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APPLIED ZOOLOGICAL RESEARCH FOR SUSTAINABLE AGRICULTURE & FOOD SECURITY

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Exploring chemical ecology for developing push-pull strategies for smallholder farmers in Africa and beyond

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Agricultural development in sub-Saharan Africa (SSA) is constrained by biophysical factors, low capacities, institutional and policy bottlenecks, while development assistance to agriculture has declined to only 4% of public expenditure (World Bank, 2008; IFAD, 2011). Although agriculture contributes to over 25% of the gross domestic product (GDP) and more than half of export earnings, Africa's per capita food production has declined over the past two decades. Rural Africa is characterized by continuing stagnation and often deterioration, low crop and livestock productivity, low farm incomes and the rising vulnerability of resource-poor smallholder farmers who constitute the majority and whose basic source of livelihood is agriculture (World Bank, 2008). More than 265 Million rural poor face higher levels of hunger and poverty. Longer-term development challenges include dependence on a few primary commodities, poor human capacity, increasing migration to urban areas, low employment especially of the youth and women, and climate change (World Bank, 2007).

Cereals remain the major food and cash crops for the majority of the resource-poor smallholders in SSA, grown alongside livestock in mixed farming systems. Production of the main cereals, maize, *Zea mays* (L.), and sorghum, *Sorghum bicolor* (L.) Moench is severely reduced by a complex of biotic constraints, namely stem borer pest complexes, parasitic striga weeds, and more recently fall armyworm invasion as well as abiotic factors, such as water stress and degraded soils. The most economically significant insect pests are Lepidopteran stem borers in the families Noctuidae and Crambidae, e.g. the indigenous *Busseola fusca* (Noctuidae) and the invasive *Chilo partellus* (Crambidae) as well as the fall armyworm (FAW) *Spodoptera frugiperda* (J E Smith) (Lepidoptera: Noctuidae) (Midega, 2018). Over 20 stem borer species attack cultivated graminae in SSA (Kfir *et al*., 2002), causing between 30% and 80% yield losses of cereal crops (Kfir *et al*., 2002). Suitable and cost-effective integrated pest management (IPM) strategies therefore need to be developed specifically for smallholder farmers in Africa.

Rationale for IPM Strategies in sub-Saharan Africa

Several factors necessitate intensification of smallholder agriculture in Africa, not least environmental degradation of the natural resource bases and human population pressure on productive resources, which have caused food insecurity, undernutrition, poverty, high morbidity and human out migrations. Intensive land use without sustainable investment in soil fertility enhancement has transformed most of the natural landscape, as the overall quality of soil and vegetation have declined and reduced agricultural yield potential. Land clearance for agriculture is causing serious deforestation (World Resources Institute, 2007), and there is progressive depletion of soil nutrients, particularly of nitrogen and soil organic carbon (Solomon *et al*., 2007). Loss of vegetation cover has exacerbated Soil erosion, further contributing to degradation of farmlands. The soils are also poor in organic matter from continuous cropping and poor farming practices, and in need of an agronomic innovation that continuously improves soil health (Sanchez, 2002; Oswald, 2005; Rodenburg *et al*., 2005). Moreover, effects of climate change are expected to have greater impacts on agricultural production in SSA, as production constraints are expected to increase during the next few decades as agriculture resources are depleted to meet the extra food demand by the growing population. The resource-constrained smallholder farmers living in the arid and semi-arid regions who practise mixed crop–livestock systems are particularly badly affected.SSA is projected to have more than 500 million food insecure people by 2020.

Rapidly increasing demand for food because of population growth, urbanization and changing food consumption patterns is outstripping food supplies and raising the need for sustainable intensification of production systems (Pretty *et al*., 2011).

Old and new biotic challenges compounding low agricultural productivity

In addition to the old biotic constraints to smallholder productivity, the fall armyworm (FAW) invasion in Africa is a new challenge. Up to total loss of maize and other crops have been reported by smallholder farmers due to the recent invasion of Africa by the FAW (CABI, 2017; Midega *et al*., 2018), originally a pest native to tropical and sub-tropical America (Todd and Poole, 1980). More than 46 countries in Africa are already affected and the pest is extending rapidly to other countries (Goergen *et al*., 2016, Cock *et al*., 2017). The pest adds to the diversity of Lepidopteran pests of cereal crops adding to negative impacts on agricultural production and food security in Africa. The FAW invasion has adverse economic impacts on smallholder farmers as it directly increases their capital costs through increased production costs in required labour and inputs, specialised knowledge required to deal with the pest, the inability of agricultural systems to respond to sudden invasions, and resultant yield loses. The FAW ravages a wide host range of economically important crops such as maize, rice, sorghum and sugarcane, as well as other crops, including cabbage, beet, peanut, soybean, alfalfa, onion, cotton, pasture grasses, millet, tomato, potato and cotton. The FAW reproduces rapidly, ovipositing egg masses in batches of 100 – 200 eggs (Sparks, 1979; Johnson, 1987; CABI, 2017). Eggs hatch in two to four days under optimum temperatures. Adult moths can survive two to three weeks during which female moths mate multiple times, producing up to 1000 eggs each. Their larval stages have 6 instars, the first of which is most voracious, consuming the most plant material. The larvae eat different parts of the plant, mainly young whorls, ears and tassels, depending on the larval age, stage of development and the host plant type. On maize young larvae eat leaves at night, leaving a 'window pane' effect, and hide in the plant funnel during the day. Larval feeding often kills the growing point and causing 'dead heart'. At the reproductive stage of maize, the larvae also attack reproductive organs, feeding on tassels and/or boring into the ears (Midega *et al*., 2018). The larger caterpillars also act as cutworms by entirely cutting the stem base of maize plantlets. As larvae grow older they hide inside the funnel, limiting the effect of pesticide applications and natural enemies. The FAW is a sporadic and long-distance migratory pest whose adult moths can fly over 100 km in a single night (Goergen *et al*., 2016). Most farming communities are ill prepared to manage the invasive pest.

Several control methods have been tried, including application of pesticides (chemical control), use of microbial organisms that attack FAW in its native range, for example *Beauvaria bassiana* and *Spodoptera frugiperda* multiple *nucleopolyhedrovirus* (SfMNPV), use of predatory insects and parasitic wasps (parasitoids), use of genetically modified crops containing Bt genes that are resistant to FAW, mass trapping of male moths using pheromones, preventing them from mating, and integrated pest management (IPM) - a combination of methods minimizing pesticide use (CABI, 2017).The most predominant method of managing the FAW has been application of synthetic chemical pesticides. The method has not been very effective, as it is dependent on farmers' knowledge, consistency of use, purchasing power and the choice of pesticide products (Midega *et al.*, 2018). Although chemical insecticides have been shown to provide control of the pest (Young, 1979), cases of resistance to some key insecticides have been reported (Yu, 1992; Al-Sarar *et al.*, 2006). Dispersion of the fall armyworm larvae lower into the maize plant canopy keeps them out of reach of topical insecticide applications (Cook *et al.*, 2004, Midega *et al.*, 2018). Single control methods are relatively costly, unsustainable or ineffective. Moreover, pesticides are not affordable for most smallholder famers in Africa, and their incorrect use has resulted in poisoning farmers and the environment.

The necessity of Integrated Pest Management (IPM) to control stem borers and fall armyworm

Most available literature on FAW control relate to agricultural systems in its native Americas which differ from those in Africa and therefore control methods that have been effective in their native habitats may not be effective in Africa. However, evidence from Latin America indicates that an IPM approach may be necessary in which pesticide use are minimised and alternative approaches used like exploiting the pest's natural enemies and crop monitoring (CABI, 2017). Climatic conditions in Africa support prolific reproduction of the FAW, which is expected to result in increasingly severe damage to crops (Goergen *et al.*, 2016) as the invasive pest is likely to have few natural enemies. Conventional control methods have limited effectiveness, as explained above, notably the difficultly in application of pesticides, and development of resistance by the pest to some insecticides and transgenic technologies such as Bt-maize. An integrated management approach for fall armyworm that fits within the mixed cropping nature of the African farming systems is necessary for the resource constrained farmers.

Suitable and cost-effective integrated pest management (IPM) strategies therefore need to be developed specifically for smallholder farmers in Africa (Midega *et al.*, 2018). Thus, an integrated pest management technology like Push-pull (www.push-pull.net) that exploits natural processes, including the use of natural enemies, is most promising.

Parasitic Striga weeds

Parasitic weeds in in the genus *Striga* (Scrophulariaceae) commonly known as striga, further severely constrain cereal production in SSA (Oswald and Ransom, 2001; Khan *et al.*, 2014). There are at least 22 species of *Striga* of which *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze have been identified in Africa as the most socioeconomically important constraints to cereal cultivation in much of SSA (Gressel *et al.*, 2004; Gethi *et al.*, 2005). Striga infestation weakens the host cereal plants by competing for and using up its supply of moisture, photosynthates, and minerals (Tenebe and Kamara, 2002). The weed quickly adapts to its environment (Bebawi and Metwali, 1991) and germinates in response to specific chemical cues present in root exudates of its hosts or certain non-host plants (Yoder 1999, Parker and Riches, 1993). Striga roots mesh with the host plant's root system and injects phytotoxins to its hosts' root system (Frost *et al.*, 1997, Gurney *et al.*, 1999; Gurney *et al.*, 2006). Striga infestation causes significant reductions in host plant height, biomass, and grain yields (Gurney *et al.*, 1999). Striga weed infestation causes up to 100% cereal yield losses. Conditions like degraded environments, low soil fertility, higher soil temperature and low rainfall (Gurney *et al.*, 2006) intensifylosses caused by Striga in subsistence farming systems in SSA.

Ineffective pest and weed control methods

Research and extension institutions in Africa often recommend the use of insecticides and herbicides which have not been effective in the management of stemborers, fall armyworm and striga. Moreover, subsistence farmers in SSA cannot afford expensive chemicals. Insecticide use in Africa is limited, largely due to shortage of information, inaccessibility of appropriate and effective products, and associated high costs (Midega *et al.*, 2018). Transgenic plant technology such as Bt maize has been tried (Frizzas *et al.*, 2014). However, development of field resistance by stemborers and FAW to transgenic crops has been documented, including resistance to Cry1F maize in Puerto Rico (Storer *et al.*, 2010). Majority of smallholder farmers therefore do not attempt to manage stemborers, FAW or striga, and consequently suffer high grain yield losses and food insecurity (Chitere and Omolo, 1993; Oswald, 2005; Midega 2018).

Sustainable management of pests, weeds and resource degradation therefore needs suitable intensification methods that maximize soil quality and crop productivity, adopting a systems approach (social, economic and environmental) to agricultural development, and developing solutions based on integrated analyses of specific agro-ecosystem conditions and farmer practices (IAASTD, 2009; Pinstrup-Andersen, 2010). Significant and sustainable productivity increases require a more holistic approach, reflecting the multi-functionality of agriculture which integrate a variety of resource-conserving technologies and practices – i.e. integrated pest management (IPM), integrated soil fertility management (ISFM), and livestock integration (Pretty *et al.*, 2006). In order tomanage the production constraints, approaches that are compatible with the polycultural nature of low-input farming systems in Africa need to be developed by understanding the intricate biological interactions within ecosystems, farm landscapes and the socio-economic conditions of smallholder farmers. One such approach is the 'push-pull' technology which is compatible with African socio-economic conditions as it does not rely on high external inputs, but biological management of local bio-resources.

The Push-Pull Innovation

The push-pull technological innovation was developed by the International Centre of Insect Physiology and Ecology (ICIPE) is a tested IPM strategy that sustainably intensifies smallholder agriculture by applying scientific knowledge based on the understanding of insect and plant interactions and ecological management of pests and soil health, and reversing land degradation. The technology significantly increases cereal and livestock productivity by addressing the interrelated problems caused by the above biotic constraints (principally insect pests and weeds), soil and environmental degradation, lack of livestock fodder, loss of biodiversity, increasing temperatures and water stress through improved management strategies (Khan *et al.*, 2014, Midega *et al.*, 2015b). The technology is a polycropping innovation that holistically combines resource-conserving principles of IPM and ISFM by using natural processes and locally available bio-resources (Cook *et al.*, 2007; Hassanali *et al.*, 2008). It was developed for smallholder farming systems based on the traditional African diversified cereal-legume-fodder intercropping practice in which the perennial intercrop maintains continuous soil cover and provides live mulching, thus conserving soil moisture, improving arthropod abundance and biodiversity as well as the food web of natural enemies of stemborers (Khan *et al.*, 2002, 2006a; Midega *et al.*, 2015a).

The technology effectively controls the major insect pests of cereals in SSA, i.e. lepidopteran stemborers and the Fall armyworm (Midega *et al.*, 2018), and the devastating parasitic striga weeds, both of which can cause total yield loss to cereals (Khan *et al.*, 2014). The technology relies on understanding natural biochemical processes, and their underlying chemical ecology, agro-biodiversity, plant-plant and insect-plant interactions (Cook *et al.*, 2007; Khan *et al.*, 2014; Pickett and Khan, 2016). It deploys inter- and trap crops in a mixed cropping system (Khan *et al.*, 2006b) which release behaviour-modifying stimuli (plant chemicals) to manipulate the distribution and abundance of stemborers and beneficial insects.

Push–pull exploits the phytochemicals released by the companion plants grown in between and around the main cereal crops.Plants with appropriate repellent and attractant properties that naturally emit signalling chemicals (semiochemicals) and influence plant-plant and insect-plant interactions were studied and selected. Plants that are highly attractive for egg laying by cereal stem borer pests were selected and employed as trap crops, to draw pests away from the main cereal crops. Of these, Napier grass (*Pennisetum purpureum* [Schumach]) produce significantly higher levels of volatile cues (stimuli), used by gravid stem borer females to locate host plants, than maize or sorghum. Despite its attractiveness to stem borer moths, P. *purpureum* grass supports minimal survival of the pests' immature stages. Plants that repelled stem borer moths notably, *Melinis minutiflora* P. Beauv., and forage legumes in the genus *Desmodium*, were selected as intercrops, which also attracted natural enemies of the pests through emission of (*E*)-*β*-ocimene and (*E*)-4,8-dimethyl-1,3,7-nonatriene. *Desmodium* intercrop suppressed parasitic weed, *Striga hermonthica* (Del.) Benth., through an allelopathic mechanism. *Desmodium* root exudates contain novel flavonoid compounds which stimulate suicidal germination of *S. hermonthica* seeds and dramatically inhibit its attachment to host roots. push–pull system effectively addresses the production constraints faced by the farmers and is an appropriate system because it uses locally available companion plants rather than expensive inputs.

Climate-Smart Push-Pull : The Push-Pull system has been recently adapted for drier areas vulnerable to climate change. We identified and selected new drought and temperature tolerant trap (*Brachiaria* cv mulato) and intercrop plants (e.g. *Desmodium intortum*) suitable for drier agro-ecologies. The new trap and intercrop plants also have appropriate chemistry in terms of stem borer control and striga suppression.This has made the technology more resilient in the face of climate change as rainfall becomes increasingly unpredictable. Our recent study has established that the climate-adapted version of push-pull is also effective in controlling the new invasive pest, fall armyworm, providing a suitable, accessible, environmentally friendly and cost-effective strategy for the management of the fall armyworm.

The companion crops in the push-pull system provide valuable forage for farm animals. The climate-adapted companion plants (both trap and repellent plants) have been proven to generate high-quality livestock fodder over long periods of drought. The plants also improve biodiversity, soil conservation and organic matter improvement among other ecosystem services. (Midega *et al.*, 2015b). The leguminous intercrops also improve soil fertility by fixing atmospheric nitrogen and improving carbon sequestration, as well as moisture retention. The system is appropriate as it is based on locally available plants, not expensive external inputs, and fits well with traditional mixed cropping systems in Africa. To date it has been adopted by more than 200,000 smallholder farmers in eastern and southern Africa whose cereal yields have tripled. There is potential for further adaptation of the push-pull technology through incorporation of even more drought tolerant African-adapted desmodium species such as *Desmodium incanum, Desmodium repandum and Desmodium ramossisimum,* which exhibit the right chemistry and ability to control the identified constraints and improve cereal crop yields (Hooper *et al.*, 2015; Midega *et al.*, 2017).

Controlling fall armyworm using the climate-adapted push-pull

ICIPE evaluated the functionality of climate-adapted push-pull using drought-tolerant Greenleaf desmodium, *Desmodium intortum* and Brachiaria as intercrop and border crops, respectively, in management of fall armyworm through direct field observations and farmers' perceptions in Kenya, Uganda and Tanzania. Multi-locational field surveys show that the climate-adapted push-pull technology effectively controls the invasive fall armyworm (Midega *et al.*, 2018). The control mechanism involves the diversionary 'push' and 'pull' tactics previously found to be effective against stemborers. Additional action by natural enemies, i.e. parasitic wasps and the generalist predators such as ants, earwigs and spiders complement the stimulo-deterrent action to reduce fall armyworm invasion of crops under push-pull. Studies have shown that the damage caused by fall armyworm is reduced by up to 100% with the technology, resulting in significant improvements in grain yields.

Data were collected from a diverse sample of farmers in different agro-ecologies on the number of fall armyworm larvae on maize, the percentage of maize plants damaged by the larvae and maize grain yields. Similarly, farmers' perceptions of the impact of the technology on the pest were assessed. There were highly significant reductions in infestation by fall armyworm larvae and plant damage in climate-adapted push–pull compared to maize monocrop plots: Reductions of 82.7% in the average number of larvae per plant and 86.7% in plant damage per plot were observed in climate-adapted push-pull compared to maize monocrop fields. Similarly, maize grain yields were significantly higher, approximately 2.7 times, in the climate-adapted push-pull fields. Farmers rated the technology significantly effective in reducing fall armyworm infestation and plant damage rates. These results demonstrate that the technology is effective in controlling fall armyworm and represent a solution that can be immediately deployed for management of the invasive pest.

New crop protection frontiers in deploying chemical ecology and biodiversity

Innate plant defence mechanisms are triggered by herbivorous insect attacks, which induce the production of plant volatiles (HIPVs), which in turn provide foraging cues for natural enemies antagonistic to the pests (Turlings *et al.*, 1990). This reaction is usually triggered by feeding by the larval stages of the pests and therefore the natural enemies are only attracted following damage to plants. This reaction comes late, as larval damage of plants is already under way, thus limiting effectiveness of biological control in reducing pest damage in farmers' fields. Ideally, responses to egg deposition on the plants should thus elicit defences that are beneficial before the larvae cause damage to the plants (Hilker and Meiners, 2006; Bruce *et al.*, 2010). Maize landraces and some selected locally adapted African open pollinated varieties (OPVs) showed promise by having this desirable trait. Oviposition by *C. partellus* on these plants was observed to induce defence responses in them, leading to attraction of both egg and larval parasitoids as well as their reduced attractiveness for further oviposition (Tamiru *et al.*, 2011, 2012). We observed that this trait was absent in the elite maize hybrids, implying that it must have been lost during the breeding processes that selected for other desirable qualities such as high yields.

Early production of HIPVs confers adaptive value to the plant and generates also selection pressure on the parasitoids to respond to such signals, because it enhances their foraging efficiency and improvement of their ecological fitness. Some selected maize varieties with the early herbivory trait have now been incorporated in the push–pull system, conferring the added benefit of this trait providing biological control of stemborers at oviposition at the earliest stage of attack. There is further opportunity to study the molecular basis of egg-induced semiochemical production with a view to developing molecular markers that can be used in advanced selection of crop varieties and introgression of these traits into mainstream commercial hybrid maize varieties (Tamiru *et al.*, 2015).

There is emerging evidence that plants can respond to HIPVs produced by neighbouring plants, adjusting their metabolism to increase their resistance to herbivores by becoming either antagonistic to foraging herbivores or more attractive to their natural enemies (Birkett et al., 2006). Such plants thus have a higher expression of resistance genes and defence-related plant compounds (Arimura *et al.*, 2000). In controlled experiments maize planted next to molasses grass was found to produce similar semiochemicals as those under attack by stemborer larvae, and that the maize becomes more attractive to both egg and larval parasitoids, and less attractive to stemborer moths for oviposition (Midega *et al.*, 2015a). This suggests that semiochemicals produced by molasses grass provide aerial signals that induce resistance in the neighbouring undamaged maize plants. Furthermore, these neighbouring maize plants are "primed" to respond more quickly or aggressively to future attack by stemborers. Further research is being undertaken to identify the key compounds within the HIPVs that induce and/or prime these responses in a variety of plants. Early production of HIPVs as a crop protection strategy may have potential for deployment again the newly invasive Fall armyworm in Africa.

Contributions of Push-Pull to the Sustainable Development Goals

These scientific discoveries have expanded the utility of the push-pull innovation. The push-pull farming system has generated a wide range of benefits either directly or indirectly to the rural households. The technology has immensely contributed towards attainment of the United Nations Sustainable Development Goals (SGDs) - http://www.push-pull.net/sdgs.shtml. The technology controls the main biotic constraints to cereal production in Africa, mainly parasitic striga weeds and stemborer insect pests, leading to three-fold increase in staple cereal yields, and significantly improved food security, nutrition and incomes. The technology 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). Farm households using push-pull were observed to have higher production of grains, milk, manure and other bye-products from the technology, the surplus of which contributed to household incomes as a poverty reduction strategy.

Secondly it increases quality fodder production and animal health which translates into higher milk production and production of farm yard manure for fertilizing soil. The two impact pathways directly address **SDG2 – Zero Hunger**, **SDG3-Good health and human wellbeing**, and **SDG1 – No poverty**. Families are able to have timely access to enough quality food either through 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 health life thus contributing to SDG 3 on ensuring health lives and promoting well-being at all ages. Consumption of quality and health food, free of chemicals helps in managing preventable diseases.

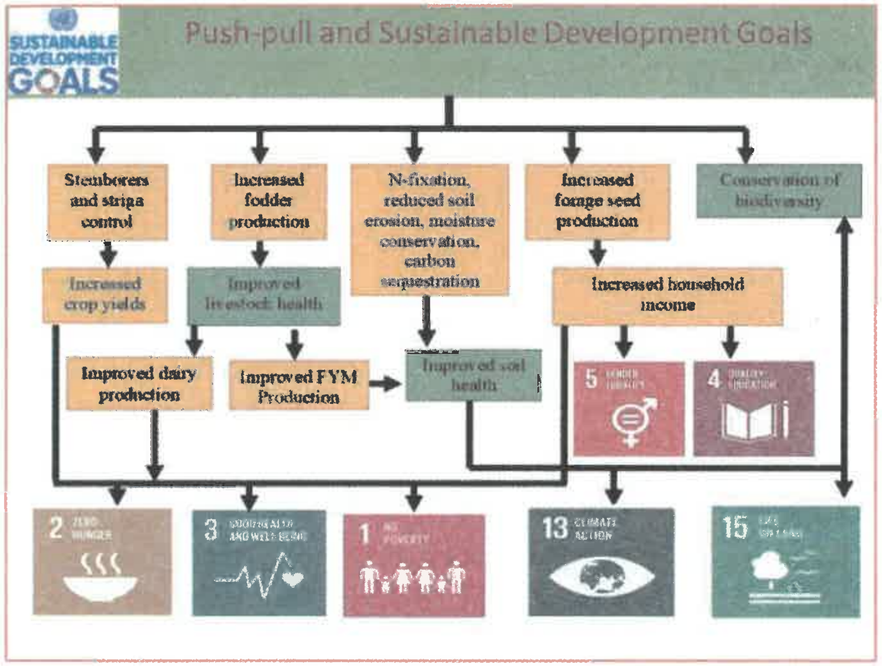

Fig. 1: Push-pull and Sustainable Development goals
(adapted from Khan *et al.*, 2014)

Higher crop and livestock productivity is leading to significantly increase household incomes. Farm communities are investing the increase income into children's **quality education (SDG4)**. Hunger and extreme poverty have been some of the reasons children keep 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 to buy other school requirement, and that their children's performance in school have improved. Moreover, the push-pull farming system contributes to SDG 5 on achievement of gender equality and empowerment of women and girls. Increasing numbers of female children are being enrolled in school, while production of forage seeds, like Desmodium seeds, increase incomes of female farmers (**SDG 5-Gender Equality**). 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 dis-abilities have unequivocally been able to participate in push-pull farming each sharing their positive experience and benefits from the technology. 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 household level such as food availability and education which often are the responsibility of women farmers in the rural community.

The climate-smart push-pull technology has been adapted to mitigate climate change effects which directly address **SDG 13– Climate action** through the use of drought-resilient local plants and natural processes to control striga and stemborers without introducing chemicals which have a high carbon footprint and negatively impact the environment. The downstream impact of improving soil health and conserving biodiversity is contributing to SGD14 - conservation and sustainable use of life under water.

In another impact pathway the technology fixes atmospheric nitrogen into the soil, reduces soil erosion, conserves soil moisture, naturally improves soil carbon sequestration, biomass and soil biota, all of which improve soil health, the conservation of biodiversity and **life on land (SDG 15 -** protecting, restoration and sustainable use of life on land**)**. Indeed, the United Nations General Assembly recognized push-pull as one of the technologies that have benefited farmers by doubling yields through integrated pest management, soil conservation (UN, 2010) and by making cereal cropping systems resilient to climate change (UN, 2015).

Fig.2: A farmer in Yayu, Oromiya Region, Ethiopia in her climate-smart push-pull field.

Conclusion

Chemical ecology-based solutions to crop protection, which are environmentally sustainable and low cost, are urgently needed to address the real and increasing dangers of food insecurity without causing any ecological and social harm.

The push-pull IPM system effectively exploits the science and knowledge of chemical-ecology based to address the key constraints to cereal production faced by resource-poor smallholder farmers in SSA. It is an appropriate system because it uses locally available companion plants rather than expensive external inputs. It is modelled on both the polycropping and mixed nature of smallholder farming systems practised in Africa. It therefore allows integration with livestock through the fodder provided by the companion plants. The companion plants provide the stimulo-deterrent functionality of the technology, with the trap plants attracting and trapping the gravid stemborer moths and the intercrop providing the push to the moths as well as attraction of natural enemies. The technology has been adapted for drier areas vulnerable to climate change by identifying and incorporating drought-tolerant trap and repellent plants. This has made the technology more resilient in the face of climate change as rainfall becomes increasingly unpredictable and temperatures increasing. Moreover, the technology is being made 'smarter' through identification and incorporation of cereal crops with innate defence systems against stemborer pests, which include early production of HPIVs induced by egg deposition by the pests. Companion plants that can signal defence systems of the neighbouring smart cereals are also being identified. Deployment of inducive HPIVs as a crop protection strategy could have tremendous potential as a cost-effective solution against the more economically devastating fall armyworm in Africa. The push-pull technology is being adopted by an increasing number of farmers in Africa, now estimated to be more than 2000,000, because it is highly relevant to their needs and is compatible with their farming systems. Further efforts are being intensified to expand the technology to millions of farmers who need it in Africa.

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