



RESEARCH ARTICLE

Mitigating *Striga hermonthica* parasitism and damage in maize using soybean rotation, nitrogen application, and *Striga*-resistant varieties in the Nigerian savannas

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Abstract

Striga hermonthica infestation causes significant losses of maize yield in the Nigerian savannas and several technologies have been developed and promoted to control *Striga* in maize. However, since no single technology has been found to be effective against *Striga*, integrated management is needed to achieve satisfactory and sustainable *Striga* control. Both on-station and on-farm trials were undertaken from 2013 to 2015 in Bauchi and Kano States of Nigeria to evaluate the performance of integrated *Striga* control technologies. In the on-station trials, a soybean–maize rotation did not suppress *Striga* in maize in either location. However, nitrogen application suppressed and reduced *Striga* infection, except in Bauchi in 2014. The soybean–maize rotation accompanied by N application reduced *Striga* damage in both locations. On farmers' fields, rotating soybean with maize significantly reduced *Striga* infection. At the same time, the use of maize varieties with a combined tolerance to drought and resistance to *Striga* parasitism also increased maize grain yield on farmers' fields, probably due to three factors: a reduction in *Striga* infection, reduced effects of a mid-season moisture deficit, and increased uptake of nutrients from the soil. We concluded that the use of *Striga*-resistant maize varieties in combination with the application of N fertilizer and rotation with soybean could increase the productivity of maize in *Striga*-infested fields in the Nigerian savannas.

Keywords: *Striga hermonthica* infestation; *Striga* infection; Integrated *Striga* management; Maize yield; Soybean–maize rotation; N application rates

Introduction

Maize is next in importance to sorghum and millet in West Africa due to its diverse uses as human food, livestock feed, cash crop, and raw material for agro-allied industry (Alabi, 2008). In Nigeria, maize is important for food security, nutrition, and as a cash crop. Almost 150 million people consume maize in one form or another; it is a staple crop for over 20 million people in Nigeria (Sahel Reports, 2014). Average grain yield currently stands at 1.6 t ha⁻¹ on farmers' fields (FAOSTAT, 2017) compared to the higher yields of about 5–7 t ha⁻¹ obtained at research stations in the region (Adnan *et al.*, 2017). This figure is approximately 75% lower than the world average yield (5.5 t ha⁻¹) and much lower when compared to the yields obtained in countries such as USA (7.8 t ha⁻¹), Canada (7.2 t ha⁻¹), and South Africa (2.6 t ha⁻¹) (FAOSTAT, 2014). If this issue of

low yields can be addressed, Nigeria could become the largest producer in Africa and one of the largest in the world without increasing the land area used for maize cultivation.

Major constraints to production of high grain yields include poor soil fertility, intermittent drought, and infestation by the parasitic weed *Striga hermonthica* (Badu-Apraku and Lum, 2007; Dugje *et al.*, 2006; Kamara *et al.*, 2013). *Striga* is a parasitic weed on up to 50 million ha and affects nearly 300 million people in sub-Saharan Africa (Dugje *et al.*, 2006). The extent to which *Striga* reduces the growth of its host is highly variable and depends on factors such as host plant genotype, infestation level, and environment (van Ast *et al.*, 2005). Several studies have attributed high *Striga* incidence to poor soil fertility, intensification of land use through continuous cultivation, and expansion of cereal production (Rodenburg *et al.*, 2005; van Ast *et al.*, 2005; Vogt *et al.*, 1991; Weber *et al.*, 1995). Infestation has been reported to be more severe in areas with low soil fertility, low rainfall, and little or no fertilizer use (Larsson, 2012; Sauerborn *et al.*, 2003). In a study conducted in the dry savanna of northern Nigeria to determine *Striga* incidence and infestation, Ekeleme *et al.* (2014) reported incidence reaching 100% on maize fields sampled in Kano and Bauchi States. Grain yield losses range from 10 to 100% as a result of *Striga* infestation (Lagoke *et al.*, 1991; Oikeh *et al.*, 1996) and farmers have had to abandon their cereal fields under severe infestation for *Striga*-free land (Khan *et al.*, 2006; Lagoke *et al.*, 1991).

Striga is difficult to control because it produces large amounts of seeds and its dormancy permits the seeds to stay alive in the soil for several years (Westerman *et al.*, 2007). A range of technologies has been identified as effective control methods (Parker and Riches, 1993), such as weeding *Striga* plants, using maize resistant to *S. hermonthica*, using organic and inorganic fertilizers and leguminous trap crops which stimulate suicidal germination and reduce the *Striga* seed bank (Berner *et al.*, 1996; Franke *et al.*, 2006; Kamara *et al.*, 2008; Kling *et al.*, 2000). However, control is made more effective by combining a range of individual technologies into a program of integrated *Striga* control (ISC) management (Ellis-Jones *et al.*, 2004; Franke *et al.*, 2006). Therefore, a combination of different control strategies, including the use of resistant varieties, crop rotation, chemical and biological control, seed treatment, and other phytosanitary practices need to be developed and disseminated to farmers to achieve satisfactory and sustainable *Striga* control (Singh and Emechebe, 1997). Here, we used participatory approaches to evaluate and disseminate a set of component technologies for control of *S. hermonthica* on maize fields in Bauchi and Kano States, Nigeria.

Materials and Methods

Experiment 1: Effect of preceding soybean varieties and N application on *Striga* infestation and maize yield

On-station experiments were conducted in Nigeria to evaluate the effects of rotation of widely used soybean varieties with maize and N application on *Striga* infestation and maize yield. The experiments were conducted during the 2013, 2014, and 2015 rainy seasons at two locations: Kafin Madaki (10°4'8"N, 9°45'47"E, 551 m asl) in Bauchi State of the Sudan Savanna (SS) zone; and Tudun Wada (11°15'N, 8°24'E, 468 m asl) in Kano State of the Northern Guinea Savanna (NGS) zone. Meteorological information was collected using WatchDog 2000 Series Weather Stations (Spectrum Technologies, Aurora CO, USA), installed at the trial sites. In 2014, the minimum and maximum air temperatures during the experimental period were 20.7 and 34.7 °C in Kafin Madaki and 21.3 and 32.9 °C in Tudun Wada. In 2015, minimum and maximum air temperatures were 20.3 and 34.6 °C in Kafin Madaki and 18.9 and 32.8 °C in Tudun Wada. In Kafin Madaki and Tudun Wada, total rainfall was higher in 2015 than in 2014 (Figure 1). In both locations and years, the rains started in May, reached a peak in August, and ended in October, except in Tudun Wada where it ended in late September 2015. Rainfall was fairly distributed in 2015 at Kafin Madaki and in 2014 at Tudun Wada, but poorly distributed in 2014 at Kafin Madaki and in

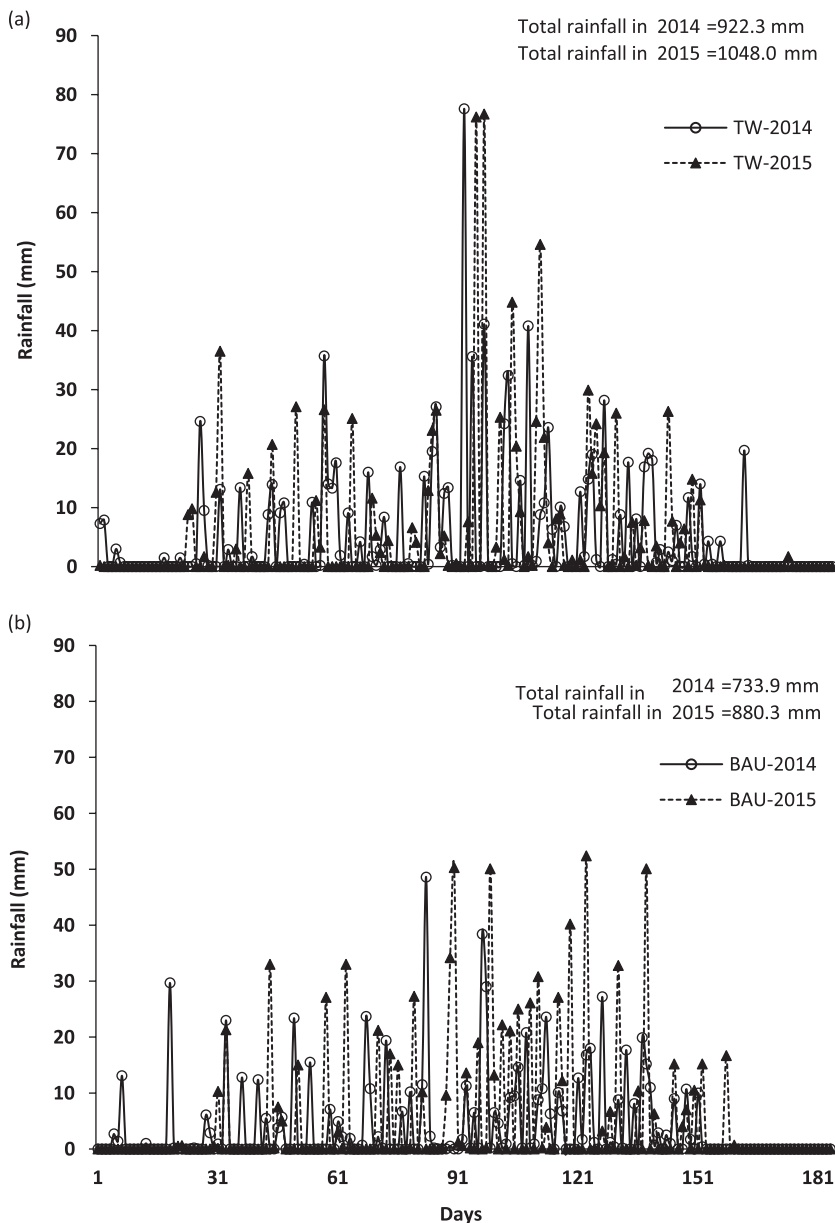


Figure 1. Daily rainfall from 1st May to 31st October during 2014 and 2015 cropping seasons at (a) Kano (TW = Tudun wada) and (b) Kafin Madaki (BAU = Bauchi).

2015 at Tudun Wada, with most of the rain falling in August. However, during the active crop growth stage (July) in both years, there was more rain in Kafin Madaki than in Tudun Wada. Prior to trial establishment, soil samples were taken from each location and characterized according to the analytical procedures of IITA (1979). The results of soil analysis showed that the soil had 47% sand, 29% silt, 24% clay, 8.9 g organic C kg⁻¹, 0.67 g N kg⁻¹, 4.3 mg Mehlich P kg⁻¹, 0.49 cmol K kg⁻¹, 0.59 cmol Mg kg⁻¹, 3.62 cmol Zn kg⁻¹, and pH 6.5 in Kafin Madaki; and 83% sand, 7% silt, 10% clay, 3.6 g organic C kg⁻¹, 0.65 g N kg⁻¹, 16.6 mg Mehlich P kg⁻¹, 0.36 cmol K kg⁻¹, 0.32 cmol Mg kg⁻¹, 3.96 cmol Zn kg⁻¹, and pH 7.3 in Tudun Wada.

For each location, the treatments in 2013 consisted of eight soybean (*Glycine max* L.) varieties (TGx1835-10E, TGx1904-6F, TGx1955-4F, TGx1935-3F, TGx1951-3F, TGx1448-2E, TGx1987-62F, and TGx1987-10F) which have been widely promoted in the Nigerian savannas with a maize (*Zea mays* (L.)) variety (TZE COMP 5 W) as control. The soybean varieties TGx1835-10E, TGx1955-4F, TGx1951-3F, and TGx1987-62F are early maturing; the remaining varieties are medium maturing. Among the varieties, TGx1448-2E has been reported to suppress and reduce *Striga* infestation when grown in rotation with maize. The maize variety TZE COMP 5 W was grown continuously as control and it is early maturing and tolerant to *Striga* infection. Similar experiments with the same treatments were laid in adjacent plots in the same sites in 2014. These soybean and maize (control) plots in 2013 and 2014 constituted the year 1 of the rotation treatments. The experiments were laid out in a randomized complete block design (RCBD) replicated three times. The experimental field was disc-harrowed and ridged before planting. Each treatment had ten rows each 5 m long, with a spacing of 0.75 m between rows. All soybean plots were planted with seven seeds hole⁻¹ at 10 cm intra-row spacing and later thinned to four plants to give a final population density of 533 333 plants ha⁻¹. Maize control plots were planted at an intra-row spacing of 25 cm between plant stands with two maize seeds sown hole⁻¹ and later thinned to one plant. This gave a plant population of 53 333 plants ha⁻¹. Thinning was done 2 weeks after sowing. A mixture of pendilin (500 g L⁻¹ pendimethalin, Meghmani Industries Ltd, India) and gramoxone (1:1-dimethyl-4,4-bipyridinium dichloride, Syngenta Crop Protection AG, Switzerland) at a rate of 1 L ha⁻¹ each was applied immediately after planting using a knapsack sprayer. This was followed by hoe weeding just before flowering to remove subsequent weeds. Recommended rates of 40 kg P₂O₅ ha⁻¹ as single super phosphate (SSP) were applied to the soybean plots at planting. For the control maize, the recommended fertilizer rate of 120:60:60 NPK was applied using a compound fertilizer (NPK 15:15:15) to provide 60 kg each of N, P, and K ha⁻¹ as basal application and urea (46% N) to supply the remaining dose of N (60 kg N ha⁻¹) at 4 weeks after sowing.

In 2014, each plot previously planted to soybean in 2013 was divided into two subplots (15 m²) and planted with maize cv. TZE COMP 5 W. The previous sole maize control plot was also divided and again planted with maize. One subplot was supplied with 30 kg N ha⁻¹ while the other received 100 kg N ha⁻¹. In 2015, the plots planted with soybean in 2014 were divided into two subplots (15 m²) and planted with maize cv. TZE COMP 5 W. The maize control plot was also divided into two, and one subplot supplied with 30 kg N ha⁻¹ while the other received 100 kg N ha⁻¹. All N treatments were applied in two splits. One half of the N rate was applied at planting as NPK 15:15:15 while the other half was applied 4 weeks after planting as urea.

Data collected in each of the second season trials included the number of emerged *Striga* plants, *Striga* damage score (host reaction), and grain yield. A quadrat (1 m²) was placed at five random points in each subplot using the diagonal transect; the number of emerged *Striga* was counted and the average was determined to obtain emerged *Striga* plants m⁻². *Striga* damage was scored using visual rating on a 1–9 scale at full silking (Kim *et al.*, 1997), with 1 meaning minimal damage and 9 maximum damage. For grain yield, maize was harvested at 95% physiological maturity. All plants in a quadrat (1 × 1.5 m) placed across the two middle rows of each subplot were harvested, leaving the outside rows as borders. The cobs were removed, dried, shelled, and weighed and the grain moisture was then determined using a Farmex MT-16 grain moisture tester (Farmcomp Oy, Tuusula, Finland). The remaining maize plants from the two middle rows were hand-cut at the soil surface. Maize ears were removed, sun-dried for 1 week, and shelled. Grains were weighed and added to those from the quadrat area and the final grain yield was expressed as kg ha⁻¹, based on 12% moisture content.

Separate analysis of variance (ANOVA) for each location was performed for each year using the PROC Mixed procedure of SAS Statistical Software version 9.1 (SAS Institute Inc. 2001). The significance of the treatment effect was determined using *F* test. Means were separated using LSMEANS statement of PROC Mixed code of SAS with option pdiff at $p \leq 0.05$. The statement

was used to calculate the difference between two means and the standard error of the difference (SAS Institute, 2012).

Experiment 2: On-farm evaluation of the effects of soybean rotation and *Striga* resistance on infestation and grain yield of maize

Participatory Research and Extension approach (PREA) was used to evaluate and promote ISC technologies and involved a four-stage process, including community analysis and mobilization, action planning, implementation through field experimentation, and sharing of experiences (Ellis-Jones *et al.*, 2004; Hagmann *et al.*, 1999). During the community analysis, problems were identified and prioritized by each innovation platform (IP) and action plans were agreed upon and implemented. During the exercise for community analysis, poor soil fertility, *Striga* parasitism on cereals and cowpea, and drought were identified as major constraints to crop production in the two States.

As a result of community mobilization, 200 lead farmers tested the *Striga* control methods for maize production during a three-season period in 2012, 2013, and 2014. Considerable emphasis was placed on the encouragement of legume–cereal rotations as part of a strategy for *Striga* control and improvement of soil fertility, with lead farmers testing these rotations consisting of legume trap crops and new maize varieties resistant to *Striga* and drought. Training was provided for the extension agents (EAs) so that they, in turn, could provide training for farmers, not only in crop and *Striga* management but also in leadership and communication skills. The lead farmers were encouraged to share with other members of their groups the skills and knowledge they had acquired during training and field evaluation activities. They were also encouraged to provide information on *Striga* and soil fertility management to other farmers in their communities and to direct participants in evaluating the performance of the *Striga* control methods.

In 2012, demonstration (demo) plots were established in 200 participating communities in *Striga* hotspots in five Local Government Areas (LGAs) in each State. The LGAs in Kano were Bebeji, Doguwa, Kiru, Rano, and Tudun Wada, while those in Bauchi were Alkaleri, Bauchi, Dass, Ganjuwa, and Toro. Each demo consisted of three plots (20 × 20 m). One plot consisted of one *Striga*-resistant variety selected from four maize varieties (TZL COMP1 SYN, 2009 EVDT STR W, 99 EVDT STR W, and IWD C2 SYN), based on farmers' choice to compare with a farmers' variety (local check) in another plot. The third plot consisted of one of the soybean varieties (TGx1835-10E, TGx1955-4F, TGx1951-3F, TGx1987-62F, TGx1904-6F, TGx1935-3F, TGx1448-2E, and TGx1987-10F) to enable the farmer to rotate the *Striga*-resistant maize plot with the soybean plots in the succeeding year. The farmers were asked to plant the local maize on the same plot in 2013. Another set of 200 farmers established plots in 2013 with similar treatments as in 2012. Then a fourth plot was added to accommodate one more treatment which consisted of a *Striga*-resistant maize selected from four varieties to be followed by the same variety in 2014. For soybean, the farmers selected varieties that were suitable for the growing environment. Maize varieties selected were either early or medium maturing. All the improved varieties were tolerant or resistant to *Striga* parasitism, and local varieties of maize were those that the farmers had been using. Most local maize varieties came from seeds of improved varieties acquired by farmers over the years previously through the State Extension Agency or from the open market.

Farmers, with the help of EAs, laid out the plots with ridges spaced 0.75 m apart with an intra-row spacing of 0.50 m apart. Two seeds of maize were planted per stand to give a plant population of 53 333 plants ha⁻¹. Soybean seeds were drilled at an intra-row distance of 0.05 m. Two seeds of soybean were maintained per stand to give a plant population of 533 333 plants ha⁻¹. For all maize plots, NPK (15:15:15) was applied 1 week after planting (WAP) at the rate of 50 kg N, 50 kg P₂O₅, and 50 kg K₂O ha⁻¹. Urea was used for top dressing maize plants with 50 kg N ha⁻¹ at 4–5 WAP to give a total of 100 kg N ha⁻¹. The soybean plots were supplied with SSP at 40 kg P₂O₅ ha⁻¹ at planting. In maize plots with farmers' local choice, farmers were asked to adopt their own

management practices and they all used the same fertilizer rates as those of the improved maize plots. Farmers were also asked to incorporate fertilizer in all the plots to minimize nutrient loss through rainwater run-off and volatilization.

EAs collected data on farmers' fields through an observation sheet. Data on *Striga* count in the maize plots were collected at 10 WAP. In each plot, four 1×1 m frames were laid along two intersecting diagonal transects (two areas were sampled on each diagonal) and *Striga* plants were counted. Grain yield was determined at physiological maturity at 10 WAP according to Kamara *et al.* (2008). At maturity, farmers with support from EAs harvested all the maize in each plot, dehusked, shelled, and weighed. Representative samples of 20 cobs were shelled and the moisture content was determined using a moisture meter (Dickey-John Corp., Auburn IL, USA) and used to adjust yield to 12% moisture content. Soybean was harvested by cutting plants at ground level and air drying before threshing. The moisture content of the grain was used to calculate grain yield ha^{-1} at 12% moisture content.

Statistical analyses were performed on data collected in the maize plots in Year 2 using SAS Statistical Software. Prior to analysis, all plots in *Striga*-free sites were removed from the data set. *Striga* count was square-root transformed before analysis of variance to meet the assumption of normal distribution. Variability of means was presented as standard errors between means (s.e.d.) with differences between means considered significant at $p \leq 0.05$.

Results

***Striga* infestation and maize yield as affected by preceding soybean and N application**

Soybean–maize rotation did not reduce *Striga* appearance in Bauchi and Kano in both years (Table 1). Nitrogen application, however, reduced the number of emerged *Striga* plants in 2015 in Bauchi and in both years in Kano. The effect of nitrogen on the number of emerged *Striga* plants was dependent on the level of infestation. In 2014, application of 100 kg N ha^{-1} did not significantly reduce the number of emerged *Striga* plants, when infestation was high in Bauchi. In 2015, the number of emerged *Striga* plants in Bauchi ranged from 7.1 to $17.1 \text{ plants m}^{-2}$ at 30 kg N ha^{-1} and from 3.4 to 11.9 m^{-2} at 100 kg N ha^{-1} . In Kano, the number of emerged *Striga* in 2014 ranged from 3.6 to $12.4 \text{ plants m}^{-2}$ at 30 kg N ha^{-1} and from 2.3 to $7.2 \text{ plants m}^{-2}$ at 100 kg N ha^{-1} . N application at 100 kg ha^{-1} reduced the number of emerged *Striga* plants by 53%. In 2015, the number of emerged *Striga* ranged from 6.5 to $13.7 \text{ plants m}^{-2}$ at 30 kg N ha^{-1} and from 2 to $4.8 \text{ plants m}^{-2}$ at 100 kg N ha^{-1} , with increasing N supply reducing *Striga* appearance by 68%.

The rotation of maize with soybean varieties and the application of nitrogen significantly reduced *Striga* damage on maize in Bauchi in both years (Table 2). Although there was no significant interaction between soybean rotation and N application, differences between continuous maize and rotation with soybean for *Striga* damage were more pronounced at 100 kg N ha^{-1} . Across N levels, all the soybean varieties significantly reduced *Striga* damage except variety TGx1935-3F, which recorded levels of damage that were not significantly different from those of continuous maize in 2014. *Striga* damage was reduced at 100 kg N ha^{-1} by 20% in 2014 and by 12% in 2015. In Kano, rotation with soybean and N application also reduced *Striga* damage except in 2014 when rotation with soybean recorded damage similar to one found for continuous maize. The damage rating in Kano was significantly reduced by 40% in 2014 and by 17% in 2015 at 100 kg N ha^{-1} .

Maize grain yield was significantly influenced by rotation with soybean and N application in both locations and years (Table 3). Interaction between soybean rotation and N application was not significant in both locations, except in Kano in 2015. In Bauchi, grain yield ranged from 2045 to 2630 kg ha^{-1} in 2014 and from 2810 to 3207 kg ha^{-1} in 2015 when maize was grown in rotation with soybean, compared to 1575 kg ha^{-1} in 2014 and 1962 kg ha^{-1} in 2015 for continuous maize. Across N levels, rotation of maize with the soybean variety TGx1448-2E produced the highest grain yield in 2014, while rotation with the soybean variety TGx1935-3F produced lower maize

Table 1. Effect of soybean–maize rotation and nitrogen rates on the number of *Striga* plants per m² in maize fields in Bauchi and Kano, during 2014 and 2015 wet seasons

	Bauchi						Kano					
	2014			2015			2014			2015		
	Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)		
	30	100	Mean	30	100	Mean	30	100	Mean	30	100	Mean
Rotation with soybean (RT)												
TGx1835-10E	26.9	25.1	26.0	9.7	4.1	6.9	3.6	2.3	2.9	8.4	2.1	5.2
TGx1955-4F	25.0	23.5	24.2	14.5	8.3	11.4	8.5	4.9	6.7	10.2	4.2	7.2
TGx1951-3F	15.3	16.5	15.9	8.6	5.6	7.1	6.9	3.5	5.2	7.3	2.1	4.7
TGx1987-62F	18.3	17.4	17.8	17.1	6.8	11.9	5.6	4.1	4.8	11.6	2.2	6.9
TGx1904-6F	29.2	25.6	27.4	10.5	4.8	7.7	12.4	2.6	7.5	10.9	2.2	6.5
TGx1935-3F	19.1	15.1	17.1	9.2	4.0	6.6	10.6	4.4	7.5	6.5	2.4	4.4
TGx1448-2E	28.7	18.7	23.7	11.2	7.0	9.1	6.9	4.0	5.4	13.7	4.8	9.3
TGx1987-10F	23.2	19.8	21.5	15.2	8.7	11.9	11.2	7.2	9.2	7.6	4.2	5.9
CCM [§] (TZE COMP 5 W)	21.6	16.7	19.2	7.1	3.4	5.3	9.6	2.4	6.0	5.8	2.0	3.9
Mean	23.0	19.8	21.4	11.5	5.9	8.7	8.4	3.9	6.1	9.1	2.9	6.0
SED [‡] RT	6.64 ^{ns}			4.36 ^{ns}			2.56 ^{ns}			2.74 ^{ns}		
SED N	2.96 ^{ns}			2.05 ^{**}			1.21 ^{**}			1.29 ^{**}		
SED RT x N	9.23 ^{ns}			6.17 ^{ns}			3.63 ^{ns}			3.88 ^{ns}		

[§]CCM = control-continuous maize.
[‡]SED = standard error of differences.
^{**}Significant at 1% level of probability; ns = not significant.

Table 2. Effect of soybean–maize rotation and nitrogen rates on *Striga* damage of maize in Bauchi and Kano, during 2014 and 2015 wet seasons. Damage score varies from 1 when damage is minimum to 9 when damage is maximum

	Bauchi						Kano					
	2014			2015			2014			2015		
	Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)			Nitrogen (N) rate (kg ha ⁻¹)		
	30	100	Mean	30	100	Mean	30	100	Mean	30	100	Mean
Rotation with soybean (RT)												
TGx1835-10E	3	3	3	3	4	3.5	5	3	4	4	3	3.5
TGx1955-4F	5	3	4	5	3	4	5	3	4	4	3	3.5
TGx1951-3F	5	3	4	4	4	4	5	3	4	5	4	4.5
TGx1987-62F	5	4	4.5	4	4	4	5	3	4	4	4	4
TGx1904-6F	4	3	3.5	4	3	3.5	4	2	3	4	3	3.5
TGx1935-3F	5	4	4.5	5	4	4.5	5	3	4	3	3	3
TGx1448-2E	4	3	3.5	4	4	4	5	3	4	4	3	3.5
TGx1987-10F	6	3	4.5	4	4	4	5	3	4	4	3	3.5
CCM [§] (TZE COMP 5 W)	6	5	5.5	5	5	5	5	3	4	5	4	4
Mean	4.8	3.4	4.1	4.2	3.9	4.05	4.9	2.9	3.9	4.1	3.3	3.7
SED [‡] RT	0.57 [*]			0.37 [*]			0.43 ^{ns}			0.33 [*]		
SED N	0.25 ^{**}			0.17 [*]			0.26 [*]			0.15 ^{**}		
SED RT x N	0.86 ^{ns}			0.53 ^{ns}			0.6 ^{ns}			0.47 ^{ns}		

[§]CCM = control-continuous maize.
[‡]SED = standard error of differences.
^{*}Significant at 5% level of probability.
^{**}Significant at 1% level of probability; ns = not significant.

grain yield as compared to ones obtained in rotation with the other soybean varieties. In 2015, rotation with the soybean variety TGx1987-10F caused higher maize grain yields than after rotation with other soybean varieties. Maize grain yields increased by 37% in 2014 and 10% in 2015 at 100 kg N ha⁻¹ compared to 30 kg N ha⁻¹. In Kano, grain yield ranged from 2425 to 2964 kg ha⁻¹ in

Table 3. Effect of soybean–maize rotation and nitrogen rates on grain yield (kg ha⁻¹) of maize in Bauchi and Kano, during 2014 and 2015 wet seasons

Rotation with soybean (RT)	Bauchi						Kano					
	2014			2015			2014			2015		
	Nitrogen rate (kg ha ⁻¹)			Nitrogen rate (kg ha ⁻¹)			Nitrogen rate (kg ha ⁻¹)			Nitrogen rate (kg ha ⁻¹)		
	30	100	Mean	30	100	Mean	30	100	Mean	30	100	Mean
TGx1835-10E	2,252	2,795	2,524	2,785	2,835	2,810	2,134	3,268	2,701	2,104	3,596	2,850
TGx1955-4F	2,165	2,662	2,413	2,625	3,250	2,938	2,591	3,337	2,964	3,306	4,312	3,809
TGx1951-3F	2,067	2,864	2,465	2,709	3,172	2,941	1,751	3,379	2,565	2,551	3,657	3,104
TGx1987-62F	1,946	2,465	2,206	2,574	3,389	2,982	2,001	2,849	2,425	1,636	3,684	2,660
TGx1904-6F	2,128	2,798	2,463	3,199	3,037	3,118	2,750	2,972	2,861	2,579	3,544	3,061
TGx1935-3F	1,373	2,717	2,045	2,733	3,175	2,954	2,469	2,787	2,628	2,301	3,936	3,119
TGx1448-2E	2,463	2,796	2,630	3,078	2,903	2,990	2,101	2,985	2,543	1,736	4,705	3,221
TGx1987-10F	1,725	2,875	2,300	3,049	3,364	3,207	2,067	3,342	2,704	3,194	4,125	3,660
CCM [§] (TZE COMP 5 W)	1,298	1,851	1,575	1,862	2,062	1,962	1,991	2,379	2,185	1,657	3,519	2,588
Mean	1,935	2,647	2,291	2,735	3,021	2,878	2,206	3,033	2,620	2,340	3,898	3,119
SED [‡] RT	175.1**			241.9**			214.5*			443.6 ^{ns}		
SED N	77.35**			114.1*			101.1**			209.1**		
SED RT × N	242.5 ^{ns}			342.2 ^{ns}			303.4*			627.4 ^{ns}		

[§]CCM = control-continuous maize.[‡]SED = standard error of differences.

*Significant at 5% level of probability.

**Significant at 1% level of probability; ns = not significant

2014 and from 2660 to 3809 kg ha⁻¹ when maize was rotated with soybean. Differences in yield of maize rotated with soybean varieties were not significant in 2014. In 2015, maize rotation with the soybean varieties TGx1955-4F and TGx1987-10F produced the highest maize grain yield. Application of N at 100 kg ha⁻¹ increased yield by 37% in 2014 and 67% in 2015 when compared to 30 kg N ha⁻¹.

On-farm evaluation of soybean rotation and *Striga* resistance on infestation and maize yield

In all communities targeted by the project, *Striga* was identified as one of the major constraints in crop production in addition to poor soil fertility and intermittent drought. In 2013, growing improved maize after soybean recorded lower *Striga* count in maize fields and produced higher grain yields than the farmers' practice of continuously growing local maize, in both locations (Table 4). When compared to continuous maize, rotation with soybean recorded significantly lower *Striga* plants m⁻² for all varieties. In Bauchi, the two medium-maturing varieties IWD C2 SYN and TZL COMP 1 SYN produced higher maize grain yield than those of the early-maturing varieties 99EVD T STR W and 2009 EVD T STR W. In Kano, IWD C2 SYN, 99EVD T STR W, and 2009 EVD T STR W produced statistically similar maize grain yields that were higher than that of TZL COMP 1 SYN.

The number of emerged *Striga* plants on local maize was significantly higher than on the improved maize with or without rotation with soybean (Table 5). The number of *Striga* plants on continuously grown local maize was also higher than those on local maize grown in rotation with soybean in Bauchi but not in Kano. The number of emerged *Striga* on continuously grown improved maize varieties did not significantly differ from that on improved maize grown after soybean in Kano. In Bauchi, continuously grown maize varieties 99EVD T STR W and 2009 EVD T STR W were more infected by *Striga* than when grown in rotation with soybean. In 2013, grain yield of *Striga*-resistant maize grown in rotation with soybean was 55–86% higher than that of continuously grown local maize in Bauchi, and 45–84% higher than that in Kano. In 2014, grain yield of continuously grown maize was lower than those of improved maize grown

Table 4. Mean maize grain yield and number of *Striga* plant per m² following soybean (rotation) on farmers' field in Kano and Bauchi State, 2013

Year 1 (2012)	Year 2 (2013)	n [†]	Bauchi		n [†]	Kano	
			Grain yield (kg ha ⁻¹)	Number of <i>Striga</i> (m ⁻²)		Grain yield (kg ha ⁻¹)	Number of <i>Striga</i> (m ⁻²)
Farmers' local maize	Farmers' local maize	86	1,963	4.10	74	2,043	2.26
Soybean	TZL COMP 1 SYN	14	3,481	0.00	4	2,971	0.03
Soybean	2009 EVDT STR W	21	3,086	0.10	31	3,426	0.13
Soybean	99 EVDT STR W	22	3,038	0.14	22	3,421	0.13
Soybean	IWD C2 SYN	8	3,645	0.00	3	3,767	0.09
Mean			2,957	0.74		3,155	0.46
SED [‡]			188.8**	0.62*		260.8**	0.15**

[†]n = number of farmers.[‡]SED = standard error of differences.

* Significant at 5% level of probability.

** Significant at 1% level of probability.

Table 5. Mean maize grain yield and number of *Striga* plant per m² following maize or soybean (rotation) on farmers' field in Kano and Bauchi State, 2014

Year 1 (2013)	Year 2 (2014)	n [†]	Bauchi		n [†]	Kano	
			Grain yield (kg ha ⁻¹)	Number of <i>Striga</i> (m ⁻²)		Grain yield (kg ha ⁻¹)	Number of <i>Striga</i> (m ⁻²)
Farmers' local maize	Farmers' local maize	178	1,741	0.95	78	1,860	0.87
2009 EVDT STRW	2009 EVDT STRW	47	3,167	0.23	29	3,244	0.18
99 EVDT STRW	99 EVDT STRW	42	3,167	0.30	30	3,241	0.17
IWD C2 SYN	IWD C2 SYN	47	3,333	0.03	21	3,428	0.09
TZLCOMP 1 SYN	TZLCOMP 1 SYN	48	3,299	0.08	19	3,380	0.05
Soybean	Farmers' local maize	177	3,054	0.68	80	3,170	0.63
Soybean	2009 EVDTSTRW	46	4,911	0.04	28	4,922	0.03
Soybean	99 EVDT STRW	42	4,896	0.03	30	4,944	0.06
Soybean	IWD C2 SYN	47	4,643	0.02	21	4,425	0.02
Soybean	TZLCOMP 1 SYN	48	4,565	0.03	19	4,464	0.02
Mean			3,677	0.24		3,708	0.21
SED			403.9**	0.12**		441.8**	0.13**

[†]n = number of farmers.[‡]SED = standard error of differences

**significant at 1% level of probability.

in rotation with soybean in both locations (Table 5). In Bauchi and Kano, grain yield of improved maize ranged from 3166 to 3427 kg ha⁻¹ when continuously grown and from 4424 to 4943 kg ha⁻¹ under rotation with soybean.

Discussion

With the exception of Tudun Wada where soil P is high, the soils of the experimental sites are generally poor and have low organic carbon and total nitrogen contents, which likely contributed to the high *Striga* infestation. In fact, poor soil fertility and moisture stress in the Nigerian savannas are usually associated with high levels of infestation (Ekeleme *et al.*, 2014). According to Kamara *et al.* (2014), moisture stress and low nitrogen usually promote the production of strigolactones by cereal crops, which trigger the germination of *Striga* seeds. Results from on-station trials showed that rotation of maize with soybean did not reduce the number of emerged *Striga* on

maize fields (Table 1). This is contrary to the results of several studies (Carsky *et al.*, 2000; Ellis-Jones *et al.*, 2004; Franke *et al.*, 2006; Kamara *et al.*, 2008) that reported reduced *Striga* infestation in maize fields primarily due to suicidal germination of *Striga* induced by the soybean crop during the first year. Among the soybean varieties used in the experiment, only the variety TGx1448 has been reported to reduce *Striga* infestation when grown in rotation with maize (Carsky *et al.*, 2000; Kureh *et al.*, 2006), by reducing the seed bank for subsequent maize. Herein, the non-reduction in the number of emerged *Striga* with the use of soybean in the on-station trial may be due to the fact that the *Striga* infestation was possibly too high. Then 1 year of soybean rotation that may be too short to notice any difference in *Striga* infestation. There is a clear need to conduct a long-term trial to evaluate the effects of these soybean varieties on the reduction of the *Striga* seed bank in heavily infested areas.

Nitrogen application reduced the number of emerged *Striga*, with the exception of fields in Bauchi in 2014 (Table 1). We found *Striga* infestation level was very high in 2014, which may have rendered N application ineffective in suppressing infestation in Bauchi. However, this changed in the following year and N application was effective in reducing *Striga* infestation on the maize crop in Bauchi in 2015 and in Kano in 2014 and 2015. This is consistent with the findings of several authors (Emechebe *et al.*, 2004; Rodenburg *et al.*, 2005; Kamara *et al.*, 2009; Kim *et al.*, 1997). Significant reduction in *Striga* emergence in maize was reported by Kamara *et al.* (2009) in northeast Nigeria when N was applied at 120 kg ha⁻¹. N application is reported to reduce the production of strigolactones by the maize host plant thereby reducing the germination of the *Striga* plants. Under N- and P-deficient conditions, cereals such as sorghum, maize, and rice are reported to produce high amounts of strigolactones that ultimately stimulate the germination of *Striga* seeds (Yoneyama *et al.*, 2012). The maize variety used is tolerant to *Striga* but allows *Striga* infection. In this situation, N application alone cannot reduce infection if the *Striga* infestation is high. Kim *et al.* (1997) suggested that N application is effective only when it is applied at very high doses. This means that for N application to be effective in controlling *Striga*, it has to be combined with other control measures such as host-plant resistance and legume rotation, as suggested by Kamara *et al.* (2013).

In 2013, growing local maize continuously recorded the highest number of *Striga* plants on farmers' fields in both sites (Table 4). *Striga* occurrence on continuously grown *Striga*-resistant maize was low and similar to those on the same varieties grown in rotation with soybean. The use of drought- and *Striga*-resistant maize provided the advantage of tolerating in-season drought spells while reducing *Striga* parasitism. Maize grown after soybean generally recorded lower *Striga* count irrespective of the maize variety in both locations and maize grain yield grown after soybean was higher than that of continuously grown maize. The medium-maturing and *Striga*-resistant maize varieties TZL COMP1 SYN and IWD C2 SYN grown after soybean produced the highest grain yields in Bauchi (Tables 4 and 5). In Kano, the early-maturing varieties 2009EVDT STR-W and 99 EVDT STR-W, and the medium-maturing variety IWD C2 SYN produced the highest grain yields when grown after soybean. The differences in the performance of the maize varieties in Bauchi and Kano may be due to the differences in the agroecologies. The target communities in Bauchi were largely located in the northern Guinea savanna zone, which has enough rainfall to support the growth of medium- to late-maturing varieties. The communities targeted in Kano are mostly in the Sudan savanna zone, which has a short growing season. The area is, therefore, suitable for early-maturing varieties and the medium-maturing variety IWD C2 SYN which is drought tolerant and resistant to *Striga*. Our results are consistent with earlier reports by Ellis-Jones *et al.* (2004), Franke *et al.* (2006), and Kamara *et al.* (2008), which showed that the rotation of maize with soybean reduced *Striga* infestation and increased grain yield on farmers' fields. There were increases in grain yield of the improved *Striga*-resistant varieties from 55 (2013) to 182% (2014) in Bauchi and from 45 (2013) to 166% (2014) in Kano when grown in rotation with soybean. This is in accordance with Carsky *et al.* (2000), Franke *et al.* (2006), and Kamara *et al.* (2008), who reported increases in maize grain yield when grown in rotation with soybean in

the Nigerian savannas. When maize is grown in rotation with soybean, the preceding soybean contributes nitrogen to the maize crop in the following season. Sangina (2003) reported that soybean provides up to an extra 40 kg N ha⁻¹ to the maize crop grown in rotation. In a study on the effects of cereal–legume rotation, Franke *et al.* (2017) retrieved 44 unique publications providing 199 observations comparing continuous cereal performance with that of a grain legume–cereal rotation. They reported that grain legume–cereal rotation increased grain yield of the cereal crops by 41%. All grain legume types significantly improved cereal yields, with stronger residual effects observed after soybean and groundnut than after cowpea. The N effect of legumes including soybean will, however, probably work better when (i) soil N levels are low and when there is no additional N applied through fertilizers, (ii) soils are not P deficient and drought prone, and (iii) the legume biomass residues are left in the field and incorporated in the soil. In our study, the yield levels of farmers' fields were higher than those previously reported for open-pollinated maize varieties in the region (Tables 4 and 5). This may be due to the use of maize varieties selected for combined tolerance to drought, *Striga* resistance, and the application of N fertilizer. Therefore, the availability of improved maize varieties tolerant to drought and resistant to *Striga* offers excellent opportunities to smallholder farmers, improving maize yield when grown in rotation with legumes such as soybean.

Conclusion

Results from the on-station trials show that N application generally suppressed and reduced *Striga* infection although N application alone did not reduce the *Striga* population under high level of infestation. Rotating maize with soybean did not reduce *Striga* infection in the on-station trials and this was because the *Striga* infestation was too high to be reduced by a single year of rotation. However, a soybean–maize rotation together with N application generally reduced *Striga* damage. The N released by the preceding soybean crops and made available to the succeeding maize combined with the applied N made the maize grow vigorously, which enhanced tolerance to the *Striga* infection. In contrast to the on-station trials, rotating soybean with maize significantly reduced *Striga* infestation in farmers' fields, suggesting that a soybean–maize rotation may be an effective strategy to control *Striga* in this situation. The soybean varieties possibly caused suicidal germination of *Striga* in the years preceding the maize crop. Nitrogen application and a soybean–maize rotation generally increased maize grain yields on both research station and farmers' fields. In addition, our results show that the use of maize varieties that combine tolerance to drought and partial resistance to *Striga* parasitism increased maize grain yield considerably on farmers' fields. This may be attributed to a reduction in *Striga* infection, reduced effects of mid-season moisture deficit, and increased uptake of nutrients from the soil. Hence, the use of *Striga*-resistant maize varieties with the application of N fertilizer and rotation with soybean should be combined as an integrated *Striga* management strategy to increase maize productivity in *Striga*-infested fields.

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