



Integrated control of *Striga hermonthica* (Del.) Benth. in Burkina Faso through host plant resistance, biocontrol and fertilizers

D. YONLI^{1*}, H. TRAORÉ¹, T.A. VAN MOURIK², D.E. HESS³, P. SÉRÉMÉ¹ and P. SANKARA⁴

¹Institut de l'Environnement et de Recherches Agricoles, 04 B.P. 8645 Ouagadougou 04, Burkina Faso.

²International Crops Research Institute for the Semi-Arid Tropics, ICRISAT-Bamako, BP 320, Bamako, Mali.

³Merry Lea Environmental Learning Center of Goshen College, P.O. Box 263, Wolf Lake, IN 46796, United States of America.

⁴Unité de Formation et de Recherches en science de la vie et de la Terre, B.P. 7021, Ouagadougou, Burkina Faso.

*Corresponding author, E-mail: d.yonli313@gmail.com

ABSTRACT

A two-year field study investigated integrated management of *Striga hermonthica* on sorghum through host crop resistance, biocontrol (*Fusarium oxysporum* isolate 34-FO), and fertilizer application. The experiment was conducted in a field with natural *Striga* infestation at Kouaré Research Station in Fada N'Gourma, Burkina Faso. Treatments combining sorghum resistance with *Fusarium* inoculum and N-fertilizer or manure significantly reduced emerged *Striga* plant number, plant vigour and dry biomass of *Striga* and the area under the *Striga* number progress curve (ASNPC) in 2002, as compared to the control. Integrated *Striga* Management (ISM) plots fertilized with urea, urea plus growth medium or urea plus manure associated with *Fusarium* inoculum resulted in improved sorghum grain yield of at least 15% in 2001 and of at least 97% in 2002. Economic analysis showed that the combination of sorghum resistance with fungal inoculum or urea at 200 kg ha⁻¹ allowed for a significant financial profit in sorghum production. The results suggest that to reduce *Striga* infestation below economic threshold, ISM treatments should be consistently applied for several years without expecting very high returns.

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Keywords: *Striga hermonthica*, integrated control, *Fusarium* inoculum, *Sorghum* resistance, fertilization, Burkina Faso.

INTRODUCTION

Striga hermonthica, the most economically important parasitic weed in the world, is endemic to the African savannah and the Sahel where it can devastate the yields of cereal crops (Parker and Riches, 1993). *S.*

hermonthica parasitizes all rain fed graminaceous crops in this region but is particularly problematic on sorghum, pearl millet and maize, the major staple cereals of over 300 million people in sub-Saharan Africa (Scholes and Press, 2008). Crop yield losses

due to *Striga* parasitism have been estimated at 10.7 million tons per year in sub-Saharan Africa (Gressel et al., 2004). The methods most commonly used by farmers to control *Striga* in Burkina Faso are hand-pulling, crop rotation, and fallow, but these practices seldom lead to long-term reductions in the populations of *S. hermonthica* in infested fields (Traoré and Yonli, 2001). Sorghum varieties with some resistance to *S. hermonthica* have been reported in Burkina Faso (Olivier et al., 1992) but no sorghum variety has so far shown complete resistance to the parasite. Consequently, small-scale farmers mostly rely on local sorghum varieties tolerant of *Striga* infestation, although their cultivation may lead to ever increasing *Striga* seed-bank densities in the soil (Van Mourik et al., 2008). Continuous cultivation and limited application of mineral and organic fertilizers have led to depletion of soil nutrients and soil degradation. These conditions combine to favour establishment and increase of *Striga hermonthica* populations, with devastating effects on cereal production. Nowadays, an integrated approach to *Striga* management is gaining popularity and generally favoured over the use of any single control method (Van Mourik, 2007). The use of soil-borne micro-organisms as biocontrol agents of *Striga* has been investigated in the region. Fungi (Abbasher et al., 1998; Marley et al., 2004; Yonli et al., 2004, 2006) and bacteria (Ahonsi et al., 2002) have been suggested as components of integrated *Striga* management strategies. Ciotola et al. (2000) concluded from their work that the use of *Fusarium oxysporum* (isolate M12-4A) combined with other control measures could contribute to an effective strategy of control *Striga*.

The field study reported here investigated the effects of fungal inoculum based on *F. oxysporum* isolate 34-FO combined with host plant resistance and fertilizer use on crop yield and control of *Striga*.

MATERIALS AND METHODS

Site, characteristics and genetic material

The study was conducted during the 2001 and 2002 cropping seasons at the INERA (Institut de l'Environnement et de Recherches Agricoles) Kouaré Research Station (11°95'03" N and 0°30'58" E) at Fada N'Gourma in the eastern Sudan-Savannah region of Burkina Faso. Trials were implemented on a sandy-loam, tropical, ferruginous soil. Experimental plots were chosen with a heavy natural infestation of *S. hermonthica* (at least 30 emerged plants m² in the previous year) (Yonli et al., 2004).

Seeds of the *Striga*-susceptible sorghum variety S 29 and *Striga*-resistant sorghum variety F2-20 were obtained from the national breeding program. *Fusarium oxysporum* isolate 34-FO demonstrated its efficacy in killing *Striga* in previous studies (Yonli et al., 2006, 2010). Fungal inoculum was prepared using the technique described by Yonli et al. (2006). The growth medium (compost) was produced from crop residues, cow dung, Burkina rock phosphate and water according to the method of Sedogo et al. (1999) and autoclaved at 120 °C for 1 hour before inoculating with *F. oxysporum* isolate 34-FO.

The chemical composition of the compost used in 2001 was: 16.72% carbon, 1.50% nitrogen (N), 0.52% phosphorus (P₂O₅) and 0.06% potassium (K₂O). The pH was 8.22 and the percentage of organic matter was 28.83%. The compost used in 2002 had: 13.48% carbon, 1.28% nitrogen (N), 2.23% phosphorus (P₂O₅) and 0.05% potassium (K₂O). The percentage of organic matter was 23.24% with a pH of 7.12.

Cow manure from a cattle barn in the village of Kouaré was used as an organic fertilizer; urea ((CO)₂NH₂, with 46% N) and NPK in 12-24-12 were the mineral fertilizers employed.

Experimental design

To investigate host plant resistance, biocontrol (*Fusarium* inoculum), fertilization (organic and mineral) and possible interactions on *Striga* emergence and sorghum growth and productivity, the following treatments were evaluated: (1) susceptible sorghum variety S29 (SUS), (2) resistant sorghum variety F2-20 (RES), (3) sorghum variety F2-20 with 30 g of sterilized growth medium planting hill⁻¹ (RES+MED), (4) sorghum variety F2-20 with 30 g of *Fusarium* inoculum hill⁻¹ (RES+INO), (5) sorghum variety F2-20 with 5 tons of cow manure ha⁻¹ (RES+MAN), (6) sorghum variety F2-20 with 200 kg of urea ha⁻¹ (RES+URE), (7) sorghum variety F2-20 with 30 g of sterilized growth medium hill⁻¹ and 5 tons of cow manure ha⁻¹ (RES+MED+MAN), (8) sorghum variety F2-20 with 30 g of sterilized growth medium hill⁻¹ and 200 kg of urea ha⁻¹ (RES+MED+URE), (9) sorghum variety F2-20 with 30 g of *Fusarium* inoculum hill⁻¹ and 5 tons of cow manure ha⁻¹ (RES+INO+MAN) and (10) sorghum variety F2-20 with 30 g of *Fusarium* inoculum hill⁻¹ and 200 kg of urea ha⁻¹. The experimental design was a randomized complete block with four repetitions. In treatments not receiving urea or manure (SUS, RES, RES+MED and RES+INO), 100 kg ha⁻¹ of NPK was applied to the plots at sowing and 50 kg ha⁻¹ of urea was applied at booting stage of sorghum. The main plot consisted of four rows of 2.4 m length with 0.8 m between rows and 0.4 m between plants within rows. To avoid the influence of treatments on the results from one year to another, the second experiment (in 2002) was not set up on the same experimental plots from the previous year.

Crop management and rainfall

The trials were sown on 17 July 2001 and on 23 July 2002. *Fusarium* inoculum and the growth medium were incorporated into

planting hills at sowing. Mineral fertilizers and manure were applied by spreading evenly over the experimental plot and incorporating into the soil. The individual treatment plots were separated by a ridge created immediately after planting to avoid plot-to-plot contamination through runoff water, etc. Plots were weeded twice [at 14 and 30 days after sowing (DAS)] with hoes before the emergence of *S. hermonthica*. Rainfall recorded in 2001 was 832.7 mm in 28 rain events and with 62.3% of rain falling during the crop growth period. In 2002, 693.7 mm of rainfall fell in 29 rain events with 57.9% falling during the crop growth period.

Data collection and analysis

Treatments combining two or more *Striga* control methods were called integrated *Striga* management (ISM) treatments. The following observations were made in the two central rows of each plot (10 hills, or a total area of 1.92 m²): (1) symptoms of fungal disease on sorghum, (2) weekly counts of emerged *Striga* plants from four to twelve weeks after the first emergence of *Striga* in the experiment, (3) visual estimation of vigour of emerged *Striga* plants (Hausmann et al., 2000) at 85 DAS, (4) weight of *Striga* dry biomass at sorghum harvest and (5) sorghum yield. *Striga* count data were used to calculate area under the *Striga* number progress curve (ASNPC, Hausmann et al., 2000).

A comparative economic analysis of treatments was performed. The costs used in this analysis were those of crop seed, the workforce, the mineral fertilizers and the cow manure. The price of a 50 kg bag of fertilizer (urea or NPK) including transportation was 15,000 F CFA (1 F CFA = 0.0017 US \$). The manure and growth medium amounted to 15 F CFA kg⁻¹. The manpower at Kouaré station in 2001 - 2002 was 152.46 F CFA hour⁻¹. The application time for manure and urea was one hour ha⁻¹ and 10 h ha⁻¹ to incorporate

Fusarium inoculum or growth medium into planting hills. The cost of sorghum grain in Kouaré area was 100 F CFA kg⁻¹ in 2001-2002.

Data were checked for normality to determine if transformation was needed (Gomez and Gomez, 1984). *Striga* counts were log-transformed ($\log_{10}(x+1)$) and *Striga* biomass was transformed by taking the square root of the individual values before performing ANOVA using the SAS program (SAS Institute, Cary, NC). Testing for significant differences between individual means of treatments was determined with the LSD's test at $P < 0.05$.

RESULTS

Effect of host plant resistance, biocontrol, and fertilizer on *Striga* infestation

Treatments did not significantly influence the date of *Striga* emergence in either cropping season. However, in 2002, experimental treatments reduced vigour of *Striga* plants at 85 DAS ($P < 0.0360$) compared to the susceptible sorghum variety. Treatments combining sorghum resistance and urea; sorghum resistance, *Fusarium* inoculum and manure or urea (RES+URE, RES+INO+MAN or RES+INO+URE) significantly reduced the number of emerged *Striga* at 85 DAS as compared to the susceptible control (SUS) by 81%, 97.7% and 96.6%, respectively (Table 2). ISM treatments including the resistant sorghum (RES), biocontrol (INO), and fertilizer (MAN, either manure or urea) had fewer emerged *Striga* than the resistant check (RES).

Striga plant vigour at 85 DAS was greatest ($P < 0.0001$) on the susceptible sorghum variety (SUS) and the four ISM treatments (RES+MAN, RES+MED+URE, RES+INO+MAN and RES+INO+URE) significantly reduced *Striga* vigour in comparison with resistant control treatment (RES) in 2001 (Table 1). In 2002, *Striga*

vigour at 85 DAS in susceptible and resistant plots (SUS, RES) were similar and significantly higher ($P < 0.0001$) than that recorded in the seven ISM treatments (Table 2). With the exception of the treatment based on sorghum resistance with *Fusarium* inoculum (RES+INO), *Striga* vigour was reduced in ISM treatments in 2002 as compared to resistant sorghum treatment (RES).

The area under the *Striga* number progress curve (ASNPC) and *Striga* dry biomass were highest in the susceptible control (SUS) treatment in 2001 and in 2002 but only in 2002 did treatments significantly affect these *Striga* parameters (Table 2). With the exception of the treatment RES+MED+MAN, ASNPC was reduced by all ISM treatments when compared to the resistant sorghum treatment, but not always when compared to the susceptible sorghum treatment in 2002 ($P < 0.029$). Treatments combining sorghum resistance, *Fusarium* inoculum and urea or manure (RES+INO+URE, RES+INO+MAN) reduced ASNPC by 94.5% and 96.4% whereas five other ISM treatments reduced ASNPC by 54-78%, as compared to the susceptible control (SUS). *Striga* dry biomass at sorghum harvest was significantly reduced ($P < 0.001$) by ISM treatments combining sorghum resistance with one or two components including manure, urea and *Fusarium* inoculum in 2002. *Striga* biomass was reduced by 100% by ISM treatments combining sorghum resistance with urea or *Fusarium* inoculum or both (RES+URE, RES+INO, RES+INO+URE) (Table 2).

Effects of host plant resistance, biocontrol, and fertilizer on sorghum yield

No fungal disease was observed on sorghum plants during either cropping season. ANOVA revealed significant differences ($P < 0.001$) between treatments for the total

biomass and grain yield of sorghum (Table 3). In 2001, the total biomass obtained with the susceptible control (SUS) was significantly lower than all other treatments which were not significantly different among each other. In 2002, the total biomass obtained with susceptible and resistant control treatments were lowest and not statistically different from each other. Four ISM treatments combining either sorghum resistance with *Fusarium* inoculum and manure or urea (RES+INO+MAN, RES+INO+URE) or sorghum resistance with growth medium and manure or urea (RES+MED+MAN, RES+MED+URE) significantly improved sorghum total biomass by 37-60%, as compared to the resistant control (RES). Sorghum grain yield of the susceptible control (SUS) was lowest in both years (Table 3). Only the grain yield from the treatment combining sorghum resistance with growth medium and urea (RES+MED+URE) obtained in 2001 was significantly different from that of the resistant control (RES). On the other hand in 2002, sorghum grain yield was higher with ISM treatments as compared to the susceptible control with the exception of the treatment combining sorghum resistance with manure (RES+MAN). ISM treatments lead to an increase of grain yield of 88.8% to 134.4% compared to the susceptible control treatment (SUS).

Profitability of *Striga* control employing host plant resistance, biocontrol, and fertilizer

The cost of treatments to control *Striga* may be ranked into three distinct groups (Table 4). The first group is the crop variety, susceptible S 29 (SUS) and resistant F2-20 (RES) whose costs were 45,305 F CFA ha⁻¹. The second group consisted of four treatments combining sorghum resistance with either

growth medium, manure, urea or *Fusarium* inoculum (RES+MED, RES+MAN, RES+URE, RES+INO) whose costs varied between 60,000 and 75,000 F CFA ha⁻¹. The third cluster was composed of treatments combining sorghum resistance with two components (RES+MED+MAN, RES+MED+URE, RES+INO+MAN, RES+INO+URE) leading to costs variation between 121,000 and 136,000 F CFA ha⁻¹. The gross income gained was lowest in the susceptible sorghum treatment (SUS) in both 2001 and 2002. The highest gross incomes in 2001 (ranging from 70,310 to 82,680 F CFA ha⁻¹) and 2002 (from 91,150 to 109,380 F CFA ha⁻¹) were obtained with five ISM treatments (RES+MED+MAN, RES+URE, RES+MED+URE, RES+INO+MAN and RES+INO+URE). Regarding the profitability of *Striga* control, a positive profit margin was obtained in 2001 only with three treatments, namely the resistant sorghum variety (RES), sorghum resistance with urea (RES+URE) and sorghum resistance with *Fusarium* inoculum (RES+INO) (Table 4). In addition to these three treatments, the treatment combining sorghum resistance and growth medium (RES+MED) also allowed a positive profit in 2002. However, a net gain of more than 10,000 F CFA ha⁻¹ was generated in 2001 only by a resistant sorghum variety and a resistant sorghum variety with urea whereas in 2002, a net gain of more than 10,000 F CFA ha⁻¹ was generated only by a resistant sorghum variety with urea and a resistant sorghum variety with *Fusarium* inoculum. ISM treatments including three components including sorghum resistance, manure, urea, growth medium and *Fusarium* inoculum and the treatment based on sorghum resistance associated with manure all led to negative net profit for both cropping seasons, due to their relatively high costs (Table 4).

Table 1: Parameters of *S. hermonthica* emergence, development and biomass in 2001 in response to different control treatments.

Treatments	<i>Striga</i> emergence, DAS	Number of <i>Striga</i> / m ² 85 DAS	Vigour of <i>Striga</i> 85 DAS	ASNPC	Dry biomass of <i>Striga</i> (kg/ha)
SUS	56.50	0.88 [!] (6.75) [§]	4.75 a ^x	1508	10.74 ^{\$} (123.70)
RES	56.00	0.80 (5.50)	3.50 b	977	7.17 (52.08)
RES+MED	61.80	0.65 (5.00)	3.00 bc	810	7.50 (55.99)
RES+MAN	63.80	0.72 (7.25)	2.50 cd	946	6.00 (45.57)
RES+URE	61.20	0.54 (2.75)	2.75 bcd	588	5.07 (32.55)
RES+MED+MAN	69.80	0.54 (3.25)	2.75 bcd	899	5.60 (39.06)
RES+MED+URE	61.50	0.69 (4.75)	2.50 cd	1009	7.38 (55.99)
RES+INO	58.90	0.66 (3.50)	3.50 b	787	8.01 (117.19)
RES+INO+MAN	66.00	0.33 (2.00)	2.50 cd	546	3.10 (13.02)
RES+INO+URE	68.80	0.37 (1.50)	2.00 d	592	7.36 (52.08)
Mean	62.40	0.617	2.98	886.	6.79
LSD	14.27	0.5139	0.8019	834.4	5.175
Sign. Level	ns	ns	*	ns	ns

Sign. level: significance level (one-way ANOVA), P: (*) <0.01; n.s.: not significant; !: Log₁₀ (x+1) transformations, x is the number of emerged *Striga hermonthica*; §: Means in brackets are back-transformations of number or dry biomass of emerged *Striga hermonthica*; \$: Square root (x+1) transformations, x is *Striga* dry biomass; &: Means followed by the same letter are not significantly different according to LSD's test at 5%.

Table 2: Parameters of *S. hermonthica* emergence, development and biomass in 2002 in response to the different control treatments.

Treatments	<i>Striga</i> emergence, DAS	Number of <i>Striga</i> / m ² 85 DAS	Vigour of <i>Striga</i> 85 DAS	ASNPC	Dry biomass of <i>Striga</i> (kg/ha)
SUS	55.60	1.08 a [!] (14.50) [§]	4.75 a	833 ab	8.90 a ^{\$} (85.94) [?]
RES	67.30	1.02 ab (18.00)	4.00 ab	1223 a	3.62 bc (19.53)
RES+MED	85.10	0.33 abc (1.67)	3.00 cd	263 bc	7.25 ab (52.08)
RES+MAN	64.30	0.98 ab (14.33)	2.50 d	382 bc	3.14 bc (13.89)
RES+URE	73.80	0.27 bc (2.75)	2.25 d	180 bc	1.00 c (0.00)
RES+MED+MAN	63.50	0.58 abc (4.25)	2.75 cd	611 abc	3.10 c (13.02)
RES+MED+URE	65.00	0.44 abc (2.50)	2.75 cd	221 bc	2.57 c (13.02)
RES+INO	74.30	0.53 abc (3.25)	3.50 bc	200 bc	1.00 c (0.00)
RES+INO+MAN	66.60	0.08 c (0.33)	2.50 d	30 c	3.35 bc (26.04)
RES+INO+URE	135.50	0.15 c (0.50)	2.25 d	46 c	1.00 c (0.00)
Mean	75.10	0.545	3.03	391	3.49
LSD	79.03	0.6726	0.7799	702.4	3.458
Sign. Level	ns	*	**	*	**

Sign. level: significance level (one-way ANOVA), P: (*) <0.05; (**) <0.01; n.s.: not significant; !: Means followed by the same letter are not significantly different according to LSD's test at 5%. ?: Log₁₀ (x+1) transformations, x is the number of emerged *Striga hermonthica*; §: Means in brackets are back-transformations of number or dry biomass of emerged *Striga hermonthica*; \$: Square root (x+1) transformations, x is *Striga* dry biomass.

Table 3: Sorghum biomass and grain yield in response to the different *Striga* control treatments.

Treatments	Total biomass of sorghum (kg/ha)		Sorghum grain yield (kg/ha)	
	2001	2002	2001	2002
SUS	25.86 ^{\$} a [!] (763) [?]	38.25 a (1527)	13.95 a (221.4)	13.91 a (195.3)
RES	47.87 b (2298)	43.19 ab (1875)	24.67 bc (610.7)	21.49 b (462.2)
RES+MED	44.78 b (2018)	50.35 bc (2643)	23.22 b (541.7)	26.26 c (696.7)
RES+MAN	46.73 b (2201)	50.25 bc (2552)	25.97 bcd (677.1)	26.21 bc (696.6)
RES+ URE	51.36 b (2734)	53.91 bcd (2917)	27.79 cd (774.7)	30.15 cd (911.5)
RES+MED+MAN	43.39 b (1888)	59.96 cde (3607)	26.25 bcd (703.1)	30.35 cd (924.5)
RES+MED+URE	43.43 b (1888)	62.28 de (3893)	28.64 d (826.8)	29.87 cd (911.5)
RES+INO	48.13 b (2357)	53.66 bcd (2995)	24.70 bc (612.0)	26.49 c (709.6)
RES+INO+MAN	48.85 b (2409)	62.23 de (3893)	28.29 cd (807.3)	32.49 d (1067.7)
RES+INO+URE	51.54 b (2663)	68.18 e (4701)	27.27 cd (755.2)	32.60 d (1093.8)
Mean	45.19	54.2	25.07	26.98
LSD	8.712	11.23	3.889	4.752
Sign. Level	*	*	*	*

Sign. level: significance level (one-way ANOVA), P: (*)<0.01. !: Means followed by the same letter are not significantly different according to LSD's test at 5%. \$: Square root (x+1) transformations, x is total biomass or grain yield of sorghum
?: Means in brackets are back-transformations of total biomass or grain yield of sorghum.

Table 4: Economic analysis of the cost/benefit of treatments for controlling *Striga hermonthica*.

Treatments	Cost of treatments F CFA ha ⁻¹	Gross income F CFA ha ⁻¹		Net gain/loss from <i>Striga</i> control F CFA ha ⁻¹	
		2001	2002	2001	2002
SUS	45,305	22,140	19,530	-23,165	-25,775
RES	45,305	61,070	46,220	15,765	915
RES+MED	60,892	54,170	69,660	-6,722	8,768
RES+MAN	75,152	67,710	69,660	-7,442	-5,492
RES+URE	60,152	77,470	91,150	17,318	30,998
RES+MED+MAN	136,044	70,310	92,450	-65,734	-43,594
RES+MED+URE	121,044	82,680	91,150	-38,364	-29,894
RES+INO	60,892	61,200	70,960	308	10,068
RES+INO+MAN	136,044	80,730	106,770	-55,314	-29,274
RES+INO+URE	121,044	75,520	109,380	-45,524	-11,664

DISCUSSION

The absence of fungal disease symptoms on sorghum plants confirmed that sorghum is immune to *F. oxysporum* isolate 34-FO. With respect to emergence of the parasite and its development, no consistent differences were seen between the two sorghum varieties in the two years. The

resistant sorghum variety had significantly higher grain yield than the susceptible variety in both years but still relatively high numbers of emerged *Striga* plants, which suggests that this variety is more tolerant to (than resistant to) *Striga* at this location. Despite the absence of significant differences between treatments for the date of *Striga* emergence, two ISM

treatments delayed *Striga* emergence about 2 weeks in 2001 (RES+MED+MAN, RES+INO+URE) and more than 3 weeks in 2002 (RES+MED, RES+INO) when compared to the susceptible control (SUS). Some components of ISM such as the growth medium and *Fusarium* inoculum may affect *Striga* seed germination, attachment or underground growth stages of *Striga* seedlings (Yonli et al., 2006). The results from counts of *Striga* plants showed that application of urea (96 kg N ha⁻¹) led to a reduction of emerged *Striga* at 85 DAS whereas cow manure did not reduce *Striga* emergence or biomass. Our results confirm the observation of Showemimo (2007) who showed in a pot experiment a negative and significant correlation between level of N fertilizer and *Striga* counts. Working in the Niger, Hess (1989) found that application of nitrogen fertilizer (50 kg ha⁻¹ at sowing and again at the tillering growth stage) restricted *Striga* number and dry biomass whereas growth was profuse on the unfertilized crop. In the Sudan, Bebawi and Farah (1981) reported that application of nitrogenous fertilizer significantly reduced both *Striga* number and dry weights. *In vitro* studies by Pesch and Pieterse (1982) showed reduction in seed germination percentage and radicle length of *S. hermonthica* in the presence of urea concentrations of ≥ 200 mg L⁻¹ under both acid and alkaline conditions. The amount of nitrogen in our cow manure was presumably insufficient to affect the number of emerged *Striga* plants in this experiment. Dembélé and Kayentao (2002) observed that the number of emerged *Striga* plants in plots fertilized with manure was higher than that recorded in plots fertilised with mineral fertilizer. This study shows that ISM treatments including sorghum resistance and urea or manure combined with *Fusarium* inoculum have the potential to reduce *Striga* emergence considerably. A similar study in Nigeria, showed that a combination of a resistant sorghum variety and mycoherbicide based on *F. oxysporum*

(isolate PSM 197) significantly reduced the number of emerged *Striga* by about 95% compared to a susceptible control sorghum variety (Marley et al., 2004). Our observations show the potential of successful *Striga* management based on *F. oxysporum* 34-Fo and the application of urea. As data for the two years were variable, we could not show a synergistic effect between cow manure and *Fusarium* inoculum in terms of *Striga* control and sorghum yield. However, the application of manure and compost to fields to increase soil organic matter is to be encouraged as this improves soil structure, nutrient supply, water holding capacity, and reduces erosion. The comparison of treatment means for emerged *Striga* at 85 DAS, vigour and ASNPC of *Striga* in 2002 showed that the treatment combining sorghum resistance and growth medium (RES+MED) was as effective as treatments including *Fusarium* inoculum. This effectiveness was probably due to the amount (937.5 kg ha⁻¹) of sterilized compost applied to each planting hole. Indeed, this amount may have constituted micro dose of well-composted organic fertilizer for enhanced sorghum growth as well as a growth medium for microbial agents present in the soil. Berner et al. (1996) investigated soil samples from Nigeria and demonstrated that natural soil suppressiveness to *S. hermonthica* is of microbial origin. So, the incorporation of uninoculated growth medium in the soil may boost the growth of edaphic pathogens that then attack *Striga*.

The basal doses of 100 kg NPK ha⁻¹ of and 50 kg urea ha⁻¹ in the treatments without fertilizers are those promoted by extension for cropping in poor soils. ISM plots fertilised with only urea, urea plus growth medium and urea or manure associated with *Fusarium* inoculum allowed an improvement of sorghum grain yield of at least 15% in 2001 and at least 97% in 2002. The application of just *Fusarium* inoculum significantly improved sorghum grain yield by 54% in 2002. Among these treatments, the application

of urea or *Fusarium* inoculum led to a positive financial return in 2001 and in 2002. However, the cost of production of the inoculum has not been taken into account in this analysis. We did not estimate the cost of production of the inoculum, but it is clear that this requires skilled labour, laboratory materials, an autoclave and incubation chambers. Therefore, the net gain with *Fusarium* inoculum treatment in reality should be lower, because of the cost of inoculum production that was not taken into account in the economic analysis.

Although the resistant sorghum variety did not significantly reduce *Striga*, its grain yield was always significantly higher and the net gain was always positive as compared to the susceptible variety. This result stresses the importance of the use of varietal resistance as a first and low cost option to control *Striga* and or mitigate its negative effect. A combination of *Fusarium* inoculum with mineral or organic fertilizers was effective in reducing number and growth of emerged *Striga* and increasing sorghum yield. Thus, the application of mineral/organic fertilizers and the incorporation of *Fusarium* inoculum can be beneficial for controlling *Striga* and improving sorghum yields. The most interesting treatment from this study in economic terms is the combination of sorghum resistance with application of urea. Despite the high cost of treatments with high doses of urea and cow manure, their use should be encouraged because organic fertilizer improves the physical properties and long term soil health and fertility of degraded soils which are heavily infested by *S. hermonthica*, while mineral fertilizer provides available soil nutrients and immediate positive effects on growth of the host crop. The combination of the application of organic and mineral fertilizers in the same treatment, although not studied here, could be included in future studies. ISM treatments that include *Fusarium* inoculum can reduce *Striga* infestation and alleviate *Striga* damage which

in turn can lead to sorghum yield increase. Although the effect of *Fusarium* inoculum with a resistant sorghum variety in terms of *Striga* control and sorghum yield improvement is promising, the marginal rate of return is lower than a resistant sorghum variety only and a resistant variety with urea. This suggests that in its current form, *Fusarium* inoculum is not a viable option for farmers and the *Fusarium* inoculum method probably needs improvement in efficacy of control as well as ways in which it can be produced. The analysis of production costs and profit margins from treatments with urea showed that, to control *Striga* infestation under field conditions, one needs to invest a considerable sum that may not immediately be recovered through increased yield. The very low profit margin is an important constraint for the adoption of the technology (high doses of urea) by farmers and broader participatory testing and evaluation in farmers' fields should be performed in order to determine feasibility of the technology.

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REFERENCES

- Abbasher AA, Hess DE, Sauerborn J. 1998. Fungal pathogens for biological control of *Striga hermonthica* on sorghum and pearl millet in West Africa. *African Crop Science Journal*, **6**: 179-188.

- Ahonsi MO, Berner DK, Emechebe AM, Lagoke ST. 2002. Selection of rhizobacterial strains for suppression of germination of *Striga hermonthica* (Del.) Benth. seeds. *Biological Control*, **24**: 143-152.
- Bebawi FF, Farah AF. 1981. Effects of nitrophenol and atrazine on relations between *Sorghum bicolor* and *Striga hermonthica*. *Expl. Agric.*, **17**: 425-430.
- Berner D, Carsky R, Dashiell K, Kling J, Manyong V. 1996. A land management based approach to integrated *Striga hermonthica* control in sub-Saharan Africa. *Outlook on Agriculture*, **25**: 157-164.
- Ciotola M, Ditommaso A, Watson AK. 2000. Chlamydospore production, inoculation methods and pathogenicity of *Fusarium oxysporum* M12-4A, a biocontrol for *Striga hermonthica*. *Biocontrol Science & Technology*, **10**: 129-145.
- Dembélé B, Kayentao M. 2002. Etude de l'association sorgho/niébé comme moyen de lutte contre le *Striga hermonthica*. Pp 80-85 In *Integrated Striga Management Technologies: From Research to Farmers*, Lagoke STO, M'Boob SS (eds). Proceedings of the 4th general workshop of the Pan African Striga Control Network (PASCON), 28 Oct.-1 Nov. 1996, Bamako, Mali.
- Gomez KA, Gomez AA. 1984. *Statistical Procedures for Agricultural Research* (2nd Edn). John Wiley & Sons, Inc: New York; 680 p.
- Gressel J, Hanafi A, Head G, Marasas W, Obilana AB, Ochanda J, Souissi T, Tzotzos G. 2004. Major heretofore intractable biotic constraints to African food security that may be amenable to novel biotechnological solutions. *Crop Protection*, **23**: 661-689.
- Hausmann BIG, Hess DE, Welz HG, Geiger HH. 2000. Improved methodologies for breeding *Striga*-resistant sorghums. *Field Crops Research*, **66**: 185-211.
- Hess DE. 1989. *Resistance to Striga hermonthica* (Del.) Benth. in *Sorghum*. Purdue University; 240 pp.
- Marley PS, Aba DA, Shebayan JAY, Musa R, Sanni A. 2004. Integrated management of *Striga hermonthica* in sorghum using a mycoherbicide and host plant resistance in the Nigerian sudano-sahelian savanna. *Weed Research*, **44**: 157-162.
- Olivier A, Ramaiah KV, Leroux GD. 1992. Evaluation de lignées de sorgho (*Sorghum bicolor*) pour leur résistance à la mauvaise herbe parasite *Striga hermonthica* au Burkina Faso. *Phytoprotection*, **73**: 13-23.
- Parker C, Riches CR. 1993. *Parasitic Weeds of the World: Biology and Control*. CAB International: Wallingford, UK; 332 p.
- Pesch C, Pieterse AH. 1982. Inhibition of germination in *Striga* by means of urea. *Experientia*, **38**: 559-560.
- Scholes DJ, Press CM. 2008. *Striga* infestation of cereal crops – unsolved problem in resource limited agriculture. *Plant Biology*, **11**: 180-186.
- Sedogo PM, Lompo F, Bonzi M, Bado BV, Segda Z. 1999. Compostage en fosse des résidus de récoltes (sorgho, mil, maïs). Fiche technique réalisée en milieu paysan et adaptée aux conditions des producteurs Burkinabé, 4 pp.
- Showemimo FA. 2007. Relationships between sources and levels of nitrogen fertilization and the control of *Striga hermonthica* in sorghum. *International Journal of Agricultural Research*, **2**: 170-174.
- Traoré H, Yonli D. 2001. *Striga* et autres adventices : perception paysanne et inventaire des méthodes endogènes de lutte dans l'Est du Burkina Faso. *Science et Technique, Sciences Naturelles et Agronomie*, **25**: 46-59.
- Van Mourik TA. 2007. *Striga hermonthica* Seed Bank Dynamics: Process Quantification and Modelling.

- Wageningen University: Wageningen; 123 p.
- Van Mourik TA, Bianchi FJJA, Van der Werf W, Stomph TJ. 2008. Long-term management of the hemi-parasitic weed *Striga hermonthica* – strategy evaluation with a spatio-temporal population model. *Weed Research*, **48**: 329-339.
- Yonli D, Traore H, Hess DE, Abbasher AA, Boussim IJ. 2004. Effect of growth medium and method of application of *Fusarium oxysporum* on infestation of sorghum by *Striga hermonthica* in Burkina Faso. *Biocontrol Science & Technology*, **14**: 417-421.
- Yonli D, Traoré H, Hess DE, Sankara P, Sereme P. 2006. Effect of growth medium, burial distance and depth of *Striga* seeds on efficacy of *Fusarium* isolates to control *Striga hermonthica* in Burkina Faso. *Weed Research*, **46**: 73-81.
- Yonli D, Traoré H, Sereme P, Hess DE, Sankara P. 2010. Pathogenicity of *Fusarium* isolates to *Striga hermonthica* in Burkina Faso. *Pakistan Journal of Biological Sciences*, **13**: 201-208.