UNDER PEER REVIEW

Original Research Article

Genetic control against *Striga hermonthica* infestation: use of host-plant tolerant maize

ABSTRACT

Aim: to practice a genetic control against *S. hermonthica* by growing *Striga* tolerant maize varieties (STR) in *Striga* endemic locations in Northern Côte d'Ivoire, to assess the performance of STR variety under *Striga* infestation, and to test the infectivity of seeds of *S. hermonthica* populations on maize.

Study Design: 3-ways factorial experiment on a randomized complete block design with three replications.

Place and Duration: Ferkessédougou research station of the National Center of Agricultural Research (CNRA), one year in 2011.

Methodology: The first factor was maize with two levels (IWD SRT and GMRP18). The second factor was *S. hermonthica* populations with six levels (StMi1, StMi2, StMa1, StSo, StMa2 and StMa3). The third factor was the geographical origin with three levels: Korhogo, Tengréla and Ferkessédougou. A plot consisted of 2 rows, 5 m long, spaced 0.80 m apart with 0.50 m spacing between plants within the row. Data were collected on 18-maize competitive plants per plot.

Results: The *Striga*-tolerant cultivar IWD Str produced up to 41% more grain ($P < 0.001$) than the susceptible cultivar. Three out of the six populations tested were able to significantly reduce grain yield ($P = .005$) by 38.5 to 58.7%. The difference in virulence of *S. hermonthica*

UNDER PEER REVIEW

populations follows a north-south gradient, with the highly virulent populations coming from the northern Sudan savanna zone. There is no strain specialization in the *S. hermonthica* populations tested.

Conclusion: Host plant tolerance is a useful control measure to combat the menace of *S. hermonthica* infestation in Côte d'Ivoire. Breeding for *Striga* resistance can be done without developing resistant cultivar to a particular strain of the parasite. Further studies should be carried out to determine the genetic diversity of *S. hermonthica* in Côte d'Ivoire and to understand the difference in virulence among populations.

***Keywords**:* Maize, *Striga*, genetic control, tolerant, virulence.

1. INTRODUCTION

Striga hermonthica (Del.) Benth. of the Orobanchaceae family is the most widespread and economically important biological constraint to cereal production in Côte d'Ivoire. Maize is a staple food crop capable to mitigate food security, but it is one of the most vulnerable cereal to *Striga* in the northern part of the country. *S. hermonthica* severely infested 57.21% (268226.1 ha) of farmlands under maize (108159.1 ha) cultivation with an infestation rate of 56.52% (Kouakou *et al.*, 2013, personal communication). Complete yield loss occurred in areas of heavy infestations obliging farmers to abandon heavy infested fields [1]. In order to reduce losses due to *Striga* infestation, some integrated control methods and growing of *Striga* tolerant maize varieties in association/rotation with trap crops have been practiced in *Striga* endemic regions in northern Cote d'Ivoire in 1999-2002 [2] before being suspended in 2002 due to the political and military war. The crisis has increased *Striga* infestations by suppressing borders seed-checkpoints, and favouring the droppings of migratory animals from neighbouring Sahelian counties where *Striga* is a serious menace to cereal cultivation. The use of cotton as trap crops has also been abandoned.

UNDER PEER REVIEW

Striga has become today a national scourge and a threat on food security in endemic areas. Extensive management actions should be conducted to curb *its* attacks. Several control methods have been developed, including genetic, [3], hand pulling and hoe weeding [4], intercropping with trap and catch crops [5, 6] application of high doses of nitrogen fertilizers [7], fallow, seed treatment and biological control [8]. The control measures are either impractical or labour intensive to the capital deficient farmers [9]. However, the use of genetic resistance is the most economical and environmentally sustainable way to control *Striga* [10]. Of this, host plant resistance or tolerance is considered the most affordable for resource-poor farmers [11] since resistant cultivars can be grown without additional inputs [12]. Genetic resistance to *Striga* has been reported in maize [13,14]. Resistance to *Striga* refers to the ability of the host plant to stimulate the germination of *Striga* seeds while preventing the attachment of the parasite to its roots, or kill the attached parasite [15]. The resistant maize has fewer *Striga* attachments, delayed parasitic development and higher mortality of attached parasites compared with the susceptible inbred. The critical step is marked by the penetration of the haustorial cells of *Striga* into the host root tissues and eventually connecting the parasite to the vascular system of the host. Histologically, haustorial ingress on the resistant inbred was often stopped at the endodermis. Parasites able to reach resistant host xylem vessels showed low haustorial development relative to those invading susceptible roots [15]. *Striga* tolerance denotes the ability of host plants to withstand the effects of the parasites already attached. A *Striga* tolerant genotype germinates and supports as many *Striga* plants (endures these infections) as the non tolerant or sensitive genotype but produces more grain and stover, and shows fewer symptom damages [3]. *Striga* on the susceptible inbred usually penetrated the xylem and showed substantial internal haustorial development [15]. Enzymes play a major role on each of the five stages of *Striga* parasitic development, including *Striga* seed germination, haustorial initiation, penetration of host root

UNDER PEER REVIEW

tissues, physiological compatibility and parasitic growth and maturity [16]. *Striga* resistance or tolerance is quantitatively inherited [17] and the most appropriate traits for screening maize for *Striga* resistances are: host plant damage score, high grain yield under *Striga* infestation and *Striga* emergence [11]. The first two traits exhibit moderate inheritance (0.37 and 04, respectively) but heritability for *Striga* emergence is low (0.11). These characters are controlled predominantly by additive gene action, though non-additive gene action could also be important [18,19].

The more practical method of control *Striga* is to grow resistant maize varieties, but the cultural methods have been used because of the lack of resistant maize varieties [9]. In the absence of absolute resistant variety Kim [3] has recommended the adoption of host tolerance. Tolerant open pollinated varieties produced 2.0 - 2.5 times the yield of susceptible varieties, especially under high *Striga* infestation [20].

Striga infestation has reached an endemic status in both the Sudan Savanna and the sub-Sudanian Savanna of Cote d'Ivoire (Kouakou *et al.*, 2013, personal communication). It represents a serious threat to maize production compelling farmers to abandon their farmlands. The objectives of this study, therefore, were (i) to implement a genetic control of *Striga* in endemic locations of Northern Cote d'Ivoire by promoting the growing of *Striga* tolerant maize varieties, (ii) to assess the performance of *Striga*-tolerant maize variety being promoted across diverse populations of *S. hermonthica* occurring in the regions and, (iii) to test the infectivity of seeds of *S. hermonthica* populations on two maize host genotypes (tolerant and non tolerant). The results were discussed with regard to *Striga* virulence within *S. hermonthica* populations and their role in host-specificity in the parasite. Understanding the relationship between geographically separated

UNDER PEER REVIEW

populations and host preference would improve the ability to successfully breed broad and durable resistance to *Striga* species among the most common host crops [21].

2. MATERIALS AND METHODS

2.1 Experimental site

The study was conducted at Ferke Station (9°36' N; 5°12' W; 330 m altitude with average annual rainfall of 1332 mm) under artificial *Striga* infestation. The soils of the station are gravelly red ferrallitic soils on shallow weathered schists with low effective cation exchange capacity and small amounts of total exchangeable bases. The levels of available P were also frequently very low. Drainage was not hampered [22]. Rain falls during one well-defined wet season were from June to October [23]. Mean annual temperature was 27.1° C. Potential evapotranspiration reach 1847 mm. The vegetation belonged to the Sudanian savanna zone [24].

2.2 Maize genotypes and *Striga* populations

Two maize genotypes of different genetic backgrounds and contrasting reactions to *Striga* were evaluated. The genotypes were one Striga-tolerant/resistant (STR) open pollinated maize varieties (IWD STR), developed by the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria, and one improved variety non tolerant to *Striga* (GMRP-18) developed by the Centre National de Recherche Agronomique (CNRA), Cote d'Ivoire. It derived from the CIMMYT QPM (Quality Protein Maize) gene pool designated Pool 18. Both are also early to medium maturing, white and yellow maize varieties with maturity cycle of 90 to 100 days, respectively.

The *Striga* seeds used for artificial infestation were collected from maize, millet and sorghum fields at the end of the previous growing field. Six samples or populations of *S. hermonthica* collected in three locations including Tengréla, Ferkessédougou and Korhogo were made. The

UNDER PEER REVIEW

first location belongs to the agro-ecological zone called Sudan savanna, and the last two belong to the Subsudan savanna [24]. The six *S. hermonthica* were as follow:

- StMi1: population collected under millet at Kodolkaha, Korhogo;
- StMa1: population collected under maize at Katiofi, Korhogo;
- StMi2: population collected under millet at Maniasso, Tengréla ;
- StSo: population collected under sorghum at Zanasso, Tengréla ;
- StMa2: population collected under maize at Pégatienvogo, Ferkessédougou (Ferké);
- StMa3: population collected under maize at Tchélogokaha, Ferké.

2.3 Field layout, experimental design and trial management

The technique for artificial infestation of *S. hermonthica* [11] was used. *Striga* seeds were mixed with finely sieved sand in the ratio of 1:9 by weight. The sand served as the carrier material and provided adequate volume for rapid and uniform infestation. About 3000 germinable *Striga* seeds were placed in each planting hole of 8 cm depth and 10 cm diameter. Three maize seeds were placed in the same hole. The maize plants were thinned to one per hill two weeks after emergence to give a final plant population density of 25,000 plants ha^{-1}. Fertilization by 15-15-15 NPK of the artificially *Striga*-infested maize plots was carried out at the rate of 150 kg ha^{-1}. One half of the fertilizer was applied the day of planting and the other half 35 days later. Regular removal of weeds other than *Striga* was manually done.

A 3-way factorial experiment, laid out on a randomized complete block design with three replications, was set up in 2011. The first factor was maize with two levels (IWD SRT and GMRP-18). The second factor was *S. hermonthica* populations with 6 levels (StMi1, StMi2, StMa1, StSo, StMa2 and StMa3). The third factor was the geographical origin where Korhogo, Tengréla and Ferkessédougou represent the three levels. A plot consisted of 2 rows, 5 m long,

UNDER PEER REVIEW

spaced 0.80 m apart with 0.50 m spacing between plants within the row. This relatively wide spacing was adopted to reduce the number of hills for artificial infestation and to minimize the movement of *Striga* seeds into the adjacent hills. Two rows of each entry were separated by a 1.5 m alley to minimize the movement of *Striga* seeds from one population to other plots. The plots were arranged in a serpentine fashion. There were 22 plants per plot.

2.4 Data collection and statistical analysis

Data were collected on 18-maize competitive plants per plot. Observations used in the *Striga* resistance-tolerance evaluation trials [11] were recorded, including grain yield, ear number, ear rot, husk cover, plant and ear heights, days to 50% anthesis, and silking, anthesis-to-silking interval (difference between 50% silking and anthesis) and percentage root lodging (percentage of plants leaning more than 30° from the vertical), and stalk lodging (percentage broken at or below the highest ear node. In addition, host plant damage syndrome rating and the number of emerged *Striga* were made 10 weeks after planting. The host plant damage syndrome rating (STRA) was scored per plot on a scale of 1 to 9, where 1 = no symptoms, indicating normal plant growth and high tolerance, and 9 = all maize plants dead or dying (i.e., highly susceptible). Maize *Striga* damage syndrome was used to calculate the "*Striga* severity" (STRSV), using the following formula:

$$STRSV = \frac{\sum_{I=1}^{9}(STRA_i \times n_i) \times 100}{STRA_{max} \times N}$$

where *n* is the number of maize plants with the *i*th damage syndrome rating ($STRA_{i)}$, $STRA_{max}$ the host plant damage syndrome rating highest score and *N* is the total number of observation (maize plants). Additional variables measured were rated such as *Striga* incidence on maize,

UNDER PEER REVIEW

number of *S. hermonthica* attached seedlings (subterranean attached *Striga* plants, i.e., *Striga* plants which are attached to the roots but have not emerged above ground) and *Striga* vigor. Assessment of parasite vigor (0-9) took into account the following parameters [25]: *Striga* height and the number of branches where 0 indicates no emerged *Striga* plant (least vigor) and 9 the highest vigor. Data were collected on several traits but only those on the most important traits in the studies were presented here.

Data were computed on plot means of the individual characters with GenStat Discovery Edition 4 VSN International Ltd. A log transformation *{*log(counts + 1)*}* was used on all *Striga* data prior to analysis, to ensure normal distribution of the error component before analysis of variance (ANOVA).

Least significant differences (LSD 0.05) values based on the analysis of variance were used for pair-wise multiple comparisons among means to identify significant differences among the means.

3. RESULTS AND DISCUSSION

3.1 Results

3.1.1 Performance of *Striga* tolerant maize variety for grain yield and other agronomic characters in *Striga* environment

Under *Striga*-infested conditions, mean squares of all traits were significant for the two maize genotypes (G) (Table 1). On the other hand, mean squares for *S hermonthica* populations (Str) were significant for grain yield and plant height with the exception of anthesis silking interval, root lodging and maize damage score at 10 week after planting (WAP). Mean squares of all characters were not significant for maize genotypes x *S hermonthica* populations (GxStr).

UNDER PEER REVIEW

Cultivar IWD Str had high grain yield value (2736 kg.ha^{-1}) and low values for *Striga* damage syndrome ratings (3.78), root lodging (12.4%), anthesis silking interval (3.56 days), and showed a normal plant height (131 cm). The STR variety produced up to 41% more grain than the non tolerant variety.

Table 1: Grain yield and other agronomic traits of two maize genotypes under *Striga*-infested conditions

Host maize varieties	**Grain yield (kg.ha^{-1})**	**Plant height (cm)**	**Maize damage score 10 WAP (1-9)**	**Root lodging (%)**	**Anthesis silking interval (days)**
GMRP1	1806	113.2	4.30	28.2	4.67

UNDER PEER REVIEW

IWD Str	2736	131.0	3.27	12.4	3.56
Grand mean	2271	122.1	3.78	20.3	4.11
LSD (0.05)	307.7	5.70	0.505	12.02	0.948
P-var	<.001	<.001	<.001	.005	.016
P-str	.005	.044	.586	.153	.204
P- var x str	.586	.255	.618	.968	.164

P-var: probability of *F* for *variety; P-str*: probability of *F* for *Striga; P-var x str;* Probability of *F* for cultivar x *Striga*; WAP: week after planting

The six *S. hermonthica* population samples used were different in term of their pathogenicity effect on both maize genotypes for grain yield and plant height (Table 2). *S. hermonthica* populations from Tengréla region were the most highly aggressive populations against the two maize cultivars tested.

Table 2: Effects on maize grain yield and other agronomic traits of *S. hermonthica* populations collected in three locations

Grain yield and other agronomic traits of two maize genotypes					
***Striga hermonthica* populations' origin**	**Grain yield (kg.ha^{-1})**	**Plant height (cm)**	**Maize damage score 10 WAP (1-9)**	**Root lodging (%)**	**Anthesis silking interval (days)**

UNDER PEER REVIEW

Tengréla	1875a	115.9a	4.01a	26.0a	4.58a
Ferké	2458b	124.2b	3.73a	19.4a	4.17a
Korhogo	2479b	126.1b	3.62a	15.5a	3.58a
LSD (0,05)	395.1	7.08	0.290	14.89	1.059
P-values	.005	.015	.390	.354	.170

The effects of the six *S. hermonthica* populations on the tolerant and intolerant maize varieties (IWD Str and GMRP18) were presented in table 3. Average percent grain yield and plant height reductions for both genotypes due to these *Striga* populations were 38.5 – 58.7% and 9.7 – 20.5%, respectively. *S. hermonthica* population collected on millet (StMi2) at Tengréla showed consistency in the reduction of grain yield of both maize varieties. Three of the six populations tested were able to significantly reduce grain yield (*P-var* < .001; *P-str* = .005) of the tolerant and non tolerant maize varieties (IWD Str and GMRP18). These *S. hermonthica* populations were collected on sorghum and millet (StSo and StMi2) in Tengréla region and on maize (StMa2) at Pegatienvogo, Ferké.

S. hermonthica population StSo was found to reduce significantly the height (13%) of the non tolerant maize variety; followed by StMi2, StMa2 and StMa1 (3 - 4%). A significant (*P-str* = .044) but also lower reduction in plant height (1 - 6%) of the tolerant maize variety was observed between *S. hermonthica* populations StMi2, StMa2, StMa1 and StSo. All six *S. hermonthica* populations were not significantly (*P-str* = .586) different for their effects on the tolerant maize genotype in terms of maize damage score at 10 WAP, (*P-str* = .450) root lodging and (*P-str* = .204) anthesis silking interval with the exception of StSo, and also StMa3 and StMa2 on the intolerant maize genotype.

UNDER PEER REVIEW

Table 3: Specific effects of six *S. hermonthica* populations collected from various crops: maize, pearl millet and sorghum on grain yield and other agronomic traits on two maize genotypes

Host maize varieties (Traits)	***S. hermonthica* populations' origin**					
	Korhogo		Ferké		Tengréla	
	Ex-maize (StMa1)	Ex-Millet (StMi1)	Ex-maize (StMa2)	Ex-maize (StMa3)	Ex-millet (StMi2)	Ex-sorghum (StSo)
			Grain yield			
GMRP18	1875a	1958b	1583a	2292b	1708a	1417a
IWD Str	3125cd	2958c	2583b	3375d	2042a	2335a[§]
LSD (0,05)	303.8 var	526.2 str				
P-values	<.001 var	.005 str				
			Plant height			
GMRP18	117.3b	119.9c	110.5b	122.5c	109.5b	99.3a
IWD Str	131.7a	135.6b	130.2a	133.5b	122.9a	132.1a[§]
LSD	5.62 var	9.74 str				
P-values	<.001 var	0.044 str				
			Maize damage score 10 WAP (1-9)			
GMRP18	4.07a	4.10a	4.57a	3.80a	4.13a	5.13b
IWD Str	3.20a[§]	3.10a[§]	3.37a[§]	3.17a[§]	3.57a[§]	3.20a
LSD (0,05)	0.499 var	0.864 str				
P-values	<.001 var	.586 str				
			Root lodging (%))			
GMRP18	17.5a	32.7a	24.8a	23.2a	18.4a	52.6b

UNDER PEER REVIEW

IWD Str	4.2a[§]	7.5a[§]	16.0a	13.5a	20.4a	12.8a
LSD	12.02	20.82				
P-values	.012 var	.450 str				
			Anthesis silking interval (day)			
GMRP18	3.33a	3.33a	5.00b	5.33bc	4.33a	6.67c
IWD Str	4.00a	3.67a	3.33a	3.00a	3.33a[§]	4.00a
LSD (0,05)	0.880 var	1.523 str				
P-values	.016 var	.204 str				

- Means with the same letter within line of the same host maize genotype are not significantly different from each other (*P* = .05) according to LSD test. Means with the same letter within column of the two host maize genotypes are not significantly different from each other (*P* = .05). Means with the following symbol '*a*[§]' within column of the two host maize genotypes are significantly different from each other (*P* = .05).
- *P-var*: Probability of *F* for maize varieties; *P-str*: Probability of *F* for *Striga* populations.

3.1. 2 *Striga* infection indices and severity on maize host plant

S hermonthica populations' infection indices (number of underground *Striga* attachments, number of emerged *Striga* plants and *Striga* vigor) and severity on maize were presented in table 4. The highly aggressive *S hermonthica* populations (5.76 parasite stems per maize plant, SE ± 1.28; 13.06 subterranean attached *Striga* plants, SE ± 3.31; 43.92 Severity of *Striga* infection SE ±2.80) seemed to come from the northern Sudan savanna zone in Tengréla region. The virulence of the parasite seemed to be medium at Ferké in the southern Sudan savanna zone (2.04 parasite stems per maize plant, SE ± 0.47; 10.55 subterranean attached *Striga* plants, SE ± 2.78; 40.84 severity of *Striga* infection SE ±2.18), and relatively lower in the northern Subsudan savanna in Korhogo zone (1.94 parasite stems per maize plant, SE ± 0.70; 7.44 subterranean attached *Striga* plants, SE ± 1.93; 38.64 severity of *Striga* infection SE ±1.72). *Striga* vigor were slightly the

UNDER PEER REVIEW

same for *S. hermonthica* populations from Tengréla and Ferké, and relatively higher for *S. hermonthica* populations sampled at Korhogo. However, there was no significant difference in infection indices and severity among populations from any of the agro-ecological zone: (P = .355) numbers of emerged, (P = .081) subterranean attached *Striga* plants, (P = .602) *Striga* vigour and (P = .200) severity of parasite infection.

Table 4: *S. hermonthica* populations' infection indices and severity on maize host plant

Parasite origin		Emerged *Striga* counts (SE)	*Underground Striga* counts (SE)	*Striga* vigor (SE)	Severity of *Striga* infection (SE)
Agro-ecological zone	**Location**				

UNDER PEER REVIEW

Northern Sudan savanna	Tengréla	5.76 (1.28)	13.06 (3.31)	2.67 (0.51)	43.92 (2.80)
Southern Sudan savanna	Ferké	2.04 (0.47)	10.55 (2.78)	2.73 (0.69)	40.84 (2.18)
Northern Subsudan savanna	Korhogo	1.94 (0.70)	7.44 (1.93)	1.83 (0.32)	38.64 (1.72)
Probability of *F* for *Striga*		.355	.081	.602	.200

SE: Standard error of mean

3.1.3 Host-specificity in *S. hermonthica* populations: intracrop specialization (strain specialization to a cultivar of a crop species)

Both tolerant and intolerant maize varieties were successfully infested by all six *S. hermonthica* populations tested (Table 5). None of the population of this species showed specificity to maize according to the parasite origin in terms of numbers of emerged *Striga* stems per host plant. Similarly, no specificity was observed for *S. hermonthica* populations sampled from plants parasitizing the different hosts maize, pearl millet and sorghum. There was no significant difference in susceptibility of both tolerant and non tolerant maize genotypes (P = .658) among the six *S. hermonthica* populations (P = .239) in term of number of emerged *S. hermonthica* stems per one host plant.

Table 5: Susceptibility of two maize host genotypes to *S. hermonthica* populations collected from various crops: maize, pearl millet and sorghum in three locations in Côte

UNDER PEER REVIEW

d'Ivoire. Mean (±SE) number of emerged *S. hermonthica* stems per one host plant at 10 weeks after sowing

Host maize varieties	**Parasite origin**					
	Korhogo		Ferké		Tengréla	
	Ex-maize var 1	Ex-Millet var 1	Ex-maize var 2	Ex-maize var 3	Ex-millet var 2	Ex-sorghum
GMRP18	3.00 (1.32)	0.25 (0.14)	2.92 (1.45)	1.25(0.72)	6.08 (1.61)	6.88 (2.97)
IWD Str	4.25 (1.66)	0.25 (0.14)	2.00 (0.38)	2.00 (1.15)	4.50 (3.56)	5.56 (3.25)
P-values	.658 var	.239 str				

P-var: Probability of *F* for maize varieties; *P-str*: Probability of *F* for *Striga* populations.

3.2 DISCUSSION

Results showed that IWD Str variety produced up to 41% more grain yield than the non tolerant variety. Such good performance under diverse *Striga*-infested population conditions confirmed that cultivar IWD Str was tolerant to *Striga* while cultivar GMRP18 was non tolerant or sensitive. The absence of Genotype x *Striga* infestation interaction for grain yield, host plant response (damage symptoms) and other agronomic traits also suggested that the two maize genotypes were different for their horizontal resistance level. These results showed the merits of growing *Striga* tolerant maize varieties (SRT) in *Striga* endemic zone rather than using non tolerant varieties or farmers' varieties. This corroborates the findings of Badu-Apraku *et al.* [26], who identified under *Striga*-infested environment STR varieties with the highest grain yield (2124 and 2158 kg ha^{-1}) and on the other hand, a group of genotypes with grain yield ranging from 1498 to 1759 kg ha^{-1} that contained mostly *Striga* susceptible cultivars. These results were also in agreement with the

UNDER PEER REVIEW

findings of Abdulai *et al.* [26] who reported that STR varieties grown in sole cropping produced up to 70% more than the farmers' maize, the susceptible check.

Furthermore, our results showed that growing STR variety could lead to gain 625 - 1083 kg more than growing *Striga* non tolerant variety. Khan *et al.* [27] reported that revenue generated by the farmers is influenced by the amounts of crop yield obtained and the prices the product can fetch in the nearby markets. In Côte d'Ivoire, maize prices fluctuated between USD 0.2 – 0.6 / kg. So the total income arising from sale of product from the STR variety could be estimated at 125 to 217 USD or 375 to 650 USD more in one hectare of farmland. Consequently, there was a general increase in the amount of income in *Striga*-tolerant maize monocrop. Thus, host plant tolerance is a useful control measure to combat the menace of *S. hermonthica* infestation in Côte d'Ivoire. It could contribute to poverty alleviation through food security and income generation of farmers in *Striga* endemic areas. Moreover, it is considered to be the most economical, affordable, effective, and environmentally sustainable approach for controlling *Striga* in Africa for resource-poor farmers [11].

S. hermonthica populations collected on sorghum and millet (StSo and StMi2) from Tengréla region in the northern Sudan savanna zone were the most highly aggressive populations in terms of maize-grain yield reduction, specially the millet population. There were followed by the population collected on maize at Pegatienvogo, Ferké in the southern Sudan savanna zone. This study revealed that there is a difference in virulence of *S. hermonthica* populations, with the highly virulent populations coming from the northern Sudan savanna zone and the relatively less virulent in the southern Sudan savanna zone of Côte d'Ivoire. This agrees with Kouakou *et al.* (2013, personal communication) who confirmed the hypothesis of *Striga* infestations in Côte d'Ivoire according to a north-south gradient. In related study, Reda *et al.* [28] found variability on

UNDER PEER REVIEW

S. hermonthica populations originating from different geographical areas. Our results clearly identify different *S. hermonthica* populations occurring in northern Côte d'Ivoire, which are capable of reducing maize grain yield between 38.5 and 58.7%. Our findings will allow the National Agency Support of Rural Development (ANADER) and NGOs in charge of distributing *Striga* control technologies to take appropriate precautionary measures on the promotion and distribution of improved varieties in general and *Striga*-tolerant maize varieties in particular.

All six *S. hermonthica* populations tested showed no specificity to maize. There is no strain specialization to a cultivar of a crop species in these populations. A similar conclusion was drawn by Johnson *et al*. [29] who pointed out that there is either no intracrop nor intercrop (strain specificity to a crop species) specialization in *S. hermonthica* from Côte d'Ivoire. In contrast, King and Zummo [30] reported the existence of physiological specialization in *S. hermonthica* from West Africa. Rasha *et al.* [31] also reported host specificity and existence of two distinct strains on sorghum and millet. One of the applications of our results is that it provides information on the extent to which no difference in host preference exists among *S. hermonthica* from Côte d'Ivoire. Such information suggested that rotations of one sensitive cereal species with another leads to the continuous build up of *S. hermonthica* populations. Farmers in Côte d'Ivoire should therefore use appropriated crops in their cropping systems in *Striga* endemic zone. Furthermore, breeding resistant cultivars in the national program could easily be done without the necessity of developing cultivar resistant to a particular strain of the parasite

4. CONCLUSION

This study showed that the *Striga*-tolerant cultivar (SRT) IWD Str produced up to 41% more grain than the non tolerant variety under diverse *Striga*-infested population conditions amounting to up to 650 USD of income for a hectare of farmland. These results prove the merits of growing

UNDER PEER REVIEW

Striga tolerant maize varieties in *Striga* endemic zone rather than using non tolerant varieties or farmers' varieties. Therefore, host plant tolerance is a useful control measure to combat the menace of *S. hermonthica* infestation in Côte d'Ivoire. It could contribute to poverty alleviation through food security and income generation of farmers in *Striga* endemic areas. No strain specialization to a cultivar of a crop species in *S. hermonthica* populations was found. Further studies are needed to determine the genetic diversity of *S. hermonthica* in Côte d'Ivoire and to understand the difference in virulence among populations.

ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to Rep of South Korea and African Union SAFGRAD for the support given to the maize, millet, sorghum Program for this study.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

Author LA designed the study and critically reviewed the first draft. Author CKK wrote the protocol, laid out the experiment; compiled the study results, performed the statistical analysis; wrote the first draft. Author IAZB supervised the study. Author LR critically reviewed the protocol. Author AHD helped a lot during field work and contributed to the results discussion.

REFERENCES

1 Kouassi B. *Striga* in Côte d'Ivoire. In Robson, T.O., Broads, R.H. (Eds), Proceedings of the FAO/OAU African Government Consultation on *Striga* control; Maroua, Cameroon. FAO; Rome. 1989.

UNDER PEER REVIEW

2 Akanvou L, Yébi S, Kouassi C. Evaluation d'une méthode de lutte intégrée contre le *Striga* en milieu paysan. *In*: Badu-Apraku, B., Fakorede M.A.B., Ouédraogo M, Carsky, R.J. and Menkir A. (Eds) Maize revolution in West en Central Africa. Proceeding of a Regional maize Workshop, 14-18, 2001, WECAMAN/IITA – Cotonou, Benin republic. 2003.

3 Kim SK. Genetics of maize tolerance of *Striga hermonthica*. *Crop Sci*. 1994; 34: 900-907.

4 Thalouarn P, Fer A. *Striga*, a threat of food crops: recent knowledge and methods of fight (In French). *Cah*. *Agric*. 1993; 2: 167-182.

5 Oswalda A, Ransom JK, Kroschel J, Sauerbornc J. Intercropping controls *Striga* in maize based farming systems. *Crop Prot.*. 2002; 21: 367-374.

6 Gbèhounou G, Pieterse AH, Verkleij JAC. Longevity of *Striga* seeds reconsidered: results of a field study on purple witchweed (*Striga hermonthica*) in Benin. *Weed Science*. 2003; 51: 940-946.

7 Kamara AY, Menkir A, Chikoye D, Omoigui LO, Ekeleme F. Cultivar and nitrogen fertilization effects on *Striga i*nfestation and grain yield of early maturing tropical maize. *Maydica*. 2007; 52: 415-423.

8 Radi A. Conventional and biotechnological approaches for control of parasitic weeds. *In Vitro Cell. Dev. Biol. - Plant*. 2007; 43: 304-317.

9 Abdulai MS, Denwar NN, Haruna M. Combating the menace of *Striga hermonthica* infestation: An integrated approach adopted in north-eastern Ghana. *J. Agron.* 2006; 5: 617-620.

10 Badu-Apraku B, Fakorede MAB, Lum AF. S1 family selection in earlymaturing maize population in Striga-infested and Striga-free environments. *Crop Sci*. 2008; 48: 1984-1994.

11 Badu-Apraku B, Akinwale RO. Cultivar evaluation and trait analysis of tropical early maturing maize under *Striga*-infested and *Striga*-free environments. *Field Crops Res*. 2011; 121: 186-194.

UNDER PEER REVIEW

12 Hess DE, Ejeta G. Inheritance of resistance to *Striga* in sorghum genotype SRN39. *Plant Breed*. 1992; 109: 233-241.

13 Gethi JG, Smith ME. Genetic responses of single crosses of maize to *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze. *Crop Sci*. 2004; 44: 2068-2077.

14 Menkir A. Assessment of reactions of diverse maize inbred lines to *Striga hermonthica* (Del.) Benth. *Plant Breed.* 2006; 125: 131-139.

15 Amusan IO, Rich PJ., Menkir A, Housley T, Ejeta, G. Resistance to *Striga hermonthica* in maize inbred line derived from *Zea diploperennis*. *New Phytologist.* 2008; 178: 157-166.

16 Heller R, Wegmann K. Mechanisms of resistance to *Striga* hermonthica (Del.) Benth. In Sorghum bicolor (L.) Moench. In: D.E.H.B.I.G. Haussmann, M.L. Koyama, L. Grivet, H.F.W. Rattunde, H.H. Geiger, ed. Breeding for *Striga* Resistance in Cereals. Weikersheim, Germany: Margraf-verlag, Proceedings of a Workshop held at IITA, Ibadan, Nigeria. 2000.

17 Ejeta G. Breeding for Striga Resistance in Sorghum: Exploitation of an Intricate Host–Parasite Biology. *Crop Sci*. 2007; 47: 216-227.

18 Badu-Apraku B. Genetic variances and correlations in an early tropical white maize population after three cycles of recurrent selection for *Striga* resistance. *Maydica*. 2007; 52: 205-217.

19 Olaoye G, Bello OB. Combining ability for maize grain yield in *Striga* endemic and non-endemic environments of the southern guinea savanna of Nigeria. *J Plant Breed Crop Sci*. 2009; 1: 72-79.

20 Kim SK, Adetimirinn VO, Thé C, Dossou R. Yield losses in maize due to *Striga hermonthica* in West and Central Africa. *Int. J. Pest Manag*. 2002; 48: 211-217.

21 Botanga CJ, Kling JG, Berner DK, Timko MP. Genetic variability of *Striga asiatica* (L.) Kuntz based on AFLP analysis and host-parasite interaction. *Euphytica.* 2002; 128: 375-388.

UNDER PEER REVIEW

22 Valentin C. A characterization of the soil resource of the research station at Ferkessédougou (northern Côte d'Ivoire) with respects to suitability of IITA's maize savannah substation. Consultancy report for IITA, Ibadan, Nigeria. 1988.

23 Beaudou, AG, Sayol R. Étude pédologique (Côte-d'ivoire) de la région de Boundiali Korhogo. Cartographie et typologie sommaire des sols Feuilles Boundiali et Korhogo. ORSTOM, Paris. 1980. (In french)

24 Guillaumet J, Adjanohou E. Le milieu naturel de la Côte d'lvoire. *Mémoire ORSTOM*.1971; 50: 157-264. (In french)

25 Haussmanna BIG, Hess DE, Welz HG, Geiger HH. Improved methodologies for breeding *Striga*-resistant sorghums. *Field Crops Res*. 2000; 66: 195-211.

26 *Badu-Apraku B, Fakorede MAB, Menkir A*. Recurrent selection for *Striga* resistance in early and extra-early maize populations in West Africa. 2009; *Afr. Crop Sci. J.*: 9: 415 – 424.

27 Khan ZR, Midega CAO, Wanyama JM, Amudavi DM, Hassanali A, Pittchar J, Pickett JA. Integration of edible beans (Phaseolus vulgaris L.) into the push–pull technology developed for stemborer and *Striga* control in maize-based cropping systems. *Crop Prot*. 2009; 28: 997-

28 Reda F, Dierick A, Verkleij JAC. Virulence Study of *Striga hermonthica* Populations from Tigray Region (Northern Ethiopia). *World J. Agric. Sci*. 2010; 6: 676-682.

29 Johnson DE Riches CR, Diallot R, Jones MJ. *Striga* on rice in West Africa; crop host range and the potential of host resistance. *Crop Prot.*. 1997; 16: 153-57.

30 King SB, Zummo N. Physiologic specialization in *Striga hermonthica* in West Africa. *Plant Dis.* 1977; 61: 770-773.

31 Rasha AMAA, Adil AEH, Mohamed KI, Babiker AGT. Specificity and Genetic Relatedness among *Striga hermonthica* Strains in Sudan. *Life Sci. Int. J.* 2009; 3: 1159-1166.