Journal of Integrated Pest Management, (2021) 12(1): 7; 1–9
doi: 10.1093/jipm/pmab002
Issues

OXFORD

Experiences and Perspectives on *Spodoptera frugiperda* (Lepidoptera: Noctuidae) Management in Sub-Saharan Africa

Elizabeth Njuguna,[1,5] Phophi Nethononda,[2] Karim Maredia,[3] Ruth Mbabazi,[3] Paul Kachapulula,[4] Arielle Rowe,[1] and Dennis Ndolo[1]

[1]Biopesticides Group, International Centre for Genetic Engineering and Biotechnology, Wernher & Beit Building (South), UCT Campus, Anzio Road, Observatory, 7925, Cape Town, South Africa, [2]Forestry and Agricultural Biotechnology Institute, University of Pretoria, Pretoria, 0002, South Africa, [3]Department of Entomology, College of Agriculture and Natural Resources, Michigan State University, Plant and Soil Sciences, 1066 Bogue St., East Lansing, 48824 MI, USA, [4]Department of Plant Sciences, School of Agricultural Sciences, University of Zambia, Great East Road Campus, P. O. Box 32379, Lusaka, Zambia, [5]Corresponding author, e-mail: Elizabeth.Njuguna@icgeb.org

Subject Editor: Christopher Sansone

Received 14 August 2020; Editorial decision 8 January 2021

Abstract

It has been over five years since the first report of an outbreak of the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) in Africa. The highly invasive pest, native to the Americas, has since spread across the African continent attacking many crops and causing significant yield loss to Africa's staple crop, maize. From the onset of the outbreak, there have been massive and varied responses from farmers, governments and nongovernmental organizations. This mini-review provides various perspectives on *S. frugiperda* control in sub-Saharan Africa, building on previously published evidence, and experiences of the authors. It also highlights new technologies and lessons learned so far from the *S. frugiperda* outbreaks in sub-Saharan Africa, based on which suggestions on possible integrated management approaches are proffered.

Key words: biopesticide, fall armyworm, integrated pest management, invasive, sub-Saharan Africa

The fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) is an invasive and destructive pest that causes significant crop loss. Endemic to the tropical regions of the Western Hemisphere (López-Edwards et al. 1999, Prowell et al. 2004, Murúa et al. 2008), it was identified for the first time in sub-Saharan Africa (West and Central Africa) around December 2015 (Goergen et al. 2016, Tindo et al. 2017). *Spodoptera frugiperda*'s year-round distribution is generally restricted to relatively warm and moist areas, as it lacks the ability to diapause through cold seasons (Nagoshi et al. 2012). The pest has capacity for long-distance seasonal migrations (Westbrook et al. 2016), with recent forecasts showing considerable potential for further widespread dispersal (Early et al. 2018). *Spodoptera frugiperda* continues to be a threat to food security in sub-Saharan Africa due to its: 1) wide range of host plants (Montezano et al. 2018), 2) high reproductive rate (one female lays about 1,000 eggs), 3) short life cycle (about 30 d) (Sparks 1979), 4) good dispersal abilities (the moths can cover a distance of about 1,600 km in 30 h, Johnson et al. 1987), and 5) suitable agroecological conditions (warm conditions exist in sub-Saharan Africa almost year round, ACMAD 2018).

Spodoptera frugiperda Distribution and Spread in Sub-Saharan Africa

To date, *S. frugiperda* has been reported in all countries in sub-Saharan Africa, except Lesotho (FAO 2019). The high elevation of Lesotho (the only country that lies fully over 1,000 m above sea level, FAO 2005) could probably explain its absence in the country. The entry and continued spread of *S. frugiperda* within the continent has been attributed to contaminated traded commodities and introductions as stowaways on commercial aircraft, followed by dispersal by wind (Cock et al. 2017, Day et al. 2017). Planes cover relatively long distances over short periods of time, and this greatly increases the chance of moving live organisms from one continent to another (Meurisse et al. 2019). Eastern, central-southern, and western Africa are the major zones of *S. frugiperda* localization, most likely due to the favorable conditions for the pests' survival prevailing in these areas. In these regions, dispersal of *S. frugiperda* moths leads to rapid outbreaks and colonization of new territories. The out-of-season rains in these regions facilitate the development of 'green belts' which favor the survival, spread of moths, and subsequent onset of outbreaks throughout the crop growing period (Early et al. 2018).

Spodoptera frugiperda Dispersal

Spodoptera frugiperda moths have the ability to fly over long distances within short periods of time, covering up to 1,600 km within a 30-h period (Rose et al. 1975). They are strong flyers and also make use of air currents to migrate from one region to another (Westbrook et al. 2016). Changing wind speeds and directions determine the flight path and distribution of migratory moths, leading to rapid outbreaks and colonization of new territories (Drake and Farrow 1988). *Spodoptera frugiperda* larvae have the ability to migrate from plant to plant. Neonates access neighboring plants through ballooning—producing a silk thread that attaches to a leaf at the oviposition site and then using the wind to spin off in the direction of a neighboring plant where more food is available. *Spodoptera frugiperda* eggs are laid directly on the surface of leaves, allowing emerging larvae to balloon off more easily than stem borers which lay their eggs between the leaf sheath and on the stem of the plant. The more mature larvae disperse by crawling, as ballooning is not possible due to their relatively large size (Zalucki et al. 2002, FAO and CABI 2019, Sokame et al. 2020). A new study showed that ballooning larvae have a higher survival rate than non-ballooning larvae (Sokame et al. 2020). The study also showed that more female larvae were found to balloon off a plant as compared to male larvae. With male moths reported to mate a mean of 6.7 times during their life span (Simmons and Marti 1992), the higher survival rate of female larvae (and hence subsequent availability of more egg-laying moths) ensures sustained pest population increase, and hence plant damage.

Spodoptera frugiperda Strains and Crops Affected

Spodoptera frugiperda has two morphologically identical strains—the corn (C) and rice (R) strains—which differ genetically in their pheromone composition, mating behavior, host range, and resistance to insecticides (Pashley et al. 1985, Pashley 1988, Dumas et al. 2015, Cock et al. 2017, Haenniger et al. 2020). As the names suggest, the C strain prefers mainly corn (maize) and related cereals, such as sorghum, whereas the R strain prefers rice and other pasture grasses (Cock et al. 2017). While Otim et al. (2018) indicated that both strains occur in sub-Saharan Africa, Rwomushwana et al. (2018) observed that rice, which is widely cultivated in the region, has not been adversely affected by the pest. In addition, a study by Nagoshi (2019) found evidence that the R strain of *S. frugiperda* is rare in Africa. Further investigation to confirm the strains present in sub-Saharan Africa may be worthwhile, as most reports of *S. frugiperda* are on maize and sorghum. Determination of the different strains is necessary as it would inform the development and use of pheromone traps (Meagher et al. 2019) for pest monitoring (different strains respond differently to various pheromones). Additionally, it would be necessary to determine if the control methods currently being developed, or in use, are effective if both strains are present. Although *S. frugiperda* prefers maize, the main food crop in sub-Saharan Africa, it has also been found on many other crops (Prasanna et al. 2018). Recent reports show that *S. frugiperda* has over 353 larval host plants from about 76 families which include Poaceae (106), Asteraceae (31), and Fabaceae (31) (Montezano et al. 2018).

Maize Production in Sub-Saharan Africa

Maize is an important cereal in sub-Saharan Africa since many people depend on it as their main food crop. In 2018, 51 African countries produced 79 million tons of maize, representing 6.9% of the total world production (FAOSTAT 2020). The majority of maize farming in the region is carried out by family smallholder farmers on less than two hectares of land (Lowder et al. 2016). In sub-Saharan Africa, white maize is the predominant variety and is mainly cultivated in mixed farming systems with other crops including beans, potatoes, cassava, sorghum, millet and vegetables. The use of purchased inputs including fertilizers, chemical pesticides and hybrid seeds is low (Rapsomanikis 2015). Despite being the most widely cultivated crop in the region, maize production in sub-Saharan Africa is very low and has stagnated at around 2 tons per hectare per year compared to a world yield of 5.9 tons per hectare per year (Cairns et al. 2013). This has been attributed to several factors including the predominant reliance on rainfall for production, limited use of inputs, drought stress, low soil fertility, weeds, pests (including the recent *S. frugiperda* invasion), diseases, and poor seed quality.

Impact of *Spodoptera frugiperda* Infestation on Maize Yield

Spodoptera frugiperda attacks all stages of maize from seedling emergence to ear development. The neonates feed on the underside of the leaves leaving transparent patches, called windows. Excessive leaf feeding can kill young plants. The older larvae frequently penetrate the leaf whorls of young plants. When the *S. frugiperda* population is high on a plant, the mature larvae might move to the tassel and the ears, where they feed on inner leaves, silks and the maize kernels reducing the yield and grain quality (Capinera 2017, FAO 2018). Several studies have attempted to quantify the impact of *S. frugiperda* infestation in sub-Saharan Africa. A social economic survey on farmers' perception of losses due to *S. frugiperda* damage estimated a national mean loss of maize at 45% in Ghana and 40% in Zambia (Day et al. 2017). In the following year, farmers reported maize yield loss of 26% in Ghana and 35% in Zambia, figures lower than those reported in 2017. This was possibly due to varying climatic factors, a build-up of natural enemies, or improved pest management techniques (Rwomushana et al. 2018). Similarly, Koffi et al. (2020a) reported a reduction of *S. frugiperda* infestation in Togo and Ghana in 2018 compared to 2017 and 2016. Extrapolation of the losses in Ghana and Zambia, due to *S. frugiperda* damage, across 12 maize-producing countries of similar agro-ecological zone in sub-Saharan Africa indicates a total yield loss of between 4.1 and 17.7 million tons per annum (Rwomushana et al. 2018). Kumela et al. (2019) estimated *S. frugiperda* maize crop damage of 32% in Ethiopia and 47% in Kenya; an estimated yield reduction of between 0.8 to 1 tons/hectare. A separate study, using a rigorous field scouting approach, estimated *S. frugiperda* damage on maize in Zimbabwe at 32–48%, with a yield loss of up to 11.6% (Baudron et al. 2019). In a recent study, a systematic and country-wide assessment of the impact of *S. frugiperda* infestation in sub-Saharan Africa was carried out by estimating crop losses in the major maize-growing areas in Kenya. The study reported a 33% loss of maize due to *S. frugiperda* infestation; resulting in a loss of approximately one million tons in annual maize production in the country (De Groote et al. 2020).

Agronomic Practices That Influence *Spodoptera frugiperda* Infestation in Smallholder Conditions

The earliest and most widespread response to *S. frugiperda* invasion in sub-Saharan Africa was panic application of chemical insecticides (Kansiime et al. 2019). Several governments supplied, or subsidized, insecticides while fast tracking the emergency registration of new ones. Consequently, chemical insecticides have been excessively and indiscriminately applied without regard for best practice, not only posing a risk to human health and the environment, but also increasing costs to resource constrained smallholder farmers. In two studies, poor efficacy of insecticide use against *S. frugiperda* infestation was noted in Kenya and Zimbabwe; possibly due to the wrong insecticide being applied, incorrect dosage or improper application processes (Baudron et al. 2019, Kumela et al. 2019). Insecticide misuse, such as adulteration, improper repackaging, and use of unverified synthetic insecticides has been reported in Africa (Karungi et al. 2011), and may also be contributing to the observed poor efficacy against *S. frugiperda*. In addition, poor insecticide efficacy against *S. frugiperda* in some parts of sub-Saharan Africa could be because of resistance to the insecticides in use. *Spodoptera frugiperda* has been reported to be resistant to some insecticides in the Americas (Carvalho et al. 2013, Bolzan et al. 2019), and it is possible that this resistance trait was also introduced to Africa with the pest. Studies are needed to establish the prevalence of insecticide resistance alleles in *S. frugiperda* in sub-Saharan Africa. Furthermore, burrowing deep in the maize whorl and stem by *S. frugiperda* larvae tends to render sprayed insecticides ineffective. Other agronomic practices that some farmers engage in that may impact *S. frugiperda* infestation include mono-cropping of maize, hence creating a uniform habitat for the development of the larvae; intercropping maize with plants that act as alternative hosts, and; the type of crop previously planted on the field, whose residue may still be hosting *S. frugiperda*. Baudron et al. (2019) showed that certain maize varieties are more susceptible to *S. frugiperda* invasion than others, and that high level of leaf damage does not necessarily translate to lower yield. The study further showed that frequent weeding, minimum- and zero- tillage, in combination with mulching, significantly reduced *S. frugiperda* damage, while intercropping with pumpkin increased damage; possibly due to the increased leaf canopy cover providing shelter or bridges for maize to maize larval migration. With intercropping a common practice in sub-Saharan Africa, studies on the most appropriate maize-intercrop combinations would be useful.

Spodoptera frugiperda Control Methods

Push–Pull Technology

The International Centre of Insect Physiology and Ecology (ICIPE) in partnership with Rothamsted Research developed the push–pull technology to control maize stem borers (*Busseola fusca* Fuller (Lepidoptera: Noctuidae) and *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae)) and striga (*Striga hermonthica* (Delile) Bentham (Scrophulariales: Orobanchaceae)) (Cook et al. 2007, Khan et al. 2014). This technology has also recently been adopted to control *S. frugiperda* (Midega et al. 2018). The push–pull technology is an effective, low cost, and environmentally friendly technology which involves intercropping maize or sorghum with Silverleaf desmodium—*Desmodium uncinatum* (Jacquin) de Candolle (Fabales: Fabaceae) or Greenleaf desmodium—*Desmodium intortum* (Miller) Urban (Fabales: Fabaceae) (intercrops) and planting Napier grass—*Pennisetum purpureum* Schumach (Cyperales: Poaceae) or *Brachiaria brizantha* cv Mulato (Richard) Webster (Poales: Poaceae) (border crops) around the intercropped field. The desmodiums produces semiochemicals that are repugnant and repel (push) insect pests from the main crop (maize or sorghum). On the other hand, Napier grass or *Brachiaria* produces semiochemicals that attract (pull), trap and kill the insects. Napier grass is a preferred trap crop since it is more attractive for oviposition by moths than maize—and subsequently kills the offspring due to production of a gummy substance that restricts the mobility of larvae; causing over 80% mortality (Khan et al. 2014). Midega et al. (2018) demonstrated the effectiveness of the climate-adapted push–pull technology to control *S. frugiperda* on maize farms in East Africa using the drought-tolerant *D. intortum* and *B. brizantha* cv Mulato II as the 'push' and 'pull' crops, respectively; maize plant damage was reduced by 86.7% and grain yield increased 2.7-fold.

Insecticides

While a number of insecticides are known to be effective for *S. frugiperda* control, many have not been registered for use in several countries in sub-Saharan Africa. Being a new pest, it is necessary to recommed a list of regulated insecticides and biopesticides that are effective against it, and share the information with farmers. This has been done in some countries. For example, in South Africa the Department of Agriculture Land Reform and Rural Development (formerly Department of Agriculture Forestry and Fisheries) has recommended a number of insecticides for control of *S. frugiperda*, with 50 insecticides registered for the pest to date (DAFF 2017). Temporary or emergency registration of recommended insecticides should also be considered and regulators urged to allow supporting data from other regions in the case of heavy *S. frugiperda* infestations. Extensive insecticide use may however impact the sustainability of small scale farming systems and therefore insecticides should only be used in cases where it is economically justifiable. It is also, therefore, important not to rely solely on chemical insecticides but to promote them as part of as part of Integrated Pest Management (IPM) programs.

Biopesticides

Although the use of synthetic insecticides has provided some control against *S. frugiperda* in Africa, inclusion of biological control options such as the use of entomopathogenic microbes and plant extracts with insecticidal properties as part of IPM programs, would provide a safer and much more environmentally friendly approach. As opposed to synthetic insecticides, biopesticides are expected to reduce *S. frugiperda* populations without leaving pesticide residue on foods or harming nontarget organisms. The development and use of biopesticides for the management of *S. frugiperda* in sub-Saharan Africa is however still in its infancy (Ndolo et al. 2019). The International Centre for Genetic Engineering and Biotechnology is among several institutions investigating potential biopesticide options for *S. frugiperda* control in sub-Saharan Africa (Dennis Ndolo, *pers. comm*). The sections below give an overview of biopesticide development and use for the control of *S. frugiperda* in sub-Saharan Africa, reflecting on their efficacy, cost, and ease of adoption by farmers.

At least 16 species of entomopathogenic microbes against *S. frugiperda* are known worldwide. They include fungi (*Metarhizium anisopliae* Metschnickoff (Hypocreales: Clavicipitaceae), *Metarhizium rileyi* (Farlow) Samson (Hypocreales: Clavicipitaceae), and *Beauveria bassiana* (Balsamo) Vuillemin (Hypocreales:

Cordycipitaceae)), bacteria (*Bacillus thuringiensis* Berliner (Bacillales: Bacillaceae)), protozoa, nematodes (*Heterorhabditis bacteriophora* Poinar (Rhabditida: Heterorhabditidae), *Heterorhabditis indica* (Poinar, Karunakar & David) (Rhabditida: Heterorhabditidae), and *Steinernema carpocapsae* Weiser (Rhabditida: Steinernematidae)), and viruses (Nuclear Polyhedrosis viruses [NPVs]) (Gardner and Fuxa 1980, Molina-Ochoa et al. 2003). Some strains of *B. thuringiensis* have shown efficacy against *S. frugiperda* in other parts of the world (Polanczyk et al. 2000) and bioprospecting for strains resident in, and suitable for use in, sub-Saharan countries is needed. In Kenya, Akutse et al. (2019) showed in laboratory screens that some *M. anisopliae* isolates could cause total mortality (egg and neonate larvae) of up to 96%. Once such isolates are identified, it is important that their efficacy under field conditions is established. Proper formulation to enhance field survival and efficacy should be investigated. Although commercial formulations of some of the foreign strains of these microbes are now available in agro retail shops of some countries in sub-Saharan Africa, their efficacy and affordability under small scale conditions need to be assessed. There is a need to identify and develop locally adapted strains of these microbes for the management of *S. frugiperda*. Given that usage of insecticides amongst smallholder farmers in sub-Saharan Africa is quite low (Rapsomanikis 2015), due to the high costs, biopesticides must be developed and formulated using materials and inputs that will minimize the cost of the final product. Another important aspect that might affect efficacy, cost, and likelihood for adoption of any identified microbes is formulation. Despite the high number of strains discovered worldwide, several of the formulations have not been suitable for field conditions (Damalas and Koutroubas 2018). A proper choice of formulation for the *S. frugiperda* biopesticides must consider cost of production, delivery systems, and product stability.

A wide array of plant species with insecticidal properties have been used to manage insect pests, including *S. frugiperda,* in different parts of the world. Unlike synthetic insecticides, botanical insecticides generally have shorter persistence in the environment, are safer for farmers and consumers, and are less likely to harm beneficial organisms or to result in development of resistance in the insect pest. Some of the plants demonstrated to have insecticidal properties include neem (*Azadirachta indica* A. Jussieu (Rutales: Meliaceae)), lemongrass (*Cymbopogon citratus* (de Candolle) Stapf (Cyperales: Poaceae)), fish poison bean (*Tephrosia vogelii* Hooker (Fabales: Fabaceae)), lippia (*Lippia javanica* (Burman) Sprengel (Lamiales: Verbenaceae), wild marigold (*Tagetes minuta* Linnaeus (Asterales: Asteraceae)), wild sage (*Lantana camara* Linnaeus (Lamiales: Verbenaceae)), chrysanthemum (*Chrysanthemum* sp. (Asterales: Asteraceae)), wild sunflower (*Tithonia diversifolia* (Hemsley) A. Gray (Asterales: Asteraceae)), pyrethrum (*Tanacetum cinerariifolium* (Treviranus) Schultz Bipontinus (Asterales: Asteraceae)), tobacco (*Nicotiana* sp. (Solanales: Solanaceae)), chillies (*Capsicum* sp. (Solanales: Solanaceae)), and onion (*Allium cepa* Linnaeus (Asparagales: Amaryllidaceae) and *Allium sativum* Linnaeus (Asparagales: Amaryllidaceae) (Mugisha-Kamatenesi et al. 2008, Ogendo et al. 2013, Stevenson et al. 2017, Phambala et al. 2020). In Malawi, Phambala et al. (2020) reported more than 60% larval mortality on *S. frugiperda* that were in contact with, or fed on, *L. javanica* or *Nicotiana tabacum* Linnaeus (Solanales: Solanaceae), while *C. citratus* and *A. indica* deterred feeding by 30% and 20%, respectively. In sub-Saharan Africa, there is paucity of information on trials to determine efficacy of botanical extracts against *S. frugiperda*. However, some plant species that have been used to control the pest in South America are also present in Africa including: *Carica papaya* Linnaeus (Brassicales: Caricaceae), *Corymbia citriodora* (Hooker) Hill & Johnson (Myrtales: Myrtaceae), *Tagetes erecta* Linnaeus (Asterales: Asteraceae), and *A. indica* (Maredia et al. 1992, Souza et al. 2010, Salinas-Sánchez et al. 2012, Figueroa-Brito et al. 2013). The efficacy of these botanical extracts needs to be further investigated especially under field conditions. Using botanicals derived from locally available plant species is expected to make the technology more affordable and accessible to the smallholder farmers in sub-Saharan Africa. Currently, some smallholder farmers who spray to manage *S. frugiperda* receive free, or subsidized, synthetic insecticides. Since such efforts by governments are inadequate, many smallholder farms are still prone to the pest infestation. It is therefore important to develop cheaper and readily accessible botanical products for the management of *S. frugiperda* in sub-Saharan Africa.

Parasitoids and Predators

There are more than 150 species of predators and parasitoids of *S. frugiperda* worldwide, spread across multiple insect orders (FAO 2018, Hruska 2019). Many of these have been shown to be just as effective against the rice strain of *S. frugiperda* as they are on the maize strain, a factor which may come in handy given that more than one strain is reported to be present in sub-Saharan Africa (Hay-Roe et al. 2016, Otim et al. 2018). Although many of the natural enemies of *S. frugiperda* are from the Americas, new associations have been found in sub-Saharan Africa, presenting a huge opportunity for the deployment of these organisms for the management of the pest. In Ethiopia, Kenya, and Tanzania, Sisay et al. (2018) reported *Cotesia icipe* Fernandez-Triana & Fiaboe (Hymenoptera: Braconidae), *Palexorista zonata* Curran (Diptera: Tachinidae), *Charops ater* Szépligeti (Hymenoptera: Ichneumonidae), and *Coccygidium luteum* Brullé (Hymenoptera: Braconidae), with parasitism ranging from 4.6% to 37.6% on the larvae of *S. frugiperda* and a low level (4.8%) of *Chelonus curvimaculatus* Cameron (Hymenoptera: Braconidae) parasitism on their eggs. In the following year, three larval parasitoids: *C. icipe*, *P. zonata*, and *C. ater*, with parasitism ranging from 2 to 42% and three egg parasitoids: *Telenomus remus* Nixon (Hymenoptera: Scelionidae), *Trichogramma chilonis* Ishii (Hymenoptera: Trichogrammatidae), and *C. curvimaculatus,* with parasitism ranging from 4% to 69.3% were also recovered in Ethiopia, Kenya, and Tanzania (Sisay et al. 2019). Furthermore, *T. remus* has been found to attack *S. frugiperda* eggs in five sub-Saharan African countries (Benin, Côte d'Ivoire, Kenya, Niger, and South Africa) (Kenis et al. 2019). In Ghana, seven parasitoids of *S. frugiperda* were reported—among which *Chelonus bifoveolatus* Szépligeti (Hymenoptera: Braconidae) and *C. luteum* were the most abundant, with parasitism rates of 1.04% and 0.85%, respectively. Additionally, three *S. frugiperda* predators were collected: *Pheidole megacephala* Fabricius (Hymenoptera: Formicidae), *Haematochares obscuripennis* Stål (Hemiptera: Reduviidae), and *Peprius nodulipes* Signoret (Hemiptera: Reduviidae) (Koffi et al. 2020b). Given the wide array of agroecological conditions existing in sub-Saharan Africa, it is important that the prevalence of parasitoids and predators in each country or region are identified, as these may be better adapted to the prevailing local conditions. The utilization of locally adapted predators and parasitoids is likely to improve their efficacy, making them more attractive, but also affordable to smallholder farmers on the continent.

Bt Maize

Transgenic (genetically modified) maize containing a gene from the soil bacterium, *Bacillus thuringiensis* (Bt)—and hence commonly referred to as Bt maize—has been used to control *S. frugiperda* in the Americas for more than 15 yr (Buntin et al. 2004, Reay-Jones et al. 2016, Burtet et al. 2017). The Bt gene encodes an insecticidal crystal protein, *Cry* protein, which confers the insect resistance trait against certain pests. Bt maize has shown efficacy for *S. frugiperda* control in South Africa (Botha et al. 2019), the only country in sub-Saharan Africa currently commercially growing Bt maize for human and animal consumption. However, there have been reports of resistance development to Bt maize hybrids in various parts of the world (e.g., Fatoretto et al. 2017). The sustainability of the current Bt maize hybrids in sub-Saharan Africa (which were generally developed for maize stem borer control) for *S. frugiperda* control is therefore still unclear. It is critical therefore that should countries take decisions to adopt Bt maize for *S. frugiperda* control, then they would have to put in place, and ensure implementation of, effective resistance management strategies.

Local and Cultural Methods

Farmers have devised simple responses to *S. frugiperda* infestation. The methods, even though sometimes lacking clear scientific basis, are effective and have therefore been adopted by many smallholder farmers, especially as they also are cheap and require readily available material (FAO 2018, Harrison et al. 2019, Kansiime et al. 2019, Tambo et al. 2020). Examples include the application of soil, sand, sawdust, or ashes into the whorl of the maize plant, hence suffocating the larvae inside the whorl. Other farmers pour water into the whorl, hence drowning the larvae. Sand, ashes, and sawdust on the maize plants desiccate neonates. Spraying the maize plant with hot pepper solution presumably irritates or damages the larvae. Lime, soap, salt, and oil have also been reportedly applied to control the pest. Some farmers spray sugar solution or fish soup on the maize plants to attract natural enemies such as ants or wasps. Another approach involves frequent handpicking and crushing of *S. frugiperda* eggs or larvae found on the plants. Additionally, planting with the first rains, when the pest population is still low, reduces the impact of *S. frugiperda* damage. Farmers can also diversify by rotating maize with crops such as cassava or sweet potato and intercropping maize with repellent plants that the *S. frugiperda* do not feed on, or prefer for oviposition. It is necessary to determine both the scientific basis as well as the degree of control offered by these farmer-developed methods. This may provide opportunities to improve their implementation and promote the most efficacious use more widely.

Digital *Spodoptera frugiperda* Early Warning Systems and Risk Prediction Systems Used in Sub-Saharan Africa

Sustainable *S. frugiperda* management requires effective early warning and detection systems. Farmers in many areas are still not sure of how to identify *S. frugiperda* (often mistaking it for the African armyworm, *Spodoptera exempta* Walker (Lepidoptera: Noctuidae)). The awareness of *S. frugiperda* including identification, damage, and control needs to be promoted. A number of web and mobile based applications for early detection, identification, and monitoring of *S. frugiperda* in sub-Saharan Africa have been developed. In Ghana, the organizations, Esoko, Satelligence, and Weather Impact developed an app that is able to provide timely warning messages to farmers in 15 local languages using voice messages indicating the *S. frugiperda* risk level within their respective districts and the precautionary measures to take given the risk. The majority of the farmers indicated that the alert was easy to understand and useful (see https://www.weatherimpact.com/faw-alert-makes-a-difference-for-ghanaian-farmers/). The Food and Agriculture Organization (FAO) has developed a tool, the Fall Armyworm Monitoring and Early Warning System (FAMEWS) to assist in pest monitoring (see http://www.fao.org/fall-armyworm/monitoring-tools/en/). The tool enables farmers and agricultural staff to identify and report the presence of *S. frugiperda* in their fields from the app, thereby generating detailed and vital information for the management of the pest. It is extremely intuitive, fast, easy to use, and available in 13 languages; the app can be downloaded for free on Google Play Store. The FAMEWS global platform maps data collected by the FAMEWS mobile app to provide real-time maps and analytics overview of the *S. frugiperda* infestation at global, country, and sub-country levels. The variation of the *S. frugiperda* population over time and with varying ecology can be determined, and thus the behavior and best management practices established. FAMEWS is very useful to farmers who are able to read, have smartphones, and a basic understanding on the software's functionality. FAMEWS provides vital information on the *S. frugiperda* risk, spread, and management, enabling the farmers to prevent further infestation and reduce crop damage. Another tool, Nuru, is an artificial intelligence digital assistant developed by PlantVillage, FAO, and CGIAR (see https://plantvillage.psu.edu/solutions#nuru). Nuru is able to diagnose *S. frugiperda* on maize, help the farmer or extension workers to recognize the pest, and provide advice on how to manage the infestation (Mrisho et al. 2020). Nuru can understand voice languages from farmers and can respond in their local language, currently speaking at least four languages. The Nuru platform is open access and available to anyone who registers onto the online system. It provides a simple, inexpensive, and robust means of conducting in-field diagnosis and real-time results or advice. Nuru is linked to the FAMEWS app and complements its data collection functionality. One advantage of Nuru is that it does not require the user to be online to use it since all the information is available within the phone thus acting as an always present agricultural extension officer.

As much as the apps developed so far have great utility in *S. frugiperda* management, they are only accessible to farmers who are able to access and use mobile phones, sometimes only smart phones. Many smallholder farmers may not as yet fall into this category, but mobile phone penetration is rapidly increasing, and these apps will find greater utility into the future—as they can also be adapted for management of other pest problems.

Developing an Integrated Pest Management Approach for *Spodoptera frugiperda* in Sub-Saharan Africa

An effective management of *S. frugiperda* requires an integrated approach based on biology, ecology and other socioeconomic and cultural aspects. In order to develop an integrated approach for *S. frugiperda* management in sub-Saharan Africa, a number of issues must be considered.

- *Spodoptera frugiperda* is a polyphagous pest. Adult moths disperse quickly and can travel as far as 1,600 km over a 30-h period (Rose et al. 1975).
- The majority of farmers in sub-Saharan Africa are smallholders (Lowder et al. 2016). These farmers are resource-poor and have limited access to technology and up to date information which define their options for management of this pest.
- *Spodoptera frugiperda* has existed in Americas over a century. Where possible, the knowledge-base and experiences of

S. frugiperda management from other regions of the world where *S. frugiperda* has occurred for a long time should be harnessed and utilized while designing integrated management strategies for countries in sub-Saharan Africa.
- Smallholders have limited access to chemical insecticides and other technologies. *Spodoptera frugiperda* resistance to chemical insecticides has already been reported (Carvalho et al. 2013, Bolzan et al. 2019). Therefore, chemical insecticides should be used judiciously.
- Resistance to Bt maize hybrids has been reported in other parts of the world. Resistance management must therefore be a key consideration in developing IPM programs, incorporating the use of this technology.
- Emphasis should be given to the *S. frugiperda* management options for smallholders, which are largely based on locally available resources and indigenous solutions using agro-ecologically based knowledge and approaches (Harrison et al. 2019).

In the long term, an integrated approach would be the most sustainable way to address the *S. frugiperda* problem in sub-Saharan Africa. This would include use of all available tools and tactics for the management of the pest including cultural, botanical, biological, biological insecticides, chemical insecticides, and biotechnological approaches, which should rely on a strong foundation of scouting and monitoring of *S. frugiperda* populations (adult, eggs, and larvae).

Given that *S. frugiperda* is relatively new insect pest in Africa, the IPM strategy should include both short-term interventions to address immediate problems and crop losses, as well as formulation of a long-term strategy for integrated management of this pest in the context of crop specific IPM approaches. IPM approaches are crop and site specific—they vary from crops to crop and from location to location. The IPM approach for *S. frugiperda* must not be viewed in isolation and must be integrated into an overall crop and pest management programs for specific crop and local agroecosystem.

Among the key food security crops in sub-Saharan Africa, maize has been affected the most by *S. frugiperda*. Based on decades of experiences all over the world, the early stages of maize crop growth (first 30–45 d) are the most vulnerable for crop damage and yield losses from *S. frugiperda* damage. The maize plant can tolerate and recover from the *S. frugiperda* damage during the later stages of crop growth. Therefore, sampling and monitoring of *S. frugiperda* moths, egg masses, and neonate larvae are critical to take appropriate action and make management decisions during the early stages of maize growth.

Based on the foregoing the following are the suggested strategies for developing an IPM program for *S. frugiperda* in sub-Saharan Africa:

1. **Education of extension workers and farmers:** The important first step is the training of extension workers and local farmers in pest identification and to understand the life cycle of *S. frugiperda*; and, know how to monitor and manage the pest. Farmers should be sensitized on existing control measures and pest management practices which have been proven to be effective in controlling *S. frugiperda*. Establishment of IPM demonstration sites should be considered to showcase the best practices for monitoring and control of *S. frugiperda*.
2. **Scouting and monitoring:** Monitoring of adult populations using pheromone traps and light traps, and sampling/scouting for egg masses and neonate larvae in very critical. Area-wide monitoring and scouting is more desirable in smallholders' situation. Given the overlap of cropping systems and crop growth stages, continuous monitoring of *S. frugiperda* populations throughout the season is very important. Management decisions should be based on the data from the scouting and monitoring programs.
3. **Prevention is better than cure:** Seed treatment with suitable biopesticides or chemical insecticides can greatly help prevent damage after the germination of maize and early stages of growth which are most vulnerable to *S. frugiperda*.
4. **Clean cultivation:** Given that *S. frugiperda* is polyphagous and feeds on crops and wild habitats, farmers should keep their fields clean from grasses and weeds that may harbor *S. frugiperda* populations in the local landscapes.
5. **Pest control options:** Based on the results of scouting and monitoring, control methods should be selected using the available tools, resources, and pest management practices (e.g., botanical/biopesticides, chemical insecticides, and other locally available techniques). Chemical insecticides should be used as a last resort and applied properly to have effective control of the pest. Insecticide management is very critical to reduce the overuse, misuse and mismanagement of chemical insecticides and prevent resistance development in *S. frugiperda* populations.

Along with addressing the *S. frugiperda* problems in the short term, the national research and outreach systems will need to establish a long-term program for sustainable management of *S. frugiperda*. Such an approach will need to integrate the current practices with new and innovative tools and approaches. This may cover the following areas:

- Testing of alternative seed treatments.
- Monitoring of *S. frugiperda* resistance to insecticides.
- Evaluation of different types of traps for monitoring.
- Development and testing of biopesticides: new botanicals and microbial control agents.
- Breeding of *S. frugiperda* resistant/tolerant varieties using conventional and biotechnological approaches.
- Evaluations of inter-cropping, crop rotations, and push–pull strategy to enhance cultural and biological control.
- Identification, mass rearing, release, and conservation of biological control agents in local landscapes (parasites and predators of *S. frugiperda*).
- Molecular characterization of *S. frugiperda* species and biotypes.

Perspectives

There are clearly a variety of perspectives and views on how best to approach the *S. frugiperda* problem. The common thread passing through these however is that IPM is the most suitable approach, even though making it work is not always as straightforward as it appears. For instance, control measures must take into account the level of damage caused, stage of crop growth, and socioeconomic considerations. Most propositions on how best to deal with the *S. frugiperda* problem have largely been based on research outcomes of various scientific studies. Even though farmers are often inundated with a variety of recommendations and advice, it must be appreciated that farmers who deal with the pest on a day to day basis are also very useful creators of knowledge, and as much as possible their views have to be sought in developing long-term solutions to *S. frugiperda* control.

Conclusion and Way Forward

Spodoptera frugiperda may remain a significant challenge for the foreseeable future and effective management strategies are required.

Different regions have adopted various ways of dealing with this pest menace, with varying degrees of success. There are therefore opportunities for researchers and farmers to continue learning from one another. The authors further note that there has been a lot of information on technical approaches that would be effective for *S. frugiperda* management but that may not be cost-effective or practical from a farmers' point of view. The ability of farmers to adopt recommended approaches should be given a significant consideration in developing and promoting sustainable *S. frugiperda* integrated management strategies.

Acknowledgments

This work was supported by the National Research Foundation of South Africa, Grant Number: 118477. However, the findings and conclusions contained in this publication are those of the authors and do not necessarily reflect positions or policies of the National Research Foundation of South Africa.

References Cited

African Centre of Meteorological Applications for Development (ACMAD). 2018. Climate service for increased resilience in the Sahel Project. Report No. 5, March 2018. The state of climate in Africa: 2017.

Akutse, K. S., J. W. Kimemia, S. Ekesi, F. M. Khamis, O. L. Ombura, and S. Subramanian. 2019. Ovicidal effects of entomopathogenic fungal isolates on the invasive fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae). J. Appl. Entomol. 143: 626–634.

Baudron, F., M. A. Zaman-Allah, I. Chaipa, N. Chari, and P. Chinwada. 2019. Understanding the factors influencing fall armyworm (*Spodoptera frugiperda* J.E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe. Crop Prot. 120: 141–150.

Bolzan, A., F. E. Padovez, A. R. Nascimento, I. S. Kaiser, E. C. Lira, F. S. Amaral, R. H. Kanno, J. B. Malaquias, and C. Omoto. 2019. Selection and characterization of the inheritance of resistance of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) to chlorantraniliprole and cross-resistance to other diamide insecticides. Pest Manag. Sci. 75: 2682–2689.

Botha, A. S., A. Erasmus, H. du Plessis, and J. Van den Berg. 2019. Efficacy of Bt Maize for Control of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in South Africa. J. Econ. Entomol. 112: 1260–1266.

Buntin, G. D., K. L. Flanders, and R. E. Lynch. 2004. Assessment of experimental Bt events against fall armyworm and corn earworm in field corn. J. Econ. Entomol. 97: 259–264.

Burtet, L. M., O. Bernardi, A. A. Melo, M. P. Pes, T. T. Strahl, and J. V. Guedes. 2017. Managing fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), with Bt maize and insecticides in southern Brazil. Pest Manag. Sci. 73: 2569–2577.

Cairns, J. E., J. Hellin, K. Sonder, J. L. Araus, J. F. MacRobert, C. Thierfelder, and B. M. Prasanna. 2013. Adapting maize production to climate change in sub-Saharan Africa. Food Secur. 5: 345–360.

Capinera, J. L. 2017. Fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Insecta: Lepidoptera: Noctuidae). http://edis.ifas.ufl.edu/in255

Carvalho, R. A., C. Omoto, L. M. Field, M. S. Williamson, and C. Bass. 2013. Investigating the molecular mechanisms of organophosphate and pyrethroid resistance in the fall armyworm *Spodoptera frugiperda*. PLoS One 8: e62268.

Cock, M. J. W., P. K. Beseh, A. G. Buddie, G. Cafá, and J. Crozier. 2017. Molecular methods to detect *Spodoptera frugiperda* in Ghana, and implications for monitoring the spread of invasive species in developing countries. Sci. Rep. 7: 4103.

Cook, S. M., Z. R. Khan, and J. A. Pickett. 2007. The use of push-pull strategies in integrated pest management. Annu. Rev. Entomol. 52: 375–400.

Department of Agriculture, Forestry and Fisheries, South Africa (DAFF). 2017. Guideline for registered agrochemicals to control Fall armyworm in South Africa. https://www.nda.agric.za/doaDev/sideMenu/plantHealth/docs/

Damalas, C. A., and S. D. Koutroubas. 2018. Current status and recent developments in biopesticide use. Agriculture 8: 13.

Day, R., P. Abrahams, M. Bateman, T. Beale, V. Clottey, M. Cock, Y. Colmenarez, N. Corniani, R. Early, J. Godwin, ***et al.*** 2017. Fall armyworm: impacts and implications for Africa. Outlooks Pest Manag. 28: 196–201.

De Groote, H., S. C. Kimenju, B. Munyua, S. Palmas, M. Kassie, and A. Bruce. 2020. Spread and impact of fall armyworm (*Spodoptera frugiperda* J.E. Smith) in maize production areas of Kenya. Agric. Ecosyst. Environ. 292: 106804.

Drake, V. A., and R. A. Farrow. 1988. The influence of atmospheric structure and motions on insect migration. Annu. Rev. Entomol. 33: 183–210.

Dumas, P., F. Legeai, C. Lemaitre, E. Scaon, M. Orsucci, K. Labadie, S. Gimenez, A. L. Clamens, H. Henri, F. Vavre, ***et al.*** 2015. *Spodoptera frugiperda* (Lepidoptera: Noctuidae) host-plant variants: two host strains or two distinct species? Genetica 143: 305–316.

Early, R., P. González-Moreno, S. T. Murphy, and R. Day. 2018. Forecasting the global extent of invasion of the cereal pest *Spodoptera frugiperda*, the fall armyworm. NeoBiota 40: 25–50.

Food and Agriculture Organization (FAO). 2005. Irrigation in Africa in figures – AQUASTAT Survey 2005. http://www.fao.org/tempref/agl/AGLW/docs/wr29_eng_including_countries.pdf

Food and Agriculture Organization (FAO). 2018. Integrated management of the fall armyworm on maize: a guide for farmer field schools in Africa. Food and Agricultural Organization of the United Nations, Rome. http://www.fao.org/3/i8741en/I8741EN.pdf

Food and Agriculture Organization (FAO). 2019. Briefing note on FAO actions on fall armyworm in Africa. http://www.fao.org/3/a-bs183e.pdf

Food and Agriculture Organization (FAO) and Centre for Agriculture and Bioscience International (CABI). 2019. Community-based fall armyworm (*Spodoptera frugiperda*) monitoring, early warning and management, training of trainers manual, First Edition. 112 pp. Licence: CC BY-NC-SA 3.0 IGO.

FAOSTAT. 2020. Maize production, 2020. http://www.fao.org/faostat/

Fatoretto, J. C., A. P. Michel, M. C. S. Filho, and N. Silva. 2017. Adaptive potential of fall armyworm (Lepidoptera: Noctuidae) limits Bt trait durability in Brazil. J. Integr. Pest Manag. 8: 1–10.

Figueroa-Brito, R., P. Villa-Ayala, J. F. López-Olguín, A. Huerta-de la Peña, J. R. Pacheco-Aguilar, and M. A. Ramos-López. 2013. Nitrogen fertilization sources and insecticidal activity of aqueous seeds extract of Carica papaya against *Spodoptera frugiperda* in maize. Cienc. e Investig. Agrar. 40: 571–580.

Gardner, W. A., and J. R. Fuxa. 1980. Pathogens for the suppression of the fall armyworm. Florida Entomol. 63: 439–447.

Goergen, G., P. L. Kumar, S. B. Sankung, A. Togola, and M. Tamò. 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.

Haenniger, S., G. Goergen, M. D. Akinbuluma, M. Kunert, D. G. Heckel, and M. Unbehend. 2020. Sexual communication of *Spodoptera frugiperda* from West Africa: adaptation of an invasive species and implications for pest management. Sci. Rep. 10: 2892.

Harrison, R. D., C. Thierfelder, F. Baudron, P. Chinwada, C. Midega, U. Schaffner, and J. van den Berg. 2019. Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: providing low-cost, smallholder friendly solutions to an invasive pest. J. Environ. Manage. 243: 318–330.

Hay-Roe, M. M., R. L. Meagher, R. N. Nagoshi, and Y. Newman. 2016. Distributional patterns of fall armyworm parasitoids in a corn field and a pasture field in Florida. Biol. Control 96: 48–56.

Hruska, A. J. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat. Resour. 14: 1–11.

Johnson, S. J. 1987. Migration and the life history strategy of the fall armyworm, *Spodoptera frugiperda* in the western hemisphere. Int. J. Trop. Insect Sci. 8: 543–549.

Kansiime, M. K., I. Mugambi, I. Rwomushana, W. Nunda, J. Lamontagne-Godwin, H. Rware, N. A. Phiri, G. Chipabika, M. Ndlovu, and R. Day. 2019. Farmer perception of fall armyworm (*Spodoptera frugiderda* J.E. Smith) and farm-level management practices in Zambia. Pest Manag. Sci. 75: 2840–2850.

Karungi, J., S. Kyamanywa, E. Adipala, and M. Erbaugh. 2011. Pesticide utilisation, regulation and future prospects in small scale horticultural crop production systems in a developing country, pp. 19–34. *In* M. Stoytcheva (ed.), Pesticides in the modern world. InTechopen, London. doi:10.5772/17170

Kenis, M., H. du Plessis, J. Van den Berg, M. Ba, G. Goergen, K. Kwadjo, I. Baoua, T. Tefera, A. Buddie, G. Cafà, *et al.* 2019. *Telenomus remus*, a candidate parasitoid for the biological control of *Spodoptera frugiperda* in Africa, is already present on the continent. Insects 10: 92.

Khan, Z. R., C. A. O. Midega, J. O. Pittchar, A. W. Murage, M. A. Birkett, T. J. A. Bruce, and J. A. Pickett. 2014. Achieving food security for one million sub-Saharan African poor through push–pull innovation by 2020. Philos. Trans. R. Soc. B Biol. Sci. 369: 20120284.

Koffi, D., K. Agboka, D. K. Adenka, M. Osae, A. K. Tounou, M. K. Anani Adjevi, K. O. Fening, and R. L. Meagher. 2020a. Maize infestation of fall armyworm (Lepidoptera: Noctuidae) within agro-ecological zones of Togo and Ghana in West Africa 3 yr after its invasion. Environ. Entomol. 49: 645–650.

Koffi, D., R. Kyerematen, V. Y. Eziah, K. Agboka, M. Adom, G. Goergen, and R. L. Meagher. 2020b. Natural enemies of the fall armyworm, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae) in Ghana. Florida Entomol. 103: 85.

Kumela, T., J. Simiyu, B. Sisay, P. Likhayo, E. Mendesil, L. Gohole, and T. Tefera. 2019. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. Int. J. Pest Manag. 65: 1–9.

López-Edwards, M., J. L. Hernández-Mendoza, A. Pescador-Rubio, J. Molina-Ochoa, R. Lezama-Gutiérrez, J. J. Hamm, and B. R. Wiseman. 1999. Biological differences between five populations of fall armyworm (Lepidoptera: Noctuidae) collected from corn in Mexico. Florida Entomol. 82: 254–262.

Lowder, S. K., J. Skoet, and T. Raney. 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. World Dev. 87: 16–29.

Maredia, K. M., O. L. Segura, and J. A. Mihm. 1992. Effects of neem, *Azadirachta indica* on six species of maize insect pests. Trop. Pest Manag. 38: 190–195.

Meagher, R. L., K. Agboka, A. K. Tounou, D. Koffi, K. A. Agbevohia, T. R. Amouze, K. M. Adjévi, and R. N. Nagoshi. 2019. Comparison of pheromone trap design and lures for *Spodoptera frugiperda* in Togo and genetic characterization of moths caught. Entomol. Exp. Appl. 167: 507–516.

Meurisse, N., D. Rassati, B. P. Hurley, E. G. Brockerhoff, and R. A. Haack. 2019. Common pathways by which non-native forest insects move internationally and domestically. J. Pest Sci. 92: 13–27.

Midega, C. A. O., J. O. Pittchar, J. A. Pickett, G. W. Hailu, and Z. R. Khan. 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (J E Smith), in maize in East Africa. Crop Prot. 105: 10–15.

Molina-Ochoa, J., R. Lezama-Gutierrez, M. Gonzalez-Ramirez, M. Lopez-Edwards, M. A. Rodriguez-Vega, and F. Arceo-Palacios. 2003. Pathogens and parasitic nematodes associated with populations of fall armyworm (Lepidoptera: Noctuidae) larvae in Mexico. Florida Entomol. Florida Entomological Society 86: 244–253.

Montezano, D. G., A. Specht, D. R. Sosa-Gómez, V. F. Roque-Specht, J. C. Sousa-Silva, S. V. Paula-Moraes, J. A. Peterson, and T. E. Hunt. 2018. Host plants of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in the Americas. African Entomol. 26: 286–300

Mrisho, L., N. Mbilinyi, M. Ndalahwa, A. Ramcharan, A. Kehs, P. McCloskey, H. Murithi, D. Hughes, and J. Legg. 2020. Evaluation of the accuracy of a smartphone-based artificial intelligence system, PlantVillage Nuru, in diagnosing of the viral diseases of cassava. bioRxiv; 2020. doi:10.1101/2020.01.26.919449.

Mugisha-Kamatenesi, M., A. L. Deng, J. O. Ogendo, E. O. Omolo, M. J. Mihale, M. Otim, J. P. Buyungo, and P. K. Bett. 2008. Indigenous knowledge of field insect pests and their management around Lake Victoria basin in Uganda. African J. Environ. Sci. Technol. 2: 342–348.

Murúa, M. G., M. T. Vera, S. Abraham, M. L. Juarçz, S. Prieto, G. P. Head, and E. Willink. 2008. Fitness and mating compatibility of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) populations from different host plant species and regions in Argentina. Ann. Entomol. Soc. Am. 101: 639–649.

Nagoshi, R. N. 2019. Evidence that a major subpopulation of fall armyworm found in the Western Hemisphere is rare or absent in Africa, which may limit the range of crops at risk of infestation. PLoS One 14: e0208966.

Nagoshi, R. N., R. L. Meagher, and M. Hay-Roe. 2012. Inferring the annual migration patterns of fall armyworm (Lepidoptera: Noctuidae) in the United States from mitochondrial haplotypes. Ecol. Evol. 2: 1458–1467.

Ndolo, D., E. Njuguna, C.O. Adetunji, C. Harbor, A. Rowe, A. Den-Breeyen, J. Sangeetha, G. Singh, B. Szewczyk, T.S. Anjorin, *et al.* 2019. Research and development of biopesticides: challenges and prospects. Outlooks Pest Manag. 30: 267–276.

Ogendo, J., A. L. Deng, E. Omollo, J. C. Matasyoh, R. Tuey, and Z. R. Khan. 2013. Management of stem borers using selected botanical pesticides in a maize-bean cropping system. Egert. J. Sci. Technol. 13: 21–28.

Otim, M. H., W. T. Tay, T. K. Walsh, D. Kanyesigye, S. Adumo, J. Abongosi, S. Ochen, J. Sserumaga, S. Alibu, G. Abalo, *et al.* 2018. Detection of sister-species in invasive populations of the fall armyworm *Spodoptera frugiperda* (Lepidoptera: Noctuidae) from Uganda. PLoS One 13: e0194571.

Pashley, D. P. 1988. Quantitative genetics, development, and physiological adaptation in host strains of fall armyworm. Evolution 42: 93–102.

Pashley, D. P., S. J. Johnson, and A. N. Sparks. 1985. Genetic population structure of migratory moths: the fall armyworm (Lepidoptera: Noctuidae). Ann. Entomol. Soc. Am. 78: 756–762.

Phambala, K., Y. Tembo, T. Kasambala, V. H. Kabambe, P. C. Stevenson, and S. R. Belmain. 2020. Bioactivity of common pesticidal plants on fall Armyworm Larvae (*Spodoptera frugiperda*). Plants 9: 112.

Polanczyk, R. A., R. F. Pires Da Silva, and L. M. Fiuza. 2000. Effectiveness of *Bacillus thuringiensis* strains against *Spodoptera frugiperda* (Lepidoptera: Noctuidae). Brazilian J. Microbiol. 31: 165–167.

Prasanna, B., J. E. Huesing, R. Eddy, and V. M. Peschke. 2018. Fall armyworm in Africa: a guide for integrated pest management. Mex. CDMX CIMMYT. First Edit: 45–62.

Prowell, D. P., M. McMichael, and J.-F. Silvain. 2004. Multilocus genetic analysis of host use, introgression, and speciation in host strains of fall armyworm (Lepidoptera: Noctuidae). Ann. Entomol. Soc. Am. 97: 1034–1044.

Rapsomanikis, G. 2015. The economic lives of smallholder farmers - An analysis based on household data from nine countries. FAO Rep, Rome.

Reay-Jones, F. P., R. T. Bessin, M. J. Brewer, D. G. Buntin, A. L. Catchot, D. R. Cook, K. L. Flanders, D. L. Kerns, R. P. Porter, D. D. Reisig, *et al.* 2016. Impact of Lepidoptera (Crambidae, Noctuidae, and Pyralidae) pests on corn containing pyramided bt traits and a blended refuge in the Southern United States. J. Econ. Entomol. 109: 1859–1871.

Rose, A. H., R. H. Silversides, and O. H. Lindquist. 1975. Migration flight by an aphid, rhopalosiphum maidis (hemiptera: Aphididae), and a noctuid, *Spodoptera frugiperda* (Lepidoptera: Noctuidae). Can. Entomol. 107: 567–576.

Rwomushana, I., M. Bateman, T. Beale, P. Beseh, K. Cameron, M. Chiluba, and J. Godwin. 2018. Fall armyworm: impacts and implications for Africa. Fall armyworm: impacts and implications for Africa. https://www.invasive-species.org/wpcontent/uploads/sites/2/2019/02/FAW-Evidence-Note-October2018.pdf

Salinas-Sánchez, D. O., L. Aldana-Llanos, M. E. Valdés-Estrada, M. Gutiérrez-Ochoa, G. Valladares-Cisneros, and E. Rodríguez-Flores. 2012. Insecticidal activity of *Tagetes erecta* extracts on *Spodoptera frugiperda* (Lepidoptera: Noctuidae). Florida Entomol. 95: 428–432.

Simmons, A. M., and O. G. Marti, Jr. 1992. Mating by the fall armyworm (Lepidoptera: Noctuidae): frequency, duration, and effect of temperature. Environ Entomol. 21: 371–375.

Sisay, B., J. Simiyu, P. Malusi, P. Likhayo, E. Mendesil, N. Elibariki, M. Wakgari, G. Ayalew, and T. Tefera. 2018. First report of the fall armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), natural enemies from Africa. J. Appl. Entomol. 142: 800–804.

Sisay, B., J. Simiyu, E. Mendesil, P. Likhayo, G. Ayalew, S. Mohamed, S. Subramanian, and T. Tefera. 2019. Fall armyworm, *spodoptera frugiperda* infestations in East Africa: assessment of damage and parasitism. Insects 10: 195.

Sokame, B. M., S. Subramanian, D. C. Kilalo, G. Juma, and P. Calatayud. 2020. Larval dispersal of the invasive fall armyworm, *Spodoptera frugiperda*, the exotic stemborer *Chilo partellus*, and indigenous maize stemborers in Africa. Entomol. Exp. Appl. 168: 322–331.

Souza, T., S. Fevero, and C. Conte. 2010. Bioatividade de óleos essenciais de espécies de eucalipto para o controle de *Spodoptera frugiperda* (J. E. Smith, 1797) (Lepidoptera: Noctuidae). Bioactivity of essential oils of eucalyptus species for control of *Spodoptera frugiperda* (J.E. Smith, 1797) (Lepidoptera: Noctuidae). Rev. Bras. Agroecol. 5: 157–164.

Sparks, A. N. 1979. A review of the biology of the fall armyworm. Florida Entomol. 62: 82–87.

Stevenson, P. C., M. B. Isman, and S. R. Belmain. 2017. Pesticidal plants in Africa: a global vision of new biological control products from local uses. Ind. Crops Prod. 110: 2–9.

Tambo, J. A., R. K. Day, J. Lamontagne-Godwin, S. Silvestri, P. K. Beseh, B. Oppong-Mensah, N. A. Phiri, and M. Matimelo. 2020. Tackling fall armyworm (*Spodoptera frugiperda*) outbreak in Africa: an analysis of farmers' control actions. Int. J. Pest Manag. 66: 298–310.

Tindo, M., A. Tagne, A. Tigui, F. Kengni, J. Atanga, S. Bila, A. Doumtsop, and R. Abega. 2017. First report of the fall army worm, *Spodoptera frugiperda* (Lepidoptera, Noctuidae) in Cameroon de lAgriculture et du Développement Rural, 4 Sous-direction de la réglementation des pesticides, Direction de la Réglementation et du Contrôle de la Qualité des. Cameroon J. Biol. Biochem. Sci. 25: 30–32.

Westbrook, J. K., R. N. Nagoshi, R. L. Meagher, S. J. Fleischer, and S. Jairam. 2016. Modeling seasonal migration of fall armyworm moths. Int. J. Biometeorol. 60: 255–267.

Zalucki, M. P., A. R. Clarke, and S. B. Malcolm. 2002. Ecology and behavior of first instar larval Lepidoptera. Annu. Rev. Entomol. 47: 361–393.