-scale farmers. This will allow small-scale farmers to continue practicing intercropping, at most with slight modification, while using maize seed treated to control *Striga*. This technology will also not conflict with recent developments using insect pest repellent-intercrops (Khan et al., 1997). Root exudates released from the herbicide-treated maize as well as from the legume intercrop stimulate suicidal germination of *Striga*. This should interact with the added fertility of the legumes, to further deplete *Striga* seed banks and allow the occasional rotation to *Striga* sensitive crops.

Acknowledgements

The excellent technical assistance of Mr. Peter Okoth Mbogo is gratefully acknowledged. The authors thank the Kenyan Agricultural Research Institute (KARI), in particular, Dr. C.G. Ndiritu (past-Director KARI), Dr. J.W. Ochieng' (Assistant Director), and Mr. W.K. Malinga (Center Director NSRC-Kibos), for their support and collaboration in making these studies possible. Drs. David Jewell and Kevin Pixley, CIMMYT, Zimbabwe, developed the synthetic IR maize variety used in this study. Dr. Peter Porpiglia of Kumiai Chemicals, USA, kindly supplied pyrithiobac. This research was supported by funds from the Rockefeller Foundation *Striga* Project and the Canadian International Development Agency (CIDA). J. Gressel is supported by the Gilbert de Botton-endowed professorial chair in Plant Sciences.

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