International Journal of Pest Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/ttpm20

Integrated management of Striga hermonthica and cereal stemborers in finger millet (Eleusine coracana (L.) Gaertn.) through intercropping with Desmodium intortum

Charles A.O. Midega [a] , Zeyaur R. Khan [a] , David M. Amudavi [a b] , Jimmy Pittchar [a] & John A. Pickett [c]

[a] International Centre of Insect Physiology and Ecology (ICIPE), Nairobi, Kenya
[b] Egerton University, Njoro, Kenya
[c] Biological Chemistry Division, Rothamsted Research, Harpenden, UK

Version of record first published: 25 Mar 2010.

International Journal of Pest Management
Vol. 56, No. 2, April–June 2010, 145–151

Taylor & Francis
Taylor & Francis Group

Integrated management of *Striga hermonthica* and cereal stemborers in finger millet (*Eleusine coracana* (L.) Gaertn.) through intercropping with *Desmodium intortum*

Charles A.O. Midega[a], Zeyaur R. Khan[a]*, David M. Amudavi[a,b], Jimmy Pittchar[a] and John A. Pickett[c]

[a]*International Centre of Insect Physiology and Ecology (ICIPE), Nairobi, Kenya;* [b]*Egerton University, Njoro, Kenya;* [c]*Biological Chemistry Division, Rothamsted Research, Harpenden, UK*

(*Received 23 April 2009; final version received 11 August 2009*)

We evaluated the potential role of greenleaf desmodium, *Desmodium intortum* (Mill.) Urb., in the combined management of *Striga hermonthica* and cereal stemborers in finger millet (*Eleusine coracana* (L.) Gaertn.) in western Kenya between 2007 and 2008. Treatments comprised finger millet planted either as monocrop stands or intercropped with *D. intortum*. *S. hermonthica* counts were significantly lower in the intercrop than in the monocrop plots. Similarly, multi-season analyses showed that the proportions of stemborer-damaged plants were significantly lower in the intercrop than in the monocrop. These differences were associated with significantly higher grain yields in the intercrop than in the monocrop. Total labour and variable costs were significantly higher in the intercrop resulting from the additional seed cost and labour to plant, manage and harvest *D. intortum*. However, total revenue and gross margins were significantly higher in the intercrop due to the higher finger millet grain yields and additional product, *D. intortum* forage, part of which is consumed by farmers' own livestock or used for own plot extension, and the remaining amount is sold. Our results demonstrate that intercropping finger millet with *D. intortum* offers an effective means of control of both pests, leading to higher grain yields and economic returns.

Keywords: intercropping; finger millet; *Desmodium intortum*; *Striga hermonthica*; stemborer; control; economic returns

1. Introduction

Finger millet (*Eleusine coracana* (L.) Gaertn.), also known as African millet, is one of the main cereal crops grown in the drier areas of Asia and Africa. It is grown globally on over 4 million hectares and is the primary food and cash crop for millions of people in tropical dryland regions (Belton and Taylor 2004). It is indigenous to Eastern Africa where it is grown by smallholder farmers, with Uganda (up to 500,000 ha), Ethiopia (238,000 ha) and Kenya (around 65,000 ha) being some of the major producers of the crop in the region (National Research Council 1996; Takan et al. 2002). Finger millet has outstanding attributes as a subsistence food and fodder crop, and has nutritional qualities superior to rice and is equivalent to wheat (Madhavi et al. 2005). It has superior storage qualities, enabling safe storage for several years, making it a traditional component of farmers' risk-avoidance strategies in drought-prone areas where environmental stresses, particularly hot and dry conditions, limit the production of other crops (Naylor et al. 2004).

Despite the importance of finger millet as a food, cash and fodder crop, its productivity remains low in most of the areas where it is grown. Reported increases in total production in some areas in recent years have been as a result of cultivation of more land (Belton and Taylor 2004). This continuous extension of cultivated area is environmentally damaging and unsustainable, and thus technologies are needed that increase productivity per unit area of available land. Apart from lack of irrigation and fertilizer for finger millet cultivation, insect pests, weeds and diseases cause huge losses in many parts of the world. In sub-Saharan Africa (SSA), the main biotic constraints to efficient production of finger millet are lepidopteran stemborers (Haile and Hofsvang 2001) and the parasitic weeds in the genus *Striga* (Nyende et al. 2001).

The major cereal stemborer species, *Busseola fusca* Füller (Lepidoptera: Noctuidae) and *Chilo partellus* Swinhoe (Lepidoptera: Crambidae), cause significant grain yield losses in cereals estimated at 10–88% (Kfir et al. 2002). They are, however, difficult to manage due to the nocturnal behavior of the adult moths and the protection provided to the larvae and pupae by the stems of the host plants (Khan et al. 1997b). *Striga* spp. (Scrophulariaceae), on the other hand, are obligate root parasites that inhibit normal host growth via three processes; competition for nutrients, impairment of photosynthesis (Joel 2000) and a phytotoxicity within days of attachment to its hosts (Gurney et al. 2006). There are about 23 species of *Striga* in SSA, with *S. hermonthica* as the most socio-economically important in eastern Africa (Gethi et al. 2005). *Striga* has infested over 40% of arable land in SSA (Lagoke et al. 1991)

*Corresponding author. Email: zkhan@mbita.mimcom.net

ISSN 0967-0874 print/ISSN 1366-5863 online

DOI: 10.1080/09670870903248843
http://www.informaworld.com

and causes yield losses of up to 100% (Hassan et al. 1994). Problems with *Striga* are most severe in degraded environments, with low soil fertility and low rainfall, and under subsistence farming systems with few options for external inputs (Sauerborn et al. 2003).

Several technologies have been employed for control of *Striga* in subsistence cereal production systems in SSA, based on the principles of reducing the number of *Striga* seeds in the soil, preventing production of new seeds and spread from infested to non-infested soils (Oswald 2005). These have been tried with limited and localized success. Adoption of most of the recommended methods has been limited, largely due to lack of immediate returns and the prohibitive cost of the technologies (Oswald 2005). Similarly, uptake of most of the approaches recommended for control of stemborers has been limited due to biological and socio-economic factors (Kfir et al. 2002).

Desmodium spp., planted as an intercrop between cereals, repel stemborer moths and also suppress and eliminate *Striga hermonthica* through a number of mechanisms, with an allelopathic effect being the most important (Khan et al. 2002). The combined control of stemborers and *Striga* leads to significant increases in maize (Khan et al. 2006c) and sorghum (Khan et al. 2006b) grain yields and higher economic returns (Khan et al. 2008b).

This study was aimed at assessing the potential role of greenleaf desmodium, *Desmodium intortum* (Mill.) Urb., in the control of stemborers and *S. hermonthica* in finger millet. *D. intortum* is relatively more drought-tolerant than the other *Desmodium* spp. (Ostrowski 1966), with relatively higher nitrogen-fixing ability, over 300 kg N/ha/year under optimum conditions (Whitney 1966). The results from this study would lead to development of a suitable strategy for combined management of these constraints in finger millet for the drier environments where the crop is grown by resource-poor farmers.

2. Materials and methods

2.1. *Study sites and plot layout*

The study was conducted between the long (March to August) rainy season of 2007 and short (October to January) rainy season of 2008 at ICIPE Thomas Odhiambo Campus, Mbita Point (0°25′S, 34°12′E), on the eastern shores of Lake Victoria in western Kenya, where both *S. hermonthica* and stemborers are a serious limitation to cereal cultivation (Khan et al. 2006c).

Finger millet (var. Local) was planted either in sole stands (monocrop) or intercropped in alternate rows with *D. intortum* in experimental plots following the methodologies of Khan et al. (2006b). Finger millet was planted at a row-to-row distance of 60 cm and a plant-to-plant distance of 15 cm within a row. The layout comprised four large plots each measuring, 30 × 30 m where finger millet – *D. intortum* intercrop and the control were diagonally placed, with 2-m buffer strips between plots as described in Khan et al. (2006b). To facilitate sampling a method adapted from Khan et al. (2001) was used, with modifications, to create subplots within the established plots. Random-paired subplots of 8 × 8 m along perpendicular transect lines bisecting both treatment and control plots were demarcated with four replications in each plot.

2.2. *Stemborer and* Striga *infestation*

Stemborer and *S. hermonthica* infestation levels were assessed non-destructively, using methodologies adapted from Khan et al. (2006b,d). At 4 weeks after emergence (WAE) of finger millet, 84 plants were randomly selected in each plot and tagged for subsequent assessments. To assess stemborer infestation levels, the number of tagged plants with characteristic ‘window-paned’ and ‘pin-holed’ leaves, and/or dead-hearts arising from stemborer larval feeding (Ampofo 1986) was recorded at 6 and 10 WAE. This damage was expressed as the percentage of finger millet plants damaged by stemborers. The number of emerged *S. hermonthica* plants was determined by counting these from within a radius of 15 cm at the base of each of the tagged finger millet plants at 6, 8 and 10 WAE. The data were expressed as the number of emerged *S. hermonthica* per 84 plants.

2.3. *Plant height and grain yields*

At full physiological maturity, heights of the tagged plants were measured and averaged for each subplot. All the plants in each subplot were then harvested and grains sun-dried separately to 12% moisture content and grain weights taken. These were then converted into kg/hectare.

2.4. *Economics and statistical analyses*

To evaluate any economic benefits of intercropping finger millet with *D. intortum*, analyses were conducted using methodologies adapted from Khan et al. (2008a), where total labour costs (TLC), total non-labour costs (TNLC), total variable costs (TVC), total revenues (TRV) and gross margins (GMN) were calculated for each sub plot as follows:

$$\mathrm{TLC} = \sum_{i=1}^{n} x_i \tag{1}$$

where x_i is the amount of money paid for the labour of carrying out activity i.

$$\mathrm{TNLC} = \sum_{i=1}^{k} y_i \tag{2}$$

where y_i is the amount of money used to buy non-farm input i such as seeds and fertilizers

$$\mathrm{TVC} = \mathrm{TLC} + \mathrm{TNLC} \quad (3)$$

$$\mathrm{TRV} = \sum_{i=1}^{K} z_i \quad (4)$$

where z_i is the amount of money generated from the sale of plot output i, including finger millet grain and stover, and desmodium forage.

$$\mathrm{GMN} = \mathrm{TRV} - \mathrm{TVC} \quad (5)$$

These were carried out for only three seasons (long and short rains of 2007, and long rains of 2008). The inputs and outputs considered in these analyses are summarized in Table 1, while the amounts of Kenyan shillings were converted to US dollars (exchange rate: USD 1.0 = Kshs 75) prior to analysis. Throughout the study period, prices of the commodities did not change (*D. intortum* forage, finger millet stover and finger millet grains sold at approximately 0.03 USD/kg, 0.007 USD/kg and USD 0.9/kg, respectively).

For each year, season and time (weeks after finger millet emergence), a two-sample *t*-test (SAS Institute 2002) was used to assess the effect of treatment (finger millet – *D. intortum* intercrop and finger millet monocrop) on *S. hermonthica* counts, percentage plant damage due to stemborers and the economic parameters. Plant height and grain yields were similarly compared between treatments using a two-sample *t*-test. *S. hermonthica* counts were expressed as $\log(x + 1)$ and percentage plant damage was arcsine – transformed prior to analysis. The significance level was set at $\alpha = 0.05$ for all analyses.

Table 1. The farm activities, inputs and outputs that were included in the financial analyses.

Treatments	Finger millet monocrop	Finger millet – *D. intortum* intercrop
Labour costs	Plant finger millet	Plant finger millet
	1st weeding	Plant desmodium[1]
	2nd weeding	Weeding desmodium[2]
	CAN topdressing	1st weeding
	Harvesting finger millet	2nd weeding
	Threshing finger millet	CAN topdressing
		Harvesting finger millet
		Threshing finger millet
		Harvesting desmodium forage
Non Labour Costs	Plough	Plough
	Harrow	Harrow[1]
	Finger millet seeds	Finger millet seeds
	DAP/CAN	DAP/CAN
		Desmodium seeds
Outputs	Finger millet grain	Finger millet grain
	Stover	Stover
		Desmodium forage

Notes: [1]*D. intortum* is a perennial crop and is planted and hand-weeded only in the first season. Harrowing is done only in the first season under desmodium.
[2]There is no second weeding in the intercrop after the first cropping season.

3. Results

3.1. *Stemborer and* Striga *infestation*

Striga hermonthica counts were significantly lower in the intercrop than in the monocrop plots during most of the study period ($P < 0.05$, *t*-test) except on the sixth week after plant emergence during the short rainy season of 2008 (Table 2). Seasonally, average *S. hermonthica* counts per 84 finger millet plants in the monocropped plots ranged between 4.5 and 2386.7 during the short rainy season of 2008 and long rainy season of 2007, respectively. Conversely, they ranged between 0.7 and 14.0 during the long rainy seasons of 2008 and 2007, respectively, in the plots intercropped with *D. intortum*. Overall, there were seasonal reductions in *S. hermonthica* infestation in the intercropped plots of between 96 and 99% (Table 2).

Seasonally, the proportions of stemborer-damaged plants were generally low, often below 10%, and not significantly different between treatments, except at 10 WAE during the 2007 and 2008 short and long rainy seasons respectively when they were significantly higher in the monocrop (13.6 and 23.9%, respectively) than in the intercrop (8 and 4.2%, respectively) (Table 3).

3.2. *Plant height, grain yields, finger millet stover and* D. intortum *forage*

Plant height did not significantly differ between treatments except during the short rainy season of 2008 when plants were significantly taller in the intercrop (103.9 and 78.3 cm in the intercrop and monocrop, respectively) (Table 4). Grain yields on the other hand were significantly higher ($P < 0.05$, *t*-test) in the intercropped than in the monocropped plots during the entire study period (Table 4). Seasonally they ranged between 240.6 and 598.9 kg/ha in the monocropped plots during the long rainy seasons of 2007 and 2008 respectively and 695.2 and 943.8 kg/ha during the long rainy seasons of 2007 and 2008 respectively in the intercropped plots. Overall, there were seasonal increases in grain yields of up to about 192%.

The amount of finger millet stover harvested was significantly higher in the intercropped than in the monocropped plots ($P < 0.05$, *t*-test), ranging between 13788.5 and 15049.7 kg/ha in the former, and between 4029.6 and 4852 kg/ha in the latter. *D. intortum* forage on the other hand ranged between 14,309.3 and 15,817.0 kg/ha, Table 5).

Table 2. Mean (±SE) seasonal *Striga hermonthica* counts in finger millet plots planted in sole stands or intercropped with *Desmodium intortum*, at 6, 8 and 10 weeks after crop emergence.

			Mean number of emerged *Striga*/84 finger millet plants			
Year	Season	WAE	Finger millet monocrop	Finger millet – *D. intortum*	*t* value	*P* value
2007	Long Rains	6	358.9(59)	6.6(2)	−10.8	<0.01
		8	470.2(89)	14.0(3)	−10.9	<0.01
		10	2386.7(108)	6.6(2)	−29.1	<0.01
2007	Short Rains	6	87.9(27)	3.5(2)	−4.8	<0.01
		8	402.9(21)	10.6(4)	−14.6	<0.01
		10	1932.7(121)	10.1(3)	−22.7	<0.01
2008	Long Rains	6	52.0(8)	0.7(1)	−13.6	<0.01
		8	197.5(16)	6.5(2)	−17.9	<0.01
		10	283.5(12)	11.7(3)	−12.7	<0.01
2008	Short Rains	6	4.5(3)	4.4(1)	1.36	0.195
		8	23.6(4)	4.5(1)	−4.1	<0.01
		10	175.2(22)	5.5(2)	−15.4	<0.01

Note: WAE, weeks after emergence of finger millet plants.

Table 3. Mean (±SE) percentage stemborer damaged plants in finger millet sole stands or intercropped with *Desmodium intortum*.

			% of finger millet plants damaged by stemborers			
Year	Season	WAE	Finger millet monocrop	Finger millet – *D. intortum*	*t* value	*P* value
2007	Long Rains	6	4.9(2)	3.4(1)	−0.8	0.42
		10	9.6(3)	7.9(2)	−0.5	0.63
2007	Short Rains	6	5.7(1)	4.9(1)	−0.7	0.49
		10	13.6(2)	8.0(1)	−3.0	0.01
2008	Long Rains	6	5.5(1)	3.6(1)	−1.4	0.19
		10	23.9(4)	4.2(1)	−4.4	<0.01
2008	Short Rains	6	0.4(0.3)	1(1)	0.8	0.45
		10	3.4(1)	3.6(1)	0.2	0.86

Note: WAE, weeks after emergence of finger millet plants.

3.3. Multi-season analyses

Data averaged over four seasons showed that there were significant reductions in both *S. hermonthica* counts and proportions of stemborer damaged plants ($P < 0.05$, *t*-test) (Table 5). Similarly, plants were significantly taller and grain yields significantly higher in the intercropped than in the monocropped plots. Intercropping finger millet with *D. intortum* led to an average of 99.3% reduction in *S. hermonthica* emergence and 53.2% reduction in percentage of millet plants damaged by stemborers (Table 6). Intercropping with *D. intortum* also caused 8.7 and 107.2% increases in plant height and grain yields respectively (Table 6).

3.4. Economic evaluations

Total labour costs, which accounted for up to 37% of the total variable costs, were significantly higher in the intercropped than monocropped plots ($P < 0.05$, *t*-test) during the three cropping seasons. They ranged between an average of USD 185/ha and 195.1/ha in the monocropped plots during the long rainy seasons of 2008 and 2007, respectively, and USD 288.3/ha and 306.1/ha in the intercropped plots during the long rainy seasons of 2007 and 2008, respectively (Table 7). Total variable costs followed the same trend where they were significantly higher in the intercropped than in the monocropped plots throughout the study period ($P < 0.05$, *t*-test). They ranged between USD 703.7/ha and 713.8/ha during the long rainy seasons of 2008 and 2007 respectively, in the monocropped plots and USD 806.9/ha and 866.8/ha during the short and long rainy seasons of 2007 respectively in the intercropped plots.

On the other hand, total revenue from sale of produce from the plots and gross margins were significantly higher in the intercropped than monocropped plots ($P < 0.05$, *t*-test). Revenue per hectare ranged between USD 235.4 and 467.9 during the long rainy seasons of 2007 and 2008 respectively in the monocropped plots and USD 1084.4 and 1324.7 during the long and short rainy seasons of 2007, respectively, in the intercropped plots. In terms of gross margins, the monocropped plots realized a loss ranging between USD 147.6 and USD 478.3/ha during the long rainy seasons of 2008 and 2007, respectively, whereas the

Table 4. Mean (±SE) height (cm) and grain yields (kg/ha) of finger millet planted in sole stands or intercropped with *Desmodium intortum*.

Year	Season	Treatment	Mean ± SE	*t* value	*P* value
Plant height (cm)					
2007	Long Rains	Finger millet – *D. intortum*	100.6(2)	0.44	0.67
		Finger millet monocrop	99.6(1)		
2007	Short Rains	Finger millet – *D. intortum*	105.4(3)	2.05	0.06
		Finger millet monocrop	97.1(3)		
2008	Long Rains	Finger millet – *D. intortum*	101.1(2)	−0.86	0.40
		Finger millet monocrop	102.8(2)		
2008	Short Rains	Finger millet – *D. intortum*	103.9(3)	7.12	<0.01
		Finger millet monocrop	78.3(2)		
Grain yields (kg/ha)					
2007	Long Rains	Finger millet – *D. intortum*	695.2(78)	5.49	<0.01
		Finger millet monocrop	240.6(27)		
2007	Short Rains	Finger millet – *D. intortum*	935.8(90)	5.78	<0.01
		Finger millet monocrop	320.8(57)		
2008	Long Rains	Finger millet – *D. intortum*	943.8(45)	5.45	<0.01
		Finger millet monocrop	598.9(44)		
2008	Short Rains	Finger millet – *D. intortum*	882.3(75)	3.99	<0.01
		Finger millet monocrop	508.0(56)		

Table 5. Mean (±SE) finger millet stover and *Desmodium intortum* forage (kg/ha).

Year	Season	Treatment	Mean ± SE	*t* value	*P* value
Finger millet stover (kg/ha)					
2007	Long Rains	Finger millet – *D. intortum*	15049.7(402)	20.6	<0.01
		Finger millet monocrop	4029.6(353)		
2007	Short Rains	Finger millet – *D. intortum*	13788.5(303)	28.4	<0.01
		Finger millet monocrop	4276.0(144)		
2008	Long Rains	Finger millet – *D. intortum*	14336.7(458)	18.8	<0.01
		Finger millet monocrop	4852.0(209)		
Desmodium intortum forage (kg/ha) from the intercropped plots					
2007	Long Rains	Finger millet – *D. intortum*	14309.3(742)	–	–
2007	Short Rains	Finger millet – *D. intortum*	15817.0(489)	–	–
2008	Long Rains	Finger millet – *D. intortum*	14391.6(795)	–	–

Note: –, no statistics since *D. intortum* was only planted in the intercrop.

Table 6. Multi-season analyses of emerged *Striga hermonthica*, percentage plants damaged by stemborers, plant height (cm) per plot and grain yields (kg/ha) of finger millet planted in sole stands or intercropped with *Desmodium intortum*. Means represent data averages of four seasons.

Treatment	Mean (±SE)	*t* value	*P* value
Emerged S. hermonthica*/plot*			
Finger millet – *D. intortum*	8.5(2)	−18.7	<0.01
Finger millet monocrop	1194.6(180)		
Mean % stemborer damaged plants			
Finger millet – *D. intortum*	5.9(1)	−3.3	<0.01
Finger millet monocrop	12.6(2)		
Plant height (cm)			
Finger millet – *D. intortum*	102.7(2)	3.6	<0.01
Finger millet monocrop	94.5(2)		
Grain yields (kg/ha)			
Finger millet – *D. intortum*	864.3(39)	8.5	<0.01
Finger millet monocrop	417.1(34)		

intercropped plots gained USD 217.5 and USD 517.8/ha during the long and short rainy seasons of 2007 respectively (Table 7).

4. Discussion and conclusions

Striga counts, both seasonal and multi-seasonal, were significantly lower in the intercropped than in the monocropped plots, while stemborer damage was only significantly lower in the former when considered multi-seasonally. The results of our study thus demonstrate that intercropping finger millet with *D. intortum* is effective in suppressing *S. hermonthica* and stemborers. The legume is perennial, requiring a one-time only investment, and is able to exert its *Striga* suppression activity even when the host plants are out of season, an attribute that makes it a more superior trap crop than the other legumes implicated in the control of *Striga* (Khan et al. 2007). Studies with other *Desmodium* spp.; *D. sandwicense* (Meyer) and *D. pringlei* (Watson), gave similar levels of *S. hermonthica* suppression with maize, suggesting general similarity in their secondary metabolism with that of *D. uncinatum* and the presence of similar or related chemical constituents in their root exudates (Khan et al. 2006c).

Table 7. Economics of intercropping finger millet with *Desmodium intortum* for control of *Striga hermonthica* and stemborers.

Season	Treatments	Total labour costs (USD/ha)	*t* value[1]	Total variable costs (USD/ha)	*t* value[1]	Total revenue (USD/ha)	*t* value[1]	Gross margins (USD/ha)	*t* value[1]
LR2007	Monocrop	195.1(3.1)		713.8(3.1)		235.4(23.6)		−478.3(23.3)	
	Intercrop	306.1(4.4)	20.5	866.8(4.4)	28.2	1084.4(80.0)	10.2	217.5(83.1)	8.1
SR2007	Monocrop	194.2(1.5)		712.9(1.5		306.6(49.2)		−406.3(49.2)	
	Intercrop	288.3(2.1)	36.2	806.9(2.1)	36.2	1324.7(77.4)	11.1	517.8(77.7)	10.1
LR2008	Monocrop	185.0(2.1)		703.7(2.1)		467.9(70.7)		−147.6(41.8)	
	Intercrop	301.1(3.2)	30.1	819.8(3.2)	30.1	1297.3(46.3)	9.8	477.5(48.1)	9.8

Note: LR2007 Long Rains 2007; SR2007 Short Rains 2007; LR2008 Long Rains 2008.
[1]All *t* values are associated with $P < 0.01$.

Polycultural systems often have fewer pest problems, partly due to reduced host searching efficiency by the herbivores and increased natural enemy abundance and activity (Root 1973). Previous studies have confirmed that intercropping maize or sorghum with *Desmodium* spp. significantly reduces stemborer infestation (e.g. Khan et al. 2008a; Vanlauwe et al. 2008). The main mechanism by which *Desmodium* spp. control stemborers is through constitutive production of volatile organic compounds (VOCs), such as (E)-β-ocimene and (E)- 4,8-dimethyl-1,3,7-nonatriene (Khan et al. 2000) which are not only repellent to ovipositing female moths but also increase foraging behaviour of stemborer parasitoids (Khan et al. 1997a, 2000). The inconsistent results obtained in the current study are explainable on the basis of the seasonal variations in stemborer infestation rates. Indeed, out of the eight observations taken, it was only on two occasions that the proportions of stemborer damaged plants were over 10%. However, multi-season analyses clearly showed a beneficial effect of intercropping finger millet with *D. intortum* in reducing stemborer infestations, even without the benefits of a trap crop.

Technologies that seek to alleviate biotic constraints to efficient production of crops have the primary goal of unlocking the crops' potential to increase grain yields. The results of the current study show that intercropping finger millet with *D. intortum* significantly enhances grain yields and stover weights through effective control of both *Striga* and stemborers. Additionally, desmodium has been found to conserve soil moisture, increase soil N and organic matter (Khan et al. 2006a), and improve ground dwelling arthropod abundance (Midega et al. 2008), factors that improve soil health and enhance agroecosystem productivity (Altieri and Nicholls 2003).

Such intercropping technologies could be of higher economic value, where farmers can grow fodder and sell or feed to their cattle, in addition to enhanced grain yields of finger millet. There were significant increases in total labour and variable costs in the intercropped plots as a result of additional cost of *D. intortum* seeds, and labour to plant, manage and harvest *D. intortum*. However, these costs were outweighed by the benefits that accrued from the increased grain yields of finger millet as explained above, and additional products for sale in the form of *D. intortum* forage. Revenue and gross margins were thus significantly higher in the intercropped plots, showing that it is profitable to invest in the desmodium-based technology.

It is estimated that human population growth over the next 30 years will be concentrated almost exclusively in the developing countries, where more than 1 billion people currently live on less than US$ 1 per day, more than 800 million people are undernourished, and 200 million children are underweight (Smil 2000). This poverty is worst in rural areas where agriculture is the leading source of incomes and employment. To address this effectively, cereal production will need to be enhanced. Therefore, technologies that enhance growth in crop yields and total production, more so in the marginal areas, have a significant role to play in addressing the serious food and nutritional insecurity. Moreover, achievement of food security dictates a focus on poor people's crops: subsistence and marketed crops grown in marginal areas where the poorest segments of the rural population are concentrated. Finger millet is an indigenous African cereal that is well adapted to African semi-arid and sub-tropical agronomic conditions.

The results of this study indicate that grain yields and indeed better economic returns can be achieved by effective management of the two most serious constraints to cereal production in the marginal areas. They also indicate that *Desmodium* spp. increase the options available to farmers that fall in different socio-economic strata, including subsistence farmers, in different agro-ecological zones in tropical Africa, many of whom practice mixed cropping and keep livestock.

Acknowledgements

The study was funded by the Gatsby Charitable Foundation, UK, Kilimo Trust, East Africa, and Biovision, Switzerland and conducted in collaboration with Rothamsted Research, which receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC) of the United Kingdom and Kilimo Trust. The field assistance provided by Dickens Nyagol, Aloice Ndiege and Joseph Ondijo is greatly acknowledged too.

References

Altieri MA, Nicholls CI. 2003. Soil fertility management and insect pests: harmonizing soil and plant health in agroecosystems. Soil Tillage Res. 72:203–211.

Ampofo JKO. 1986. Maize stalk borer (Lepidoptera: Pyralidae) damage and plant resistance. Environ Entomol. 15:1124–1129.

Belton PS, Taylor JRN. 2004. Sorghum and millets: protein sources for Africa. Trends Food Sci Technol. 15:94–98.

Gethi JG, Smith ME, Mitchell SE, Kresovich S. 2005. Genetic diversity of *Striga hermonthica* and *Striga asiatica* populations in Kenya. Weed Res. 45:64–73.

Gurney AL, Slate J, Press MC, Scholes JD. 2006. A novel form of resistance in rice to the angiosperm parasite *Striga hermonthica*. New Phytol. 169:199–208.

Haile A, Hofsvang T. 2001. Survey of lepidopterous stem borer pests of sorghum, maize and pearl millet in Eritrea. Crop Prot. 20:151–157.

Hassan R, Ransom J, Ojiem J. 1994. The spatial distribution and farmers strategies to control *Striga* in maize: survey results from Kenya. Fourth Eastern and Southern Africa Regional Maize Conference; 1994 Mar 28–Apr 1. p. 250–254.

Joel M. 2000. The long-term approach to parasitic weed control: manipulation of specific developmental mechanisms of the parasite. Crop Prot. 19:753–758.

Kfir R, Overholt WA, Khan ZR, Polaszek A. 2002. Biology and management of economically important lepidopteran cereal stemborers in Africa. Annu Rev Entomol. 47:701–731.

Khan ZR, Ampong-Nyarko K, Chilishwa P, Hassanali A, Kimani S, Lwande W, Overholt WA, Pickett JA, Smart LE, Wadhams LJ, et al. 1997a. Intercropping increases parasitism of pests. Nature (London). 388:631–632.

Khan ZR, Chilishwa P, Ampong-Nyarko K, Smart LE, Polaszek A, Wandera J, Mulaa MA. 1997b. Utilisation of wild gramineous plants for the management of cereal stemborers in Africa. Insect Sci Appli. 17:143–150.

Khan ZR, Hassanali A, Overholt W, Khamis TM, Hooper AM, Pickett AJ, Wadhams LJ, Woodcock CM. 2002. Control of witchweed *Striga hermonthica* by intercropping with *Desmodium* spp., and the mechanism defined as allelopathic. J Chem Ecol. 28:1871–1885.

Khan ZR, Hassanali A, Pickett JA. 2006a. Managing polycropping to enhance soil system productivity: a case study from Africa. In: Uphoff N, Ball AS, Palm C, Fernandes E, Pretty J, Herren H, Sanchez P, Husson O, Sanginga N, Laing M, Thies J, editors. Biological Approaches to Sustainable Soil Systems. Boca Raton (FL): CRC Press, Taylor and Francis. p. 575–586.

Khan ZR, Midega CAO, Amudavi DM, Hassanali A, Pickett JA. 2008a. On-farm evaluation of the 'push-pull' technology for the control of stemborers and striga weed on maize in western Kenya. Field Crops Res. 106:224–233.

Khan ZR, Midega CAO, Hassanali A, Pickett JA, Wadhams LJ. 2007. Assessment of different legumes for the control of *Striga hermonthica* in maize and sorghum. Crop Sci. 47:728–734.

Khan ZR, Midega CAO, Njuguna EM, Amudavi DM, Wanyama JM, Pickett JA. 2008b. Economic performance of 'push-pull' technology for stem borer and striga weed control in smallholder farming systems. Crop Prot. 27:1084–1097.

Khan ZR, Midega CAO, Pickett JA, Wadhams LJ, Hassanali A, Wanjoya A. 2006b. Management of witchweed, *Striga hermonthica*, and stemborers in sorghum, *Sorghum bicolor*, through intercropping with greenleaf desmodium, *Desmodium intortum*. Int J Pest Manage. 52:297–302.

Khan ZR, Pickett JA, Van den Berg J, Wadhams LJ, Woodcock CM. 2000. Exploiting chemical ecology and species diversity: stemborer and *Striga* control for maize and sorghum in Africa. Pest. Manage Sci. 56:957–962.

Khan ZR, Pickett JA, Wadhams LJ, Hassanali A, Midega CAO. 2006c. Combined control of *Striga* and stemborers by maize-*Desmodium* spp. intercrops. Crop Prot. 25:989–995.

Khan ZR, Pickett JA, Wadhams LJ, Muyekho F. 2001. Habitat management strategies for the control of cereal stemborers and *Striga* in maize in Kenya. Insect Sci Appl. 21:375–380.

Lagoke STO, Parkinson V, Agunbiade RM. 1991. Parasitic weeds and control methods in Africa. In: Kim SK, editor. Combating Striga in Africa. Proceedings of an International Workshop organized by IITA, ICRISAT and IDRC; 1988 August 22–24; IITA, Ibadan, Nigeria. p. 3–14.

Madhavi LA, Venkateswara KR, Dashavantha VR. 2005. Production of transgenic plants resistant to leaf blast disease in finger millet (*Eleusine coracana* (L.) Gaertn.). Plant Sci. 169:657–667.

Midega CAO, Khan ZR, Van den Berg J, Ogol CKPO, Dippenaar-Schoeman AS, Pickett JA, Wadhams LJ. 2008. Response of ground-dwelling arthropods to a 'push–pull' habitat management system: spiders as an indicator group. J Appl Entomol. 132:248–254.

National Research Council. 1996. Finger millet in 'Lost crops of Africa: volume I: grains'. National Academy of Sciences. 39–57.

Naylor RL, Falcon WP, Goodman RM, Jahn MM, Sengooba T, Tefera H, Nelson RJ. 2004. Biotechnology in the developing world, a case for increased Investments in orphan crops. Food Policy. 29:15–44.

Nyende P, Tenywa JS, Oryokot J, Kidoido M. 2001. Weed profiles and management assessment for increased finger millet production in Uganda. Afr Crop Sci J. 9:507–516.

Ostrowski H. 1966. Tropical pastures for the Brisbane district. Queensland Agric J. 92:106–116.

Oswald A. 2005. *Striga* control technologies and their dissemination. Crop Prot. 24:333–342.

Root RB. 1973. Organisation of plant-arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleraceae*). Ecol Monographs. 43:95–124.

SAS Institute. 2002. SAS User's Guide. Statistics, version 8.2 ed. Cary (NC): Author.

Sauerborn J, Kranz B, Mercer-Quarshie H. 2003. Organic amendments mitigate heterotrophic weed infestation in savannah agriculture. Appl Soil Ecol. 23:181–186.

Smil V. 2000. Feeding the world: a challenge to the 21st century. Cambridge: MIT Press.

Tsanuo MK, Hassanali A, Hooper AM, Khan ZR, Kaberia F, Pickett JA, Wadhams L. 2003. Isoflavanones from the allelopathic aqueous root exudates of *Desmodium uncinatum*. Phytochemistry. 64:265–273.

Takan JP, Muthumeenakshi S, Sreenivasaprasad S, Akello B, Bandyopadhyay R, Coll R, Brown AE, Talbot NJ. 2002. Characterization of finger millet blast pathogen populations in East Africa and strategies for disease management; [cited 2009 July]. Available from: www.bspp.org.uk/archives/bspp 2002/bspp02postertitles.htm.

Vanlauwe B, Kanampiu F, Odhiambo GD, De Groote H, Wadhams LJ, Khan ZR. 2008. Integrated management of *Striga hermonthica*, stemborers, and declining soil fertility in western Kenya. Field Crops Res. 107:102–115.

Whitney AS. 1966. Nitogen fixation by three tropical forage legumes and the utilization of legume-fixed nitrogen by their associated grasses. Herbage Abstracts. 38:143.