UPSCALE

UPSCALING THE BENEFITS OF PUSH-PULL TECHNOLOGY FOR SUSTAINABLE AGRICULTURAL INTENSIFICATION IN EAST AFRICA

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D6.1:
Synthetic review of opportunities and options for expansion of push-pull in East Africa

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Abstract:	Over the last two decades, the push-pull technology has been widely tested in the maize-mixed farming system in East Africa and commercial sugarcane farms in South Africa. Although different generations of this technology were evaluated and their scientific underpinnings well-documented, adoption by farmers is not yet commensurate with the potential benefits of the technology. Therefore, the objectives of this review were to (1) provide a synthesis of the evidence for benefits of push-pull to inform design of evidence-based practices and policies, and (2) explore options and opportunities for expansion of push-pull in other crops and farming systems in sub-Saharan Africa. We report the evidence for reduction in witchweed (Striga spp.) infestation (by > 90%), spotted stemborers (*Chilo partellus*) and African maize stalk borer (*Busseola fusca*) (by >70%), and fall armyworm (*Spodoptera frugiperda*) damage (>70%) in the push-pull maize-mixed farming system in East Africa. We have also found evidence for higher maize yields (~100%) and financial viability of the technology. We further found some evidence for lower damage to sugarcane by the sugarcane stemborer (*Eldana saccharina*) in South Africa. In addition, our review identifies opportunities for expansion of push-pull for pest management in other crops, especially sorghum, millet, upland rice, pulses, vegetables, root and tuber crops and cotton. The expansion of the geographic range of invasive alien species, such as the spotted stemborer and fall armyworm, and emerging infectious plant diseases, such as maize lethal necrosis disease (MLND), provides strong motivation for expanding push-pull into other farming systems and regions of Africa. Many emerging infectious plant diseases are spread by vectors, and push-pull may hold the potential for integrated vector and disease management. Therefore, we recommend routine monitoring of MLND and its vectors in existing push-pull trials in areas where the disease occurs. We also strongly recommend the development and sharing of best-practice guidelines for trial design and monitoring of push-pull performance indicators. **Keywords**: Agroecology; habitat management; integrated vector and disease management

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AIS	Alien invasive species
CMD	Cassava mosaic disease
CBD	Cassava brown streak disease
EIPD	Emerging infectious plant diseases
FAW	Fall army worm
MRR	Marginal rate of return
NPV	Net present values
PPT	Push-pull technology
R&D	Research and development
SSA	Sub-Saharan Africa

1 Introduction

The first use of push-pull as a strategy for insect pest management dates back to the 1980s in Australia, where Pyke and colleagues (1987) coined the term. They used repellent and attractive stimuli arranged in tandem to manoeuvre the distribution of bollworms (Heliothis species) in cotton, where the pest was becoming resistant to insecticides (Pyke et al., 1987). The name "push–pull" was later formalized by Miller and Cowles (1990). Since then, various forms of the push-pull technology have been tested in cereal, fruit and vegetables, sugarcane, and tree crops across the globe (Cook et al., 2007; Kergunteuil et al., 2015; Khan and Pickett, 2004; Poveda et al., 2019; Sampson et al., 2020; Xu et al., 2018; Yan et al., 2015; Yi et al., 2019). The definition and typologies of push-pull as a pest management strategy are evolving (Eigenbrode et al., 2016). In some instances (e.g., Meats et al., 2012; Sampson et al., 2020; Yan et al., 2014) what was described as push-pull involved spraying crops with repellent and attractant chemicals to provide the "push" or "pull" stimulus. The push-pull strategy in the medical field involves the combination of an attractive trapping system and spatial repellent to reduce human-vector contacts (Gordon et al., 2018). Table 1 provides a summary of the crops and pathosystems where push-pull has been tested in different parts of the world.

Push-pull has been cited as a climate-smart and agroecological approach to achieve high yields, and profitability while also providing other ecosystem services (D'Annolfo et al., 2020; Gugissa et al., 2022; Kopper and Ruelle, 2022). In Africa, push-pull was developed as an integrated pest management strategy in cereal cropping systems (Cook et al., 2007; Khan et al., 1997; Khan and Pickett, 2004). In principle, push-pull employs a stimulo-deterrent strategy that seeks to divert pests from a valued crop using repellents or deterrents to provide a 'push', while simultaneously relocating them to another less-valued resource such as a trap crop using attractants, arrestants, feeding or oviposition stimulants and other cues or behaviour-modifying stimuli to provide a 'pull' (Cook et al., 2007; Eigenbrode et al., 2016; Reddy, 2017; Zhang et al., 2013). According to Zhang et al. (2013), the behaviour-modifying stimuli could be either long- or short-term, visual or chemical cues. The chemical cues could be synthetic, plant-derived or insect-derived semiochemicals. Visual stimuli, repellent and trap plants, host and non-host volatiles, insect pheromones, and antifeedants and oviposition deterrents are usually applied as potential stimuli in the "push–pull" strategy for pest control (Zhang et al. 2013). The push-pull strategy can also pull natural enemies into the valued crop (Khan et al., 1997; Sampson et al., 2020), potentially enhancing biological control. The following are the main mechanisms identified for pulling natural enemies: (a) concentrating pests in the trap crop; (b) providing resources for natural enemies, such as floral or extrafloral nectar; or (c) directly affecting natural enemy behaviour e.g., through attractive volatiles (Cook et al., 2007; Eigenbrode et al., 2016; Khan et al. 1997). Since push-pull utilizes plant diversification and non-toxic phytochemicals, often produced directly by companion plants, to manipulate the behaviour of pests, it is considered to be environmentally friendly (Yi et al., 2019), and an appropriate strategy to increase productivity in complex landscapes (Poveda et al., 2019).

The animal-behaviour basis of push-pull and its applications has been widely reviewed and established (Cook et al., 2007; Eigenbrode et al., 2016). Although push-pull has been shown to be successful in reducing stemborer damage as well as witchweed (Striga spp.) infestations in cereals in East Africa (Khan et al., 2001; 2002; Midega et al., 2010; Pickett et al., 2014) and suppressing pests of forestry elsewhere (Lindgren & Borden 1993; Shea & Neustein 1995; Bennison et al., 2001; Borden et al, 2006), its potential is yet to be fully realized in sub-Saharan Africa (Eigenbrode et al., 2016; Letourneau et al., 2011). Several reviews have highlighted challenges of replicating successes from cereal and sugarcane in other systems (Eigenbrode et al., 2016; Finch & Collier 2012). Even within the cereal and sugarcane cropping systems in Africa, where it has been researched for several decades, the adoption of push-pull by farmers is not yet commensurate with its promises and potential (Cockburn et al., 2014). For example, the use of push-pull in East Africa has been limited to maize and sorghum cropping, mostly at the scale of individual fields. Establishing push-pull in new systems, as well as modifying existing systems, requires sufficient understanding of the associated chemical ecology, as interactions between pests and crop plants are based on semiochemicals released by the plants (Kergunteuil et al., 2015). The adoption of push-pull has also been shown to depend on the magnitude of pest pressure and the risk perception of farmers (Cockburn et al., 2014; Poveda et al., 2019).

Eigenbrode et al. (2016) conducted a global review of published work on push-pull and found that literature tends to focus on longer-range stimulo-deterrent strategies, rather than the full range of cues and modalities involved. They argue that this has yielded an imperfect understanding of cues involved in most systems. These observations suggest that opportunities exist to improve and broaden push-pull. Therefore, the objectives of this review are to (1) provide a synthesis of the evidence for the benefits of push-pull, thus aiding the formulation of evidence-based practices and policies, and (2) explore options and opportunities for expansion of push-pull in the context of other cropping and farming systems in sub-Saharan Africa. We review published work from Africa and elsewhere in the world as a basis for further exploration, testing, and co-development of push-pull innovations with different stakeholders.

2 Scope of the review, search strategy, and selection of studies

2.1 Population and eligibility criteria

The scope of this systematic literature review was limited to push-pull technology, with a focus on studies involving experiments across Africa. Wherever available, similar studies conducted outside Africa were included to provide background and perspective. This review considered all types of relevant studies published in peer-reviewed journals, book chapters, and reports on the subject matter.

Studies were classified according to their implementation (field vs laboratory) and experimental design (e.g., observational, quasi-experimental and randomised controlled trials). All studies were included or excluded using pre-defined eligibility criteria and further checked for duplication. To be eligible for inclusion in the review, a publication must: (1) focus on push-pull in crop production systems, (2) rely on field-based experimental studies, (3) be published in a peer-reviewed scientific journal or book chapter, (4) report crop yields, pest infestation, crop damage or changes in soil quality in any part of the world. Publications that focus on push-pull in medical and veterinary applications were excluded.

In addition to reviewing publications available on the push-pull network (http://www.push-pull.net/adoption.shtml), we conducted a comprehensive literature search to maximize the number of identified studies, including those in previous reviews. We conducted the literature search for studies matching the eligibility criteria in various databases, including CAB index, Google Scholar, and Scopus. Finally, references of identified relevant studies were scanned to identify additional publications matching the study eligibility criteria. Free-text was used for the search, considering different keywords and their combinations. The key words used were push*pull*stimulo-deterrent, push*pull*crop*yield, push*pull*insect*damage, push*pull*infestation, push*pull*striga, push*pull*disease, push*pull*stemborer, push*pull*adoption, push*pull*soil*health. All eligible studies published until February 2022 were retrieved without language restrictions, and if the study was published in a non-English language, the abstract was translated into English.

Table 1. Types of crops and pathosystems where various forms of push-pull have been tested

Crop type	Pathosystem	Country	Reference
Cereals	Maize-*Chilo partellus*	Kenya	Khan and Pickett (2004)
		Malawi	Nyassi et al. (2022)
	Maize-*Busseola fusca*	Kenya	Khan and Pickett (2004)
	Maize-*Striga*	Kenya	Khan and Pickett (2004)
		Malawi	Nyassi et al. (2022)
	Millet-*Striga*	Kenya	Midega et al. (2010)
	Rice-*Chilo auricilius*	China	Yi et al. (2019)
	Maize-*Spodoptera frugiperda*	Kenya	Midega et al. (2018)
		Tanzania	*ibid*
		Uganda	*ibid*
		Mexico	Guera et al. (2021)
Fibre crops	Cotton-*Heliothis*	Australia	Pyke et al. (1987)
	Cotton-*Helicoverpa*	India	Duraimurugan and Regupathy (2005)
	Cotton-*Helicoverpa*	India	Jadhav et al. (2008)
Sugar crops	Sugarcane-*Eldana saccharina*	South Africa	Kasl (2004)
Vegetables	*Brassica-Delia radicum*.	Netherlands	Kergunteuil et al. (2015)
	Onion- *Delia antiqua*	USA	Miller and Cowles (1990)
Tuber crops	Potato- *Tecia solanivora*	Colombia	Poveda et al. (2019)
Fruits	Strawberry-*Frankliniella*	United Kingdom	Sampson et al. (2020)
	Blueberry-*Dasyneura oxycoccana*	United Kingdom	Sampson et al. (2020)
	Citrus-psyllid	China	Yan et al. (2015)
	Tomato- *Bactrocera tryoni*	Australia	Meats et al. (2012)

2.2 Screening of studies and data extraction

Wherever available, full-text articles of the selected papers were retrieved, the contents perused (text review), and the relevant outcome variables were extracted. If a given study reported several outcomes of interest, each outcome was taken as a separate record. The main findings and conclusions for each study were also extracted as free text. Accordingly, a total of 156 publications were identified (Supplementary Table S1), of which 96 publications were excluded through the selection process (Figure 1). The publications excluded from the review only focussed on laboratory studies, or on describing the mechanisms for push-pull effects on pests or natural enemies. A total of 63 publications were selected for review and analysis. Only seven publications had quantitative data suitable for analysis of variables chosen. These are Guera et al. (2021), Hailu et al. (2018), Khan et al. (2008), Midega et al. (2015), Midega et al. (2018), Ndayisaba et al. (2020) and Nyassi et al. (2022).

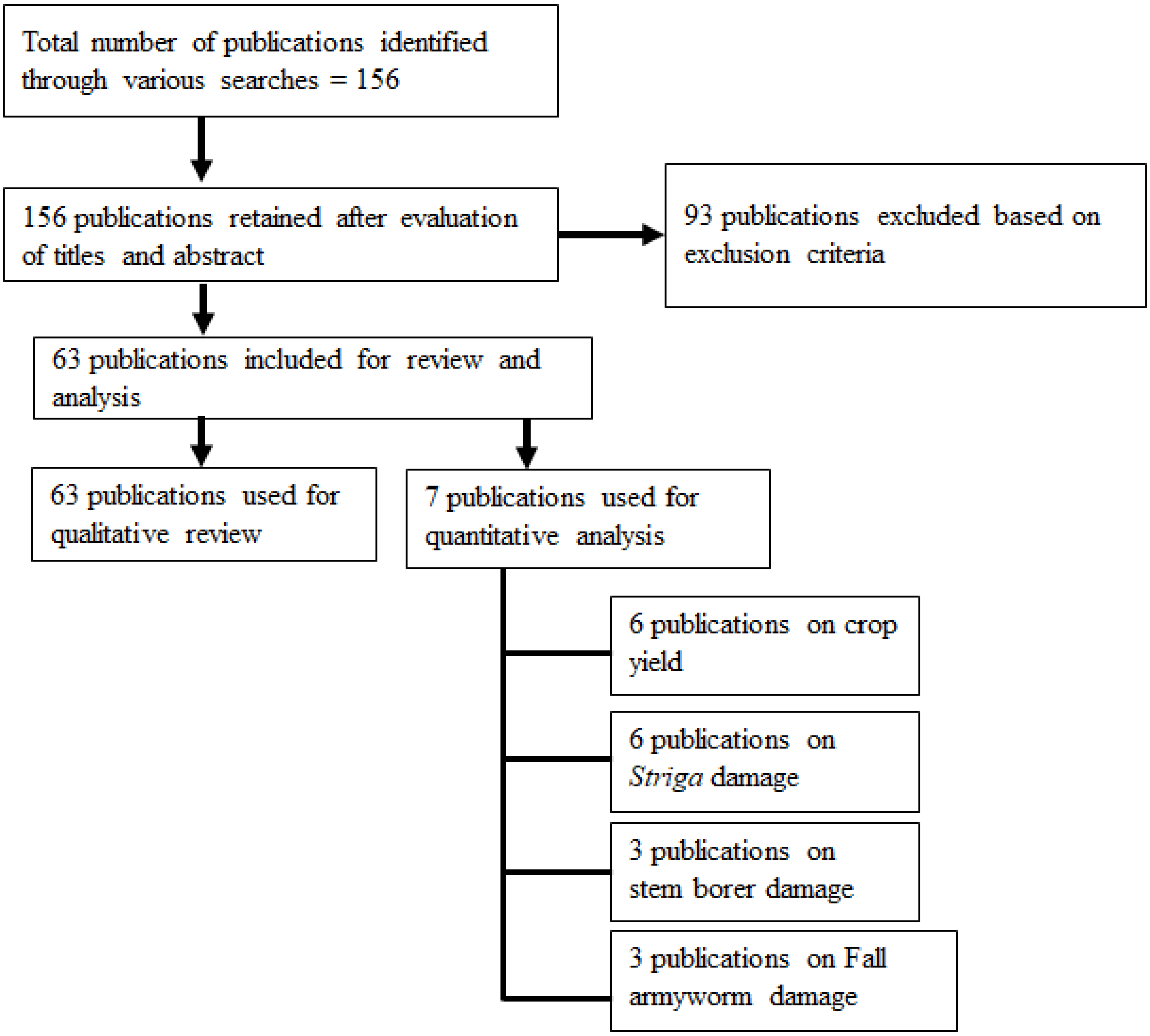

Figure 1. Total number of publications identified through literature search, and those used for qualitative review and quantitative analyses.

2.3 Selection of outcome measures and performance metrics

Initially, we consider any measurable independent change in the outcome variables that were reported in the selected publications. Since some variables were less frequently reported across studies, we focussed on a few that were reported by at least three independent studies. Accordingly, crop yields, insect pest density, infestation, damage, weed infestation, plant diseases, mycotoxins, and soil fertility measures were selected (Figure 1). To provide a quantitative summary of the various studies, we selected a single metric that provides both the magnitude and direction of change due to the application of push-pull. Accordingly, we chose the percent change, calculated in equation 1 below, as a more appropriate metric than others, such as the response ratio. Percent reduction in incidence (infestation), severity of damage, yield etc. were calculated as:

$$Percent\ change = 100 * \left(\frac{Control - PPT}{Control}\right) \qquad (Equation\ 1)$$

The percent change may be conceived as a measure of the effectiveness of push-pull, showing both the magnitude and direction of change. Negative values represent reduction in the measured variable in push-pull relative to control, while positive values represent increase in the magnitude of effect. As such, a negative value of pest incidence or damage is indicative of a positive effect of push-pull. In terms of crop yields, a negative value is indicative of a reduction in yield with push-pull in comparison to control. We expect that as pest pressure increases, the effectiveness of push-pull will increase. Given the small number of publications (maximum 6 on each outcome as shown in Figure 1), we did not conduct any formal statistical analysis. We only present the median, mean, minimum and maximum values (Table 2).

2.4 Exploring opportunities for expansion

To explore options and opportunities for expansion of push-pull, we reviewed literature on the cropping and farming systems where it has been studied. We then identified suitability maps for the key pests and the main crop they affect (maize and sugarcane) in those cropping and farming systems.

3 Synthesis and discussion

Several reviews and syntheses are available on the various forms of push-pull and underlying mechanisms. Eigenbrode et al. (2016) provide a mechanistic framework and the range of possible combinations of animal behavioural effects contributing to push-pull in different systems. Here, we focus on describing the evolution and generations of push-pull developed over the years in Africa.

3.1 Definition and typology of push-pull

For the purpose of this review, we take a broad scope of push-pull, encompassing all stimulo-deterrent strategies in which specifically chosen companion plants grown between and around the main crop release semiochemicals that fend off insect pests from the main crop. As such, the system consists of an intercrop, which is the “push” component, and a trap crop attracting insect pests away from the main crop, which is the “pull” component (Cook et al., 2007; Miller and Cowles, 1990). Over the last two decades, various push-pull configurations were rigorously tested, and three generations suited to the maize-mixed farming system in East Africa have been developed.

The original push-pull promoted in sub-Saharan Africa (SSA) was developed in the late 1990’s by scientists at the International Centre of Insect Physiology and Ecology (icipe) based in Kenya, in close collaboration with Rothamsted Research (UK) and national partners in Kenya. This technology, referred to as first-generation push-pull, uses silverleaf desmodium (*Desmodium uncinatum*) as the push component and Napier grass (*Pennisetum purpureum*) as the pull component. These species were selected and combined for the management of stemborers in maize crops in the late 1990s (Cook et al., 2006; Khan et al., 2000).

Efforts to adapt push-pull to climate change conditions led to the identification of drought-tolerant greenleaf desmodium (*Desmodium intortum*) and *Brachiaria brizantha* cv *Mulato* II (hereafter Mulato-II) as the push and pull companion crops, respectively. This was identified as the second generation or “climate-smart” push-pull (Khan et al., 2018; Midega et al., 2015b). In addition to tolerance to drought, Mulato II was found to be preferred as livestock fodder (Chidawanyika et al., 2014). *D. intortum*, on the other hand, has similar effects on witchweed as *D. uncinatum*, and is considered by farmers as excellent fodder (Midega et al., 2010; Murage et al., 2015). Second-generation push-pull was also demonstrated to be highly effective in reducing fall armyworm damage (Khan et al., 2018; Midega et al., 2018). Not long after the introduction of second-generation push-pull, an invasive spider mite (*Oligonychus trichardti*) emerged as a new threat to Mulato II, especially in hot and dry weather (Cheruiyot et al., 2018a). Another problem arising was that *D. intortum* does not flower and produce seeds near the equator (Cheruiyot et al., 2022). To address these challenges, better adapted alternative Brachiaria and Desmodium varieties have been identified (Cheruiyot et al., 2018a, b; 2020; Midega et al., 2018). *D. incanum* was selected for its tolerance to longer drought stress conditions

(Midega et al., 2015; 2017) and its ability to produce seeds in regions where *D. intortum* is unable to flower (Cheruiyot et al., 2022).

A third-generation push-pull was developed by combining *D. incanum* as the push and *B. brizantha* cv *Xaraes* as the pull component for stemborer control. Cheruiyot et al. (2022) compared field performance and farmer opinions of third-generation push-pull with second-generation push- pull in terms of controlling stemborers, fall armyworm, and witchweeds in western Kenya in 2019. Both second- and third-generation push-pull technologies were reported to have significantly lower witchweed incidence, fall armyworm, and stemborer damage, and higher grain yield than in farmers' existing practice. Although the third-generation push-pull suffered higher stemborer damage, farmers preferred it over the second-generation technology (Cheruiyot et al., 2022).

3.2 Evidence for benefits

3.2.1 Increased crop yields

Changes in maize yields due to first-generation push-pull have been rigorously evaluated in western Kenya, and the results show significantly higher grain yields than in the monoculture plots in almost all sites (Khan et al., 2008; Midega et al., 2015). Similarly, second-generation push-pull has given significantly higher maize yields across test sites in Kenya, Tanzania, Uganda (Midega et al., 2015; 2018; Ndayisaba et al., 2020) and Mexico (Guera et al., 2021). A summary of the various studies shows that yields increase by 53-133% relative to the monoculture maize (Table 2). On the other hand, in Malawi, average yields in push-pull were lower than in monoculture plots. Push-pull combined with conservation tillage produced a greater yield reduction (-10.2%) than conventional tillage (-3.7%), relative to monoculture plots (Table 2).

Table 2. Percent change in maize grain yield, witchweed infestation, stem borer infestation, and fall armyworm damage under first- and second-generation (climate-smart) push-pull relative to control. Positive effects of push-pull are indicated by positive values for crop yield, or negative values for pest incidence and damage.

Variable	Push-pull generation	Country (N)†	Median	Mean	Min	Max
Witchweed infestation	First	Kenya (77)	-87.0	-84.6	-100.0	-50.0
		Uganda (2)	62.0	-62.0	-59.6	-64.4
	Second	Kenya (66)	-95.5	-92.1	-100.0	-40.0
		Uganda (10)	-97.8	-92.4	-99.8	-63.3
		Malawi-CA (2)	-20.9	-21.0	-23.1	-18.8
		Malawi-conv (2)	-10.5	-10.5	-30.0	9.1
		Overall (159)	**-91.8**	**-86.2**	**-100.0**	**9.1**
Stem borer infestation	First	Kenya (81)	-66.5	-66.3	-100	-2.4
		Uganda (2)	-55.1	-55.1	-80.4	-29.8
	Second	Kenya (60)	-84.5	-83.2	-100	-56.4
		Uganda (10)	-82.5	-77.9	-93.9	-33.1
		Overall (153)	**-76.9**	**-73.5**	**-100.0**	**-2.4**
Fall armyworm damage	Second	Kenya (12)	-94.7	-94.1	-99.7	-80.3
		Mexico (18)	-51.1	-52.2	-69.6	-41.0
		Tanzania (2)	-93.3	-93.3	-94.7	-92.0
		Uganda (12)	-71.7	-68.4	-79.5	-51.9
		Overall (44)	**-69.7**	**-69.9**	**-99.7**	**-40.9**
Maize yield	First	Kenya (81)	87.5	92.9	18.9	275.0
	Second	Kenya (72)	131.4	133.0	-7.5	363.6

		Mexico (9)	49.0	57.0	8.0	121.0
		Tanzania (1)	-	-	109.5	109.5
		Uganda (12)	101.7	125.6	63.3	257.1
		Malawi-CA (9)	-5.9	-10.2	-47.0	18.2
		Malawi-conv (9)	-18.4	-3.7	-54.5	62.2
		Overall (193)	**100.0**	**99.0**	**-54.5**	**363.6**

†N represents the total number of observations; CA = conservation agriculture; Conv = conventional tillage.

3.2.2 Suppression of witchweeds

Witchweed (Striga spp.) is a root parasite that inhibits host growth and productivity of cereals. It is an important weed distributed in Africa, where S. hermonthica and S. asiatica parasitize maize, sorghum and pearl millet. Although not a problem in irrigated rice, Striga species inflict serious losses in upland rice in sub-Saharan Africa (Kaewchumnong and Price, 2008). Witchweed infests 40% of Africa's arable land, and causes an estimated loss of USD 7-11 billion to the agricultural economy. There are two species of witchweed, namely Striga asiatica and Striga hermonthica, but the latter is the most important in East Africa. In Africa, the witchweed problem is intimately associated with agricultural intensification and land degradation (Sileshi et al., 2006).

Intensification is reflected in greater use of cereal monoculture with little or no fallow period for non-host plants. The level of witchweed infestation depends largely on the fertility status of the soil (Gacheru and Rao, 1998; Sileshi et al., 2006). The effect of different generations of push-pull has been studied in Kenya (Khan et al., 2008; Midega et al., 2015), Uganda (Hailu et al., 2018) and Malawi (Ndayisaba et al., 2020). Our summary of these studies shows that push-pull provides significant suppression of witchweed in maize (Table 2). First-generation push-pull reduced witchweed infestation of maize by 62-85% in Kenya and Uganda, relative to monoculture maize.

Corresponding reductions by second-generation push-pull were 92% in Kenya and Uganda, but 10-21% in Malawi (Table 2).

The mechanisms by which push-pull suppresses witchweed have been shown to involve increased availability of nitrogen, soil shading, and allelopathic root exudation of novel flavonoid compounds (Khan et al., 2002; 2008; Hooper et al., 2015). As Desmodium is a perennial crop, it is able to control witchweed even when the host crop is out of season (Hooper et al., 2015; Khan et al., 2008). According to analyses by D'Annolfo et al. (2020) in Western Kenya, farmers perceive the reduction of witchweed as one of the main benefits of adopting push-pull.

3.2.3 Suppression of stem borers and fall armyworm

A number of stemborer species, including six species in the genus *Chilo* (*aleniellus, diffusilineus, orichalcociliellus, partellus, sacchariphagus* and *zacconius*), *Busseola fusca*, four species in the genus *Sesamia* (*calamistis, nonagrioides, botanephaga,* and *cretica*), *Eldana saccharina* and *Maliarpha separatella*, affect maize, sorghum, millet, rice and sugarcane across Africa (Kfir et al., 2002). *Busseola fusca*, known as the African maize stalk borer, has become an economically important pest in most of the maize-growing African countries (Kfir et al., 2002). The main crop hosts for *B. fusca* are maize, sorghum, millets (both pearl and finger millet) and sugarcane (Kfir et al., 2002). Among *Chilo* species, the spotted stemborer (*Chilo partellus*) and *C. sacchariphagus* are alien invasive species native to Asia (Kfir et al., 2002). *C. partellus* poses the greatest threat to maize and sorghum in East Africa. It was established in East Africa in the 1950s, and has since spread across 18 African countries (Sileshi et al., 2019; Yonow et al., 2017). A growing body of evidence suggests that *C. partellus* is competitively displacing the indigenous stem borers in East and southern Africa (Kfir, 2002).

Various studies have assessed the effect of different generations of push-pull on stem borer infestation and damage across sites in Kenya (Khan et al., 2008; Midega et al., 2015; Hailu et al., 2018) and Uganda (Hailu et al., 2018). Our summary of the results shows reduction of stem borer infestation of maize by 66-83% across sites in Kenya and Uganda (Table 2). There are not many studies on other cereals, except sorghum in Uganda. According to a recent study by Hailu et al. (2018), the severity of stemborer infestation was significantly higher on sorghum than on maize.

The fall armyworm (*Spodoptera frugiperda*) is an invasive alien pest native to the Americas, currently affecting over 43 countries in Africa (Cock et al., 2017; Sileshi et al., 2019). It causes 45%-67% loss of annual average production of maize in the affected countries (Day et al., 2017), equivalent to $ 6.2 billion annually. The effect of second-generation push-pull on fall armyworm infestation and damage was recently evaluated across sites in Kenya, Tanzania, Uganda (Hailu et al., 2018; Midega et al., 2015; Njeru et al. 2020) and Mexico (Guera et al., 2021). Most of the studied systems showed lower levels of fall armyworm infestation and severity of damage than on maize monoculture. In Uganda, the severity of fall armyworm damage was generally higher on maize than on sorghum (Hailu et al., 2021). These results support the effectiveness of push-pull for management of the fall armyworm.

Overall, the expansion of the geographic range of invasive alien species (e.g., spotted stem borer, fall armyworm) as well as emerging infectious plant diseases (e.g., maize lethal necrosis) of staples, such as maize and sorghum (see next section), provide a strong motivation for expanding push-pull into other farming systems and regions, where push-pull has remained unexplored.

3.2.4 Reduction of plant diseases and mycotoxins

Increased infestation of maize by insect pests, such as stemborers, has been reported to increase infection by mycotoxin-producing fungi (Opoku et al., 2019). In a study conducted in western Kenya (Njeru et al., 2020), a significant reduction was recorded in the incidence of *Fusarium verticillioides* (60%) and *Aspergillus flavus* (86%) in push-pull, which was reflected in reduced incidence of ear rots (50%). Fumonisin in maize from push-pull farms was also reduced by 39% (Njeru et al., 2020), which could further improve food security among smallholder maize farmers (Njeru et al., 2020).

3.2.5 Improvement of soil health

Soil health reflects the capacity of soil systems to respond beneficially to management, maintaining agricultural production as well as the provisioning of ecosystem services, nutrient cycling, and biodiversity conservation in the long term (Kibblewhite et al., 2008). The limited number of studies on soil variables measured so far indicate improvement in push-pull relative to maize monoculture. A study by Ndayisaba et al. (2021) recorded higher soil available nitrogen and phosphorus in push-pull compared to maize monoculture plots across three seasons. Drinkwater et al. (2021) showed that soil organic nitrogen was 20% greater and labile organic nitrogen reserves were five-fold greater in push-pull compared to non-push-pull soils. Extractable soil phosphorus was also two-fold greater in push-pull compared to non-push-pull soils (Drinkwater et al., 2021).

Although fewer studies have been conducted on soil biological health variables, those available provide evidence for improvement in push-pull over maize monoculture. A study by Midega et al. (2008) showed higher ground-dwelling arthropod abundance and diversity in push-pull. According to a recent study by Mwakilili et al. (2021), push-pull supported more diversified fungal microbiomes than monoculture plots in Western Kenya. Few differences were noted between push-pull and monoculture in soil bacterial communities (Mwakilili et al., 2021). Soil microorganisms play a significant role in soil health and productivity through direct and indirect mechanisms mediated through root systems.

Taken together, these results indicate that push-pull has the potential to improve soil health. However, most of these studies were conducted in a limited number of sites in the maize-mixed farming system in Kenya, and comparable data are lacking in other parts of Africa. With the increasing interest in expanding push-pull, it is important to monitor various aspects to demonstrate the soil health benefits of the technology, and inform good policy and practice.

3.2.6 Climate change adaptation and mitigation

Emerging evidence suggests that push-pull can provide opportunities for adaptation to climate change, while also providing mitigation benefits. A study by Gugissa et al. (2022) in Ethiopia indicated that push-pull farming systems are more climate-resilient than their non-push-pull counterparts. Push-pull maize farming had a significant impact on 8 out of the 13 agroecosystem indicators of climate resilience (Gugissa et al., 2022). The contribution of push-pull to adaptation to climate change is based on inference about the role of the technology on crop productivity. In terms of mitigation benefits, preliminary data show that soil carbon is higher in push-pull than in monoculture plots (Ndayisaba et al., 2022). In western Kenya, push-pull increased aboveground biomass in the maize-based production system (Ndayisaba et al., 2020). This suggests that push-pull has the potential to add more organic residues into soils, which can increase carbon accumulation.

Build-up of soil carbon helps farming systems adapt to climate change, by increasing resilience of soils to drought and flood. With the expansion of push-pull into other crops and farming systems, collecting data on adaptation and mitigation benefits will be an important contribution to providing evidence that can inform policy and good practice.

3.2.7 Financial returns and viability

Several authors have analysed the profitability of push-pull, providing evidence that the benefits of the technology outweigh the costs compared to non-push-pull plots. For example, Khan et al. (2001) compared the benefit-cost ratio of push-pull with maize monoculture and/or use of pesticides, and established a positive return on investment of 2.2 for push-pull, compared to 0.8 for monoculture and 1.8 for pesticide use. In a more detailed economic analysis using data over seven cropping years, returns on investment for basic factors of production under push-pull were evaluated and compared with other cropping methods (Khan et al., 2001). This study showed that the establishment of push-pull requires extra labour and capital costs for initial establishment.

However, in subsequent years, the cost is significantly reduced. Despite land being perceived as lost to trap cropping, the resultant benefits of push-pull through maize yield increase and extra income from sale or utilization of Napier grass and Desmodium were more than sufficient to cover all initial capital costs and still make a substantial profit margin (Khan et al., 2014). Khan et al. (2008b) reported positive total annual revenues, ranging from $351 ha-1 in low potential areas to $957 ha-1 in high potential areas, which generally increased in subsequent years. Returns on labour within the first year of establishment ranged from $0.5 per man-day in low potential areas to $5.2 per man-day in higher potential areas under push-pull, whereas in maize monoculture, this was negligible or even negative (Khan et al., 2008b; Kassie et al., 2018). Furthermore, net present values (NPV) from push-pull were positive and consistent over the years. Using discounted partial budget and marginal analysis, De Groote et al. (2010) concluded that push-pull earned the highest revenue compared with other soil fertility management technologies in Western Kenya. According to a more recent study by Murage et al. (2016) in Western Kenya, Tanzania and Ethiopia, the marginal rate of return (MRR) was 109.2% for sorghum and 143.4 % for maize, suggesting an expected positive impact on the community, should they adopt the technology. However, profitability does not stem from higher maize yields, but from the value of fodder crops in Western Kenya (De Groote et al., 2010).

Two scenarios below underscore the economic value to farmers of push-pull in Africa and elsewhere. Chepchirchir et al. (2018) analysed the financial viability of push-pull in four districts of eastern Uganda, and showed that the economy of these districts would derive an overall net gain of 3.8 million USD. At a discount rate of 12% for a period of 20 years (2015–2035), the net present value was estimated at 1.6 million USD, the internal rate of return at 51%, and the benefit to cost ratio at 1.54. Guera et al. (2021) analysed the financial returns of push-pull in Mexico, and found that the establishment costs were higher than those of monoculture maize. However, these costs were offset by the aggregate value of the companion crops. The net present value (NPV) of all systems was positive, indicating that systems are economically viable. These systems, in addition to recovering the investment, generated a minimum profit of 70 cents per dollar invested (Guera et al., 2021).

Taken together, these findings demonstrate that push-pull is economically viable and profitable. However, sustained adoption of the technology has not been commensurate with its economic potential (see 3.3 below). The slow adoption has been previously attributed partly to lack of availability of desmodium seeds, and consequently a high opportunity cost of procuring the seeds. Although desmodium seed is now much more readily available, farmers seem to consider it expensive despite the profitability of the investment as demonstrated by the reviewed studies. It should be noted that the PPT strategy shows the strongest economic benefits over the long term, due to the high opportunity costs of establishment, which may be at odds with farmers' need for short-term returns on investments. We thus highlight a need for more exhaustive cost-benefit analyses that consider the temporal scale of investment represented by adoption of the PPT. In addition, profitability alone may not determine technology adoption. Another possible explanation is farmers' knowledge, attitudes and subjective norms that have been known to affect adoption of similar agricultural technologies (e.g., Meijer et al., 2015a,b). The effect of these factors in the adoption of push-pull has not been studied. Therefore, we recommend future studies to examine the importance of socio-psychological factors including social influence, knowledge, attitudes and subjective norms for PPT adoption.

3.3 Adoption by farmers

Technology adoption is a complex concept, and its definition may vary from one technology to another. For instance, Mwangi and Kariuki (2015) define technology adoption in agriculture as a mental process that farmers go through from hearing about a technology to the point of using it. Beyond the initial use, technology adoption is achieved through a period of trying and achieving some degree of adaptation (Loevinsohn et al., 2012; Fadeyi et al., 2022). Here, adoption of push-pull is said to have taken place if a farmer has tried or tested it for at least two seasons. Accordingly, push-pull had been adopted by over 68,800 smallholder farmers in Kenya, Uganda, Tanzania and Ethiopia by 2014 (Khan et al., 2014). Of these, 52,746 adopters were in western Kenya, about 5000 in central Kenya and another 10,600 in Uganda and Tanzania, along with 343 in Ethiopia (Khan et al., 2014). According to Khan et al. (2014), adoption of push-pull has continuously risen with an estimated rate of 30% annually by 2014. An adoption rate of 50% was anticipated for later years, because of extensive on-going efforts in technology transfer in the cereal-livestock farming systems of sub-Saharan Africa (SSA) (Khan et al., 2014). By 2021, push-pull has been adopted by over 258,574 farmers across East Africa, of which 87683, 170027 and 864 have adopted first-, second- and third-generation push-pull, respectively (http://www.push-pull.net/adoption.shtml). In each case, adoption was more common for female (about 58%) than male farmers.

Using a sample of 898 respondents (360 in Kenya, 240 in Tanzania, 298 in Ethiopia), Murage et al. (2016) found high willingness to adopt second-generation push-pull among farmers: 87.8% overall; 92.1% in Tanzania, 88.6% in Ethiopia and 84.3% in Kenya. Gender, perceptions of Striga severity, technology awareness, and input market access were the most likely factors to positively influence the decision to adopt. Among the main drivers of adoption of push-pull, first and foremost was the need to control witchweed, followed by the need to increase yields of cereal crops, control stemborers, provide fodder, control soil erosion, and improve soil fertility. Khan et al. (2008) found that high pest pressure was a strong motivation for adoption of push-pull. According to De Groote et al. (2010), push-pull is likely to be profitable in areas with sufficient livestock and a demand for fodder.

A number of studies have evaluated adoption of push-pull, including gender dimensions of adopting (e.g., Murage et al., 2011; 2015a, b; Muriithi et al., 2018; Diiro et al., 2018; Kassie et al., 2020). In a study in Western Kenya, Muriithi et al. (2018) did not find any gender differences in adoption of push-pull and other practices, including maize-grain legume intercropping, crop rotation, fertilizer use and improved maize seeds. This suggests that the promotion and dissemination of push-pull can be supported equally for male and female farmers. Murage et al. (2015a, b) analysed gender perceptions in adoption of push-pull, but examined the gender of the household head, rather than the specific plot or farm manager within the household. Diiro et al. (2018) and Kassie et al (2020) assessed women empowerment among cereal growers, as well as changes in maize productivity and dietary diversity caused by adopting push-pull. Both studies reported positive impacts, suggesting the need for promoting empowerment along with technology dissemination. In a more recent study in Western Kenya by D'Annolfo et al. (2020), farmers cited seven reasons for adopting push-pull: Striga weed control (31% of farmers); increasing yields (19%); additional access to extension services (19%); reducing soil erosion (11%); increasing fodder production (8%); enhancing soil fertility (8%); control of stemborer (4%). Farmers also cited six benefits from adoption of push-pull farming: reduction in Striga weed (30% of farmers); increased yields (22%); enhanced soil fertility and increased animal feed (13%); reduced soil erosion (11%) and improved quality of products (11%).

While a number of studies exist that have examined the factors of push-pull adoption, to date no studies were identified that have examined the factors and dynamics of push-pull disadoption after >2 seasons of practicing the technology. Preliminary data of UPSCALE (unpublished data; Public Deliverable D7.1, Month 42) point to several factors driving this, which are key in order to understand the potential for long-term adoption, sustained practice and possible spontaneous diffusion of the PPT among smallholder farmers.

3.4 Scope and opportunities for expansion of push-pull

Although most studies on push-pull have been implemented in Kenya, a growing body of evidence suggests that there is scope for expansion. The scientific underpinnings of push-pull and the mechanisms by which companion crops help reduce target pests have been well-documented in reviews and syntheses (Cook et al., 2007; Khan et al., 2016; Pickett et al., 2014). Therefore, in this section we will focus on the scope and opportunities for expansion to crops and farming systems not covered before. Obviously, this task requires careful analysis and identification of priority pests and crops that merit investment, which is outside the scope of this work. We can, however, propose priority "categories" of pests and target crops based on recent reviews and analyses on the subject matter (Anderson et al., 2004; Paini et al. 2016; Savary et al., 2019; Sileshi et al., 2019; Sileshi and Gebeyehu, 2021; Turbelin et al. 2017). The primary factors considered in such prioritization are the status of the pest (i.e., endemic vs alien invasive) or disease (endemic vs emerging infectious plant diseases) and the value of the commodity affected. Generally, alien invasive species (AIS) and emerging infectious plant diseases (EIPDs) merit greater attention in Africa, because they can destabilize food systems and economies due to their larger impact (Anderson et al., 2004; Paini et al. 2016; Savary et al., 2019; Sileshi et al., 2019; Sileshi and Gebeyehu, 2021).

Alien invasive species are defined as species whose introduction and/or spread outside their natural past or present distribution threatens ecosystems, habitats or species (https://www.cbd.int/invasive/). Newly established alien invasive species may benefit from the absence of natural enemies in the invaded areas, sometimes resulting in damage that by far exceeds that of native pests. EIPDs are defined as new diseases with increased virulence, geographical spread and/or host range, resulting in epidemics or pandemics (Anderson et al., 2004). Unlike endemic diseases, EIPDs are caused by incursions of alien invasive pathogens and/or emergence of hypervirulent pathotypes, and are hence characterized by epidemics or pandemics that intensify over successive growing seasons (Sileshi and Gebeyehu, 2021). Analysis of recent global invasion patterns (Paini et al., 2016; Turbelin et al., 2017) suggests that Africa is exposed to significant alien invasive species and EIPD impacts. We presume agroecological farming practices such as push-pull are likely to be more buffered against alien invasive species and EIPD threats than monoculture systems. Therefore, investment in push-pull should focus on alien invasive species and EIPDs that affect crops of significant food security and/or livelihood value. In the following sections we will discuss such crops and associated pests, with example cases where push-pull has been successful.

3.4.1 Expansion with other crops

3.4.1.1 Cereals

The existing push-pull involves the combined use of intercropping and a trap crop to attract stem borers on a highly susceptible trap plant (pull) and drive them away from the maize crop by a repellent intercrop (push). Theoretically, this can be expanded to other crops, such as sorghum and millets, that are staple crops in most parts of Africa. Like maize, these crops are vulnerable to a number of endemic and alien invasive species (Sileshi et al., 2019) and emerging infectious plant diseases (Sileshi and Gebeyehu, 2021). For the last two decades, most of the studies on push-pull focussed on controlling stem borers (mainly *B. fusca, C. partellus*) and the witchweed in maize cropping systems in East Africa (Table 2). As indicated in Figures 2 and 3, stem borers are expected to expand their distribution, affecting greater areas of Africa. Until recently, *C. partellus* was restricted to low and mid altitudes in eastern and southern Africa, but its range has recently expanded into higher altitude areas (Mutamiswa et al. 2018; Yonow et al. 2017). Various models predict further expansion of its geographical range to higher altitudes with future climate changes in eastern, southern, central and much of western Africa (Figure 3; for details see Sileshi et al., 2019), thus threatening sorghum and millet production. Even in East Africa, prime maize and sorghum production areas may fall under greater threat.

Recently, fall armyworm, another invasive species, has spread to over 43 African countries, affecting maize cultivation (Sileshi et al., 2019). According to Timilsena et al. (2022), a large area in eastern and central Africa is projected to have an optimal climate for fall armyworm persistence. Areas that are currently optimal and suitable for its expansion in the future are given in Figure 3.

Push-pull was tested and shown to effectively control fall armyworm in Kenya, Tanzania and Uganda (Hailu et al., 2018; Midega et al. 2018), and more recently in Mexico (Guera et al., 2020; 2021). Therefore, opportunities exist for expanding push-pull for management of these pests in other areas that are suitable for maize and sorghum (Figures 4-7). Opportunities also exist for expansion of push-pull for the management of witchweeds in millet (Midega et al., 2010). Taking all the evidence into account, we recommend further testing and promoting push-pull in the prime maize and sorghum production areas (highlighted green in Figures 4-7) in the East African countries, where the technology has not been piloted before.

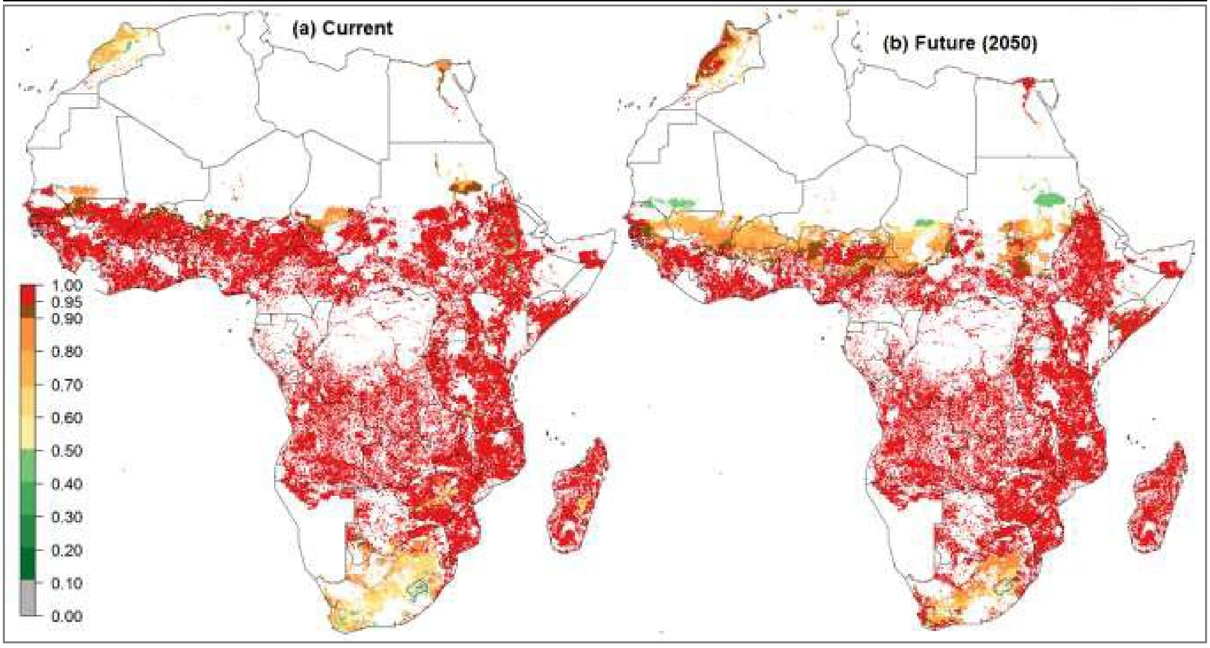

*Figure 2. Current and future potential distribution of the maize stalk borer (*Busseola fusca*) in maize production systems in Africa (Ong'amo et al., 2016).*

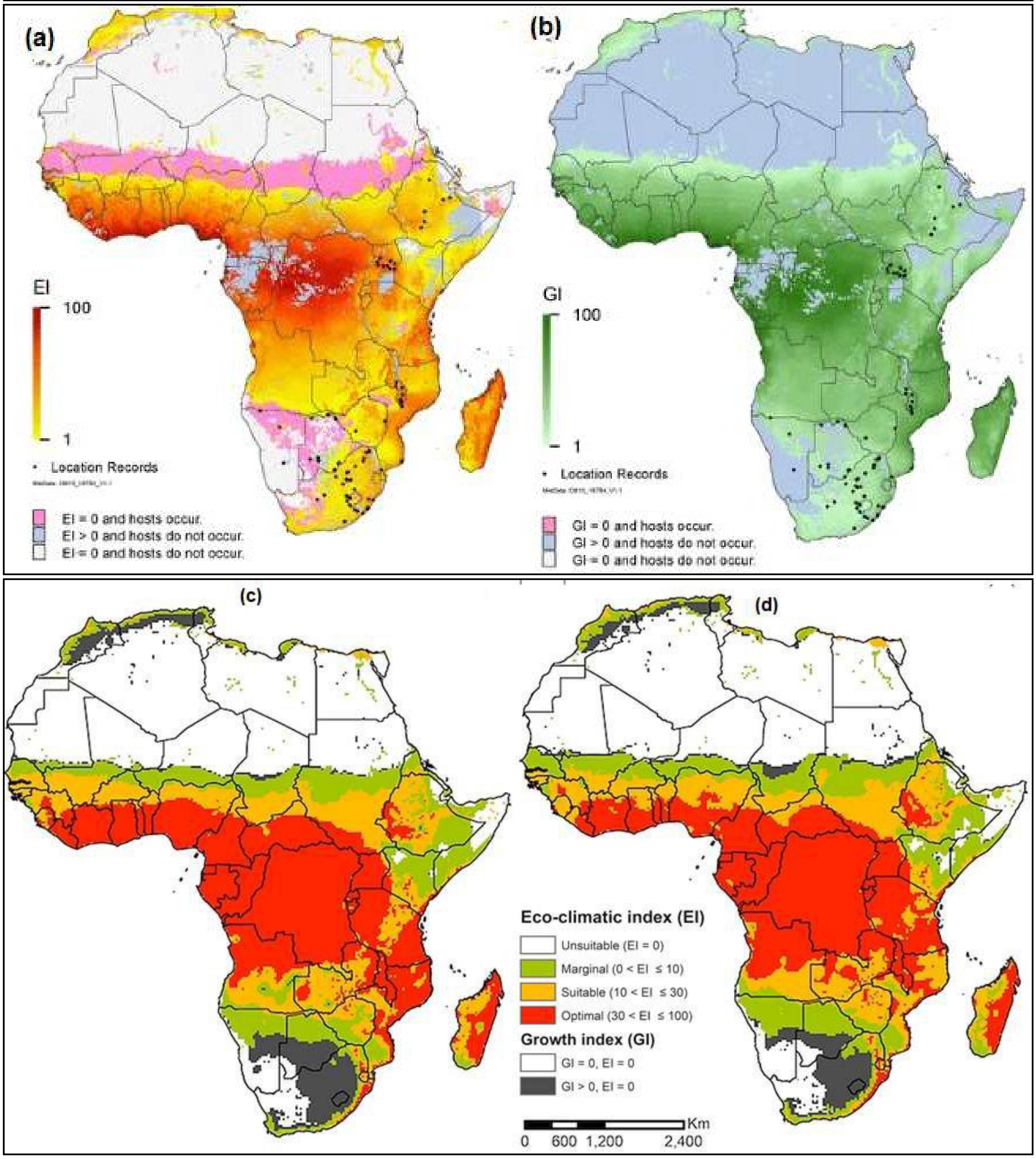

*Figure 3. Climate suitability of Africa for the spotted stem borer (*Chilo partellus*) to (a) persist and (b) show positive growth under natural rainfall and irrigation, masked by harvested areas of host plants (maize, sorghum, sugarcane, pearl millet and rice) from Yonow et al. (2017). (c) Current and (d) future (by 2030) distribution of fall armyworm (*Spodoptera frugiperda*) from Timilsena et al. (2022). Areas with eco-climatic index (EI) = 0 but growth index (GI) > 0 support fall armyworm seasonal population growth, while areas with EI = 0 and GI = 0 are unsuitable for fall armyworm.*

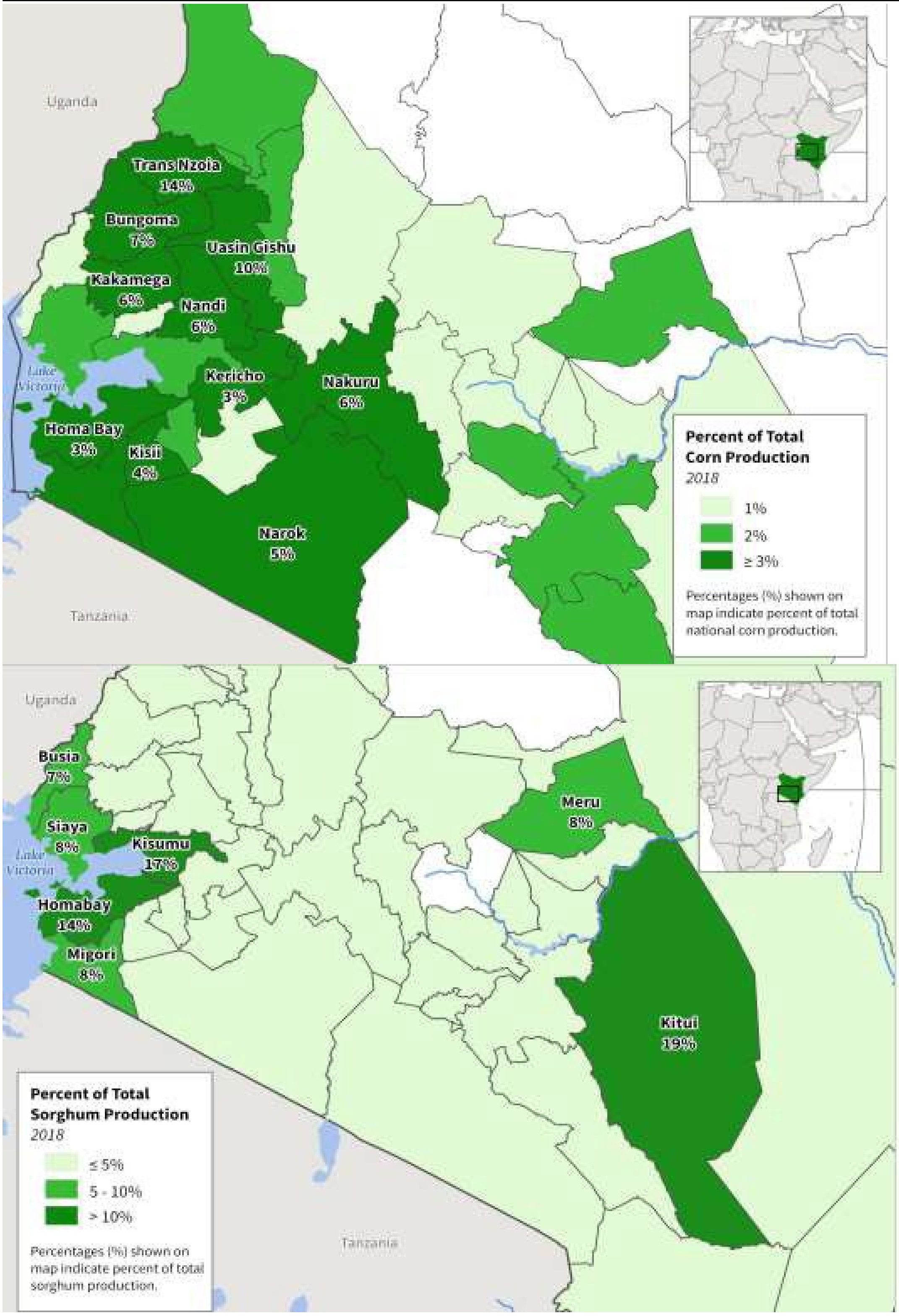

Figure 4. Maize (top) and sorghum (bottom) production areas in Kenya.

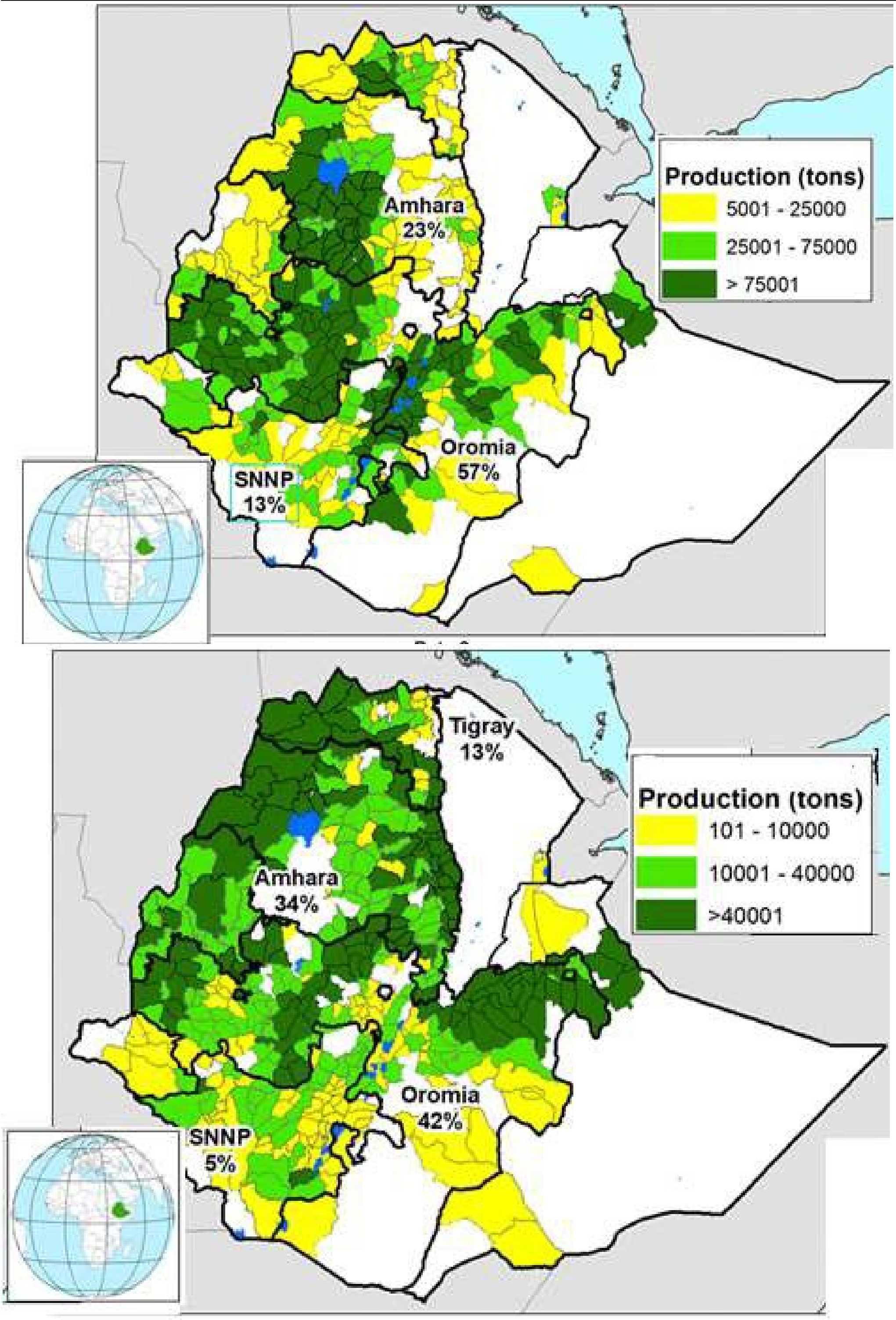

Figure 5. Maize (top) and sorghum (bottom) production areas in Ethiopia (2011-2016 average), based on data from the Central Statistical Agency (Source: USDA Foreign Agricultural Service).

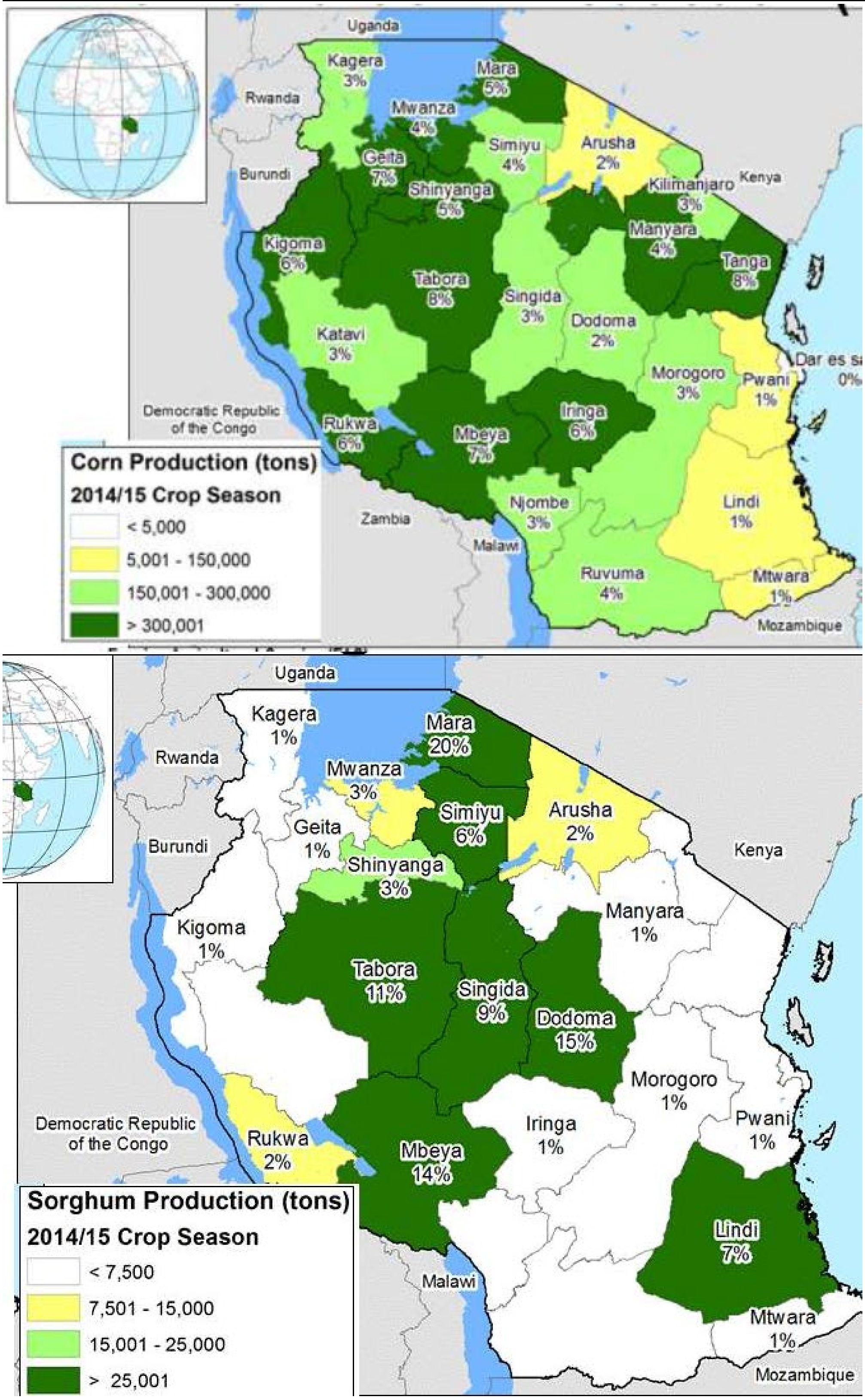

Figure 6. Maize (top) and sorghum (bottom) production areas in Tanzania (2014-2015 annual agricultural survey by the National Bureau of Statistics (Source: USDA Foreign Agricultural Service).

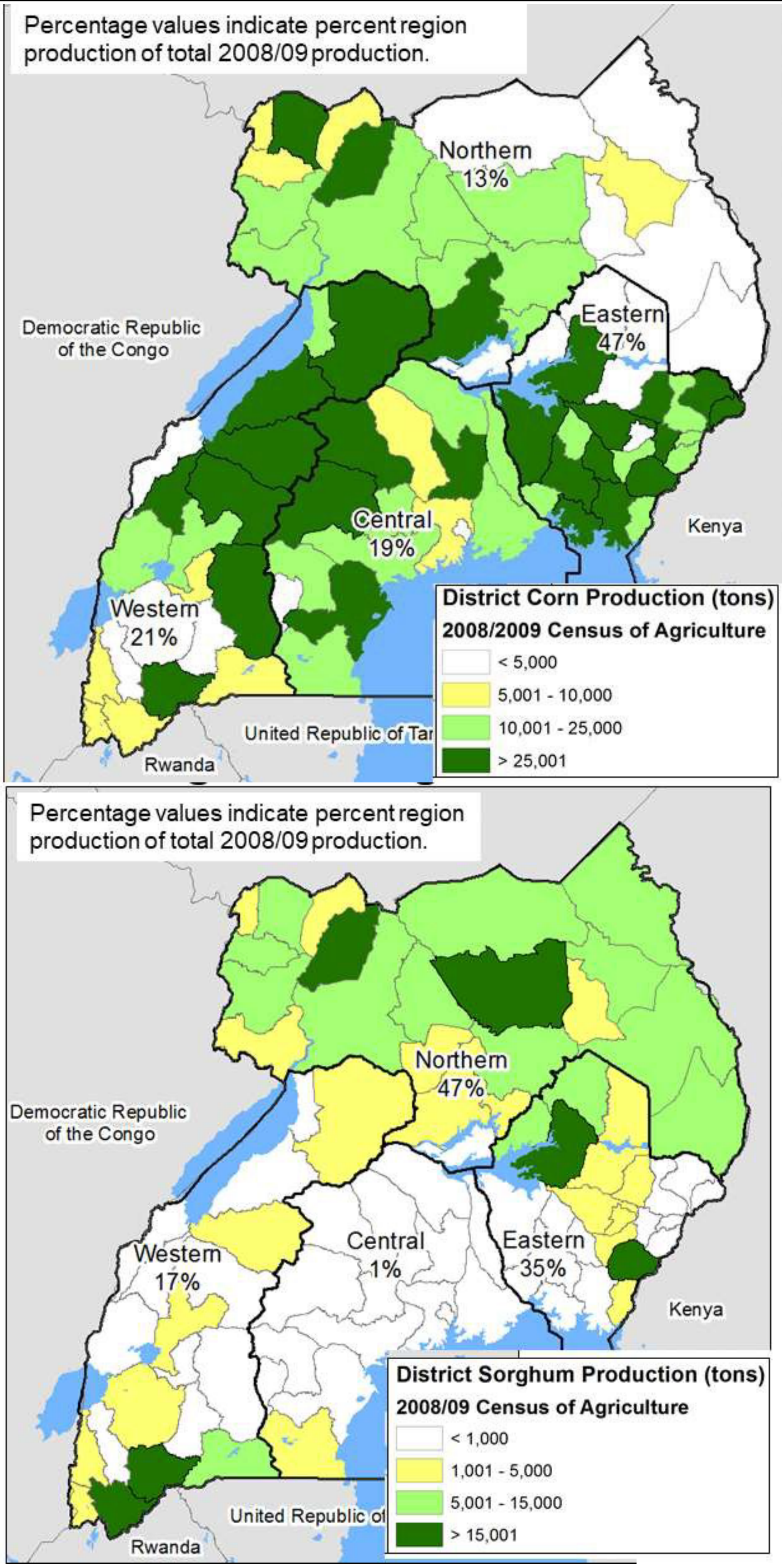

Figure 7. Maize (top) and sorghum (bottom) production areas in Uganda (2008-2009 Census of Agriculture, Uganda Bureau of Statistics (Source: USDA Foreign Agricultural Service).

3.4.1.2 Sugarcane

Sugarcane production and processing are important sources of employment and foreign exchange in sub-Saharan Africa (Hess et al., 2016). The continent is considered a critical region for expansion of production, due to high production potential, demand for biofuels, low cost and proximity to European markets (Hess et al., 2016). Sugarcane production ranges from large commercial estates to small plots managed by smallholders in out-grower schemes. Figure 8 shows the distribution of sugarcane production areas, with regions of concentration in west, east and southern Africa. The sugarcane stem borer (*Eldana saccharina* Walker) is the most damaging insect pest of sugarcane in many parts of Africa (Cockburn et al., 2014). This species is widely distributed in the continent and is also considered a pest of maize and rice (Kfir et al., 2002).

Various laboratory, cage and field trials have demonstrated that push-pull can lead to suppression of *E. saccharina* abundance and reduction in damage to sugarcane in South Africa (Kasl, 2004; Barker et al., 2006). The technology was also promoted as part of area-wide integrated management of the sugarcane stem borer in the South African sugar industry (Cockburn et al., 2014). Push-pull is currently being implemented on sugarcane farms in the Midlands North area of KwaZulu Natal (Webster et al., 2009). The 'push' component is molasses grass (Melinis minutiflora), which has a repellent effect on sugarcane stem borer (Kasl, 2004; Barker et al., 2006). Molasses grass is also attractive to *Xanthopimpla stemmator*, which is a natural enemy (parasitoid) of sugarcane stem borer (Kasl, 2004). The 'pull' components are Bt maize and indigenous wetland sedges. Bt maize is used as a 'dead-end trap crop', because of the toxic effect of the cry protein against the borer larvae (Keeping et al., 2007). Cockburn et al. (2014) surveyed 53 farmers representing 30% of the registered large-scale farmers across the Midlands North region, and found that perceived barriers to adoption of push-pull were attitudes towards the pest (33% of respondents), cost and time constraints (27%), insufficient knowledge (25%), management problems (8%) and cooperation between farmers (7%). According to Barker et al. (2006), push-pull becomes economically feasible only at high pest pressure levels. High adoption rates in the near future are not likely, due to the perception of sugarcane borer as low-risk by some commercial sugarcane farmers in the Midlands North region (Cockburn et al. 2014). Little is known about the compatibility of push-pull with other crop management practices, especially in large scale commercial operations. For example, burning of sugarcane prior to harvest and using machinery in field operations may destroy the perennial companion plants. This issue needs to be further investigated.

3.4.1.3 Pulses (seed legumes)

Among pulse crops, only common bean (*Phaseolus vulgaris*) has been incorporated into push-pull (Khan et al., 2009). Traditionally, farmers intercrop maize with beans, normally planted either between rows of maize or in between maize plants within a row. According to Khan et al. (2009), integration of beans in push-pull does not compromise the witchweed and stemborer control efficacy of Desmodium, although it significantly increases labour and total variable costs (Khan et al., 2009). These findings highlight opportunities for expanding the portfolio of crops to pulses, and investigating the potential of push-pull to reduce bean pests.

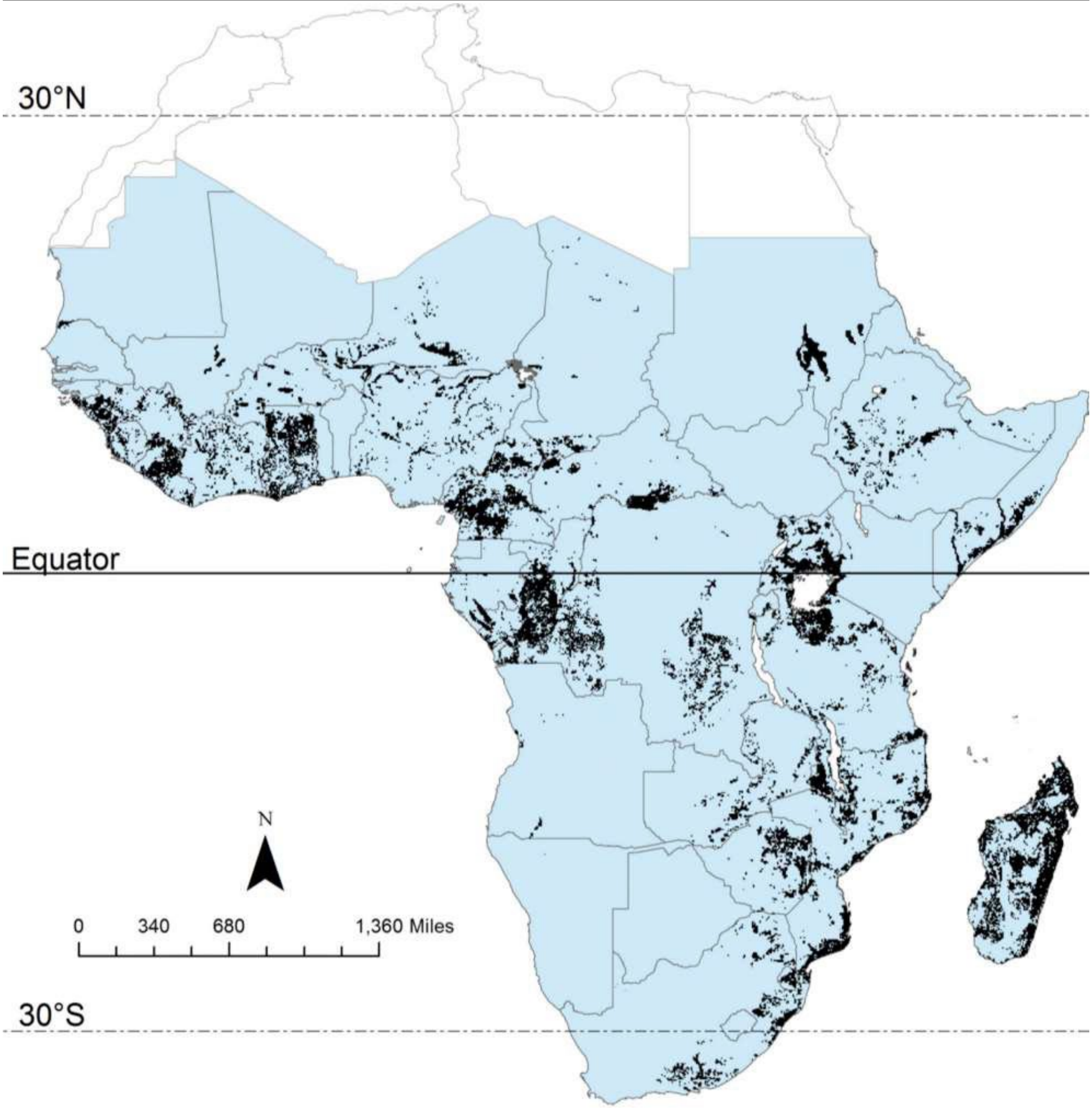

Figure 8. Distribution of sugarcane production areas in Africa based on modelled data (Hess et al., 2016).

3.4.1.4 Vegetables

Vegetables, such as brassicas (e.g., rape, mustard, cabbage), tomato and onions, are an important source of carbohydrates and essential nutrients. Vegetables also have high market value, and generate household income throughout the year. A recent review and analysis (Sileshi et al., 2019) identified the tomato leaf miner (*Tuta absoluta*), other leaf miners (*Liriomyza trifolii, Liriomyza huidobrensis, Liriomyza sativae*) and Western flower thrips (*Frankliniella occidentalis*) as the most important alien invasive species affecting vegetables and horticultural crops across Africa.

However, reviewed literature on push-pull in Africa did not provide any reports on vegetable pests. Experimental work on vegetable integration in push-pull is still in its infancy.

Experience from outside Africa may shed some light on the possibility of expanding push-pull to vegetables. A good example of such research is the evaluation of push-pull for management of cabbage root fly (*Delia radicum*) in brassicas (Kergunteuil et al. 2015). Cabbage root fly is a worldwide pest specialized on brassicaceous plants. Cabbage root fly infestations can cause a yield loss of up to

90 % in fields not treated with pesticides. Kergunteuil et al. (2015) conducted studies aimed at selecting both plants and olfactory stimuli that could be used in the development of a push-pull strategy against the cabbage root fly in the Netherlands. This study concluded that plants belonging to the same family (even species) may exhibit different levels of attractiveness toward *D. radicum* (Kergunteuil et al., 2015).

3.4.1.5 Root and tuber crops

Root and tuber crops, such as cassava and potato, play a critical role in food security and household income in Africa. However, production of these crops is constrained by a number of alien invasive species and EIPDs. For example, cassava production is constrained by cassava green spider mite (*Mononychellus progresivus*), cassava mealybug (*Phenacoccus manihoti*), spiralling whitefly (*Aleurodicus dispersus*) and the Southern armyworm (*Spodoptera eridania*) (Sileshi et al., 2019), plus two EIPDs, namely cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), with combined annual losses estimated at US$ 1 billion across Africa (Sileshi and Gebeyehu, 2021).

Although no information is available on the use of push-pull in root and tuber crops, experience from outside Africa may shed some light on the possibility of expansion. For example, Poveda et al. (2019) tested a variant of push-pull for protection of potatoes in the high Andes of Colombia. On each farm they established two potato plots (cv. Parda Pastusa). The push-pull treatment consisted of the Roja Nariño potato variety as a trap crop (pull), which was grown in the middle row of the plot, and a repellent spray of garlic pepper extract (push). The results suggest that diversification using push-pull can reduce pest damage through behaviour modification, resulting in increased crop productivity (Poveda et al., 2019).

3.4.1.6 Cotton

As mentioned in the Introduction, the push-pull strategy was first conceived in the context of *Heliothis* management in cotton (Pyke and colleagues, 1987). A few studies (e.g., Duraimurugan and Regupathy, 2005; Jadhav et al., 2008) have tested push-pull for management of *Helicoverpa armigera* in cotton. According to Duraimurugan and Regupathy (2005) a combination of push-pull (with okra as a trap crop), neem seed kernel extract and nuclear polyhedrosis virus resulted in a reduction in *H. armigera* incidence and damage to fruiting bodies and boll, compared to cotton sole crop in India. *H. armigera* has a widespread global distribution, and it attacks over 200 species in nearly 20 families of flowering plants. In Africa, it is a pest of cotton, pigeon pea, chickpea, tomato, sorghum, maize, cowpea, okra, peas, beans and soybeans. Because of the widespread use of Bt cotton and large-scale and indiscriminate use of chemical pesticide, *H. armigera* has developed resistance to Bt cotton and many pesticides (Bird, 2017). We thus recommend future studies to examine the potential of push-pull in cotton cropping systems.

3.4.2 Expansion to other farming systems

The push-pull technology has been widely tested in the maize mixed farming system in Kenya, and to some degree in Tanzania and Uganda. This farming system covers over 10% of the land area of East Africa (Ethiopia, Kenya, South Sudan, Uganda and Tanzania), central Africa (DR Congo, Angola) and southern Africa (Zambia, Malawi, Zimbabwe, Botswana, South Africa, Swaziland, Lesotho and Madagascar) (Garrity et al., 2012). With a total area of over 395 million ha and a human population of over 142 million people, this is the most important food production system, the food basket and driver of agricultural growth in SSA (Garrity et al., 2012). Opportunities, therefore, exist for testing and expansion of push-pull in those countries. Other farming systems where push-pull holds significant potential include agropastoral farming systems, cereal-root crop mixed farming systems and root and tuber crop farming system. Agropastoral farming systems cover semi-arid areas in West, East and Southern Africa. Livelihoods are derived from sorghum, maize, pearl millet, dryland pulses, sesame and livestock. Cereal-root crop mixed farming systems cover sub-humid areas in West and Central Africa. Here, livelihoods are derived principally from sorghum, maize, millet, cassava, yams, legumes and cattle. Root and tuber crop farming systems cover lowland areas in West and Central Africa. Here, livelihoods are derived principally from yams, cassava and legumes (Garrity et al., 2012). These farming systems are currently in crisis due to several interacting factors, including declining farm sizes, low input use, land degradation, increasing poverty (Garrity et al., 2012), vulnerability to climate change, alien invasive pests (Sileshi et al., 2019) and emerging infectious plant diseases (Sileshi and Gebeyehu, 2021). These challenges drive the demand for testing and expanding push-pull into regions such as central and southern Africa. Moreover, an area that has remained largely unexplored by research and development of push-pull is vector management. Most of the emerging infectious plant diseases are spread by vectors, and push-pull can play a significant role in integrated vector and disease management.

4 Limitations and challenges

4.1 Lack of information on crops other than maize

Information is lacking on the performance of push-pull in crops other than maize. This hampers formulation of concrete recommendations on the choice of specific crops to be included in the promotion of push-pull.

4.2 Lack of uniform and standardized methodology

Metrics used and variables measured may vary from study to study. For example, three different authors assessed the severity of fall armyworm infestation by scoring damage on a 1–5 scale in apparently similar ways. However, close examination of the scales reveals subtle differences between methods (Table 3). Measures of witchweed infestation similarly vary from study to study. For example, Khan et al. (2008) reported the number of witchweed plants per 100 maize plants, while Midega et al. (2015) recorded the number of emerged witchweed plants within a radius of 15 cm around the base of tagged maize plants, and expressed observations as number per 100 plants. Ndayisaba et al. (2020) recorded the number of witchweed plants per meter square, whereas Hailu et al. (2018) recorded witchweed counts within a circumference of 94.2 cm, and Niassy et al. (2022) recorded witchweed infested plants in 3 m by 3 m quadrants. This level of variability in sampling and enumeration makes comparison of results across studies very difficult. There is a strong need for development of guidelines and methodology for uniform and consistent application across studies in different countries. Clear criteria, indicators and metrics of performance must be established for each target farming system. In some studies, push-pull was compared with the prevalent farmer practices, considered as the “control”. In other studies, push-pull was compared with what is called “non-push-pull” plots (e.g., Drinkwater et al., 2021; Ndayisaba et al., 2020).

Drinkwater et al. (2021) designated monocultures and maize-food legume intercrops as non-push-pull cropping systems, and broadly compared them with push-pull. It must be noted that farmers’ practices and non-push-pull are not consistent treatments, but an agglomeration of heterogeneous treatments. Therefore, such comparisons may yield non-significant results, and obscure true differences simply because of the heterogeneity of treatment.

The lack of consensus on what constitutes ‘control’ and best-practice guidelines on how to do research and development (R&D) is likely to continue being a stumbling block in expanding the technology to other crops or farming systems. Harmonization of approaches and methods can significantly reduce transaction costs and increase efficiency. In that sense, a common research methodology, including joint trials across multiple locations/regions, common design principles, data collection and sharing platforms, must be put in place. A transparent mechanism for technology evaluation and release should also be in place. Validity may be judged by compliance with National Technology Release Committees and national guidelines for technology release. A well-defined scaling-up strategy with gender and youth orientation should also be put in place, so that push-pull proved to be viable can be promoted.

Table 3. Differences in methods used by different authors quantifying severity of fall armyworm infestation.

Hailu et al., (2018)	Guera et al. (2021)
1 = Clean with no visual infestation symptoms	1. Damage-free plants (plants without visual symptoms of damage)
2 = Very little damage	2. Plants with low damage (plants with leaf area damage less than 25%)
3 = High level of damage where plants show the presence of fall army worm (FAW) larvae feeding and most of the young leaves show infestation symptom,	3. Plants with medium damage (plants with leaf area damage between 25% and 50%)
4 = Severe damage where almost 75% of the leaves are severely affected and excrement is visible on the infested areas and the maize whorls	4 = Plants with high damage (plants with leaf area damage between 50% and 75%)
5 = Very severe damage where total plant damage due to FAW is visible	5 = Plants with very high or severe damage (plants with more than 75% of their leaf area damaged)

4.3 Limited focus on the acceptable level of effect

Most of the papers reviewed have focussed on statistical significance, and therefore acceptable levels of increase or decrease in measured variables in push-pull relative to “control” were often not clearly defined. For example, it is often stated that stem borer damage and striga counts in maize plants were significantly lower in push-pull than in monoculture plots; but it was often unclear whether this translated into acceptable levels of reduction to warrant adoption of push-pull.

Researchers have rarely asked, for example, what is the acceptable to farmers in terms of decrease in stem borer damage or striga infestation due to push-pull. Investment in a particular treatment will be justified only if there is an acceptable decrease in risks or increase in benefits over current farmer practices. Information on the magnitude of differences can have an important bearing on decision-making by clients. Without such information, even a well-conducted experiment will be a mere list of statistically significant differences with little practical significance. In future, more emphasis should be placed on the magnitude of differences and their variability (i.e., risk) rather than the mere detection of statistical significance.

5 Conclusions and recommendations

Based on our review and quantitative analyses, we conclude that push-pull technology significantly reduces witchweed infestation of maize, damage by spotted stemborers, maize stalk borer and fall armyworm in the locations where the technology was tested in the maize-mixed farming system in East Africa. We also conclude that the technology significantly increases maize yields, and it is financially viable wherever this was tested. The review has identified opportunities for expansion of the technology in other cereal crops, pulses, vegetables, root and tuber crops and cotton. The potential role of push-pull for integrated vector and disease management has remained unexplored. For example, routine monitoring of maize lethal necrosis disease and its vectors is highly recommended in existing push-pull trials in areas where the disease occurs. Push-pull should also be tried out with smallholder cotton production where out-grower schemes exist. When trying out the technology in commercial farms, the compatibility of practices, such as burning and use of machinery, with companion crops should also be investigated. We also highly recommend the development and sharing of best-practice guidelines for trial design and monitoring of performance of the push-pull technology as it is promoted across different regions in Africa.

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7 Supplementary material

Table S1. List of publications retrieved

#	Title
1	Cheruiyot D, Chidawanyika F, Midega CAO, Pittchar JO, Pickett JA, Khan ZR. (2022). Field evaluation of a new third generation push- pull technology for control of striga weed, stemborers, and fall armyworm in western Kenya. Experimental Agriculture https://doi.org/10.1017/S0014479721000260
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