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Opportunities for expansion of push-pull technology as an agroecological and sustainable intensification approach in Africa

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The push-pull technology (PPT) has often been presented as a management strategy for stemborers and witchweed. However, its value as an agronomic practice and an agroecological approach remains largely underappreciated. This review aims to appraise the PPT used in eastern Africa, synthesize evidence for its ecological and economic benefits, and identify barriers to its adoption and opportunities for its expansion to other crops and farming systems in sub-Saharan Africa.

Push-pull was first introduced as a pest management strategy during the 1980s in Australia, where Pyke and colleagues (1987)[1] coined the term. Since then, various forms of push-pull technology (PPT) have been tested in agricultural, forestry, medical and veterinary settings worldwide[2–12]. In Africa, PPT was initially developed to control stemborers in smallholder cereal and sugarcane production systems[3,13–15]. Over time, this form of PPT has proven effective in mitigating yield losses due to stemborer damage. PPT is also considered environmentally friendly as it utilises plant diversification and non-toxic semiochemicals from companion plants to manipulate pest behaviours[11]. Instead of pesticides, short- or long-term visual or chemical cues[16] from semiochemicals, pest-repelling and trap crops, host and non-host volatiles, insect pheromones, antifeedants and oviposition deterrents are applied as potential stimuli and deterrents in various forms of PPT[14,16,17]. This strategy can also attract natural enemies into crop fields, enhancing biological pest control[14,18]. Established mechanisms for attracting natural enemies include: (a) providing resources for natural enemies, such as floral or extrafloral nectar; or (b) attractive volatiles directly affecting pest or natural enemy behaviour[3,12,14,19].

The scientific underpinnings of PPT and how it reduces pest damage to crops have been extensively documented in previous reviews and syntheses from Africa and elsewhere in the world[3,17,19–21]. For example, Eigenbrode and co-workers[12] detailed a mechanistic framework and possible combinations of PPT effects on animal behaviour in different systems. A recent systematic review by Lang and co-workers[19] compiled a database of specific compounds and evidence of chemical mediation by PPT. In African maize, PPT has also been shown to reduce witchweed (*Striga* spp.), while producing animal fodder as a side benefit[22,23]. However, other benefits of PPT and opportunities to maximise its agronomic potential by exploiting synergies within farming systems remain largely underexplored.

PPT as it is practiced in East African cereal systems was recently found to be among the key agroecological practices generating large and consistently positive outcomes for yields and economic impacts among smallholder farmers[24]. Yet, the successes recorded in maize cropping systems in East Africa have rarely been replicated elsewhere or extended to other cropping systems. Even within East African maize systems, farmers' adoption of PPT is yet to be commensurate with its potential benefits[25,26]. Establishing PPT in new systems and regions requires sufficient understanding of the opportunities and factors of success[5]. However, our understanding of the success factors of PPT in Africa is limited by the lack of quantitative syntheses. Therefore, we focus this review on key aspects of PPT as it is practiced in Africa. The objectives of this review are to (1) provide an up-to-date description of the different generations of PPT used in African cereal production; (2) synthesise evidence for its ecological and economic benefits using a systematic review of relevant literature; and (3) identify barriers to adoption and opportunities for further testing, co-development

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and expansion of PPT in other crops and farming systems with a particular focus on sub-Saharan Africa.

The push-pull technology in Africa

Globally, definitions and typologies of PPT as a pest management strategy have been continuously evolving[12]. PPT is sometimes equated with trap cropping, intercropping, or the mere use of chemical inputs to manipulate insect behaviour[9–11]. Here, we describe the different generations of PPT used in African cereal and sugarcane production systems to reduce confusion with those applied elsewhere. The PPT applied in Africa consists of two main components: (1) a repellent intercrop, termed the 'push' and (2) a trap crop attracting insect pests away from the main crop, termed the 'pull'[3,14,27]. Typically, maize is intercropped with perennial, pest-repellent, nitrogen-fixing legumes in the genus *Desmodium* at a 1:1 ratio with maize and forage grasses are planted as trap crops[27,28]. Over the years, various PPT configurations have been developed and rigorously tested, resulting in three distinct generations. The first-generation PPT, developed in the 1990s, uses silverleaf desmodium (*Desmodium uncinatum*) and Napier grass (*Pennisetum purpureum*) or Molasses grass *(Melinis minutiflora)*. This species combination was selected to control stemborers and witchweeds in maize crops[3,29].

The second-generation or 'climate-smart' PPT[27,30] involves a combination of the drought-tolerant greenleaf desmodium (*Desmodium intortum*) and *Brachiaria* hybrid *Mulato* II (hereafter Mulato). Mulato II, a three-way hybrid of *Brachiaria ruziziensis*, *B. decumbens* and *B. brizantha*, is also preferred over Napier grass by smallholder farmers as animal fodder[30,31]. *Desmodium intortum* has similar effects on witchweed as *D. uncinatum*[23] and is a high-quality fodder[22,32]. The second-generation PPT was reported to be highly effective in reducing fall armyworm damage[27,33]. Then, an invasive spider mite (*Oligonychus trichardti*) emerged as a new threat to Mulato in hot and dry weather[34]. In addition, *D. intortum* does not reliably flower and produce seeds near the equator[35]. Consequently, better-adapted *Brachiaria* and *Desmodium* species and cultivars were screened[36,37] and *Desmodium incanum* was selected for its tolerance to longer drought[23] and ubiquitous seed setting[35]. Accordingly, the third-generation PPT was developed combining *D. incanum* as the push and *B. brizantha* cv *Xaraés* as the pull components[35]. This third generation is now being promoted for the management of stemborers, the fall armyworm and witchweed in East Africa.

Evidence for benefits of PPT

Past literature presented PPT mainly as a management strategy for stemborers and witchweeds, with little emphasis on the other benefits of PPT as an agronomic intervention. In this section, we review the evidence for its various benefits and identify those benefits for which substantial evidence exists, to inform the design of evidence-based practices and policies in Africa. We conducted a comprehensive literature search and added articles from previous reviews. The search covered various databases, including the CAB index, Scopus, Google Scholar and references from the selected studies. We used free text for the search, considering the following combinations of keywords: 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, and push*pull*soil*health. Publications were selected for the quantitative analysis and qualitative review based on the following criteria: (1) the study focused on PPT in crop production systems, (2) the study must be based on field-based experimental studies published until January 2025, and (3) the study reports on crop yields, pest infestation, crop damage, changes in soil quality, financial returns and viability. We excluded duplicates and the following types of publications: (1) studies focussing on PPT in medical and veterinary applications; (2) greenhouse and laboratory studies; (3) studies solely describing the mechanisms underlying PPT effects on pests or natural enemies. We retrieved the full text of all eligible studies without language restrictions. Then, we reviewed their contents and extracted relevant outcome variables. For studies that reported multiple outcomes of interest, each outcome was recorded separately. We identified 166 publications (Supplementary References), of which 123 publications were excluded based on the exclusion criteria above (Supplementary Fig. S1). Finally, we selected 45 publications for review and quantitative analysis (Supplementary Fig. S1). However, only 13 of these had data suitable for quantitative analysis of the chosen variables. The papers used in the quantitative analysis are presented in Supplementary Table S1 and those used in the qualitative review are in Supplementary Table S2.

As some outcome variables were reported less frequently across studies, we focused on those reported by at least three independent studies for the quantitative analysis. Accordingly, we selected crop yields, insect pest infestation and damage, and witchweed infestation for quantitative analyses. We conducted a qualitative review of other outcome variables including plant diseases, mycotoxins, soil fertility measures, climate change adaptation and financial viability. For ease of interpretation, we chose the percent change, calculated as in Eq. 1, as a single metric to provide both the magnitude and direction of change due to PPT, and thus as a measure of its effectiveness. We calculated percent changes in pest infestation, severity of damage and yield due to PPT relative to controls (monocrop) as follows:

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

Given the small number of publications reporting quantitative data (maximum 6 on each outcome), we were unable to conduct a formal meta-analysis. Instead, we created violin plots to visualise and compare the distributions of the effect size among countries (Fig. 1) and present the medians, means, maximum and minimum values for each PPT generation (Table 1). Due to the asymmetric distributions of the measured values, we based all inferences on the median and its 95% confidence limits (CL) estimated via bootstrapping. Results are presented below according to the strength of evidence from the quantitative analyses and the qualitative literature review under two categories, i.e. those benefits for which strong evidence exists and those for which evidence is still emerging.

Benefits for which strong evidence exists

Based on the quantitative analysis and the review of literature, strong evidence was found for improvement of crop yields and suppression of stemborers, fall armyworm and witchweeds with PPT (Fig. 1; Table 1).

Increased crop yields. The distribution of changes in maize grain yield in PPT relative to monocrop was positive except in Malawi (Fig. 1; Table 1); the overall median increase across countries was 96.2% (95% CI: 88.6–108.3%). Relative to monocrop, PPT combined with conservation tillage led to yield reduction by 10.2% compared to conventional tillage (−3.7%) in Malawi. However, the results were from a short-term study, which warrants cautious interpretation of the findings. The combined analysis revealed significantly higher grain yields with first-generation PPT than with monocrops in most sites (Table 1). Most of the data for the first-generation PPT came from Kenya, where yields were monitored over several years. In a recent analysis of data from 476 farmers across 24 cropping seasons in western Kenya, yields steadily improved over time in the first-generation PPT[38]. The second-generation PPT gave significantly higher maize yields across test sites in Kenya, Tanzania and Uganda (Table 1). Despite over two decades of research on PPT, there is a clear gap in the PPT literature on field data relevant to crop yield benefits and yield losses avoided by farmers adopting PPT across the East Africa region. We thus strongly argue for more field research to quantify the avoided yield loss with PPT under comparable environmental and soil conditions, in addition to a focus on pest damage and/or incidence.

Suppression of stemborers. Diverse stemborer species, including *Busseola fusca*, six species in the genus *Chilo*, four species in the genus *Sesamia*, *Eldana saccharina* and *Maliarpha separatella* affect cereals and sugarcane across Africa[25,39]. *Busseola fusca* is native to Africa and is

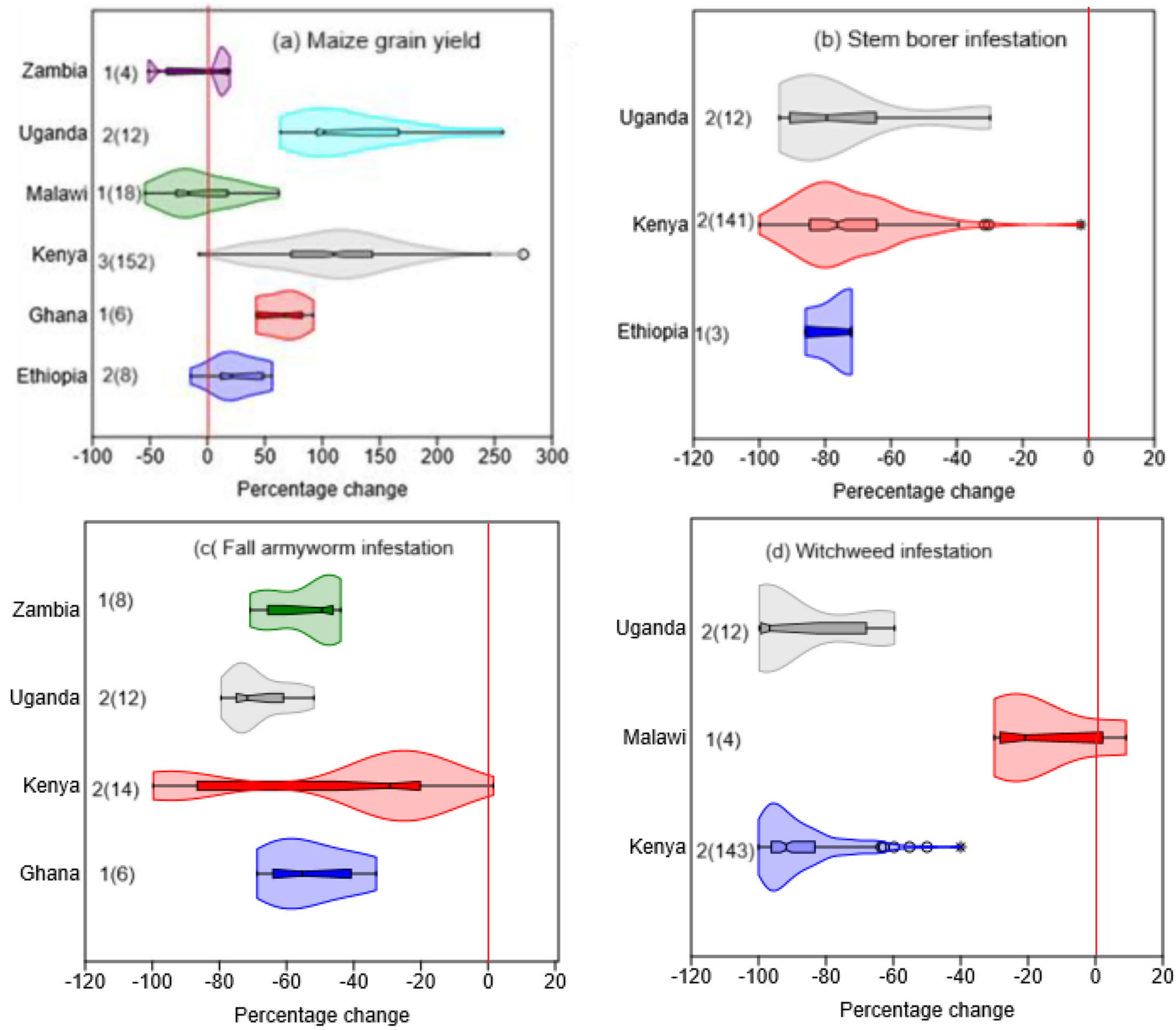

Fig. 1 | Changes in response variables. a–d Represent the distribution of changes in maize grain yield, stemborer infestation, fall armyworm infestation and witchweed infestation due to PPT relative to maize monocrop, respectively. Results for the first and second PPT generations were combined for each country. The CL of medians are indicated by the notches in the box plots. The medians of two or more distributions are deemed not significantly different if their CLs overlap. Significant increase or decrease is indicated by CLs falling above or below the red vertical line. The figures in front of each country represent the number of studies, and those in parenthesis represent the total number of observations available for each country. Violin plots for Tanzania were not included due to small number of observations. Figures were created by the authors using the Paleontological Statistics (PAST) software Version 4.11. https://www.nhm.uio.no/english/research/resources/past/.

known as the African maize stemborer. It has become an economically important pest of maize, sorghum, millets (both pearl and finger millet) and sugarcane[39]. Its distribution range is expected to expand with future climate change. Among *Chilo* species, the spotted stemborer (*C. partellus*) and *C. sacchariphagus* are invasive species native to Asia[39]. *Chilo partellus* was first reported in East Africa around 1950s, has since spread across 18 African countries[40,41] with a potential to invade and persist in other countries. It poses the greatest threat to maize and sorghum crops in Africa. The remaining four *Chilo* species are endemic to Africa and are considered minor pests[39].

Quantitative data on stemborer infestation were available from five studies that assessed the effects of the first- and second-generation PPTs across sites in Kenya[30,38,42], Ethiopia[43] and Uganda[44]. Previous studies have reported stemborer infestation in maize fields without disaggregating by species. Our analysis showed that maize PPT significantly reduces stemborer infestation compared with monocrops (Fig. 1b; Table 1). Across studies, the median reduction in stemborer infestation was 76.8% (95% CI: 73.9–78.7%). Earlier analysis of data from 24 cropping seasons in western Kenya[38] revealed a steady decline in stemborer abundance over time since the establishment of the PPT. Taken together, these observations suggest that adoption of PPT can reduce stemborer damage over the long-term on smallholder farms. However, this benefit may increase if PPT is adopted on a large number of contiguous farms creating more complex agroecosystems than the current practice of maize monoculture. As demonstrated in the Rift Valley region of Ethiopia[45], landscape complexity can play an important role in mediating stemborer suppression by PPT.

Suppression of the fall armyworm. The fall armyworm (FAW; *Spodoptera frugiperda*) is an alien invasive pest native to the Americas that currently affects over 43 countries in Africa[40]. Its distribution range is expected to expand, covering larger areas of Africa[46]. Currently, it causes 45–67% loss of annual average production of maize in the affected countries, which is equivalent to $ 6.2 billion annually[46]. The fall armyworm infestation and damage were recently evaluated on

Table 1 | Percent change in maize grain yield, witchweed infestation, stemborer infestation and fall armyworm damage under first- and second-generation (climate-smart) PPT relative to the control

Variable	PPT generation	Country (S; N)[a]	Median	Mean	Minimum	Maximum
Maize grain yield	First	Ghana (1; 6)	53.9	54.8	42.3	69.0
		Kenya (1; 81)	87.5	92.9	18.9	275.0
		Ethiopia (2; 6)	15.3	22.7	−14.6	56.4
		Zambia (1, 4)	11.7	−2.1	−51.4	19.7
	Second	Kenya (2; 72)	131.4	133.0	−7.5	363.6
		Ethiopia (1; 2)	-	30.8	25.0	36.7
		Tanzania (1; 1)	-	-	109.5	109.5
		Uganda (2, 12)	101.7	125.6	63.3	257.1
		Malawi (1; 18)	-16.3	-6.9	−54.5	62.2
		Overall (10; 202)	96.2	94.9	−54.5	363.6
Stemborer infestation	First	Kenya (1; 81)	−66.5	−66.3	−100	−2.4
		Uganda (1; 2)	−55.1	−55.1	−80.4	−29.8
		Ethiopia (1, 3)	-	−76.8	−71.9	−86.0
	Second	Kenya (1; 60)	−84.5	−83.2	−100	−56.4
		Uganda (2; 10)	−82.5	−77.9	−93.9	−33.1
		Overall (5; 156)	−76.8	−73.6	−100.0	−2.4
Fall armyworm damage	First/second	Ghana (1; 6)	−55.3	−53.1	−68.8	−33.3
		Kenya (2; 44)	−29.2	−43.4	−99.7	1.5
		Tanzania (1; 2)	−93.3	−93.3	−94.7	−92.0
		Uganda (2; 12)	−71.7	−68.4	−79.5	−51.9
		Zambia (1, 8)	−49.5	−54.5	−70.8	−43.9
		Overall (5; 72)	−46.4	−51.0	−99.7	1.5
Witchweed infestation	First	Kenya (1, 77)	−87.0	−84.6	−100.0	−50.0
		Uganda (1, 2)	−62.0	−62.0	−59.6	−64.4
	Second	Kenya (2, 66)	−95.5	−92.1	−100.0	−40.0
		Uganda (2, 10)	−97.8	−92.4	−99.8	−63.3
		Malawi-CA (1, 2)	−20.9	−21.0	−23.1	−18.8
		Malawi-conv (1, 2)	−10.5	−10.5	−30.0	9.1
		Overall (8, 159)	−91.6	−86.1	−100.0	9.1

Positive effects of PPT are indicated by positive values for crop yield (increase), or negative values for pest incidence and damage (reduction).
CA conservation agriculture, *Conv* conventional tillage.
[a]S and N represent the number of studies and the total number of observations available for quantitative analysis.

second-generation PPT across sites in Ghana, Kenya, Tanzania, Uganda and Zambia[33,44,47] (see also Table 1). Our summary of the results from these studies showed a significant reduction in FAW infestation and severity of damage compared to monocrops (Fig. 1c; Table 1). Across studies and countries, the median reduction in FAW damage on maize was 46.4% (95% CI: 34.6–60.5%). In Uganda, the severity of FAW damage was generally higher on maize than on sorghum[48]. Similarly, the second-generation PPT was found to reduce FAW infestations by up to 51% in Mexico[49].

Suppression of witchweeds. Witchweeds (*Striga* species) are root parasites that inhibit cereal growth and productivity. *Striga hermonthica*, *S. asiatica*, *S. forbessii* and *S. aspera* cause significant yield losses in different cereal crops in SSA[50,51]. Over 50% of the land cultivated for cereals in SSA is *Striga*-infested, causing ~7–10 billion USD loss to the agricultural economy[50–52]. In terms of economic importance, *Striga hermonthica* is the most destructive parasitic weed of maize across Africa[50]. The witchweed problem is closely associated with cereal monoculture and poor soil fertility[53,54], and is exacerbated under moisture stress conditions.

The effect of different PPT generations on witchweeds has been studied in Kenya[33,42], Uganda[44], Ethiopia[43] and Malawi[47]. Our summary of results from these studies show that PPT can significantly suppress witchweed in maize fields (Fig. 1d; Table 1). The median reduction in infestation relative to cereal monocrops was 91.6% (95% CI: 89.3–93.2%) across Kenya, Uganda and Malawi. The first-generation PPT reduced witchweed infestation of maize by 62–87% in Kenya and Uganda relative to monocrops. The corresponding reductions by second-generation PPT were 95–98% in Kenya and Uganda, but 10–21% in Malawi (Table 1). In Ethiopia, witchweed seedlings (numbers/m^2) 10 weeks after emergence of maize seedlings were recorded on two sites. On both sites, witchweed emergence was reduced by ~78% in PPT compared to the maize monocrop. It is not surprising that Kenyan farmers perceive witchweed suppression as one of the main benefits of adopting PPT[55]. The mechanisms by which PPT suppresses witchweed include increased availability of nitrogen in the soil, shading and allelopathic root exudation of flavonoid compounds by the companion crop[29,54,56].

Benefits for which evidence is emerging

The benefits for which evidence is still emerging are those demonstrated in a few countries or studies. For these, a meta-analysis was not possible due to insufficient studies. Based on the qualitative review of literature, some evidence was found for reduction in ear rot and mycotoxins, improvements in soil health and climate change adaptation and mitigation. Ear rot caused by plant pathogenic fungi is one of the common diseases of maize. Some of these fungi produce mycotoxins (toxic compounds) in maize grains and maize-based food products, which pose a threat to food and feed safety[57]. We found three studies[57–59] that reported the effect of PPT on plant diseases and mycotoxins in Africa. In western Kenya, there was a significant reduction in the incidence of *Fusarium verticillioides* (60%) and *Aspergillus flavus* (86%) in PPT, which was also reflected in a 50% reduction in the incidence of ear rots[58]. Concentrations of the mycotoxin Fumonisin in maize grains were also reduced by 39% in PPT farms[58] relative to maize monocrops. The incidence and severity of ear rot and mycotoxins were also significantly lower in PPT than in maize monoculture[59]. These findings suggest the potential of PPT in managing ear rot and ultimately limiting mycotoxin contamination in cereal grains[57–59].

Despite decades of work on PPT, only six studies published in the last 2–3 years have reported biomass inputs to the soil and improvements in soil health indicators[28,43,60–63]; the data reported in these studies was not adequate for meta-analysis. This paucity of data indicates that the potential of PPT as an agroecological approach for managing soil health remains under-explored. However, the available evidence suggests that PPT can significantly increase organic matter and nutrient inputs to the soil. For example, data from three sites in Ethiopia[43] revealed significant increases in SOC (33–53%), total N (26–92%), available P (32–174%) and available K (13–26%) in PPT fields compared to maize monocrops. Similarly, in Western Kenya the soil organic carbon (SOC) stored in PPT fields was consistently higher than in non-PPT fields[63]. Long-term adoption of PPT also appears to achieve greater improvements in SOC. For example, fields where PPT was practiced for more than 5 years had 5.5 tonnes more SOC per hectare than those that had PPT for less than 2 years[63]. In three long-term experiments in Western Kenya, Drinkwater and co-workers[28] found that soil organic N was 20% higher and labile organic N reserves were five-fold greater in PPT compared to the control. Extractable soil P was also two-fold higher in PPT than in the control[28]. Similarly, higher soil available N and P concentrations were recorded in PPT compared to maize monocrop fields across three seasons in western Kenya[62]. Mwakilili and co-workers[60] reported that PPT fields in western Kenya supported a more diversified fungal microbiomes than monoculture. The build-up of soil organic matter, nutrients and associated diversity of soil life may increase the resilience of soils to droughts and floods, natural control of pests and help cropping systems adapt to climate change. The available data also suggests that the potential benefits of PPT for climate change adaptation and mitigation remain underexplored and poorly documented. We found only four studies[28,63–65] addressing this issue, and all suggest that PPT can provide opportunities for both adaptation and mitigation. A study conducted in Ethiopia[65] found that maize grown in PPT had positive benefits in 8 of the 13 agroecosystem indicators of climate resilience. The increased soil organic carbon recorded in PPT compared to monoculture fields in Ethiopia[43] and Kenya[28,63] highlight the mitigation benefits, of PPT. In terms of its adaptation benefits, information was found in only on review and modelling exercise[64].The results suggested variable impacts of climate change on PPT components by the end of the 21st century including reduction in soil fertility, increased weed, insect pest and disease pressure but increased biological control by natural enemies[64].

Financial returns and viability

Seven publications[15,26,30,66–69] analysed the financial returns of PPT using different metrics, and their results provide strong evidence that the benefits of PPT outweigh the costs. Using benefit-cost ratio, Khan and co-workers[15] found a return on investment of 2.2 for PPT compared to 0.8 for monoculture maize or 1.8 for pesticide use. PPT often requires extra labour and capital costs for the establishment in the 1st year, but the costs are significantly lower in subsequent years[15,66]. Despite land being perceived as 'lost' to trap-cropping, the resultant benefits of PPT through maize yield increase and additional income from the sale or utilisation of Napier grass and Desmodium were sufficient to cover all initial capital costs and generate a substantial profit margin[66]. Total annual revenues ranging from \$351 ha^{-1} to \$957 ha^{-1} have also been reported[67]. Returns on labour within the 1st year of establishment ranged from \$0.5 to \$5.2 per man-day in low-potential and higher-potential areas under PPT, whereas in maize monocrop, the returns were negligible[26,67]. The net present values from PPT were also consistently positive over the years[68]. PPT in Western Kenya earned the highest revenue among other soil fertility management technologies, which is attributable to both higher maize yields and the value of fodder from the companion crops. Hence, it is more likely to be profitable in areas with sufficient livestock and a demand for fodder[68]. Additionally, a study in Western Kenya, Tanzania and Ethiopia[30] found a marginal rate of return of 143.4% for maize and 109.2% for sorghum under PPT.

Using a combination of econometric and economic surplus methods, Kassie and co-workers[26] analysed the macroeconomic impacts of adopting PPT on aggregate welfare and concluded that widespread adoption can increase economic surplus and reduce the number of people considered poor in Kenya. Similarly, Chepchirchir and co-workers[69] found that the economy in four districts of eastern Uganda would derive an overall net gain of 3.8 million USD from switching to PPT. The internal rate of return from PPT was estimated at 51%, while the net present value was estimated at 1.6 million USD with a discount rate of 12% for a period of 20 years (2015–2035)[69]. These findings indicate that PPT is profitable and economically viable in the contexts evaluated so far.

Adoption of PPT by farmers

A few studies have evaluated the adoption of PPT, including the perceived barriers and gender dimensions of adoption. By 2014, PPT was reported to have been adopted by over 68,800 smallholder farmers in Kenya, Uganda, Tanzania and Ethiopia[66]. Of these, 52,746 users were in western Kenya, about 5000 in central Kenya, 10,600 in Uganda and Tanzania and 343 in Ethiopia[66]. By 2021, over 258,574 farmers across East Africa had practiced PPT for over 2 years, of which 87,683, 170,027 and 864 had utilised first-, second-, and third-generation PPT, respectively (http://www.push-pull.net/adoption.shtml). In each case, adoption was about 58% among female farmers. In Western Kenya, no gender differences were found in the adoption of PPT[70], suggesting that male and female farmers equally adopt PPT. Two studies[71,72] independently assessed women's empowerment and changes in maize productivity due to PPT adoption, and both found positive impacts of women's empowerment.

In a sample survey of 898 respondents from Kenya, Tanzania and Ethiopia, Murage and co-workers[32] found high willingness (87.8% of respondents) to adopt the second-generation PPT among farmers. The breakdown by country was 92.1% in Tanzania, 88.6% in Ethiopia and 84.3% in Kenya. Factors such as access to input markets, gender, awareness of the technology and perception of witchweed severity were found to likely influence the decision to adopt the second-generation PPT[32]. Another study in Western Kenya[55] showed that farmers adopted PPT for various reasons, including reduction in witchweed (30% of respondents), increased yields (22%), enhanced soil fertility and increased animal feed (13%), reduced soil erosion (11%) and improved quality of products (11%). These findings are consistent with earlier studies[42,67,73] in East Africa.

A few studies have also analysed the intensity of PPT adoption (defined as the proportion of land allocated to PPT) and the extent of disadoption[32,65,74–77]. In a survey of 491 PPT and non-PPT maize farmers in Western Kenya, the average land area under PPT was estimated at 5.2% of the total land area cultivated by individual farmers[73]. A study in Rwanda[77] found that among farmers that practice PPT, the average PPT use intensity was 26%, i.e. on average 26% of individual farmers' maize acreage is cultivated under PPT. Varying proportions of PPT farmers reportedly expanded the land area under PPT across study areas in Kenya, depending largely on the average size of landholding[78]. For example, up to 60% of PPT adopters in Trans-Nzoia marginally increased their PPT area, whereas the overall average was 16%. In Homa Bay, less than 50% of PPT-practicing farmers expanded their PPT land areas[75]. Murage and co-workers[73] observed that farmers' participation in field days is likely to raise the intensity of PPT use by up to 3.79%. However, in PPT, the use of Desmodium as a 1:1 intercrop in place of the otherwise frequent combination of intercropping maize with beans likely represents a barrier to PPT area expansion on small land holdings for food production.

Despite the demonstrated benefits of PPT, disadoption (discontinuation) is also evident from recent surveys in East Africa. The main reasons reported for disadoption of PPT were lack of Desmodium and Brachiaria seeds (24%), the complexity of managing PPT fields (20%) and the limited knowledge and technical skills related to PPT (18%)[70]. Where PPT was actively promoted in Eastern Uganda, a survey of 849 farmers across seven districts noted that 19% and 2% of the farmers discontinued PPT by 2014 and 2015, respectively[74]. In Homabay, Kenya, about 40% of surveyed 123 farming households that once adopted PPT had abandoned it[75]. Common barriers to PPT adoption and expansion include inadequate access and high costs of Desmodium and Brachiaria seeds, land shortages, lack of knowledge about PPT and/or a lack of long-term follow-up of received trainings, labour requirements and incompatibility with some traditional practices of crop rotation, ox-drawn ploughing (e.g. in Ethiopia) and free grazing of plots in the dry season are also common reasons for disadoption[76,78,79]. These findings emphasise the need for concerted efforts to increase access to seeds and information, technical training and targeted dissemination to increase adoption and expansion of PPT.

Opportunities for expansion of PPT

In this section, we focus on the opportunities for expanding PPT beyond its current use as a pest management strategy, but as an agronomic intervention for sustainable intensification of agriculture in under-served farming systems. Obviously, this task requires in-depth analysis and identification of priority areas/regions, crops and pests that merit investment, which is outside the scope of this work. To explore these prospects, we reviewed the literature on farming systems[80] where PPT has been studied. Specifically, we identified studies that analysed the current and future distributions of key pests, including stemborer and fall armyworm. We also considered the suitability maps of maize, which is the staple cereal crop affected by these pests across Africa, to identify priority regions to be targeted for PPT interventions.

So far research and development in PPT has focused on controlling stemborers and the witchweed in East Africa, primarily in Kenya. The current maize area under PPT covers only a small fraction of the area suitable for sustainable intensification of maize cropping. The knowledge-base about PPT built in East Africa can be readily applied in the rest of Africa where maize is a dominant cereal. This includes the mixed-farming system, the agropastoral farming system and the cereal-root crop farming system[80]. The maize mixed-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)[80,81]. With over 361 million ha of land area[81], the maize mixed-farming system is the food basket of Africa[80]. This provides an opportunity for testing and expanding of PPT in the maize mixed-farming system. Palm and co-workers[82] identified areas classified as 1, 2, or 3 as optimal for significantly increasing maize yields. These classes cover about 1.1 million km^2 or 44% of the total area of the East Africa, including Burundi, Ethiopia, Kenya, Rwanda, Tanzania and Uganda[82].

Other African farming systems where PPT holds significant potential include the agropastoral, cereal-root crop and root and tuber crop farming systems, as defined in Dixon and co-workers[80]. Indeed, many of the benefits of the PPT model for African maize are likely to carry over to the production of other crops including cereals, sugarcane[83–85], pulse crops[86], vegetables[87] and cotton. Some of these crops are affected by a similar set of challenges which PPT is either designed to address (e.g. insect pests and witchweeds), or which PPT may improve indirectly through its soil health benefits, moisture retention, and diversification of production. Whereas distinct push-pull systems have been developed and tested in a range of crops around the world with the primary aim of managing pests, in contrast to East African PPT, to date these have not been implemented at comparable scales, and there is no evidence for their generalisability beyond the systems they were developed for. We hypothesise that PPT can be effectively adapted to agronomic systems beyond maize, potentially overcoming barriers to its adoption. Here, we review evidence for successful expansion of PPT in Africa beyond its original maize-focused design.

Cereal crops

The research and development of PPT focussed on maize, which is predominantly grown in subhumid and humid climates. The limited number of studies available[44,88] suggests that PPT can be extended to the drylands (arid and semiarid) regions of Africa where other crops such as sorghum and millets are the staple cereals. Sorghum and millets are the main cereals grown in the drylands (agropastoral and pastoral farming systems). The only study so far in semiarid areas was conducted in Mbeere South Sub-county (Embu County Kenya)[88]. Here, a drought-tolerant greenleaf *Desmodium* (*D. intortum*) was used as the push crop[88]. PPT development is likely to require a different mix of plant species to provide the push and pull in the sorghum and millet growing areas. For example, dryland legumes such as cowpea, pigeon pea and greengram could be used as the push crops[88,89], but little information is available on their effectiveness in PPT systems. Among the non-food legumes, *D. incanum* and *Brachiaria Xaraes* have shown promise in dryland areas[35]. Like maize, sorghum and millets are vulnerable to stemborers and witchweed. There are no studies on sorghum and millet, except in Zambia, where the efficacy of PPT against the fall armyworm was assessed on sweet sorghum and millet[90]. Over the coming years, some stemborers are expected to expand their distribution in certain areas[41,91,92]. In the case of the maize stalk borer, slight range expansion is expected in highland maize production areas of East Africa and in Southern Africa, but a decline in most lowland areas of West, East and Central Africa[91]. Model predictions also indicate risks of expansion of the geographical range of the spotted stemborer to higher altitudes in eastern, southern, central and much of western Africa[40]. Similarly, a large area of eastern and central Africa is projected to have an optimal climate for fall armyworm persistence[46]. Since PPT has been demonstrated to effectively reduce fall armyworm infestations (Fig. 1c; Table 1), opportunities exist for expanding PPT for its management in areas suitable for maize and sorghum across sub-Saharan Africa.

Sugarcane

The African continent has suitable areas for expansion of sugarcane farming due to the high production potential, demand for biofuels, low cost and proximity to European markets[93]. The sugarcane stemborer (*E. saccharina*) is the most damaging insect pest of sugarcane in many parts of Africa[25] and is also a pest of maize and rice[39]. Field trials in South Africa have demonstrated that PPT can suppress stemborer damage to sugarcane[13,83]. PPT was also promoted as part of the area-wide integrated management of the sugarcane stemborer in South African large-scale sugar farms[25,84]. Here, the 'push' component is molasses grass (*Melinis minutiflora*), which has a repellent effect on the pest but is also attractive to *Xanthopimpla stemmator*, which is sugarcane stemborer parasitoid[13,83]. 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[85]. In a survey of 53 farmers representing 30% of the registered large-scale farmers across the Midlands North region of South Africa, Cockburn and co-workers[25] found that perceived barriers to adoption of PPT were farmers' perception of pest damage (i.e. whether farmers perceive the damage to be sufficiently large to warrant implementation of push-pull) (33% of respondents), cost and time constraints (27%), insufficient knowledge (25%), management problems (8%) and lack of cooperation between farmers (7%). Farmers' knowledge, attitudes and perceptions can play a key role in their implementation of intensive management practices such as push-pull. Opportunities exist for expanding PPT for the management of the sugarcane stemborer if these and other barriers to adoption could be identified and addressed.

Pulse crops

Among pulse crops, only common bean (*Phaseolus vulgaris*) has been incorporated into PPT[86]. Studies in Kenya[86] show that integration of common beans into PPT does not compromise the efficacy of Desmodium in controlling witchweed and stemborer, although it may increase labour and total variable costs. In a study in Ethiopia, common bean in PPT was found to be as efficient as Desmodium in repelling stemborers[45]. Common bean also increased the abundance of generalist predators and egg predation on stemborers[45]. These findings highlight opportunities to extend the portfolio of crops integrated with PPT to beans and other pulses. However, these results are from a small number of studies based on one or a few landscapes, and the outcomes might be different in a more complex landscape context[45]. Other studies have also shown that intercropping with edible legumes does not have the same effects as intercropping with Desmodium[44,88,89]. Therefore, further research is warranted to address the conflicting results regarding the 'push' potential of edible legume species for expansion of PPT in pulse cropping[89].

Vegetable crops

Our review of the literature did not find many reports on the application of PPT in vegetable pest management in Africa. There are only two publications so far, and these describe the integration of vegetables in what is called vegetable-integrated PPT[87,94]. The evidence from those studies suggests a marked reduction in pest infestation of vegetables owing to the repellent properties of Desmodium and presumably increased parasitoid activity[87]. Improved quality and high yield of tomato and kale were reported in the vegetable-integrated PPT plots relative to control plots (tomato intercropped with maize) in western Kenya[94]. Soil fertility improvement was also associated with increased yield, which underlies the potential for the sustainable intensification of vegetable production[87]. Although the limited number of studies so far suggest positive outcomes, the evidence available is limited to western Kenya. Further studies are needed to evaluate the expansion of push-pull options in vegetable production systems elsewhere in East Africa.

Cotton

Although PPT was first conceived in the context of *Heliothis* management in cotton[1], no study has tested it for managing *Helicoverpa armigera* in cotton in Africa. *Helicoverpa armigera* is a pest of cotton, pigeon pea, chickpea, tomatoes, sorghum, maize, cowpea, okra, peas, beans and soybeans in Africa. Its broad host range and resistance to pesticides provide a strong motivation for investment in research and development in PPT in cotton production systems in Africa.

In conclusion, this review has provided evidence for the benefits of PPT in the maize mixed farming systems in East Africa and sugarcane plantations in South Africa. Such evidence is lacking for other farming systems and staple crops such as sorghum and millet. We conclude that PPT has consistently and significantly increased maize yields, reduced infestation of maize by stemborers, fall armyworm and witchweed, and improved soil health, while providing climate change adaptation and mitigation benefits in East Africa. Based on the review of available evidence in the literature[15,26,30,66–69,95], we also conclude that PPT is financially viable under the conditions where it was tested in East Africa. Collectively, these findings suggest that expansion of PPT in other farming systems in Africa could play a key role in achieving agroecological transitions towards resilient food production systems. Despite the decades of research on PPT, there is a clear gap in the literature on the yield losses avoided by farmers adopting PPT at the landscape level. This kind of information is useful to inform policy to support the promotion of PPT. We strongly argue for future studies to go beyond the current focus on scoring pest damage or incidence and quantify the avoided yield loss. We also strongly recommend inclusion of indicators and metrics of agronomic performance such as resource use efficiencies (nutrient and water use efficiency) and soil health in future research and development on PPT. Future developments on PPT should also consider landscape complexity as an integral part of the design of PPT as an agroecologically intensive systems.

Data availability

No datasets were generated or analysed during the current study.

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Competing interests
The authors declare no competing interests.

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