5 Integrated Pest Management in Tropical Cereal Crops

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5.1 Introduction

The supply of food – especially grains – in developing countries should increase by about 70% by 2050 if the approximately 9.7 billion people who are expected to be living then are going to be food-secure (Godfray *et al*., 2010; FAO, 2017a). Annual cereal production will need to rise to about 3 billion tons from the current 2.1 billion (Alexandratos and Bruinsma, 2012; FAO, 2017a). This ambitious goal can be achieved through an increase in yield of the major grains and by lowering the crop losses caused by pests. Cereals are major staple food crops that are cultivated on approximately 75% of the arable land (484 million ha) in the tropics and contributing about 1.71 billion tons (65.7%) of the total world cereal production (FAO, 2014). The four most important cereals in the tropics are rice, maize, sorghum and pearl millet (Bragg *et al*., 2016). The winter cereals, wheat and barley, are also grown in the tropics, but to a limited extent, and largely at high altitudes. As opportunities for expanding irrigation and productive arable land are limited, improved pest management is an important strategic component for increasing available supplies of food, especially in developing countries. This chapter will highlight strategies for managing cereal pests that are most suitable for smallholder farmers, who in tropical countries produce more than 70% of the cereals. Examples highlighting major biotic constraints for each major cereal will be given, followed by an in-depth analysis of opportunities for harnessing IPM for increased cereal productivity.

5.1.1 Integrated management of pests in tropical cereals

Integrated pest management (IPM) is a systematic plan that brings together different pest-control tactics into one programme. The primary objective is to keep pest intensity below an economic injury threshold and prevent reductions in crop yield and quality (Hill, 2008). In an IPM programme, use of pesticides is reduced and emphasis is placed on using cultural, biological, genetic, physical, regulatory and mechanical control methods. The goal is to prevent pests from reaching economically damaging levels (Ehler, 2006). Success of an IPM programme depends on careful observation, a thorough knowledge of the pest and the damage caused, and an understanding of all available control options.

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5.1.2 Biotic constraints to cereal production

Crop losses to biotic stresses (weeds, insect pests and pathogens) vary among crops and regions, and this results primarily from differences in host reaction to the interaction (Oerke and Dehne, 2004). On average, 15.8% of maize is lost to pests, and this ranges from 9% to 31%, depending on pest type (Gibbon *et al.*, 2007). In rice, average yield losses are higher than maize, at 22%, but vary for different constraints, with diseases (25% loss) contributing more than insects (20% loss) (Diagne *et al.*, 2013). Sorghum and millets are generally grown in dry and marginal lands and, as such, losses from pests are low, averaging 6.9% and ranging from 0.3 to 17% (Oerke and Dehne, 2004; Dhaliwal *et al.*, 2010).

5.2 Maize

Maize (*Zea mays* L.) is one of the most important cereal crops in the world and, together with rice and wheat, provides at least 30% of the food calories to more than 4.5 billion people in 94 developing countries (Shiferaw *et al.*, 2011). It is estimated that maize is being cultivated on approximately 8.12 million ha with annual production of 19.77 million tons (Dass *et al.*, 2008; FAO, 2014). Currently, maize covers 25 million ha in sub-Saharan Africa, largely in smallholder systems that produce 38 million metric tonnes, primarily for food (Smale *et al.*, 2011). The highest amounts of maize consumed are in southern Africa at 85 kg/capita/year; and contributing more than 40% of total calories (Shiferaw *et al.*, 2011).

5.2.1 Losses by insect pests and diseases

Many pests constraint maize production in the tropics (Ehler, 2006), and the intensity of damage vary according to type of disease or frequency of pest occurrence, prevailing environmental conditions, host genotype, and time (growth stage of the crop) of infection (Oerke and Dehne, 2004; Dhaliwal *et al.*, 2010). As shown in Table 5.1, an estimated 54% of attainable yield is lost annually to diseases (16%), animals and insects (20%) and weeds (18%) in Africa alone (Oerke *et al.*, 1994; Oerke, 2006). Similar losses have been observed for Central and South America (48%) and Asia (42%) (Oerke *et al.*, 1994). Therefore, efforts to reduce losses from diseases and insect pests offer tremendous opportunities for increasing and stabilizing maize productivity.

5.2.2 Important diseases of maize in the tropics

More than 100 pathogens infect maize, but only a fraction cause economic damage in a specific location (White, 1999). Some major diseases of maize in the tropics and the estimated yield losses are listed in Table 5.2. Some diseases are of regional importance such as tar spot complex (TSC) and corn stunt complex (CSC) in Central America (Mahuku and Kumar, 2017); maize streak virus (MSV), and the parasitic weed Striga (*Striga asiatica* (L.) Kuntze and *S. hermonthica* (Delile) Benth.) in Africa (Gethi *et al.*, 2005; Karavina, 2014; Khan *et al.*, 2016). Some emerging disease, such as maize lethal necrosis (MLN) has devastated maize production in eastern Africa (Mahuku *et al.*, 2015).

Table 5.1. Estimated yield losses for maize from different biotic constraints.

		Percent losses associated with		
Region	Attainable Yield (t×106)[a]	Diseases	Animals/ Insects	Weeds
Africa	74	16	20	18
C/S America	98	12	17	19
Asia	203	12	18	12
North America	258	9	11	11
Europe	68	7	9	9

[a] Based on 1988–1990 data summarized by Oerke *et al.*, 1994.

Table 5.2. Some important diseases and insect pests of maize in tropical countries and estimated yield losses.

Common name	Scientific name	Estimated yield loss (%)	References
Diseases			
Northern corn leaf blight	*Setosphaeria turcia* ((Luttrell) Leonard & Suggs)	0–66	Pataky *et al.*, 1998
Gray leaf spot	*Cercospora zeae* (Tehon & E.Y. Daniels)	5–30	Ward *et al.*, 1999
Sothern corn rust	*Puccinia polysora* (Underwood)	0–50	Castellanos *et al.*, 1998
Common rust	*Puccinia sorghi* (Schweinitz)	12–61	Dey *et al.*, 2012
Post flowering stalk rots	*Fusarium verticillioides* ((Saccardo) Nirenberg), *Macrophomina phaseolina* ((Tassi) Goidànich), *Colletotrichum graminicola* ((Cesati) G.W. Wilson), *Stenocarpella maydis* ((Berkeley) B. Sutton), *Gibberella zeae* ((Schweinitz) Petch)	10–42	Khokhar *et al.*, 2014
Tar spot complex	*Phyllachora maydis* (Maublanc) and *Monographella maydis* (E. Müller & Samuels)	0–75	Bajet *et al.*, 1994
Corn stunt complex	*Spiroplasma kunkelii* (Whitcomb), Maize bushy stunt phytoplasma, Maize rayado fino virus	0–50	Bradfute *et al.*, 1981
Fusarium ear rots	*Fusarium verticillioides* (Saccardo)	5–15	Chen *et al.*, 2016
Maize lethal necrosis	Maize chlorotic mottle virus and Sugarcane mosaic virus	0–100	Mahuku *et al.*, 2015
Maize streak	Maize streak virus	0–90	Karavina, 2014
Field and storage pests			
Stem borers	*Chilo partellus* (Swinhoe), *Busseola fusca* (Fuller), *Sesamia calamistis* (Hampson), *Eldana saccharina* (Walker), *Mussidia nigrivenella* (Ragonot)	9–80	De Groote, 2001; Kfir *et al.*, 2002
Armyworms	*Spodoptera exempta* (Walker) and *Spodoptera frugiperda* (J. E. Smith)	7–100	Dal Pogetto *et al.*, 2012
Maize weevil	*Sitophilus zeamais* (Motschulsky) and *Sitophilus oryzae* (L.)	4–30	De Groote *et al.*, 2013; Suleiman and Rosentrater, 2015
Larger grain borer	*Prostephanus truncatus* (Horn)	9–45	Suleiman and Rosentrater, 2015
Termites		10–30	Wood and Cowie, 1988; Sekamatte *et al.*, 2003

5.2.3 Integrated management of maize diseases

Effective management of maize diseases involves the selection and use of appropriate techniques that prevent or suppress disease development to a tolerable level (Maloy, 2005). Techniques for reducing initial pathogen inoculum include tillage practices, crop rotations and other agronomic practices, and reducing rate of disease development. The latter can be done through host resistance, choice of shorter-season hybrids and early planting, ensuring optimum plant density, irrigation and soil fertility, as well as the judicious use of fungicides (Ward and Nowell, 1998; Nutter and Guan, 2001). Proper disease management requires correct identification of the pathogen and symptoms, as well as knowledge of the impact of the pathogen/disease (Ward and Nowell, 1998; Nutter and Guan, 2001). The cornerstone of an integrated approach will be the development of high-yielding resistant hybrids grown in rotation with non-host crops.

Reduction of initial inoculums

Quarantine is very effective in minimizing introduction of a potential pest or pathogen to new areas or country where the pest is currently absent (Waage and Mumford, 2008). This can be done at country/regional and/or continental level and should be supported by pest risk analysis (Beed, 2014). For maize, seeds are inspected before leaving and entering country or before being moved from a disease endemic region to a disease free region within a country and prevent spread of pest/pathogen to new areas. For example, strict quarantine measures have been effective in limiting the introduction and spread of maize chlorotic mottle virus (MCMV) and MLN into southern and western Africa (Mahuku *et al.*, 2015). However, for quarantine to be effective, it should be supported by continual surveillance, appropriate diagnostic tools, and regional, continental and international cooperation to monitor known quarantine pests and pathogens simultaneously.

Eradication is a technique that reduces pathogen inoculum between seasons, making sure that the amount of pathogen present is not sufficient to cause significant disease or affect the plant's development and hence yield reduction (Maloy, 2005). Sanitation methods such as cleaning tools used in infected fields, removal of infected maize plant debris that will act as a source of inoculum in the next season, roguing diseased maize plants, eliminating weeds and other alternative hosts which serve as reservoir for viruses, crop rotation and control of vectors are methods employed in eradication (Webster *et al.*, 2004; Maloy, 2005). Rotating maize with MCMV non-host crops, such as Irish potatoes, sweet potatoes, cassava, beans, onions, vegetables and garlic has been used to minimize the impact of MLN (Wangai *et al.*, 2012).

Reducing the rate of infection

Avoidance aims at preventing contact between host plant and the pathogen by planting in fields with no history of the disease, providing adequate plant spacing to avoid crowding and plant injury, as well as inhibiting the use of recycled maize seeds by using certified seeds. Planting on the onset of the main rainy season and not during the short rain season to create a break in maize planting seasons will also reduce the population of vectors and result in a low rate of infection and disease severance.

Plant protection involves protection of the host (maize) from invading pathogens and can be achieved by modifying plant nutrient base (the use of manure and fertilizers) and environment. For example, MLN viruses cannot be controlled using chemicals, but chemicals can be used to kill vectors that transmit/spread these viruses. Several insecticides, formulated either as granules or spray applications can be used to manage vectors (e.g. aphids, rootworms, thrips) that transmit MLN causing viruses. However, the use of chemicals is not adequate for managing plant virus diseases (Perring *et al.*, 1999), and also insects might develop resistance (Satapathy, 1998).

Host plant resistance has proven to be the most reliable, effective, environmental friendly and economical way of controlling maize diseases (Pratt *et al.*, 2003). It is especially attractive to small holder farmers because once the technology is developed it is packed and disseminated as seed; therefore, it is practical, cost-effective, and environmentally friendly. For cereals, the use of host plant resistance is regarded as the only realistic pest management strategy, especially for smallholder farmers who cannot afford chemical control options. Resistance is available to almost all the major diseases of maize; the big challenge to breeders is to incorporate these genes into elite but susceptible cultivars (Pratt *et al.*, 2003; Mahuku and Kumar, 2017). CIMMYT and the International Institute for Tropical Agriculture (IITA) have been working closely with scientists from national maize programs in developing countries to develop maize varieties and hybrids with resistance to major maize diseases (Pratt *et al.*, 2003; CGIAR, 2012). Several varieties with resistance to MSV, GLS, TLB, TSC, common rust and ear rots are available and have been deployed (Mahuku and Kumar, 2017).

Integrated management of selected maize diseases

Maize Streak Virus (MSV) was reported first from East Africa, and has now extended to several other African countries (Alegbejo *et al.*, 2002; Karavina, 2014). The virus is transmitted by *Cicadulina* spp. leafhoppers. *Cicadulina mbila* (Naudé) is the most prevalent vector, and it transmits the virus for most of its life after feeding on an infected plant. Losses from MSV can be 100%, if infection occurs early in the disease cycle on susceptible hybrids. Severe infection causes stunting; plants will not develop cobs and can die prematurely (Karavina, 2014). Several cereal crops and wild grasses host virus and vectors. MSV is managed using resistant maize hybrids (Barrow, 1993; Alegbejo *et al.*, 2002; Karavina, 2014). To date, several MSV-tolerant cultivars have been released throughout the sub-Saharan region (Karavina, 2014). In Zimbabwe, for example, SeedCo. (a private company) has released the cultivars SC403, SC411, SC621, SC713 and SC719 with acceptable levels of tolerance to MSV and these are being marketed in several countries in the region (SeedCo., 2010–2011).

Gray Leaf Spot (GLS) is caused by *Cercospora zeae-maydis* (Tehon & E.Y. Daniels) and *Cercospora zeina* (Crous & U. Braun). Disease development is favoured by extended periods of leaf wetness and cloudy conditions, and can result in severe leaf senescence after flowering and poor grain fill (Ward *et al.*, 1999). Managing GLS relies on host resistance and several sources of resistance are available and these have been incorporated and deployed in resistant varieties and hybrids (Ward *et al.*, 1999). As resistance to GLS is controlled by minor genes, complete resistance cannot be achieved (Maroof *et al.*, 1996; Benson *et al.*, 2015). For this reason, cultural practices are deployed with tolerant varieties for sufficient GLS management. Extended period of leaf surface moisture is critical for GLS development, as such, avoiding scheduling irrigation during late afternoon or early evening, especially after outbreaks have already occurred significantly contributes to adequate GLS management. GLS overwinters in crop residue in the field, thus destroying plant debris after harvest, removal of crop residues or deep ploughing to reduce the amount of initial inoculum, and crop rotation with non-host plants have successfully been used to manage GLS (Ward *et al.*, 1999). The disease can also be managed by fungicides, which are routinely used in seed production (Ward *et al.*, 1997). Though very important and effective in managing GLS, fungicides are rarely used by smallholder farmers.

Turcicum Leaf Blight (TLB), caused by *Exserohilum turcicum* ((Passerini) K.J. Leonard & Suggs), can lead to complete burning of the foliage, resulting in more than 70% yield reduction when infection occurs prior to silking and conditions are optimum for disease development (Perkins and Pedersen, 1987; Reddy *et al.*, 2013). Host resistance is the most efficient and cost-effective means for managing TLB and several sources of resistance have been identified and are being used to develop improved varieties (Welz and Geiger, 2000). A high level of resistance characterize some hybrids, such as SC627, Longe 2H, Longe 6H, Longe 7h and Longe 8H. Cultural practices, such as crop rotations with non-cereal crops (like sunflower, soybean), burying infected debris soon after harvest are effective in reducing initial inoculum and subsequent disease pressure (Reddy *et al.*, 2013). Application of fungicides is effective in managing TLB, but this is rarely used by smallholder farmers.

Maize Lethal Necrosis (MLN) is a new viral disease of maize in Africa that is caused by synergistic interaction of MCMV and any of the viruses belonging to potyviridae family. In Africa, MLN, results from co-infection of maize plants by MCMV and Sugarcane mosaic virus (SCMV). Loss of maize productivity to MLN in Kenya has been estimated at 0.5 million tons per year, or 23% of the average annual production equivalent to US$188 million (De Groote *et al.*, 2016). No commercial maize varieties are resistant (Mahuku *et al.*, 2015). When infection occurs early, plants are killed, while later infections results in poorly filled grain that is prone to ear rots. Presently, management strategy is based on prevention of the introduction of the disease through quarantine, careful control of plant material and early destruction of diseased plants. Rotation with legumes has been proposed to break disease cycle (Kiruwa *et al.*, 2016).

5.2.4 Insect pests of maize

Maize is attacked by about 139 insect-pests with varying degree of damage under field and storage conditions (Dhaliwal *et al.*, 2010; Dhillon *et al.*, 2014). Insect pests reduce maize production by directly attacking roots (rootworms, wireworms, white grubs, and seed-corn maggots), leaves (aphids, armyworm, stem borers, thrips, spider mites and grasshoppers), stalks (stem borers and termites), ears and tassels (stem borers, earworms, adult rootworms and armyworm), and grain during storage (grain weevils and grain borers) (Kfir *et al.*, 2002; Hill, 2008).

Stem borers

Stem borers are the most important field pests in maize cultivation in the tropics (De Groote, 2001; Kfir *et al.*, 2002). Five species of stem borers (*Chilo partellus* (Swinhoe), *Busseola fusca* (Fuller), *Sesamia calamistis* (Hampson), *Eldana saccharina* (Walker) and *Mussidia nigrivenella* (Ragonot) are the dominant pests (De Groote, 2001; Kfir *et al.*, 2002; Culliney, 2014). Damage is from feeding by the larvae and yield losses of up to 88% – depending on the cultivar, plant developmental stage at infestation and prevailing environmental conditions – have been reported (Kfir *et al.*, 2002).

INTEGRATED MANAGEMENT OF STEM BORERS The most success in stem borer management has been obtained from using cultural control strategies, early planting and implementing the ‘push–pull’ technique (Khan *et al.*, 2000; Dhillon *et al.*, 2014). Cultural control is the first line of defense against pests and includes techniques such as destruction of crop residues, intercropping, crop rotation, manipulation of planting dates, and tillage methods. Farmer cooperation is essential for these control measures to be effective, because insects emerging from untreated fields can infest adjacent crops. Destroying larvae in old stalks to reduce the first generation of adult population is very effective in limiting damage of new maize crops. This is achieved through tillage to bury infested stalks deeply into the soil; disking to break stems and expose larvae to adverse weather conditions, birds, rodents, ants, spiders, and other natural enemies and burning infested old stalk and crop residues are effective in destroying the pest (Kfir *et al.*, 2002).

Planting early ensures that the most vulnerable crop stage does not coincide with periods of peak insect activity (Dhillon *et al.*, 2014). The ‘push–pull’ strategy involves combined use of intercropping and trap crop systems (Khan *et al.*, 2014; Pickett *et al.*, 2014). Stem borers are attracted to highly susceptible trap plants (pull) and are driven away from the maize crop by repellent intercrops (push) (Hassanali *et al.*, 2008; Pickett *et al.*, 2014). Napier grass and Sudan grass are used as trap plants, whereas molasses grass (*Melinis minutiflora* P. Beauv.) and silverleaf desmodium (*Desmodium uncinatum* (Jacq.) DC.) repel ovipositing stem borers (Khan *et al.*, 2014). In addition, molasses grass produce volatile compounds that attract the stem borer natural enemy, *Cortesia sesamiae* (Cameron), thus leading to increased parasitism of stem borer larvae (Kfir *et al.*, 2002).

HOST PLANT RESISTANCE Although several sources of stem borer resistance have been identified, most of the maize varieties and hybrids on the market do not have adequate resistance (Kumar, 1997; Dhillon *et al.*, 2014). This is because the mechanisms, inheritance, nature of gene action for resistance to stem borers are poorly understood making it difficult to breed for resistance. Transgenic maize expressing the *Bacillus thruringiensis* (Bt) gene have been effective in controlling Lepidopteran pests, but this can only be used in countries that have embraced cultivation of genetically modified crops (Christou *et al.*, 2006). Bt maize has not been widely adopted by smallholder farmers due to regulatory problems (Symth, 2017).

Armyworms

The African fall armyworm, *Spodoptera exempta* (Walker), is a major widespread migratory insect pest that is a perennial threat to cereal production over much of eastern and southern Africa (Grzywacz *et al.*, 2014). In 2007/08, severe armyworm outbreaks in Ethiopia affected >279,000 hectares of cropland (USAID, 2008). Outbreaks of a similar scale occurred in southern Africa in 2012/13, when in Zambia alone armyworm were reported in seven of the country's ten provinces and more than 96,000 hectares of maize and pasture were infested, affecting close to 73,000 farmers (USAID, 2013). Fall armyworm *Spodoptera frugiperda* (J.E. Smith), an invasive species, was reported on the African continent for the first time in 2016 (Goergen *et al.*, 2016). Recently, this pest was reported for the first time in southern Africa (Malawi, Mozambique, Namibia, South Africa, Zambia and Zimbabwe) and it is causing considerable damage to maize (FAO, 2017b). The fall armyworm is a voracious pest and, given its polyphagous nature, it is expected that its accidental introduction in the African continent will constitute a lasting threat to several cereal crops.

INTEGRATED MANAGEMENT OF ARMYWORM

Armyworms are mainly controlled using contact insecticides such as dimethoate or similar organophosphorous insecticide sold under many different brand names (Adamczyk *et al.*, 1999). Transgenic maize cultivars expressing the Cry1F toxin are effective against armyworms, but are currently not cultivated in Africa. Moreover, reports about increasing cases of fall armyworm resistance to Cry1F (Storer *et al.*, 2010) show there is need to develop alternative control options including the use of nucleopolyhedroviruses (NPV), endophytic entomopathogenic fungi and insect biological control agents (Grzywacz *et al.*, 2014).

Termites

Termites are becoming important maize pests in many tropical countries (Rouland-Lefèvre, 2010; Dhillon *et al.*, 2014; Bragg *et al.*, 2016). Maize is attacked by several species of termites and the damage can be seen especially during drought seasons or in areas where rainfall is scarce. Termites can destroy the roots causing the lodge of the stem. Destruction continues even on fallen plants. Attacks at the early stage may cause 100% yield loss. Damage after physiological maturity will lead to grains of poor quality because after lodging, cobs are exposed to contamination (Sileshi *et al.*, 2005). Termites are mainly controlled using chemical insecticides (Riekert and Van den Berg, 2003).

Aflatoxins in cereals and their management

Aflatoxins are highly toxic and carcinogenic mycotoxins that frequently contaminate several cereal crops grown in warm agricultural areas across the globe (Shephard, 2008; Liu and Wu, 2010). Aflatoxin contamination is widespread in maize and sorghum and can end up in milk from animals fed with contaminated feed (Shephard, 2008; Udomkun *et al.*, 2017). Several *Aspergillus* species possess the ability to produce aflatoxins although the major causal agent of contamination globally is *Aspergillus flavus* Link (Klich, 2007). Consumption of foods containing high aflatoxin concentrations can cause acute health effects, such as liver cirrhosis and death (CDC, 2004), while sub-lethal chronic exposure may cause cancer and is associated with immune system suppression, and impaired food conversion, interference with micronutrient metabolism, increased incidence and severity of infectious diseases, as well as retarded child growth and decrease in human and animal productivity (Williams *et al.*, 2004; Liu and Wu, 2010; Chan-Hon-Tong *et al.*, 2013). Women may expose their unborn child to aflatoxins during pregnancy and through breastfeeding, if they consume aflatoxin contaminated foods (Chan-Hon-Tong *et al.*, 2013). An estimated 4.5 billion people in developing countries are exposed to aflatoxins (CAST, 2003; Williams *et al.*, 2004).

INTEGRATED MANAGEMENT OF AFLATOXINS Aflatoxin contamination is a complex process that starts in the field and persists in storage (Lillehoj *et al.*, 1980; Williams, 2006). Deployment of good agricultural practices (GAP) is the most effective and economical strategy for achieving 'aflatoxin safe' crops and foods. Several pre-harvest and post-harvest management strategies have been recommended for the reduction of aflatoxin accumulation (Hell *et al.*, 2008). These include cultural practices, biological control of aflatoxin-producing fungi and proper post-harvest handling (Lillehoj *et al.*, 1980; Jones, 1987; Hell *et al.*, 2008; Bandyopadhyay *et al.*, 2016).

PRE-HARVEST MANAGEMENT OF AFLATOXINS Pre-harvest aflatoxin contamination can be minimized by ploughing to bury crop debris that provide a food source for *A. flavus*, selection of appropriate planting date (to take advantage of periods of rainfall and avoid end-season drought effects), seed dressing with systemic fungicides or bio-control agents, maintaining good plant density in the fields, removal of premature dead plants, managing weeds, pest and diseases and proper fertilizer application (Lillehoj *et al.*, 1980; Jones, 1987; Hell *et al.*, 2008). These practices minimize proliferation of aflatoxin producing *A. flavus.*

RESISTANT CROP VARIETIES Aflatoxin contamination flares when plants are grown under stressful conditions (Bandyopadhyay *et al.*, 2016). Use of crop varieties with tolerance to drought and insect pests, resistance to major biotic stress will minimize stressing plants and contribute towards minimizing aflatoxin contamination. Resistance to aflatoxin contamination exists in maize populations, but this is complex and is controlled by multiple genes (Warburton and Williams, 2014). Progress has been made in selecting maize inbred lines with resistance to aflatoxin accumulation (Windham and Williams, 2002; Warburton and Williams, 2014). However, despite all efforts, the level of resistance in available maize hybrids is not yet adequate to prevent unacceptable aflatoxin contamination.

BIO-CONTROL OF AFLATOXIN Biological control of aflatoxins is considered as the most promising strategy for pre-harvest control of aflatoxin as it does not demand much of the farmer's time (Bandyopadhyay *et al.*, 2016). It employs the ability of non-toxigenic *A. flavus* strains to effectively out-compete toxigenic strains for the same ecological niche (Cotty, 2006). Strains of atoxigenic *A. flavus* immobilized on heat killed carrier (i.e. wheat, sorghum or barley grain) that also serves as a nutrient source is broadcast in the field (Bandyopadhyay *et al.*, 2016). The biocontrol formulation provides atoxigenic *A. flavus* with both reproductive and dispersal advantages over resident aflatoxin-producers (Cotty *et al.*, 2008). Timing of bicontrol application is very crucial for success; normally it is carried out before resident *Aspergillus* populations begin to increase, 2–3 weeks before crop flowering, and this allows for effective displacement of aflatoxin producers (Atehnkeng *et al.*, 2014; Bandyopadhyay *et al.*, 2016). Application of the biological control has consistently been shown to reduce aflatoxin contamination by more than 80% and the effect carries into storage (Atehnkeng *et al.*, 2014).

POST-HARVEST MANAGEMENT OF AFLATOXINS Although pre-harvest control strategies are emphasized for control of aflatoxin, these should be augmented by post-harvest strategies (Table 5.3). The crop should be properly dried to safe moisture levels (10–13%) before storage, to reduce and prevent fungal growth in storage (Hell *et al.*, 2008). Naked

Table 5.3. Strategies for integrated management of aflatoxin in cereals for improved food safety and health.

Stage	Actions
Pre-harvest	Timing of planting; Crop variety used; Genotype of seed planted; Irrigation, insecticides; Biological control through competitive exclusion; Timing of harvesting
Post-harvest: drying and storage	Hand sorting; Drying on mats; Sun drying; Storing bags on wooden pallets or elevated platforms; Use of insecticides and hermetic storage structures; Rodent control

cobs or grain should be dried off the ground and on tarpaulins or raised platforms. Solar dryers have been introduced for faster and efficient maize drying under a controlled environment that offers improved sanitation (Sharma *et al.*, 2009; Ogunkoya *et al.*, 2011). To increase adoption of solar-drying technology, affordable, low maintenance solar dryers are required for smallholder farmers (Sharma *et al.*, 2009; Ogunkoya *et al.*, 2011).

IMPROVED STORAGE STRUCTURES Use of controlled atmosphere storage (hermetic) with high CO_2 and low O_2 has been shown to inhibit *A. flavus* growth and reduce aflatoxin production in staple grains (Anankware *et al.*, 2012; De Groote *et al.*, 2013). When used together with grain sorting to remove damaged grain, hermetic storage is very effective in minimizing aflatoxin contamination in storage (Chulze, 2010). Several storage technologies are available, including hermetic storage bags such as super grain bags and metal silos that are suitable for smallholder farmers (Anankware *et al.*, 2012; De Groote *et al.*, 2013).

5.3 Sorghum and Millets

Sorghum and millets (a diverse group of small-grain annual cereal grasses including pearl millet, foxtail millet, finger millet and several others) are particularly important for smallholder farmers on drought-prone marginal lands. In sub-Saharan Africa, sorghum and millets are typically grown as the primary food crop in dry rain fed systems on poor soils with minimal synthetic inputs (Belton and Taylor, 2004; Reynolds *et al.*, 2015). In contrast, in South Asia sorghum and millet crops are increasingly irrigated and given higher input as they are grown for market sale in sequence and rotation with other crops, mainly pulses and oilseeds (Reynolds *et al.*, 2015). Of the small grains, sorghum is the more commonly grown. The area under sorghum in sub-Saharan Africa increased by 82% from 1984 to 2014 (FAOSTAT, 2014). By 1994, sorghum production in the tropics was 55.2 million tons, with Africa accounting for 54% of production; while millet production was 27.2 million tons, with Asia contributing 54% of the quantity (FAO, 2014).

5.3.1 Diseases and insect pests of sorghum and millets

Yields of sorghum and millets are generally low, (<500 kg/ha) and this is attributed to several factors, including genetics, environmental, weeds, diseases and pests (Chandrashekar and Satyanarayana, 2006; Rurinda *et al.*, 2014). On average, about 17% of sorghum and millet yield is lost annually to weeds, 8% to insect pests and 5% to diseases (Reddy and Usha, 2004). Important diseases of sorghum include several leaf diseases (sorghum leaf blight, anthracnose, sooty stripe, leaf rust, grey leaf spot, downy mildew, and several bacterial diseases), grain diseases (such as head smut, and false smut, root and stalk diseases, insect pests), and weeds (such as *Striga*) (Reddy and Usha, 2004; Chandrashekar and Satyanarayana, 2006). Diseases of economic importance to millet cultivation include rust (*Puccinia substriata* Ellis & Bartholomew), ergot (*Claviceps fusiformis* Loveless), leaf blast (*Pyricularia grisea* Cavara), foot rot (*Sclerotium rolfsii* Saccardo), smut (*Tolyposporidium penicillariae* Brefeld), leaf spot (*Helmithosporium sp.*), and downy mildew (*Sclerospora graminicola* (Saccardo) J. Schröter) (Lubadde, 2014). *Striga hermonthica*, (Del.) Benth. is an important weed pest in East Africa. Insects of economic importance to millet cultivation include armyworms, stem-fly (*Atherigona miliaceae* Malloch), stripe borer, pink borer flea beetle and millet head miner, *Heliocheilus albipunctella* (de Joannis) (Youm and Owusu, 1998).

Integrated management of selected sorghum and millet diseases

In smallholder farming systems in tropical countries, sorghum and millets are grown in dry marginal areas that are prone to drought. Therefore major diseases are the ones that affect the panicle and do well under dry conditions. Insect pests, including stem borers and gall midges are very important as they cause significant economic losses. Use of host resistance is the preferred pest management option for the smallholder farmers (Ejeta, 2007a). Resistance to most biotic problems is available and is widely deployed and used (Chandrashekar and Satyanarayana, 2006). However, as these crops are considered orphan crops, most farmers use their own seed and thus do not have access to improved technology. Awareness creation and extension are needed to bring the technology to farmers.

Sorghum leaf blight, caused by *Exserohilum turcicum*, ((Luttr.) K.J. Leonard & Suggs), is a foliar disease common under conditions with heavy dew. Leaf blights are effectively controlled using resistant cultivars (Hennessy *et al.*, 1990; Ejeta, 2007a) and through rotation to non-susceptible crops. Although fungicides that are effective against foliar diseases are available, these are rarely used in managing sorghum and millet diseases in the tropics.

Head smut, caused by the soilborne fungus *Sporisorium reilianum* ((J.G. Kühn) Langdon & Fullerton), is a serious disease of sorghum and millets. When infected, some hybrids are dwarfed and will tiller profusely. As head smut spores can remain viable for years in the soil, crop rotation and fungicides are not effective in managing the diseases. Hence host resistance is the only effective strategy for managing head smut. Sources of resistance are available and have been incorporated into preferred cultivars (Zou, 2010).

Pearl millet downy mildew, caused by *Sclerospora graminicola* ((Sacc.) J. Schröt.), is a serious disease in India and Africa with losses of at least 30% reported on susceptible varieties (Singh, 1995). Two types of spores, sporangia on the leaves and oospores on all plant parts, can survive in the soil and can be spread long distances in soil blown by the wind. Management is dependent on hybrids bred for resistance (Breese *et al.*, 2000), and treatment of the seeds with fungicides, most commonly metalaxyl (Williams and Singh, 1981). However, use of resistant varieties is the most suitable management strategy for stallholder farmers.

Rust of pearl millet (*Puccinia substriata* Ellis & Bartholomew) causes substantial losses in grain yield, especially if infection is early. Spores carried by the wind spread the rust, and the pathogen can survive in soil, on plant debris, volunteer pearl millet and alternative hosts (Khairwal *et al.*, 2007; Lubadde *et al.*, 2014). Management strategy includes crop rotation, removal of weeds, cultivation of tolerant varieties and destruction of the crop remains after harvest. Fungicides are not economically viable unless crops are grown for commercial purposes (Khairwal *et al.*, 2007).

Sorghum downy mildew (*Peronosclerospora sorghi* (W. Weston & Uppal) C.G. Shaw) is predominantly a soilborne disease, whose thick-walled oospores can survive for several years in the soil before infecting young plants. Oospores can also be carried over in seed. Infected plants fail to produce grain. Host-plant resistance has been a very effective method to control sorghum downy mildew and numerous resistant lines have been identified (Rashid *et al.*, 2013). The fungicide metalaxyl is effective in reducing the incidence of sorghum downy mildew when applied as a seed dressing (Williams and Singh, 1981). The main control methods are the use of a resistant varieties combined with a fungicide seed treatment (Hash and Witcombe, 2002; Rashid *et al.*, 2013).

Integrated management of selected sorghum and millet insect pests

Millet stem borer (*Coniesta ignefusalis* Hampson) is a major pest of millet in the Sahelian and sub-Saharan regions (Ajayi, 1990). The larvae tunnel into stems leading to lodging, dead hearts, poor grain development and yield reduction. The use of chemicals is rarely justified due to difficulty in timing of application and cost. A combination of cultural practices, such as early planting, intercropping, the 'push–pull' system, and managing crop residues are the most effective approaches for controlling the pest (Ajayi, 1990; Khan *et al.*, 2014).

Sorghum midge (*Stenodiplosis sorghicola* (Coquillett)) is one of the most important pests of sorghum. The larvae feed on developing seeds resulting in malformation of the grain and empty or chaffy heads. The pest can effectively be managed by a combination of resistant varieties (Sharma *et al.*, 1993; Tao *et al.*, 2003), and cultural control measures, such as planting early and planting varieties that flower (Sharma, 1985). Chemical sprays are not very effective as the pest spends most of its life cycle protected inside the spikelets.

Sorghum stem borers (*Busseola* spp., *Chilo* spp., *Eldana* spp. and *Sesamia* spp.) are major pests of sorghum (Nwanze and Mueller, 1989). Their larvae feeds by digging the internal tissue of the plant stem, causing the weakening of the plant. The pest can be controlled through a combination of cultural practices, most notably intercropping and the 'push–pull' system as outlined under maize pests (Kfir *et al.*, 2002; Pickett *et al.*, 2014; Khan *et al.*, 2016).

Ear head caterpillar (*Helicoverpa armigera* (Hübner)) may attack sorghum from head emergence to early grain fill. The insect feeds on the developing grain, resulting in poorly filled and shrivelled seeds (Reddy and Usha, 2004; Gandhi and Balikai, 2013). Ear head caterpillar is best managed using a naturally occurring nuclear polyhedrosis virus (NPV). There are several cost-effective, commercially formulated NPV products on the market. In addition, natural enemies of *Helicoverpa* are very effective in managing the pest (Reddy and Usha, 2004).

5.4 Rice

Rice is the principal food grain consumed by almost half of the world's population (Khush, 2005), making it the most important food crop currently produced. Rice is grown on over 163 million ha in more than 110 countries, and occupies almost one-fifth of the total world cropland under cereals (FAO, 2014). Most of the world's rice production is from irrigated and rainfed lowland rice fields in warm and humid environments that are conducive for insect pest proliferation (Pathak and Khan, 1994). Rice yield losses in tropical countries have been estimated at 10.9% from diseases, 12.9% from insect pests and 9.2% from weeds (Gianessi, 2014). The estimates caused by diseases (16.6%) were highest in Asia, while those caused by weeds (11.9%) were highest in Africa (Gianessi, 2014).

5.4.1 Important diseases of rice

Many pathogens affect rice productivity in tropical countries worldwide (Webster and Gunnell, 1992). These are classified into: (i) **major pathogens** that include blast fungus (*Magnaporthe oryzae* B.C. Couch), Rice yellow mottle virus (RYMV) and the bacterium responsible for leaf blight (*Xanthomonas oryzae* pv. *oryzae* (Ishiyama) Swings *et al.*); (ii) **secondary pathogens** responsible for brown spot (*Bipolaris oryzae* (Breda de Haan) Shoemaker), leaf scald (*Gerlachia oryzae* (Hashioka & Yokogi) W. Gams) and sheath blight (*Rhizoctonia solani* J.G. Kühn); (iii) **minor pathogens** responsible for false smut (*Ustilaginoides virens* (Cooke) Takahashi), narrow brown spot

(*Cercospora jansenea* (Raciborski) Constantinescu), sheath rot (*Sarocladium oryzae* (Sawada) W. Gams & D. Hawksworth), bakanae disease (*Fusarium moniliforme* J. Sheldon), bacterial leaf streak (*Xanthomonas oryzae* pv. *oryzicola* (Fang *et al.*) Swings *et al.*) and grain discoloration (caused by a complex of fungi) (Séré *et al.*, 2013).

Integrated management of rice diseases

Host plant resistance is the most important tool for managing rice diseases, especially for smallholder farmers in developing countries (Buddenhagen, 1983). The use of resistant varieties is very much welcomed by resource-poor farmers because it does not require additional cost and it is environmentally friendly. Rice varieties resistant to rice blast (Bonman and Mackill, 1988), bacterial blight (Mew *et al.*, 1992), rice tungro (Azzam and Chancellor, 2002) and brown spot (Ou, 1985) are widely used. Examples of integrated rice disease management for the major diseases are given below, taking host resistance as the main component of the strategy.

Rice blast (*Magnaporthe grisea* (T.T. Hebert) M.E. Barr) affects all aerial parts of the plant, causing their death up to tillering, or reducing grain yield and quality on mature plants. Yield loses ranging from 9% to 80% have been reported, depending on cultivar, prevailing environmental conditions and stage of infection (Bonman *et al.*, 1992). An effective control of rice blast can be achieved by using tolerant or resistant varieties, fractioning the distribution of nitrogen fertilizers, satisfying the water needs of the plants, destroying the crop residues and using certified and fungicide treated seeds. Sources of resistance to rice blast are available (Bonman *et al.*, 1992; Bonman and Mackill, 1988), and these have been used to develop resistant/tolerant varieties for different localities (Fukuoka and Okuno, 2001; Suh *et al.*, 2009). Rice varieties with stacked resistance genes (gene pyramiding) have been used to extend the usefulness of host resistance to manage rice blast (Séré *et al.*, 2013). Multi-lines composed of a mixture of varieties with different blast resistance genes have routinely been used to manage the disease (Wolfe, 1985; Zhu *et al.*, 2000). Although effective, chemical control is rarely used for managing blast under field conditions. Rather, fungicides, such as benomyl and edifenphos, tricyclazol, kitazin and thiophanate-methyl are commonly used in nurseries (Séré *et al.*, 2013).

Rice yellow mottle disease (Rice yellow mottle virus (RYMV)) is responsible for major epidemics and yield loss in lowland irrigated rice (Kouassi *et al.*, 2005). Leaves turn yellow or orange with green streaks, plants become stunted, tiller number is reduced and panicles produce unfilled or sterile grain (Kouassi *et al.*, 2005). Yield losses ranging from 10% to 90% have been reported in susceptible cultivars and when infection occur early (Taylor, 1989). RYMV is spread by beetles and grasshoppers and perhaps also other insects and mites, through leaf-to-leaf and root-to-root contact, and on harvest implements (Koudamiloro *et al.*, 2015). Use of host resistance is the most efficient method for managing the diseases. Tolerant varieties are available and are routinely deployed in areas where the disease is a problem (Pinto, 1999; Salaudeen, 2014). The use of tolerant varieties in conjunction with cultural techniques, e.g. removal of rice ratoons, grasses and sedges that are alternative hosts of both virus and insects before planting and destruction of crop residues after harvest is very effective in managing the disease (Sorho *et al.*, 2005). Managing insect vectors in the nursery and weeds in fields surrounding the nurseries is important for controlling vectors of important viruses.

Bacterial leaf blight of rice (*Xanthomonas oryzae* pv. *oryzae* (Ishiyama) Swings *et al.*) kills seedlings and destroys the leaves of older plants. The disease is extremely serious worldwide and has emerged as a major problem in irrigated crops (Mizukami and Wakimoto 1969; Séré *et al.*, 2013). Yield losses ranging from 2.7% to 41% have been reported in Africa (Awoderu *et al.*, 1991). Wild hosts maintain the disease between crops and spread occurs through irrigation and floodwaters as well as by wind, rain and seed. Management requires use of pathogen-free seed or seed coming from pathogen-free crops. Resistant or tolerant varieties should be planted. Resistance to bacterial blight is available and more than 30 resistance genes have been characterized (Sun *et al.*, 2004). Gene pyramiding has been used as a strategy to develop rice varieties with stable and durable resistance to bacterial blight (Huang *et al.*, 1997; Datta *et al.*, 2002). Cultural practices, such as burning crop residues after harvesting heavily infected fields, destroying the surrounding weeds that serve as a reservoir of the pathogen, good drainage and removal of volunteer seedlings and proper use of nitrogen fertilizer have been effective in managing bacterial blight (Verdier *et al.*, 2012; Séré *et al.*, 2013).

5.4.2 Insect pests of rice

Over 100 species of insect pests attack rice and about 20 of these can cause economic damage (Pathak and Khan, 1994; Muralidharan and Pasalu, 2006), through either direct feeding and/or transmission of viruses. Important insect pests include stem borers, gall midge (*Orseolia oryzae* Wood-Mason), brown planthopper (*Nilaparvata lugens* (Stål)), leaf folder (*Cnaphalocrocis medinalis* (Guenée)), and green leafhopper (*Nephotettix virescens* (Distant)). Yield losses due to pests have been estimated at about 20% (Pathak and Khan, 1994). The stem borers are the most serious pests of rice and they infest plants from seedling stage to maturity. In Asia, the most destructive and widely distributed are yellow stem borer, *Scirpophaga incertulas* (Walker) and striped stem borer *Chilo suppressalis* (Walker) which are responsible for an annual damage of 5–10% (Pathak and Khan, 1994). In Africa, sorghum stem borer *Chilo partellus* (Swinhoe), *C. diffusilineus* (de Joannis), white stem borer *Maliarpha separatella* Ragonot, and African pink borer *Sesamia calamistis* Hampson are serious rice pests (Nwilene *et al.*, 2013). In South America, *Diatraea saccharalis* (Fabricius) is the most widespread species, followed by *Rupela albinella* Cramer and *Elasmopalpus lignosellus* (Zeller) (Pathak and Khan, 1994).

Integrated management of rice insect pests

YELLOW STEM BORER Feeding larvae of this insect cause deadhearts at the vegetative stages and whiteheads at the reproductive stages. Deadhearts cause a curl of the central leaf that remain unfolded, turns brownish and dries out, and do not support the panicle. Whereas whiteheads cause non emergence to the panicle, that remains empty and white. Yields can be reduced by as much as 23%. Yellow stem borer can effectively be controlled using cultural practices but most are effective only if carried out through community-wide cooperation, while others are effective on a single field (Singh *et al.*, 2014). Practices that can be carried out on a single field include using optimal rates of nitrogen fertilizer in split applications. Applying slag increases the silica content of the crop, making it more resistant. Since the eggs of *S. incertulas* are laid near the tip of the leaf blade, the widespread practice of clipping the seedlings before transplanting greatly reduces the carry-over of eggs from the seedbed to the transplanted fields. Majority of the larvae, including those remaining in the stubble, can be removed by harvesting at ground level burning or removing the stubble, decomposing the stubble with low rates of calcium cyanide, ploughing and flooding (Pathak and Khan, 1994). In several countries, delayed seeding and transplanting have been effective in evading first-generation moths. Crop rotation with non-graminaceous crops significantly reduces the borer population.

Most biological control of stem borers in tropical Asia and Africa comes from indigenous predators, parasites, and entomopathogens (Nwilene *et al.*, 2013). The success and the development of stable IPM systems depend primarily on the conservation of these valuable organisms. Over 100 species of stem borer parasitoids have been identified. The species belonging to the genera *Telenomus*, *Tetrastichus* and *Trichogramma* are the most important egg parasitoids. Egg masses are also the food of several predators, e.g. the longhorned grasshopper *Conocephalus longipennis* (Haan), Coccinellid beetles *Micraspis crocea* (Mulsant), *Harmonia octomaculata* (Fabricius) and carabid beetles such as *Ophionea* spp. prey on young newly emerged larvae before they penetrate the stem (Pathak and Khan, 1994).

Although a lot of rice germplasm (17,000 varieties) has been screened for resistance to stem borers, high levels of resistance have not been found; only partial resistance is available (Nwilene *et al.*, 2013). In addition, varieties are rarely resistant to all stem borer species, thus complicating the use of host resistance to manage the pest. Some wild rice germplasm, such as *Oryza officinalis* (Well ex Watt) and *Oryza ridleyi* (Hook. f.) have very high levels of resistance to stem borers; however, this resistance has so far been not transferred to cultivated rice (Pathak and Khan, 1994). Efforts are underway to transfer this resistance to cultivated rice (Pathak and Khan, 1994; Datta *et al.*, 2002). Stem borers are difficult to control with insecticides because after hatching, the larvae are exposed only for a few hours before they penetrate the stem (Pathak and Khan, 1994; Nwilene *et al.*, 2013).

AFRICAN RICE GALL MIDGE (*ORSEOLIA ORYZIVORA* HARRIS AND GAGNÉ) Larvae of the African rice gall midge feed on young shoots (tillers) of rice, causing long cylindrical galls and prevent growth of tillers, leading to severe yield reductions (Nacro *et al.*, 1996; Nwilene *et al.*, 2013). The most noticeable symptom of infestation is silvery white galls, also known as 'silver shoots' or 'onion leaf galls', unique to the gall midge. Breeding for resistance or tolerance to midge attack shows greatest promise (Omoloye *et al.*, 2002; Bragg *et al.*, 2016). An improved variety, Cisadane, is highly tolerant to natural midge infestations (Omoloye *et al.*, 2002). More sources of resistance have been found and these are being incorporated into high-yielding and adapted varieties. Other options include managing alternative hosts outside the cropping season, synchronizing wet season planting of rice to limit midge colonization of early planted rice crops. A combination of natural control, through encouragement of parasitic wasps, and planting of resistant or tolerant varieties is the most effective method for managing this damaging pest (Nwilene *et al.*, 2013).

5.5 Storage Pests

Cereal crops play a major role in smallholder farmers' livelihoods in sub-Saharan Africa (SSA), with maize being the most important food and cash crop for millions of rural farm families in the region (Cairns *et al.*, 2013). Therefore, proper storage significantly contributes to food security (Tefera, 2012). On average, an estimated 20–30% of cereal produce, amounting to more than US$4 billion annually is lost to storage pests (FAO, 2010). In maize, losses as high as 45% have been reported (Tefera, 2012). Millet and sorghum grains are relatively resistant to post-harvest pest attacks, and under good storage conditions, they can be kept for two or three years with relatively little damage, even in the absence of pesticides.

The main storage insect pests of maize are the maize weevil *Sitophilus zeamais* (Motschulsky), the larger grain borer (LGB), *Prostephanus truncatus* (Horn), angoumois grain moth *Sitotroga cereallela* (Olivier) and the lesser grain weevil *Sitophilus oryzae* (L.); these collectively cause an estimated 20–30% loss (Abass *et al.*, 2014; Tefera, 2012). LGB has emerged as the most important storage pest of maize. The pest was accidentally introduced into Africa (Tanzania, East Africa, West Africa) during the late 1970s, where it has spread rapidly (Farrell and Haines, 2002; Tefera, 2012; Abass *et al.*, 2014). The pest makes long-term storage of maize impossible, thus affecting food security and livelihoods of many smallholder farmers (Tefera, 2012; Abass *et al.*, 2014).

5.5.1 Integrated management of cereal storage pests

Several strategies are currently being used to manage storage pests of maize (Midega *et al.*, 2016), but the most effective is the use of storage pesticides. Correct identification of the pest is essential as efficacy of insecticides vary depending on pest species (Midega *et al.*, 2016). For example pyrethroids pesticides can effectively control the lesser grain borers (*Rhyzopertha dominica* (Fabricius)), but not maize weevil (*Sitophilus zeamais*) and rice weevil (*S. oryzae*), while *R. dominica* can be controlled by organophosphate insecticides (Lorini and Filho, 2006).

Storage hygiene

Poor storage hygiene can lead to the perpetuation of storage problems from one season to the other. Proper cleaning and maintaining good store hygiene are essential to good storage-pest management. Drying the harvested grains to safe storage moisture content, aeration and cooling, followed by suitable packaging in sanitized insect-proof containers can prevent grain loss.

Physical control

Altering the physical environment variables such as temperature, relative humidity/grain moisture content and composition of atmospheric gases can effectively be used to manage storage pests. Inert dusts including sand and other soil components, Diatomaceous earth, silica aerogel, non-silica dusts (e.g. rock phosphate) and clays (e.g. kaolin) kill storage insects through dehydration (Fields and Muir, 1996). Diatomaceous earths are the fossil remains of aquatic plankton that are as effective as the synthetic conventional insecticide, but are nontoxic to humans and animals (Fields and Muir, 1996; Stathers *et al.*, 2008).

Hermetic storage

A new technology using thick plastic bags 'Super Bags' that does not allow gaseous exchange (hermetic), thus suffocating the pests by depleting oxygen is gaining prominence for managing storage pests in smallholder settings (Abass *et al.*, 2014). One such method currently under extensive promotion is the use of 'triple bagging' technique that was developed as an effective hermetic storage method in Cameroon (Anankware *et al.*, 2012). It provides the use of two polyethylene inner bags of 80 µ and one external bag, more durable and resistant. The control of insects given by the bags is very effective and with a duration of 3–4 years.

Chemical treatment

The judicious use of synthetic insecticides offers farmers storing grain a potent means of protection against storage pests. The best example of this has been the campaigns against LGB, in which shelling of maize cobs, the admixture of an insecticidal cocktail (mixture of organophosphorus and synthetic pyrethroid), and storage in sacks or other containers has limited grain losses. Fumigation uses gaseous pesticides to suffocate or poison the pests and this is applied mainly in commercial storage facilities such as warehouses or silos. Currently, phosphine is the most common fumigant used for stored crop protection worldwide despite reported failures in some countries due to insect resistance (Nguyen *et al.*, 2015). However, synthetic insecticides are falling out of favour for environmental and health reasons, and the future is likely to rest more on other approaches such as good hygiene, hermetic stores, and the application of alternatives to synthetic insecticides, such as diatomaceous earths.

Crop variety

The choice of grain variety is a critical initial step in preventing loses during storage. There have been efforts to breed maize varieties with increased resistance to storage pests over many years (Kumar, 2002), but to date these have not resulted in crops with both desired agronomic characteristics and the required resistance.

5.6. Striga

Striga is a parasitic weed that seriously constrains the productivity of staples such as maize, sorghum, millet and upland rice in sub-Saharan Africa (Ejeta, 2007b). The weed survives by siphoning-off water and nutrients from the crop for its own growth and impairs normal host growth via three processes: competition for nutrients, impairment of photosynthesis (Joel, 2000) and a phytotoxic effect within days of attachment to the hosts (Frost *et al.*, 1997; Gurney *et al.*, 1999). There are about 23 species of *Striga* in Africa, out of which *Striga hermonthica* (Del.) Benth. and *Striga asiatica* (L.) Kuntze, are the most important (Gressel *et al.*, 2004; Gethi *et al.*, 2005). Roughly 300 million people in sub-Saharan Africa (SSA) are adversely affected by *Striga* (Ejeta, 2007b). *Striga* infests nearly 100 million hectares, that is more than 40% of arable land in SSA (Lagoke *et al.*, 1991) and causes yield losses ranging from 20% to 80% and even total crop failure in severe infestation (Kanampiu *et al.*, 2002a; Khan *et al.*, 2016). Unfortunately, the problem of *Striga* is continuing to extend to new areas in SSA as farmers abandon heavily infested fields for new ones (Gressel *et al.*, 2004; Khan *et al.*, 2016).

5.6.1 Integrated management of *Striga*

Striga seeds can remain dormant and viable in the soil for up to 20 years (Khan *et al.*, 2016). Effective control of *Striga* should target reducing the seed bank in the soil, preventing new seed production and spread from infested to non-infested soils, and improving soil fertility (Ejeta, 2007b). *Striga* infestation can be controlled through heavy application of nitrogen fertilizer (Igbinosa *et al.*, 1996), crop rotation (Oswald and Ransom, 2001), use of trap crops that are not susceptible to parasitism by *Striga* such as legumes (Gbehounou and Adango, 2003), chemical stimulants (Worsham *et al.*, 1959) to abort seed germination, hoeing and hand-pulling (Ransom, 1996), herbicide application (Oswald, 2005), imazapyr herbicide-resistant maize (IR-maize) (Kanampiu *et al.*, 2001, 2002a, 2003), and use of resistant/tolerant crop varieties (Showemimo *et al.*, 2002).

Host-crop resistance

Relatively good progress in identifying resistance/tolerance in maize and sorghum has been achieved (Ejeta and Butler, 1993; Kim, 1994). Resistance is mainly quantitative, i.e. as the level of *Striga* infestation and virulence increases the resistance will eventually break down. *Striga* tolerance/resistance (STR) maize varieties have been developed and are being grown widely in West Africa (Menkir *et al.*, 2010), and East Africa (De Groote *et al.*, 2008). Recently maize inbred lines and hybrids with polygenic field resistance and the IR-genes have been developed (Menkir *et al.*, 2010). These hybrids sustained less damage and yield loss under *S. hermonthica* infestation and supported fewer emerged parasites than the susceptible hybrid check (Menkir *et al.*, 2007).

Hand weeding

Although it seems to be a straightforward approach to interrupt the growth cycle of *Striga*, easy to practice and understand, it is not very effective and farmers are reluctant to employ it. One reason is that *Striga* emerges 5–6 weeks after planting and it takes another 3 weeks until the plants are big enough to be uprooted. At that time the farmer has already done the ‘normal’ weeding of the crop, which means coming back to weed *Striga* not only once but several times, as *Striga* continues to emerge until a few weeks before harvest (Oswald, 2005). Second, *Striga* not only absorbs water and nutrients from its host-crop but also exerts a potent phytotoxic effect on the host-crop, which means that although *Striga* is weeded, it has already done considerable damage to the crop (Ransom, 1996). Third, *Striga* densities are often so high that hand-weeding is extremely time-consuming. Nevertheless, it remains an integral part of an integrated *Striga* control approach to minimize mature plants and replenishing the seed bank.

Herbicides

There are number of herbicides available for controlling pre-flowering *Striga* (Langston and English, 1990), but these are largely unavailable to smallholder farmers mainly because of cost. Seed-dressing of imazapyr-resistant maize gets direct action on *Striga* seed. This causes *Striga* plants, which attach to the maize roots or around coated seeds, to immediately die. The maize remains *Striga*-free for the first weeks after planting and this considerably increases yield (Kanampiu *et al.*, 2002b). Development of imazapyr and pyrithiobac seed coatings for the control of *Striga* offers an effective means of controlling *Striga* with smaller amounts of herbicide than is used in spray applications (Berner *et al.*, 1997; Abayo *et al.*, 1998; Kanampiu *et al.*, 2002b, 2003). As little as 30 g/ha imazapyr seed coating applied to imidazolinone resistant (IR) maize seed before or at the time of *Striga* attachment to the maize root will prevent the phytotoxic effect of *Striga*. Imazapyr that is not absorbed by the maize seedling diffuses into the surrounding soil, thus killing ungerminated *Striga* seeds. Maize varieties that have been converted to herbicide resistance are available for use by smallholder farmers (Menkir *et al.*, 2010). This technology reduces yield loss to less than 20%, depletes the *Striga* seed bank in the soil so subsequent *Striga* numbers are less the following year, is cost-effective, and is compatible with existing cropping systems.

Crop rotations

Striga seed banks can be reduced by inducing suicidal germination with trap crops or through natural demise (Berner *et al.*, 1995; Khan *et al.*, 2016). Rotating susceptible cereal crops with crops that are not parasitized by *Striga* has long been advocated as a simple way of avoiding *Striga*-related losses. Rotating with trap crops that induce the germination of *Striga* but are not themselves parasitized is an effective way to reduce levels of *Striga* seeds in the soil. Cotton, sunflower and soybean are effective in reducing *Striga* seed bank and improve cereal yields (Teka, 2014). Crop rotation is probably the most effective way to reduce *Striga* infestation and increase cereal yields considering the limited resource base of smallholder farmers in SSA (Oswald and Ransom, 2001).

Intercropping

An important prerequisite to success in developing *Striga* control in Africa is an understanding of the cropping systems used. Multiple cropping predominates in smallholder farmers in the tropics (Akobundu, 1991). Intercropping cereals with legumes, such as cowpea, groundnut, green gram, dolichos bean and soybean has been shown to reduce the number of *Striga* plants that mature in an infested field (Carson, 1989; Carsky *et al.*, 1994). Effect of intercrops on *Striga* under intercropping might be acting as trap crops, stimulating suicidal *Striga* germination or altering the microclimate of the crop's canopy and soil surface to interfere with *Striga* germination and development (Parker and Riches, 1993).

The push–pull technology has been used to effectively manage *Striga* in sorghum and maize cropping systems. The 'push–pull' technology is based on a stimulo-deterrent concept (Miller and Cowles, 1990). In this strategy, maize is intercropped with a stem borer moth-repellent plant, *Desmodium uncinatum* (Jacq.) DC., while an attractant host plant, Napier grass (*Pennisetum purpureum* Schumach), is planted as a trap plant around this intercrop. Volatiles produced by the *Desmodium* repel the host-seeking moths, while those produced by the Napier grass are attractive to them (Chamberlain *et al.*, 2006). In Kenya, the above-mentioned forage legume, *D. uncinatum*, intercropped with maize has been found to reduce infestation by its allelopathic root exudates that stimulate germination of *S. hermonthica* seeds and concurrently inhibit growth of its radicle (Tsanuo *et al.*, 2003). The system has been modelled into the 'push–pull' technology for control of *Striga* and stem borers (Khan *et al.*, 2014). Though novel, adoption of the system is constrained by the use of *Desmodium* as a fodder crop and not directly as a food crop (Odhiambo *et al.*, 1994).

5.7 Challenges to IPM

Although IPM is viewed as the best strategy for managing pest and diseases of cereal crops, adoption by resource-limited farmers has been slow. A huge gap still exists that has limited the adoption and implementation of IPM strategies, including the following.

- Inadequate knowledge about actual losses from pests and the real as well as potential gains from pest management. Improving the estimation of cereal crop losses and the costs and benefits of reducing crop losses will help in adoption of IPM strategies by smallholder farmers.
- IPM requires collective action within a farming community (Parsa *et al.*, 2014). The recognition that pest management is most effective when implemented collectively at the country and regional level precedes IPM itself, and gave rise to the development of area-wide pest management (Knipling, 1960) and metapopulation theory (Levins, 1969). Success of such a programme requires buy-in from all people in the community. For example, smallholder farmers in Kenya were advised to plant maize only in one season to minimize the effect of MLN. However, some of the farmers planted maize in both the first and second season and this served as a virus reservoir and impeded proper management of MLN.
- For farmers, especially in developing countries, IPM is time-consuming and complicated; given the multiple demands of farm production, farmers cannot be expected to carry out the integration of multiple, suppressive tactics for all classes of pests (Ehler, 2006).

5.8 Conclusion

In most developing tropical countries, cereals are a major staple food crops and as such, there is no incentive from farmers to implement IPM strategies. The revenue from implementing IPM strategies is not huge enough to justify the time and resources that goes into IPM. In such a scenario, successful pest management should rely on the use of host resistance. This strategy is very attractive to farmers as they do not have to invest more for the benefit accrued. However, improved insect pests, diseases and weeds management through IPM, relying primarily on interventions supporting crop health and discouraging pest outbreaks (such as through intercropping and use of 'push–pull' systems to attract and trap pests (Khan *et al.*, 2016), have seen growing effectiveness and acceptance among farmers. More investments from governments to support extension services will be required for IPM to take root.

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