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Nitrogen in combination with *Desmodium intortum* effectively suppress *Striga asiatica* in a sorghum-*Desmodium* intercropping system

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Abstract

It is well known that the parasitic weed *Striga asiatica* (L.) Kuntze can be suppressed by *Striga*-tolerant sorghum (*Sorghum bicolor* L. Moench) cultivars, *Desmodium* intortum (Mill.) Urb. (greanleaf desmodium), and by fertilization with nitrogen. The study objective was the assessment of *Striga* control provided by integration of *Desmodium* density, timing of sorghum-*Desmodium* intercrop establishment, and nitrogen fertilization. Growth responses and yield of three sorghum cultivars were measured in three pot experiments. A soil naturally infested with *Striga* was used, and that part of the soil which served as uninfested control was chemically sterilised. *Striga* numbers and growth were affected significantly by sorghum cultivars, sorghum-*Desmodium* intercrop ratios, timing of the sorghum-*Desmodium* association, as well as by their interactions. *Desmodium* caused 100% suppression of *Striga* emergence when *Desmodium* was established in the 1:3 sorghum-*Desmodium* ratio at seeding of sorghum. Total control of *Striga* was also achieved with the 1:1 sorghum-*Desmodium* ratio when *Desmodium* was transplanted 30 days before sorghum seeding. However, these two treatments also caused significant reductions in sorghum yield. In contrast, 100% *Striga* control and a dramatic increase in sorghum yield were achieved with 100 kg N ha $^{-1}$ in the 1:1 sorghum-*Desmodium* intercrop. Compatibility of sorghum and *Desmodium* was evident at the 1:1 sorghum-*Desmodium* intercrop established at sorghum seeding. Overall, the Ethiopian cultivars Meko and Abshir showed better agronomic performance and higher tolerance to *Striga* than the South African cultivar PAN 8564. It is recommended that the N × *Desmodium* × sorghum interaction be investigated under field conditions.

Keywords: allelopathy, competition, *Desmodium*, intercropping, plant parasite, sorghum, *Striga*

1 Introduction

Striga asiatica (L.) Kuntze causes substantial yield losses throughout the sorghum growing areas of the tropics and sub-tropics (Parker & Riches, 1993). Small-scale farmers with limited resources and knowledge to control the parasite are the main sorghum producers in these areas (Haussmann *et al.*, 2000). Consequently, *Striga* is considered as one of the biggest biological constraints on sorghum production when compared with diseases, insect pests and birds (Ejeta, 2007). The parasite is mostly problematic in agricultural systems characterized by a short or non-existent fallow period, depleted soil fertility and low inputs of fertilizers, pesticides, improved seeds and other modern management practices (Oswald & Ransom, 2001). *Striga* infestation is increasing in area and intensity in cereal monocultures which are associated with aggravated depletion of nutrients from the soil. Crop yield losses attributed to *Striga* infestation are estimated to range from 70 to 100% (Sauerborn *et al.*, 2007).

Because of the unique ecological adaptation of *Striga* in terms of establishment, growth and development, 80% of its host-limiting effect on sorghum occurs at subterranean level, from when haustoria attach to the host roots until the parasite emerges above-ground (Stewart & Press, 1990). In addition to the requirements

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that other weeds have for germination, *Striga* spp. requires a period of suitable environmental conditions for pre-conditioning and an exogenous chemical signal derived from the host plant to initiate germination, haustoria development, attachment and penetration of sorghum roots. These specific requirements to start its life cycle entail that implementation of control strategies should best be directed at these physiological stages (Stewart & Press, 1990).

Cereal-legume (grain or forage) intercropping represents dual or multiple cropping systems that are often used by subsistence farmers for higher productivity per unit land area as a result of gains in fertility and the control of weeds, diseases and insect pests; such systems also reduce the risk of crop failure attributed to drought, thus giving better returns for precious resources used, such as family labour (Willey, 1990). The role of intercropping in sustaining farm productivity and diversity of farm products, either as feed or food, justifies the practice (Willey, 1990; Ransom, 2000; Hess & Dodo, 2004).

In most of the sub-Saharan African countries, farmers do not apply recommended rates of fertilizer in *Striga* prone areas, possibly due to the high cost of fertilizers and low returns from the added input costs. For instance, N rates between 120 and 280 kg ha^{-1} have been reported to be effective in reducing *Striga* damage and emergence (Kim *et al.*, 1997). In contrast, farmers in most sub-Saharan countries apply 20 to 50 kg N ha^{-1} for sorghum and 20 to 90 kg N ha^{-1} for maize (Kim & Adetimirin, 1997), which is apparently too low to control the parasite and improve crop productivity. However, the need for relatively high N rates may be at least partially be obviated by combining *Striga*-tolerant cultivars with sub-optimal N in an intercropping system that includes a legume.

Khan *et al.* (2001) reported that intercropping of *Desmodium* species with sorghum or maize enhanced soil fertility and increased the effectiveness of applied N for suppressing the parasite. *Desmodium intortum* (greenleaf desmodium) could be one of the forage crops that have the potential for intercropping with sorghum cultivars for the trapping of *Striga* through stimulation of suicidal seed germination (Khan *et al.*, 2001). A legume such as *Desmodium* is likely to supplement applied N, and it has been reported that N inhibits *Striga* seed germination (Farina *et al.*, 1985). *Striga*-tolerant cultivars will further contribute to exclusion of parasite attachment and root penetration (Ejeta, 2007).

The hypothesis tested in the present study was whether the tolerance of sorghum cultivars towards *Striga* could be promoted by intercropping with *Desmodium intortum* and N application. Specific objectives of the study were: (1) to determine the optimum *Desmodium intortum* population in a sorghum-*Desmodium* intercrop and the role of timing in the intercrop's establishment; (2) to evaluate the integrated efficiency of N application, *Desmodium* intercropping and *Striga*-tolerant sorghum cultivars for suppressing *Striga* growth and its effect on this crop.

2 Materials and Methods

2.1 Experimental site, soil collection and preparation

Pot experiments were conducted in a glasshouse on the experimental farm of the University of Pretoria. The experimental farm is located at 28016'E longitude, 25045'S latitude, at an altitude of 1372 m above sea level. The soil used as growth medium was collected from a farm field in the Settlers district about 110 km northeast of Pretoria. The field had been heavily infested by *Striga asiatica* for several years prior to the study, and sorghum was grown there in monoculture for at least five seasons. The soil consisted 73.2% sand, 7.4% silt and 19.4% clay, 0.36% organic matter (%C) and had a pH(H_2O) of 6.3. Soil levels of P, K, Ca and Mg at sampling were: 46, 183, 347, and 202 mg kg^{-1}, respectively. Soil from the field was thoroughly mixed on a concrete floor in order to obtain as homogenous as possible distribution of the *Striga* seed contained in the soil. The soil was subsequently separated into two parts; one part, representing the non-infested treatment, was heaped as a seed bed ($6 \times 2 \times 0.3$ m) and covered by a gas-proof tarpaulin for fumigation for 24 h with methyl bromide at the rate of 40 g m^{-3}. The other part of the soil was not fumigated, thus serving as both growth medium and the source of *Striga* seed.

2.2 General practices and treatments

Two Ethiopian sorghum cultivars, Abshir and Meko, and one South African cultivar PAN 8564 were grown in pots in all three experiments. Each pot contained 10 kg of either *Striga* infested or non-infested soil depending on the treatment involved. Plants were grown in a glasshouse at a mean daily temperature regime of 18/33°C (min/max). The soil was not fertilized in case it would have influenced the crop and parasite responses to the treatments. Watering was done every second day to replenish water lost by applying the same amount of water to each pot. The volume required was estimated by considering the combined mass of pot + soil + water at the inception of each experiment. Soil moisture at field capacity was gravimetrically determined to be 15% for the particular soil, i.e. field capacity = 1.5 L H_2O per 10 kg soil. Once a week for the duration of the trials all pots were weighed to adjust soil moisture levels to as close as possible to the field capacity. Weekly adjustments in water supply were made on a pot by pot basis for sorghum and *Desmodium* in order to compensate for biomass increases over time. Calculations for sorghum were based on data for the relationship plant height/biomass, and on the leaf number/biomass relationship for *Desmodium*, which were determined in preliminary experiments. Any weeds other than *Striga* that emerged were removed by hand. A mixture of two insecticides (AVIGARD, active ingredient: mercaptothion; MITAC, active ingredient: amitraz) were sprayed a total of four times during the trial period to control aphids and red spider mite.

In Experiment 1, *Desmodium* plants (45-day old; 4–6 leaf stage) were transplanted from seedling trays at the time sorghum was sown in the pots. Two weeks after emergence of sorghum, plants were thinned out to one sorghum plant in order to establish the four sorghum:*Desmodium* intercrop treatments on *Striga*-infested (unsterilized) soil: sole sorghum, 1:1, 1:2 and 1:3. The sorghum control treatment comprised one plant on uninfested (sterilized) soil.

In Experiment 2, three transplanting dates of *Desmodium* plants (4-6 leaf stage) were used: 30 days before sorghum planting, simultaneously with sorghum planting, and 30 days after sorghum planting. As controls two sole sorghum treatments (*Striga* infested and uninfested) were included. A single sorghum-*Desmodium* intercrop ratio of 1:1 was maintained from two weeks after emergence of sorghum.

In Experiment 3, two levels of *Desmodium* intercropping (without and with *Desmodium*) and two levels of N fertilizer (zero and 100 kg N ha^{-1}) were employed. One *Desmodium* and one sorghum plant per pot were maintained for a 1:1 sorghum-*Desmodium* intercrop that was established at the sowing of sorghum.

2.3 Data recorded and statistical analysis procedures

2.3.1 Striga parameters

Striga parameters recorded at the grain-filling stage of sorghum (110 DAP) were parasite density, parasite vigour and crop syndrome ratings. Assessment of parasite vigour (0–9 scale), which was based on the system of Sinebo & Drennan (2001), took into account the following parameters: plant height, number of branches, flowers, capsules and number of parasite shoots per sorghum plant, where 0 indicates no emerged *Striga* plants (least vigour) and 9 the highest vigour (Table 1).

Crop syndrome ratings, which reflect the damage caused to the host plant in reaction to *Striga* infection, were done based on the 0 to 9 rating scale employed by Sinebo & Drennan (2001). The assessment considers chlorosis, blotching, scorching, and stunting, where 0 indicates no symptom development and 9 indicates the highest intensity of symptoms (Table 2).

Table 1: *Striga asiatica vigour ratings on parasitized sorghum plants (adapted from Sinebo & Drennan (2001)*

Rating	Description
0	No emerged *Striga* plants
1	*Striga* plant height < 5 cm, without branches
2	6–10 cm, without branches
3	6–10 cm, with < 5 branches
4	11–20 cm, with < 5 branches
5	11–20 cm, with > 5 branches
6	21–30 cm, with < 10 branches
7	21–30 cm, with > 10 branches
8	> 30 cm, with < 10 branches
9	> 30 cm, with > 10 branches

Table 2: *Crop syndrome rating system for parasitized sorghum plants (adapted from Sinebo & Drennan (2001)*

Rating	Description
0	No chlorosis or other symptoms; normal sorghum growth.
1	Chlorosis or other symptoms just visible at about 1%; normal plant growth.
2	Leaf blotching and scorching on about 10% of leaves with purplish-brown necrotic spots; almost normal plant growth. No stunting.
3	Moderate leaf blotching and scorching on about 20% of leaves with some purplish-brown necrotic spots. Mild stunting.
4	Leaf scorching on about 30% of leaves with some purplish-brown necrotic spots. Some stunting.
5	Leaf scorching on about 40% of leaves with some gray-brown necrotic spots. Some stunting.
6	Leaf scorching on about 50% of leaves with mostly gray necrotic spots. Some stunting.
7	Leaf scorching on about 60% of leaves with severe gray necrotic spots and leaf wilting and rolling. Definite stunting.
8	Leaf scorching on about 70% of leaves with definite gray necrotic spots. Conspicuous stunting and leaf wilting. Death of host plant.
9	Complete scorching of all leaves (100%); death of host plant.

2.3.2 Sorghum growth and yield components

Data collected on sorghum were days to flowering, days to maturity, plant height, stem diameter, biomass, leaf area, harvest index, number of kernels head-1 and grain yield. Leaf area (cm^2 $plant^{-1}$) was determined using a leaf area meter (Li-Cor Inc, Model 3100, Lincoln, Nebraska, USA). Top growth biomass yield of sorghum was measured at harvest, 145 DAP after drying the fresh material in an oven at 65°C to constant weight. Thousand seed mass and number of kernels head-1 were measured with a seed counter. Harvest index was computed as: HI = grain yield/above-ground biomass

2.3.3 Experimental design and data analysis

Both Experiment 1 and Experiment 2 were 3 (cultivar) × 5 (intercrop) factorials, and the experimental design for both was a randomized complete block with four treatment replications. Experiment 3 was a 3 (cultivar) × 2 (nitrogen) × 2 (*Desmodium*) factorial, with the same design and number of treatment replications as the other two experiments. In order to allow standard analysis of variance (ANOVA) to be performed, the transformation $\sqrt[2]{(x+0.5)}$ was used on all *Striga* data prior to analysis in order to ensure normal distribution of the error component. Data were subjected to analysis of variance using the GLM (general linear model) procedure of SAS, and means were compared at $P = 0.05$ and $P = 0.01$ using the Least Significant Difference Test of Tukey (LSD_T).

3 Results

3.1 Striga parameters

3.1.1 Experiment 1: Sorghum-Desmodium intercropping

The interaction effect cultivar × intercrop was highly significant ($P < 0.0001$) for *Striga* density, vigour and crop syndrome (Table 3). Sorghum-*Desmodium* intercropping reduced *Striga* density for all cultivars compared to the respective sole sorghum treatments. The highest density of sorghum-*Desmodium* intercrop (1:3) gave 100% *Striga* control for all cultivars. At the 1:2 intercrop, Meko and to a lesser extent Abshir also attained 100% control. In the case of all three sorghum cultivars the 1:1 intercrop was effective in suppressing *Striga* significantly.

The highest crop syndrome levels were recorded where *Desmodium* was absent in the intercrop (Table 3). Cultivar PAN 8564 supported the highest number and the most vigorous *Striga* plants, and this was revealed in crop syndrome ratings for the cultivar. Increases in *Desmodium* plants relative to sorghum progressively and effectively suppressed *Striga* growth and concomitantly decreased the parasite's effect on the crop. The trend in propensity of sorghum to host *Striga* was: PAN 8564 > Abshir > Meko, and the same order was reflected in crop syndrome.

Table 3: *Effect of sorghum cultivar and sorghum-Desmodium intercrop ratio on Striga density, vigour, and crop syndrome on three sorghum cultivars*

Treatment	*Striga count*	*Striga vigour*	*Crop syndrome*
Sole Abshir, non-infested	0.0^{g}	0.0^{g}	0.0^{h}
Sole Abshir, infested	21.0^{b}	5.5^{b}	5.0^{b}
1:1 Abshir:*Desmodium*	2.3^{e}	2.5^{d}	3.0^{d}
1:2 Abshir:*Desmodium*	0.5^{f}	0.0^{g}	1.0^{g}
1:3 Abshir:*Desmodium*	0.0^{g}	0.0^{g}	0.0^{h}
Sole Meko, non-infested	0.0^{g}	0.0^{g}	0.0^{g}
Sole Meko, infested	11.8^{c}	3.5^{c}	2.0^{f}
1:1 Meko:*Desmodium*	2.0^{e}	1.5^{e}	2.0^{f}
1:2 Meko:*Desmodium*	0.0^{g}	0.0^{g}	0.0^{h}
1:3 Meko:*Desmodium*	0.0^{g}	0.0^{g}	0.0^{h}
Sole PAN 8564, non-infested	0.0^{g}	0.0^{g}	0.0^{h}
Sole PAN 8564, infested	33.3^{a}	7.5^{a}	8.5^{a}
1:1 PAN 8564:*Desmodium*	6.0^{d}	3.5^{c}	4.0^{c}
1:2 PAN 8564:*Desmodium*	0.8^{f}	1.0^{f}	2.5^{e}
1:3 PAN 8564:*Desmodium*	0.0^{g}	0.0^{g}	0.0^{h}
$LSD_{T(0.01)}$ Cult × Intercrop	0.88	0.49	0.18
CV (%)	16.6	12.9	4.2

Means with the same letter within each column are not significantly different.
1:1 = 1 sorghum : 1 *Desmodium*; 1:2 = 1 sorghum : 2 *Desmodium*; 1:3 = 1 sorghum : 3 *Desmodium*

3.1.2 Experiment 2: Timing of the sorghum-Desmodium intercrop

The interaction effect of *Striga* infestation × cultivar × transplanting date of *Desmodium* was highly significant for *Striga* density, vigour, and crop syndrome (Table 4). The highest *Striga* population of 21.3 per sorghum plant was recorded for cv PAN 8564 growing without *Desmodium*. No *Striga* emerged from any sorghum cultivar when intercropped with *Desmodium* transplanted either 30 days before sorghum (30 DBS) sowing or simultaneously with sorghum (SWS) sowing. However, even where *Desmodium* was transplanted late, 30 days after sorghum (30 DAS) sowing, very few parasites developed. As was the case in Experiment 1, the trend in sorghum sensitivity to *Striga* was: PAN 8564 > Abshir > Meko, with the same order being reflected in crop syndrome.

Table 4: *Effect of timing of Desmodium transplanting and sorghum cultivar on Striga density, vigour, and crop syndrome on three sorghum cultivars.*

Treatment	*Striga density*	*Striga vigour*	*Crop syndrome*
Sole Abshir, non-infested	0.0^{g}	0.0^{e}	0.0^{e}
Sole Abshir, infested	15.5^{a}	5.5^{b}	4.6^{b}
Abshir:*Desmodium* 1:1 (30 DBS)	0.0^{g}	0.0^{e}	0.0^{e}
Abshir:*Desmodium* 1:1 (SWS)	0.0^{g}	0.0^{e}	0.0^{e}
Abshir:*Desmodium* 1:1 (30 DAS)	1.3^{e}	2.5^{d}	1.8^{d}
Sole Meko, non-infested	0.0^{g}	0.0^{e}	0.0^{e}
Sole Meko, infested	7.0^{c}	3.5^{c}	2.5^{c}
Meko:*Desmodium* 1:1 (30 DBS)	0.0^{g}	0.0^{e}	0.0^{e}
Meko:*Desmodium* 1:1 (SWS)	0.0^{g}	0.0^{e}	0.0^{e}
Meko:*Desmodium* 1:1 (30 DAS)	0.5^{fg}	2.5^{d}	1.4^{d}
Sole PAN 8564, non-infested	0.0^{g}	0.0^{e}	0.0^{e}
Sole PAN 8564, infested	21.3^{a}	8.5^{a}	7.8^{a}
PAN 8564:*Desmodium* 1:1 (30 DBS)	0.0^{g}	0.0^{e}	0.0^{e}
PAN 8564:*Desmodium* 1:1 (SWS)	0.0^{g}	0.0^{e}	0.0^{e}
PAN 8564:*Desmodium* 1:1 (30 DAS)	3.3^{d}	5.5^{b}	4.7^{b}
$LSD_{T(0.01)}$	0.64	0.55	0.41
CV (%)	16.1	6.2	11.3

Means with the same letter in a column are not significantly different. DBS=30 days before sorghum, SWS=simultaneously with sorghum, DAS=30 days after sorghum.

3.1.3 Experiment 3: Nitrogen supply and sorghum-Desmodium intercropping

The interaction effect of cultivar × intercropping × N level was highly significant for *Striga* density, vigour and crop syndrome scores (Table 5). Intercropping of sorghum with *Desmodium* (1:1), irrespective of whether N was applied or not, gave significant control of *Striga* for all cultivars. In the absence of *Desmodium*, and with no N added, *Striga* numbers on Abshir, Meko and PAN 8564 were 23, 9.5 and 34, respectively. Without *Desmodium*, N application of 100 kg ha^{-1} caused a significant drop in parasite counts to 6.5, 2 and 8.5 for Abshir, Meko and PAN 8564, respectively. Where no N was applied sorghum plants associated with *Desmodium* supported 4, 3 and 13.5 *Striga* plants for the cultivars Abshir, Meko and PAN 8564, respectively. Treatment combinations of N application and *Desmodium* intercropping gave 100% parasite control for all cultivars. The trends in *Striga* vigor and crop syndrome were similar to those observed in parasite density for all treatment combinations.

3.2 Sorghum growth and development

3.2.1 Experiment 1: Sorghum-Desmodium intercropping

The interaction effect of cultivar × intercrop was highly significant ($P < 0.0002$) for all growth and yield components of sorghum (Table 6). Only data for plant height, above-ground biomass, leaf area, and grain yield are presented. Generally, all three cultivars flowered and matured earlier and grew taller and denser in the absence of *Striga* and *Desmodium*. The highest grain yield of 231 g plant^{-1} was obtained from PAN 8564 grown alone on non-infested soil, whereas the lowest yield of 35 g plant^{-1} was obtained from Abshir plants associated *Desmodium* in the ratio of 1:3. *Striga* alone (sole sorghum, infested treatment) significantly reduced sorghum growth and yield for all three cultivars. The introduction of *Desmodium* at the lowest density (1:1) caused significant further reductions in the case of only Abshir. However, *Desmodium* at higher densities (1:2, 1:3) resulted in significantly poorer performance of all three cultivars.

Striga infestation (without *Desmodium*) reduced grain yield by 31, 41 and 72%, for Abshir, Meko and PAN 8564, respectively, compared to the respective sole sorghum, non-infested treatments (Table 6). Severe competition appears to have been exerted on sorghum by *Desmodium* at the 1:3 intercrop. However, the fact that no *Striga* emerged at the 1:3 intercrop (Table 3) does not imply that the parasite had no effect on sorghum, therefore, the influence of *Desmodium* cannot be totally separated from that of *Striga*.

Table 5: *Effect of nitrogen applied in the sorghum-Desmodium intercrop on Striga emergence, vigour, and crop syndrome on three sorghum cultivars (1:1 = 1 sorghum:1 Desmodium; N0 = 0 kg N ha^{-1}; N1 = 100 kg N ha^{-1}).*

Treatment	*Striga count*		*Striga vigour*		*Crop syndrome*	
	N0	N1	N0	N1	N0	N1
Sole Abshir	23.0 ^{b}	6.5 ^{f}	6.0 ^{b}	3.0 ^{d}	4.5 ^{b}	2.0 ^{d}
1:1 Abshir:*Desmodium*	4.0 ^{g}	0.0 ^{j}	1.0 ^{e}	0.0 ^{f}	1.0 ^{f}	0.0 ^{g}
Sole Meko	9.5 ^{d}	2.0 ^{i}	3.5 ^{c}	1.0 ^{e}	4.0 ^{c}	1.0 ^{f}
1:1 Meko:*Desmodium*	3.0 ^{h}	0.0 ^{j}	1.0 ^{e}	0.0 ^{f}	1.0 ^{f}	0.0 ^{g}
Sole PAN 8564	34.0 ^{a}	8.5 ^{e}	8.5 ^{a}	3.5 ^{c}	8.5 ^{a}	4.3 ^{b}
1:1 PAN 8564:*Desmodium*	13.5 ^{c}	0.0 ^{j}	3.3 ^{c}	0.0 ^{f}	1.3 ^{e}	0.0 ^{g}
LSD $_{T (0.01)}$	0.68		0.30		0.24	
CV (%)	10.5		6.8		6.2	

Means with the same letter within the same column are not significantly different.

Table 6: *Effect of Striga infestation and Desmodium intercropping on growth and yield components of three sorghum cultivars.*

Treatment	*Plant height (cm)*	*Biomass (g plant^{-1})*	*Leaf area (cm^{2} plant^{-1})*	*Grain yield (g plant^{-1})*
Sole Abshir, non-infested	146 ^{b}	278 ^{b}	6183 ^{c}	158 ^{b}
Sole Abshir, infested	141 ^{b}	238 ^{c}	4725 ^{d}	109 ^{c}
1:1 Abshir:*Desmodium*	120 ^{c}	116 ^{e}	2489 ^{g}	52 ^{de}
1:2 Abshir:*Desmodium*	113 ^{c}	85 ^{f}	2068 ^{gh}	37 ^{e}
1:3 Abshir:*Desmodium*	128 ^{bc}	84 ^{f}	1736 ^{h}	35 ^{e}
Sole Meko, non-infested	164 ^{a}	532 ^{a}	7793 ^{b}	220 ^{a}
Sole Meko, infested	154 ^{ab}	290 ^{b}	4718 ^{d}	124 ^{c}
1:1 Meko:*Desmodium*	147 ^{b}	276 ^{b}	4650 ^{de}	118 ^{c}
1:2 Meko:*Desmodium*	167 ^{a}	117 ^{e}	2268 ^{gh}	53 ^{de}
1:3 Meko:*Desmodium*	147 ^{b}	86 ^{f}	2050 ^{gh}	36 ^{e}
Sole PAN 8564, non-infested	152 ^{ab}	513 ^{a}	8715 ^{a}	231 ^{a}
Sole PAN 8564, infested	123 ^{c}	161 ^{d}	4190 ^{de}	64 ^{d}
1:1 PAN 8564:*Desmodium*	125 ^{c}	227 ^{c}	4005 ^{e}	115 ^{c}
1:2 PAN 8564:*Desmodium*	133 ^{bc}	159 ^{d}	3162 ^{f}	69 ^{d}
1:3 PAN 8564:*Desmodium*	142 ^{bc}	136 ^{de}	2823 ^{fg}	54 ^{de}
LSD $_{T (0.01)}$	20	29	653	16
CV (%)	7.2	4.2	5.3	5.5

Means with the same letter within the same column are not significantly different.

Table 7: *Effect of Striga infestation and Desmodium transplanting date on growth and yield components of three sorghum cultivars (DBS=30 days before sorghum, SWS=simultaneously with sorghum, DAS=30 days after sorghum).*

Treatment	*Plant height (cm)*	*Leaf area (cm^2 $plant^{-1}$)*	*Biomass (g $plant^{-1}$)*	*Grain yield (g $plant^{-1}$)*
Sole Abshir, non-infested	109 ^{d}	4410 ^{c}	200 ^{e}	83 ^{e}
Sole Abshir, infested	100 ^{d}	2972 ^{f}	130 ^{f}	59 ^{f}
Abshir:*Desmodium* 1:1 (30 DBS)	145 ^{b}	1533 ^{h}	70 ^{g}	32 ^{g}
Abshir:*Desmodium* 1:1 (SWS)	122 ^{cd}	1850 ^{h}	112 ^{f}	56 ^{f}
Abshir:*Desmodium* 1:1 (30 DAS)	122 ^{cd}	2292 ^{g}	112 ^{f}	56 ^{f}
Sole Meko, non-infested	152 ^{ab}	6753 ^{a}	464 ^{a}	207 ^{a}
Sole Meko, infested	154 ^{ab}	3475 ^{e}	211 ^{e}	156 ^{b}
Meko:*Desmodium* 1:1 (30 DBS)	163 ^{a}	2011 ^{gh}	105 ^{f}	55 ^{f}
Meko:*Desmodium* 1:1 (SWS)	152 ^{ab}	3316 ^{ef}	194 ^{e}	63 ^{f}
Meko:*Desmodium* 1:1 (30 DAS)	142 ^{bc}	4555 ^{c}	301 ^{bc}	156 ^{b}
Sole PAN 8564, non-infested	125 ^{c}	5967 ^{b}	337 ^{b}	153 ^{bc}
Sole PAN 8564, infested	126 ^{c}	4177 ^{cd}	213 ^{e}	79 ^{e}
PAN 8564:*Desmodium* 1:1 (30 DBS)	139 ^{bc}	2151 ^{gh}	117 ^{f}	47 ^{fg}
PAN 8564:*Desmodium* 1:1 (SWS)	128 ^{c}	3952 ^{d}	250 ^{d}	119 ^{d}
PAN 8564:*Desmodium* 1:1 (30 DAS)	131 ^{bc}	4476 ^{c}	296 ^{c}	138 ^{c}
$LSD_{T(0.01)}$	15	414	29	16
CV (%)	3.8	3.9	5.0	5.6

Means with the same letter within the same column are not significantly different.

3.2.2 *Experiment 2: Timing of the sorghum-Desmodium intercrop*

The interaction effect of cultivar × transplanting date of *Desmodium* was highly significant ($p = 0.01$) for sorghum days to flowering and maturity, plant height, internode length and stem diameter (only plant height data are presented in Table 7). This interaction effect was significant ($p = 0.05$) for biomass, leaf area and grain yield (Table 7). *Striga* infestation alone reduced grain yield by 29, 25 and 48% for the cultivars Abshir, Meko and PAN 8564, respectively. All three cultivars, when associated with *Desmodium* transplanted 30 DBS, produced the lowest leaf area and grain yield. The highest yield for all of the cultivars was obtained from their respective sole non-infested treatments. *Desmodium* established 30 DBS exerted the highest competition effect on sorghum plants, which was exhibited in grain yield reduction of 62, 74 and 69% for the cultivars Abshir, Meko and PAN 8564, respectively. The SWS and 30 DAS transplant treatments were less debilitating for sorghum that the 30 DBS treatment, probably because of the stronger competition effect exerted by *Desmodium* in the latter treatment. The effects of intercropped *Desmodium* on leaf area and biomass for all three cultivars followed the same trend as for grain yield.

3.2.3 *Experiment 3: Nitrogen supply and sorghum-Desmodium intercropping*

The interaction effect of cultivar × *Desmodium* intercrop × N level was highly significant for growth and yield components (Table 8). Application of N significantly increased the growth and yield of sorghum, irrespective of whether intercropped with *Desmodium* or not. Cultivar Meko planted as sole crop with N application gave the highest grain yield of 124 g plant^{-1}, whilst the lowest grain of 47 g plant^{-1} was obtained from *Striga*-sensitive PAN 8564 in sole crop without N application (Table 8). The highest biomass and leaf area for all three cultivars were obtained from sole cropped sorghum with N application. In this experiment, *Desmodium* was transplanted in the pots at the same time as sorghum was sown (same as the SWS treatment in Experiment 2). It appears that the competition effect of *Desmodium* on sorghum, which was apparent in Experiment 2 (Table 7) was negated by N application (Table 8).

Table 8: *Effect of nitrogen applied in the sorghum-Desmodium intercrop on sorghum growth and yield parameters for three sorghum cultivars (1:1 = 1 sorghum:1 Desmodium; N0 = 0 kg N* ha^{-1}*; N1 = 100 kg N* ha^{-1}*).*

Treatment	*Plant height (cm)*	*Leaf area (cm^2 plant^{-1})*	*Biomass (g plant^{-1})*	*Grain yield (g plant^{-1})*
Sole Abshir; N0	123 ^{g}	2091 ^{e}	151 ^{f}	64 ^{ef}
Sole Abshir; N1	138 ^{ef}	2494 ^{cd}	176 ^{d}	86 ^{c}
1:1 Abshir:*Desmodium*; N0	136 ^{ef}	1889 ^{e}	146 ^{f}	57 ^{f}
1:1 Abshir:*Desmodium*; N1	141 ^{e}	2170 ^{de}	162 ^{e}	75 ^{d}
Sole Meko; N0	160 ^{c}	3352 ^{b}	232 ^{bc}	97 ^{b}
Sole Meko; N1	180 ^{a}	3914 ^{a}	262 ^{a}	124 ^{a}
1:1 Meko:*Desmodium*; N0	171 ^{b}	3209 ^{b}	224 ^{c}	96 ^{b}
1:1 Meko:*Desmodium*; N1	177 ^{ab}	3196 ^{b}	235 ^{b}	102 ^{b}
Sole PAN 8564; N0	131 ^{f}	2395 ^{d}	120 ^{h}	47 ^{g}
Sole PAN 8564; N1	152 ^{d}	2679 ^{c}	145 ^{f}	66 ^{e}
1:1 PAN 8564:*Desmodium*; N0	139 ^{e}	2437 ^{cd}	131 ^{g}	57 ^{f}
1:1 PAN 8564:*Desmodium*; N1	157 ^{cd}	2604 ^{cd}	134 ^{g}	76 ^{d}
$LSD_{T(0.01)}$	8	283	10	7
CV (%)	2.0	3.4	1.9	3.0

Means with the same letter within the same column are not significantly different.

4 Discussion

Farming practices such as crop rotation, fertilization and skillful use of herbicides are already being recommended to control *Striga* on the noble hosts sorghum, maize and millets. However, these recommendations are viewed as impractical for the millions of subsistence farmers who have no surplus land for crop rotations and can afford neither fertilizer nor herbicides (Ejeta, 2007). Yield losses of 100% are a common occurrence due to *Striga* parasitism. Consequently, farmers are often forced to either abandon their farms or to switch their cropping systems to non-host crops of lower economic value (Sauerborn *et al.*, 2007). Khan *et al.* (2000) suggested that the use of *Striga*-tolerant cultivars, N application and intercropping of false host plants are effective in inducing suicidal seed germination of *Striga* before infection of the host plants.

In the present study, *Desmodium intortum*, which is known for stimulating *Striga* seed germination before the host releases signals for haustoria development and attachment, was successfully used to suppress *Striga* infestation on sorghum. Although *Desmodium* intercropping suppressed *Striga* emergence and growth significantly, its interference effect on sorghum contributed to a substantial yield loss for all three sorghum cultivars. The effectiveness of *Desmodium* depended on its population density in the intercrop, the timing of its introduction, and whether it is integrated with N application or not. Sorghum proved sensitive to interference from *Desmodium*, which could possibly be attributed to both competition and allelopathic effects. In order to minimize interference from *Desmodium* on sorghum, it would be necessary to time their establishment in such a way that the one does not dominate the other in terms of development. Planting them at the same time will make this possible, and the present study has shown that the establishment of *Desmodium* from transplants could be effective in case this practice would be practical. In accordance with the findings of Hess & Dodo (2004), the study confirmed that appropriate timing of the companion crop's association with the main crop, and optimum populations for both will not only check *Striga* infestation, but will also allow sorghum cultivars to exhibit their tolerance to *Striga* and their potential yield. Khan *et al.* (2000) reported that intercropping of *Desmodium* species with maize was efficient in suppressing development of *S. hermonthica* through the release of exudates that exerted allelopathic effects in the form of stimulation of germination and interference with haustoria development. Olupot *et al.* (2003) reported that inter-planting of *Celosia argentia* into sorghum reduced *Striga* emergence by an average of 55% and increased the yield of a susceptible sorghum cultivar by 35%. In addition to this, they reported that inter-planting of *Celosia argentia* into sorghum at a ratio of 2:1 suppressed *Striga* by 48% and resulted in the highest yield increase of 100% in greenhouse experiments. Kuchinda *et al.* (2003) reported that intercropping of maize with soybean and groundnut significantly reduced the *Striga* incidence and the maize reaction score. Likewise, Hess & Dodo (2004) reported that emerged *Striga* numbers and fruiting were strongly reduced on pearl millet when intercropped with sesame compared to sole millet. Intercropping maize with non-host crops (soybean, groundnut, pigeon pea, cotton, sesame) caused suicidal germination of *Striga* seeds (Carsky *et al.*, 1996). Companion crops that formed a dense canopy smothered emerged parasites before they could flower (Oswald & Ransom, 2001). In addition to suppression of *Striga* emergence, Khan *et al.* (2000) reported that intercropping with *Desmodium* had the added advantage of a repellent effect against stem borer. The *Desmodium* intercrop also provides valuable forage for cattle, which is often reared in association with subsistence cereal production.

Results showed that *Striga* infestation dramatically reduced the growth and yield of sorghum, as reflected in stunted growth, chlorosis of leaves and small head mass. In contrast to the susceptible cultivar PAN 8564, the tolerant and intermediate-tolerant cultivars, Meko and Abshir, respectively, supported fewer parasites probably due to their genetic ability to prevent or withstand infection. Gurney *et al.* (1995) reported that *Striga* infection reduced growth and development of infested sorghum plants and distorted its allometry. These negative effects of the parasite were attributed to physiological imbalances in the crop, which might be attributed to lower efficiency in rate of transpiration, stomatal conductance, and photosynthesis. The physiological imbalance in turn affects grain yield and yield components due to the limited translocation of photosynthates from stems and leaves to the grains. In the present study, the Ethiopian cultivars Meko and Abshir showed superior performance based on growth and yield parameters in the absence of *Striga*. In accordance with these findings, it has been reported that sorghum cultivars differ significantly in their response to *Striga* infection attributed to differences in the production and releasing efficiency of stimulating exudates from host roots (Showemimo *et al.*, 2002; Ejeta, 2007). Haussmann *et al.* (2001) found that *S. hermonthica* seed from different localities varied in sensitivity to germination stimulants which makes it necessary to consider inter- and intra-species differences in *Striga* populations as regards host-specificity across environmentally diverse sites.

N fertilization combined with *Desmodium* intercropping drastically reduced the level of *Striga* infection for all three cultivars. N supply effectively obviated the need for higher *Desmodium* numbers, which in turn limited the risk of interference between the two crops. The total inhibition of parasite emergence might have been the result of suicidal germination of *Striga* seed. The effectiveness of N for suppressing *Striga* proliferation probably depended on the responsiveness of the cultivars to fertilization and on differences in their sensitivity to *Striga* infestation. In addition to its suppression of *Striga*, N fertilization increased sorghum plant vigour, dry matter accumulation, leaf area development and grain yield. This reduction in parasite density due to N application might be the result of prevention of the formation of root exudates in sorghum that initiate parasite seed germination. In accordance with these findings, Farina *et al.* (1985) reported that N application reduced *S. asiatica* density in maize by 93% of the control. Parker & Riches (1993) reported that the extent to which *S. asiatica* reduces the growth of its host depends on the concentration of N supplied to the plant.

Sorghum yield in the intercrop was less than that obtained from the sole crop for all cultivars, possibly due to competition from *Desmodium* for nutrients and water; and the latter's allelopathic effect on sorghum cannot be ruled out. Khan *et al.* (2007) identified allelochemicals in extracts prepared from *D. uncinatum* and linked them to the suppression of *S. hermonthica*. *D. intortum* was found to have similar effects as *D. uncinatum* on *S. hermonthica* and stemborer suppression and the consequent enhancement of grain yields (Khan *et al.*, 2006). In the present study, differences in the *Striga* suppression efficiency of the sorghum cultivars in combination with *Desmodium* might be due to the combined effects of differential tolerance to *Striga* and suicidal seed germination effected by *Desmodium*. The effect of *Desmodium* in diminishing the parasite seed bank is recognized as a major benefit of intercropping, in addition to its substantial value as a forage crop (Khan *et al.*, 2002).

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