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Push-pull technology enhances resilience to climate change and prevents land degradation: Perceptions of adopters in western Kenya

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ABSTRACT

Climate change and land degradation adversely affect food security in sub-Saharan Africa (SSA). Smallholder farmers are the most affected. Therefore, it is imperative to identify technologies that boost resilience to climate change, and restore lands. Push-pull technology is among proposed solutions. This technology controls stem borers, fall armyworm, striga, mycotoxins; improves availability of nitrogen and phosphorus, and stores increased carbon in biomass and soils. Though much has been published about push-pull technology, there is a lean in publications about how this technology can help smallholder farmers to cope with climate change and variability. Here, we present perceptions of adopters of push-pull technology in western Kenya with regard to climate change and land degradation, and discuss reasons it should be adopted widely. We compared push-pull and other maize-based cropping systems in western Kenya, through interviews. Push-pull technology produces 0.3–1.1 t more maize ha^{-1} compared to maize-bean intercrop, and maize monocrop when the season is drier than normal. Additionally, push-pull provides 3.6–9.8 t more fodder during drought-stricken seasons. Push-pull technology covers 70% of the soil surface compared to 20% cover found in maize-bean intercrop and maize monocrop. In push-pull farms, 150–280 kg nitrogen, 13–24 kg phosphorus and 370–470 kg potassium can be recycled through biomass and this is five times greater than the potential for maize-bean intercrop and maize monocrop. There is need for wide adoption of push-pull technology to increase resilience of farmers to climate change and restore degraded lands.

1. Introduction

Food and nutrition security are of great concern in sub-Saharan Africa. Agriculture in sub-Saharan Africa is majorly subsistence and is practiced on small lands as land per capita reduces with increasing population. This shows how much current and future generations are challenged by land sizes per household when producing the needed quantity and quality of food, fodder and fuel (Descheemaeker et al., 2016). In addition, climate change has already altered rainfall patterns at alarming levels, and affects the performance of crops and lives of farming communities especially in rain-fed agro-ecosystems (Altieri and Koohafkan, 2008; Leisner, 2020). Adapting agriculture to the changing climate might need adoption of innovative options with possible modification of cropping systems design and/or partner crops (Zhao et al., 2022). Other needed measures include adjusting planting dates to changes in season onset, introducing new species and varieties that fit in current conditions, shifting to perennial species such as fruit trees or agroforestry in general or banana and other crops that stay in farms for long, irrigation, good soil management practices that are mindful of soil moisture dynamics, subscribing for crop insurance, changing cropping systems, and judicial management of mineral and organic fertilizers (Leisner, 2020; Zhao et al., 2022).

Climate change affects both crop and livestock production (Descheemaeker et al., 2016). This has to do with the quality and

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quantity of fodder the farm can produce to feed animals, and this can be tackled through cropping systems. For example, planting agroforestry fodder trees in boundaries of fields and contours provides alternative source of fodder and increases the resilience of livestock farming to climate change (Dawson et al., 2014). Crop failures due to climate change might cause to shift from cropping to livestock keeping as livestock farming might be more resilient to climate change than crops (Jones and Thornton, 2009). Finding a balance between cropping and livestock keeping might be a way to enhance resilience of farming systems to climate change.

The modern agriculture is facing rampant land degradation. Soil erosion is a major driver for land degradation and accounts for up to 40% of yield reduction in Africa (Eswaran et al., 2019). Other drivers of land degradation are depletion of soil organic carbon (SOC), loss of biodiversity, loss of soil fertility and elemental imbalance, acidification and salinization (Lal, 2015; Negi et al., 2022; Tully et al., 2015). Farmers need to be aware of land degradation and its consequent dangers. Soil scientists and agricultural extension agents should participate in creating this awareness, co-create and assess with farmers technologies that reverse land degradation and foster land productivity. Restorative activities include increasing land cover to reduce erosion; to input manure, crop residues, mulch, composts and green manure to build up the SOC; to increase diversity in farms that boost microbial activities and soil health at large; and controlling grazing (Lal, 2015; Purwanto and Alam, 2020). Adoption of land restoration practices will rehabilitate the ability of land to produce food, fiber and fuel; to regulate micro-climate; to maintain biodiversity; to sequester carbon; to play its role in hydrological cycling and filtering of various chemicals and potentially toxic pollutants such as heavy metals, pesticides, aromatic hydrocarbons, etc (Edrisi et al., 2018).

Several practices have been promoted as climate smart and restorative agriculture in Africa. For example, Kuyah et al. (2021) documented technologies such as cereal – food legumes intercrop, conservation agriculture, agroforestry with parkland trees, and push-pull technology as innovative agronomic practices for sustainable intensification of agriculture in sub-Saharan Africa. However, adoption of these technologies is still low due to several challenges that include lack of proper publicity, as adoption may happen in places where the technology has been developed and tested from. Here we present perceptions of adopters of push-pull technology in Western Kenya to show its potential to increase resilience of smallholder farming communities to climate change, to reverse soil degradation through providing soil cover, and increasing its fertility through recycling crop residues.

Push-pull technology is a cropping system that involves planting a cereal crop such as maize (*Zea mays* L.) or sorghum (*Sorghum bicolor* (L.) Moench) in additive intercrop with Desmodium (*Desmodium intortum* (Mill. Urb.) or *D. uncinatum* (Jacq.) DC.), a fodder legume crop. This intercrop is surrounded by two or three rows of Napier grass (*Pennisetum purpureum* Schumach.) or Brachiaria (*Brachiaria brizantha* (Hochst. ex A. Rich.) Stapf. (brachiaria, Mulatto II cultivar), a grass fodder species. This complex system is set up to control pests of cereals such as stem borers (*Busseola fusca and Chilo partellus*), fall armyworm (*Spodoptera frugiperda*), and striga (*Striga hermonthica*) (Khan et al., 2018; Zeyaur et al., 2010). Push-pull also limits the growth and spread of mycotoxins and ensures quality and safety of food (Njeru et al., 2019). This control is purely based on natural processes. Desmodium emits semiochemicals that repel stem borer moths from a cereal plantation while Napier grass or Brachiaria emits semiochemicals that attract these moths. Napier grass or Bracharia kills stem borer eggs by limiting their movement, and recruiting natural enemies that feed on them (eggs), such as *Cotesia sesamiae* Cameron and *Bracon sesamiae* Cameron (Simpraga et al., 2016; Tamiru et al., 2011). Roots of Desmodium exude chemicals that stimulate germination of striga and at the same time prevent them (striga) from infesting the root of the cereal. Eventually, the striga that germinates is smothered by the aboveground biomass of desmodium before it flowers and releases its dusty seeds. This depletes the striga seed bank in soils with time (Khan et al., 2016; Khan et al., 2002; Vanlauwe et al., 2008). These exudates (desmodium root exudates) also control the growth of fungi responsible for aflatoxins, while the biomass of desmodium hinders the movement of the fungi to the ear or spike of the cereal (Njeru et al., 2019). Soils of push-pull farms emit volatiles that enhance chemical plant defense against herbivores (Mutyambai et al., 2019). Push-pull technology is a conservation agriculture technology that builds up SOC (Ndayisaba et al., 2022), improves the availability of nitrogen and phosphorus (Drinkwater et al., 2021; Ndayisaba et al., 2021), and produces relatively higher biomass than monocultures of cereals. This biomass can be recycled through feeding animals, producing manure and applying it. Push-pull technology is also resilient to climate change (Drinkwater et al., 2021; Midega et al., 2018; Ndayisaba et al., 2020).

Push-pull technology needs to be adopted widely. Because farmers are the best agricultural extension agents as they harness adoption of technologies by their fellow farmers through farmer-to-farmer learning and doing (Nakano et al., 2018), it is imperative to understand their perceptions (perceptions of farmers) about technologies. This is important because the perception of farmers about an agricultural technology determines its adoption or failure to be adopted (Adesina and Baidu-forson, 1995). Furthermore, because climate change and land degradation are tough challenges of agriculture production in Western Kenya, it is important to comprehend perceptions of farmers with regard to these challenges. In this study, climate change is in the form of inadequate rainfall coupled with droughts and long dry spells experienced in Western Kenya. Knowledge of farmers' perceptions about push-pull will help in increasing climate action through enhanced adoption of this climate-smart technologies, and concurrently, control land degradation. Here we present findings about perceptions of adopters of push-pull technology in Western Kenya about its ability to (i) increase resilience to climate change, (ii) protect soils against erosion and degradation, and (iii) increase soil fertility through recycling the biomass. Indicators that were studied are productivity in the face of climate change, soil cover, and nutrient recycling in farming systems. In addition to perceptions of farmers, we provide updated information from published literature to show how push-pull technology has been upgraded to enhance its resilience to climate change.

2. Methodology

2.1. Study sites

Perceptions of adopters of push-pull technology were documented from three sites in western Kenya: Bondo and Siaya in Siaya county and Vihiga in Vihiga county. The description of these three sites has been reported by Ndayisaba et al. (Ndayisaba et al., 2020, 2022). Vihiga receives higher rainfall than the two other sites (1800–2000 mm), followed by Siaya (1200–1800 mm), and lastly by Bondo (750–1200 mm) (County Government of Siaya, 2018; County Government of Vihiga, 2018). These sites also vary in elevation, with a gradient from low in Bondo (1100–1350 m), medium in Siaya (1140–1400 m) and high in Vihiga (1300–1800 m). The climate in the area is sub-humid tropical (Vihiga and Siaya) and semi-arid (Bondo). Bondo belongs to a cotton zone (LM3), while Siaya and Vihiga belong respectively to marginal sugar cane zone (LM2), and sugar cane zone (LM1) (Jaetzold and Schmidt, 1983). Rainfall in western Kenya is bimodal with two rain seasons: long rains season (April–July) and short rains season (September–November). Soils in the study area are mainly Acrisols, Ferralsols and Nitisols (Jaetzold et al., 2009). Soil texture varies from sandy loam in Bondo and loamy sand in Siaya and Vihiga. Table 1 summarizes characteristics of study sites while Fig. 1 shows study sites on map.

Agriculture is the main source of livelihood in western Kenya and is predominantly smallholder-rainfed for subsistence (Kuyah et al., 2012; Kuyah et al., 2013). Farms per household are relatively bigger in Bondo (3.0 ha) than in Siaya (1.02 ha) and Vihiga (0.41 ha). Land preparation is mainly done by oxen or tractors in Bondo and Siaya and hand hoeing in Vihiga. Cereals (e.g. maize, sorghum, and millet (*Pennisetum glaucum*))

Table 1
Biophysical and climatic characteristics at three study areas for on farm experiments in western Kenya.

Site	Agro-ecological zone	Location (latitude; longitude)	Population density (persons per km^2)	Soil texture	Elevation (m)	Rainfall regime	Rainfall (mm)	Seasonal temperature (°C)
Vihiga	LM1, sugar cane zone	0°–0°15′N; 34°30′– 35°0′E	1033	Loamy sand	1300–1500	Bimodal (short and long rains)	1800–2000	17–35
Siaya	LM2, marginal sugarcane zone	0°26′S – 0°18′N; 33°58′– 34°33′E	316	Loamy sand	1135–1500	Bimodal (short and long rains)	1200–1800	17–35
Bondo	LM3, cotton zone	0°2′– 0°25′S; 34°0′– 34°33′ E	246	Sandy loam	1135–1350	Bimodal (short and long rains)	750–1200	17–31

Source: (County Government of Siaya, 2018; County Government of Vihiga, 2018; Jaetzold and Schmidt, 1983; Weather and Climate, 2022).

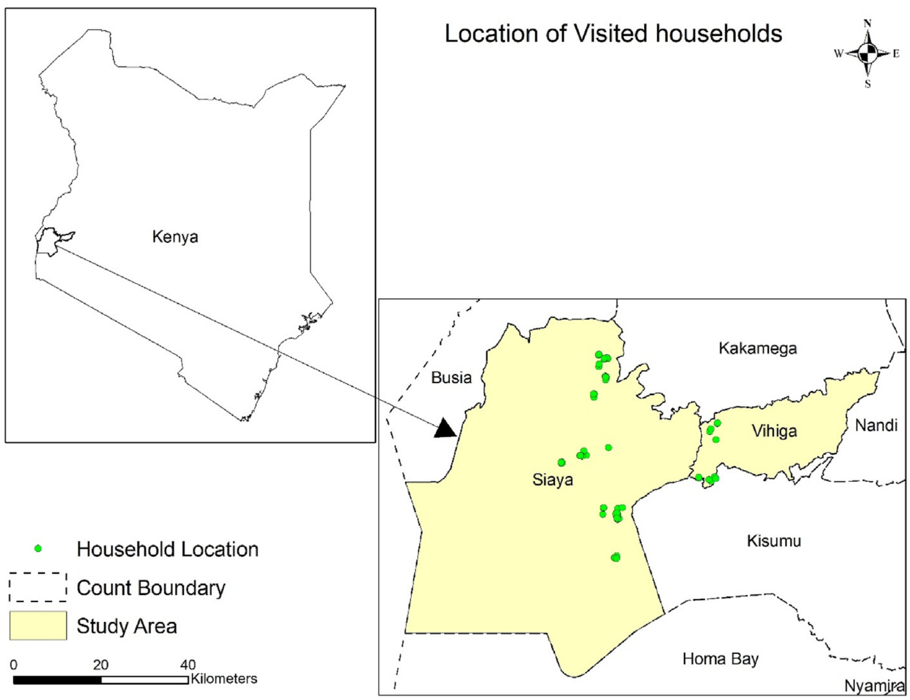

Fig. 1. Location of households (green round dots) that participated in the study in Bondo and Siaya in Siaya county, and Vihiga in Vihiga county. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

are traditionally intercropped with legumes such as common bean (*Phaseolus vulgaris* L.), groundnut (*Arachis hypogaea* L.), cowpea (*Vigna unguiculata* (L.) Walp.)) or green gram [*Vigna radiata* (L.) Wilczek]. Other food crops common in smallholder farms in western Kenya include sweet potatoes (*Ipomoea batatas* (L.) Lam.), cassava (*Manihot esculenta* Crantz) and vegetables (County Government of Siaya, 2018; County Government of Vihiga, 2018). Livestock units such as donkey, cattle, sheep, goats, pigs, chicken and rabbits are reared in mixed crop-livestock farming. Soil infertility, irregular and unreliable rainfall, pests (weeds such as striga and insect pests such as stem borers and fall armyworm) are major constraints of crop (cereal) production in the region. Push-pull technology is also practiced in western Kenya.

2.2. Sampling method and data collection

Household interviews were done at the end of 2016 long rains season, in the three sites: Bondo, Siaya and Vihiga. A sample of 96 farmers (32 per each of the three sites) was selected using purposive methods by selecting farmers who had practiced push-pull technology for at least one year (two consecutive cropping seasons). To do so, a list of adopters of push-pull technology in a site was obtained from ICIPE (International Centre for Insect Physiology and Ecology) agricultural extension officers (field officers) in charge of the site. To identify adopters of push-pull technology to interview, thirty-two random numbers were generated in excel spreadsheet for each site. Adopters of push-pull technology whose number on the list corresponded to one of the random numbers that were generated in excel sheet were selected for interviews. In case the adopter of push-pull technology was not available for interviews, a replacement was done by picking the adopter whose number on the list is next to the number of the missing adopter of push-pull technology.

The questions sought to obtain information on household characteristics; cropping systems; performance of cropping systems under different climatic conditions; challenges of agriculture in the site and resilience of cropping systems to the challenges, and merits of cropping systems that commensurate with resilience to the challenges; and production of partner crops in a cropping system during the season that was perceived as *'bad season'*, and the one that was perceived as *'good season'*. A *'bad season'* was a season with low and poorly distributed rainfall, causing a decline in crop production. A *'good season'* was a season with no limitation nor excess in rainfall, and provides a good crop production (perceptions of interviewees). *'Bad* and *'good season'* were identified by counting backward from 2016 long rains season. The 2016 long rains season was perceived a *'bad season'* while the 2016 short rains season was a *'good season'*, and this was consistent across the three study sites. We also asked farmers the percentage of land protected from incoming sunrays and raindrops in the three major cropping systems: push-pull, intercrop of maize and beans, and monocrop of maize. We calculated the amount of nitrogen, phosphorus and potassium that can be recycled through crop biomass based on the yield of the biomass: stover of maize and beans, biomass of desmodium, Napier grass, or Brachiaria. This was done by multiplying the yield with the content of nitrogen, phosphorus, and potassium summarized in Table 2. The maize grain yield estimated for 'bad' and 'good season' were compared with maize grain yield measure in farms in 2017 long and short rains seasons, and 2018 long rains season to see how much perceptions deviate from or agree with farm measured yields. Also, perceptions of farmers on soil cover were compared with observations made by 16 farmers from a long-term experiment in ICIPE Mbita research station in 2018 long rain season.

2.3. Statistical analysis

Qualitative data were analyzed using descriptive statistics such as frequency of mention. Quantitative data were analyzed by comparing means for sites, and for cropping systems using paired-t test'. Comparison of perceptions of farmers about maize grain yield in 'bad' and 'good season' and yields measured in farms in 2017 short and long rains seasons, and 2018 long rains season was done by analyzing the variance and comparing their respective means. Analysis of variance was also used to compare % soil cover perceived by farmers for the three cropping systems with observations made in field experiments. The analysis of variance was done in mixed models with seasons as fixed effect and farmers as a random effect. Data transformation was done for normality before analyzing the variance, but untransformed data were used for reporting. Means were separated using Tukey test at $\alpha = 0.05$. Statistical analysis was done using IBM SPSS statistics version 22 (IBM Corp, 2013) and R software package (R Core Team, 2022).

3. Results

3.1. Farm and household characterization

Out of 96 respondents, 58 were female (60.4%). Most of the respondents (95%) were 30 years old and above, 78% being between 40 and 69 years of age (Table 3). Eighty percent (80%) of respondents had the farming experience of at least 10 years (Table 3). Their experience in push-pull cropping system was mainly 1–6 years (70%). Farmers whose experience in push-pull farming was above 6 years were 28% of respondents and 52% of them were from Vihiga (Table 3).

The land under push-pull was significantly larger in Siaya and Vihiga compared to Bondo by 0.1 and 0.06 ha, respectively (Fig. 2a). Farmers from Vihiga devoted a big proportion of land to push-pull than did farmers from Siaya and Bondo (Fig. 2b). Intercrop of maize and beans is common in the three sites (56%, 72% and 75% of respondents, respectively from Bondo, Siaya and Vihiga), followed by maize mono crop (34%, 25% and 15.6%, from Bondo, Siaya and Vihiga, respectively). The intercrop of maize and groundnut was practiced by few farmers that were mainly from Bondo. Almost the majority of respondents were planning to expand push-pull to the totality of their farms (50, 56 and 42% of respondents in Bondo, Siaya and Vihiga, respectively). The reason for wanting to practice push-pull on the totality of household farms is higher yields in push-pull compared to other cropping systems and the fact that push-pull produces fodder even in dry seasons.

Table 2
Nitrogen (N), Phosphorus (P), and Potassium (K) content of commodities harvested in push-pull, maize-bean intercrop and maize monocrop.

Item/commodity	N	P	K	Reference
	Percentage (%)			
Maize grain	1.30	0.40	0.48	Bak et al. (2016)
Biomass of Desmodium	1.75	0.13	0.69	Campanhola and Pandey (2019)
Biomass of Napier grass	1.45	0.14	3.79	Campanhola and Pandey (2019)
Bean grain	3.05	0.42	1.76	Fageria et al. (2012)
Bean stalks	3.51	0.73	1.68	Mitova and Stancheva (2013)
Maize stover	0.89	0.08	2.78	Bak et al. (2016)

3.2. Resilience to climate change

3.2.1. Push-pull technology and cropping seasons

Ten cropping systems were mentioned by respondents and were ranked as first, second, third, fourth and fifth best-fit with regard to the environment, or climatic conditions in a cropping season. Out of 10 cropping systems mentioned, 5 had a relatively higher frequency of mention than others. These are push-pull technology (because all the selected farmers were push-pull adopters), intercrop of maize and beans, monocrops of maize, monocrops of groundnut, and mixed cropping of maize and sorghum (Fig. 3).

In the three study sites, push-pull technology was perceived to be the best cropping system that fits well in the short as well as the long rain season. Intercrop of maize with beans was ranked the second best cropping system that fits well with both the short and long rain seasons in Bondo and Vihiga. In Siaya, the second-best cropping system that fits well in long and short rain seasons was maize monocrop. Maize monocrop ranked third in Bondo and Vihiga for both long and short rains seasons, while the intercrop of maize and beans ranked third in Siaya for both seasons (Fig. 4).

Push-pull technology is perceived to fit well in the long rains season because it produces higher yields compared to other cropping systems (90% of respondents across the three sites). It (push-pull) is perceived to fit well in short rain seasons because desmodium retains and maintains moisture in soils and makes the system resilient to dry spells experienced in short rain seasons (91.7% of respondents across the three sites).

3.2.2. Push-pull technology versus agricultural challenges

Respondents described the issue of climate as inadequate rainfall, unreliable weather, unfavorable weather patterns, drought, and climate change. Climate related issues seriously limit agriculture production in the three sites (88.5% of respondents) and were perceived to be the top most challenge in these sites (63.5% of respondents who mentioned this challenge perceive it as challenge number one in their environment). Other challenges were pests and diseases such as stem borers, ants, birds and ear-rot, and a parasitic weed, striga. Respondents also mentioned input related challenges which include high cost of seeds and fertilizers and limited access to them. Soil related issues were also mentioned among serious challenges faced in agriculture in the study sites (Bondo, Siaya and Vihiga). These issues related to soils include poor soils, declining soil fertility, and soil erosion. Based on the frequency of mention, challenges were listed as follows: climate related challenges (88.5% of respondents) > pest and disease related challenges (45.8% of respondents) > striga related challenges (37.5% of respondents) > input related challenges (26% of respondents) > and soil related challenges (11.5% of respondents).

Push-pull technology was ranked better than intercrop of maize and bean, and monocrop of maize in facing the three major agriculture challenges in the region (climate change related issues, pests, and striga related issues). This was related to its merits (merits of push-pull technology) listed in Table 4, namely conserving moisture in soils, ability to resist droughts and attacks by termites, providing appropriate soil cover and protecting the soil from erosion, improving soil fertility, ability to suppress striga and other weeds in general, and the ability to control pests like stem borers and diseases.

3.2.3. Push-pull technology and food and fodder production

Push-pull technology produced higher maize grain yield than intercrop of maize and beans, and monocrop of maize when the season was bad and when the season was good. In fact, the mean yield of maize for push-pull when the season was bad was four times the yield for the intercrop of maize and bean in Bondo (during a bad season, 2016 long rains season) (Table 5). Similarly, the yield of maize in push-pull in bad

Table 3
Characteristics of respondents.

	Bondo (N = 32)		Siaya (N = 32)		Vihiga (N = 32)		Total (N = 96)	
	Frequency	%	Frequency	%	Frequency	%	Frequency	%
Age category (years)								
20–29	0	0	0	0	1	3.1	1	1.0
30–39	3	9.3	8	25.0	1	3.1	12	12.5
40–49	9	28.1	4	12.5	8	25.0	21	21.8
50–59	8	25.0	10	31.2	10	31.2	28	29.1
60–69	9	28.1	7	21.8	10	31.2	26	27.0
70–79	3	9.3	1	3.1	1	3.1	5	5.2
Farming experience (years)								
1–9	3	9.3	11	34.3	5	15.6	19	19.7
20–29	9	28.1	14	43.7	14	43.7	37	38.5
30–39	3	9.3	4	12.5	6	18.7	13	13.5
40–49	11	34.3	0	0	4	12.5	15	15.6
50–59	4	12.5	3	9.3	3	9.3	10	31.2
60–69	2	6.2	0	0	0	0	2	2.0
70–79	0	0	0	0	0	0	0	0
Experience in push-pull farming (years)								
1–3	14	43.7	10	31.2	7	21.8	31	32.2
4–6	10	31.2	17	53.1	10	31.2	37	38.5
7–9	2	6.2	4	12.5	0	0	6	6.2
10–15	6	18.7	0	0	12	37.5	18	18.7
16–20	0	0	0	0	2	6.2	2	2.0
21–25	0	0	1	3.1	0	0	1	3.1

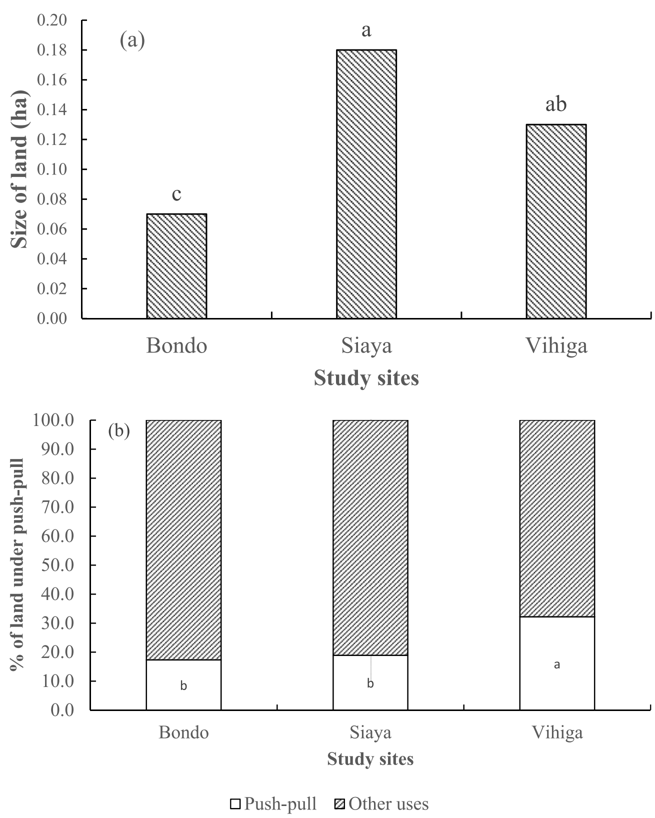

Fig. 2. Size (a) and percentage (b) of land that is under push-pull technology, per farm household. Means followed by the same letter are not significantly different at P<0.05.

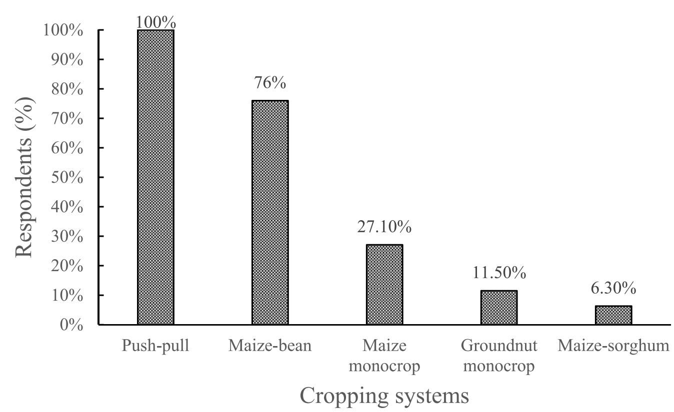

Fig. 3. Frequent cropping systems in western Kenya.

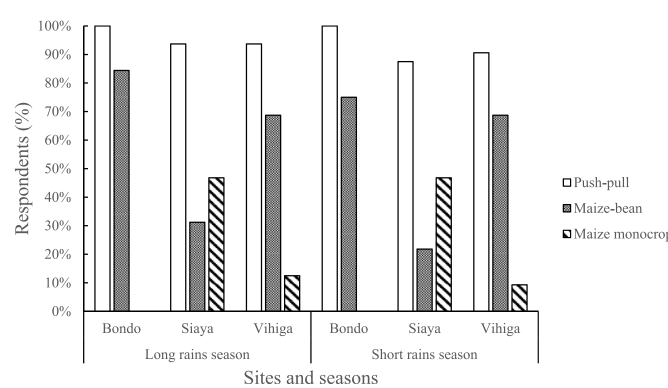

Fig. 4. Cropping systems that fit well in long and short rains seasons.

season (2016 long rains season) was higher by around 300 kg ha^{-1} compared to the yield for intercrop of maize and bean and maize monocrop in Siaya. In Vihiga, the yield for push-pull in the bad season (2016 long rains season) was higher than the yield for intercrop of maize and beans by 600 kg ha^{-1}, and by 1100 kg ha^{-1} compared to maize monocrop. When the season was good (2016 short rains season), the estimated average yield of maize in push-pull was almost three times the yield estimated for maize-bean intercrop in Bondo and Siaya, and was higher by around 900 kg maize grains ha^{-1} in Vihiga compared to maize-bean intercrop (Table 5).

The average maize yield for push-pull was five times the average for maize monocrop in Vihiga. Siaya was an exception to this as averages for push-pull and maize monocrop were comparable to each other when the season was good (2016 short rains). It is worth to note that maize-bean

Table 4
Merits of push-pull technology with regard to agriculture challenges in Bondo, Siaya and Vihiga. N means the sample size.

Criteria	Bondo	Siaya	Vihiga	Total	N	Relative frequency (%)
Plants are not attacked by pests and diseases	4	8	9	21	96	21.8
The infestation by striga and other weeds is relatively low	12	6	8	26	96	27.0
It conserves moisture in soils	13	2	11	26	96	27.0
Provides good harvest/self-running cropping system	8	14	4	26	96	27.0
Provides an appropriate soil cover and prevents soil erosion	6	2	5	13	96	13.5
Needs less labour	5	1	0	6	96	6.2
The border crops protect the main crop from strong winds	4	0	2	6	96	6.2
Needs small land	1	2	0	3	96	3.1
Produces fodder as well	1	3	2	6	96	6.2
Resists drought and termites	2	8	5	15	96	15.6
It improves soil fertility	1	1	8	10	96	10.4
Provides both food and fodder	0	2	0	2	96	2.0
Easy to maintain	0	1	0	1	96	1.0

intercrops produced 50–200 kg of beans when the season was bad (2016 long rains season), and 300–600 kg when the season was good (2016 long rains season). It is also good to note that push-pull produced 4.0 to 10.0 t dry matter fodder made of desmodium and Napier grass or brachiaria when the season was bad (2016 long rains season) and between 8.0 and 17.0 t dry matter when the season was good (2016 short rains season).

Estimations based on perceptions of farmers were significantly lower than estimations based on farm measurements. This was observed in maize-bean intercrop and maize monocrop, but not in push-pull technology (Fig. 5a, b and 5c). For example, the estimated mean maize grain yield for maize-bean intercrop during a ‘good season’ was 38.4% the lowest yield measured in the field (yield for 2017 short rains) (Fig. 5b). Similarly, the mean yield of maize in maize monocrop based on perceptions of farmers during a ‘good season’ was 56.0% the yield measured in farms in 2017 short rains (Fig. 5c). Contrary to this, the estimate of maize yield for push-pull during a ‘good season’ was similar to the one measured in farms in 2017 long rains season.

3.3. Controlling land degradation

3.3.1. Push-pull technology and soil cover

Push-pull had a higher soil cover estimate than maize-bean intercrop and maize monocrop in the three sites (Fig. 6). The estimate of percentage of soil covered in push-pull farms was at least three times the soil cover in maize-bean intercrop and maize monocrop in the three sites (Fig. 6). The exception was observed in Siaya where the soil cover by push-pull was estimated to be twice the soil cover in maize monocrop. Soil under the three cropping systems (push-pull, maize-bean intercrop and maize monocrop) remains covered after harvesting the major crops: maize and beans (93.7% and 96.8% of respondents, respectively in Bondo and Siaya, and 100% of respondents in Vihiga for push-pull, 71.8%, 65.6% and 15.6% of respondents, respectively in Bondo, Siaya and Vihiga for intercrops of maize and bean, and 6%, 45.7%, and 3% of respondents, respectively from Bondo, Siaya, and Vihiga for maize monocrop). The source of soil cover is crop residues (93.7% of respondents in Bondo, 96.8% of respondents in Siaya, and 6% of respondents in Vihiga), and desmodium (only for push-pull).

Perceptions of farmers about soil cover did not significantly deviate from observations made in the field experiment for push-pull and maize-bean intercrop (Fig. 7). The exception to this was observed in maize monocrop where the mean % soil cover perceived by farmers was four times the mean observed in field experiment, because plots for maize monocrop in experiments were severely affected by striga, and could not cover well the soil.

Table 5
Yields of maize, beans, desmodium, and Napier/Brachiaria grass in push-pull, maize-bean intercrop, and maize mono crop in Bondo, Siaya, and Vihiga. NA stands for *‘not applicable’* and is meant for crops not grown in the system. Values in brackets are standard errors to the mean.

Cropping system	Bad season				Good season			
	Maize	Bean	Desmodium	Napier grasss	Maize	Bean	Desmodium	Napier grass
	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}	kg ha^{-1}
Bondo								
Push-pull	667.1 (±90.7)	NA	2630.8 (±297.3)	3504.1 (±369.4)	2964.7 (±293.0)	NA	7145.5 (±661.6)	9026.4 (±1104.1)
Maize-bean	165.2 (±32.2)	55.5 (±12.6)	NA	NA	977.3 (±112.3)	349.1 (±41.5)	NA	NA
Maize monocrop	NA	NA	NA	NA	NA	NA	NA	NA
Siaya								
Push-pull	892.0 (±106.3)	NA	1758.4 (±266.7)	1905.2 (±268.5)	3384.4 (±379.4)	NA	4047.7 (±597.5)	4053.4 (±604.7)
Maize-bean	562.7 (±135.9)	164.0 (±57.6)	NA	NA	1229.4 (±269.8)	322.9 (±103.7)	NA	NA
Maize monocrop	560.8 (±156.1)	NA	NA	NA	2662.0 (±532.5)	NA	NA	NA
Vihiga								
Push-pull	1523.5 (±285.5)	NA	2735.9 (±640.4)	6902.7 (±2142.1)	3048.6 (±457.3)	NA	4086.9 (±1100.4)	6902.7 (±2142.1)
Maize-bean	951.0 (±139.6)	214.3 (±60.6)	NA	NA	2167.3 (±273.3)	592.1 (±150.3)	NA	NA
Maize monocrop	415.1 (±176.3)	NA	NA	NA	667.1 (±178.5)	NA	NA	NA

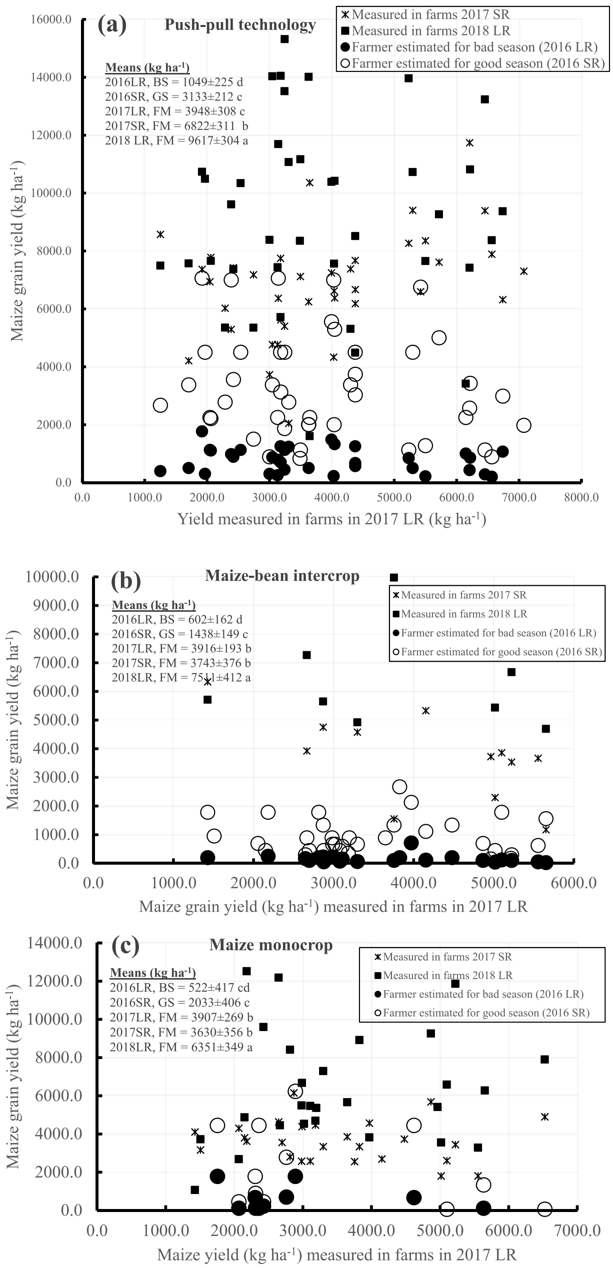

Fig. 5. Comparison of farmers' perceptions and field measurements in push-pull (a), maize-bean intercrop (b), and maize monocrop (c). Means followed by the same letter are not significantly different at P<0.05. LR and SR mean long and short rains season, respectively. BS and GS mean 'bad' and 'good season', respectively.

3.3.2. *Push-pull technology and soil fertility management*

Harvested commodities from push-pull during the good season (2016 short rains) contained 200–320 kg N, 27–36 kg P, and 290–490 kg K ha^{-1} across the three sites, and had the potential to recycle 160–280 kg N, 13–24 kg P and 270–470 kg K ha^{-1}. These estimates were higher by at least 2.5 times than what was estimated for maize-bean intercrop and maize monocrop (Table 6). The potential of push-pull technology to recycle N was 5–11 times the ability of maize-bean intercrop, and 6–33 times the ability of maize monocrop. Similarly, its ability to recycle phosphorus (ability of push-pull) was 3–8 times and 6–34 times compared respectively to the ability of maize-bean intercrop and maize monocrop, while its ability to recycle potassium was 5–12 times and 3–20 times compared respectively to the ability of maize-bean intercrop and maize monocrop.

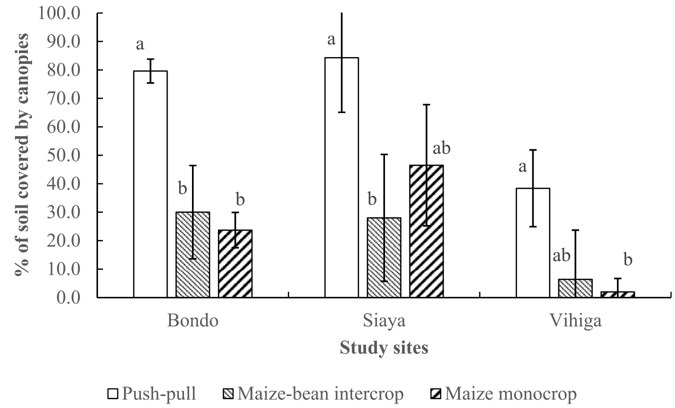

Fig. 6. Estimated soil cover (%) in push-pull, maize-bean intercrop, and maize mono crop in Bondo, Siaya and Vihiga. Means followed by the same letter in a site are not significantly different at P<0.05.

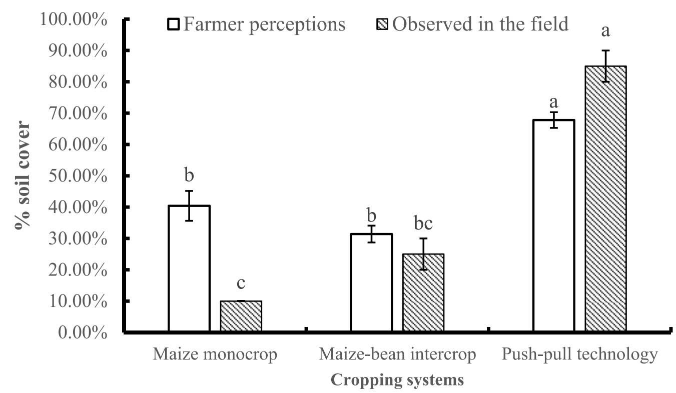

Fig. 7. % soil cover perceived by farmers and measured in field experiments. Means followed by the same letter are not significantly different at P<0.05.

4. Discussion

4.1. *Resilience to climate change*

Adopters of push-pull technology showed that this technology (push-pull) produces significantly more maize grain compared to maize-bean intercrop and maize monocrop even in unfavorable seasonal conditions, and produces fodder of desmodium, and Napier grass/Brachiaria in addition to food production. This is so important for farmers, especially crop – livestock mixed farmers as their evaluation of push-pull includes not only the performance of maize in push-pull, but also the amount of fodder the technology produces (Cheruiyot et al., 2021). Farmers from the study area have small pieces of land that were on average 0.49, 0.65 and 1.31 ha in Vihiga, Bondo and Siaya, respectively (Fig. 2). This is consistent with observations by Klapwijk et al. in East Africa (Klapwijk et al., 2014). However, the land that was devoted to push-pull technology was really small (Fig. 2). With this size of land, push-pull farms produced extra 429, 659, and 1253 kg dry matter fodder of desmodium and Napier grass or Brachiaria (combined), respectively in Bondo, Siaya, and Vihiga when the season was bad, compared to the scenario of maize-bean intercrop and maize monocrop. This extra fodder is enough to feed one local breed cow for 16, 24, and 47 days, respectively in Bondo, Siaya, and Vihiga, and 8, 12, and 23 days in Bondo, Siaya and Vihiga for one European breed cow. In fact, the local breed cow can consume 70 kg while the European breed can consume 140 kg fresh weight of fodder (dry matter estimated at 38%) per day (Klapwijk et al., 2014). Should the livestock unit be in a lactating period, householders will have milk for home consumption or sale for income, or both, hence boosting their

Table 6
Fertility management in push-pull, maize bean intercrop and maize monocrop in Bondo, Siaya and Vihiga.

Parameter	Push-pull technology			Maize-bean intercrop			Maize monocrop		
	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium	Nitrogen	Phosphorus	Potassium
Bondo									
Maize grain	38.5	11.8	14.2	12.7	3.9	4.6	NA[a]	NA	NA
Bean grain	0.0	0.0	0.0	10.6	1.4	13.2	NA	NA	NA
Maize stover biomass	26.7	2.4	83.4	8.9	0.8	27.8	NA	NA	NA
Desmodium biomass	125.0	9.2	49.3	0.0	0.0	0.0	NA	NA	NA
Napier grass biomass	130.8	12.6	342.1	0.0	0.0	0.0	NA	NA	NA
Bean biomass	0.0	0.0	0.0	15.2	2.1	8.8	NA	NA	NA
Total nutrient in harvested parts	**321**	**36**	**489**	**47.4**	**8.2**	**54.4**	**NA**	**NA**	**NA**
Recyclable nutrients	282.5	24.2	474.8	24.1	2.9	36.6	NA	NA	NA
Siaya									
Maize grain	43.9	13.5	16.2	15.9	4.9	5.9	34.6	10.6	12.7
Bean grain	0.0	0.0	0.0	9.6	1.3	5.6	0.0	0.0	0.0
Maize stover biomass	30.1	2.7	94.0	10.9	0.98	34.1	23.6	2.1	74.0
Desmodium biomass	70.8	5.26	27.9	0.0	0.0	0.0	0.0	0.0	0.0
Napier grass biomass	58.7	5.6	153.6	0.0	0.0	0.0	0.0	0.0	0.0
Bean biomass	0.0	0.0	0.0	17.5	3.6	8.4	0.0	0.0	0.0
Total nutrient in harvested parts	**203.5**	**27.06**	**291.7**	**53.9**	**10.78**	**54**	**58.2**	**12.7**	**86.7**
Recyclable nutrients	159.6	13.5	275.5	28.4	4.5	42.5	23.6	2.1	74
Vihiga									
Maize grain	39.6	12.1	14.6	28.1	8.6	10.4	8.6	2.6	3.2
Bean grain	0.0	0.0	0.0	18.0	2.5	10.4	0.0	0.0	0.0
Maize stover biomass	27.1	2.4	84.7	19.2	1.7	60.2	5.9	0.5	18.5
Desmodium biomass	71.5	5.3	28.1	0.0	0.0	0.0	0.0	0.0	0.0
Napier grass biomass	100.0	9.6	261.6	0.0	0.0	0.0	0.0	0.0	0.0
Bean biomass	0.0	0.0	0.0	21.0	4.41	10.1	0.0	0.0	0.0
Total nutrient in harvested parts	**238.2**	**29.4**	**389.0**	**86.3**	**17.2**	**91.1**	**14.5**	**3.1**	**21.7**
Recyclable nutrients	198.6	17.3	374.4	40.2	6.1	70.3	5.9	0.5	18.5

[a] NA stands for 'not applicable'. Maize monocrop was not mentioned in Bondo.

resilience to the effects of bad season characterized by scarce rainfall and prolonged dry spells. Should the farm household not have livestock to feed, they can sale fodder to livestock keepers and get cash to spend.

Additionally, push-pull farms (considering sizes of land already converted to push-pull in the three study sites) produced extra 35.0 kg maize in Bondo compared to maize-bean intercrop, 59 kg extra maize in Siaya compared to maize-bean intercrop and maize monocrop, and 74 and 144 kg extra maize compared to maize-bean intercrop and maize monocrop, respectively, in Vihiga when the season was bad. This quantity of maize is enough to feed a family of six for 19, 32, and 41 days, respectively in Bondo, Siaya and Vihiga (and 80 extra days in Vihiga compared to maize monocrop) should one person consume 300 g maize per day (Tanyanyiwa et al., 2022). It is important to note that maize-bean intercrop produced 31, 185, and 77 kg of beans, respectively in Bondo, Siaya, and Vihiga during the bad season (based on available land at household level). This quantity is enough to feed a family of six for 56, 331, and 77 days, should a person consume 93 g of beans per day (Farrow and Muthoni-Andriatsitohaina, 2020). However, the farm household will have missed the opportunity to produce extra fodder for livestock. On the contrary, it has been proven that bean can be produced in push-pull as well through planting beans in the same holes with maize or between holes of maize in a row (Drinkwater et al., 2021; Khan et al., 2009). In the case householders grow beans in push-pull farms, and consume leaves of beans, young pods, fresh beans, and dry beans, the resilience of householders to climate change will be increased further (Farrow and Muthoni-Andriatsitohaina, 2020; Woomer, et al., 2004). Therefore, increasing the land under push-pull will increase the number of days humans and livestock feed when the bad season happens, and this will boost resilience of households to climate change. This concurs with the existing knowledge that says that the more diverse a farm is, the more resilient it is to climate change (Altieri and Koohafkan, 2008).

The ability of push-pull to boost resilience to climate change has been strengthened. This was done by replacing varieties of Desmodium and Brachiaria with varieties that are more resistant to drought and pests. *Desmodium intortum* has been replaced with *Desmodium incanum*, and the later has the ability to withstand a 50 days dry spell at temperatures of 17–35 °C without compromising its biomass yield (Midega et al., 2017). Similarly, *Brachiaria brizantha* var Mulato II has been replaced with *Brachiaria brizantha* var Xaraes that can withstand a dry spell of 28 consecutive days under 18–35 °C temperatures without losing its productivity (Cheruiyot et al., 2018). This shows that the current push-pull technology is even more adapted to severe droughts and temperature increases predicted as climate continues to change.

The ability of push-pull to increase maize production is due to improving soil organic matter, availing crop nutrients, controlling pests and parasites such as striga weed, stem borers, fall armyworm, etc, and providing a soil cover (Drinkwater et al., 2021; Ndayisaba et al., 2020, 2022, 2021; Ojiem et al., 2007; Vanlauwe et al., 2008). All these contribute to a better nutrition of maize grown in push-pull than that grown in maize-bean intercrop or maize monocrop. These improvements were documented in push-pull plots, while there was no improvement detected in maize-bean intercrops compared to maize monocrops (Drinkwater et al., 2021; Ndayisaba et al., 2021, 2022). This explains why the production is higher in push-pull farms than in those that have maize-bean intercrop and maize monocrop, even when the season is unfavorable. Additionally, the presence of Desmodium as a cover crop contributes to improving the penetration of roots of maize into soils, and conserving moisture (Chen and Weil, 2011; Rusinamhodzi et al., 2012).

Farmers also showed their appreciation of how push-pull technology controls other threats of maize production in the region namely striga, stem borers, and termites. As climate gets wormer, insect pests are expected to increase in number of generations per year, increase in number and feeding, be more disperse with possibly more migrations than before (Altieri and Koohafkan, 2008; Diffenbaugh et al., 2008). The example is the recent invasion of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) in Africa and Asia. Fortunately, push-pull controls a range of these pests, including stem borers, fall armyworm, and in addition, it controls striga. This was witnessed by adopters and researchers in field experiments (Chepchirchir et al., 2017; Khan et al., 2018; Lang et al., 2022; Midega et al., 2018; Murage et al., 2015; Mutyambai et al., 2019). This confirms that push-pull technology is likely to help in offsetting attacks by insects pests and parasites as climate change boosts their occurrence and virulence.

4.2. Controlling land degradation

Adopters of push-pull showed that it offers to the soil more cover which can double or more than double the cover offered by maize-bean and maize monocrop. This is because in addition to the cover provided by maize canopy, Desmodium grows and moves on the surface of soils, covering the loops left by maize canopy. This is also higher than the cover offered by maize and bean grown together because beans were planted at 0.3 m space between two hills, and their canopy may not touch each other or cover well the spaces close to maize rows the way Desmodium does. This is so important as far as land degradation is concerned because soil erosion due to rainfall runoff from farms carries soil organic matter and nutrients including bases along with finer soils to lower lands, or downwards in the profile to lower horizons. Higher soil cover means reduced effect of falling drops, thus altering or even halting the process of soil detachment and transport along runoff water. As a consequence, soils are retained in place, soil organic matter and nutrients are not lost, and the health of soils is maintained. For example, practicing push-pull in a farm for 20 years increased its particulate organic matter by three to five folds compared to common maize based cropping systems in western Kenya (Drinkwater et al., 2021). This organic matter is majorly occluded insuring protection from losses compared to common maize based cropping systems of western Kenya (Drinkwater et al., 2021). Moreover, Desmodium is more efficient in halting runoff water from upstream that runs through the maize plantation because it offers a continuous spread on the surface contrary to what maize and beans do. This makes push-pull more appropriate for erosion control than maize-bean and maize monocrop.

Respondents showed that the soil under push-pull conserves more moisture compared to other cereal cropping systems of the region (maize-bean intercrop and maize monocrop) through its higher land cover. This is because push-pull halts and conserves water in three processes. First, rain drops land on maize canopy (upper story canopy) and their velocity is reduced (velocity of drops). Second, drops that fall from maize leaves or that pass into loops of the maize canopy are intercepted by Desmodium canopy which is thick. Thirdly, water that runs from upstream is halted and spread slowly in the farm as its movement downstream is hampered by the spread of Desmodium vines and their leafy nature. Additionally, the farm is surrounded by Napier grass or Brachiaria that checks the movement of water from upstream. This allows water more time to infiltrate into soils rather than running downstream. Henceforth, maize grown in push-pull suffers less from dry spells than maize grown with beans or grown as a monoculture. This partially explains higher yields in push-pull than in these two cropping systems: maize-bean intercrop and maize monocrop. Because push-pull land is protected from losses of bases, organic matter, and clay, degradation and acidification will not take place (Gachene et al., 1997).

From calculations based on what farmers estimated as production from maize cropping systems, push-pull ability to recycle nitrogen, phosphorus, and potassium is higher compared to commonly practiced maize-bean intercrop and maize monocrop, through higher biomass production. Observations by farmers concurred with measurements done on farm (Ndayisaba et al., 2020). Though the use of crop residues for soil health purpose is limited especially in crop-livestock farming (Turmel et al., 2015), there is a likelihood of having more residue leftovers in push-pull than in maize-bean intercrop and maize monocrop due to larger production of biomass in push-pull. These residue leftovers contribute to restoring land or maintaining a healthy soil. Moreover, the biomass fed to livestock is partially recycled as manure and returns to the farm (Rufino et al., 2006; Tittonell et al., 2010). Cropping systems with high biomass production like push-pull technology will help to rehabilitate 200 million hectares of land in developing countries by 2030 (IRENA, 2017).

From existing literature, push-pull technology has proven its ability to restore degraded lands as it stores more soil organic carbon than other maize cropping systems in western Kenya (Drinkwater et al., 2021; Ndayisaba et al., 2022). Also, Desmodium pumps in soils around 110 kg nitrogen ha^{-1} per year through biological fixation (Ojiem et al., 2007; Pickett et al., 2014). Moreover, Desmodium and Napier/Brachiaria remain in the farm after maize and beans are harvested, and provide fodder, soil cover and improvement. This contributes to increased resilience to climate change (Lal, 2006). This study was based on farmers' perceptions about resilience to climate change and controlling land degradation. Perceptions of farmers might sometimes deviate from measurements in farms and bias comparison between cropping systems. As observed in this study, the maize grain yield for maize-bean intercrop and maize monocrop based on perceptions of farmers during the ‘good season’ was half or less than the yield measured in farms in 2017–2018 in western Kenya. This might lead to exaggeration of comparative benefits of push-pull compared to maize-bean intercrop and maize monocrop, especially when seasons are normal. However, the general trend depicted by perceptions of farmers corroborate with the trend reported from farm measurements by Ndayisaba and colleagues for farm productivity, and Drinkwater and colleagues for land degradation (Drinkwater et al., 2021; Ndayisaba et al., 2020, 2022). Additionally, perceptions by farmers about % soil cover were similar to what was observed in experiments (Fig. 7). Therefore, the information generated in this study is enough and reliably shows that adoption of push-pull can increase resilience to climate change, and control land degradation.

5. Conclusions

From views of adopters in western Kenya, push-pull technology does significantly better than maize-bean intercrop and maize monocrop when the season is bad and when the season is good. Additionally, it controls pests and parasites such as stem borers and striga, and proved to control fall armyworm when it invaded maize plantations in western Kenya. Its productivity provides extra food and fodder to sustain lives for householders and their livestock units when a season is bad. The push-pull system is better in covering soils and has the capacity to recycle more nutrients than maize-bean intercrop and maize monocrop. As a conclusion, adoption of push-pull at large scale may be a way to strengthening resilience to climate change and control land degradation. It is recommendable to carry out a comprehensive study on push-pull as a mixed crop – livestock system to understand its carrying capacity in terms of livestock feeding, and its supply of nitrogen through biological fixation. Also, a study on emissions from farms would increase light on reduction of emissions and sequestration of greenhouse gases, including nitrous oxides.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adesina, A.A., Baidu-forson, J., 1995. Farmers' perceptions and adoption of new agricultural technology: evidence from analysis in Burkina Paso and Guinea, West Africa. Agric. Econ. 13, 1–9. https://doi.org/10.1016/0169-5150(95)01142-8.

Altieri, M.A., Koohafkan, P., 2008. Enduring Farms: Climate Change, Smallholders and Traditionall Farming Communities. Third World Network, Penang, Malaysia.

Bak, K., Gaj, R., Budka, A., 2016. Accumulation of nitrogen, phosphorus and potassium in mature maize under variable rates of mineral fertilization. Fragmenta Agronomica 33 (1), 7–19.

Campanhola, C., Pandey, S., 2019. Push-pull redesign: multifaceted innovation systems in Africa. In: Sustainable Food and Agriculture: an Integrated Approach, first ed. The Food and Agriculture Organization of the United Nations and Elsevier Inc, pp. 199–204. https://doi.org/10.1016/B978-0-12-812134-4.00017-0.

Chen, G., Weil, R.R., 2011. Root growth and yield of maize as affected by soil compaction and cover crops. Soil Till. Res. 117, 17–27. https://doi.org/10.1016/j.still.2011.08.001.

Chepchirchir, R.T., Macharia, I., Murage, A.W., Midega, C.A.O., Khan, Z.R., 2017. Impact assessment of push-pull pest management on incomes, productivity and poverty among smallholder households in Eastern Uganda. Food Secur. 9 (6), 1359–1372. https://doi.org/10.1007/s12571-017-0730-y.

Cheruiyot, D., Chidawanyika, F., Midega, C.A.O., Pittchar, J.O., Pickett, J.A., Khan, Z.R., 2021. Field evaluation of a new third generation push-pull technology for control of striga weed, stemborers, and fall armyworm in western Kenya. Exp. Agric. 57, 301–315. https://doi.org/10.1017/S0014479721000260.

Cheruiyot, D., Midega, C.A.O., Berg, J.V.D., Pickett, J.A., Khan, Z.R., 2018. Genotypic responses of Brachiaria grass (Brachiaria spp.) accessions to drought stress. Agronomy 17, 136–146. https://doi.org/10.3923/ja.2018.136.146.

County Government of Siaya, 2018. County Integrated Development Plan 2018 - 2022. Government of Kenya. Retrieved from. https://www.google.com/search?ei=9NEuXeP3G8q8ae2SjvAL&q=cidp+Siaya+county&oq=cidp+Siaya+county&gs_l=psy-ab.12..0.4492.9938..12180...0.0..0.326.2581.0j1j9j1......0....1..gws-wiz.......0i71j0i7i30.pqkIagubxIQ.

County Government of Vihiga, 2018. Second County Integrated Development Plan 2018 - 2022. Government of Kenya.

Dawson, I.K., Carsan, S., Franzel, S., Kindt, R., Graudal, L., Orwa, C., Jamnadass, R., 2014. Agroforestry, livestock, fodder production and climate change adaptation and mitigation in East Africa: issues and options. ICRAF Working Paper No. 178. World Agroforestry Centre, Nairobi. https://doi.org/10.5716/WP14050.PDF.

Descheemaeker, K., Oosting, S.J., Tui, S.H., Masikati, P., Falconnier, G.N., Giller, K.E., 2016. Climate change adaptation and mitigation in smallholder crop – livestock systems in sub-Saharan Africa: a call for integrated impact assessments. Reg. Environ. Change. https://doi.org/10.1007/s10113-016-0957-8.

Diffenbaugh, N.S., Krupke, C.H., White, M.A., Alexander, C.E., 2008. Global warming presents new challenges for maize pest management. Environ. Res. Lett. 3, 1–9. https://doi.org/10.1088/1748-9326/3/4/044007.

Drinkwater, L.E., Midega, C.A.O., Awuor, R., Nyagol, D., Khan, Z.R., 2021. Perennial legume intercrops provide multiple belowground ecosystem services in smallholder farming systems. Agric. Ecosyst. Environ. 320, 1–12. https://doi.org/10.1016/j.agee.2021.107566.

Edrisi, S., Tripathi, V., Abhilash, P.C., 2018. Towards the sustainable restoration of marginal and degraded lands in India. Trop. Ecol. 59 (3), 397–416. Retrieved from. www.tropecol.com.

Eswaran, H., Lal, R., Reich, P.F., 2019. Land Degradation: an Overview. Response to Land Degradation. In: Bridges, E., Hannam, I., Oldeman, L., Penning de Vries, F., Scherr, S., Sompatpanit, S. (Eds.), Proc. 2nd International Conference on Land Degradation and Desertification. Oxford Press, Khon Kaen, Thailand, New Delhi.

Fageria, N.K., Moreira, A., Coelho, A.M., 2012. Nutrient uptake in dry bean genotypes. Commun. Soil Sci. Plant Anal. 43 (September), 2289–2302. https://doi.org/10.1080/00103624.2012.701689.

Farrow, A., Muthoni-Andriatsitohaina, R., 2020. Atlas of common bean production in Africa. In: Pan-Africa Bean Research Alliance, 2nd ed. PABRA); International Center for Tropical Agriculture (CIAT, Nairobi, Kenya. https://doi.org/10.7910/DVN/8W0QK7.

Gachene, C.K.K., Mbuvi, J.P., Jarvis, N.J., Linner, H., 1997. Soil erosion effects on soil properties in a highland area of Central Kenya. Soil Sci. Soc. Am. J. 61 (2), 559–564. https://doi.org/10.2136/sssaj1997.03615995006100020027x.

IBM Corp, 2013. IBM SPSS Statistics for Windows. IBM Corp, Armonk, NY, Version 22.0.

IRENA, 2017. Bioenergy from Degraded Land in Africa: Sustainable and Technical Potential under Bonn Challenge Pledges. International Renewable Energy Agency, Abu Dhabi.

Jaetzold, R., Schmidt, H., 1983. Farm Management Handbook of Kenya, Volume II: Natural Conditions and Farm Management Information; Annex: Atlas of Agro-Ecological Zones, Soils and Fertilising by Group of Districts; Subpart A2: Nyanza Province Homa Bay and Migori County.

Jaetzold, R., Schmidt, H., Hornetz, B., Shisanya, C., 2009. Farm Management Handbook of Kenya, Subpart A2 Nyanza Province, Volume II: Natural Conditions and Farm Management Information, second ed. Ministry of Agriculture, Nairobi, Kenya.

Jones, P.G., Thornton, P.K., 2009. Croppers to livestock keepers: livelihood transitions to 2050 in Africa due to climate change. Environ. Sci. Pol. 12, 427–437. https://doi.org/10.1016/j.envsci.2008.08.006.

Khan, Z., Midega, C.A.O., Hooper, A., Pickett, J., 2016. Push-pull: chemical ecology-based integrated pest management technology. J. Chem. Ecol. 42 (7), 689–697. https://doi.org/10.1007/s10886-016-0730-y.

Khan, Z.R., Hassanali, A., Overholt, W., Khamis, T.M., Hooper, A.M., Pickett, J.A., et al., 2002. Control of witchweed Striga hermonthica by intercropping with Desmodium spp., and the mechanism defined as allelopathic. J. Chem. Ecol. 28 (9), 1871–1885. https://doi.org/10.1023/A:1020525521180.

Khan, Z.R., Pittchar, J., Midega, C., Pickett, J., 2018. Push-pull farming system controls fall armyworm: lessons from Africa. Outlooks Pest Manag. 29 (5), 220–224. https://doi.org/10.1564/v29.

Khan, Zeyaur 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 (15), 4185–4196. https://doi.org/10.1093/jxb/erq229.

Khan, Zeyaur R., Midega, C.A.O., Wanyama, J.M., Amudavi, D.M., Hassanali, A., Pittchar, J., Pickett, J.A., 2009. Integration of edible beans (Phaseolus vulgaris L.) into the push–pull technology developed for stemborer and Striga control in maize-based cropping systems. Crop Protect. 28, 997–1006. https://doi.org/10.1016/j.cropro.2009.05.014.

Klapwijk, C.J., Bucagu, C., Wijk, M.T.V., Udo, H.M.J., Vanlauwe, B., Munyanziza, E., Giller, K.E., 2014. The 'One cow per poor family' programme: current and potential fodder availability within smallholder farming systems in southwest Rwanda. Agric. Syst. 131, 11–22. https://doi.org/10.1016/j.agsy.2014.07.005.

Kuyah, S., Dietz, J., Muthuri, C., Jamnadass, R., Mwangi, P., Coe, R., Neufeldt, H., 2012. Allometric equations for estimating biomass in agricultural landscapes: I. Aboveground biomass. Agric. Ecosyst. Environ. 158, 225–234. https://doi.org/10.1016/j.agee.2012.05.010.

Kuyah, S., Dietz, J., Muthuri, C., van Noordwijk, M., Neufeldt, H., 2013. Allometry and partitioning of above- and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes. Biomass Bioenergy 55, 276–284. https://doi.org/10.1016/j.biombioe.2013.02.011.

Kuyah, S., Sileshi, G.W., Nkurunziza, L., Chirinda, N., Ndayisaba, P.C., Dimobe, K., Öborn, I., 2021. Innovative agronomic practices for sustainable intensification in sub-Saharan Africa. A review. Agron. Sustain. Dev. 41 (16), 1–21. https://doi.org/10.1007/s13593-021-00673-4 (2021).

Lal, R., 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. Land Degrad. Dev. 17, 197–209. https://doi.org/10.1002/ldr.696.

Lal, R., 2015. Restoring soil quality to mitigate soil degradation. Sustainability 7, 5875–5895. https://doi.org/10.3390/su7055875.

Lang, J., Chidawanyika, F., Khan, Z.R., Schuman, M.C., 2022. Ecological chemistry of pest control in push-pull intercropping systems: what we know, and where to go? Chimia 76 (11), 906–913. https://doi.org/10.2533/chimia.2022.906.

Leisner, C.P., 2020. Review : climate change impacts on food security- focus on perennial cropping systems and nutritional value. Plant Sci. 293, 1–7. https://doi.org/10.1016/j.plantsci.2020.110412.

Midega, C.A.O., Pittchar, J.O., Pickett, J.A., Hailu, G.W., Khan, Z.R., 2018. A Climate-adapted push-pull system effectively controls fall armyworm, Spodoptera Frugiperda (J E Smith), in maize in East Africa. Crop 105, 10–15. https://doi.org/10.1016/j.cropro.2017.11.003.

Midega, C.A.O., Wasonga, C.J., Hooper, A.M., Pickett, J.A., Khan, Z.R., 2017. Drought-tolerant Desmodium species effectively suppress parasitic striga weed and improve cereal grain yields in western Kenya. Crop Protect. 98, 94–101. https://doi.org/10.1016/j.cropro.2017.03.018.

Mitova, I., Stancheva, I., 2013. Effect of fertilizer source on the nutrients biological uptake with garden beans production. Bulgarian J. Agric. Sci. 19 (5), 947–951.

Murage, A., Midega, C.A.O., Pittchar, J.O., Pickett, J., Khan, Z.R., 2015. Determinants of adoption of climate-smart push-pull technology for enhanced food security through integrated pest management in eastern Africa. Food Secur. 7 (June). https://doi.org/10.1007/s12571-015-0454-9.

Mutyambai, D.M., Bass, E., Luttermoser, T., Poveda, K., Midega, C.A.O., Khan, Z.R., Kessler, A., 2019. More than "push" and "pull"? Plant-soil feedbacks of maize companion cropping increase chemical plant defenses against herbivores. Front. Ecol. Evol. 7, 1–14. https://doi.org/10.3389/fevo.2019.00217.

Nakano, Y., Tsusaka, T.W., Aida, T., Pede, V.O., 2018. Is farmer-to-farmer extension effective? The impact of training on technology adoption and rice farming productivity in Tanzania. World Dev. 105, 336–351. https://doi.org/10.1016/j.worlddev.2017.12.013.

Ndayisaba, P.C., Kuyah, S., Midega, C.A.O., Mwangi, P.N., Khan, Z.R., 2020. Push-pull technology improves maize grain yield and total aboveground biomass in maize-based systems in Western Kenya. Field Crops Res. 256. https://doi.org/10.1016/j.fcr.2020.107911.

Ndayisaba, P.C., Kuyah, S., Midega, C.A.O., Mwangi, P.N., Khan, Z.R., 2022. Push-pull technology improves carbon stocks in rainfed smallholder agriculture in Western Kenya. Carbon Manag. 13 (1), 127–141. https://doi.org/10.1080/17583004.2022.2035823.

Ndayisaba, P.C., Kuyah, S., Midega, C.A.O., Njoroge, P., Khan, R.Z., 2021. Intercropping desmodium and maize improves nitrogen and phosphorus availability and performance of maize in Kenya. Field Crops Res. 263. https://doi.org/10.1016/j.fcr.2021.108067.

Negi, V.S., Pathak, R., Dhyani, V., Durgapal, M., Joshi, R.K., Bhatt, I.D., 2022. Land restoration in the himalayan region: steps towards biosphere integrity. Land Use Pol. 121. https://doi.org/10.1016/j.landusepol.2022.106317.

Njeru, N.K., Midega, C.A.O., Muthomi, J.W., Wagacha, J.M., Khan, Z.R., 2019. Influence of socio-economic and agronomic factors on aflatoxin and fumonisin contamination of maize in western Kenya. Food Sci. Nutr. 1–11. https://doi.org/10.1002/fsn3.1070.

Ojiem, J.O., Vanlauwe, B., De Ridder, N., Giller, K.E., 2007. Niche-based assessment of contributions of legumes to the nitrogen economy of Western Kenya smallholder farms. Plant Soil 292 (1–2), 119–135. https://doi.org/10.1007/s11104-007-9207-7.

Pickett, J.A., Woodcock, C.M., Midega, C.A.O., Khan, Z.R., 2014. Push-pull farming systems. Curr. Opin. Biotechnol. 26, 125–132. https://doi.org/10.1016/j.copbio.2013.12.006.

Purwanto, B.H., Alam, S., 2020. Impact of intensive agricultural management on carbon and nitrogen dynamics in the humid tropics. Soil Sci. Plant Nutr. 66 (1), 50–59. https://doi.org/10.1080/00380768.2019.1705182.

R Core Team, 2022. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from. https://www.r-project.org/.

Rufino, M.C., Rowe, E.C., Delve, R.J., Giller, K.E., 2006. Nitrogen cycling efficiencies through resource-poor African crop – livestock systems. Agric. Ecosyst. Environ. 112, 261–282. https://doi.org/10.1016/j.agee.2005.08.028.

Rusinamhodzi, L., Corbeels, M., Nyamangara, J., Giller, K.E., 2012. Maize – grain legume intercropping is an attractive option for ecological intensification that reduces climatic risk for smallholder farmers in central Mozambique. Field Crops Res. 136, 12–22. https://doi.org/10.1016/j.fcr.2012.07.014.

Simpraga, M., Takabayashi, J., Holopainen, J.K., 2016. Language of plants: where is the word? J. Integr. Plant Biol. 58 (4), 343–349. https://doi.org/10.1111/jipb.12447.

Tamiru, A., Bruce, T.J.A., Woodcock, C.M., Caulfield, J.C., Midega, C.A.O., Ogol, C.K.P.O., et al., 2011. Maize landraces recruit egg and larval parasitoids in response to egg deposition by a herbivore. Ecol. Lett. 14, 1075–1083. https://doi.org/10.1111/j.1461-0248.2011.01674.x.

Tanyanyiwa, V.I., Kanyepi, T., Katanha, A., 2022. Zimbabwe's pfumvudza agriculture programme - reality or rhetoric? In: Filho, W.L., Kovaleva, M., Popkova, E. (Eds.), Sustainable Agriculture and Food Security. Gewerbestrasse, Cham, Switzerland, pp. 327–348. https://doi.org/10.1007/978-3-030-98617-9. Springer Nature.

Tittonell, P., Rufino, M.C., Janssen, B.H., Giller, K.E., 2010. Carbon and nutrient losses during manure storage under traditional and improved practices in smallholder crop-livestock systems — evidence from Kenya. Plant Soil 328, 253–269. https://doi.org/10.1007/s11104-009-0107-x.

Tully, K., Sullivan, C., Weil, R., Sanchez, P., 2015. The state of soil degradation in sub-saharan Africa: baselines, trajectories, and solutions. Sustainability 7, 6523–6552. https://doi.org/10.3390/su7066523.

Turmel, M.-S., Speratti, A., Baudron, F., Verhulst, N., Govaerts, B., 2015. Crop residue management and soil health: a systems analysis. Agric. Syst. 134, 6–16. https://doi.org/10.1016/j.agsy.2014.05.009.

Vanlauwe, B., Kanampiu, F., Odhiambo, G.D., De Groote, H., Wadhams, L.J., Khan, Z.R., 2008. Integrated management of Striga hermonthica, stemborers, and declining soil fertility in western Kenya. Field Crops Res. 107, 102–115. https://doi.org/10.1016/j.fcr.2008.01.002.

Weather and Climate, 2022. weather data Kenya.pdf. Retrieved March 16, 2022. https://tcktcktck.org/.

Woomer, P.L., Lan'gat, M., Tungani, J.O., 2004. Innovative maize-legume intercropping results in above-and below-ground competitive advantages for understory legumes. West Afr. J. Appl. Ecol. 6, 85–94.

Zhao, J., Bindi, M., Eitzinger, J., Ferrise, R., Gaile, Z., Gobin, A., et al., 2022. Priority for climate adaptation measures in European crop production systems. Eur. J. Agron. 138, 126516. https://doi.org/10.1016/j.eja.2022.126516.