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Insect pest and disease management practices and benefits in Conservation Agriculture systems: a case of push–pull practice

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1 Introduction

National and international agricultural research institutions are engaged in developing technologies and formulating dissemination packages in order to manage constraints, to enhance production, and to guarantee food security. The main crops grown in sub-Saharan Africa (SSA) are cereals which include maize, rice, sorghum, and millet supporting livelihoods of over 80% small-scale farmers. These staple cereals form the principal food and cash crops for millions of the poorest people. Their production has however been characterized by small holdings, low capitalization, and low yield per unit of land.

Low productivity is attributed to unreliable rainfall, pests, diseases, poor soil fertility, and weeds. In particular, cereals are adversely affected by stemborers (mainly *Chilo partellus* (Swinhoe) and *Busseola fusca* (Füller)) (Kfir, 2002) and parasitic Striga weeds (mainly *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze) (Khan et al., 2006b; Hassanali, 2008). Furthermore, the recent outbreak of fall armyworms (FAWs) (*Spodoptera frugiperda*) (J. E. Smith) has posed a serious threat to food security, causing crop losses estimated to be more than US$6.2 billion annually in SSA, while

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the combination of stemborers and Striga are estimated to cause losses of up to US$14 billion annually (Goergen et al., 2016; Midega et al., 2018). The FAW invasion, in particular, has adverse economic impacts at the household level as it directly increases yield losses, production costs, requires specialized knowledge to control, and confounds the ability of cropping systems to respond to production constraints all of which have an overall impact on household incomes (Midega et al., 2018).

In addition, the natural resource base for agricultural production is severely degraded (FAO, 2004; Khan et al., 2014; Kassam et al., 2017). Land degradation in tillage agriculture further constrains the production of cereals, particularly maize and sorghum, the main staple and cash crops for millions of smallholder farmers in SSA. Low and declining yields cause food and nutrition insecurity, poor incomes, rising poverty and poor health. The resource-constrained smallholder farmers living in the arid and semi-arid regions who practice mixed crop–livestock systems are particularly affected. As a result of these constraints, every year there is a critical shortage of cereals in many smallholder households leading to high prices of grain, hunger, and widespread poverty (Khan et al., 2006b). Future projections indicate that without urgent intervention, SSA will have more than 500 million food insecure people by 2020 (USDA, 2010).

Farmers have attempted to minimize the adverse effects of the above-mentioned pests through conventional control strategies such as hand weeding, direct uprooting, use of nitrogen fertilizers, and other chemical means. However, research findings have shown that these methods are insufficient, expensive, unaffordable, and unfriendly to the environment (Berner et al., 1995; Woomer et al., 2004). Developing climate-resilient, adaptable, and productive agricultural systems such as Conservation Agriculture (CA) is imperative to meet future demands for food (Pretty, 2011; Khan et al., 2014; Kassam et al., 2017). Part of resilience building needs to involve climate-smart agricultural technologies such as those practiced in CA, which also protect and enhance natural resources and ecosystem services in ways that mitigate future climate change effects (Tittonel and Giller, 2013; Kassam et al., 2017; Gonzalez-Sanchez et al., 2018).

Significant and sustainable increases in grain yields and animal production require ecologically sound methods of managing weeds and pests, including CA systems and practices, with a strong focus on a systems approach that maximizes soil quality, moisture conservation, and crop productivity. Sustainable agricultural intensification and resource-conserving technologies such as push–pull (www.push-pull.net), which produce more output per unit area of land while reducing the negative environmental impacts, and increasing agricultural system contributions to natural capital and the flow of environmental services, are necessary for agricultural development (Royal Society, 2009; Conway and Waage, 2010; Godfray et al., 2010).

In 2015/16, CA covered more than 1.5 million ha in Africa (Kassam et al., 2019). CA promotes integrated insect pest and disease control through the practical application of its three interlinked principles. Push–pull practice of insect pest control fits well into the CA cropping systems as it utilizes the CA principles in building and optimizing the effectiveness of the practice, adding further to system output, factor productivity, resilience, and profit margins. This chapter elaborates on how the CA-based push–pull practice works at the farm level and what benefits are harnessed. The chapter also addresses how disease management works in CA systems and with what benefits.

2 Push–pull technology: a sustainable innovation in Conservation Agriculture

The push–pull production and protection system was developed by the International Centre of Insect Physiology and Ecology (*icipe*) and partners as a control measure for stemborers, the striga weed, and low soil fertility. The push–pull practice harnesses resource-conserving integrated pest management (IPM) and integrated soil fertility management (ISFM) approaches, using natural processes and locally available bio-resources to increase farm productivity by controlling both biotic and abiotic constraints to smallholder agriculture (Cook et al., 2007; Hassanali et al., 2008). The practice design originated from tillage-based cereal–legume intercropping strategies practiced in Africa to maximize staple crop productivity.

As part of a CA-based approach, the push–pull practice was further developed for no tillage-based systems, providing continuous soil cover with a perennial cover crop (live mulch) and plant residue, and a diversified cereal–legume-fodder intercropping practice. The push–pull CA practice is based on companion cropping, which effectively controls stemborer and fall armyworm insect pests as well as parasitic Striga weeds, while improving soil fertility by fixing nitrogen, sequestering carbon, and conserving soil moisture. Farmers practicing push–pull have realized substantial grain yield increases with minimal use of external synthetic inputs. The push–pull's diversified cereal–legume–fodder intercropping strategy conforms to the CA principles of minimum soil disturbance, mulching through continuous soil cover by Desmodium, which is a perennial cover crop that generates biomass. The perennial legume intercrop improves above-ground and below-ground arthropod abundance, agro-biodiversity, and the food web of natural enemies of stemborers (Midega et al., 2006, 2009, 2015). This practice effectively controls the major insect pests of cereals in SSA, mainly the lepidopteran stemborers, and more recently the invasive FAW, as well as parasitic Striga weeds. Furthermore, it improves soil health and conserves soil moisture. The technology involves the use of inter- and trap-crops in a mixed cropping system (Khan et al., 2006a). These companion plants release chemicals in a stimulo-deterrent tactic that mitigates the behavior of both stemborers and beneficial insects, thus controlling their distribution and abundance as a pest-management strategy. The push–pull practice is based on an in-depth understanding of chemical ecology, agro-biodiversity, and plant–plant and insect–plant interactions (Miller and Cowles, 1990; Cook et al., 2007) and is well suited to African mixed cropping practices.

In the push–pull practice, cereals are intercropped with Desmodium (e.g. *Desmodium uncinatum* (Jacq)), and Napier grass (*Pennisetum purpureum* Schumach) is planted as a border crop around this intercrop (Khan et al., 2001, 2003; Midega et al., 2010, 2015). The Desmodium repels stemborers moths (push), while the surrounding Napier grass attracts them (pull) (Khan et al., 2001). In addition, Desmodium suppresses Striga weeds through several mechanisms, with allelopathy (chemical growth inhibition) being the most important (Tsanuo et al., 2003). Due to the adverse effects of climate change on the companion crops, the push–pull technology was adapted by selecting and incorporating drought-tolerant companion crops in a new strategy, termed 'climate-smart push–pull' where the cereal crops are intercropped with the drought-tolerant Greenleaf Desmodium, (*D. intortum* (Mill.) Urb.), with the drought-tolerant Brachiaria cv 'Mulato' (*Brachiaria* spp.) grass planted as a border crop (Khan et al., 2014; Midega et al., 2015; Cheruiyot et al., 2018) (Fig. 1).

Figure 1 Maize under conventional push–pull technology, Kisumu West, Kenya.

This chapter presents a review of information on the dissemination, adoption, and benefits of the push–pull practice at the household level. The study reviews various studies that have been conducted on the push–pull technology since its inception in order to elicit the significance of the practice.

3 Dissemination and adoption of push–pull practice

Dissemination and adoption of the push–pull practice have widely been studied and documented (e.g. Amudavi et al., 2008, 2009; Khan et al., 2008a,b; Murage et al., 2011, 2012, 2015a,b; Hailu et al., 2017). Since its inception, the practice has been disseminated and widely adopted by farmers in East Africa and beyond. The dissemination of the push–pull practice started in early 2000 in Vihiga County and has progressively diffused in other counties in western Kenya and the neighboring countries in eastern and southern Africa including Uganda, Tanzania, Ethiopia, Malawi, Zambia, Zimbabwe, Rwanda, Bururndi, Burkina Faso, and Ghana. *icipe* and partners have employed a wide range of dissemination pathways to reach as many farmers as possible. These include mass media, the print media, and the interpersonal pathways such as field days, farmer field schools (FFSs), farmer teachers/trainers, fellow farmers, and public meetings.

Dissemination pathways play a key role in determining the adoption of new innovations. It has been shown that farmer preferences for certain dissemination pathways do exist and farmers are likely to be persuaded to adopt a technology if they perceive information pathways to be credible and reliable (Rogers, 1997; Gloy et al., 2000; Tucker and Napier, 2002; Roderick et al., 2008; Murage et al., 2011). Previous studies by Murage et al. (2011) showed that adopters of the push–pull practice mostly preferred field days as the pathway through which they could effectively receive information about a new agricultural technology. Indeed, further analysis by Murage et al. (2012) showed that use of field days as the desired dissemination pathway triggered the highest impact on both the probability and intensity of push–pull adoption, followed by use of FFSs, and farmer teachers in that order. The results were corroborated by Kassie et al. (2018), who noted that the adoption of push–pull practice appeared to increase according to the number of field days a farmer attended.

Under the push–pull production system, field days were organized by the participating farmers groups usually at one of the members' plot. It is through these interactions that publicity and knowledge about the practice were increased from the on-farm experiments and gave an opportunity to solicit feedback from the participating farmers (Oswald, 2005; Amudavi et al., 2008). Furthermore, field days provide a forum for sharing information, exchanging experiences, and encouraging farmer-to-farmer dissemination (Doss, 2003; Minja et al., 2004).

Field days are used to catalyze interactive learning among participants and they have a higher tendency to elicit farmer's interest compared to other dissemination pathways (Doss, 2003). They have been predominantly used as extension events where farmers interact with the facilitators as well as with other farmers and exchange ideas and experiences (Madukwe, 2006). In some cases, hands-on training and physical participation of the farmers are encouraged. Farmers' propensity to seek new agricultural knowledge motivates them to attend field day sessions (Amudavi et al., 2008) and in view, they favorably rated them in terms of effectiveness in information dissemination. In the study by Amudavi et al. (2008), the effectiveness of using field days in disseminating the push–pull practice was highly rated by the participating farmers particularly in being able to acquire knowledge and skills related to the technology component. Further analysis by Amudavi et al. (2008) showed that the effectiveness of field days was dependent on the knowledge and the capacity of the host farmer and the facilitator. This implies that the choice of the field day site and the facilitator is critical in encouraging farmers' participation and adoption particularly in making the farmers feel at ease during the sessions.

The farmer-to-farmer extension model using the farmer teachers has also been studied and was found to be very effective in disseminating the push–pull technology. Amudavi et al. (2009) showed that a farmer teacher was able to directly influence 17 other farmers to adopt the push–pull practice, while the follower farmers influenced on average two farmers each over a period of 2–3 years. This implies that, through a multiplier effect, the farmer-to-farmer extension model was able to drastically increase awareness and adoption of the practice. Most farmer teachers acknowledged that their desire to share knowledge with other farmers motivated them to become trainers.

Other pathways such as the FFS and print and the electronic media were also found to have niches within different farmers segments with selected socio-economic characteristics implying that a 'one-size fits all' approach would clearly not be appropriate in dissemination of the push–pull practice. Recommendations have been made to initially understand the socio-economic and demographic factors within a given region prior to choosing an appropriate information transfer mechanism (Murage et al., 2011, 2012).

The wide adoption of the push–pull practice has also been triggered by various factors. Studies have shown that the main drivers of adoption of the push–pull practice are to control Striga and stemborers, increase cereal yields, provide livestock fodder, control soil erosion, and improve soil fertility (Khan et al., 2014; Midega et al., 2015). Farmers who adopted a CA-based push–pull system reported lower proportions of stemborer-damaged plants. The studies by Khan et al. (2014) and Midega et al. (2015) further showed that farmers who practiced the push–pull technology were able to establish new initiatives in dairy and poultry farming. Moreover, Khan et al. (2014) noted that the increase

Figure 2 Sorghum under climate-smart push–pull technology, Siaya, Kenya.

in grain yields and availability of the leguminous Desmodium gave farmers the impetus to keep more poultry. In addition, farmers have been able to start organic farming through preparation and use of animal manure, thus allowing nutrient cycling and reduction in the use of chemical fertilizers (Fig. 2).

4 Benefits of push–pull practice in Conservation Agriculture systems

The push–pull practice fits well with the traditional mixed farming practiced under CA and is appropriate for the resource-poor farmers as it is based on locally available plants, not expensive external inputs like fertilizers (icipe, 2018). With its increased adoption of push–pull as a CA system, a wide range of direct and indirect benefits to farmers and the economy at large have been realized and documented.

4.1 Control of pests and weeds

Prior to the invention of the push–pull practice, the conventional control of stemborers, Striga weeds, and other pests in cereal farming using chemicals and other conventional methods had serious setbacks. Apart from being expensive, the use of chemicals to control pests often failed to reach the inside of plant stems where the stemborer larvae are found (Khan et al., 2006a). Furthermore, the behavior of the adult moth often makes it difficult to kill it as it lays eggs after dusk, making the use of pesticides ineffective in addition to being harmful to the environment (Khan et al., 2001, 2003). Pest larvae that are the damaging stage of all lepidopteran borers as well as the FAW are cryptic in their feeding behavior and feed inside plant whorls and stems where they cannot be effectively reached by insecticides (Midega et al., 2018). Similarly, the use of herbicides against Striga is neither effective nor feasible among smallholders because they are not affordable and do not prevent the buildup of Striga seed density in the soil.

Use of the push–pull practice has been proven very effective as it simultaneously controls the stemborers and Striga weeds significantly (Khan et al., 2006c). Recently, Midega et al. (2018) noted that use of the push–pull practice leads to a significant reduction of infestation by FAW in maize leading to lower damage levels. This novel practice uses a combination of behavior-modifying stimuli to manipulate the distribution and abundance of insect pests by repelling them away from the main crop (push) and simultaneously attracting them (pull) using other trap crops where the insect pest becomes concentrated and therefore facilitate their control (Khan et al., 2001, 2003, 2014; Midega et al., 2015). On the other hand, Desmodium suppresses Striga weed through a combination of mechanisms ranging from increased availability of nitrogen, soil shading, and by an allelopathic root exudation, which diminishes Striga seeds through suicidal germination, thus providing a novel means of *in situ* reduction of the Striga seed bank in the soil (Khan et al., 2003; Tsanuo et al., 2003; Midega et al., 2015).

4.2 Increasing grain yields

The main reason as to why the push–pull practice was developed was to minimize stemborer damage on cereals such as maize and sorghum, especially, in the SSA where it had caused a major yield loss. With the adoption of the push–pull practice, cereal production has significantly increased with minimal input use thus making it available in the household and providing surplus for the market at affordable prices. Khan et al. (2011) noted that the push–pull system is highly used by smallholders in Africa as it addresses the major constraints to achieving higher yields and it is economical. So far, over 197 000 farmers are achieving higher yields of maize and sorghum and over 75% reporting three-fold to four-fold increase, having harvested more than five tons of maize per hectare, up from previous yields of below one ton per hectare (Khan et al., 2006b; Fischler, 2010; icipe, 2018).

A study by Khan et al. (2008b) showed that although the initial costs of establishing the push–pull practice were significantly higher compared to the maize–bean intercrop and the monocrop, these costs were significantly reduced in the subsequent years. Further analysis from the same study showed that farmers were able to recoup the initial costs within the first year of establishment following the higher grains and fodder yields that they were able to harvest. Data from all the districts where the study was done showed a significantly higher total variable cost under push–pull in the initial years that significantly dropped in the subsequent years; despite the higher costs, the gross benefits from the push–pull system were reported to be higher during the same period. Furthermore, the returns to land and labor for the push–pull practicing farmers were higher than that for the non-push–pull farmers (Khan et al., 2008b). These results are corroborated by a recent study by Chepchirchir et al. (2017, 2018), who noted that the total revenues from sale of farm produce, total variable costs, and material input costs were significantly higher with push–pull than without push–pull in eastern Uganda. Chepchirchir et al. (2017) demonstrated that the intensity of adoption of the push–pull practice determined the average maize yields obtained, which ranged from 2.6 t ha^{-1}, if a farmer had a small plot of 0.01 ha, to 3.5 t ha^{-1} for farmers with 0.4 ha of land. A similar study by Kassie et al. (2018) showed that the unconditional mean of maize yield from plots with the push–pull practice was 3.9 t ha^{-1} while that for the non-push–pull plot was 2.3 t ha^{-1}, and that the per capita consumption of maize was higher for push–pull farmers (132 kg) compared to the non-push–pull farmers (113 kg).

4.3 Increasing dairy milk production

Most farmers in SSA and any other part of Africa practice mixed farming that includes cultivation of crops and livestock keeping; thus, lack of fodder can be a major constraint to productivity (Khan et al., 2006b). Provision of livestock feeds from push–pull fields became one of the main entry points for adopting the practice by most farmers (Khan et al., 2008a). The push–pull system generates quality fodder for livestock thus stimulating increased milk production and enhanced growth rate (Khan et al., 2006b). Furthermore, farmers practicing the push–pull system noted that the maize plants were relatively tall and hence apart from the feed from the companion crops, they were also able to harvest higher volumes of crop residues that were fed to livestock. In the study by Kassie et al. (2018), the annual mean milk production for push–pull adopters was approximately 460 liters per cow, relative to 263 liters per cow for the non-adopters. Farmers who were interviewed in this study observed that the companion plants (Desmodium and Brachiaria fodders) more than doubled their cows' daily milk production. Desmodium being a legume contains high protein, dry matter, and fiber, which are good for rumen digestibility hence leading to higher milk yield and improved growth of the livestock. On the other hand, Napier grass is very important in milk production thus increasing the farmers' economic returns. Farmers acknowledged that when animals are fed with quality fodder, they were also able to produce products that are healthy to human beings for consumption (icipe, 2018). Many farmers referred to the push–pull as a 'springboard' for diversifying farming systems, especially through the incorporation of dairy operations using Napier and Desmodium as fodder (Fig. 3).

4.4 Improved market participation

Compared to non-adopters, farmers who practiced push–pull farming can participate in the market to sell their excess products such as grain, milk, fodder, and manure. Kassie et al. (2018) noted that, on average, a push–pull adopter sold approximately 406 liters of milk per year while non-adopters sold 161 liters. Furthermore, adopters of the push–pull practice sold more maize than the non-adopters. In terms of net income from maize, adopters achieved a 55% higher return in comparison with non-adopters demonstrating a higher productivity and income from the adoption of the push–pull practice, which can translate into improved household food security and reduced poverty. Previous studies by Khan et al. (2008b) showed that even though the total labor cost and total variable cost were lower in farmers' practice as compared to the push–pull fields, the total gross revenue and gross benefit of push–pull were significantly higher and that farmers were able to earn more by being able to sell their products in the

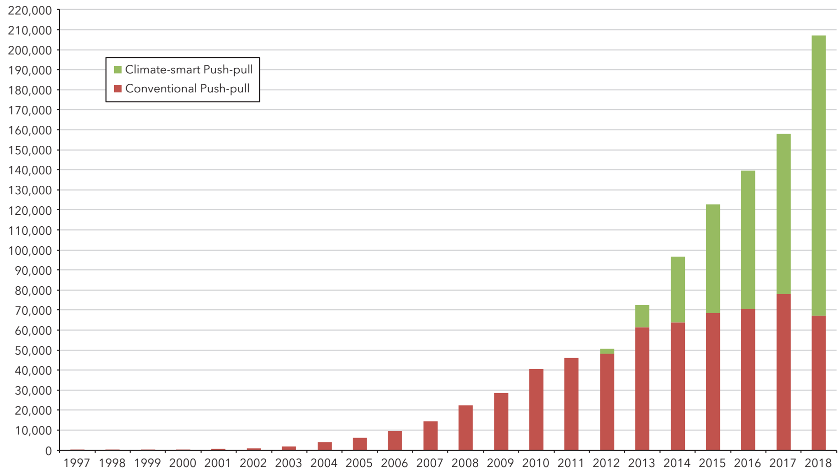

Figure 3 The trend in adoption of conventional and climate-smart push–pull technology.

market. Market participation is important to economic growth and farm level poverty reduction as farmers can benefit from welfare gains derived from trade (Barrett, 2008).

4.5 Increased household economic returns

Agriculture is classified as the highest contributor to the Gross Domestic Product (GDP) in Kenya in terms of food productivity and employment. The contribution of the push–pull strategies to household food security and economic returns cannot be over-emphasized. The intercropping of maize, grasses, and fodder legumes has enabled farmers to increase crop yields and thus improve their food security and gross benefits. Not only are farmers able to use the resultant yields for their household consumption, but also are able to sell the excess to the market. Furthermore, the increased production of quality fodder from push–pull farms enhances household economic returns through sale of excess milk and fodder (Khan et al., 2008b; Kassie et al., 2018; Chepchirchir et al., 2018). In a study by Khan et al. (2008b), it was noted that with effective control of stemborers, striga, and other biotic stresses, a significant cost–benefit return of 2.2 was reported in the push–pull technology relative to 0.8 for the maize monocrop. This study further reported a sustainable increase in maize grain yields and higher returns to labor.

Using long-term researcher-managed trial data and partial budget and marginal analysis, De Groote et al. (2010) found that the push–pull practice was more profitable than other practices used to control Striga weed and stemborer. Further economic studies by Kassie et al. (2018) observed that although adoption of push–pull increased the cost of maize production by 15.3%, the average net maize income increased by 38.6%, representing an additional US$20.34 per capita per year (approximately US$20). Overall, Kassie et al. (2018) found that the push–pull technology generates economic benefits of US$73 million, thus contributing to lifting out of poverty 75 790 people per year. This compares closely with Chepchirchir et al. (2018) who through a 20-year period of the simulation of the economic model observed that push–pull farmers in eastern Uganda would have an overall net gain of US$3.8 million with a net present value of US$1.61 million, internal rate of return of 51%, and the benefit cost ratio of 1.54.

Additionally, the companion crops have an added advantage of being useful fodder for livestock; hence, farmers can confine their livestock into zero-grazing units and therefore accumulate excess manure for use in their farms and also for sale if in excess. Further analysis by Chepchirchir et al. (2018) showed a higher gross margin per hectare of US$725 from maize and fodder in a push–pull field, a gross margin of US$405 from maize without fodder, and a gross margin of US$239 from a non-push–pull farm. This implies that the fodder in a push–pull farm on average contributed an additional US$320 to the farm income, which was much higher than a gross margin from a non-push–pull farm. These are additional farm incomes on top of extra profits arising from cost savings from reduced time, labor, and fuel input in land preparation in CA systems.

All these form a wide range of economic benefits that enhances the livelihoods of smallholder farmers. Another economic benefit of the push–pull practice is the ability to use fewer or no pesticides and other chemicals, hence making it a low-cost practice that is affordable to smallholders. Since there is less use of costly chemical inputs such as fertilizers as well as labor and fuel in push–pull CA farming, farmers can minimize their production expenses and hence increase their income without causing any negative impact to the environment. Furthermore, the push–pull practice is based on locally available plants that are not expensive, and thus fits well with traditional mixed cropping systems under CA. This cuts on the cost of training about the technology since most of the farmers are familiar with the methods, that is, the planting of Napier grass and Desmodium and its techniques.

4.6 Improving soil health

The push–pull practice in CA systems has been proven to ecologically enhance soil biodiversity, thereby improving soil health and fertility. Being a leguminous crop, Desmodium fixes the atmospheric nitrogen to improve the nitrogenous component in the soil in addition to organic matter from the fallen leaves, hence improving soil fertility (icipe, 2018). Increasing nitrogen into the soil is important in the food chain where nitrates are converted into proteins and produce ammonia (Vitousek et al., 2002). Vitousek et al. (1997) had earlier noted that microbial breakdown of ammonium and nitrates in the soil enhanced the release of nitrous oxide. Nitrates are important in tissue development and building immune systems in the plants (Liu et al., 2015). Most of the fertilizers contain high concentrations of nitrate to help in production of seeds and plant development. The use of the push–pull practice limits fertilizers and pesticides application thus reducing the harmful chemicals that go into the soil. As a result, the push–pull practice contributes to reduced levels of greenhouse gasses that originate from conventional tillage-based agricultural practices. Furthermore, the increased use of mineral fertilizers especially during the rainy season is harmful to the water bodies if soil erosion is not controlled (Moss, 2008). In CA systems, runoff and soil erosion are minimized.

Besides improving fertility, Desmodium together with the surrounding Napier grass protects the soil against erosion Khan et al. (2003). Furthermore, because of its ground cover, Desmodium provides a mulch that reduces soil temperatures. Therefore, farms under the push–pull practice become more sustainable and resilient, with improved potential to mitigate the effects of climate change. Majority of push–pull adopters integrate the technology with crop–livestock production in mixed farming systems. This close association with livestock means that farmyard manure can be added to the soil, increasing the fertility benefits already gained from nitrogen fixation by the Desmodium intercrop. Most of the farmers thus notice an improvement in their soil within a very short time of adopting the technology (Khan et al., 2011). Therefore, farmers who are using the push–pull method can improve their potential to mitigate climate change (Midega et al., 2015).

Other benefits of CA-based push–pull practice to the soil include conserving soil moisture and improving soil carbon sequestration, biomass, and soil biota (Midega et al., 2015). The push–pull practice when applied in CA systems contributes to conserving and enhancing the production resource base. The technology improves the overall agro-ecosystem resilience through the practical application of the CA principles of continuous minimum mechanical soil disturbance, continuous soil cover, addition of organic matter, prevention of loss of top soil through soil erosion, improved water conservation, and other ecosystem services (Kassam et al., 2017).

4.7 Improving human health

The improvement of human health is one of the indirect benefits of CA-based push–pull practice to the livelihoods of the community. Enhancing the production of fodder indirectly impacts on health indices, especially for children through increased protein uptake in milk and milk products. Farm households practicing push–pull have higher dietary diversity scores than non-push–pull households (Ogot et al., 2018). Moreover, the additional income realized from the sale of push–pull products and by-products enables many farm households to purchase foods that they are not able to produce for themselves. Additionally, the push–pull practice allows less or no use of mineral fertilizers and chemicals in controlling the pests and weeds and hence the products from the push–pull technology offer nutritional health to smallholder households. Mineral fertilizer contains toxic chemicals that are consumed by human beings through the vegetables and cereals and are very harmful when the chemicals flow into ground water used for drinking. Therefore, the CA-based push–pull practice contributes to reduced levels of chemicals in the environment that could cause human ill-health. The reduction in the use of costly synthetic insecticides and herbicides also potentially enhances human health (Pickett et al., 2014). The control in soil erosion also reduces the potential hazards of human displacement and a high rate of death as a result of land and mudslides caused by loose soils.

4.8 Environmental health

The adoption of the push–pull practice in CA systems has enormous positive impacts to the environment, in general, which are basically because of other benefits such as improved soil health, crop and livestock health, and household economy. Climate-resilient technologies contribute to maintaining agro-ecosystems functions and services that are usually provided by natural systems. This means integrating instead of segregating, closing water and nutrient cycles, increasing biological and genetic diversity, and regenerating instead of degrading bio-resources (Pretty, 2011).

Push–pull practice in CA systems contributes to stable and climate-resilient agro-ecosystems by providing farmers with a tool for on-farm diversification which is in line with these underlying principles. With increased economic returns from farming, there is a probability of reduction in rural urban migration since households can make more money from farming than in towns. Urbanization has been a major cause of heavy agricultural mining, deforestation, and overpopulation in the urban areas leading to negative environmental effects. By use of the push–pull practice in CA systems, rural communities can earn a better income from crop and livestock farming (Khan et al., 2006b). Besides, increase in fodder production allows farmers to intensify dairy production and hence there is reduced soil erosion since the animals do not trample and compact the soil. Furthermore, intensification of dairy farming leads to less attack by ticks, hence the low use of acaricides, which would otherwise be harmful to the environment.

4.9 Gender equality

The basic principle in the dissemination of the push–pull practice has been targeting all gender groups equally. These include men, women, youth, and people living with disabilities. Adoption of the push–pull practice has however had particular benefits for women farmers and has been demonstrated that being a female farmer accelerated the speed of uptake (Murage et al., 2011). A quick and rapid adoption of the push–pull practice by women farmers was observed, while men were seen to allocate larger portions of land to the practice (Murage et al., 2015). It has been argued that women often try out new innovations to tackle the overarching constraints such as the Striga and stemborers, which affected them more directly than men. Indeed, the study by Murage et al. (2015) showed that women rated the Striga and stemborers constraints higher than men and hence their desire to adopt the push–pull technology. Specifically, adopting the practice ensured more grain using less labor, hence reducing the time women must spend digging and weeding. As a result, women are able to save extra time to invest in other productive activities and therefore increase and diversify their income (Khan et al., 2015; Grassi et al., 2015).

Women seem to be more affected by Striga infestation as they provide the bulk of labor for manual uprooting. Subsequently, the reduction in yields, hunger, and malnutrition disproportionately affect women and children more than men (World Bank, 2008). In addition, women bear the burden of feeding their livestock with the limited sources of fodder given the constraining land sizes. The adoption of the push–pull practice in CA systems avails women with options to increase cereal yields, control Striga, and increase fodder for their livestock *in situ*. However, men also tend to take over enterprises that seem to have promising financial benefit with less labor requirement as do all CA systems. Hence, with the expected increase in cereal yield, some of which can be sold to the market and the expected income from the sale of excess milk and fodder coming, it is expected that men would take up the practice.

Households with increased incomes, particularly for women, are able to educate both boys and girls. Previous studies have shown that girls' education tended to be given less emphasis, especially in poor families (e.g. Stromquist, 2001; Hossain, 2004). In such cases, boys were taken to school while girls remained behind to help their mothers with household chores. However, this scenario has changed in most families that have adopted the push–pull practice in eastern Africa.

The dissemination of the practice has also built the skills, confidence, and networks of many women farmers, hence improving their social status in the community; they are seen as intellectuals who offer advice to upcoming farmers (icipe, 2018). Empowering women and girls has a multiplier effect in the economy and brings about growth and development in the country (OECD, 2010). Kassie et al. (2015) stated that women who are empowered are able to access financial services, develop new skills, increase income-earning opportunities, and access information about the market.

4.10 General economic welfare

The push–pull practice has led to improvements in the general welfare of the households practicing through increased incomes (Khan et al., 2008a). The practice has been rated as efficient and low cost; hence, families are now able to use the extra income to pay school fees for their children, purchase household items, and improve their overall nutrition and health (Khan et al., 2014). The general food security of push–pull adopters has improved with a proven increase in per capita consumption of grains and milk. Kassie et al. (2018) noted that the per capita milk and maize consumption was higher for push–pull adopters than the non-adopters. A similar study by Chepchirchir et al. (2017) in eastern Uganda showed that on average, the household income ranged from US$135 for a farmer with 0.01 ha of push–pull to an average of US$273 for a farmer who plants 0.4 ha of the practice implying that income varied with the intensity of production. The study further demonstrated that the per capita food consumption increased from US$15 for a farmer with 0.01 ha area to US$27 for a farmer with 0.4 ha, with a clear indication that the extent of poverty declined significantly with the intensity of adoption. Increasing food production especially for staple crops can essentially lead to food security and sustainable economic growth (AGRA, 2014). Kassie et al. (2018) and Chepchirchir (2018) observed a general welfare improvement in gains from income and poverty reduction with the adoption of the push–pull practice.

4.11 Contribution to the Sustainable Development Goals (SDGs)

The above information clearly shows that the push–pull practice in the CA system has generated a wide range of benefits either directly or indirectly to the rural households. The chapter has demonstrated that the practice has immensely contributed toward attainment of the sustainable development goals (SDGs) – http://www.push-pull.net/sdgs.shtml. For example, the practice directly contributes to SDG 1 on ending extreme poverty through generation of incomes from the sale of excess grains, milk, fodder, and manure. This has been alluded to by studies by Chepchirchir et al. (2018) and Kassie et al. (2018). We have seen that the participating households were able to produce excess grains, milk, manure, and other by-products from the technology, all of which contributed to household income which in turn led to reduction in poverty.

It is also evident that the practice has contributed to SDG 2 by ending hunger, achieving food security and improved nutrition, and promoting sustainable agriculture. Families are able to have timely access to enough quality food either through their own production or through purchase from the market. Moreover, they have nutrition security through consumption of diverse diets such as proteins from milk and from other purchased food products. With good-quality food and diverse nutrition, household members can live a quality and healthy life thus contributing to SDG 3 in ensuring health lives and promoting well-being at all ages. Consumption of quality and healthy food free of toxic chemicals helps in managing preventable diseases.

Hunger and extreme poverty have been some of the reasons children were kept out of school. With a well-fed family and good-quality health, children are able to fully participate in schooling. Notably, most of the households practicing push–pull have also indicated that they are now able to give their children proper education by being able to pay school fees promptly and buy other school requirements; their children's performance in school has improved, hence contributing to SDG 4.

Evidently, the push–pull practices in CA systems have also in a special way contributed to SDG 5 on achievement of gender equality and empowerment of women and girls. This has been made possible by using a dissemination strategy that equally targets all gender groups in the society. It has been shown that women, men, youth, and people living with disabilities have unequivocally been able to participate in the push–pull production system each sharing their positive experience and benefits from the practice. Furthermore, this review has already demonstrated how women farmers have benefited through capacity building and skills development, being able to address the day-to-day challenges at the household level such as food availability and education, which often are the responsibility of women farmers in the rural community.

The use of the climate-smart push–pull production system has contributed to SDG 13 in the action to combat climate change and its impacts. This has been achieved through the use of drought-resilient local plants and natural processes to control Striga and stemborers without introducing toxic chemicals that have a high carbon footprint and negatively impact the environment. This has in addition helped in improving soil health and conserving biodiversity, hence contributing to SDG 14 focusing on conservation and sustainable use of life under water as well as SDG 15 on protecting restoration, using sustainably the life on land. Indeed, the United Nations General Assembly recognized push–pull as one of the practices that have benefited farmers by doubling yields through IPM, soil conservation (United Nations General Assembly, 2010), and by making cereal cropping systems resilient to climate change (United Nations General Assembly, 2015).

4.12 Disease management and benefits in Conservation Agriculture systems

The push–pull CA practice exploits the chemical ecology and natural plant genetic diversity of repellent intercrops and trap plants (Khan et al., 2006b; Cook et al., 2007) and is based on an understanding of chemical ecology, agro-biodiversity, and plant–plant and insect–plant interactions (Miller and Cowles, 1990; Cook et al., 2007). The companion plants used in push–pull release chemicals in a stimulo-deterrent tactic that mediate the behavior of both stemborers and beneficial insects, thus controlling their distribution and abundance as a pest-management strategy (Khan et al., 2006c). Behavior of insect pests is mediated by herbivore-induced plant volatiles (HIPVs) emitted by these plants. This approach is exploited to reduce pest, disease, and parasitic weed – related constraints to the production of staple cereals, principally maize and sorghum in Africa (Pickett and Khan, 2016). The push–pull CA practice has been proven to reduce populations of stemborers and FAWs and subsequent damage on maize plants (Khan et al., 2014; Midega et al., 2015).

In a study conducted in western Kenya on the effect of cropping system on the incidence and severity of maize ear rots, the authors found that the push–pull CA practice had a significant effect ($p \leq 0.001$) on the incidence of ear rots by reducing stemborer infestation of maize (Owuor et al., 2018). Maize ear rots fungal infections are found in all agro-ecologies where maize is grown (Dragich and Nelson, 2014), with the most prominent genera found in maize grown in SSA being Aspergillus, Fusarium, Sternocarpella, and Penicillium, causing estimated yield losses ranging between 10% and 30% (Kapindu et al., 1999; Ajanga and Hillocks, 2000; Bigirwa et al., 2007). Stemborer insect infestation and mechanical damage of maize have been shown to predispose the maize grains to ear rots and mycotoxin attack. Stemborer infestation has been observed to have a positive and high correlation with incidence of ear rots in maize (Ajanga and Hillocks, 2000). Maize crop losses due to ear rot damage is associated with mycotoxins, the most prevalent of which are fumonisins, zearalenone, deoxynivalenol, and aflatoxins (Gxasheka et al., 2015). Mycotoxins cause serious diseases both in humans and animals (Zain, 2011) and are thus stringently regulated (Otsuki, 2001).

The significant reduction in the incidence of ear rots observed in the push–pull fields resulted from the multiple ecological benefits provided by the practice (Owuor et al., 2018), particularly stemborer control as well as improvement of soil organic matter (Midega et al., 2005). Moreover, interaction of other ecological factors such as buildup of soil organic matter (Alakonya et al., 2008), cover cropping (Tédihou et al., 2012), and intercropping (Vincelli, 1997; Flett and Ncube, 2015) have been observed to reduce the incidence of ear rots in maize. The push–pull CA practice deploys an intercropping strategy, increases soil organic matter, and Desmodium used in push–pull is a cover crop. Maize grown under the push–pull CA practice had significantly less ear rots than monocrop maize, reducing the incidence level to 7.3%. Monocropped maize fields had significantly higher ($p \leq 0.001$) incidences of all the types of ear rots than maize planted under push–pull (Owuor, et al., 2018). Ear rot incidences in monocropped maize and push–pull, respectively, were 7.31% and 3.33%, Diplodia; 4.48% and 1.30%, Gibberella; 2.09% and 0.65%, Aspergillus; 0.51% and 0.21%, Fusarium; and 0.40% and 0.11%, Penicillium (Owuor et al., 2018). The severities of maize ear rots were also significantly different ($p \leq 0.001$) between the two cropping systems but different ear rot types had different severity levels. For example, Diplodia and Gibberella ear rots were the most severe, 1.85 and 1.15 $\mu g\ kg^{-1}$ in sole maize, and 0.84 and 0.62 $\mu g\ kg^{-1}$ in push–pull, when compared to other ear rots. Aspergillus had higher incidence than Fusarium, yet it had the lower severity rating (0.25 and 0.09 $\mu g\ kg^{-1}$) than Fusarium (0.68 and 0.19 $\mu g\ kg^{-1}$) in monocropped maize and push–pull, respectively. Penicillium ear rot rated less severely, 0.05 and 0.03$\mu g\ kg^{-1}$ in monocrop maize and push–pull, respectively.

5 Future trends and conclusion

This chapter describes the benefits of the push–pull practice in CA systems that has been developed by *icipe* and partners. Since its inception almost two decades ago, the practice has continuously been improved to address the challenges facing smallholder farming in SSA. The conventional push–pull that was originally using Napier grass was challenged by climate change conditions and hence was improved by selecting drought-tolerant crops. Other chemical experiments on the practice continue to be implemented in order to enhance its benefits. The two versions of push–pull production systems have been steadily adopted over the years and the diffusion is still expanding to other regions in SSA.

The push–pull CA practice exploits the chemical ecology and natural plant genetic diversity of repellent intercrops and trap plants and is based on understanding of chemical ecology, agro-biodiversity, and plant–plant and insect–plant interactions. The companion plants used in push–pull release chemicals that mediate the behavior of both stemborers and beneficial insects, thus controlling their distribution and abundance as a pest-management strategy that reduces pest, disease, and parasitic weed – related constraints to the production of staple cereals in Africa. Stemborer insect infestation and mechanical damage of maize have been shown to predispose the maize grains to ear rots and mycotoxin attack. Mycotoxins cause serious diseases both in humans and animals. The push–pull CA practice has been proven to reduce populations of stemborers and FAWs and subsequent damage on maize plants and thus had a significant effect ($p \leq 0.001$) on the incidence of ear rots by reducing stemborer infestation of maize. The significant reduction in incidence of ear rots observed in the push–pull fields resulted from the multiple ecological benefits provided by the CA practice, particularly stemborer and FAW control as well as cover cropping, intercropping, and improvement of soil organic matter. Maize grown under the push–pull CA practice had significantly less ear rots than monocrop maize, reducing the incidence level to 7.3%. Monocrop maize fields had significantly higher ($p \leq 0.001$) incidences of all the types of ear rots than maize planted under push–pull.

While the initial proposition for the CA-based push–pull practice was to control stemborers in cereal production, the adoption of push–pull production systems led to other multiple benefits, which have brought welfare to smallholder farmers. The system has brought under control the parasitic Striga weed as well as the new threats posed by the outbreak of FAW. Further, farmers who have adopted the CA-based push–pull practice have experienced more benefits including increase in production of cereals, improved dairy enterprise, improved soil, environmental and human health, market participation, gender equality, and general household economic welfare. This has led to direct contributions to the attainment of the SDGs making the system a unique pathway to come out of poverty. With the practice addressing critical constraints to smallholder production, it is expected that its expansion will continue both at the farm level and in the region as one way of scaling up the benefits of the push–pull practice in CA systems.

There are at least 350 million smallholders in sub-Saharan Africa (SSA) whose cereal crops suffer from stemborers, fall army worm and striga, and they could immediately benefit from adoption of push-pull technology. The *icipe's* technology transfer unit is disseminating push-pull in SSA by proving training.

Efforts are underway to further adapt push-pull to more drought and rising temperature in Africa by replacing 'Mulato II' with new Brachiaria cultivars, for example, 'Piata' and 'Xaeres' as trap plants and by replacing *D. intortum* with more drought-tolerant *D. ramosissimum or D. Incanum*. The push-pull technology has been demanded in Asia also due to recent invasion of fall armyworm in the continent.

Although push-pull was originally developed for maize production systems, it has been applied successfully to sorghum, millet, upland rice and sugarcane. Research is also being carried out to adapt its application to cotton, coffee and horticultural crops and this adaptability will give it enormous potential for its reproduction elsewhere.

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