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Climate-adapted companion cropping increases agricultural productivity in East Africa

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ABSTRACT

Production of cereals, the main staple and cash crops for millions of farmers in sub-Saharan Africa (SSA) is severely constrained by parasitic striga weed *Striga hermonthica*, stemborers and poor soil fertility. A companion cropping system known as 'push–pull' overcomes these constraints while providing additional soil fertility and forage grass benefits to smallholder farmers. To ensure the technology's long-term sustainability in view of the current and further potential aridification as a consequence of climate change, drought-tolerant crops, *Brachiaria* cv mulato (border crop) and greenleaf desmodium (intercrop), have been identified and incorporated into a 'climate-adapted push–pull'. The aims of the current study were to evaluate effectiveness of the new system (i) in integrated control of striga and stemborer pests and (ii) in improving maize grain yields, and to evaluate farmers' perceptions of the technology to assess potential for further adoption. 395 farmers who had adopted the technology in drier areas of Kenya, Uganda and Tanzania were randomly selected for the study. Each farmer had a set of two plots, a climate-adapted push–pull and a maize monocrop. Seasonal data were collected in each plot on the number of emerged striga plants, percentage of maize plants damaged by stemborers, plant height and grain yields. Similarly, farmers' perceptions of the benefits of the technology were assessed using a semi-structured questionnaire. There were highly significant reductions in striga and stemborer damage to maize plants in the climate-adapted push–pull compared to the maize monocrop plots: striga levels were 18 times lower and stemborer levels were 6 times lower. Similarly, maize plant height and grain yields were significantly higher. Mean yields were 2.5 times higher in companion planting plots. Farmers rated the climate-adapted push–pull significantly superior in reducing striga infestation and stemborer damage rates, and in improving soil fertility and maize grain yields. These results demonstrate that the technology is effective in controlling both weeds and pests with concomitant yield increases under farmers' conditions. It thus provides an opportunity to improve food security, stimulate economic growth, and alleviate poverty in the region while making agriculture more resilient to climate change.

1. Introduction

Agriculture is the most important enterprise in Africa, with about 60% of people in the continent earning their livelihood from it (FAO, 2011), with maize *Zea mays* L. and sorghum *Sorghum bicolor* (L.) Moench being the most important food and cash crops for millions of rural farm families in the predominantly mixed crop-livestock farming systems of the region. These cereal crops are mostly produced by smallholder farmers in sub-Saharan Africa (SSA). In spite of the importance of cereal crops in the region, grain yields have not risen as fast as in other parts of the world, with typical yields being generally around 1.0 t/ha (Jagtap and Abamu, 2003), representing some of the lowest in the world (Cairns et al., 2013). Consequently there is a widening gap between food supply and demand, with per capita production steadily declining (World Bank, 2008).

Efficient production of cereal crops in SSA is severely constrained by a number of biotic factors, with lepidopteran stemborers and the parasitic weeds in the genus *Striga* (Orobanchaceae) being the most important. A complex of 21 species of

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stemborers attack cereal crops in SSA and represent the most injurious insect pests of these crops in the region, with the indigenous *Busseola fusca* (Fuller) (Noctuidae) and the invasive *Chilo partellus* Swinhoe (Crambidae) being the most important (Kfir et al., 2002). Stemborer attack results in significant yield losses ranging from 15 to 88% of the potential grain output, depending on the pest population density and the phenological stage of the crop at infestation (Kfir et al., 2002). Furthermore, there are about 23 species of *Striga* in Africa, of which *Striga hermonthica* (Del.) Benth., commonly known as striga, is the most socioeconomically important in cereal cultivation in eastern Africa (Gressel et al., 2004; Gethi et al., 2005). In western Kenya alone, it is estimated that 76% of land planted to maize and sorghum is infested by striga (Gethi et al., 2005). Infestation by striga causes grain yield losses of up to 100%, translating into annual losses estimated at $40.8 million (Kanampiu et al., 2002), with these effects being most severe in degraded environments with low soil fertility and low rainfall, and in subsistence farming systems where there are few options for purchasing external inputs (Gurney et al., 2006).

Infestation by striga weakens the host by absorbing its supply of moisture, photosynthates and minerals (Tenebe and Kamara, 2002), and causes a phytotoxic effect within days of attachment to its hosts (Frost et al., 1997; Gurney et al., 1999), resulting in large reduction in host plant height, biomass, and eventual grain yield (Gurney et al., 1999). Striga infestation continues to extend to new areas in the region as farmers abandon heavily infested fields for new ones (Khan, 2002; Gressel et al., 2004), a practice that is unsustainable due to consistent reduction in landholdings due to increases in human population (Khan et al., 2008).

A habitat management approach called 'push–pull' was developed for management of stemborer pests by exploiting behavior-modifying stimuli to manipulate the distribution and abundance of stemborer pests and their natural enemies (Cook et al., 2007). The technology involved intercropping maize with a repellent plant desmodium, *Desmodium uncinatum* Jacq. (push), and planting an attractive trap plant Napier grass, *Pennisetum purpureum* Schumach (pull), as a border crop around this intercrop. Gravid stemborer moths are repelled from the main crop and are simultaneously attracted to the trap crop (Cook et al., 2007; Khan et al., 2010). The technology also enhances productivity of cereal-based systems through powerful in situ suppression and elimination of striga (Khan et al., 2002). The striga control is provided by desmodium that acts through a combination of mechanisms, including abortive germination of striga seeds that fail to develop and attach onto the hosts' roots (Khan et al., 2002; Tsanuo et al., 2003). On-farm implementation of the technology has led to its rapid uptake as it addresses the key constraints, striga and stemborer, and at the same time improves soil fertility, and provides the much needed fodder for livestock and desmodium seed for sale (Khan et al., 2008).

Productivity of rainfed agriculture in SSA is severely constrained by climate variability, particularly in terms of drought and high temperatures, with results indicating significant negative effects on food production, crop season length, and higher-order social impacts including food security (Akong'a et al., 1988; Sivakumar, 1993). This is further aggravated by the significant degradation and loss of arable land that accompanies climatic shifts (Oldeman et al., 1990). The persistence of periodic droughts and the potential for them to change in frequency and severity in the region indicate the need to develop adaptive strategies to ensure sustainable food production and environmental conservation. Although the push–pull technology described previously was found to be effective under a range of agro-ecologies (Khan et al., 2008), the companion plants did not survive extended periods of drought (>2 months) and higher temperatures (>30 °C) prevalent in drier parts of eastern Africa (Khan Z.R., unpublished data).

Therefore to ensure the technology's long-term sustainability in view of the current and further potential aridification as a consequence of climate change, drought tolerant companion plants were identified and incorporated into the technology. In careful screening studies, *Brachiaria* spp. and particularly the commercial *Brachiaria* cv mulato, developed by CIAT and grown locally, was found to tolerate long droughts of up to two months with no water and more than 30 °C (Pickett et al., 2014). *Brachiaria* species are also preferred to maize and sorghum by stemborer moths for oviposition (Midega et al., 2011), with *Brachiaria* cv mulato being preferred by smallholder farmers as animal fodder (Khan et al., 2014). Similarly, greenleaf *Desmodium intortum* was found to tolerate higher temperatures and with ability to survive under drier conditions. *Brachiaria* cv mulato was therefore incorporated into the push–pull technology as the border crop while greenleaf demodium became the intercrop in the climate-adapted push–pull technology. The objectives of the current studies were to (i) evaluate effectiveness of the climate adapted push–pull in integrated control of maize stemborer pests and striga (ii) establish the impact of the technology on improvement of maize grain yields (iii) evaluate farmers' perceptions of the technology as a means of predicting potential of adoption.

2. Materials and methods

2.1. Study sites

Field studies were conducted in 16 sub-counties (formerly called districts) in western Kenya (0°40′ to 0°58′S, 34°0′ to 34°67′E), 3 sub-counties 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) (Table 1), over varied number of cropping seasons, ranging from two to five, between the years 2012 and 2014. These are locations where the climate-adapted push–pull technology is being introduced for adoption by smallholder farmers. The sites were selected on the basis of being relatively dry and experience extended periods of drought (Khan et al., 2014). They are also exposed to biotic stress from stemborers (both *B. fusca* and *C. partellus*) and striga, with effects being aggravated by the degraded and infertile soils. All the sites are characterized by two cropping seasons in a year, the long (March–August) and short (October–January) rainy seasons, although annual rainfall averages have fallen to below the 1500 mm average for the region (Mugalavai et al., 2008; Fig. 1).

2.2. Plot layout and data collection

Studies were conducted using modifications of the methodologies of Khan et al. (2008). In each sub-county or district, smallholder farmers (15 in Uganda, 20 in Kenya, and 30 in Tanzania) who were within their first season of adoption of the climate-adapted technology 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 had recently planted the technology in these sites, followed by a semi-structured questionnaire interview where they were asked whether they were willing to participate in a long-term study assessing the pest management efficiency of the technology on their farms. One criterion of selecting a farmer to participate in the study was presence of two adjacent plots, one planted with the climate-adapted push–pull and one planted with sole maize, a monocrop plot to allow comparison of the two systems. The climate-adapted push–pull plot comprised maize intercropped with greenleaf desmodium, with *Brachiaria* cv mulato planted around this intercrop at a spacing of 50 cm within and 50 cm between rows. The innermost row of *Brachiaria* was spaced

Table 1
Mean (±SE) striga[a] counts in plots of maize planted in sole stands (monocrop–mm) or in climate-adapted push–pull (pp) at 10 weeks after crop emergence as estimated from the negative binomial model.

Sub-county	Short Rains 2012		Long Rains 2013		Short Rains 2013		Long Rains 2014		Short Rains 2014	
	mm	pp	mm	pp	mm	pp	mm	pp	mm	pp
Kuria	329(34)	30(3)	197(27)	9(1)	464(54)	12(2)	543(67)	69(9)	433(57)	80(11)
Migori	466(39)	39(4)	584(78)	19(3)	582(68)	13(2)	716(89)	20(3)	636(83)	13(2)
Rachuonyo	182(19)	31(3)	341(46)	12(2)	489(57)	49(6)	319(40)	41(5)	251(33)	33(4)
Suba	419(44)	62(7)	383(51)	13(2)	288(34)	56(7)	288(36)	35(5)	244(32)	34(5)
Bondo	**	**	310(42)	21(3)	281(33)	12(2)	295(37)	12(2)	306(40)	24(3)
Bungoma	**	**	344(46)	2(0.4)	450(52)	18(2)	415(52)	10(1)	740(97)	8(1)
Busia	**	**	640(86)	49(7)	324(38)	21(3)	396(49)	59(8)	209(27)	13(2)
Kisumu	**	**	604(81)	32(4)	380(44)	31(4)	594(74)	26(3)	471(62)	12(2)
Nyando	**	**	88(12)	2(0.4)	113(13)	8(1)	200(25)	9(1)	204(27)	11(2)
Siaya	**	**	632(85)	9(1)	911(106)	2(0.4)	675(94)	30(4)	1105(144)	17(2)
Teso	**	**	228(31)	1(0.3)	423(49)	2(0.3)	400(50)	16(2)	328(43)	8(1)
Rongo	**	**	**	**	372(43)	37(5)	232(29)	13(2)	246(32)	11(2)
Vihiga	**	**	**	**	527(61)	5(0.7)	399(50)	9(1)	442(58)	12(2)
Butere	**	**	**	**	**	**	286(36)	22(3)	235(31)	9(1)
Homabay	**	**	**	**	**	**	339(43)	23(3)	441(58)	52(7)
Kisii	**	**	**	**	**	**	245(30)	19(3)	311(41)	14(2)
$^{\alpha}$Busia	**	**	**	**	**	**	1138(51)	5(2)	2104(355)	4(1)
$^{\alpha}$Bugiri	**	**	**	**	**	**	548(114)	6(2)	220(68)	7(3)
$^{\alpha}$Tororo	**	**	**	**	**	**	902(73)	3(1)	764(79)	10(3)
$^{\beta}$Tarime	**	**	**	**	**	**	235(14)	8(2)	227(18)	19(2)

In all sites and seasons, striga counts were significantly lower in the climate-adapted push–pull than in the maize monocrop plots ($p < 0.0001$). Means represent data averages of 20 farmers in each site in Kenya, 15 in Uganda and 30 in Tanzania.
[**] Before the introduction of the technology in the study areas.
[a] Number of striga per 100 maize plants.
[α] Sub-counties in Uganda.
[β] District in Tanzania.

1 m from the first row of maize as is often the practice (Khan et al., 2008), while greenleaf desmodium was planted in between each row of maize. In both plots maize was planted at inter and intra-row spacing of 75 cm and 30 cm, respectively. At 4 weeks after crop emergence maize was thinned to one plant per hill. Greenleaf desmodium is a perennial crop and was therefore cut back at the beginning of subsequent cropping seasons to allow for planting of maize, and was trimmed again during weeding of maize, after which it was left to spread and cover the ground for the multiple benefits of weed control, moisture retention and overall beneficial effects on soil health (Khan et al., 2006a, 2008). Farmers planted their local maize varieties, 'Nyamula' and 'Jowi' (Tamiru et al., 2012), known by different names in each country with only a small proportion (<30%) planting medium maturity hybrids WH505 and Longe 5 in Kenya and Uganda, respectively, but all were susceptible to both pests. Farmers applied lower amounts of inorganic fertilizers, phosphorus in form of di-ammonium phosphate (DAP) in each plot at planting at the rate of 60 kg/ha, while nitrogen was applied in the form of calcium ammonium nitrate (CAN), at the rate of 60 kg/ha, after thinning of maize (Khan et al., 2008). The plot size varied from farmer to farmer, ranging from 18 m by 18 m to 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 to 25 m apart. The participating farmers made all crop management decisions including dates for planting, weeding, fertilizer application and harvesting, but both sets of plots were maintained equally throughout the study period and the companion crops maintained between seasons.

2.3. *Infestation levels of stemborers and striga*

Stemborer infestation levels were assessed non-destructively using methodologies adapted from Khan et al. (2008) where at

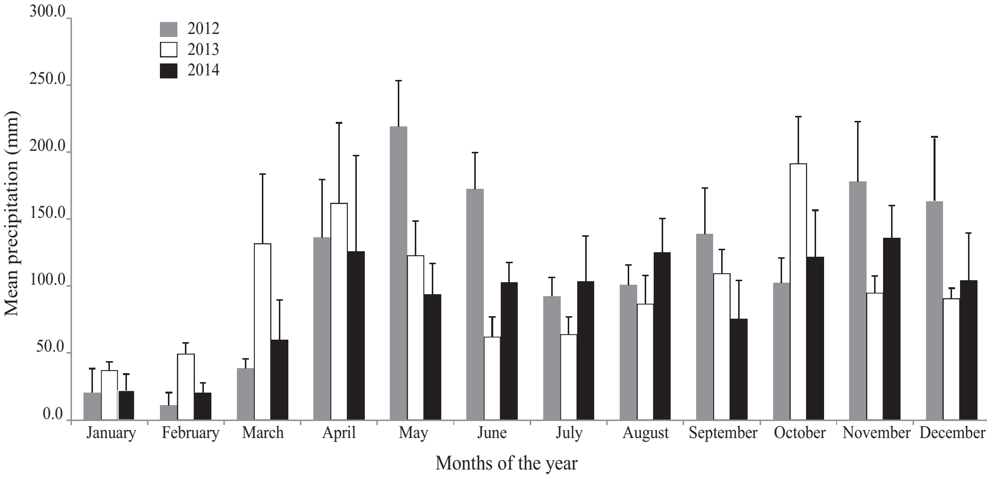

Fig. 1. Mean (±SE) annual rainfall in western Kenya (Kisumu, Busia, Bungoma, Homabay and Siaya sub-counties) during the years 2012–2014. *Source*: Agricultural Training Centres, County ministries of Agriculture, livestock and fisheries.

four weeks after crop emergence, 100 maize plants were randomly selected in each plot and tagged for subsequent observations. At 10 weeks after emergence, the tagged plants were inspected for any characteristic foliar damage caused by stemborer larval feeding, expressed as ‘window-paned’ and ‘pin-holed’ leaves, and/or deadhearts (Kfir et al., 2002). The data were expressed as the percentage of maize plants damaged by stemborers per plot. At the same time, the number of emerged striga plants was counted from the tagged plants from within a radius of 15 cm around the base of each maize plant and data expressed as the number of emerged striga per 100 plants. This is because striga emergence often peaks at about 10 weeks of maize emergence in the region (Midega et al., 2013).

2.4. *Plant height and grain yields of maize*

At full physiological maturity of the maize, heights of the tagged plants were measured and data expressed as average plant height per plant and plot. All the maize plants in each plot were then harvested and cobs 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 tones/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 (Khan et al., 2008).

2.5. *Farmer perceptions of the technology’s attributes*

Farmer perception studies were conducted in all of the studied sub-counties in western Kenya, except in Kisii, during farmers’ field days. Using a semi-structured survey questionnaire a total of 450 farmers were interviewed, 30 farmers per sub-county, sampled from those who had attended farmers’ field days organized as a means of exposing more farmers to the climate-adapted technology (Amudavi et al., 2009). During the interviews, farmers’ perceptions of the technology were sought on five attributes: striga control (taking counts of emerged striga), stemborer control (checking damage by stemborer larval feeding), grain yields (checking the number and size of maize cobs) and ability to improve soil fertility (comparing qualitative soil fertility indicators such as colour and texture of soil samples) from the climate-adapted push–pull plots and the maize monocrop. Using these attributes, the farmers were asked to compare and rate the technology’s performance against maize monocrop plots on a scale of 1–4 (1 = poorest; 4 = best; in terms of improvements in grain yields and soil fertility; and 1 = best and 4 = poorest in terms of striga and stemborer control).

2.6. *Data analysis*

Data on striga counts were analyzed using a generalized linear model assuming a negative binomial distribution error with logarithmic link to compare the effect of the two treatments, maize monocrop and climate-adapted push–pull at each site separately for the different cropping seasons. Data on stemborer damage, plant height, maize grain yield and rating of the attributes of the climate-adapted push–pull by farmers were analyzed using a *t*-test. Since multiple tests were performed for each variable, Bonferroni correction was used to avoid type I error at $p = 0.05$, thus statistical results were considered significant only if they reached a probability threshold of $p < 0.05/s$, where s is the number of tests, which is the same as the number of sites the treatments were tested. All data analyses were performed in R version 3.1.1 statistical software (R Core Team, 2014).

3. Results

3.1. *Infestation levels of striga and stemborers*

There was a highly significant reduction in emerged striga counts ($p < 0.0001$) in climate-adapted push–pull compared to the maize monocrop plots in all sites during all the study seasons (Table 1). Overall, there was an 18-fold reduction in striga infestation in push–pull plots. Seasonally, these counts ranged between 88 in Nyando and 2104 in Busia-Uganda during the long rainy season of 2013 and short rainy season of 2014, respectively, per 100 maize plants in the monocrop plots. In the climate-adapted push–pull however these counts ranged between 1 in Teso and 80 in Kuria during the long rainy season of 2013 and short rainy season of 2014, respectively. Proportionally, climate-adapted push–pull significantly reduced striga infestation by between 80.6% in Suba and 99.9% in Busia–Siaya during the short rainy season of 2013 and 2014, respectively (Table 1).

Stemborer infestation of maize was generally low, with average proportions of stemborer-damaged plants being below 40% throughout the study period in all sites (Table 2). However, these proportions were significantly lower in the climate-adapted push–pull than in the maize monocrop plots. Overall, there was a 6-fold reduction in stemborer infestation in climate-adapted push–pull plots. Stemborer infestation was significantly reduced in all sites during all seasons, except in Rachuonyo during the short rainy season of 2013. These proportions ranged between 0.9% in Rachuonyo and 38.4% in Butere during the short rainy season of 2013 and long rainy season of 2014, respectively. Proportionally, climate-adapted push–pull reduced damage caused by stemborer larval feeding by between 56% in Kuria and 100% in Rachuonyo during the long rainy season of 2014 and short rainy season of 2013, respectively (Table 2).

3.2. *Plant height and grain yields of maize*

The observations above were associated with significantly taller maize plants in the climate-adapted push–pull than in the maize monocrop plots ($p < 0.0001$) in all areas studied (data not provided). Grain yields of maize were significantly higher in the climate-adapted push–pull than in the maize monocrop ($p < 0.0001$, *t*-test) (Fig. 2). Overall mean yield was 2.5 times higher in companion cropped plots due to improved health and performance of the crop. Grain yields ranged between 1.1 t/ha in Suba and 2.9 t/ha in Bugiri during the short rainy seasons of 2012 and 2014, respectively, in the maize monocrop plots. However, in the climate-adapted push–pull plots they ranged between 3.0 t/ha in Suba during the short rainy seasons of 2012 and 2013, and 6.2 t/ha in Bugiri during the short rainy season of 2014. Climate-adapted push–pull thus improved grain yields of maize by between 105% and 333% in Bungoma and Kisumu during the long rainy season of 2013 and short rainy season of 2014, respectively, representing up to five-fold increase in maize grain yields.

3.3. *Farmer perceptions of the technology’s attributes*

The interviewed farmers provided responses that corroborated the findings from the field studies on the effectiveness of the climate-adapted push–pull in integrated control of stemborers and striga in maize in the drier agro-ecologies studied. They rated the climate-adapted push–pull significantly superior in reducing stemborer and striga infestations, and in increasing soil fertility in all the sub-counties studied ($p < 0.05$ in all cases) (Fig. 3). The rating of impacts of the technology on reducing both stemborer and striga infestations were 1.9 and 1.8, respectively, indicating a measure of ‘low infestation’ based on the rating scale used.

Table 2
Mean (±S.E.) seasonal percentage[a] of maize plants damaged by stemborer larvae at 10 weeks after crop emergence in plots of maize planted in sole stands (monocrop–mm) or in climate-adapted push–pull (pp).

Sub-county	Short Rains 2012		Long Rains 2013		Short Rains 2013		Long Rains 2014		Short Rains 2014	
	mm	pp	mm	pp	mm	pp	mm	pp	mm	pp
Kuria	12.4(0.6)	1.9(0.5)	13.0(0.9)	3.1(0.5)	17.2(1.4)	1.9(0.3)	21.1(1.6)	9.2(0.9)	21.0(1.9)	6.6(0.9)
Migori	11.2(0.6)	2.2(0.4)	9.7(0.5)	1.9(0.3)	9.8 (0.5)	0.8(0.2)	12.5(1.7)	1.9(0.3)	13.3(1.4)	2.3(0.3)
Rachuonyo	17.1(1.4)	5.9(0.5)	14.1(1.0)	3.0(0.4)	0.9(0.2)	0.0(0.0)	12.4(1.7)	1.9(0.3)	16.2(1.4)	3.3(0.3)
Suba	13.8(1.6)	3.2(0.7)	14.9(1.3)	3.6(0.5)	21.2(0.9)	5.9(0.6)	17.2(1.5)	5.5(0.5)	25.2(1.2)	7.0(0.6)
Bondo	**	**	12.7(0.7)	1.8(0.4)	13.4(0.7)	2.4(0.5)	19.3(1.9)	3.5(0.5)	18.0(1.2)	4.8(0.7)
Bungoma	**	**	34.5(1.6)	2.1(0.6)	13.0(0.5)	1.4(0.4)	18.8(1.4)	2.9(0.4)	19.7(1.8)	1.0(0.3)
Busia	**	**	13.4(0.5)	2.0(0.4)	14.4(0.6)	3.1(0.5)	11.6(0.9)	0.9(0.2)	18.7(1.6)	3.3(0.5)
Kisumu	**	**	17.1(1.1)	2.0(0.4)	13.9(0.9)	2.1(0.3)	16.4(1.2)	3.0(0.5)	14.5(1.5)	0.5(0.2)
Nyando	**	**	21.1(1.1)	0.8(0.2)	20.2(0.8)	2.1(0.5)	25.8(1.0)	2.5(0.4)	27.3(1.3)	4.6(0.7)
Siaya	**	**	13.5(0.5)	2.1(0.4)	13.0(0.6)	2.4(0.4)	12.6(0.6)	3.1(0.5)	18.7(2.2)	2.2(0.5)
Teso	**	**	12.4(0.8)	1.2(0.3)	10.2(0.5)	0.3(0.2)	13.2(0.8)	1.5(0.8)	17.3(1.8)	1.1(0.3)
Rongo	**	**	**	**	23.6(0.9)	3.2(0.6)	20.9(1.4)	2.2(0.4)	22.5(1.1)	1.2(0.3)
Vihiga	**	**	**	**	7.9(0.3)	1.0(0.2)	12.7(1.3)	2.7(0.4)	15.5(1.5)	2.2(0.2)
Butere	**	**	**	**	**	**	38.4(1.9)	2.3(0.5)	12.4(1.2)	2.3(0.4)
Homabay	**	**	**	**	**	**	25.6(1.0)	6.8(0.8)	25.0(0.7)	8.6(0.6)
Kisii	**	**	**	**	**	**	17.2(2.1)	2.7(0.5)	14.0(1.0)	4.5(0.6)
$^{\alpha}$Busia	**	**	**	**	**	**	37.8(2.9)	2.3(0.6)	39.1(3.6)	8.4(0.9)
$^{\alpha}$Bugiri	**	**	**	**	**	**	30.0(1.7)	6.8(1.6)	27.4(1.9)	2.2(0.7)
$^{\alpha}$Tororo	**	**	**	**	**	**	35.6(2.1)	4.8(1.4)	39.7(2.9)	5.1(1.2)
$^{\beta}$Tarime	**	**	**	**	**	**	15.8(0.6)	3.6(0.4)	21.9(1.2)	8.7(0.7)

In all sites and seasons, except in Rachuonyo during the short rainy season of 2014, proportions of maize damaged by stemborers were significantly lower in the push–pull than in the maize monocrop plots ($p < 0.05$, *t*-test). Means represent data averages of 20 farmers in each site in Kenya, 15 in Uganda and 30 in Tanzania.

** Before technology was introduced in the study area.

[a] Counted from 100 tagged maize plants.

$^{\alpha}$ Sub-counties in Uganda.

$^{\beta}$ District in Tanzania.

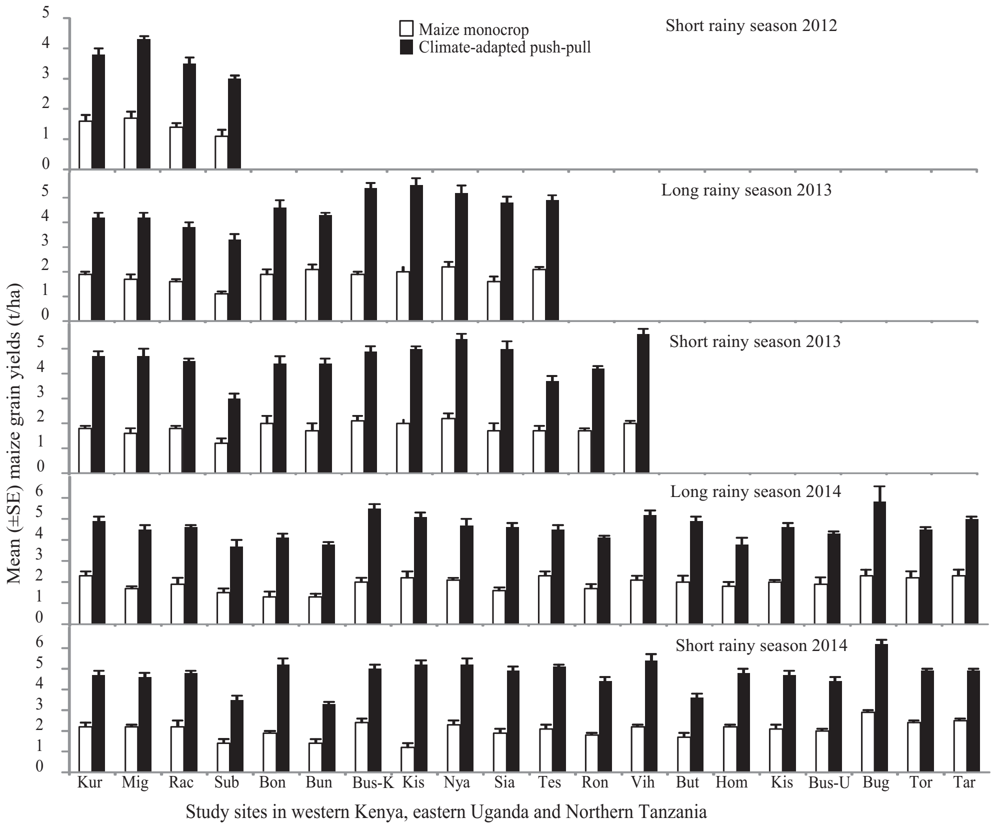

Fig. 2. Mean (±S.E.) grain yields of maize (t/ha) planted in sole stands (maize monocrop) or in climate-adapted push–pull.
In all sites and seasons, maize grain yields were significantly higher in the climate-adapted push–pull than in the maize monocrop plots ($p < 0.0001$). Means represent data averages of 20 farmers in each sub-county in western Kenya, 15 in Uganda and 30 in Tarime, Tanzania. Blank spaces within graphs indicate periods before the introduction of the technology in the study sites.
Key: Kenya: Kur, Kuria; Mig, Migori; Rac, Rachuonyo; Sub, Suba; Bon, Bondo; Bun, Bungoma; Bus-K, Busia-Kenya; Kis, Kisumu; Nya, Nyando; Sia, Siaya; Tes, Teso; Ron, Rongo; Vih, Vihiga; But, Butere; Hom, Homabay; Kisi, Kisii. Uganda: Bus-U, Busia-Uganda; Bug, Bugiri; Tor, Tororo. Tanzania: Tar, Tarime

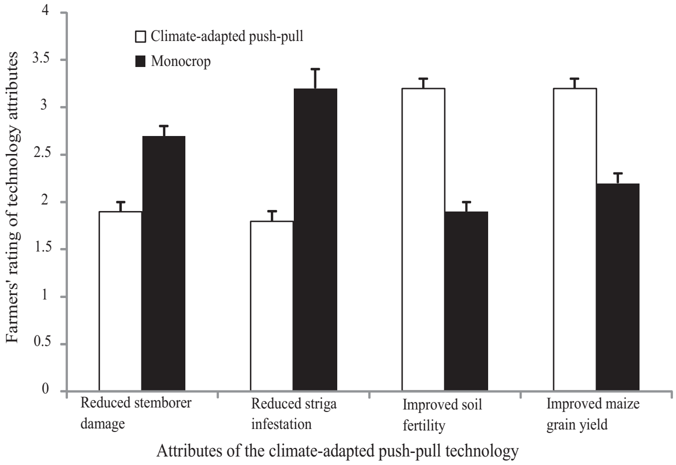

Fig. 3. Mean (±SE) farmers' rating of attributes of the climate-adapted push–pull compared to maize monocrop during farmers' field days in the long rainy season of 2014 in western Kenya. Monocrop, Maize planted in sole stands. Stemborer control: 1 = No damage; 2 = low damage; 3 = high damage; 4 = very high damage. Striga control: 1 = no infestation; 2 = low infestation; 3 = high infestation; 4 very high infestation. Increased maize yield: 1 = poor; 2 = average; 3 = good; 4 = excellent. Soil fertility improvement: 1 = deteriorated; 2 = not improved; 3 = improved; 4 = greatly improved. In all attributes, differences between the two cropping systems were significant ($\alpha = 0.05$).

These parameters were however rated at 2.7 and 3.2, respectively, indicating 'high infestation' by stemborer and striga in the maize monocrop. In terms of improvements in soil fertility and grain yields, the rating of the technology was 3.2 for both, indicating 'improved' levels of these. However, these parameters were rated at 1.9 and 2.2, respectively, indicating 'not improved' levels of soil fertility and grain yields in the maize monocrop plots.

4. Discussion and conclusions

Our results showed significant reductions in the number of emerged striga in the plots planted with climate-adapted push–pull, indicating effective control of this noxious weed at levels similar to those obtained with the conventional push–pull technology (Khan et al., 2008). These results corroborate earlier findings from on-station studies conducted at *icipe*-Thomas Odhiambo Campus in western Kenya that reported effective control of striga by greenleaf desmodium (Khan et al., 2006b; Midega et al., 2010), and thus contribute to the accumulating body of knowledge of the importance of intercropping with desmodium in smallholder cereal farming systems in the region. It is noteworthy that the number of striga plants that emerge represents an unknown and often variable percentage of the total number of striga plants that actually parasitize the host's roots (Musambasi et al., 2002). Moreover, germination and emergence of striga varies from season to season, depending on weather conditions (Doggett, 1988). There were not much variations in within-season rainfall during the study period in western Kenya, and indeed in the rest of the study sites, and therefore, the significant reductions in the number of emerged striga in the climate-adapted push–pull plots observed in the current study across the study sites over the cropping seasons indicates stability of the striga control efficiency of greenleaf desmodium and suggests that its use in smallholder farming systems in drier agro-ecological conditions has potential to stabilize these systems.

Desmodium controls striga through a number of mechanisms, with an allelopathic effect in the legume's rhizosphere being the most important. Desmodium root exudates contain novel isoflavanones, some of which stimulate germination of striga seeds while others and a group of *C*-glycosylflavones inhibit radicle growth (Tsanuo et al., 2003; Hooper et al., 2009, 2010). This combination provides a novel means of in situ reduction of striga seed bank in the soil even in the presence of graminaceous host plants in the proximity. Additionally, because desmodium is a perennial crop, it is able to exert its control effect on striga even when the host crop is out of season, making it a more superior trap crop than most of the other legumes that have been reported to give only some limited level of striga control (Oswald, 2005; Khan et al., 2007; Midega et al., 2014a). The results of the current study thus demonstrate that these effects are achievable and sustainable under smallholder farmers' management conditions in the drier agro-ecologies in East Africa.

Effects of striga are most severe in degraded and infertile soils (Reda et al., 2005), and therefore rehabilitation and/or improvement of soil health has an important role in an integrated striga management strategy for smallholder farming systems in SSA. Drier agro-ecologies have some of the most degraded soils, and as the negative effects of climate change increase, it is anticipated that the extent and severity of soil degradation is going to increase (Heisey and Edmeades, 1999). Apart from the direct negative effects of soil degradation on agricultural production and food security, low soil fertility increases susceptibility of the crop to biotic pests (Abdul et al., 2012). Approaches that replenish soil organic matter and deliver soil nutrients in changing environments are therefore crucial in improving crop productivity while ensuring resilience and sustainability of the soil as a resource-base (Altieri and Nicholls, 2003). The technology described herein enhances soil integrity in a number of ways. Desmodium is an efficient legume in nitrogen fixation, with greenleaf being able to fix over 300 kg N/ha per year under optimum conditions (Whitney, 1966) and, therefore, is appropriate as an intercrop for degraded environments. Desmodium also improves soil organic matter content (Midega et al., 2005), and conserves soil moisture (Khan et al., 2002), with an overall increase in soil microbial and arthropod diversity and activity (Midega and Khan, 2003; Midega et al., 2008, 2009), factors that improve soil health and enhance agro-ecosystem productivity (Altieri and Nicholls, 2003).

Proportions of stemborer damaged maize plants were significantly lower in plots planted with the climate-adapted push–pull relative to those planted with maize monocrop in all the study sites. Stemborer control through companion cropping is mediated by green leaf volatiles emitted by the companion crops (Khan et al., 2010). Previous studies have shown that *Brachiaria* spp. are preferred to maize for oviposition, and with minimal feeding and survival of stemborer larvae on *Brachiaria* cv mulato (Midega et al., 2011). The latter is a useful quality of a trap/border plant for management of insect pests in two ways: (1) it ensures significant mortality of the damaging stemborer larvae and thus provides a natural reduction in pest population without acting as a 'nursery' crop from where pests could multiply and invade the main crop (Midega et al., 2015, in press); (2) in addition to the key stemborer species that are pests of cereal crops, there are also other stemborer species that utilize wild grasses as hosts but are not pests of cereal crops, for example the genus *Poeonoma*, and serve as alternative hosts of stemborer natural enemies such as *Cotesia sesamiae* Cameron (Khan et al., 1997). Minimal survival rates of stemborer larvae on such host plants is therefore favorable for conservation of the parasitoids by providing continuous refugia to natural enemies and therefore improving biological control of the pests. Additionally, use of greenleaf desmodium has been shown to repel stemborer moths resulting in effective control of the pests (Khan et al., 2006b). Volatile organic compounds emitted by desmodium, including (*E*)-ocimene and (*E*)-4,8-dimethyl-1,3,7-nonatriene repel stemborer moths (Khan et al., 1997, 2000) and attract the pests' natural enemies (Midega et al., 2009, 2014b).

Technologies that seek to alleviate biotic constraints to efficient production of crops have the primary goal of unlocking the crops' potential to increase grain yields as this is often the immediate benefit considered by farmers (Midega et al., 2014a). Results of the current study show that climate-adapted push–pull significantly enhances plant growth, indicated by significantly taller plants, and grain yields through effective control of both striga and stemborers, and improvement in soil fertility in farmer-managed fields in East Africa. These observations were corroborated by farmers' perceptions of effectiveness of the technology in striga and stemborer control, and in improving soil fertility and maize grain yields. This shows appreciation of the technology in addressing the key constraints to maize production in the region, and indicates potential for adoption. Indeed by the December 2014 about 35,000 smallholder farmers in drier areas of western Kenya, eastern Uganda, Lake Victoria basin of Tanzania and Northern Ethiopia had adopted the technology. Farming systems in SSA are dominated by mixed crop-livestock systems, and as land becomes an important constraint due to steady increases in human population, and environmental conditions become harsher, there is need for intensification of such systems by allowing integration of complimentary enterprises while enriching and conserving the resource base of the production systems. Platform technologies such as the climate-adapted push–pull in addition to being resilient and stable under drier areas blend well with the smallholder farmers' practice of mixed-cropping and enables addition of livestock keeping since both companion crops are valuable fodder.

Productivity of smallholder agricultural systems is strongly influenced by weather and climate. Moreover, environmental conditions play an important role in influencing effectiveness of pest management approaches, with magnitude of these effects largely dependent on the extent to which the conditions change locally and regionally. Warming in SSA is expected to be greater than the global average, and drought is gradually becoming a widespread phenomenon across large areas of the region (Heisey and Edmeades, 1999). Rainfall is becoming less predictable, for example, projections for Kenya using global climate model scenarios in particular indicate that sub-humid and semi-arid areas supporting socioeconomically vulnerable groups will be negatively affected (Downing, 1992), largely through increased growing season temperatures and frequency of droughts (IPCC, 2007). Notably, environmental changes are projected to aggravate the incidence and severity of stemborers through direct effects, such as increases in temperature that influence the pests' biology (Kfir et al., 2002), and indirect effects through influences on availability and distribution of suitable hosts (Hassall et al., 2007). Also, such changes are predicted to affect distribution and competitiveness of striga (Rodenburg and Meinke, 2010), which means there is a need to adapt crop management practices to such harsh conditions.

Temperature is one of the most important environmental factors influencing insect behavior, distribution, development and survival, and reproduction. Indeed rises in temperature have been observed to have significant reductions in the mean developmental time of stemborers (Khadioli et al., 2014), resulting in increased number of generations of the pests in a cropping season. Therefore, the increased global warming and drought incidences will favor insect proliferation and herbivory. Additionally, elevated temperature and drought stress could alter the phytochemistry of host plants and affect the insect growth and development directly or indirectly through effect on host plants. Approaches developed to manage insect pests therefore need to be stable and resilient, and should offer effective control of pests in such changing climates. Our studies indicate insignificant effect of drought stress on relative attractiveness of *Brachiaria* cv mulato to stemborer moths for oviposition (Chidawanyika et al., 2014). Additionally, drought stress only minimally alters secondary metabolism in *Brachiaria* cv mulato, with emission of key volatile organic compounds necessary for stemborer host location such as (*Z*)-3-hexenyl acetate not significantly affected (Chidawanyika, 2015). *Brachiaria* spp. have been observed to support minimal survival of stemborer larvae (Midega et al., 2011), with these rates not affected by drought stress (Chidawanyika et al., 2014). Additionally, recent studies indicate that greenleaf, together with other drought-tolerant desmodium of African origin, such as *Desmodium incanum*, are able to effectively suppress striga under drier agro-ecologies in eastern Africa, suggesting relative stability of allelochemical production and release by the rhizosphere of these plants (Hooper A., unpublished data).

In conclusion, most smallholder farmers in SSA are vulnerable to climate change as most of the region is getting hotter and rainfall more unpredictable, large areas are arid or semi-arid, and more than 60% of the population depends directly on agriculture. The farmers also have few adaptive technological opportunities available to limit or reverse adverse effects of climate change which threatens to undermine food security in the region (Cairns et al., 2013). Intensification of production on existing cropland through platform technologies such as climate-adapted push–pull thus represents one of the options for arresting environmental degradation and reversing the negative trends. The results of the current study indicate that the technology ensures stable increases in maize productivity and thus contributes to achievement of food security, with potential to stimulate economic growth and alleviation of poverty since it allows integration with livestock enterprises. They also indicate that desmodium increases the options available to subsistence farmers that fall in different socio-economic strata in different agro-ecologies in tropical Africa, many of whom practice mixed cropping and keep livestock. The technology is appropriate as it fits within the practice of mixed cropping prevalent in the region, and is economical since it is dependent on perennial companion plants that require a one-time only investment, not expensive seasonal inputs. Efforts are underway to bring the technology to the millions of smallholder farmers living in drier agro-ecologies in eastern Africa and beyond through a combination of dissemination pathways catering to different socio-cultural and socio-economic contexts of these farmers; and multi-level partnerships that will allow exploitation of different individual and institutional capacities. Additionally, there is a need to understand the drivers of climate change and its effects on the diversity, responsiveness and population dynamics of stemborer pests and striga in order to further adapt management approaches to ensure continued effectiveness in the longer term.

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