# Chapter 12
# Outbreak of Fall Armyworm (*Spodoptera frugiperda*) and Its Impact in Rwanda Agriculture Production

**Placide Rukundo, Patrick Karangwa, Bellancile Uzayisenga, Jeanne Priscille Ingabire, Bancy Waithira Waweru, Joelle Kajuga, and Jean Pierre Bizimana**

**Abstract** Agriculture is the major economic activity of the people of Rwanda, providing employment to about 86% of total population and contributing up to 47% of domestic goods and exports. Actual threats include outbreak of a new invasive insect pest, the fall armyworm *Spodoptera frugiperda*. In this review we describe the fall armyworm outbreak in African countries, particularly in Rwanda. An overview is given on available control options, management of the fall armyworm outbreak, and its implications in Rwanda. The information gathered will assist in controlling fall armyworm in newly invaded regions.

**Keywords** New invasive insect pest · Maize · Pest

P. Rukundo (✉)
Rwanda Agriculture and Animal Resources Development Board (RAB), Roots and Tubers Program, Musaze Station, Musanze, Rwanda

P. Karangwa · B. Uzayisenga
Rwanda Agriculture and Animal Resources Development Board (RAB), Research Department, Rubona Station, Huye, Rwanda

J. P. Ingabire
Rwanda Agriculture and Animal Resources Development Board (RAB), Crop Protection Program, Rubirizi Station, Kigali City, Rwanda

B. W. Waweru · J. Kajuga
Rwanda Agriculture and Animal Resources Development Board (RAB), Laboratory of Bio-control, Rubona Station, Huye, Rwanda

J. B. Bizimana
Rwanda Agriculture and Animal Resources Development Board (RAB), Cassava Program, Rubona Station, Huye, Rwanda



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## 12.1 Introduction

According to FAO (2003), food security is defined as a "situation that exists when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active and healthy life". In Rwanda, agriculture plays an important role in the contribution to food security, but it provides insufficient quantities to meet the needs of the country, which leads to the importation of food products to complement local productions. For example, the Rwanda food imports were reported at 18.25% in 2015 (WB 2017). The low production in Rwanda, leading to insufficient food security, is associated with the prevalence of a number of constraints that are abiotic, biotic, management, and socio-economic in nature. According to Reynolds et al. (2015), moisture scarcity, nutrient limitation, and biotic stresses are the major constraints in cereal crops such as wheat and rice. The shortage of quality seeds, drought, soil degradation, and poor soil fertility are the main challenges for maize production. In banana crops, *Xanthomonas* wilt (BXW) and *Fusarium* wilt, also known as Panama disease, are major challenges for production (Nkuba et al. 2015). Biotic stresses and post-harvest losses are the major constraints in root and tubers such as potato, cassava and sweet potato, while viral diseases and shortages of resistant varieties constitute one of the major constraints for cassava production (Nduwumuremyi et al. 2016). The production of many crops in Africa, and particularly in Rwanda, has declined due to pest and disease outbreaks (Goldman 1996; Tadele 2017). Insects are major pests in Africa and they cause crop yield losses, estimated between 30 and 60% (Oerke 2006). Furthermore, viral and bacterial diseases cause considerable damage to crops cultivated in different agro-ecological zones. Currently, cereals in Rwanda are threatened by an outbreak of a new invasive insect pest, the fall armyworm, *Spodoptera frugiperda* (*Lepidoptera*: Noctuidae). This study is aimed at reviewing the life cycle of fall armyworm, its outbreak in African countries and particularly in Rwanda, the available control options, the status of current management, and the implications of its outbreak in the country.

## 12.2 Review of Fall Armyworm

*Spodoptera frugiperda* is an important pest of members of family *Poaceae* that include major food crops such as corn, sorghum, rice and wheat, and diverse pasture grasses (Pashley 1996; Prowell et al. 2004). This polyphagous insect is native to and widely distributed in the tropical and subtropical regions of America, and known as an occasional serious pest of small grains and corn (Sparks 1979; Buntin et al. 2001; Murúa et al. 2009; Malo et al. 2013). Its invasion into Africa was reported for the first time in January 2016 in Nigeria. Since then, it has become an epidemic pest in several central and southern African countries (Goergen et al. 2016). Due to the importance of maize crop in these regions, the fall armyworm has become one of the most serious problems for the continent (Murúa et al. 2009).

In Central and South America, farmers face three or more generations of fall armyworm every year, and occasionally severe outbreaks occur as early as mid-April (Flanders et al. 2011). Every year, fall armyworm moths, carried by air currents, spread into the southern and central parts of the USA. The size and timing of the initial moth flights are two factors that influence the outbreak potential of this pest (Flanders et al. 2011). The infestation outbreak is sudden, because the larger fall armyworms sometimes quickly invade an uninfected area in search of food, once an adjacent field has been defoliated. Large fall armyworms frequently disappear almost as suddenly as they appeared, by either dropping onto the ground to pupate, or moving on in search of food (Flanders et al. 2011). The infestations usually develop first in fields of small grains or other grass-cover crops. In conventional tillage systems, larvae can migrate into crop fields such as corn, wheat and sorghum. The damage is usually first noticeable around the field margins adjacent to these areas (Barfield et al. 1980). The name "armyworm" in fact arose from its behaviour of migrating in large numbers into fields, similar to invading armies (Flanders et al. 2011). Cool and wet weather usually favours fall armyworm development, but they are susceptible to cold, and are unable to survive even the mildest winter (Sparks 1979; Flanders et al. 2011).

### *12.2.1 Life Cycle of Fall Armyworm*

The life cycle of the fall armyworm passes through four main stages (moth, egg, larvae, and pupae). The adult fall armyworm is a dark, brownish-grey, mottled moth with oblique markings near the centre of the front wing, and an irregular white or grey patch, near the wing tips. Female moths are darker than males. The back wing is white in females, with a narrow, opaque brown edge. The wingspan of the fall armyworm is approximately 3–4 cm (Bohmfalk et al. 2011; Flanders et al. 2011). Moths have an average life span of 11–14 days, become active at nightfall, and feed on nectar (Flanders et al. 2011). The female moths lay eggs at night, in masses of up to several hundred eggs, on light-coloured surfaces, such as fence rails, tree trunks, and the undersides of tree leaves. These eggs are light grey and are covered with greyish hair from the female's body. The mass of eggs becomes dark with age. All the eggs within a mass hatch at about the same time, within 3–5 days (Flanders et al. 2011). Patterns of newly hatched worms are commonly hard to differentiate. The newly hatched larva of the fall armyworm is white, with a black head. As feeding progresses, the larva becomes darker. As the larvae mature, they turn greenish-brown, with a white line below the top of the back, usually a brownish-black stripe above the midline, and a pale stripe with reddish-brown traces below. Mature larvae are about 3–4 cm long, with a prominent white inverted "Y" on the front of the head. Fall armyworm larvae can also be distinguished from other armyworms by the presence of black hairs on the body (Bohmfalk et al. 2011; Flanders et al. 2011). The development from egg to fully-grown larva requires about 14–28 days. At this stage, larvae hole into the soil and form pupae. The moths emerge in about 7–14 days (Flanders et al. 2011). In one growing season, three and more generations of fall armyworms can be produced. Therefore, when eliminating fall army worms from leaves in the plantation, another generation is preparing to emerge from the soil to replace them (Flanders et al. 2011). In regions with insignificant winters, fall armyworms will stagnate as eggs and pupae beneath the soil, to become active as climate gets warmer.

### *12.2.2 Damages Due to Fall Armyworms*

Caterpillars of the fall armyworm harm crops and grasses by chewing plant tissues (Flanders et al. 2011). They are mostly active early in the morning and late in the afternoon, although on taller, unsheared grasses, they can be observed feeding on the foliage during the day. On grazed or recently cut pasture and hayfields, fall armyworm larvae spend the warmer hours of the day deep in the turf (Flanders et al. 2011). The larvae of fall armyworm attack a variety of crops as well as grasses, sometime moving *en masse* as an army on the march, and consuming about everything in their way to new areas (Koehler and Short 1979). This assault is mostly aerial, with the grey moths usually arriving under cover of darkness to lay eggs (Koehler and Short 1979). When armyworms are numerous, small corn plants may be completely eaten and destroyed (Koehler and Short 1979). Fall armyworm damage often seems to appear overnight. This damage is mainly caused by the oldest caterpillars, which eat more than all other ages put together. It has been reported that the damage due to young armyworms is insignificant because they do not eat much. Therefore, an infestation may have been present, but not detected, because of the small size of the caterpillars (Flanders et al. 2011). The damage also varies in appearance and severity, according to the type of grass and management practices. In closely grazed fields, the grass may seem to thin out and develop brown spots, while in hayfields or in pastures where there has been substantial growth accumulation, almost all tender green material may be removed, leaving only tough stems a few centimetres long, protruding from the soil surface (Flanders et al. 2011). Fall armyworm larvae hole into the growing point of plants, such as buds, whorls, and others, destroying the growth potential of plants, or clip the leaves. In maize, they also burrow into the ear and feed on kernels in the same way as the corn earworm (*Helicoverpa zea* Boddie) (Sparks 1979).

Armyworms primarily feed on grasses but, under hunger stress, they will also attack some legumes and other plants (Koehler and Short 1979). It has been shown that although maize is one of the major primary host of fall armyworm, the pest is capable of causing extensive damage to an array of crops, including wheat, rice, sorghum, millets, cotton, rice, groundnut, cowpea, sesame, and cassava (Flanders et al. 2011). The expansion of fall armyworm into important cereals and other major food crops of Africa will negatively impact on the livelihoods and well-being of millions of smallholder farmers, as maize is the main staple food crop in Eastern, Central and Southern Africa.

New plantations of maize are mainly damaged by caterpillars originating in a nearby small-grain field. The poorly managed small-grain cover crops appear to be a frequent source of caterpillars (Koehler and Short 1979). A newly cultivated maize plantation is rarely damaged by fall armyworms. Outbreaks are only experienced infrequently in cultivated fields that had small-grain cover crops growing in the previous season (Ali et al. 1989; Cruz et al. 1999). On a pasture, however, fall armyworms can reach densities as intense as 1000 caterpillars per square meter. This causes quick and severe damage to the pasture and neighbouring crops (Koehler and Short 1979).

In Northern Argentina, the fall armyworm is the most important pest of maize, causing yield losses ranging from 17 to 72% (Murúa et al. 2009). Damage is caused by the loss of photosynthetic area due to foliar feeding, structural damage due to feeding in the whorl, lodging due to cut stems, and direct damage to grains due to feeding larvae. Severe infestations are uncommon, however, and most plants recover from partial foliar feeding. Under severe infestation, the complete defoliation of maize plant is possible. Damage is most severe when worms cause direct damage to the ear. Under severe infestation, larvae are frequently observed migrating in large numbers to new fields. Late-planted maize and advanced growth stages are more vulnerable to damage. Under severe infestation, yield losses ranging from 25 to 50% have been documented. Fall armyworm densities that are as low as 0.2–0.8 larvae per plant during the late whorl stage may be sufficient to reduce yields by 5–20% (Marenco et al. 1992). These observations of damages attributable to fall armyworms reveal the gravity of its outbreak in African countries.

### *12.2.3 Outbreak of Fall Armyworms in African Countries and Particularly in Rwanda*

The fall armyworm was reported for the first time in January 2016 in Nigeria (Goergen et al. 2016). Afterwards, its epidemic proportions were reported in several African countries, including Togo, Ghana, Zambia, Zimbabwe, South Africa, Malawi, Mozambique, Namibia, Kenya, Rwanda, and Tanzania (Abrahams et al. 2017). There is much speculation as to how the fall armyworm arrived in Africa. Scientists believe that fall armyworms crossed the Atlantic on container ships ferrying grain imports from South America. Biological invasions such as fall armyworm threaten the function of the natural equilibrium, agricultural ecosystems, biodiversity, and food security. Any biological invasive species seriously affects Sub-Saharan Africa because this part of the continent relies mainly on agriculture (Kruger 2017).

The spread of a biological species is limited by barriers such as forests, mountains, and oceans. However, international business and travel has critically facilitated biological invasions in recent years. For example, the larger grain borer, *Prostephanus truncatus* Horn, another species native of the Americas, was unintentionally introduced into Tanzania in the 1970s. This insect spread rapidly through infested, imported shipments of maize and dried cassava, and invaded numerous countries since its first introduction into Africa (Kruger 2017). The cassava brown streak Virus (CBSV) was noticed in Rwanda after cuttings were imported in 2007 (unpublished results). Maize leaf necrosis virus disease (MLND) was first detected in 2013 (Adams et al. 2014) on maize plants grown from seed imported by seed companies in Rwanda, after which the disease became epidemic in different Rwandan agro-ecologies (unpublished results).

There is disagreement about how the fall armyworm reached Africa. It was thought that it arrived through food products imported from the Americas. This could happen when insects cross borders with infested plant materials. The possibility of this having happened is very high, because some insect species have been detected several times on shipments destined to Europe (Kruger 2017).

It is also possible that the pest arrived in Africa on wind currents. It is known that the adult fall armyworm month can travel long distances. Moreover, this would not be the first insect species that crossed the Atlantic in this way: the monarch butterfly (*Danaus plexippus* L.) is a well-known species that crossed the Atlantic from America to the United Kingdom (Kruger 2017).

Fall armyworms were first detected in West Africa in 2016, before making their way to southern, eastern and central African countries. According to Goergen et al. (2016), the presence of at least two distinct haplotypes of fall armyworm within samples collected on maize in Nigeria and São Tomé suggests multiple introductions into the African continent. The armyworm is able to expand from its endemic area to other areas more than 2000 km away (Pair et al. 1986). The high-spreading performance of fall armyworm, its large reproductive capacity, absence of dormancy, and wide host-plant range will favour its colonisation of tropical Africa (Johnson 1987; Murúa and Virla 2004). Therefore, there is an urgent need for developing ecologically sustainable, economically profitable, and socially acceptable IPM programmes to mitigate its impact in Africa (Goergen et al. 2016).

The establishment of fall armyworm in African countries will have consequences for their economies, agricultural production and access to foreign markets (Goergen et al. 2016). According to EUROPHYT (2017), there is an increase in the rates of quarantine interceptions of fall armyworm caterpillars on fresh vegetables and living plants found at European entry points. It has been reported that the assessment of the status of *S. frugiperda* in 2015 categorised this pest for A1 quarantine on the list of the European and Mediterranean Plant Protection Organization (EPPO 2017). With its new range in extension, it is anticipated that the fall armyworm will shortly be included in the list of quarantine pests of other regional plant protection organisations (Goergen et al. 2016).

The invasion of fall armyworm into Southern Africa countries and its establishment in maize, sorghum, cotton, some vegetables, and sunflower has been reported. In February 2017, the pest had been recorded in many South Africa provinces, including Limpopo, Northwest, Gauteng, Free State, Mpumalanga, Northern Cape, the Western Cape, KwaZulu-Natal, and the Eastern Cape (CropLife 2017). The

Government of Zambia has already spent 3 million USD in an endeavour to control the fall armyworm that has affected approximately 130,000 hectares of crops (Ogolla et al. 2017). As a result, the high severity of fall armyworm outbreak forced farmers to replant their crops. Around 17,000, 50,000 and 130,000 hectares of crops have been affected by fall armyworm in Malawi, Namibia and Zimbabwe, respectively (FAO 2017). In Uganda, this pest has been confirmed to exist in at least twenty districts, damaging maize, sugarcane and pasture grasses (Halima 2017). The Minister of Agriculture and Animal Resources informed the Cabinet Meeting, held on 5th April 2017, that an outbreak of fall armyworms was then destroying grain crops in Rwanda. This outbreak has, so far, been reported in 108 Sectors in 23 Districts, where the pests infected 15,699 ha of maize and sorghum crops (Mugabo 2017). Because of the complexity of the fall armyworm infestation and gaps in technical abilities, countries are still struggling to assess the damage that has been caused so far. Pest identification services are also inadequate in some of the countries. This has a negative impact in making decisions and recommendations on response actions (FAO 2017).

Outbreaks in African countries of other armyworms, different from fall armyworms, have been identified in previous reports. East Africa countries (Tanzania, Kenya and Ethiopia) faced outbreaks of the African armyworm (*S. exempta* Walker) in 1994, 1996 and 1999. The 1994 armyworm outbreak in Ethiopia was the most serious in the experience of crop protection officials since 1984 (Borton 1999). The control of this outbreak required aid from the governments of Japan, Sweden, Korea, Switzerland, Norway and the Netherlands for covering the costs incurred in acquiring and air lifting pesticides to infected regions (Gary 1994). Large-scale African armyworm outbreaks were reported in both Rwanda and Burundi in April 1999. This outbreak affected about 100,000 hectares of cropland and 400,000 hectares of pasture in Rwanda. In spite of heavy rains and rapid interventions from the Government and FAO, the next generation spread to many new areas (Borton 1999). The African armyworm was again reported in Rwanda in May 2008, but its impact on crop production was insignificant (Nambi 2008). In January 2013, an outbreak of African armyworm was reported in Lesotho. Out of 10 districts, 8 were reported to be infected by African armyworm and about 35,000 hectares, representing 25% of the estimated planted area in 2012–2013, were affected. In this outbreak, the pest density ranged from 50 to 250 larvae per square metre (Noko 2013). These perennial outbreaks of the African armyworms in the same locality lead to a prediction of the outbreak of the new coming pest, the fall armyworms.

## 12.3 Management Options for Fall Armyworm

Management of the fall armyworm involves the integration of several approaches, including the use of insecticides, host plant resistance, and biological control. All these approaches depend on several characteristics of the agro-ecosystems involved (Altieri et al. 1978). Control is based mainly on the use of chemical insecticides.

However, other approaches, such as biological control, the use of resistant varieties and genetically modified varieties harbouring the Bt gene, and agriculture practices, have been reported as alternatives to insecticide spraying (Murúa et al. 2009). Interventions, based on pest-incidence thresholds, have been suggested to better protect young plants and the reproductive stages of the crop (Altieri et al. 1978).

Control of fall armyworm infestations requires fields to be checked to identify the treatment threshold, prior to the use of insecticidal control. Scouting the crop field or pasture assists in identifying fall armyworm infestations, prior they cause economic damage. A simply detectable sign of fall armyworms is the occurrence of groups of birds, feeding in crop fields or pastures. Through a careful exploration of field or pasture sites where many birds are seen feeding, particularly around areas with dead grass in established pastures, or at the base of the plants in the straw, the presence of the larvae and their excrements, in the form of green pellets, can reveal the first evidence of a fall armyworm infestation (Abrahams et al. 2017). Field scouting during the day should focus on looking for leaf feeding and presence of caterpillars in the whorl, where they hide. Fall armyworm moths are difficult to track because they are active during the night, and can move long distances on seasonal winds. Therefore, the setting up of insect net traps during the early morning or later afternoon has been suggested for use in tracking the presence of fall armyworms (Flanders et al. 2011). The use of pheromone traps, using a synthetic female hormone to attract males of fall armyworm, is an approach for tracking and predicting fall armyworm infestation (Kinyua 2017). The trapped male moths are counted each morning, and 30 or more moths trapped per day indicate that an outbreak will be eminent within 7–10 days, followed by a second-generation outbreak within a month, which can be severe (Capinera 2014). The speed, wide dispersal, and damage of fall armyworm infestation is difficult to imagine, and once established, it is difficult to control because there are sudden and urgent needs to acquire control equipment and pesticides, throughout a very large geographical area.

Moth populations can be sampled with black light traps and pheromone traps, of which the latter are more efficient. Pheromone traps should be suspended at canopy height, preferably in maize during the whorl stage. Catches are not necessarily good indicators of density, but do indicate the presence of moths in an area. Once moths are detected, it is advisable to search for eggs and larvae. A sample of 20 plants in five locations, or 10 plants in 10 locations, is generally considered to be adequate for assessing the proportion of plants infested. However, the numbers of individuals captured are not directly related to damage levels in a field. This is especially true of regional trapping (Capinera 2014). Cruz et al. (2012) found that the pheromone trap approach is the best, compared with others, for deciding on the time for insecticide applications in cases of fall armyworm outbreaks. The use of pheromone traps facilitates the identification of insect performance causing 90% of larvae mortality.

Control efforts are generally not economical to undertake, unless 10% or more of the crop plantation is infested. A number of insecticides can be used as rescue treatments (Gary 1994). The decision to undertake insecticide spraying depends on the developmental stage of the fall armyworms and the intended use of the crop and forage. A population of three or more fall armyworms per one square metre is a judicious treatment threshold. In the case of pasture or hayfields, mowing is the best option for salvaging a plantation. With this approach, insecticide application is not necessary (Flanders et al. 2011). In the management of pest and diseases, time is very important. If infestations are detected, the damage may already have been done. It is known that small fall armyworms are much easier to eliminate than the larger ones, and that some insecticides will never control large larvae. Therefore, it has been suggested to spray with appropriate insecticides, at the right time (Gary 1994). Without application of insecticides in a maize plantation, a yield reduction up to 39% has been recorded (Cruz et al. 2012).

The chosen insecticide is applied early or late in the day, when fall armyworm larvae are most active (Flanders et al. 2011). Their control in tall or dense stands of pasture grasses may be difficult to achieve. Grazing of an infected area before insecticide spraying has been suggested (Flanders et al. 2011). The pest is more virulent in favourable conditions. Consequently, its control with one type of pesticide is difficult, particularly when it has reached an advanced larval development stage (Gary 1994). A very low density and wide dispersal of armyworms in areas makes spraying operations uneconomical. This requires other approaches, or waiting for a certain degree prior to commencing control with insecticides. The spray of a natural horticultural oil such as neem oil can be applied on plants that show signs of armyworm infestation. This oil showed beneficial combatting effects on various stages of the larvae (Randall and Joey 2016). In some cases, resistance to insecticides may be developed and widely spread in fall armyworm populations, and this complicates their control process. Insects can develop resistance to an insecticide through behavioural, penetration, metabolic and altered target-site capacities. The use of very little amounts of insecticide, a rotation of different chemicals, a mixture of insecticides, and spraying two insecticides in a mosaic have been reported to delay the evolution of insecticide resistance (Mallet 1989). All these practices, preventing the development of resistance to insecticides, should be considered during insecticide application to control fall armyworm. Recommended insecticides for controlling fall armyworm are detailed in Flanders et al. (2011). However, their availability and use depends on the ministerial order establishing the list of registered and prohibited agrochemicals in the respective country.

The date of planting and type of agriculture system used has revealed significant effects in crop and interactions with pests such as leafhoppers and beetles. A reduction of 66% of leafhoppers (*Empoasca kraemeri* Ross & Moore) on beans was observed when maize was planted 30 and 20 days earlier than beans, as compared with simultaneous planting, while the maize damage due to the fall armyworm was reduced up to 88% when beans were planted 20–40 days earlier than maize (Altieri et al. 1978). The adult populations of *E.kraemeri* and of th beetle *Diabrotica balteata* LeConte were 26 and 45%, respectively, fewer in number in the intercrop of bean and maize, as compared with monoculture of these crops. In the same culture, the *S. frugiperda* incidences and infestations in maize was reduced by 14 and 23%, respectively, in polycultures (Altieri et al. 1978). Nevertheless, the regulation mechanisms are not fully understood, some factors which condition a lower pest incidence in polycultures than in monocultures include natural enemies, microclimatic gradients and chemical interactions. These factors may function together as an associational resistance. The intensive application of intercropping systems by farmers in tropical regions appears to be a suitable pest and diseases management strategy. It is well known that a greater stability in animal populations facilitates the colonisation of complex ecosystems. This suggests that intercropping systems are less vulnerable to insect population outbreaks than monoculture systems (Gold 1994). The current Rwandan policy of land consolidation and crop intensification, under which monoculture is favoured, may have facilitated the outbreak and high incidence of crop diseases and pests. Therefore, this policy should be reviewed, and other, new appropriate measures of disease and pest management should be adopted for achieving sustainable agriculture productions.

Different biological approaches have been reported for fall armyworm control. The success of any of these approaches depends on appropriate biological, ecological, and population studies of the involved species (Miller 1983; Murúa et al. 2009). A natural equilibrium governs the balance between plant pathogens and pests, and their natural predators such as birds, beneficial insects, entomopathogenic nematodes, and larvae of predators. Based on this this principle, the outbreaks of crop pests suggest that the populations of natural predators have decreased. This may be due to the application of the very toxic pesticides to kill crop pests. In this regard, it is advised to avoid the use of harmful pesticides or carrying out practices that would inadvertently destroy the natural predators of pests. Birds are especially fond of the moths, and they will pull larvae out from grasses and plants. Therefore, in case of armyworm infestations, birds should be given a chance to pick off the pupae that are exposed after turning the soil and prior putting it to bed (Veley 1902). Ground beetles (Carabidae), rove beetles (Staphylinidae), ants (Formicidae), and spiders (Araneae) are well known armyworm predators. When these generalist predators were selectively removed from the field, armyworm damage to corn plants was significantly greater than in the control, where predator populations were unaltered (Clark et al. 1999). This revealed the importance of natural predators in the control of plant pests. The beneficial insects, such as *Trichogramma* wasps, lacewing and ladybugs, have the potential to insert their eggs inside the pest body, killing them before they enter the plant-eating larval stage. The use of these parasitoids has shown potentials for controlling armyworm infestation (Clark et al. 1999; Shimat 2006). Entomopathogenic nematodes are killers of armyworm eggs and pupae found in the soil, and can feed on more than 200 pests. The release of these nematodes into soil has been recommended when there was an infestation or where conditions occur that might encourage the development of armyworms (Molina-Ochoa et al. 1999).

The use of live strains of *Bacillus thuringiensis* (Bt) has been shown experimentally to reduce the abundance of fall armyworm larvae in corn. However, its intensive application and success depend on having the product on the foliage when the larvae first appear to feed. Natural strains of *B. thuringiensis* tend not to be very potent, but the use of their genes in genetically modified crops improves their performance (All et al. 1996; Buntin et al. 2001). Several transgenic maize hybrids, such as Bt11 (Novartis Seeds) and MON810 (Monsanto Co.), which express the insecticidal proteins Cry1Ab from *B. thuringiensis* in vegetative and reproductive structures, have been developed to control European corn borer (Buntin et al. 2001). These transgenic hybrids also revealed the potential to reduce losses due to fall armyworm (Buntin et al. 2001). Thus, cultivars expressing the Cry1F toxin against insect defoliators are currently widely commercialised in the western hemisphere (Goergen et al. 2016). Transgenic maize, containing genes encoding delta-endotoxins from *B. thuringiensis* subsp. *kurstaki*, have been commercialised in the USA and Brazil. Vegetative insecticidal proteins (VIP) have been isolated from *B. thuringiensis* during the vegetative phase of growth that show a wide spectrum of activities against *Spodoptera* spp. (Estruch et al. 1996). In a confined field trial in Kasese by NARO, it was observed that the only maize variety that was resistant to the fall armyworm was Bt maize, which is a genetically modified maize variety harbouring *B. thuringiensis* genes. However, this variety is not available on the market because of the absence of biotechnology and biosafety regulations (Lutaaya 2017). Although these toxins appear to control *Spodoptera* spp., the development of pest resistance is another concern (Moar et al. 1995). For example, Omoto et al. (2016) have reported that the efficacy of Bt maize expressing the Cry1Ab protein in controlling fall armyworm was reduced in Brazil. The release of transgenic Bt-maize in tropical Africa is not as straightforward, due to economic, logistic and socio-cultural considerations (Goergen et al. 2016). Moreover, the increase in the number of reports on the development of fall armyworm resistance to Bt toxins reveals the need to develop alternative control approaches, such as the use of endophytic entomopathogenic fungi, nucleopolyhedro viruses, insect biological control agents, and entomopathogenic nematodes (Storer et al. 2010; Goergen et al. 2016).

The use of resistant crop genotypes is a reliable approach to apply to control pests and diseases. In the study of foliar resistance to fall armyworm in corn germplasm lines that confer resistance to root-and ear-feeding insects, it was shown that there is the possibility of developing foliage, root, and ear-feeding insect-resistant germplasm covering multiple corn growth stages (Ni et al. 2011). According to Wiseman et al. (1980), a breeding programme to develop maize lines that are resistant to fall armyworm has been implemented. Within this project, inbred lines with resistance to fall armyworm have been developed and released. The plants that revealed the most resistance were self-pollinated and were evaluated in successive generations. In this programme, the Antigua Gpo. 2 genotype was used as a source of resistance to fall armyworm. The study aimed at identifying the quantitative trait loci that confer resistance to leaf-feeding damage by fall armyworm and southwestern corn borer. Data revealed that the resistance to fall armyworm and southwestern corn borer involves many of the same QTL, and candidate genes for insect resistance include the *glossy15* candidate locus on chromosome nine (Brooks et al. 2004).

In the screening of 20 maize genotypes, three genotypes that were derived from tropical maize germplasm, originated from Uruguay, Cuba, and Thailand, were identified as the best fall armyworm resistant lines, using the leaf injury ratings and predator survey data. These findings suggested that tropical germplasm is an important source of resistance genes to the fall armyworm (Ni et al. 2014). Genotypes revealed variations for diseases and pest resistances. For example, Cruz et al. (1999) found that sweetcorn is much more susceptible to fall armyworm larval infestations than normal yellow or white endosperm and high-quality protein maize (Cruz et al. 1999). Efforts to increase the levels of resistance in maize to leaf feeding were initiated by the USDA-Agriculture Research Service team in Mississippi, in the mid'60s. This programme was expanded to include research on resistance to fall armyworm, *S. frugiperda*. Inbred germplasm lines with resistance to corn borer and fall armyworm have been developed and released (Williams and Davis 1989). This showed that plant breeders should consider this trait in the selection process for the development of new cereal crop varieties that are the main target of armyworms. Fall armyworm resistance breeding programmes have developed for field crop varieties with improved resistant traits. One resistance mechanism that appears to be operating in maize is increased leaf toughness, with a thicker epidermis (Mihm et al. 1988; Davis et al. 1995). All these data suggest the possibility of breeding maize to incorporate fall armyworm resistance in Rwanda.

In addition to their role in tracking and predicting fall armyworm infestation, pheromone traps are also used to control fall armyworms because the attraction of males by the traps disrupts the mating process of this pest. Fall armyworm pheromone traps have the potential to suppress moth populations, leading to reductions in eggs laid and in resultant larvae (Kinyua 2017). Malo et al. (2013) found that the pheromone Z9–14:TFMK acted as a pheromone antagonist under field conditions and caused a significant reduction of the electro-antennogram pheromone responses in *S. frugiperda*. It thus behaved as a pheromone antagonist in the field.

This finding suggests that this pheromone analogue may be a good candidate to consider as a mating disrupting technique in future strategies to control *S. frugiperda*. The perception of pheromones by insects is facilitated by olfactory receptor cells that are localised in long sensilla (trichodea) of the male antennae. This pheromone is catabolised by key enzymes such as antennal esterase (Hansson 1995). Therefore, the use of inhibitors of these enzymes in male olfactory tissues, like trifluoromethyl ketones, has shown the positive effects in insect pest control (Prestwich et al. 1986; Plettner and Gries 2010; Malo et al. 2013). Therefore, the efficient development of applicable pheromone traps to control fall armyworm requires an understanding of its olfactory system.

In cases of infestation, the handpicking and elimination of larvae and caterpillars that are feeding on the undersides of leaves and on new growth crop has been advised, prior insecticide spraying (Beseh 2017). A Push–Pull system has been developed by the International Centre of Insect Physiology and Ecology (ICIPE) in Kenya, and is effective in protecting maize from dangerous stem borers and the parasitic witchweed *Striga* (Cook et al. 2007; Tadele 2017). In this system, maize is intercropped with a forage legume called *Desmodium uncinatum* (Jacq.) D.C., whereas Napier grass (*Pennisetum purpureum* Schumach.) is planted around the field. While *Desmodium* produces a smell that drives stem borer adults away ("push"), it also produces a chemical that suppresses *Striga* from attaching to maize roots. The Napier grass instead attracts stem borer adults towards it ("pull"). The adult insects lay their eggs on the Napier grass, and when the eggs hatch, the grass produces a sticky substance that kills the larvae and young stem borers. The system is also useful in reducing the amount of pesticide application (Cook et al. 2007; Tadele 2017). With the current outbreak of this new pest, fall armyworm in east and Central Africa, this approach has to be explored.

### *12.3.1 Management of Armyworm in Rwanda*

When there is an outbreak of such a pest, the most serious problem is the shortage of appropriate pesticides, safety equipment, and means of transport. Gary (1994) reported that less than 10% of the pesticide applicators had respirators or other safety equipment during the outbreak of African armyworm in Ethiopia. The outbreak in Rwanda of armyworm in the earlier season B (March, 2017) raised the attention of various institutions to the threat of an extension of famine conditions that had been caused by the severe drought conditions that occurred in the growing season A in 2017 (September 2016–January 2017). Government institutions, such as the Rwanda Agriculture and Animal Resources Board (RAB), the Ministry of Agriculture and Animal Resources, and the Ministry of Defence, focused intensively on insecticide spraying and hand-picking of fall armyworms. In addition to these approaches, small-scale farmers tried other approaches, such as the application of mixtures of ash and hot pepper, and the use of cattle urine.

Community works were organised for hand-picking caterpillars of the fall armyworm. This approach can be efficient on a small plot, but the efficacy of this approach is complicated in the situation in Rwanda, where fields are scattered, with a dominance of an intercropping system of maize and beans. According to farmers and extension officers, various pesticides, such as Roket 44/EC, Pyrethrum 5 EW and Pyrethrum EWC, were sprayed to combat the fall armyworm. However, the efficacy of the pesticides was found to vary. At the recommended rate (2 ml/l of water), Pyrethrum 5 EW and Pyrethrum EWC did not provide significant effects in eliminating caterpillars of fall armyworm. The shortage of other pesticide brands and the lack of availability of these pyrethrenoids in Rwandan stock led to increases of the recommended dose, up to 8 ml/litre of water. This dose revealed appreciable toxic effects on fall armyworm, although the accompanying environmental contamination and other unexpected effects were not documented. Until now, Roket 44/EC has been the best pesticide preferred by farmers for controlling fall armyworm due to its quick and efficient killing effects on this pest. This pesticide has profenofos 40% and cypermethrin 4% EC as active ingredients. These two active ingredients have different modes of action; profenofos acts as an acetylcholine esterase inhibitor, while cypermethrin acts as a sodium channel modulator. Roket 44/EC is a non-systemic insecticide, having a contact and stomach action. It is effective against several insect pests, of both chewing and sucking types. Its application depends on the occurrence of insect pests, and application intervals of 10 to 15 days, at a rate of 2 ml/l, were suggested.

### 12.3.2 Implications of Management Approaches of Fall Armyworm in Rwanda

The outbreak of fall armyworm in Rwanda has negative effects on crop production. It is known that the occurrence of noticeable symptoms of the pest or disease damages in crop plantations means that the yield potential has been affected, in spite of measures taken to control the pest or the disease. Based on yield reductions of 15–73% reported by Malga (2017) and on an area of 16,000 ha of infected maize plantations reported by the Minister of Agriculture and Animal Resources, it is expected that estimated yield losses of between 7500 and 35,000 tons will be suffered, due to fall armyworm. Different approaches have been applied to control the fall armyworm in Rwanda. The Rwanda Agriculture and Animal Resources Board (RAB) conducted a follow-up exercise to eradicate this outbreak. Different pesticides, such as Pyrethrum 5EW, Pyrethrum EWC+, and Roket 44/EC, were sprayed in different doses in the various districts where the pest was identified. This model of spraying different pesticides, without controls, by farmers trying to rescue their maize plantations, could lead to the development of insecticide resistance by the pest. This outbreak of fall armyworm in Rwanda leads to wide spraying of insecticides, which will also cause harmful effects to beneficial insects, such as bees and other natural enemies of crop pests.

Other control approaches, such as hand-picking and the application of pepper and ash, have been applied to control the outbreak of fall armyworm in Rwanda. In the localities where fall armyworm was noticed, community works were organised for hand-picking caterpillars of fall armyworms, which were buried prior insecticide spraying. This approach revealed fruitful results, but its application on large plantations is complicated. Farmers on small maize plots reported that the application of the mixture of ash and pepper provided successful results in controlling the fall armyworm. Although this approach has been commonly used by rural Rwandan farmers to control post-harvest losses of grains, its precise application and recommended doses need further investigation.

The climate and vegetation of Rwanda are favourable for the fall armyworm. In Rwanda, there are no severe winters to reduce the fall armyworm, as there are in its endemic areas of America. The climate of Rwanda is characterised by an alternation of rainy and sunny seasons, with average temperatures varying between 15 and 25 °C. These climatic conditions are appropriate for the proliferation of fall armyworm. According to Flanders et al. (2011), more than 60 plant species have been reported to be hosts of the fall armyworm, including forage grasses, maize, millet, sorghum, rice, wheat, sugar cane, alfalfa, cotton, soybeans, and others vegetable crops. Some of these plants species are found in Rwanda. Therefore, the presence of a favourable climate and many host plant species for the fall armyworm, complicate its eradication in Rwanda.

## 12.4 Conclusion

The fall armyworm is a serious pest of plant species in the *Poaceae* family, including major food crops such as corn, sorghum, rice and wheat, and diverse pasture grasses. The life cycle of the pest passes through four main stages, from moth, egg, larvae, to pupae. The development from an egg to a fully grown larva takes from 14 to 28 days. In one growing season, three and more generations of fall armyworms can be produced. In regions with insignificant winters, fall armyworms will stagnate as eggs and pupae beneath the soil, while in warm climates, they will remain active. Caterpillars of fall armyworm harm crops and grasses by chewing plant tissues. Observations of this type of damage have revealed the gravity of its outbreak in African countries. Outbreaks of fall armyworm have been reported in Africa from January 2016. Previously, other armyworms (African Armyworm – *S. exempta*), different from the fall armyworms, were reported in 1994, 1996 and 1999 in the East African countries of Tanzania, Kenya and Ethiopia. The endless outbreak of African armyworms in the same locality leads to a prediction of outbreaks of the new coming pest, fall armyworms. The management of fall armyworm by different approaches, based on insecticide spraying, host-plant resistance, and biological control, has been suggested. The application of these approaches in the environmental conditions of Rwanda requires a specific exploration. The fall armyworm outbreak in Rwanda has led to the widespread spraying of insecticides. However, the effects of this spraying on other non target living organisms, such as bees and other natural enemies of crop pests, and on environmental pollution, have not been documented. The presence of a favourable climate and of many species of plants host for fall armyworm could complicate its eradication in Rwanda.

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## References

Abrahams, P., Beale, T., Cock, M., Corniani, N., Day, R., Godwin, J., et al. (2017, April). *Fall armyworm status impacts and control options in Africa: Preliminary Evidence Note*. CABI.

Adams, I. P., Harju, V. A., Hodges, T., Hany, U., Skelton, A., Rai, S., et al. (2014). First report of maize lethal necrosis disease in Rwanda. *New Disease Reports, 29*, 22. https://doi.org/10.5197/j.2044-0588.2014.029.022.

Ali, A., Luttrell, R., Pitre, H., & Davis, F. (1989). Distribution of fall armyworm (*Lepidoptera: Noctuidae*) egg masses on cotton. *Environmental Entomology, 18*, 881–885.

All, J., Stancil, J., Johnson, T., & Gouger, R. (1996). Controlling fall armyworm infestations in whorl stage corn with genetically modified *Bacillus thuringiensis* formulations. *The Florida Entomologist, 79*, 311–317.

Altieri, M. A., Francis, C. A., Van Schoonhoven, A., & Doll, J. D. (1978). A review of insect prevalence in maize (*Zea mays* L.) and bean (*Phaseolus vulgaris* L.) polycultural systems. *Field Crops Research, 1*, 33–49.

Barfield, C., Stimac, J., & Keller, M. (1980). 1980 Fall armyworm symposium: State-of the art for predicting damaging infestations of fall armyworm. *The Florida Entomologist, 63*, 364–375.

Beseh, P. (2017). *Fall armyworm on maize. Pest management decision guide: Green and yellow list*. Plantwise, Ghana.

Bohmfalk, G. T., Frisbie, R. E., Sterling,W. L., Metzer, R. B., & Knutson, A. E. (2011). *Identification, biology and sampling of cotton insects*. http://www.soilcropandmore.info/crops/CottonInformation/insect/B-933/b-933.htm. Last modified: January 12, 2011 by Billy E. Warrick.

Borton, J. W. (1999). *Armyworms infestations in Ethiopia*. Addis Ababa: UNDP-EU.

Brooks, T. D., Martha, W. C., Williams, W. P., & Buckley, P. M. (2004). Quantitative trait loci conferring resistance to fall armyworm and southwestern corn borer leaf feeding damage. *Crop Science, 45*, 2430–2434.

Buntin, G. D., Lee, R. D., Wilson, D. M., & McPherson, R. M. (2001). Evaluation of yieldgard transgenic resistance for control of fall armyworm and corn earworm (*Lepidoptera*: *Noctuidae*) on corn. *The Florida Entomologist, 4*, 37–42.

Capinera, J. L. (2014). *Fall armyworm,* Spodoptera frugiperda *(J.E. Smith) (Insecta: Lepidoptera: Noctuidae)*. Gainesville: Entomology and Nematology Department, UF/IFAS Extension. http://entomology.ifas.ufl.edu/creatures

Clark, M. S., Luna, J. M., Stone, N. D., & Youngman, R. R. (1999). Generalist predator consumption of armyworm (*Lepidoptera: Noctuidae*) and effect of predator removal on damage in no-till corn. *Environmental Entomology, 23*, 617–622.

Cook, S. M., Khan, Z. R., & Pickett, J. A. (2007). The use of push-pull strategies in integrated pest management. *Annual Review of Entomology, 52*, 375–400.

CropLife. (2017, February 14). *Managing the fall armyworms (faw) outbreak in South Africa. A Cropfile South Africa perspective*. Ver. 2.

Cruz, I., Figueiredo, M., Oliveira, A. C., & Vasconcelos, C. A. (1999). Damage of *Spodoptera frugiperda* (Smith) in different maize genotypes cultivated in soil under three levels of aluminium saturation. *International Journal of Pest Management, 45*, 293–296.

Cruz, I., de Lourdes Corrêa Figueiredo, M., da Silva, R. B., da Silva, I. F., deSouza Paula, C., & Foster, J. E. (2012). Using sex pheromone traps in the decision making process for pesticide application against fall armyworm (*Spodoptera frugiperda* [Smith] [*Lepidoptera: Noctuidae*]) larvae in maize. *International Journal of Pest Management, 58*, 83–90.

Davis, F. M., Baker, G. T., & Williams, W. P. (1995). Anatomical characteristics of maize resistant to leaf feeding by southwestern corn borer (*Lepidoptera: Pyralidae*) and fall armyworm (*Lepidoptera: Noctuidae*). *Journal of Agricultural Entomology, 12*, 55–65.

EPPO. (2017). *Reporting service*. Paris: European and Mediterranean Plant Protection Organization.

Estruch, J. J., Warren, G. W., Mullins, M. A., Nye, G. J., Craig, J. A., & Koziel, M. G. (1996). Vip3A, a novel *Bacillus thuringiensis* vegetative insecticidal protein with a wide spectrum of activities against lepidopteran insects. *Proceedings of the National Academy of Sciences, 93*, 5389–5394.

EUROPHYT. (2017). *European union notification system for plant health interceptions* (Number of interceptions with harmful organisms*,* Vol. 160). https://ec.europa.eu/food/sites/food/files/plant/docs/ph_biosec_europhyt-interceptions-2017-05.pdf

FAO. (2003). *Trade reforms and food security: Conceptualizing the linkages*. Rome: Food and Agriculture Organization.

FAO. (2017). *Southern and Eastern African countries agree on urgent actions to tackle armyworm and other crop pests and animal diseases*. Regional Office for Africa: FAO.

Flanders, K. L., Cobb, P. P., & Ball, D. M. (2011). *Management of fall armyworm in pastures and hayfields*. The Alabama Cooperative Extension System, Alabama A&M and Auburn Universities.

Gary, J. (1994). *Environmental impact assessment of African armyworm control in Ethiopia: An amendment to supplemental environmental assessment of locust/grasshopper control in Ethiopia. African Emergency Locust and Grasshopper Assistance*. Addis Ababa: USAID.

Goergen, G., Kumar, P. L., Sankung, S. B., Togola, A., & Tamò, M. (2016). First report of outbreaks of the fall armyworm *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in West and Central Africa. *PLoS One, 11*, e0165632. https://doi.org/10.1371/journal.pone.0165632.

Gold, C. (1994). The effects of cropping systems on cassava whiteflies in Colombia: Implications for control of African cassava mosaic virus disease. *African Crop Science Journal, 2*, 423–436.

Goldman, A. (1996). Pest and disease hazards and sustainability in African agriculture. *Experimental Agriculture, 32*, 199–211.

Halima, A. (2017). *Uganda confirms outbreak of fall armyworm in crops*. Kampala, Uganda. http://aa.com.tr/en/africa/

Hansson, B. (1995). Olfaction in lepidoptera. *Experientia, 51*, 1003–1027.

Johnson, S. J. (1987). Migration and the life history strategy of the fall armyworm, *Spodoptera frugiperda* in the Western Hemisphere. *International Journal of Tropical Insect Science, 8*, 543–549.

Kinyua, Z. M. (2017). *Interim recommendations for management of fall armyworm in Kenya*. Nairobi: Crop Health Sub-Unit, KALRO.

Koehler, P., & Short, D. (1979). Scientific notes: Fall armyworm in Florida pasturegrass: 1977. *The Florida Entomologist, 62*, 154–155.

Kruger, K. (2017). *Why it's hard to control the fall armyworm in southern Africa*. University of Pretoria. http://theconversation.com/why-its-hard-to-control-the-fall-armyworm-in-southern-africa-72890

Lutaaya, H. (2017). Ugandan maize trial proves successful in controlling the armyworm but farmers cannot yet access the variety due to regulatory roadblocks. *The Sunrise*, March 17, 2017. http://www.sunrise.ug/news/201703/experts-on-pesticide-resistant-caterpillars.html

Malg, I. (2017). *General information note on fall armyworm Spodoptera frugiperda J. E. Smith: A very harmful and polyphagous pest to watch!* AGRHYMET Regional Centre/CILSS.

Mallet, J. (1989). The evolution of insecticide resistance: Have the insects won? *Trees, 4*, 336–340.

Malo, E., Rojas, J., Gago, R., & Guerrero, A. (2013). Inhibition of the responses to sex pheromone of the fall armyworm, *Spodoptera frugiperda*. *Journal of Insect Science*, *13*. Available online: http://www.insectscience.org/13.134

Marenco, R. J., Foster, R. E., & Sanchez, C. A. (1992). Sweet corn response to fall armyworm (*Lepidoptera: Noctuidae*) damage during vegetative growth. *Journal of Economic Entomology, 85*, 1285–1292.

Mihm, J., Smith, M., & Deutsch, J. (1988). Development of open pollinated varieties, non-conventional hybrids and inbred lines of tropical maize with resistance to fall armyworm, *Spodoptera frugiperda* (*Lepidoptera: Noctuidae*), at CIMMYT. *The Florida Entomologist, 5*, 262–268.

Miller, J. (1983). Ecological relationships among parasites and the practice of biological control. *Environmental Entomology, 12*, 620–624.

Moar, W. J., Pusztai-Carey, M., Van Faassen, H., Bosch, D., Frutos, R., Rang, C., et al. (1995). Development of *Bacillus thuringiensis* CryIC Resistance by *Spodoptera exigua* (Hubner) (*Lepidoptera: Noctuidae*). *Applied and Environmental Microbiology, 61*, 2086–2092.

Molina-Ochoa, J., Lezama-Gutierrez, R., Hamm, J. J., Wiseman, B. R., & Lopez-Edwards, M. (1999). Integrated control of fall armyworm (*Lepidoptera: Noctuidae*) using resistant plants and entomopathogenic nematodes (*Rhabditida: Steinernematidae*). *The Florida Entomologist, 82*, 263–271.

Mugabo, S. F. (2017). *Statement on cabinet decisions of 05/04/2017*. Republic of Rwanda. http://gov.rw/newsdetails2/

Murúa, G., & Virla, E. (2004). Population parameters of *Spodoptera frugiperda* (Smith)(Lep.: Noctuidae) fed on corn and two predominant grasses in Tucuman (Argentina). *Acta Zoologica Mexicana, 20*, 199–210.

Murúa, M., Molina-Ochoa, J., & Fidalgo, P. (2009). Natural distribution of parasitoids of larvae of the fall armyworm, *Spodoptera frugiperda*, in Argentina. *Journal of Insect Science (Online), 9*, 1–17.

Nambi, K. I. (2008). Farmer's knowledge: Armyworms invade Kigali. *Newtimes*, May 23, 2008. www.newtimes.co.rw/section/Printer/2008-05-23/3832/

Nduwumuremyi, A., Melis, R., Shanahan, P., & Asiimwe, T. (2016). Participatory appraisal of preferred traits, production constraints and postharvest challenges for cassava farmers in Rwanda. *Food Security, 8*, 375–388. https://doi.org/10.1007/s12571-016-0556-z.

Ni, X., Chen, Y., Hibbard, B. E., Wilson, J. P., Williams, W. P., Buntin, G. D., et al. (2011). Foliar resistance to fall armyworm in corn germplasm lines that confer resistance to root and ear-feeding insects. *The Florida Entomologist, 94*, 971–981.

Ni, X., Xu, W., Blanco, M. H., & Williams, W. P. (2014). Evaluation of fall armyworm resistance in maize germplasm lines using visual leaf injury rating and predator survey. *Insect Science, 21*, 541–555.

Nkuba, J., Tinzaara, W., Night, G., Niko, N., Jogo, W., Ndyetabula, I., et al. (2015). Adverse impact of Banana Xanthomonas Wilt on farmers' livelihoods in Eastern and Central Africa. *African Journal of Plant Science, 9*, 279–286. https://doi.org/10.5897/AJPS2015.1292.

Noko, L. (2013). *Armyworm infestation in Lesotho: FAO in emergency*. Lesotho: FAO.

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science, 144*, 31–43.

Ogolla, E., Makonde, L., & Rachel, N. (2017). *Fall army worm outbreak, a blow to prospects of recovery for southern Africa*. FAO Regional Office for Africa. http://www.fao.org/africa/news/detail-news/en/c/469532/

Omoto, C., Bernardi, O., Salmeron, E., Sorgatto, R. J., Dourado, P. M., & al, C. A. (2016). Field evolved resistance to Cry1Ab maize by *Spodoptera frugiperda* in Brazil. *Pest Management Science, 72*, 1727–1736.

Pair, S. D., Raulston, J. R., Sparks, A. N., Westbrook, J. K., & Douce, G. K. (1986). Fall armyworm distribution and population dynamics in the southeastern states. *The Florida Entomologist, 69*, 468–487.

Pashley, D. (1996). Host associated genetic differentiation in fall armyworm (*Lepidoptera: Noctuidae*) a sibling species complex. *Annals of the Entomological Society of America, 79*, 898–904.

Plettner, E., & Gries, R. (2010). Agonists and antagonists of antennal responses of gypsy moth (*Lymantria dispar*) to the pheromone (+)-disparlure and other odorants. *Journal of Agricultural and Food Chemistry, 58*, 3708–3719.

Prestwich, G. D., Vogt, R. G., & Riddiford, L. M. (1986). Binding and hydrolysis of radiolabeled pheromone and several analogs by male-specific antennal proteins of the moth *Antheraea polyphemus*. *Journal of Chemical Ecology, 12*, 323–333.

Prowell, D., McMichael, M., & Silvain, J. (2004). Multilocus genetic analysis of host use, introgression, and speciation in host strains of fall armyworm (*Lepidoptera: Noctuidae*). *Annals of the Entomological Society of America, 97*, 1034–1044.

Randall, P. G., & Joey, W. (2016). *Insect pests of sweet corn*. Horticulture Extension, Clemson University. http://www.clemson.edu/extension/hgic

Reynolds, T. W., Waddington, S. R., Anderson, C. L., Chew, A., True, Z., & Cullen, A. (2015). Environmental impacts and constraints associated with the production of major food crops in Sub-Saharan Africa and South Asia. *Food Security, 7*, 795–822.

Shimat, V. J. (2006). *The potential role of heteropteran predators – Geocoris punctipes (Say), Geocoris uliginosus (Say) (Geocoridae) and Orius insidiosus (Say) (Anthocoridae) in warm – Season turfgrass*. MSc. Thesis, University of Georgia.

Sparks, A. N. (1979). A review of the biology of the fall armyworm. *The Florida Entomologist, 62*, 282–287.

Storer, N., Babcock, J., Schlenz, M., Meade, T., Thompson, G., Bing, J., & Huckaba, R. (2010). Discovery and characterization of field resistance to Bt maize: Spodoptera frugiperda (*Lepidoptera: Noctuidae*) in Puerto Rico. *Journal of Economic Entomology, 103*, 1031–1038.

Tadele, Z. (2017). Raising crop productivity in Africa through intensification. *Agronomy, 7*, 1–30. https://doi.org/10.3390/agronomy7010022. www.mdpi.com/journal/agronomy

Veley, L. J. (1902). Birds attacking butterflies and moths. *Nature, 65*, 392–392.

WB. (2017). *World development indicators 2017*. Washington, DC: World Bank.

Williams, W. P., & Davis, F. M. (1989). *Breeding for resistance in maize to southwestern corn borer and fall armyworm.* Mississippi: USDA, Agricultural Research Service, Crop Science Research Laboratory.

Wiseman, B., Davis, F., & Campbell, J. (1980). 1980 Fall armyworm symposium: Mechanical infestation device used in fall armyworm plant resistance programs. *The Florida Entomologist, 63*, 425–432.