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Integrated management of *Striga hermonthica*, stemborers, and declining soil fertility in western Kenya

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Abstract

Striga hermonthica (Delile) Benth., stemborers, and declining soil fertility are serious threats to sustainable food production in the Lake Victoria zone of Kenya. To address these constraints, promising integrated crop management technologies were evaluated, using a multi-locational design in four sub-locations in Siaya and Vihiga district (western Kenya) for six cropping seasons. Technologies evaluated consisted of the traditional maize (*Zea mays* L.) – bean (*Phaseolus vulgaris* L.) intercrop, maize – *Desmodium (Desmodium uncinatum* (Jacq.) DC.) push–pull intercrop, *Crotalaria* (*Crotalaria ochroleuca* G. Don) – maize rotation, and soybean (*Glycine max* (L.) Merr) – maize rotation. Within each of these systems, imazapyr-coated herbicide-resistant maize (IR-maize) and fertilizer were super-imposed as sub-plot factors. The push–pull system was observed to significantly reduce *Striga* emergence and stemborer damage from the second season onwards. IR-maize reduced and delayed *Striga* emergence from the first cropping season. Differences in *Striga* emergence and stemborer damage between the other systems were not significantly different. After five cropping seasons, the *Striga* seedbank was significantly higher in the maize-bean intercrop system than in the push–pull system under both maize varieties while the rotational systems had intermediate values not different from the day zero values. Under IR-maize, the *Striga* seedbank was significantly lower than under local maize for all cropping systems. Maize yields varied between seasons, districts, and cropping systems. Yields in the push–pull system were higher than in the maize-bean intercrop after two seasons and in the absence of mid-season drought stress. Both maize and soybean responded significantly to fertilizer application for both districts and for most seasons. The various interventions did not substantially affect various soil fertility-related parameters after five seasons. In the short term, IR-maize integrated in a push–pull system is the most promising option to reduce *Striga* while the rotational systems may need a longer timeframe to reduce the *Striga* seedbank. Finally, farmer-led evaluation of the various technologies will determine which of those is really most acceptable under the prevailing farming conditions.

Keywords: *Crotalaria ochroleuca*; Fertilizer; *Glycine max*; Imazapyr-coated herbicide-resistant maize; Push–pull intercrop; *Striga* seedbank

1. Introduction

Maize (*Zea mays* L.) is one of the most important cereal crops in eastern Africa, where it serves as both a staple food and cash crop for millions of people. Grain yields under farmers' conditions in the Lake Victoria Basin in Kenya (1.0 ± 0.5 t ha^{-1}) were observed to be less than 25% of the potential yield of 4–5 t ha^{-1} (Tittonell et al., 2005). During so-called Rapid Rural Appraisals, which are short, informal surveys with farmer groups, farmers systematically ranked *Striga* spp. (witchweed), stemborers, and declining soil fertility as three major constraints affecting maize production in western Kenya (Odendo et al., 2001).

Striga spp. has infested about 212,000 hectares or about 15% of the arable land in the Lake Victoria Basin of Kenya alone (www.fao.org; CEPA, 2004), causing yield losses of between 30–50%, although losses of up to 100% have been reported (Hassan et al., 1995). Increased incidence of *Striga* has been

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attributed to cereal mono-cropping and declining soil fertility (Ransom, 2000). Of the 23 species of *Striga* spp. prevalent in Africa, *Striga hermonthica* (Delile) Benth. is by far the most socio-economically important in East Africa (Emechebe and Ahonsi, 2003). In western Kenya, this weed infests about 76% of the total area under maize and sorghum (*Sorghum bicolor* (L.) Moench), which are the main staple crops for the people in target area, causing annual losses estimated at US$ 41 million (Hassan et al., 1995; Kanampiu et al., 2002). Adoption of recommended control methods to reduce *Striga* infestation has been limited, partly by farmers' reluctance to adopt such methods, accentuated by unfavourable biological and socio-economic conditions (Kanampiu et al., 2003; Oswald, 2005).

Cereal stemborers are important injurious insect pests of maize, with *Chilo partellus* Swinhoe (Lepidoptera: Crambidae) and *Busseola fusca* Fuller (Lepidoptera: Noctuidae) being the most important in the region. Farmers' estimates of crop loss due to stemborers in western Kenya were 12.9% (De Groote, 2002), while direct observation of damage was 13.5% (De Groote et al., 2004). Although, several insecticides are able to effectively control stemborers, their use in western Kenya is limited (De Groote, unpublished data). The effectiveness of some of the recommended cultural control methods (e.g., burning of crop residues, manipulation of planting dates, removal of infested plants) is questionable (Van den Berg et al., 1998) and as a result, most smallholder farmers do not make any conscious attempt to control stemborers (Grisley, 1997).

A number of technologies have been developed to alleviate stemborer and/or *Striga* constraints in smallholder farms. These include the 'push–pull' technology for stemborer and *Striga* control, and imazapyr-coated herbicide-resistant maize (IR-maize) and cereal-legume rotations for *Striga* control. The 'push–pull' technology is based on a stimulo-deterrent concept (Miller and Cowles, 1990). In this strategy, maize is intercropped with a stemborer moth-repellent plant, *Desmodium uncinatum* (Jacq.) DC., while an attractant host plant, Napier grass (*Pennisetum purpureum* Schumach.) is planted as a trap plant around this intercrop. Volatiles produced by the *Desmodium* repel the host-seeking moths while those produced by the Napier grass are attractive to them (Khan et al., 2000; Chamberlain et al., 2006). Studies have shown that *Desmodium* also significantly suppresses *Striga*, leading to enhanced grain yields (Khan et al., 2000, 2006). The root exudates of *Desmodium* contain blends of secondary metabolites with *Striga* seed germination stimulatory and post-germination inhibitory properties (Tsanuo et al., 2003). The first group of semiochemicals stimulates *Striga* seeds to germinate while the second group inhibits lateral growth thereby hindering the development of the haustorial root system and subsequent attachment to the host plant (Tsanuo et al., 2003).

Rotations between fast-growing, nitrogen-fixing herbaceous legumes and cereals have also been used to deplete the *Striga* seedbank and reduce *Striga* emergence, since certain legumes have the ability to trigger suicidal *Striga* germination (Carsky et al., 2000). Scientists at the International Institute of Tropical Agriculture, Nigeria, have developed dual purpose soybean (*Glycine max* (L.) Merr) germplasm that produces leafy biomass without sacrificing high grain yields, often resulting in substantial yield increases for a subsequent maize crop compared with less leafy soybean varieties (Sanginga et al., 2003). These soybean varieties were also bred for promiscuity or the ability to establish an effective N fixation symbiosis with the native *Bradyrhizobium* spp., thus reducing or eliminating the need for inoculation through application of external bacteria. Not surprisingly, maize growing after these improved soybean varieties had 1.2–2.3-fold grain yield increase compared to the control (Sanginga et al., 2002). Some of these soybean varieties also triggered suicidal germination of *Striga* (Sanginga et al., 2003). Herbaceous legumes, such as *Crotalaria ochroleuca* G. Don, have also been demonstrated to reduce the *Striga* seedbank (Gacheru and Rao, 2001).

IR-maize is resistant to imazapyr herbicide, which is used as a coating around the seeds. After absorption by the crop roots, the herbicide is exuded and kills attaching or attached *Striga* seedlings as well as its nearby non-germinated *Striga* seeds in the soil (Kanampiu et al., 2002). It has been demonstrated that seed dressings of IR-maize with small amounts of imazapyr can provide season long control of *Striga* while allowing for intercropping with legumes (Kanampiu et al., 2002, 2003). Development of IR-maize germplasm used in this study and its commercialization in Kenya is outlined in Kanampiu et al. (2003).

Declining soil fertility is another major limitation to crop production in the target area (Vanlauwe et al., 2006). In the Lake Victoria Basin, nitrogen (N) and phosphorus (P) have been identified as the main limiting nutrients (Vanlauwe et al., 2006). Whereas biological N fixation in the push–pull or rotational systems can contribute to reducing soil nitrogen depletion, replenishment of the available soil P pool mainly happens through application of P fertilizer.

Clearly, while some of the above-mentioned technologies were developed with specific constraint(s) in mind, they all potentially alleviate other maize production constraints. Furthermore, some of the above technologies can be integrated, for instance, through inclusion of IR-maize in the push–pull or the rotational systems. Moreover, single technologies are often promoted by the research institute that developed these, thereby preventing farmer communities from evaluating a range of alternative technologies. The objective of this study was to evaluate a set of promising integrated technologies for controlling *Striga*, stemborers, and declining soil fertility in the Lake Victoria basin. This multi-institutional evaluation was implemented through multi-locational and multi-seasonal, on-farm trials encompassing all above technology components. The main hypothesis was that integrated technologies exist that can simultaneously alleviate various constraints to maize production in the target area.

2. Materials and methods

2.1. Site selection and trial design

Trials were implemented in farmer's fields in Siaya and Vihiga districts of western Kenya between 2003 and 2005.

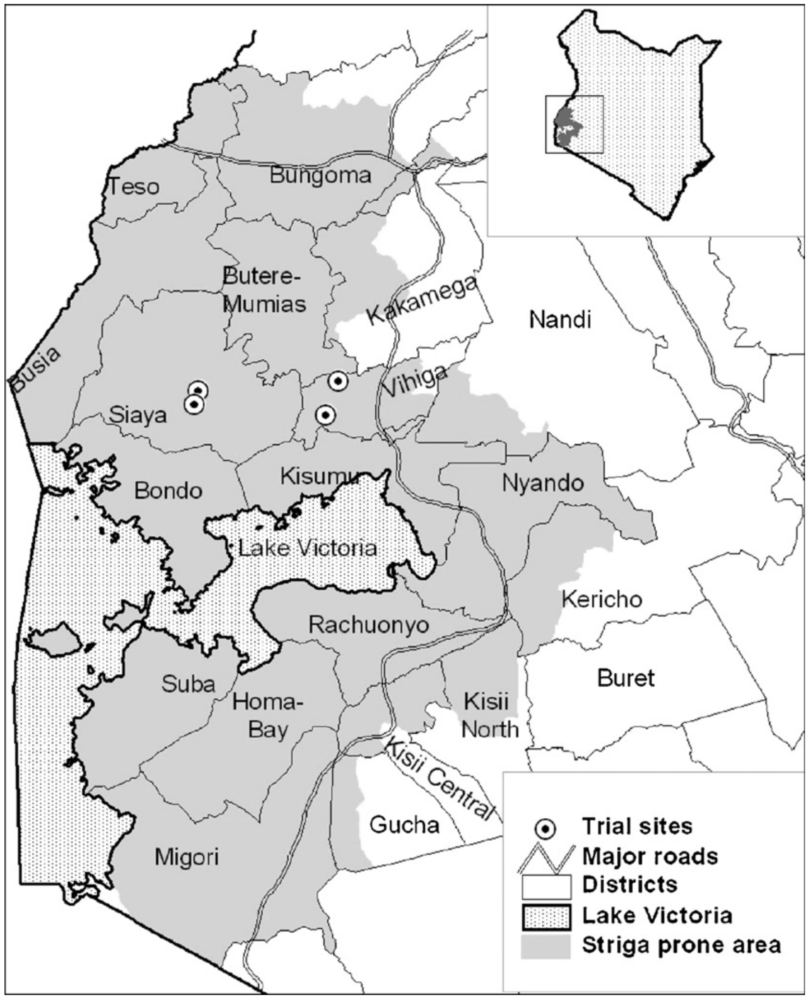

Fig. 1. Target sites overlaid on a map showing areas with occurrence of *Striga hermonthica* in western Kenya. Adapted from De Groote et al. (2005). The map inserted at the top right depicts Kenya.

These districts were chosen because of their high *Striga* incidence (Hassan et al., 1995) (Fig. 1) and stemborer pressure (De Groote, 2002) and poor soil fertility status (Tittonell et al., 2005). Rainfall is distributed over a long rainy season from March to July and a short rainy season from September to December, both suitable for maize production. Rainfall data for the six seasons are presented in Fig. 2. Soils in both districts are Nitisols (FAO, 1991) and contained 15 g kg^{-1} organic C and 6 mg kg^{-1} available P in Vihiga district and 12 g kg^{-1} C and 5 mg kg^{-1} P in Siaya district (Table 1). Their average pH was 5.3 in Vihiga district and 5.7 in Siaya district.

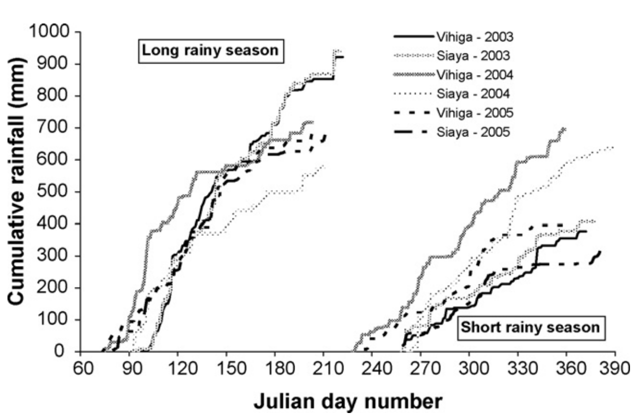

Fig. 2. Cumulative rainfall for each rainy season. Note that the data cover the period from maize planting to harvesting for the respective seasons.

In Siaya district, Ngoya (0°3′N 34°19′E) and Nyalugunga (0°5′N 34°19′E) sub-locations were selected as the target sites while in Vihiga district, Ebulonga (0°2′N 34°36′E) and Ematsuli (0°6′N 34°38′E) sub-locations were selected. Based on discussions with farmers and visual observations during maize growth, two farmers' fields with high *Striga* pressure and relatively low soil fertility status were selected in each of the two sub-locations in Siaya district, while in Vihiga district, due to the small area of most fields, four fields were selected in Ematsuli and six in Ebulonga.

In Siaya district, in each of the selected farmer's fields, a complete trial (16 sub-plots) was laid out using a split-plot arrangement with 'cropping system' as main plot factor and 'variety' and 'fertilizer' as sub-plot factors (Fig. 3). In Vihiga district, a similar design was allocated randomly between the various farmer's fields selected, thereby ensuring that each of

Table 1
Selected soil fertility characteristics at the start of the trials or the long rainy season of 2003 (LR2003) and before the short rainy season of 2005 (SR2005)

District	Season	Treatment	Organic C (g kg^{-1})	Total N (g kg^{-1})	Available P (mg kg^{-1})	pH (water)	ECEC (cmol kg^{-1})	Sand (g kg^{-1})	Silt (g kg^{-1})	Clay (g kg^{-1})
Vihiga	LR2003	[Day 0]	15.1 (3.5)	1.47 (0.38)	6.1 (2.4)	5.3 (0.3)	10.6 (3.7)	421 (56)	215 (56)	364 (43)
	SR2005	Intercrop	13.2	1.93	6.7	5.4	ND	ND	ND	ND
		Push–Pull	12.8	1.86	13.0	5.4	ND	ND	ND	ND
		Crot Rot	13.5	1.71	5.3	5.2	ND	ND	ND	ND
		Soy Rot	13.0	1.89	9.9	5.6	ND	ND	ND	ND
		SED	6.2	0.14	2.0	0.2				
Siaya	LR2003	[Day 0]	12.4 (1.0)	1.37 (0.11)	4.9 (1.9)	5.7 (0.4)	8.4 (0.6)	228 (48)	280 (77)	492 (65)
	SR2005	Intercrop	13.2	1.58	3.2	5.6	ND	ND	ND	ND
		Push–Pull	14.1	1.71	4.9	5.8	ND	ND	ND	ND
		Crot Rot	13.8	1.81	3.2	5.6	ND	ND	ND	ND
		Soy Rot	13.4	1.78	4.0	5.8	ND	ND	ND	ND
		SED	3.8	0.09	1.5	0.1				

'ECEC' means 'effective cation exchange capacity'; 'Intercrop' means 'maize-bean intercrop'; 'Crot Rot' means 'Crotalaria rotation'; 'Soy Rot' means 'Soybean rotation'; 'SED' means 'Standard Error of the Difference' for the SR2005 season; 'ND' means 'Not determined'.
Values between brackets are standard deviations for the day 0 values.

the fields accommodated eight sub-plots in Ematsuli and four or eight sub-plots in Ebulonga. One replicate was thus allocated to one field in Siaya district and two to three fields in Vihiga district. Sub-plot size was 10.5 m by 10 m. The 'cropping system' factor had four levels: maize-bean (*Phaseolus vulgaris* L., variety KK8) intercrop, maize-*Desmodium* push–pull intercrop, dual purpose soybean (variety TGX-1448-2E) rotated with a maize-bean intercrop, and *Crotalaria* rotated with a maize-bean intercrop. The 'variety' factor had two levels: IR-maize (variety Ua Kayongo, a double cross hybrid) and local maize (variety Msamaria, an open-pollinated local variety, in 2003 and 2004 and variety WH502, a commercial hybrid, in 2005). The grain filling period of all maize varieties started between 70 and 75 days after planting. The 'fertilizer' factor had two levels: with and without fertilizer application, as described below. The overall design was a randomised complete block design with four replications per district.

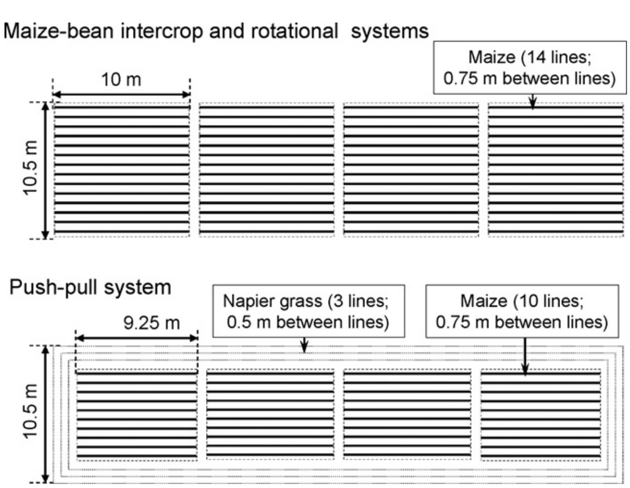

Fig. 3. Detailed sketch of the layout of a main plot for the maize-bean intercrop and rotational systems and for the push–pull system. The four subplots contained 2 levels of variety and 2 levels of fertilizer.

2.2. Trial management

The trials were managed by researchers with assistance from the hosting farmers and management was standardized for all sub-locations. Before the start of the trials during long rainy season of 2003 (LR2003), land was either prepared by ox-plough before harrowing in Siaya district and by hand-hoe in Vihiga district. At the start of each rainy season in the subsequent seasons, land was prepared using a hand-hoe to a depth of 10–15 cm, thereby incorporating any weeds or crop residues from the previous season, except in the push–pull intercrop. In the maize-bean intercropping systems, 14 rows of maize, each 10 m long, were planted between March and April (long rainy season) and between September and October (short rainy season) using a spacing of 0.75 m between the rows and 0.30 m between hills within a row (Fig. 3). Planting holes were dug and di-ammonium-phosphate (DAP) fertilizer was applied banded near the planting line at a rate of 23 kg P ha^{-1} in the treatments with fertilizer application. The fertilizer was covered with some soil and two seeds were planted per hill. In all sites in seasons where maize was planted, except in push–pull cropping system, beans were planted, 30 cm apart, between maize rows. However, due to severe bean root rot and bean stem maggot diseases, yields were not determined. Maize plants were thinned to 1 plant per hill after the first weeding (about four weeks after planting). At six weeks after planting, after the second weeding, the maize was top-dressed through banding and incorporating urea near the stem base at a rate of 46 kg N ha^{-1}. Any further weeding was done by hand to remove weeds other than *Striga*. Maize stover at harvest was removed from all plots.

In the push–pull system, *Desmodium* was drilled in a single furrow between the maize lines during the LR2003 season. To allow establishment, care was taken during the initial weeding not to uproot the *Desmodium* seedlings. In subsequent seasons, land was not tilled because of the perennial nature of this legume. Three lines of perennial Napier grass cuttings with three internodes were planted around the push–pull plots at a spacing of 0.5 m between the plants and 0.5 m away from the plot and between the lines around the main plot area, leaving space for 10 maize lines, of 9.25 m long (Fig. 3). The first *Desmodium* harvest took place immediately after the maize harvest of the first season by cutting all biomass about 5 cm above the soil surface and removing this. In subsequent seasons, *Desmodium* was harvested at least three times, once before maize planting, and twice during the maize growing season. Starting one season after planting, the Napier grass rows were frequently harvested at a rate of about 35 m of grass per week or about 10% of the total Napier area per week, starting with the outer lines.

In the soybean-maize rotation, during each long rainy season, soybean was drilled in rows, 0.75 m apart, and thinned to 5 cm between plants at about two weeks after germination. The soybean was not inoculated with a symbiont because the variety used had been selected to nodulate with indigenous *Bradyrhizobium* populations (Sanginga et al., 2003). In the treatments with fertilizer, DAP was drilled along the row at a rate of 23 kg P ha^{-1} and covered before drilling the soybean seeds. Soybean haulms at harvest were left on the field. In the *Crotalaria*-maize rotation, during each long rainy season, *Crotalaria* was drilled in rows, 0.75 m apart. In the treatments with fertilizer application, fertilizer was applied as in the soybean-maize treatment. *Crotalaria* residues were cut down before land preparation and incorporated using a hand-hoe. During each short rainy season, maize and beans were planted in both rotation systems and managed as in the maize-bean intercrop system.

2.3. Data collection

Soils were sampled for physical and chemical characterization and to estimate the *Striga* seedbank density. Soils were sampled prior to land preparation of the first season by taking nine soil cores (diameter of 5 cm) to a depth of 0–15 cm following a systematic 'W' scheme and bulking these per plot. The soils were sieved through 2 mm, air-dried, and analysed for organic carbon (C) (Dumas combustion method), total Kjeldahl-N, Olsen-P, texture, pH in water, and effective cation exchange capacity (ECEC) (ICRAF, 1995). Another subsample of 250 was used for elutriating *Striga* seeds in the soil, as described by Eplee (1976) and Ndung'u et al. (1993). In summary, 250 g of soil was placed in an elutriator overflowing into three sieves of different mesh sizes (850, 250 and 90 μm). Tap water was sent through the base of the elutriator and lifted the lighter soil fraction through a spout and onto the meshes. *Striga* seeds were captured on the 90 μm mesh while coarse materials were captured on the larger mesh sieves and dispersed finer minerals were washed through the sieves. The sample on the 90 μm sieve was recovered by washing into a 500 ml glass burette column containing a potassium carbonate (K_2CO_3) solution with a specific density of 1.8 g cm^{-3}. When tap water was applied to the column, *Striga* seeds were retained between the K_2CO_3–water interface. The K_2CO_3 was then drained away through the burette and the seeds were drained from the K_2CO_3–water interface onto a 90 μm nylon cloth before being counted using a binocular microscope. Soil samples were taken again before the short rainy season of 2005 (SR2005) and analysed for organic C, total N, Olsen-P, and pH.

At six, eight, and ten weeks after planting, the number of emerged *Striga* plants and maize plants affected by stemborers were counted in the central 6 rows (45 m^2 for the maize-bean intercrop and the rotation systems and 41.6 m^2 for the push–pull system). *Striga* emergence data were converted to number of *Striga* plants m^{-2} and stemborer damage data was expressed as the percentage of maize plants with visible stemborer damage. Stemborer data were not taken in Siaya district in 2005.

At maize and soybean harvest, maize and soybean grain yields were obtained from the central 45 m^2 (6 rows, 10 m long) in the maize-bean intercrop and the rotation systems and from the central 41.6 m^2 (6 rows, 9.25 m long) in the push–pull system and presented on a dry matter basis. Grain moisture contents were measured using a moisture tester. Yield data in the push–pull systems were adjusted to take into account the land area occupied by Napier grass (34% of the plot area, Fig. 3). Because on average across all seasons and sites 29% of the maize plants were missing, mostly due to damage caused by small deer, rodents and termites, maize grain yields were linearly adjusted for missing stands, in order to get yields that are not deflated by site-specific events. The used procedure is based on the observed linearity between maize grain yield and maize population for values ranging from zero to the plant population used in this work (4.4 plants m^{-2}) (Tokatlidis and Koutroubas, 2004).

2.4. Data analysis

All crop-related data were analysed using mixed models fitted by REML, the appropriate generalisation of analysis of variance when the experimental design is hierarchical and incomplete (Spilke et al., 2005). In the model, 'district', 'cropping system', 'variety', and 'fertilizer' and their interactions were included as fixed effects while 'farmer within district' and 'farmer × cropping system within district' were included as random effects, with each season analysed separately. *Striga* emergence and seedbank data were transformed to $\log_{10}(n+1)$ before statistical analysis. Calculations were done with the MIXED procedure of the SAS system (SAS, 1992).

3. Results

3.1. Striga emergence

Striga data are presented showing the 'district × cropping system' and 'variety × cropping system' interactions (Table 2). *Striga* emergence was significantly lower under the push–pull system than under all other systems for all seasons and both districts, except for the LR2003 season (Fig. 4). *Striga* emergence was consistently higher in the maize-bean intercrop in Siaya than in Vihiga district. Differences in *Striga* emergence between the other cropping systems were not significant for all

Table 2
Analysis of variance of the tested fixed effects and their interactions for the studied growing seasons

	LR2003	SR2003	LR2004	SR2004	LR2005	SR2005
Striga emergence						
District (D)	0.077	**0.049**	0.074	0.483	0.070	**<0.001**
Cropping system (C)	0.712	**0.014**	**0.007**	0.086	**0.005**	**<0.001**
D × C	0.085	0.452	**0.020**	0.411	**0.044**	**0.007**
Variety (V)	**0.011**	**<0.001**	**<0.001**	0.346	**<0.001**	**<0.001**
D × V	0.220	0.420	0.377	0.760	0.103	**0.015**
C × V	0.737	0.598	**<0.001**	0.355	**<0.001**	**<0.001**
D × C × V	0.647	0.453	0.676	0.535	0.239	**0.002**
D × Fertilizer (F)	0.959	0.165	0.346	**0.036**	0.634	0.458
Stemborer damage						
District (D)	0.995	**<0.001**	0.126	**<0.001**	0.091	**<0.001**
Cropping system (C)	0.092	**<0.001**	**0.041**	**<0.001**	0.100	**<0.001**
D × C	0.388	**0.047**	0.890	**0.012**	NA	NA
Variety (V)	**0.009**	0.186	0.866	**<0.001**	0.340	0.807
D × C × V	**0.005**	0.660	0.621	0.983	NA	NA
D × Fertilizer (F)	**0.034**	0.597	0.796	0.154	NA	NA
D × C × V × F	**0.041**	0.619	0.996	0.936	NA	NA
Maize grain yield						
District (D)	0.233	**0.007**	0.635	0.117	0.327	**<0.001**
Cropping system (C)	0.318	0.060	0.440	0.242	**0.017**	0.729
Variety (V)	0.213	0.535	0.233	0.834	**<0.001**	0.584
Fertilizer (F)	**<0.001**	**0.003**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
D × F	0.761	0.457	0.097	**0.030**	0.601	**<0.001**

Values in bold are significant ($P < 0.05$). Factors or two-, three-, and four-way interactions that were not significant during anyone of the seasons have been omitted from the table.
'LR', 'SR', and 'NA' mean 'long rainy season', 'short rainy season', and 'not applicable', respectively.

seasons. Except for the short rainy season of 2004 (SR2004), when the *Striga* emergence levels were exceptionally low, IR-maize significantly reduced *Striga* emergence in the maize-bean intercrop and both rotations (Fig. 5), while in the push–pull system, *Striga* emergence was low after the LR2003 season and not affected by the maize variety used. Generally, *Striga* emergence was lower during the short than during the long rainy season (Figs. 4 and 5). Time to emergence of the *Striga* seedlings was substantially greater for treatments with IR-maize and in the push–pull system after the SR2003 season (data not shown).

3.2. Stemborer damage

Stemborer data are presented showing the 'district × crop-cropping system' interaction (Table 2). Stemborer damage was significantly lower in the push–pull systems than in the other cropping systems after the LR2003 season (Fig. 6). During the SR2003 and SR2004 seasons, stemborer damage was consistently higher in Siaya than in Vihiga district, except in the push–pull treatment where damage was low (<1%) (Fig. 6).

3.3. Maize and soybean grain yields

Maize and soybean grain yield data are presented showing the 'district × cropping system' and 'district × fertilizer' interactions (Table 2). In Siaya district, maize grain yields were significantly higher in the push–pull system than in the maize-bean intercrop during the SR2004 and the LR2005 seasons (Fig. 7). During the SR2003 and SR2004 seasons, yields were similar in the rotation and push–pull systems. In Vihiga district, yields in the push–pull systems were lower than the other systems during the LR2003 and SR2003 season (Fig. 7). Push–pull yields were higher than the maize-bean intercrop in the LR2005 season while for the other seasons, the cropping system did not have a significant impact on maize yields. Maize yields were significantly higher in Siaya district than in Vihiga district for the SR2003 and SR2004 seasons while the opposite was true for the SR2005 season (Fig. 7). Overall, maize yields varied between 0.3 and 1.6 t ha^{-1} and those of soybean between 0.2 and 0.8 t ha^{-1} (Figs. 7 and 8). Both maize and soybean responded significantly to fertilizer application for both districts and all seasons, except for the SR2003 season in Vihiga district and SR2005 season in Siaya district (Fig. 8). Maize yields of the IR-maize were significantly larger than those of the local maize only during LR2005 season (1.4 and 1.1 t ha^{-1}, respectively).

3.4. Striga seedbank and soil fertility status

After five cropping seasons, the *Striga* seedbank was significantly higher in the maize-bean intercrop (61–158 million seeds ha^{-1}) than in the push–pull system (21–34 million seeds ha^{-1}) under both maize varieties while the rotational systems had intermediate values not different from the values at the start of the trial (Fig. 9). Under IR-maize, the *Striga* seedbank was significantly lower than under local maize for all cropping systems, and particularly with the push–pull

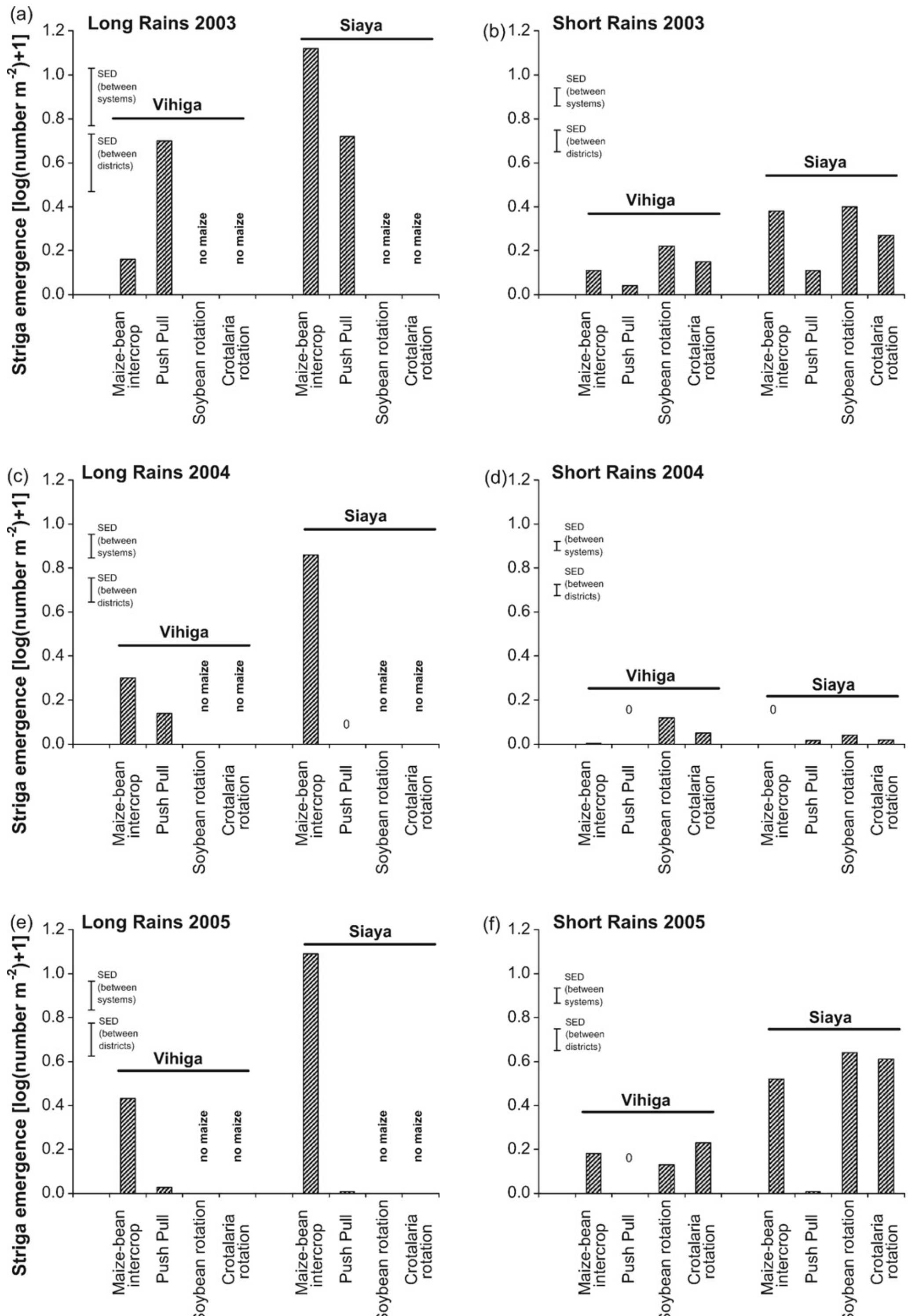

Fig. 4. *Striga* emergence for the 'district × cropping system' interaction. 'SED' refers to 'Standard Error of the Difference'. Treatments indicated with 'no maize' did not have maize in that particular season.

system (Fig. 9). Top soil organic C and total N content and pH were not significantly affected by the treatments after five cropping seasons and not different from those obtained at the start of the trial (Table 1). In Vihiga district, the soil available P status was significantly higher in the push–pull treatment than in the treatments with the maize-bean intercrop or the *Crotalaria*-maize rotation. In Siaya district, no differences in available P content were observed between the various treatments (Table 1).

4. Discussion

The push–pull system outperformed all other systems for controlling *Striga* emergence but only after one full cropping

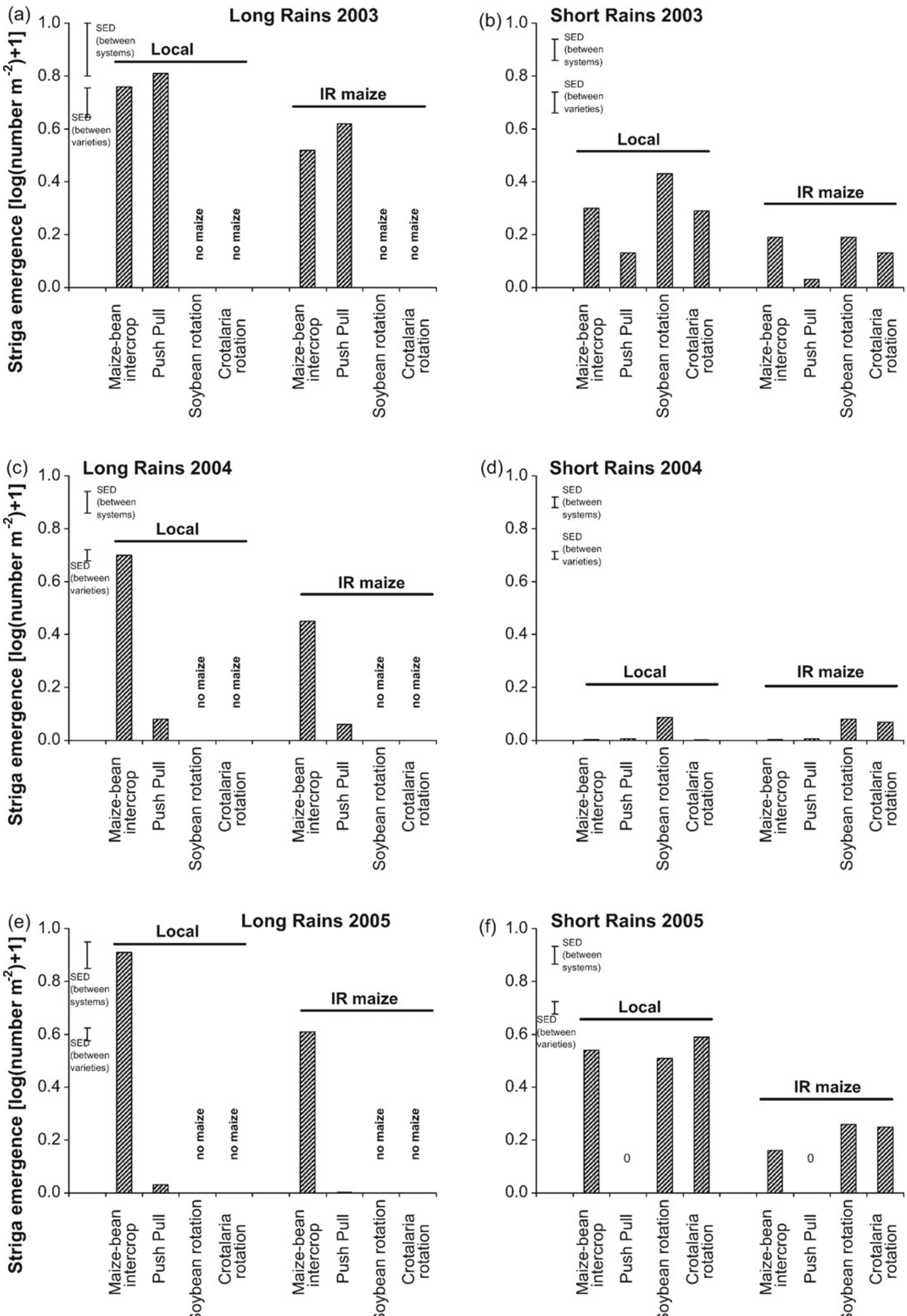

Fig. 5. *Striga* emergence for the 'variety × cropping system' interaction. 'SED' and 'IR' refer to 'Standard Error of the Difference' and 'Imazapyr-coated herbicide-resistant maize', respectively. Treatments indicated with 'no maize' did not have maize in that particular season.

season. This delayed response indicates that farmers will need to invest resources to establish the *Desmodium* and Napier grass without immediately harvesting benefits in terms of extra produce. Experiences with other cropping systems having a similar lag period (e.g., conservation agricultural practices) have shown that farmers are often reluctant or incapable to support such investments (Erenstein, 2002). The crops associated with maize in the push–pull system are attractive in areas with livestock due to provision of high quality livestock feed (mixtures of *Desmodium* and Napier grass) (Kariuki et al., 1999; Khan and Pickett, 2004). Associated crops with multiple benefits (e.g., fodder, grain) are likely to attract greater farmer interest and reduce reluctance to invest in establishment of the push–pull system compared to systems where such crops are

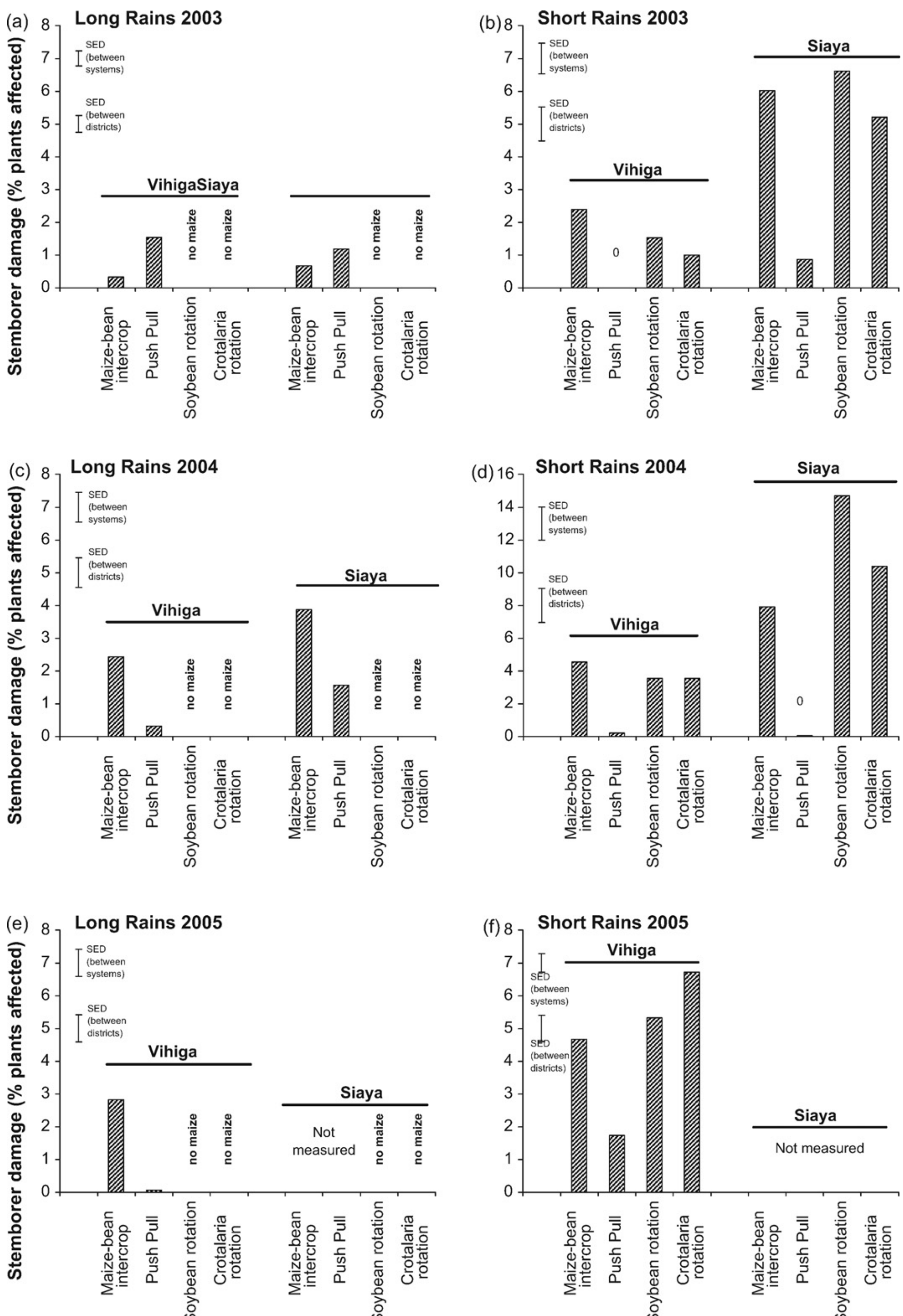

Fig. 6. Stemborer damage for the 'district × cropping system' interaction. 'SED' refers to 'Standard Error of the Difference'. Treatments indicated with 'no maize' did not have maize in that particular season. Note that the *Y*-axis scale is larger for the 2004 short rainy season. Also note that no data were taken in Siaya district in 2005.

only having a soil-fertility improving role (Vanlauwe et al., 2003). While neither the *Desmodium* nor the Napier grass was fully established after six months, their effects were already visible on both *Striga* emergence and stemborer repellence in the second season. This indicates that both plants produce the necessary chemicals that attract or repel the stemborer moths away from the maize crop at an early stage, and that *Desmodium* produced the necessary allelochemicals to inhibit *Striga* well before complete soil cover. Obviously, soil fertility-related effects through biological N fixation can only be

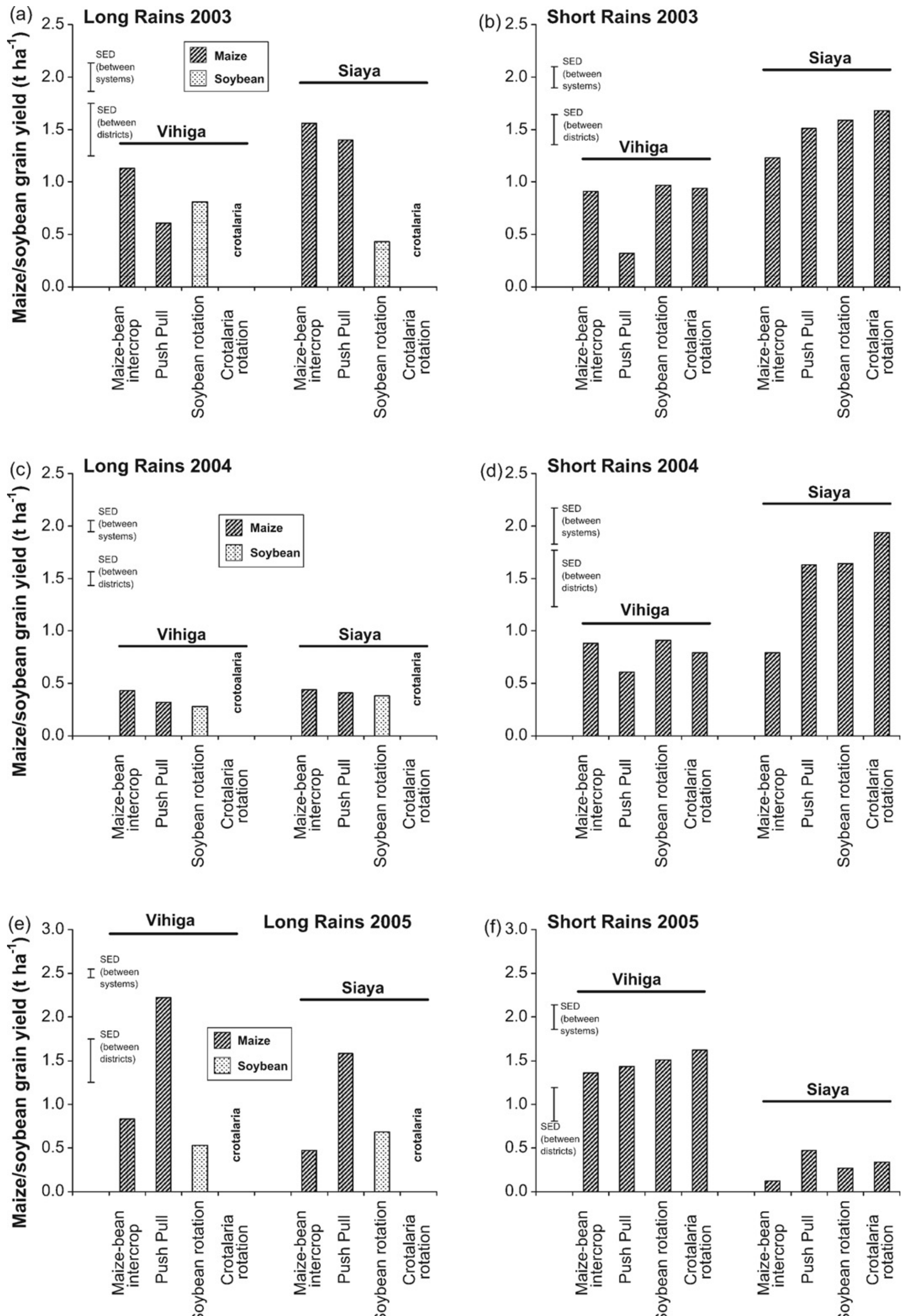

Fig. 7. Maize and soybean grain yield for the 'district × cropping system' interaction. 'SED' refers to 'Standard Error of the Difference'. SEDs to compare soybean data were not included since there were no significant differences between districts for soybean yield. Treatments indicated with 'crotalaria' contained *Crotalaria* in that particular season. Note that the *Y*-axis scale is larger for both 2005 rainy seasons.

expected to contribute optimally to the system's N supply after the *Desmodium* plants have produced substantial amounts of biomass.

IR-maize significantly reduced *Striga* emergence in most seasons, and delayed the time to emergence by, on average, one to two weeks compared to the local maize variety (data not shown). Early attachments have more effect on maize yield compared to late attachment (Kanampiu et al., 2003). De Groote et al. (2007), for instance, showed that a *Striga* plant that emerged after six weeks had a larger impact on yield reduction than one that emerged two weeks later. Even a few plants (two to three) can cause substantial yield reduction by *Striga* because

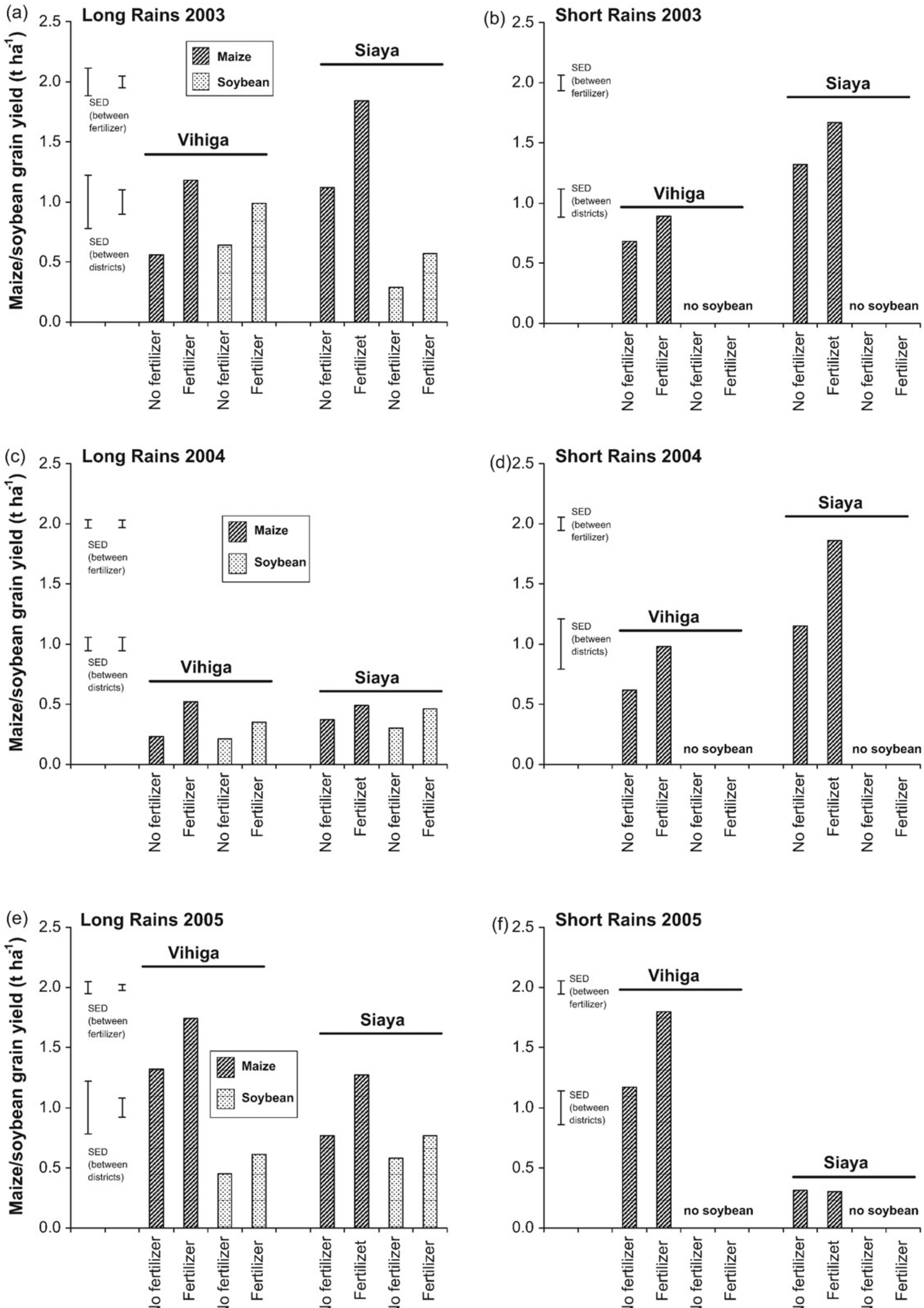

Fig. 8. Maize and soybean grain yield for the 'district × fertilizer application' interaction. Treatments indicated with 'no soybean' did not have a soybean in that particular season. 'SED' refers to 'Standard Error of the Difference' and in graphs with four SEDs, the left ones refer to the maize crop and the right ones to the soybean crop.

of hormonal imbalance in the plant (Gurney et al., 1995). *Striga* emergence under IR-maize is not totally prevented since the activity of the herbicide coating is likely to decrease in time due to dilution of the herbicide around the seed by infiltrating rainfall and adsorption of the herbicide to the soil matrix (Pusino et al., 1997). Inclusion of IR-maize in the push–pull system could reduce *Striga* emergence during the first seasons while the *Desmodium* is being established, thus offering *Striga*

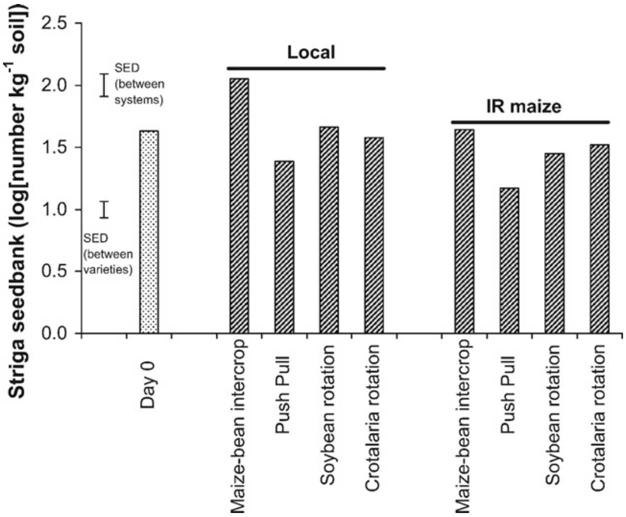

Fig. 9. *Striga* seedbank for the 'variety × cropping system' interaction, before the 2005 short rainy season. 'SED' and 'IR' refer to 'Standard Error of the Difference' and 'Imazapyr-coated herbicide-resistant maize', respectively. The left bar labelled as 'Day zero' shows the average *Striga* seedbank at the start of the trial (before the 2003 long rainy season).

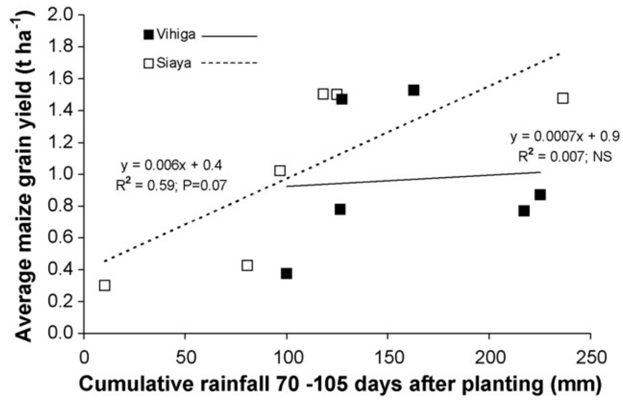

Fig. 10. Relationship between average maize grain yield and cumulative rainfall between 70 and 105 days after planting for Vihiga and Siaya district.

control during the first season. Inclusion of a legume phase in a rotational system and application of fertilizer did not significantly affect *Striga* emergence, relative to the maize-bean intercrop. Earlier reports have suggested that fertilizer application can reduce *Striga*-inflicted crop damage, but this may be the result of a healthier crop rather than reduced *Striga* emergence (Mumera and Below, 1993; Showemimo et al., 2002).

An important feature of any technology that aims at reducing *Striga* damage is its potential to reduce the *Striga* seedbank. *Striga* is very prolific and seeds can remain viable for a long time (Parker and Riches, 1993). The *Striga* seedbank was significantly lower in the push–pull system than in the maize-bean intercrop with both local and IR-maize varieties. In the treatments with IR-maize, herbicide that is diluted in the rhizosphere can imbibe *Striga* seeds in the soil and thus reduce the *Striga* seedbank, as demonstrated in the maize-bean intercrop (Fig. 9) (Kanampiu et al., 2002). The maize-bean intercrops were observed to increase the seedbank, probably due to flowering *Striga* plants in this treatment, re-infesting the soil. Although, the average *Striga* seedbank under both soybean and *Crotalaria* was lower than under the maize-bean intercrop, especially for the treatments with local varieties (Fig. 9), these differences were not significant ($P = 0.08$–0.13). This indicates that more seasons would be needed for the used legumes to significantly reduce the seedbank through suicidal germination of the *Striga* seeds. Earlier, Gacheru and Rao (2001) had observed that *Crotalaria* could reduce the *Striga* seedbank. As for soybean, a large variation in suicidal germination potential has been observed for different soybean varieties (Sanginga et al., 2003). Obviously, the current data are based on two legume seasons only and more seasons may be required to visibly reduce the *Striga* seedbank. Important to note, however, is that due to the relatively small plot size, the overall seedbank reduction is probably overestimated since there would be a more considerable re-innoculation in larger plots (Parker and Riches, 1993).

Overall, maize yields were rather low, ranging from 0.3 to 1.6 t ha^{-1}, averaged across all treatments, districts and seasons. The relatively low yields are likely to be the result of a combination of factors affecting yields in the various cropping systems. First, there was drought stress during maize filling in the SR2004 and SR2005 seasons. This affected maize yield in Siaya but not in Vihiga, because maize in Vihiga was planted earlier (Fig. 10). Secondly, there were effects caused by the cropping system. Maize yields were likely affected by *Striga* in the rotational systems, because the *Striga* seedbank was large (about 60 million seeds ha^{-1}, Fig. 9), and the legumes did little to alleviate the problem. Thirdly, in the push–pull system, where both *Striga* emergence and the proportion of maize plants affected by stemborer were relatively low, maize occupied only 66% of the total cropped area, thus resulting in deflated yields. When push–pull systems are implemented at larger scale, however, this factor can be increased to 91% while still retaining the benefits of Napier grass (Khan, unpublished data). Fourthly, maize yields in the push–pull systems may also have been reduced through competition between the maize and the *Desmodium* and/or Napier, especially under drought stress. Although IR-maize significantly reduced *Striga* emergence in most sites, this was not reflected in increased maize yields, which could be related to earlier observations demonstrating that the yield potential of IR-maize is likely not exceeding that of the locally available varieties. This indicates a need to back-cross the IR-gene conferring material into locally adapted material to control both *Striga* and improve yields. The IR-maize variety used in the current work is one of the earlier developed varieties that are being improved through on-going breeding programs (Diallo and Makumbi, 2006).

Overall stemborer damage was low and variable, with Siaya district showing consistently more damage than Vihiga district except for the LR2003 season. Although, relationships between stemborer damage and yield loss depend on a large number of factors (e.g., stage of the crop attached, density of the stemborer population at the time of attach, and cultivar grown) (Seshu Reddy and Walker, 1990), with the current damage rates, yield losses are expected to be minimal. Stemborer damage also appeared to be higher during the short than during the long rainy seasons. Since rainfall is a major mortality factor for young stemborer larvae (Bonhof and Overholt, 2001) and since Siaya district received less rainfall than Vihiga district, survival of stemborers is expected to be greater in the former district. Similarly, Ndemah and Schulthess (2002) observed that stemborer populations in Cameroon were generally higher during short rainy seasons due to higher survival rates of young larvae occasioned by less rainfall. Results of the current study show a general effectiveness of the push–pull technology in controlling stemborers, consistent with earlier reports (Khan et al., 2001; Midega et al., 2005), but only after the first cropping season. A general observation made was that the companion crops, particularly *Desmodium*, took longer to establish, accounting for the results observed in the first cropping season (LR2003).

While some of the tested options showed considerable impact on alleviating *Striga* and stemborer-related constraints, impacts on the overall soil fertility status were minimal, probably due to the relatively short time span of the trial. More seasons are needed to judge whether specific technologies can be classified as Integrated Pest and Soil Fertility Management (IPSFM) options that address both pest and soil fertility-related constraints.

5. Conclusions

Amongst all systems tested, the push–pull system was shown to reduce *Striga* emergence and stemborer damage, from the second season onwards. IR-maize consistently reduced *Striga* emergence from the first season onwards. The other cropping systems neither affect *Striga* emergence nor stemborer damage relative to the maize-bean intercrop control treatment. Above differences in alleviating pest constraints were not expressed in differences in maize grain yield between the rotational and the push–pull systems, probably due to a shift in growth-limiting factors. IR-maize and the push–pull system were observed to reduce the *Striga* seedbank suggesting a potential for integration of these components to deal with *Striga* in both the short and the medium term. Short-term effects on soil fertility-related properties were minimal. Finally, farmer-managed adaptation trials, in which farmers themselves will implement, evaluate, and adapt the various technologies, are needed to get firm information on the necessary conditions for each of the above technologies to be adoptable by many farmers. Medium to long-term trials are desirable to evaluate the impact of different cropping system scenarios on grain yields and soil fertility.

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References

Bonhof, M.J., Overholt, W.A., 2001. Impact of solar radiation, rainfall and cannibalism on disappearance of maize stemborers in Kenya. Insect Science and its Application 21, 403–407.

Cambridge Economic Policy Associates (CEPA), 2004. Business Plan: Striga Control in Africa. London, UK.

Carsky, R.J., Berner, D.K., Oyewole, B.D., Dashiell, K., Schulz, S., 2000. Reduction of *Striga hermonthica* parasitism on maize using soybean rotation. International Journal of Pest Management 46, 115–120.

Chamberlain, K., Khan, Z.R., Pickett, J.A., Toshova, T., Wadhams, L.J., 2006. Diel periodicity in the production of green leaf volatiles by wild and cultivated host plants of stemborer moths, *Chilo partellus* and *Busseola fusca*. Journal of Chemical Ecology 32, 565–577.

De Groote, H., 2002. Maize yield losses from stemborers in Kenya. Insect Science and its Application 22, 89–96.

De Groote, H., Bett, C., Okuro, J.O., Odendo, M., Mose, L., Wekesa, E., 2004. Direct estimation of maize crop losses due to stemborers in Kenya, preliminary results from 2000 and 2001. In: Friesen, D.K., Palmer, A.F.E. (Eds.), Integrated Approaches to Higher Maize Productivity in the New Millennium. Proceedings of the 7th Eastern and Southern Africa Regional Maize Conference, CIMMYT, Mexico, D.F., Mexico, pp. 401–406.

Diallo, A.O., Makumbi, D., 2006. Summary of 2006 Breeding Activities. International Maize and Wheat Improvement Centre (CIMMYT), Mexico City, Mexico.

De Groote, H., Wangare, L., Kanampiu, F., Odendo, M., Diallo, A., Friesen, D., 2005. Potential markets for herbicide resistant maize seed for *Striga* control in Africa. In: Poster paper presented at the European Association of Agricultural Economists Congress, Copenhagen, Denmark.

De Groote, H., Wangare, L., Kanampiu, F., 2007. Evaluating the use of herbicide-coated imidazolinone-resistant (IR) maize seeds to control Striga in farmers’ fields in Kenya. Crop Protection 26, 1496–1506.

Emechebe, A.M., Ahonsi, M.O., 2003. Ability of excised root and stem pieces of maize, cowpea and soybean to cause germination of *Striga hermonthica* seeds. Crop Protection 22, 347–353.

Eplee, R.E., 1976. Determination of *Striga* Seeds in Soil. USDA Witchweed laboratory, Whiteville, North Carolina, USA.

Erenstein, O., 2002. Crop residue mulching in tropical and semi-tropical countries: an evaluation of residue availability and other technological implications. Soil and Tillage Research 67, 115–133.

FAO, 1991. World Soil Resources: An Explanatory Note on the FAO World Soil Resources. Map at 1:25,000,000 scale. Food and Agriculture Organisation of the United Nations, Rome, Italy.

Gacheru, E., Rao, M.R., 2001. Managing *Striga* infestation on maize using organic and inorganic nutrient sources in western Kenya. International Journal of Pest Management 47, 233–239.

Grisley, W., 1997. Crop pest yield loss: a diagnostic study in the Kenya highlands. International Journal of Pest Management 43, 137–142.

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

Hassan, R., Ransom, J.K., Ojiem, J.O., 1995. The spatial distribution and farmers strategies to control *Striga* in Corn: survey results from Kenya. In: Jewell, D.C., Waddington, S., Ransom, J.K., Pixley, K. (Eds.), Proceedings of the Fourth Eastern and Southern Africa Regional Corn Conference. CIMMYT, Harare, Zimbabwe, pp. 250–254.

ICRAF, 1995. Laboratory Methods of Soil and Plant Analysis. International Centre for Research in Agroforestry, Nairobi, Kenya.

Kanampiu, F.K., Ransom, J.K., Friesen, D., Gressel, J., 2002. Imazapyr and pyrithiobac movement in soil and from maize seed coats to control *Striga* in legume intercropping. Crop Protection 21, 611–619.

Kanampiu, F.K., Kabambe, V., Massawe, C., Jasi, L., Friesen, D., Ransom, J.K., Gressel, J., 2003. Multi-site, multi-season field tests demonstrate that herbicide seed-coating herbicide-resistance maize controls *Striga* spp. and increases yields in several African countries. Crop Protection 22, 697–706.

Kariuki, J.N., Gitau, G.K., Gachuiri, C.K., Tamminga, S., Muia, J.M.K., 1999. Effect of supplementing Napier grass with *Desmodium* and lucerne on DM CP and NDF intake and weight gains in dairy heifers. Livestock Production Science 60, 81–88.

Khan, Z.R., Pickett, J.A., 2004. The 'Push–Pull' strategy for stemborer management: a case study in exploiting biodiversity and chemical ecology. In: Gurr, G., Waratten, S.D., Altieri, M.A. (Eds.), Ecological Engineering for Pest Management: Advances in Habitat Manipulations for Arthropods. CSIRO and CABI Publishing, Wallingford, UK, pp. 155–164.

Khan, Z.R., Pickett, J.A., Van den Berg, J., Wadhams, L.J., Woodcock, C.M., 2000. Exploiting chemical ecology and species diversity: stemborer and *Striga* control for maize and sorghum in Africa. Pest Management Science 56, 957–962.

Khan, Z.R., Pickett, J.A., Wadhams, L.J., Muyekho, F., 2001. Habitat management strategies for the control of cereal stemborers and *Striga* in maize in Kenya. Insect Science and Application 21, 375–380.

Khan, Z.R., Pickett, J.A., Wadhams, L.J., Hassanali, A., Midega, C.A.O., 2006. Combined control of *Striga hermonthica* and stemborers by maize—*Desmodium* spp. intercrops. Crop Protection 25, 989–995.

Midega, C.A.O., Khan, Z.R., Van den Berg, J., Ogol, C.K.P.O., 2005. Habitat management and its impact on maize stemborer colonization and crop damage levels in Kenya and South Africa. African Entomology 13, 333–340.

Miller, J.R., Cowles, R.S., 1990. Stimulo-deterrent diversion: a concept and its possible application to onion maggot control. Journal of Chemical Ecology 16, 3197–3212.

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

Ndemah, R., Schulthess, F., 2002. Yield of maize in relation to natural field infestations and damage by lepidopteran borers in the forest and forest/savanna transition zones of Cameroon. Insect Science and Applications 22, 183–192.

Ndung'u, D., Odhiambo, G.D., Ransom, J.K., 1993. Methodology for quantifying *Striga* seed numbers in soils of East Africa. In: African Crop Science Conference Proceedings, Kampala, Uganda, pp. 220–221.

Odendo, M., De Groote, H., Odongo, O.M., 2001. Assessment of farmers' preferences and constraints to maize production in the moist Midaltitude zone of western Kenya. In: ACSA (Eds.), African Crop Science Conference Proceedings. African Crop Science Association, Kampala, Uganda, pp. 769–775.

Oswald, A., 2005. *Striga* control—technologies and their dissemination. Crop Protection 24, 333–342.

Parker, C., Riches, C.R., 1993. Parasitic Weeds if the World: Biology and Control. CAB International, Wallingford, UK.

Pusino, A., Petretto, S., Gessa, C., 1997. Adsorption and desorption of imazapyr by soil. Journal of Agricultural and Food Chemistry 45, 1012–1016.

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

Sanginga, N., Okogun, J., Vanlauwe, B., Dashiell, K., 2002. The contribution of nitrogen by promiscuous soybeans to maize base cropping in the moist savanna of Nigeria. Plant and Soil 241, 223–231.

Sanginga, N., Dashiell, K., Diels, J., Vanlauwe, B., Lyasse, O., Carsky, R.J., Tarawali, S., Asafo-Adjei, B., Menkir, A., Schulz, S., Singh, B.B., Chikoye, D., Keatinge, D., Rodomiro, O., 2003. Sustainable resource management coupled to resilient germplasm to provide new intensive cereal–grain legume–livestock systems in the dry savanna. Agriculture, Ecosystems and Environment 100, 305–314.

SAS, 1992. The MIXED procedure. SAS Technical Report P-229: SAS/STAT Software: Changes and Enhancements. SAS Institute Inc., Cary, NC, USA.

Seshu Reddy, K.V., Walker, P.T., 1990. A review of yield losses in graminaceous crops caused by Chilo partellus. Insect Science and its Application 11, 563–569.

Showemimo, F.A., Kimbeng, C.A., Alabi, S.O., 2002. Genotypic response of sorghum cultivars to nitrogen fertilization in the control of *Striga hermonthica*. Crop Protection 21, 867–870.

Spilke, J., Piepho, H.P., Hu, X., 2005. Analysis of unbalanced data by mixed linear models using the MIXED procedure of the SAS system. Journal of Agronomy and crop science 191, 45–54.

Tsanuo, M.K., Hassanali, A., Hooper, A.M., Khan, Z.R., Kaberia, F., Pickett, J.A., Wadhams, L., 2003. Isoflavanones from the allelopathic aqueous root exudates of *Desmodium uncinatum*. Phytochemistry 64, 265–273.

Tittonell, P., Vanlauwe, B., Leffelaar, P.A., Rowe, E., Giller, K.E., 2005. Exploring diversity in soil fertility management of smallholder farms in western Kenya. I. Heterogeneity at region and farm scale. Agriculture, Ecosystems and Environment 110, 149–165.

Tokatlidis, I.S., Koutroubas, S.D., 2004. A review of maize hybrids' dependence on high plant populations and its implications for crop yield stability. Field Crops Research 88, 103–114.

Van den Berg, J., Nur, A.F., Polaszek, A., 1998. Cultural control. In: Polaszek, A. (Ed.), African Cereal Stemborers: Economic Importance, Taxonomy, Natural Enemies and Control. CAB International, Wallington, UK, pp. 333–347.

Vanlauwe, B., Bationo, A., Carsky, R.J., Diels, J., Sanginga, N., Schulz, S., 2003. Enhancing the contribution of legumes and biological nitrogen fixation in cropping systems: experiences from West Africa. In: Grain Legumes and Green Manures of Soil Fertility in Southern Africa: Taking Stock of Progress, CIMMYT, Harare, Zimbabwe, pp. 3–13.

Vanlauwe, B., Tittonell, P., Mukalama, J., 2006. Within-farm soil fertility gradients affect response of maize to fertilizer application in western Kenya. Nutrient Cycling in Agroecosystems 76, 171–182.