Exploiting Phytochemicals for Developing Sustainable Crop Protection Strategies to Withstand Climate Change: Example from Africa

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Zeyaur R. Khan, Charles A.O. Midega, Jimmy O. Pittchar, and John A. Pickett

Abstract

Africa suffers chronic food insecurity resulting from ravaging effects of insect pests, weeds and poor soil fertility, with rising poverty and increasingly dry and hot weather conditions associated with climate change further aggravating this situation. Scientists at the International Centre of Insect Physiology and Ecology (*icipe*) together with national and international partners have developed a platform technology, 'push–pull', based on locally available companion plants for integrated management of these constraints by exploiting innate plant defence systems including secondary metabolism. This involves intercropping cereal crops, the main staple and cash crops for millions of smallholder farmers in the continent, with forage legumes in the genus *Desmodium* and planting Napier grass as a trap plant around this intercrop. Stemborer pests are attracted to Napier grass (pull) and are repelled from the main cereal crop by the repellent desmodium (push). Desmodium root exudates effectively control the parasitic striga weed by causing abortive germination and also improve soil fertility through nitrogen fixation, provide natural mulching and improve biomass. Both companion plants provide high-value animal fodder, facilitate milk production and fetch additional income for farmers. The technology is appropriate to smallholder mixed cropping systems in sub-Saharan Africa (SSA) as it effectively addresses major production constraints and significantly increases cereal yields. It is currently being practiced by about 90,000 smallholder farmers in eastern Africa and has also been adapted

Z.R. Khan, Ph.D. (✉) • C.A.O. Midega, Ph.D.
J.O. Pittchar, Ph.D.
Plant Health Division, International Centre of Insect Physiology and Ecology (*icipe*), PO Box 30772, Nairobi 00100, Kenya
e-mail: zkhan@icipe.org

J.A. Pickett, Ph.D.
Biological Chemistry and Crop Protection Department, Rothamsted Research, Harpenden, Hertfordshire AL5 2JQ, UK

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to harsh conditions associated with climate change by incorporating drought-tolerant companion plants. This chapter highlights the developmental process of the technology and its benefits in SSA in the face of climate change.

Keywords
Food insecurity • Cereals • Push–pull • Semiochemicals • Stemborer • Striga

1 Introduction

Food insecurity is a major setback to realisation of economic growth in Africa and is complicated by continuous decline in per capita food production in the recent past, making the continent a net importer of agricultural commodities. The situation is graver in sub-Saharan Africa (SSA) where land degradation, pests and weeds are major constraints to efficient production of crops and to human and livestock health. These constraints in addition to being partly responsible for the food insecurity in the region also affect nutrition and income thus causing abject poverty, with over 30 % of the population (close to 200 million people) being undernourished. Cereals, principally maize, *Zea mays* (L.); sorghum, *Sorghum bicolor* (L.) Moench; finger millet, *Eleusine coracana* (L.) Gaertn.; and rice, *Oryza sativa* (L.), are the most important food and cash crops for millions of rural farm families in SSA. Cereal production in the region is however severely affected by a series of constraints, mainly biotic and abiotic. Among the biotic constraints is a complex of about 20 economically important lepidopteran stemborers (Maes 1998), the most injurious insect pests attacking cereal crops in the region, with the indigenous *Busseola fusca* (Noctuidae) and the invasive *Chilo partellus* (Crambidae) being the most important. Attack by stemborer pests causes significant yield losses, ranging from about 10–80 % depending on the crop cultivar, stage of the crop at infestation and infestation level (Kfir et al. 2002). Effective control of stemborers is difficult, largely due to the cryptic and nocturnal habits of the adult moths and the protection provided by the host stem for immature pest stages (Ampofo 1986). Moreover, the conventionally recommended chemical control strategies are often impractical and uneconomical for smallholder farmers (Van den Berg and Nur 1998), while effectiveness of some of the cultural control methods, considered cheaper for resource-constrained farmers, is not empirically demonstrated (Van den Berg et al. 1998).

In addition to stemborers, parasitic weeds in the genus *Striga* (Orobanchaceae) (Oswald et al. 2001), commonly known as striga, are another group of serious biotic factors constraining cereal production in SSA. There are over 20 species of striga out of which *S. hermonthica* is by far the most important, infesting over 40 % of the arable land in the region (Lagoke et al. 1991). Infestations of cereal crops by striga result in severe grain yield losses, estimated at US$ 7 billion annually (Berner et al. 1995), with the most affected being the resource-poor subsistence farmers (Gurney et al. 2006). Striga weakens the host, wounding its outer root tissues and absorbing its supply of moisture, photosynthates and minerals (Tenebe and Kamara 2002), and is so ingeniously adapted to its environment (Bebawi and Metwali 1991) and integrated with the host that it will only germinate in response to specific chemical cues present in root exudates of its hosts or certain non-host plants (Yoder 1999; Parker and Riches 1993). It also causes ‘phytotoxic’ effects within days of attachment to its hosts (Frost et al. 1997; Gurney et al. 1999), whose underlying mechanism has not yet been elucidated (Gurney et al. 2006). These effects result in a large reduction in host plant height, biomass and eventual grain yield (Gurney et al. 1999). Various control strategies have been tried, some with partial or local success, but all have limitations and none has provided a complete solution (Oswald 2005). It has also been complicated by the abundant seed production by striga plants, longevity of the seed bank (Bebawi et al. 1984) and a complicated mode of parasitism. The effects of striga are most severe in degraded environments, with low soil fertility and low rainfall, and in subsistence farming systems where there are few options for purchasing external inputs (Sauerborn et al. 2003; Gurney et al. 2006). Unfortunately striga infestation continues to extend to new areas in the region as farmers abandon heavily infested fields for new ones (Khan et al. 2002; Gressel et al. 2004), a practice that is untenable due to consistent reduction in landholdings due to increases in human population.

The soils are also severely degraded, and these conditions are further aggravated by the effects of climate change. This results into high food and nutrition insecurity and poverty as the average cereal yields are less than 1 t/ha. The smallholder farmers are resource-constrained and therefore unable to invest in pest and soil fertility management. They are expected to increase during the next few decades as agriculture intensifies to meet the extra food demand from a growing population and as a result of increasingly dry and hot weather conditions associated with climate change.

2 Opportunities for Agricultural Development in Sub-Saharan Africa

It is recognised that economic growth led by the agricultural sector has a disproportionately positive impact on the poor and has a documented effect on reducing poverty (World Development Report 2008). Increasing cereal production is therefore an important challenge in addressing economic growth, alleviating poverty and arresting environmental degradation over most of SSA. Most of these cereals are produced by millions of smallholder farmers in predominantly mixed crop–livestock farming systems in the region (Romney et al. 2003). There is thus a need to enhance technical efficiency in the production systems in order to address the widening gap between food supply and food demand in the region. Given that SSA is the only region in the world where hunger and poverty are projected to worsen over the next two decades, there is a need for drastic action to improve agriculture and economic development. Attention should strongly focus on environmental sustainability of soil, crop and water resources and sustainable ways of managing weeds and pests through ecologically sound agronomic innovations. According to the poverty reduction strategy reports, growth in the agricultural sector, achievable by reducing major constraints to productivity mentioned above, in target countries is essential to reducing poverty and ensuring food security. This will benefit mainly poor cereal–livestock smallholders (about 80 % of the producers). Although in some cases insecticides and herbicides can help to alleviate these problems, complete control is seldom achieved. Moreover, the resource-constrained subsistence farmers in SSA cannot afford expensive chemicals. A large number of farmers, therefore, do not attempt to manage stemborers or striga, resulting in high grain yield losses and food insecurity (Chitere and Omolo 1993; Oswald 2005).

3 Exploiting Phytochemicals for Sustainable Cereal Production

To provide an effective and compatible management approach to smallholder farmers in SSA, a series of studies were conducted to identify companion plants that would naturally manipulate the pest behaviour while delivering additional benefits to the farmers. These studies led to development of a cropping strategy, known as ‘push–pull’, which exploits phytochemicals released by carefully chosen companion plants grown in between and around the main cereal crops. These companion plants release semiochemicals that (1) repel insect pests from the main crop using an intercrop which is the ‘push’ component and (2) attract insect pests away from the main crop using a trap crop which is the 'pull' component (Cook et al. 2007). Such a system requires a good understanding of the chemical ecology of plant–insect and plant-plant interactions on the different crops. In the development process of the technology, candidate crops needed to be systematically evaluated in field trials. During the process described herein that was specifically for the control of cereal stemborers, we discovered that certain intercrops had further benefits in terms of suppression of striga. However, the mechanism underpinning this was established to be an allelopathic effect of intercrop root exudates (nonvolatile) and hence only required the intercrop component of the push–pull system.

Development of the push–pull technology therefore began with an extensive field survey that involved over 500 grass species belonging to Poaceae, Cyperaceae and Typhaceae, as well as some leguminous crops in different agro-ecological zones in Kenya. The survey identified appropriate species that could be used as intercrop (push) and trap crop (pull) components of the push–pull mixed cropping system. Plant species selected as potential intercrops had to be repellent to stemborers and reduce their populations on the main cereal crop, maize, while those selected as potential trap crops had to be preferred by stemborers to maize and other cereal crops for oviposition. The best trap crops were those which were attractive but did not support development of the immature stages of the stemborer pest. Napier grass, *Pennisetum purpureum* Schumach, a forage crop, attracted considerably more oviposition by stemborer moths than maize but did not support development of the stemborer pest populations (Khan et al. 2000, 2006a). Stemborer larvae did not survive on Napier grass because it produces a gummy substance that immobilises the young larvae as they try to bore into the stem.

Molasses grass, *Melinis minutiflora* P. Beauv, another indigenous forage plant, attracted no stemborer oviposition at all and was identified as an effective repellent (push) plant. Since farmers in SSA practice multiple cropping where cereal crops are interplanted with legumes, selected legumes were also evaluated in these studies although they are not attacked by cereal stemborers. Two plants in the *Desmodium* genus, silverleaf, *D. uncinatum* DC and greenleaf, *D. intortum* (Mill) Urb, were observed to repel gravid stemborer moths as had been observed with molasses grass (Khan et al. 2000). Planting 3 rows of Napier grass as a trap crop around a plot of maize resulted in significant reductions in the infestation of maize by stemborers (Khan et al. 1997, 2000). Additionally, planting molasses grass or desmodium between the rows of maize resulted in >80 % reduction in stemborer infestation in maize (Khan et al. 2000).

While the putative trap and repellent intercrops were being evaluated for stemborer control, it was noticed that maize intercropped with *D. uncinatum* or *D. intortum* suffered far less striga infestation than maize in monoculture. This effect was confirmed by further field testing and shown to be significantly greater than that observed with other legumes widely recommended as intercropping solutions to striga problems, for example, cowpea, *Vigna unguiculata* (L.) Walp. as were the concomitant yield increases (Khan et al. 2002, 2007b).

4 Semiochemistry of Companion Plants

4.1 Semiochemistry of Companion Plants for Stemborer Control

Insects are attracted to their host plants through sophisticated detection of specific attractive semiochemicals (natural signal chemicals mediating changes in behaviour or development) (Nordlund and Lewis 1976) or specific ratios of semiochemicals (Bruce et al. 2005) emitted by these plants and other host organisms. Detection of specific semiochemicals or mixtures of semiochemicals associated with non-host taxa (Hardie et al. 1994) also guides avoidance of emitters of those chemical compounds by insects. From a series of studies, Napier grass trap crop was found to produce significantly higher amounts of volatile organic compounds (VOCs) used by gravid stemborer females to locate host plants, than maize or sorghum (Birkett et al. 2006). Additionally, it was established that there was also an increase of approximately 100-fold in the total amounts of these compounds produced in the first hour of nightfall (scotophase) by Napier grass (Chamberlain et al. 2006), the period during which stemborer moths seek host plants for oviposition (Päts 1991), causing the differential oviposition preference. However, about 80 % of the stemborer larvae did not survive (Khan et al. 2006a, 2007a) as Napier grass tissues produce sticky sap in response to feeding by the larvae which traps them causing their mortality. The intercrops, molasses grass and desmodium on the other hand were found to produce repellent VOCs that push away the stemborer moths. These include (*E*)-β-ocimene and (*E*)-4,8-dimethyl-1,3,7-nonatriene, semiochemicals typically produced during damage to plants by herbivorous insects and are responsible for the repellence of desmodium to stemborers (Khan et al. 2000) (Fig. 3.1).

4.2 Allelopathic Mechanism for Striga Control

Desmodium was found to effectively control striga, resulting in significant yield increases in maize from 1 to 3.5 t/ha per cropping season (Khan et al. 2008a). Similar results have also been observed with sorghum (Khan et al. 2006b), finger millet (Midega et al. 2010) and upland rice (Khan et al. 2010). In the elucidation of the mechanisms of striga suppression by *D. uncinatum*, it was found that, in addition to benefits derived from increased availability of nitrogen and soil shading, an allelopathic effect of the root exudates of the legume, produced independently of the presence of striga, is responsible for the dramatic reduction of striga in an intercrop with maize. Presence of blends of secondary metabolites with striga seed germination stimulatory, 4″,5″,-dihydro-5,2′,4′-trihydroxy-5′′,-isopropenylfurano-(2″,3″;7,6)-isoflavanone, and post-germination inhibitory, 4″,5″-dihydro-2′-methoxy-5,4′-dihydroxy-5″-isopropenylfurano-(2″,3″;7,6)-isoflavanone, activities in the root exudates of *D. uncinatum* which directly interferes with parasitism was observed (Tsanuo et al. 2003). This combination thus provides a novel means of *in situ* reduction of the striga seed bank in the soil through efficient suicidal germination even in the presence of graminaceous host plants in the proximity. Other *Desmodium* spp. have also been evaluated and have similar effects on stemborers and striga (Khan et al. 2006b) and are currently being used as intercrops in maize, sorghum and millets. Recently another key post-germination inhibitor, di-*C*-glycosylflavone 6-*C*-α-L-arabinopyranosyl-8-C-β-D-glucopyranosylapigenin, also known as isoschaftoside, as well as other *C*-glycosylflavones have been characterised from a more polar fraction of *D. uncinatum* root exudates and solvent extracts (Pickett et al. 2007; Hooper et al. 2009), and full chemical elucidation of other allelopathic agents is ongoing. Detailed studies on understanding of structure of chemicals, elucidation and understanding the mechanisms by which desmodium suppresses striga will ensure sustainability of desmodium-based cropping systems and provide an opportunity for exploitation of the biochemical pathways in desmodium root system beyond the smallholder cereal cropping systems.

5 Field Implementation and Benefits of the Push–Pull Technology

5.1 Agronomic and Environmental Benefits of the Technology

Following extensive research and development efforts, it was found that not only were stemborers and striga effectively controlled by the technology under farmers' conditions but farmers also reported additional benefits such as increased soil fertility and improved availability of animal fodder resulting in increased milk production (Khan et al. 2008b) and up to threefold increases in grain yields (Khan et al. 2008a). Desmodium also fixes atmospheric nitrogen (110 kg N/ha) (Whitney 1966), adds organic matter to the soil,

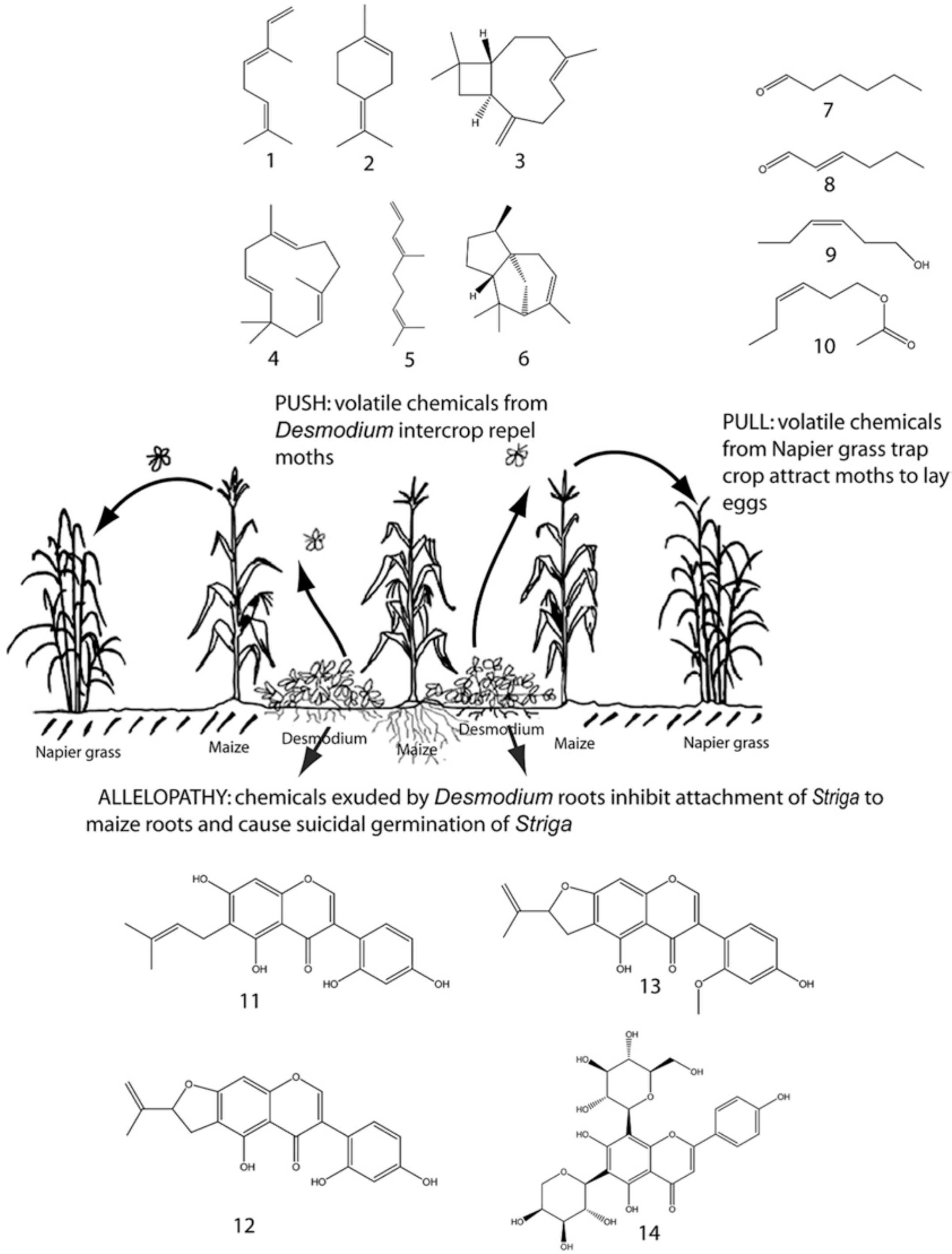

Fig. 3.1 How the push–pull system works: stemborer moths are repelled by intercrop volatiles while attracted to trap crop volatiles. Root exudates from the desmodium intercrop cause suicidal germination of striga and inhibit attachment to maize roots (*1* (*E*)-β-ocimene, *2* α-terpinolene, *3* β-caryophyllene, *4* humulene, *5* (*E*)-4,8-dimethyl-1,3,7-nonatriene, *6* α-cedrene, *7* hexanal, *8* (*E*)-2-hexenal, *9* (Z)-3-hexen-1-ol, *10* (Z)-3-hexen-1-yl acetate, *11* 5,7,2′,4′-tetrahydroxy-6-(3-methylbut-2-enyl) isoflavanone (uncinanone A), *12* 4″,5″-dihydro-5,2′,4′-trihydroxy-5″-isopropenylfurano-(2″,3″;7,6)-isoflavanone (uncinanone B), *13* 4″,5″-dihydro-2′-methoxy-5,4′-dihydroxy-5″-isopropenylfurano-(2″,3″;7,6)-isoflavanone (uncinanone C), and *14* di-*C*-glycosylflavone 6-*C*-α-L-arabinopyranosyl-8-*C*-β-D-glucopyranosylapigenin (Adapted with permission from Khan et al. (2010))

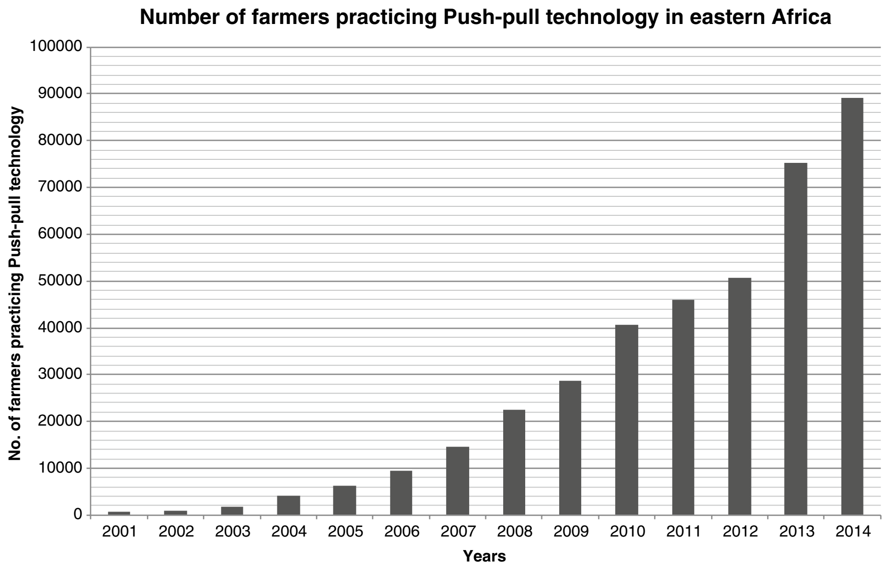

Fig. 3.2 Number of farmers practicing the push–pull technology in East Africa as of August 2014

conserves soil moisture and enhances soil biodiversity, thereby improving soil health and fertility (Khan et al. 2006b). Additionally, it provides ground cover and, together with surrounding Napier grass, protects the soil against erosion. The technology also enhances arthropod abundance and diversity, part of which is important in soil regeneration processes, pest regulation (Midega et al. 2008) and stabilisation of food webs. In deed there is also a clear demonstration of the value of biodiversity because of the important roles played by companion plants and beneficial insects in the system. It therefore improves agro-ecosystem sustainability and resilience, with great potential to mitigate the effects of climate change (Khan et al. 2014). Both desmodium and Napier grass provide valuable year-round quality animal forage while the sale of desmodium seeds generates additional income for the farmers. The push–pull technology thus opens up significant opportunities for smallholder growth and represents a platform technology around which new income generation and human nutritional components, such as livestock keeping, can be added. It therefore affords the smallholder farmers an opportunity to enter into the cash economy.

On-farm uptake of the technology by about 90,000 farmers in East Africa (Fig. 3.2) has confirmed the technology's effectiveness and significant impacts on food security, human and animal health, soil fertility, conservation of agrobiodiversity, agro-ecosystem services, empowerment of women and income generation for resource-poor farmers (Fig. 3.3). Upscaling of the technology to reach the current adopters and beyond has been achieved through deployment of a combination of dissemination pathways catering to different sociocultural contexts and literacy levels of farmers. This has been complimented by a multilevel collaboration with research institutions, national extension networks and non-governmental organisations (NGOs), and farmer groups, combined with extension efforts underpinned by a robust scientific base and continuous technical backstopping. Further involvement of a series of interventions (Khan et al. 2008b) including information bulletins (brochures, detailed practical manuals on how to plant push–pull) and mass media (radio programmes in local languages and newspaper articles) have boosted transfer of the technological information to a wider audience.

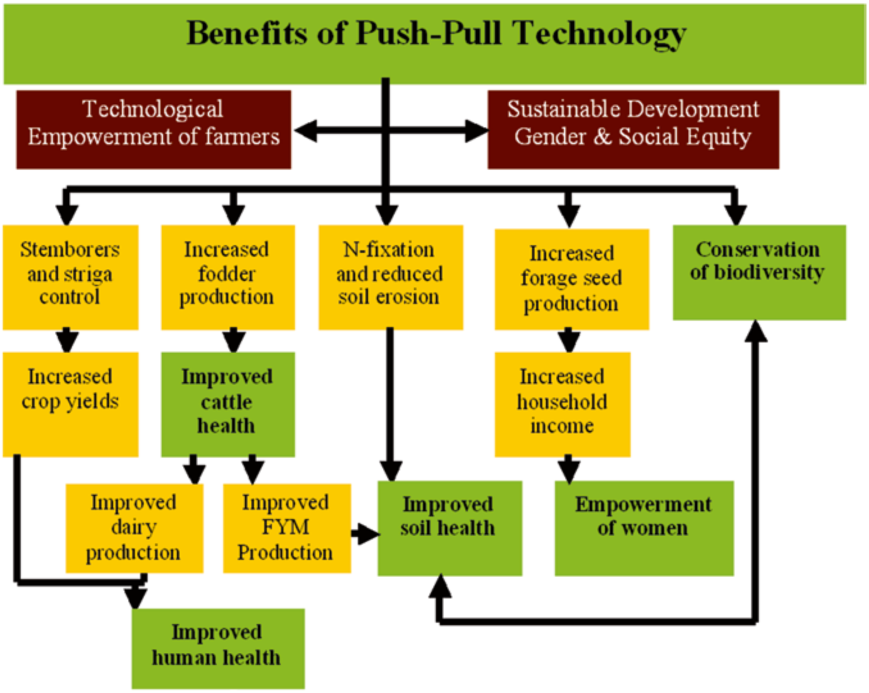

Fig. 3.3 Diagrammatic representation of benefits of the push–pull technology

5.2 Economic Benefits of the Technology

A number of studies have demonstrated that push–pull is more profitable than farmers' own practices, and some of the practices designed to improve soil fertility. Significantly higher benefit/cost ratio was realised with push–pull compared with maize monocrop and/or use of pesticides, posting a positive return on investment of over 2.2 compared with 0.8 obtained with the maize monocrop, and slightly less than 1.8 for pesticide use (Khan et al. 2001). Additionally, push–pull with no additional fertiliser had the best gross returns, while less profit was recorded with the use of fertiliser, implying it was economically propitious for poor smallholders who could not afford external inputs to invest in push–pull. Further economic analyses on returns to investment for the basic factors of production under push–pull showed these were significantly higher compared to those from maize–bean intercropping and maize monocrop systems (Khan et al. 2008c). Positive total revenues ranged from \$351/ha in low potential areas to \$957/ha in the high potential areas, with general increases in subsequent years. The returns to labour which were recovered within the first year of establishment of push–pull ranged from \$ 0.5/man day in the low potential areas to \$ 5.2/man day in the higher potential areas, whereas in the maize monocrop, this was negligible or even negative. Furthermore, the net present value (NPV) from push–pull was positive and consistent over several years. A more recent study (De Groote et al. 2010) that used discounted partial budget and marginal analysis corroborated these findings and concluded that push–pull earned the highest revenue compared to other soil fertility management technologies, including green manure rotation.

6 Adaptation of Push–Pull Technology

6.1 Adaptation of the Technology to Farmers' Needs

Smallholder farmers in SSA practice multiple cropping that closely integrates cereal crops and food legumes, with the latter forming an important part of diets of these farm families. Typically farmers plant edible legumes between rows of cereal crops or with the cereal crops in the same holes. To respond to farmers' need for food legumes, strategic research efforts were made that led to integrating beans into the technology thereby adapting it to farmers' need (Khan et al. 2009). Results indicated that integration of beans in the maize–desmodium intercrops and the planting arrangement did not compromise the striga and stemborer control efficacy of desmodium. While this integration significantly increased labour and total variable costs, total revenue, gross benefits and benefit/cost ratios did not significantly differ between the bean integration and maize–desmodium intercrops. Where labour is easily available, farmers are advised to plant cereal crops and beans in separate holes to avoid the risk of competition for moisture and nutrients where these might be limiting. This has increased the technology's appeal to the farmers as it guaranteed an additional protein source in the diet (Khan et al. 2009), resulting into higher technology adoption rates in eastern Africa ranging from 10,000 to about 90,000 farmers.

6.2 Adaptation of Push–Pull Technology to Climate Change

Climate change is anticipated to have far-reaching effects on the sustainable development of SSA, including the ability to attain the Millennium Development Goals (MDGs). The predictions indicate that atmospheric temperature will continue to increase, so will the incidences of flood and drought. These will result into progressively more serious land degradation and increased pest and weed pressure, increased incidences of crop failure and general increases in food and nutritional insecurity for resource poor farmers in many parts of SSA. To adapt to these adverse conditions, the resource-constrained smallholder farmers are moving to more drought-resilient cereal crops, such as sorghum and millet, and small ruminants for dairy production. The constraints will be addressed through wide-scale dissemination of climate-smart agricultural approaches like push–pull for smallholder cereal–livestock production in drier and hotter areas to withstand climate change.

With rising uncertainties in the region's rain-fed agriculture due to the continent's vulnerability to climate change, there was a demand and need to adapt conventional push–pull to withstand increasingly adverse and variable conditions. The trap and intercrops used in conventional push–pull were rainfall and temperature limited as the initial system was developed under average rainfall (800–1,200 mm) and moderate temperatures (15–30 °C). In order to ensure that push–pull continues to affect food security positively in Africa over the longer term, new drought-tolerant trap (*Brachiaria* cv. mulato) and intercrop (drought-tolerant species of desmodium, e.g. *D. intortum*) plants have been selected from research undertaken in collaboration with national and international partners. The new companion plants also have the appropriate chemistry in terms of natural enemy attractancy for the trap component, and stemborer repellence and striga suppression, and ability to improve soil fertility and soil moisture retention, for the intercrop component, and have been shown to significantly improve yields of maize and sorghum (Khan et al. 2014). Both trap and repellent plants provide high-quality livestock fodder over long periods of drought. In addition, they provide other ecosystem services such as biodiversity improvement and conservation, and organic matter improvement.

In identification of trap plants, *icipe* and partners screened about 400 grass species from which 21 drought-tolerant species were initially selected. Out of these, *Brachiaria* cv. mulato was chosen as the trap plant for the climate-adapted push–pull given also its ability to control stemborers, farmers' preference for it as livestock fodder and commercial availability of its seed that would allow faster dissemination and uptake. Additionally, it allowed minimal survival of stemborer larvae, a suitable characteristic of a trap plant that would support populations of natural enemies within season and when the cereal crop is not in season. Additionally, drought-tolerant species of desmodium that emit volatiles that repel stemborers, fix nitrogen to improve soil

Fig. 3.4 Sorghum planted in sole stand (**a**) and sorghum intercropped with greenleaf desmodium (**b**)

fertility, produce high biomass, cover the soil and improve soil health were identified. From a collection of 43 accessions collected from dry and hot areas in Africa and other arid environments, greenleaf (*D. intortum*) was observed to be more drought tolerant and was chosen as the intercrop species for immediate integration into a climate-adapted push–pull. Greenleaf desmodium was chosen given its known ability to control striga and stemborers (Khan et al. 2007b) (Fig. 3.4) coupled with commercial availability of its seed that would enable its wider testing by farmers within the project target areas. The work to isolate and purify all the active compounds in the desmodium root exudates and fully elucidate their effects on striga suppression is currently ongoing. Similarly, the full mechanism of stemborer control by the new companion plants is currently being elucidated with the aim of providing both sustainability and quality assurance as more companion plants are selected for new agro-ecologies.

Currently over 30,000 smallholder farmers in drier parts of Kenya, Tanzania and Ethiopia have taken up the climate-smart push–pull and have reported effective control of stemborers and striga weed resulting in significant increases, up to fivefold, in grain yields of both maize and sorghum (Khan et al. 2014). The new companion plants have also ensured availability of high quality fodder at the farms thereby increasing productivity of livestock. Validation of gross return from the adapted climate-smart push–pull showed \$1075.8/ha and \$1,289/ha gross benefits for sorghum and maize respectively and significantly higher marginal rates of return (MRR) implying that the net increase in benefits of climate-smart push–pull outweighs the net increase in costs compared to farmers' own practices.

7 Conclusions and Future Outlook

The push–pull system effectively addresses the constraints to production faced by the farmers and is an appropriate system because it uses locally available companion plants rather than expensive inputs. It 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. Moreover, the technology is being made 'smarter' through identification and incorporation of cereal crops with defence systems against stemborer pests that are inducible by egg deposition by the pests. Companion plants that are able to signal defence systems of the neighbouring smart cereals are also being identified. Accompanying these are efforts to elucidate full mechanisms of striga and stemborer control by conventional and the new companion plants. Science-based solutions to crop protection, which are environmentally sustainable and low cost, like push–pull, are urgently needed to address the real and increasing dangers of food insecurity without causing any ecological and social harm.

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