



A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J E Smith), in maize in East Africa



Charles A.O. Midega^{a,*}, Jimmy O. Pittchar^a, John A. Pickett^b, Girma W. Hailu^a, Zeyaur R. Khan^a

^a International Centre of Insect Physiology and Ecology (icipe), Nairobi, Kenya

^b Department of Biological Chemistry and Crop Protection, Rothamsted Research, Harpenden, UK

ARTICLE INFO

Keywords:

Climate-smart push-pull
Fall armyworm
Management
Maize
Africa

ABSTRACT

Fall armyworm, *Spodoptera frugiperda* (J E Smith), an economically important pest native to tropical and sub-tropical America has recently invaded Africa, causing substantial damage to maize and other crops. We evaluated functionality of a companion cropping system, 'climate-adapted push-pull', developed for control of cereal stemborers in drier agro-ecologies, as an added tool for the management of fall armyworm. The technology comprises intercropping maize with drought-tolerant greenleaf desmodium, *Desmodium intortum* (Mill.) Urb., and planting *Brachiaria cv* Mulato II as a border crop around this intercrop. Protection to maize is provided by semiochemicals that are emitted by the intercrop that repel (push) stemborer moths while those released by the border crop attract (pull) them. 250 farmers who had adopted the technology in drier areas of Kenya, Uganda and Tanzania were randomly selected for the study during the long rainy season (March–August) of 2017. Each farmer had a set of two plots, a climate-adapted push–pull and a maize monocrop. Data were collected in each plot on the number of fall armyworm larvae on maize, percentage of maize plants damaged by the larvae and maize grain yields. Similarly, farmers' perceptions of the impact of the technology on the pest were assessed using a semi-structured questionnaire. Reductions of 82.7% in average number of larvae per plant and 86.7% in plant damage per plot were observed in climate-adapted push-pull compared to maize monocrop plots. Similarly, maize grain yields were significantly higher, 2.7 times, in the climate-adapted push-pull plots. Farmers rated the technology significantly superior in reducing fall armyworm infestation and plant damage rates. These results demonstrate that the technology is effective in controlling fall armyworm with concomitant maize grain yield increases, and represent the first documentation of a technology that can be immediately deployed for management of the pest in East Africa and beyond.

1. Introduction

Maize, *Zea mays* L., is one of the most important food and cash crops for both commercial and many rural farm families in Africa. Much is however produced by smallholder farmers in predominantly mixed crop-livestock farming systems (Cairns et al., 2013). Fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is an economically important pest that attacks maize and other graminaceous crops throughout much of its native tropical and sub-tropical America (Andrews, 1980). Its host range however includes almost 100 recorded plant species in 27 families (Pogue, 2002). It is a well-known sporadic and long-distance migratory pest with the adult moths being able to fly over 100 km in a single night (Johnson, 1987). The fall armyworm larvae feed on young leaf whorls, ears and tassels causing substantial damage to maize, occasionally resulting in total yield loss (Cruz and Turpin, 1982; De Almeida Sarmiento et al., 2002). Larger larvae can act

as cutworms by entirely sectioning the stem base of maize seedlings (Goergen et al., 2016). The extent of damage, however, depends on factors such as planting season, geographical region, cultivar planted and cultural practices inherent in and around the field (De Almeida Sarmiento et al., 2002).

From its native tropical and sub-tropical America, the fall armyworm has spread and become a serious pest of maize and other crops in many parts of the world. Most recently, the pest has invaded Africa, with the first detections being reported in Central and Western Africa in early 2016 (Goergen et al., 2016), and in late 2016 and 2017 in parts of Southern, Eastern and Northern Africa (FAO, 2017). It is expected to further spread in the continent, with devastating effects. Indeed, large numbers of fall armyworm larvae plaguing various crops of economic importance are now recurrently recorded in many African countries (Goergen et al., 2016). The continent provides a number of host plants, including grasses, and with favourable environmental conditions, it is

* Corresponding author.

E-mail address: cmidega@icipe.org (C.A.O. Midega).

Table 1

Mean (\pm S.E.) number of fall armyworm larvae and proportion of maize plants damaged in plots of maize planted in sole stands (monocrop) or in climate-adapted push–pull treatments in different sub-counties in western Kenya, eastern Uganda and northern Tanzania.

Country	Sub-county ^a	Cropping System	% plants damaged	t-value	% reduction	Number of larvae/plant	t-value	% reduction	
Kenya	Bungoma	Push-pull	5.2(1.0)			0.003(0.002)			
		Monocrop	95.4(1.0)	32.7	94.6(1.0)	0.49(0.04)	11.4	82.7(6.3)	
	Busia	Push-pull	18.6(1.5)			0.18(0.02)			
		Monocrop	94.3(0.8)	30.3	80.2(1.6)	2.07(0.08)	30.7	90.7(1.1)	
	Siaya	Push-pull	4.1(0.9)			0.008(0.004)			
		Monocrop	80.0(1.5)	34.4	95.0(1.1)	0.23(0.08)	3.01	96.5(1.6)	
	Vihiga	Push-pull	4.7(0.6)			0.003(0.002)			
		Monocrop	85.2(1.3)	32.1	94.4(0.7)	0.36(0.04)	10.7	99.3(0.4)	
	Migori	Push-pull	3.2(0.7)			0.002(0.001)			
		Monocrop	91.3(1.4)	27.6	95.5(0.7)	0.69(0.03)	30.4	99.6(0.2)	
	Homabay	Push-pull	9.5(2.2)			0.06(0.03)			
		Monocrop	84.4(2.7)	16.2	88.2(2.6)	0.95(0.08)	12.9	94.6(2.5)	
Uganda	Iganga	Push-pull	27.3(2.1)			0.15(0.23)			
		Monocrop	94.0(2.3)	13.2	70.9(2.2)	0.60(0.02)	12.2	75.2(4.7)	
	Bugiri	Push-pull	23.8(3.2)			0.13(0.04)			
		Monocrop	88.0(3.3)	10	72.6(3.9)	0.52(0.05)	6.01	72.4(8.7)	
	Tororo	Push-pull	22.0(4.0)			0.14(0.04)			
		Monocrop	80.0(5.0)	7.9	71.1(6.8)	0.56(0.06)	5.93	68.1(11.5)	
	Bukedea	Push-pull	26.0(2.8)			0.17(0.03)			
		Monocrop	86.0(4.7)	7.3	68.4(4.3)	0.83(0.12)	6.01	76.2(6.1)	
	Tanzania	Tarime	Push-pull	5.4(1.6)			0.02(0.01)		
			Monocrop	67.1(3.5)	12.7	92.3(2.1)	0.38(0.03)	15.8	96.5(1.6)
	Average	reduction				86.7(0.8)		82.7(1.9)	

In each sub-county and district, means represent data averages of 30 farmers in Kenya, 10 in Uganda and 30 in Tanzania. Figures in parentheses are standard errors. All t-values were associated with $p < 0.0001$ except in Siaya where the t-value under mean number of larvae per plant was associated with $p = 0.004$.

^a The regions are known as sub-counties in Kenya and districts in Tanzania and Uganda.

postulated that the invading populations will persist and cause serious damage to key crops that provide livelihoods to many farmers (FAO, 2017).

Management of the fall armyworm has been mainly effected through use of synthetic insecticides (Cook et al., 2004). Although some of these are both effective against the pests and less harmful to the environment, experience indicates that choice of insecticides is largely based on a farmer's knowledge and purchasing power, with a tendency to select cheaper products (Dal Pogeto et al., 2012). Overall, the conventional chemical control strategies are sometimes inconsistent and often unsatisfactory to control the pest in fields of maize (Tinoco and Halperin, 1998). This is complicated by chronic poisoning of farmers in some localities due to incorrect use (Tinoco and Halperin, 1998). Use of insecticides as a pest management tool for small scale farmers in Africa is minimal, largely due to shortage of information, inaccessibility of appropriate and effective products, and high costs (Midega et al., 2012). There is thus a need to develop integrated pest management (IPM) packages that are suitable and cost-effective, especially for smallholder farmers in the region.

Invasion of Africa by the fall armyworm adds to the diversity of lepidopteran pests of cereal crops, and signals increased negative impacts on agricultural production and food security on the continent. Other devastating lepidopteran pests of cereal crops in the continent include the indigenous *Busseola fusca* (Füller) (Noctuidae), *Eldana saccharina* Walker (Pyralidae) and the invasive *Chilo partellus* Swinhoe (Crambidae) (Kfir et al., 2002). Control of these pests through conventional methods such as use of insecticides is complicated by the nocturnal behavior of the adult moths, the boring activity of the damaging larval stage, the availability of diverse alternative host plants and the resource-poor nature of many of the farmers (Kfir et al., 2002). One of the most effective ways of managing these pests is through the use of a companion cropping system, the push-pull technology, which was developed by the International Centre of Insect Physiology and Ecology (*icipe*) and partners through exploiting behavior-modifying stimuli to manipulate the distribution and abundance of stemborer pests and their natural enemies (Cook et al., 2007). Conventionally, it

involves intercropping maize with a repellent plant, such as desmodium, *Desmodium uncinatum* Jacq. (Leguminaceae) (push), and planting an attractive trap plant, such as Napier grass, *Pennisetum purpureum* Schumacher (Poaceae) (pull), as a border crop around this intercropped field. Gravid stemborer moths are repelled from the main crop by the repellent plant, and are simultaneously attracted to the trap plant (Khan et al., 2010).

The push-pull technology has recently been adapted to the increasingly dry and hot conditions associated with climate change through identification and incorporation of drought tolerant companion plants. Dubbed 'climate-adapted push-pull', the technology uses the drought tolerant greenleaf desmodium, *Desmodium intortum* (Mill.) Urb. (Leguminosae), and *Brachiaria* cv Mulato II (Poaceae) as the 'push' and 'pull' crops respectively (Khan et al., 2014). Results from field implementation of this technology indicate that it effectively limits stemborer infestation and striga (*Striga hermonthica* (Del.) Benth. (Orbanchaceae)), a devastating parasitic weed of cereal crops in Africa, resulting in significant increases in maize grain yields (Midega et al., 2015a,b). The purpose of the current study was to evaluate field performance of the technology against the fall armyworm in East Africa. Specifically, we sought to establish (i) the impact of the climate smart push-pull on infestation and damage of maize by the fall armyworm; and (ii) farmers' perceptions on effectiveness of the technology in management of the pest.

2. Materials and methods

2.1. Study sites

Multi-site field studies were conducted during the long rainy season (March–August) of 2017 in drier areas of western Kenya, eastern Uganda and northern Tanzania where the climate-adapted push–pull is being practiced against stemborers and striga by smallholder farmers (Table 1) (Midega et al., 2015a). This covered 6 sub-counties (formerly called districts) in western Kenya (0°40' to 0°58'S, 34°0' to 34°67' E), 4 districts in eastern Uganda (0°11' to 0°44' S, 34°0' to 34°55' E) and one

district in northern Tanzania (0°01' to 0°42' S, 33°03' to 34°57' E). The sites experienced extended periods of drought and were exposed to biotic stress from lepidopteran stemborers and striga, with effects being aggravated by the degraded and infertile soils. These sites also represent some of the areas that have been recently invaded by the fall armyworm in the region (FAO, 2017). Annual rainfall averages in the selected sites have also decreased over the last decade to below the 1500 mm mean for the region (Midega et al., 2015a).

2.2. Plot layout and data collection

Studies were conducted following methodologies adapted from Midega et al. (2015a). In each sub-county and district, smallholder farmers (30 in western Kenya, 10 in eastern Uganda and 30 in northern Tanzania) who had practiced the climate-adapted push-pull for at least 2 cropping seasons were randomly selected and recruited into the study through a two-stage process. First, a checklist was made from a survey of all farmers who were practicing the technology in these sites, followed by a semi-structured questionnaire interview where they were asked whether they were willing to participate in a study assessing the pest management efficiency of the technology on fall armyworm in their farms. An additional criterion used in selection of farmers was presence of two adjacent plots, one planted with the climate-adapted push-pull system and one planted with maize as a monocrop, to allow comparison of the two systems. In the climate-adapted push-pull plot, maize was intercropped with greenleaf desmodium and *Brachiaria* cv Mulato II was planted around this intercrop at a spacing of 50 cm within and 50 cm between rows. Greenleaf desmodium was planted in between rows of maize. Maize was planted at inter and intra-row spacing of 75 cm and 30 cm, respectively, in both plots. Farmers applied phosphorus in the form of di-ammonium phosphate (DAP) in each plot at planting, at a rate of 60 kg/ha, and nitrogen in the form of calcium ammonium nitrate (CAN), at a rate of 60 kg/ha, 4 weeks after emergence of maize. The plot size varied from farmer to farmer, ranging from 18 m by 18 m–40 m by 40 m, but for each farmer in the study, the sizes of both plots were the same, and were spaced 5 m–25 m apart (Midega et al., 2015a).

2.3. Infestation levels of fall armyworm and plant damage

Depending on the growth stage of maize, fall armyworm larvae are found on young leaves, leaf whorls, tassel or cobs (Goergen et al., 2016). Therefore, infestation levels of the pest on these parts of the plants were assessed non-destructively using methodologies adapted from Midega et al. (2015a). In each plot, a 5 m-wide transect line was demarcated diagonally across the field and 30 maize plants randomly selected from within the transect line. Each plant was then visually examined and larvae on the plant counted. The larval data from the plants examined were summed, then divided by the total number of plants and expressed as number of larvae per plant. During the vegetative phase of the plants, feeding by the fall armyworm larvae results in skeletonized leaves and heavily windowed whorls loaded with larval frass (Goergen et al., 2016). At the reproductive stage of maize, the larvae also attack reproductive organs, feeding on tassels and/or boring into the ears. Additionally, because farmers planted at different times within the season, maize plants in different sites were at different growth stages at the time of the survey. Therefore, damage caused by larvae was assessed by examining the various vegetative and reproductive parts of each of the 30 plants for visible larval damage and data expressed as percentage of plants damaged per plot.

2.4. Maize grain yields

Maize grain yields were determined at the crop's full physiological maturity when all the cobs on the maize plants in each plot were harvested, and sun-dried separately for each plot and farmer. The cobs

were then shelled and maize grain sun-dried to 12% moisture content, confirmed using a moisture meter (Multi-grain tester, Dickey-john corporation, Auburn, USA), and weights individually taken for each plot and farmer. The grain weights were calculated per plot area harvested, and data converted into tonnes/hectare, with maize yields in the climate-adapted push-pull plots calculated taking into account the entire plot including area occupied by *Brachiaria* cv Mulato II (Midega et al., 2015a).

2.5. Farmer perceptions of the technology's ability to control fall armyworm

Perceptions of farmers on the impact of the technology on fall armyworm infestation and plant damage was assessed during the survey described above using a semi-structured survey questionnaire following methodologies adapted from Midega et al. (2012), where a total of 212 smallholder farmers were interviewed; 150 in western Kenya, 30 in Tanzania and 32 in Uganda. These farmers were sampled from those whose farms were surveyed for the fall armyworm infestation and plant damage studies described in section 2.2 above. During the interviews, farmers' perceptions were sought on whether the pest had invaded their own and neighbors' farms; severity of the infestation relative to their control plots; impact of climate-smart push-pull in reducing fall armyworm infestation; and rating of the damage caused to maize by the pest. Rating of plant damage ranged from none to very high damage: None, 0% plants damaged by fall armyworm larvae; Low, < 25% plants damaged; Average, 25–50% plants damaged; High, 50–75% plants damaged; Very high, > 75% plants damaged. Where a farmer's own plot had no pest invasion, they evaluated infested plots of their neighbors. These interviews were conducted on the farms to allow cross-checking of responses with the actual situation of the crops in the farms.

2.6. Data analysis

Data on fall armyworm infestation levels, plant damage and grain yields of maize were averaged for each plot and farmer (each farmer being a replicate) and analysed using a *t*-test to derive comparisons between the climate-adapted push-pull and maize monocrop plots. Data on fall armyworm larval counts were log transformed ($\log_{10}x + 1$), while data on proportions of plants damaged were subjected to arcsine transformation prior to analysis to normalize the data and stabilize the variance. These analyses were performed in R version 3.1.1 statistical software (R Core Team, 2014). Data on farmers' perceptions on the other hand were summarized using cross tabulations and processed descriptively using means and percentages. Chi-square analysis was then performed to compare the responses. Non-transformed data are presented in the results section.

3. Results

Infestation by stemborer species in these fields was negligible, and so only fall armyworm data were collected, analysed and presented.

3.1. Infestation levels of fall armyworm and plant damage

Overall, there were highly significant reductions in infestation levels of fall armyworm (average of 82.7%) in the climate-adapted push-pull relative to the maize monocrop (*t*-test, $p < 0.01$) across study sites. These observations were associated with highly significant reductions in proportions of maize plants damaged by the larvae (average of 86.7%) in the climate-adapted push-pull plots (Table 1). In Kenya, the average number of larvae per maize plant ranged from 0.002 to 0.18 in the climate-adapted push-pull, and from 0.23 to 2.07 in the maize monocrop. In Uganda, the average number of larvae per maize plant ranged from 0.13 to 0.17 in the climate-adapted push-pull, and from 0.52 to 0.83 in the maize monocrop plots. In Tanzania, the number of larvae per maize plant averaged 0.02 in the climate-adapted push-pull,

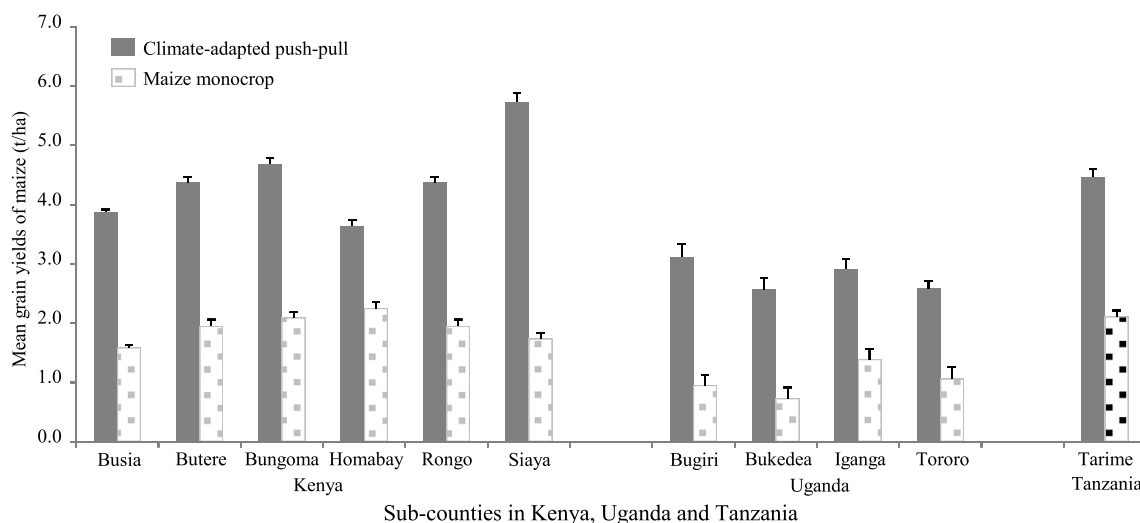


Fig. 1. Mean (\pm S.E.) grain yields of maize (t/ha) planted in sole stands (maize monocrop) or in climate-adapted push-pull stands.

In all sub-counties, maize grain yields were significantly higher in the climate-adapted push-pull than in the maize monocrop plots (t -test, $p < 0.0001$). In each sub-county, means represent data averages of 30 farmers in Kenya, 10 in Uganda and 30 in Tanzania.

and 0.38 in the maize monocrop plots (Table 1). Proportions of the maize plants damaged by the larvae in Kenya ranged from 3.2 to 18.6% with the climate-adapted push-pull, and from 80.0 to 95.4% in the maize monocrop. In Uganda, the damage ranged from 22.0 to 27.3% in the climate-adapted push-pull, and from 80.0 to 94% in maize monocrop. In Tanzania, the damaged averaged 5.4% in climate-adapted push-pull, and 67.1% in maize monocrop.

3.2. Maize grain yields

Overall mean yields were 2.5, 2.1 and 3.5 times higher in Kenya, Tanzania and Uganda in the climate-adapted push-pull plots than in the maize monocrop plots (Fig. 1). Grain yields in Kenya ranged from 3.6 to 5.7 t/ha in the climate-adapted push-pull plots, and from 1.7 to 2.3 t/ha in the maize monocrop plots. In Uganda, yields ranged from 2.6 to 3.1 t/ha in the climate-adapted push-pull plots, and from 0.7 to 1.4 t/ha in the monocrop plots. In Tanzania, the mean grain yields were 4.5 t/ha in the climate-adapted push-pull and 2.1 t/ha in the monocrop plots.

3.3. Farmer perceptions of the technology's ability to control fall armyworm

All the farmers interviewed had experienced infestation of fall armyworm either on their own farms, or on their neighbors' farms, with significantly higher proportions of the respondents stating they had the pest on their own farms relative to those whose farms had no infestation, except Tanzania (Table 2). The respondents confirmed that this was their first encounter of the pest. Out of the respondents who had fall armyworm infestations on their farms, significantly higher proportions of these reported lower infestation levels in the climate-adapted push-pull plots relative to the maize monocrop, confirmed through direct observation of the crops by the interviewers; overall, 97%, 100% and 87.5% in Kenya, Tanzania and Uganda, respectively, reported significantly lower pest infestation levels in their climate-adapted push-pull plots relative to the maize monocrop plots. Additionally, all the respondents in Kenya and Tanzania, and 96.9% in Uganda reported that the technology effectively reduced pest infestation in maize. In terms of actual damage to maize by the larvae, 92.9% of the respondents in the three countries reported no damage to low (< 25%) levels of damage in climate-adapted push-pull plots. Conversely, 96.7% of the respondents reported high (50–75%) and severe (> 75%) damage levels in maize caused by the larvae in the maize monocrop plots (Table 2).

4. Discussion

Results of the current study indicate effective reduction of infestation by fall armyworm with the climate-adapted push-pull system, resulting in significantly lower damage levels on maize in the East African country trials. These observations were supported by farmers' perceptions on the effectiveness of the technology against the pest in the region. While the technology was initially developed to control lepidopteran stemborers attacking cereal crops in Africa (Khan et al., 2010), its adaptation and extension to drier agro-ecologies has expanded its pest management functionality, including effective management of fall armyworm in the region. The mechanism of stemborer control by this system is mediated by green leaf volatiles emitted by the companion crops (Khan et al., 2010). The trap plants emit semiochemicals that are attractive to the gravid female moths while the intercrops emit semiochemicals that deter oviposition on the maize (Chamberlain et al., 2006) but attract the pests' natural enemies (Khan et al., 1997; Midega et al., 2009). The trap plants, however, are not suitable for survival of the larval stages of the pests, resulting in high mortality rates and delayed development of the larvae (Khan et al., 2006; Midega et al., 2011). There is also increased abundance, diversity and activity of predatory arthropods in this system, further contributing to reducing pest populations (Midega et al., 2006). The reduced infestation levels of the fall armyworm in climate-smart push-pull plots might have resulted from some of the mechanisms above, since fall armyworm is a noctuid like *B. fusca* that is effectively controlled by the technology (Midega et al., 2014a). However, there is need to fully elucidate the mechanism of fall armyworm control by this technology to allow its optimization and strategic dissemination as a management tool for this invasive pest in East Africa and beyond.

Control of fall armyworm in the localities where it has been reported in Africa and elsewhere remains a challenge. Although judicious use of chemical insecticides has been shown to provide effective control of the pest (Young, 1979), cases of resistance to some key insecticides have been reported (Yu, 1992; Al-Sarar et al., 2006). Additionally, dispersion of the fall armyworm larvae lower into the maize plant canopy makes them more difficult to control, largely due to the difficulty in insecticide applications penetrating the plant canopy to the location of larvae (Cook et al., 2004). While fall armyworm is a major target of genetically modified Bt maize crops in places where transgenic plant technology is adopted (Frizzas et al., 2014), field resistance by the pest to such crops has been documented, including resistance to Cry1F maize in Puerto Rico (Storer et al., 2010). The introduction of this

Table 2

Farmers' perceptions on fall armyworm and effectiveness of climate-adapted push-pull on its management in western Kenya, eastern Uganda and northern Tanzania.

Parameter	Response/rating	Country								Statistics	
		Kenya		Tanzania		Uganda		Total		Chi	Sig
		N	%	N	%	N	%	N	%		
Pest presence on own farm	No	50	33.3	19	63.3	0	0.0	69	32.5	36.46	0.000
	Yes	100	66.7	11	36.7	32	100.0	143	67.5		
Seriousness of infestation in CAPP vs mono	Lower	97	97.0	11	100.0	28	87.5	136	95.1	21.21	0.000
	Same	3	3.0	0	0.0	4	12.5	7	4.9		
	Higher	0	0.0	0	0.0	0	0.0	0	0.0		
CAPP decreases infestation	Yes	150	100.0	30	100.0	31	96.9	211	99.5		
^a Maize damage under CAPP	None	94	62.7	17	56.7	0	0.0	111	52.4	26.967	0.000
	Low (< 25%)	47	31.3	12	40.0	27	84.4	86	40.5		
	Average (25-50%)	9	6.0	1	3.3	5	15.6	15	7.1		
^b Pest damage in maize mono	Average	4	2.7	1	3.3	2	6.3	7	3.3	9.681	0.139
	High (50-75%)	65	43.3	14	46.7	20	62.5	99	46.7		
	Severe (> 75%)	81	54.0	15	50.0	10	31.2	106	50.0		

^a No respondents rated maize damage by fall armyworm as high and severe under climate-adapted push-pull.

^b No respondents rated maize damage by fall armyworm as none and low under maize monocrop system. CAPP, Climate-adapted push-pull; mono, maize monocrop. Rating of plant damage: None, 0% plants damaged by fall armyworm larvae; Low, < 25% plants damaged; Average, 25-50% plants damaged; High, 50-75% plants damaged; Very high, > 75% plants damaged.

highly polyphagous pest into the African continent is projected to constitute a lasting threat to several important crops (reviewed by Goergen et al., 2016). This projection is based on a number of factors, including the fact that the larvae have comparatively stronger mandibles with serrated cutting edges, which ease the feeding on plants with high silica content (Pogue, 2002); the older larvae are cannibalistic and have the ability to dominate inter- and intraspecific competitors (Chapman et al., 2000); the continent provides favourable climatic conditions for a constant reproduction of the pest, which is expected to result in severe damage to crops (Goergen et al., 2016); and being a new pest in the continent, it might have found an enemy-free space.

The challenges observed with the conventional control methods highlighted above, notably development of resistance by the pest to some insecticides and Bt-maize events, indicate that an integrated management approach for fall armyworm that fits within the mixed cropping nature of the African farming systems is necessary for resource constrained farmers. This study represents the first report of effectiveness of the climate-adapted push-pull technology in the management of fall armyworm, and also the first demonstration of an effective management tool for the pest in Africa, resulting in higher crop yields. The improved yields, however, cannot be solely attributed to effective control of fall armyworm by the technology, but to a cumulative impact including control of the parasitic striga weed, together with improvements in soil health through factors such as nitrogen fixation by desmodium (Midega et al., 2014b, 2015a).

In conclusion, these studies demonstrate that climate-adapted push-pull technology developed for control of cereal stemborers and striga weed (Khan et al., 2010) effectively controls fall armyworm in smallholder farming systems in East Africa. The technology thus has potential for expansion in the African continent to manage key pests affecting cereal production in the continent. The ability of the technology to manage such a devastating pest, together with the positive perceptions of the smallholder farmers, where it was already implemented for stemborer and striga control, indicate its stability and resilience, and confirms that it is an ecologically sustainable and socially acceptable approach to pest management.

Acknowledgments

We gratefully acknowledge the financial support for this research by

the following organizations and agencies: the European Union, Biovision Foundation, UK's Department for International Development (DFID); Swedish International Development Cooperation Agency; the Swiss Agency for Development and Cooperation (SDC); and the Kenyan Government. The views expressed herein do not necessarily reflect the official opinion of these donors. The studies were conducted in collaboration with Rothamsted Research, which receives grant-aided support from the Biotechnology and Biological Sciences Research Council (BBSRC), UK, with additional funding provided under the Biological Interactions in the Root Environment (BIRE) initiative. The farmers who allowed us to collect data in their farms, and field assistance provided by Dickens Nyagol and Eunice Mumbo are also greatly acknowledged.

References

- Al-Sarar, A., Hall, F.R., Downer, R.A., 2006. Impact of spray application methodology on the development of resistance to cypermethrin and spinosad by fall armyworm *Spodoptera frugiperda* (J.E. Smith). *Pest Manage. Sci.* 62, 1023–1031.
- Andrews, K.L., 1980. The whorlworm, *Spodoptera frugiperda*, in central America and neighboring areas. *Fla. Entomol.* 63, 456–467.
- Cairns, J.E., Hellin, J., Sonder, K., Araus, J.L., MacRobert, J.F., Thierfelder, C., Prasanna, B.M., 2013. Adapting maize production to climate change in sub-Saharan Africa. *Food Secur.* 5, 345–360.
- Chamberlain, K., Khan, Z.R., Pickett, J.A., Tshova, T., Wadhams, L.J., 2006. Diel periodicity in the production of green leaf volatiles by wild and cultivated host plants of stemborer moths, *Chilo partellus* and *Busseola fusca*. *J. Chem. Ecol.* 32, 565–577.
- Chapman, J.W., Williams, T., Martinez, A.M., Cisneros, J., Caballero, P., Cave, R.D., 2000. Does cannibalism in *Spodoptera frugiperda* (Lepidoptera: Noctuidae) reduce the risk of predation? *Behav. Ecol. Sociobiol.* 48, 321–327.
- Cook, S.M., Khan, Z.R., Pickett, J.A., 2007. The use of 'push-pull' strategies in integrated pest management. *Annu. Rev. Entomol.* 52, 375–400.
- Cook, D.R., Leonard, B.R., Gore, J., 2004. Field and laboratory performance of novel insecticides against armyworms (Lepidoptera: Noctuidae). *Fla. Entomol.* 87, 433–439.
- Cruz, I., Turpin, F.T., 1982. Effects of *Spodoptera frugiperda* on different growth stages of corn. *Pesqu. Agropecu. Bras.* 17, 355–359.
- Dal Pogetto, M.H.F.A., Prado, E.P., Gimenes, M.J., Christovam, R.S., Rezende, D.T., Aguiar-Junior, H.O., Costa, S.I.A., Raetano, C.G., 2012. Corn yield with reduction of insecticidal spray against fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). *J. Agron.* 11, 17–21.
- De Almeida Sarmiento, R., de Souza Aguiar, R.W., Vieira, S.M.J., de Oliveira, H.G., Holtz, A.M., 2002. Biology review, occurrence and control of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in corn in Brazil. *Biosci. J.* 18, 41–48.
- FAO, 2017. Briefing note on FAO actions on fall armyworm in Africa. Visited on 2nd November 2017. <http://www.fao.org/emergencies/resources/documents/resources-detail/en/c/902985/>.

- Frizzas, M.R., Neto, S.S., de Oliveira, C.M., Omoto, C., 2014. Genetically modified corn on fall armyworm and earwig populations under field conditions. *Ciência Rural* 44, 203–209.
- Goergen, G., Kumar, P.L., Sankung, S.B., Togola, A., Tamò, M., 2016. First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PLoS One* 11 (10), e0165632. <http://dx.doi.org/10.1371/journal.pone.0165632>.
- Johnson, S.J., 1987. Migration and the life history strategy of the fall armyworm, *Spodoptera frugiperda* in the Western Hemisphere. *Insect Sci. Appli* 8, 543–549.
- Kfir, R., Overholt, W.A., Khan, Z.R., Polaszek, A., 2002. Biology and management of economically important lepidopteran cereal stemborers in Africa. *Annu. Rev. Entomol.* 47, 701–731.
- Khan, Z.R., Ampong-Nyarko, K., Chilishwa, P., Hassanali, A., Kimani, S., Lwande, W., Overholt, W.A., Pickett, J.A., Smart, L.E., Wadhams, L.J., Woodcock, C.M., 1997. Intercropping increases parasitism of pests. *Nature* 388, 631–632.
- Khan, Z.R., Midega, C.A.O., Bruce, T.J.A., Hooper, A.M., Pickett, J.A., 2010. Exploiting phytochemicals for developing a push–pull crop protection strategy for cereal farmers in Africa. *J. Exp. Bot.* 61, 4185–4196.
- Khan, Z.R., Midega, C.A.O., Hutter, N.J., Wilkins, R.M., Wadhams, L.J., 2006. Assessment of the potential of Napier grass (*Pennisetum purpureum*) varieties as trap plants for management of *Chilo partellus*. *Entomol. Exp. Appl.* 119, 15–22.
- Khan, Z.R., Midega, C.A.O., Pittchar, J.O., Murage, A.W., Birkett, M.A., Bruce, T.J.A., Pickett, J.A., 2014. Achieving food security for one million sub-Saharan African poor through push–pull innovation by 2020. *Philos. Trans. R. Soc. B* 369, 20120284.
- Midega, C.A.O., Bruce, T.J., Pickett, J.A., Khan, Z.R., 2015a. Ecological management of cereal stemborers in African smallholder agriculture through behavioural manipulation. *Ecol. Entomol.* 40 (Suppl. 1), 70–81.
- Midega, C.A.O., Bruce, T.J.A., Pickett, J.A., Pittchar, J.O., Murage, A., Khan, Z.R., 2015b. Climate-adapted companion cropping increases agricultural productivity in East Africa. *Field Crops Res.* 180, 118–125.
- Midega, C.A.O., Jonsson, M., Khan, Z.R., Ekbom, B., 2014a. Effects of landscape complexity and habitat management on stemborer colonization, parasitism and damage to maize. *Agric. Ecosyst. Environ.* 188, 289–293.
- Midega, C.A.O., Khan, Z.R., Pickett, J.A., Nylin, S., 2011. Host plant selection in *Chilo partellus* and its implication for effectiveness of a trap crop. *Entomol. Exp. Appl.* 138, 40–47.
- Midega, C.A.O., Khan, Z.R., van den Berg, J., Ogol, C.K.P.O., Bruce, T.J., Pickett, J.A., 2009. Non-target effects of the ‘push–pull’ habitat management strategy: parasitoid activity and soil fauna abundance. *Crop Prot.* 28, 1045–1051.
- Midega, C.A.O., Khan, Z.R., Van den Berg, J., Ogol, C.K.P.O., Pickett, J.A., Wadhams, L.J., 2006. Maize stemborer predator activity under ‘push–pull’ system and Bt-maize: a potential component in managing Bt resistance. *Int. J. Pest Manage* 52, 1–10.
- Midega, C.A.O., Salifu, D., Bruce, T.J., Pittchar, J., Pickett, J.A., Khan, Z.R., 2014b. Cumulative effects and economic benefits of intercropping maize with food legumes on *Striga hermonthica* infestation. *Field Crops Res.* 155, 144–152.
- Midega, C.A.O., Nyang’au, I.M., Pittchar, J., Birkett, M.A., Pickett, J.A., Borges, M., Khan, Z.R., 2012. Farmers’ perceptions of cotton pests and their management in western Kenya. *Crop. Prot.* 42, 193–201.
- Pogue, M.A., 2002. World revision of the genus *Spodoptera* Guenée (Lepidoptera: Noctuidae). *Mem. Am. Ent. Soc.* 43 1–202.
- R Core Team, 2014. *R: a Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria. <http://www.R-project.org/>.
- Storer, N.P., Babcock, J.M., Schlenz, M., Meade, T., Thompson, G.D., 2010. Discovery and characterization of field resistance to Bt maize: *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in Puerto Rico. *J. Econ. Entomol.* 103, 1031–1038.
- Tinoco, R., Halperin, D., 1998. Poverty, production and health: inhibition of erythrocyte cholinesterase through occupational exposure to organophosphate insecticides in Chiapas, México. *Arch. Environ. Health* 53, 29–35.
- Young, R., 1979. Fall armyworm: control with insecticides. *Fla. Entomol.* 62, 130–133.
- Yu, S.J., 1992. Detection and biochemical characterization of insecticide resistance in fall armyworm (Lepidoptera: Noctuidae). *J. Econ. Entomol.* 85, 675–682.