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Managing a Transboundary Pest: The Fall Armyworm on Maize in Africa

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Abstract

The fall armyworm (*Spodoptera frugiperda* J.E Smith) (Lepidoptera: Noctuidae) invaded Africa in 2016, and has since spread to all countries in sub-Saharan Africa, causing devastating effects on mainly maize and sorghum. The rapid spread of this pest is aided by its high reproductive rate, high migration ability, wide host range and adaptability to different environments, among others. Since its introduction, many governments purchased and distributed pesticides for emergency control, with minimal regard to their efficacy. In this chapter, we review efforts towards managing this pest, highlight key challenges, and provide our thoughts on considerations for sustainable management of the pest.

Keywords: agroecology, parasitoids, pesticides, *Spodoptera frugiperda*, *Zea mays*

1. Introduction

The fall armyworm (FAW) *Spodoptera frugiperda* (J.E Smith) (Lepidoptera: Noctuidae) was first reported in Africa in 2016 [1], where it mainly impacts maize production. Annual yield losses in maize due to FAW infestation are estimated between 8.3 and 20.6 million tons in just 12 African countries, valued at US\$2,481–6,187 million [2]. When the FAW was reported in Africa in 2016 [1], there was a general lack of knowledge on its management, causing a panic that resulted in many African governments procuring and distributing non-validated insecticides for its control. At this time, many African scientists relied mainly on information and experiences from the management of FAW in the Americas. If left unattended, the continued destruction by the FAW, leading to reduced yields, would aggravate the already precarious conditions of over 400 million Africans living below the poverty line [3]. The impact of FAW would be much felt in Africa with an ever-increasing population and its demand for maize, a preferred food for the poor [4, 5]. The impact of FAW at the household level may not affect the amount of maize consumed, but rather the amount sold because farmers mostly sell off the excess harvest after catering for household food demands. This may affect the income

earned and result in cash shortages, leading to failure to afford basic necessities [4]. Since its appearance on the continent, substantial research has been conducted on FAW in different African countries, resulting in several publications. The objective of our review is therefore to provide an overview of the management of FAW on maize in Africa, challenges faced and thoughts towards sustainable management of the pest on the continent.

2. Origin and distribution

The FAW is native to the tropical and sub-tropical regions of the Americas [1]. It was first described in 1797 in the state of Georgia, USA. It remained a pest in the Americas until 2016 when it was first reported in West Africa (Nigeria), and the island of São Tomé and Príncipe [1], and subsequently in almost all sub-Saharan African countries within one year [6–11]. To date, it is known to occur in five continents (Africa, Asia, Australia, North and South America). The FAW possesses a great potential to cover wide geographical locations in a short period [12]. The rapid spread of the pest is attributed to its high reproductive capacity, high migration ability and a wide host range.

3. Biology of the fall armyworm

The FAW undergoes complete metamorphosis (egg, larva, pupa and adult) (**Figure 1**). Under optimal conditions, the development of FAW takes approximately 30 days. The eggs are laid on leaves in batches containing 100–200 eggs [13]. Each female can lay an average of 1500 eggs, with a maximum of over 2,000 eggs in a life time [14]. Eggs hatch in two to three days during summer [14]. There are six larval instars with a development duration of two to three weeks, with the last instar being most destructive (causing 70% of FAW damage) [15]. The FAW generally pupates in the soil at a depth of 2 to 8 cm in a cocoon constructed by tying together particles of soil with silk [14]. The pupal stage lasts about eight to nine days

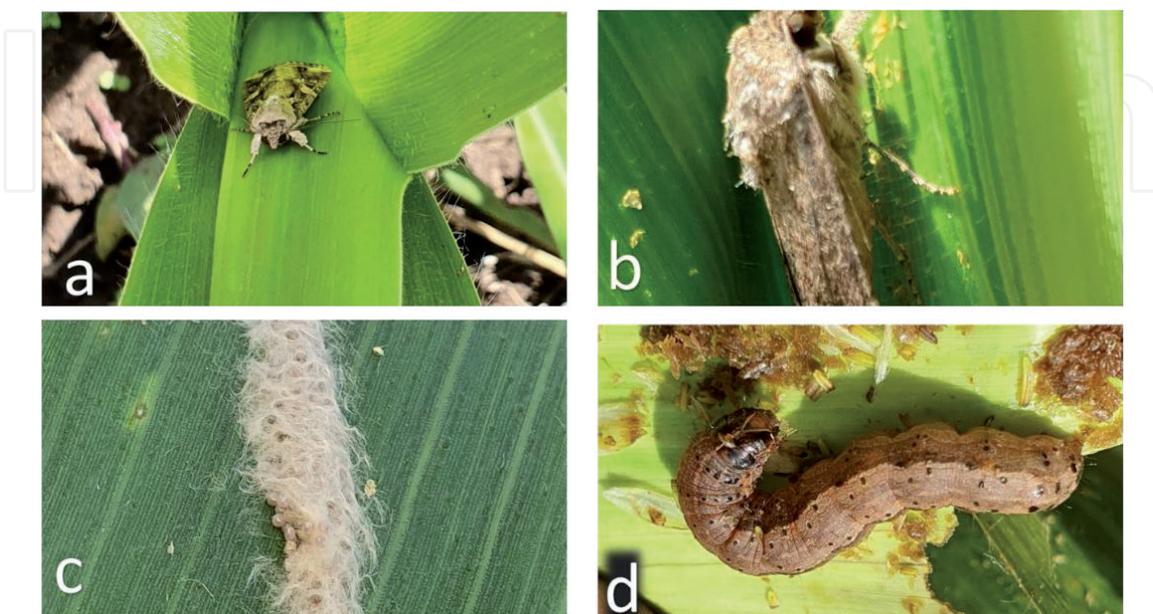


Figure 1. Developmental stages of the FAW. (a) Adult male (b) adult female, (c) an egg batch (c) and (d) a mature larva. Photo credit: Dr. Girma Hailu.

during summers [14]. Adults are nocturnal, and most active during warm, humid evenings. The adults live for about, but lifespan ranges between 7 to 21 days [14].

Presently, there are two major strains of FAW known in both the native and invasive range [16, 17]. These are the ‘corn’ (C strain) and the ‘rice’ (R strain) strains, which are defined by the host where they develop. The corn strain attacks corn/maize, sorghum and cottons, while the rice strain attacks grasses, like rice, silk grass and some forage grasses. The two strains are morphologically identical but differ in genetics, physiology and behavioral characteristics, such as mating and resistance to insecticides [18]. Both strains are present on the African continent [17]. In addition to these strains, there exist mutant strains with resistance to different insecticide classes in both the Americas [19–21] and Africa [22, 23].

4. Host plants, damage and losses caused in maize

The FAW is a polyphagous pest reported to feed on at least 353 crop and non-crop species from 76 plant families [24], with a high preference for the Gramineae family [25]. Farmed grasses like maize, rice, sugarcane, and sorghum are recorded as major hosts whereas dicotyledonous vegetables and cotton are documented as minor hosts [26]. The number of hosts is likely to increase as this pest expands into newer areas [27–29]. Although it is polyphagous, FAW prefers to feed on maize causing substantial yield loss in SSA [2].

The larvae damage plant leaves, stems, branches, and reproductive organs, such as flowers and fruits. The damage by first instar larvae on grasses such as maize appear as silvery patches called the “windowpanes” because one side of the leaf is eaten, leaving the opposite epidermal layer intact. Damage by the third and fourth instar larvae is more pronounced with holes appearing on the edges going inwards and the characteristic row of perforations due to feeding on the whorl of the growing plants are visible. The larvae also migrate from the leaves to the tassels and the developing ears/grains leading to grain yield losses and exposing the grains to mycotoxin contamination (**Figure 2**). Commonly observed in maize is reduced plant stand in young crops and defoliation of older plants [30].

The losses associated with FAW vary with factors such as host species, varieties, environmental conditions, and socio-economic factors. In maize, FAW infestation



Figure 2.
Symptoms of maize foliage damage. And inset damage to a cob at maturity.

starts from the seedling stage till the reproductive stages (**Figure 2**), causing quantitative and qualitative grain losses. The qualitative losses involve contamination with aflatoxins and fumonisins [31]. In Africa, maize losses were estimated to be 8.3 to 20.6 million tons, causing annual losses of US\$2,481–6,187 million [2]. Yield losses in selected African countries are shown in **Table 1**.

Beside the direct effects on yields, FAW infestation may result in significant expenditures on insecticides for both the farmers and governments, and detrimental effects of residual chemicals on human health and the environment [4, 32]. The reduced yields may affect other value chain actors such as livestock farmers who may suffer reduced quantities and quality of maize stover, maize-based food processors who may suffer reduced volumes leading to reduced trade.

Country	Percentage yield losses (%)	References
Benin	42.8 – 59.5	[32, 33]
Ethiopia	11.9	[4]
Ghana	0-40	[34]
Kenya	32-34	[4]
South Africa	26.5 – 56.8	[35]
Tanzania	10.8	[36]
Uganda	0 - 50	Otim et al, unpublished
Zambia	0-50	[34, 37, 38]
Zimbabwe	11.57	[39]

Table 1.
Yield losses caused by FAW in selected countries in sub-Saharan Africa

5. FAW surveillance, monitoring and field assessments

Surveillance at the farm level is an informal and passive way of detecting pest problems as they emerge [33]. Monitoring on the other hand is an exercise that actively tracks the presence and movement of a pest within a given area [33] and is often organized and implemented at various scales, mostly by governments, through trained technical personnel who collect data according to prescribed sampling protocols. Data collected is used to make decision on management of the pest.

In 2019, FAO and CABI advocated for FAW monitoring using commercial pheromone lures and traps to give advance warning to farmers at the beginning of the maize cropping season. To promote harmonization of data collection and reporting procedures as well as foster collaboration among regional member countries, FAO developed a Fall Armyworm Monitoring and Early Warning System (FAMEWS) mobile application tool which requires users to input both field scouting and pheromone trap data [13]. The application tool also helps farmers to correctly identify FAW while providing them with off-line, free control advice delivered via satellites [34].

In addition to FAMEWS, FAO and Pennsylvania State University jointly developed and launched an innovative talking mobile app called *Nuru* (Swahili for “light”) in several African countries [13]. *Nuru* is an innovative talking app that uses cutting-edge technologies involving machine learning and artificial intelligence. *Nuru* helps farmers recognize FAW and take immediate measures to destroy it. It runs inside a standard Android phone and can also work offline. *Nuru* is embedded

in the *PlantVillage* app, which is a free app built by FAO, CGIAR and other public institutions at Pennsylvania State University and is proposed to be linked into FAO's FAMEWS app. This platform analyses data from all submitting countries across Africa and generates real-time maps giving an overview of the FAW infestations, severities and the measures applied to reduce its impact.

Monitoring of adult FAW using sex pheromone traps (attractive to male moths) is informative of the presence of the pest within a location. Experiments conducted in French Guiana [35] showed that FAW pheromone trap data can be used to estimate, a week in advance, the subsequent abundance of larvae in pastures. However, the above prediction method has been found to be unreliable in crops. For example, McGrath et al. [33] observed no relationship between the number of FAW male moths caught in traps and the number of female moths laying eggs in the same locality. The foregoing can be attributed to FAW's pre-oviposition period of 3–4 days and migratory tendencies, which therefore means that populations of egg-laying moths in an area may be dominated by migrants which previously mated elsewhere. Thus, catches of male moths in traps should simply be used to estimate the presence of potential egg-laying females in the area.

FAW's lack of diapause combined with a conducive climate in most countries of SSA obviously mean that there are always some populations which do not undertake long-distance migrations as they simply shift to off-season irrigated maize. In the context of managing resistance at a national or regional level, surveillance and monitoring programs can be very useful in mapping the dispersal of insecticide resistant FAW populations. Using an appropriate mark-recapture approach as that used by Osborne et al. (e.g., [36]), it should be possible to identify the invasion zones of an insecticide-resistant FAW population arising from a known area. Guidelines on what pesticides to use or not to use in these invasion zones can be issued to curtail the further buildup of selection pressure for resistance development.

Four most used parameters in a FAW field assessments include: [1] pest incidence (% field infestation), [2] plant damage (based on a visual scoring system), [3] pest density per plant or field and [4] yield. For scoring of damage, the Davis and Williams [37] 0–9 visual rating scale is the most commonly used in sub-Saharan Africa [38–40]. However, other researchers have collected FAW damage data using modified versions of the above visual scale. For example, Caniço et al. [41] from Mozambique assessed plant damage in the field using a scale of 0–5, where 0 equals plants with no visual foliar damage, and 5 plants with more than 75% foliar damage or dead from FAW. For evaluating the effectiveness of Bt maize and insecticides for FAW control in Brazil, Burtlet et al. [42] collected damage data based on a visual scale [43] and converted the scales to percentage damages. Maize yield losses due to FAW attack have also been estimated using a variety of protocols, for example the digital imaging method [43]. Rodriguez-del-Bosque et al. [44] compared the weights of damaged kernels per cob with the weight of the same number of undamaged kernels [44]. Based on these few examples, standardization of data collection and analysis protocols is needed to enable comparison of results across regions and countries.

6. Management of the FAW

The methods advocated for controlling the FAW in Africa are agroecological/cultural, biological control, host plant resistance, transgenic approaches and chemical pesticide use [26]. Below is a review of the use of the above methods on the continent.

6.1 Agroecological management

Agroecological management is the science of applying ecological principles to enhance productivity while reducing the negative impacts on the environment [45, 46]. Successful agroecological management is based on the understanding of key principles such as complex interactions within the ecosystem and contextualized solutions to local problems [47]. Agroecological management practices to reduce FAW populations in Africa include cultural and mechanical control, intercropping, crop rotation with non-host crop, weed management and intercropping maize with the moth repellent Greenleaf desmodium (“Push”) with *Brachiaria* cv Mulato planted around the intercrop (“Pull”) [47–49].

6.1.1 Cultural and mechanical control of FAW

Cultural control methods for FAW include removal of crop residues and no-tillage. A significant reduction of FAW infestation on maize was observed in maize farms under minimum or no-tillage in Zimbabwe [43]. Minimum tillage also enhances activities of natural enemies. Among the mechanical control methods recommended for and used by smallholder farmers in Africa is squashing egg masses and hand-picking small larvae [4, 50, 51]. Farmers in different parts of Africa also resorted to applying sand, ash, or soil in the maize whorl [43, 51, 52]. However, ash, soil, and alata samina soap (made from the ash of the barks of plants that are locally harvested, such as plantain, palm tree leaves, and shea tree bark) [53] treatments were found not to be effective in reducing FAW larvae numbers or crop damage at the dosages tested, and thus did not significantly increase maize yields [53].

6.1.2 Weed manipulation

There are mixed observations about the influence of weeds on the population and damage by FAW. For example, Altieri [54] observed significantly less infestation of maize due to FAW in weedy (natural weed complex or selected weed associations) plots compared to weeded plots. Furthermore, in the weedy farm of maize, significantly greater number of FAW predators were encountered. On the contrary, in Zambia, the incidence of FAW was low in frequently weeded plots that were dominated by graminaceous spp. [43]. Bearing in mind the crop-weed competition effect, allowing weeds other than graminaceous in between maize rows and as guard rows enhances the population of natural enemies [55]. Despite the beneficial effect of weeds on the population of arthropod pests, their infestation could cause about 20–50% yield losses in maize [56]. Thus, striking a balance in keeping and removing weeds is important in ensuring high farm productivity.

6.1.3 Intercropping

Intercropping (**Figure 3**) practiced widely by smallholder farmers in sub-Saharan Africa has long been recognized as an efficient farming system providing improved resource utilization and increased productivity [57, 58]. The practice is reported to reduce pest populations and enhance the potential of their natural enemies [59, 60]. In Latin America, maize-bean intercrops reportedly reduced FAW infestation when compared to a maize monocrop [54]. Similarly, studies in Uganda and Cameroon have demonstrated that intercropping maize with beans or groundnuts significantly reduces FAW infestation and damage severity in maize (**Figure 3**) [41, 44]. In Cameroon, a maize intercrop with climbing beans resulted in higher reduction of FAW numbers, compared to bush beans [61]. In the above



Figure 3.
Maize intercropped with groundnuts and common bean in Kamuli, district, Uganda.

studies, the yield of maize in the intercrop increased by almost two-fold, compared to the monocrop. However, the effect of intercropping on grain yield was not comparable to that of synthetic pesticides where a three-fold yield increment was observed. Although further studies are required to determine the mechanism by which intercropping reduces damage caused by the FAW, barrier effect, repellent volatiles emission and enhanced natural enemy abundances are speculated to be key mechanisms [62].

6.1.4 *Planting dates of maize in intercrops and monocrops*

Early planting of companion crops in a maize cropping system seems to provide masking effect resulting in reduced FAW infestation. For example, a study where simultaneous planting of maize with beans and sequential planting where maize was planted after 20 to 30 days resulted in a significantly less FAW infestation compared to simultaneous cropping [54]. Similar observation was made in maize under push-pull technology where the perennial desmodium sprouted prior to the maize germination. It is however observed that sole maize planted early equally suffers less damage compared to late-planted maize (Otim, pers. Obsv).

6.1.5 *Conservation agriculture*

The basic principles around conservation agriculture include minimum tillage, crop rotation, and cover crop or mulching [63]. In no-tillage plots where crop residue from the previous harvest was applied as mulch, oviposition and damage by FAW was significantly lower in maize at 2 to 3 leaf stage compared to the plowed plots [64]. The masking effect of the mulch helps maize to escape the early infestation of FAW. Although the level of infestation was less, the effect of the mulch was at par with the plowed farm 20 days after planting, implying the masking effect. Findings from Zambia showed significantly less FAW infestation in maize under zero tillage followed by minimum tillage [43].

6.1.6 *Push-pull technology*

A novel agricultural technology based on cereal/legume intercropping was developed to tackle multiple problems including insect pests and weeds while augmenting soils with nutrients. The technology was developed by the International Center of Insect Physiology and Ecology (*icipe*) in collaboration with Rothamsted Research in the UK and national partners in east Africa. This technology used stimulo-deterrent diversionary tactic to repel gravid moths of cereal stemborers and FAW from maize due to the intercropped desmodium (push) while attracting them

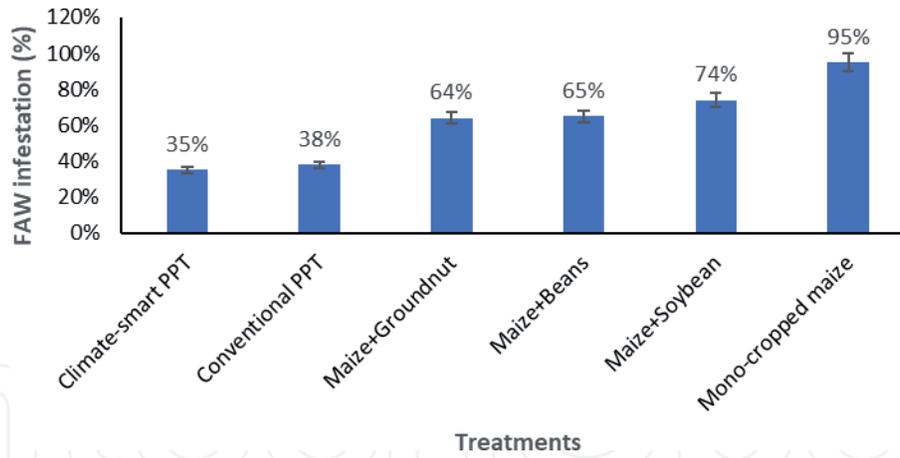


Figure 4. Percentage fall armyworm infestation of maize in a monocrop, intercroops and under the push-pull technology in Uganda [48].

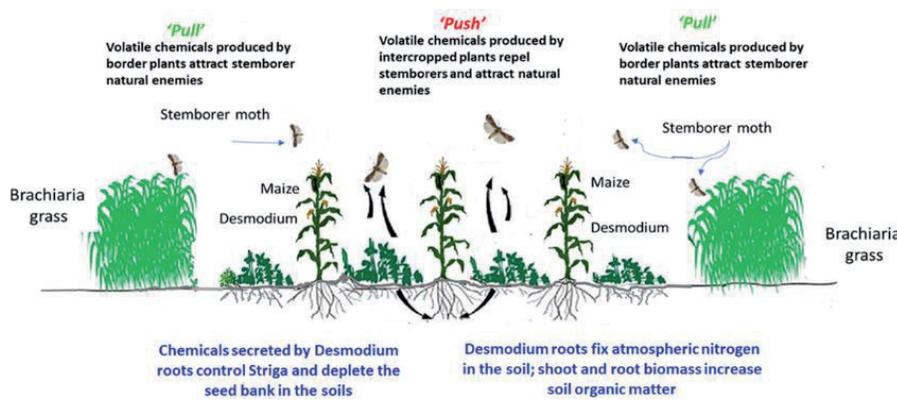


Figure 5. Climate-smart push-pull technology: Maize intercropped with repellent green leaf desmodium and Brachiaria grass as border crops.

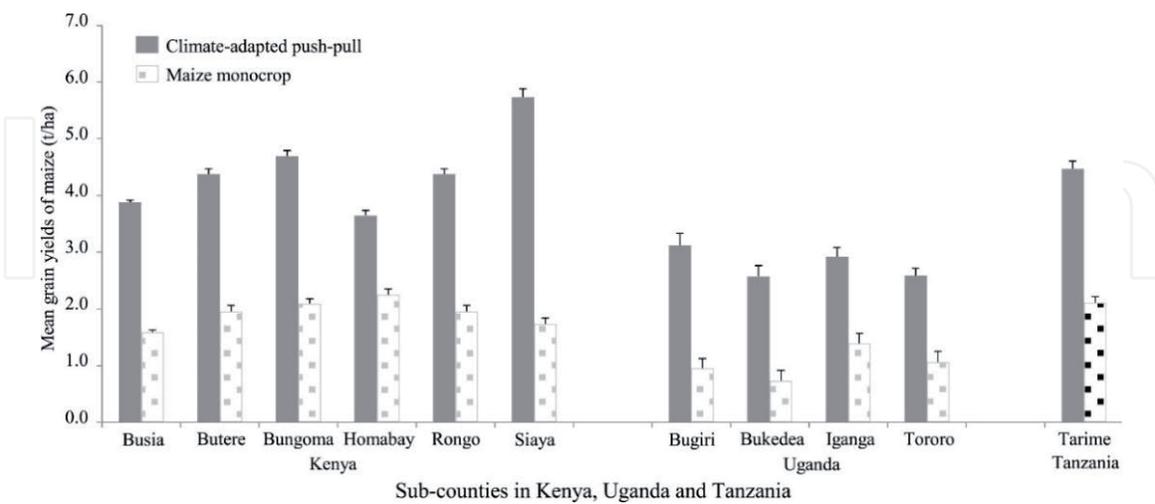


Figure 6. Mean (\pm S.E.) grain yields of maize (t/ha) planted in sole stands (maize monocrop) or in climate-adapted push-pull stands [49].

to the trap companion plants such as Brachiaria and Napier grass (pull) planted around the maize plots [65] (Figure 4). There are two types of push-pull technologies conventional (maize intercropped with silverleaf desmodium and Napier grass planted around the farm) and climate-smart a climate adapted technology where

maize is intercropped with green leaf desmodium and the plot surrounded by *Brachiaria* (Mulato II) grass (**Figure 5**) [65].

In a study conducted by Midega et al. [49] in Kenya, Uganda, and Tanzania, the team reported 82.7% and 86.7% reduction in larvae per plant and plant damage, respectively in climate-adapted push-pull compared to maize monocrop plots, and a resultant 2.7-fold higher grain yield in the climate-adapted push-pull plots (**Figure 6**). There was a similar finding in Uganda, where maize yield from climate-adapted PPT was significantly greater compared with maize intercropped with edible legumes or mono-cropped maize [48].

6.2 Biological control of FAW in Africa

Centuries of research on FAW in the Americas have recognized the importance of biological control in the management of FAW in its native range. Biological control does not only offer a sustainable solution to FAW management, but also presents an economically and environmentally safer alternative or complement to synthetic pesticides as well as a vital solution for mitigating potential pesticide resistance that is often associated with inappropriate pesticide use [19]. The key categories of natural enemies of FAW are predators, parasitoids, entomopathogens (fungi, bacteria, viruses and nematodes). In Africa, efforts are underway to identify the natural enemies of FAW, assess their impacts and harness their use in the overall management of the pest.

6.2.1 Natural enemies of FAW reported in Africa

Studies on the identification of natural enemies of the FAW in Africa have been reported from different countries including Benin, Cameroon, Cote d'Ivoire, Ethiopia, Ghana, Kenya, Mali, Mozambique, Niger, South Africa, Tanzania, and Uganda. Most of the natural enemies of FAW reported since the advent of the pest on the continent are parasitoids. These are mainly Dipterans and Hymenopterans and were found on either egg, larvae, or pupae of the pest. Highest diversity was found among larval parasitoids, and included *Anatrichus erinaceus* Loew, *Charops ater* Szépligeti, *Chelonus bifoveolatus* Szépligeti, *Coccygidium luteum* Brullé, *Cotesia icipe* Fernandez-Triana & Fiaboe, *Drino quadrizonula* Thomson, *Meteoridaea testacea* Granger, *Metopius discolor* Tosquinet, *Palexorista zonata* Curran, *Pristomerus pallidus* Kriechbaumer, and *Procerochasmas nigromaculatus* Cameron [66–72]. Other parasitoid species belonging to the Ichneumonidae (i.e. ichneumonids) and Tachinidae (i.e. tachinids) families were, however, observed in maize and sorghum fields during surveillance studies conducted between 2017 and 2018 [66]. The most promising parasitoids, judged through their widespread distribution on the continent and high parasitism rates, are the egg parasitoids: *Chelonus curvimaculatus* (Cameron), *T. remus*, *Trichogramma* sp. and *Trichogrammatoidea* sp. (both Hymenoptera: Trichogrammatidae) [66, 68, 69, 73]. The occurrence of *T. remus* for instance was reported in Benin, Cameroon, Côte d'Ivoire, Kenya, Niger and South Africa. On the other hand, species in the genus *Chelonus* that were reported to have wide geographical distribution in the Americas [74] and Australia [75], has equally been documented in some parts of Africa (Uganda, Benin, Ghana, etc). In the case of egg parasitoids parasitism of up to 64% were observed in Niger following augmentative release of *T. remus* in sorghum fields [76]. Larval parasitism is still low averaging 9.2 and 9.5% in Uganda and Mozambique, respectively [70, 72].

Few studies have paid attention to predatory species on FAW in Africa. Koffi et al. [71] recorded *Pheidole megacephala* (F.) (Hymenoptera: Formicidae), *Haematochares obscuripennis* Stål, and *Peprius nodulipes* Signoret (both Heteroptera:

Reduviidae) in Ghana. From a field survey conducted in Ghana, *Cheilomenes lunata* Fabricius (Coleoptera: Coccinellidae) and *Ropalidia fasciata* Fabricius (Hymenoptera: Vespidae) were highlighted as predators on FAW larvae, with *R. fasciata* being more recurrent from field observations [77].

Since FAW was reported in Africa, limited research reports exist on entomopathogens of FAW. Akutse et al. [78] demonstrated ovicidal and larvicidal potency of isolates from *Metarhizium anisopliae* and *B. bassiana* under laboratory conditions in Kenya. Promising efficacy of *B. thuringiensis* serotype *kurstaki* and *Pieris rapae* granulovirus based formulations in laboratory and field conditions were reported in Ghana [79]. In Tanzania, attempts have equally been made to integrate *M. anisopliae* and *B. bassiana* into diverse cropping systems for FAW management [80].

6.3 Use of botanical against fall armyworm in Africa

In Ethiopia, Sisay et al. [40] associated more than 90% larval mortality to botanical insecticides, namely *Azadirachta indica* Juss, *Schinus mole* L. and *Phytolacca dodecandra* L'Her under greenhouse conditions.

The ever-increasing diversity of natural enemies being reported across the continent calls for an intensification in the search for local natural enemies coupled with their conservation and mass rearing for conservative and augmentative biological control programs. Priority should be given to this approach over classical biological control and more efforts are required across the continent for prospection for natural enemies, rearing, performance assessment, mass production and release. Efficacy trials are being conducted in various countries for botanicals and biopesticides. Critical aspect hindering their adoption might be the comparatively higher costs compared to chemical pesticides. Thus, strong advocacy activities are required to engage policy makers in establishing conducive environment for wider use of biological control products over chemical pesticides.

6.4 Host plant resistance for managing fall armyworm

Host plant resistance (HPR) is a cornerstone for any pest management strategy. The use of insect-resistant crop varieties as a component of IPM arises from the ecological compatibility and compatibility with other direct control tactics [81]. HPR works in synergy with biological, cultural, chemical and agroecological practices and works with synergy [82]. HPR is very specific to the target pest or group of pests and does not affect the non-target organisms. HPR is also very persistent throughout the cropping season. The quantitative or polygenic nature of native genetic resistance also offers the opportunity to minimize selection pressure on FAW and prevents emergence of new resistant strains. Moreover, HPR does not involve any additional cost to the farming community the farmers do not need any training and the scaling up will be easily adopted in the farming community in Africa.

The FAW, an invasive pest which recently invaded Africa has evolved with wild maize and later with domesticated maize in Latin America. It is expected therefore that these constant interactions resulted in some degree of genetic adaptation. The genetic resistance to FAW in some plants including maize was available since 1990's [83]. The United States Department of Agriculture (USDA) Agricultural Research Service (USDA-ARS, Mississippi) developed and released a series of maize inbred lines with resistance to FAW including Mp496, Mp701–708, Mp713, Mp714, and Mp716 [81, 84–89], derived primarily from germplasm held by the International Maize and Wheat Improvement Center (CIMMYT, Mexico). CIMMYT developed populations from tropical and subtropical maize inbred lines, CML59–74 and CML121–127, from USDA-ARS germplasm, with FAW resistance [90].

Since the invasion of FAW in Africa, intensive and precise screening of maize germplasm against FAW under artificial infestation by CIMMYT has been ongoing in Kiboko, Kenya [91]. The germplasm screened include CIMMYT Multiple Borer Resistance (MBR) and Multiple Insect Resistance Tropical (MIRT), germplasm developed during Insect Resistant Maize for Africa (IRMA) project, USDA Mississippi germplasm and subtropical elite germplasm. CIMMYT scientists have developed within two years several inbred lines and more than 200 single cross hybrids. The first generation of FAW hybrids were announced on the 23rd of December 2020 [92], including three FAW tolerant hybrids (FAWTH2001–2003), which passed the test of screening in the screenhouse, and later under natural infestation in both on station and on farm fields. The next step will be the national performance trials, variety release and registration by private sector (seed company) for the deployment in target geography in eastern and southern Africa. The same exercise is being done by IITA in West Africa to develop FAW maize resistant varieties and in Southern Africa by ICRISAT on sorghum. A lot of NARs in sub-Saharan Africa (especially in Uganda, Malawi) have also initiated germplasm screening to identify tolerant/resistance materials.

6.5 Transgenic approach to control FAW in Africa

The first transgenic Bt plants were introduced on the market in 1996 [93], whilst the first Bt maize for FAW control was introduced in the USA and Puerto Rico in 2013 [94]. On the continent, Bt maize is currently commercially available only in South Africa, where regulatory authorities have overseen multiple approvals, with more than 20 years of deployment of such products. The MON810 event, which has been cultivated in South Africa since 1997 for the stem borer control, also confers partial resistance (50%) to FAW while the MON89034 event which has demonstrated efficacy for control of both FAW and stem borers has been cultivated in South Africa since 2010 [95]. MON89034 is recommended for FAW control due to its high efficacy against the pest. The Water Efficient Maize for Africa (WEMA) project now TELA which is operating in 8 countries namely South Africa, Mozambique, Tanzania, Uganda, Kenya, Ethiopia, and Nigeria is to test and deploy the transgenic maize in Africa. Although Genetic engineering would provide an additional intervention that other countries struggling with FAW can explore alongside other integrated pest management practices, there are still contentions on the safety and sustainability of control using Bt maize. Many African countries also lack the legal frameworks for research on and deployment of Genetically Modified Organisms.

6.6 Chemical control of the fall armyworm

Chemical control is one of the key methods for controlling FAW in the Americas and Africa [91]. Initial efforts to control FAW in Africa using chemicals relied on recommendations of effective pesticides from the Americas, leading to the purchase, distribution and application of several synthetic pesticides in many countries. Consequently, many maize farmers have adopted the use of pesticides, a practice that was rare before the advent of FAW. In this section, we review information on the use of chemical pesticides to control the FAW in selected countries on the continent as it is difficult to obtain country-specific information.

A variety of synthetic pesticides have been registered and recommended for control of FAW in different African countries. These include Carbamates, Organophosphates, Ryanodine Receptor modulators, Avermectins, Spinosyns, Oxadiazines, Nereistoxin and Pyrethroids (**Table 2**). Among the above, Pyrethroids

Pesticide class	IRAC Group	WHO classification	Active ingredient(s)	Country of registration	Pesticide brand examples
Avermectins	6	II	Abamectin + Emamectin	Uganda [104]	Amdocs
			Abamectin	Malawi [105]	Snowmectin 1.6 EC , Antario
		IIV	Emamectin benzoate	Uganda [104]	Chlobenzo, Prove (EC), Dynamo (WG)
				South Africa [106]	Emma, Proclaim, Promec 20EW, etc.
				Zambia [107]	Prove (EC), Denim Fit 50WG
Benzoylureas	15	II	Lufenuron	South Africa [106]	Judge, Sorba
				Kenya [108]	Heritage 5%, Legacy, Match
		Diflubenzuron	South Africa [106]	Dimilin 25 WP, Dimilin 48 SC	
Carbamate	1A	IB	Methomyl	South Africa [106]	Spitfire 900 SP, Cyplamyl 90 SP, Masta 900 SP
		II	Carbosulfan	South Africa [106]	Marshal 48 EC
			Kenya [108]	Marshall 250EC	
	14		Cartap hydrochloride	South Africa [106]	Ag-Tap 500 SP
Organophosphates	1B	II	Chlorpyrifos	South Africa [106]	Avi Klorpirifos, Agropyrifos, Pyrinex 480 EC
				Malawi [105]	Chlorpyrifos 480 EC
			Profenofos	Malawi [105]	Snoweron 500 EC
		III	Mercaptothion + Malathion	South Africa [106]	Avi-Merkaptothion DP
			Acephate	Kenya [108]	Lotus 75% SP, Ortran 97, Orthene pellet
Oxadiazine	22A	II	Indoxacarb	South Africa [106]	Doxstar Flo, Advance, Steward, Addition
				Malawi [105]	Steward 150 EC
				Kenya [108]	Merit 150 SC, Avaunt150 SC
				Zambia [107]	Devacarb
				Sudan [109]	Vaulent 150S C

Pesticide class	IRAC Group	WHO classification	Active ingredient(s)	Country of registration	Pesticide brand examples	
Pyrethroids	3A	II	Beta- cypermethrin	South Africa [106]	Akito	
			Alpha- cypermethrin	Kenya [107]	Bestox 20 EC, Navigator 100 EC	
			Deltamethrin	Malawi [105] Zambia [107]	Decis Forte, Deltanex 25 EC, Deltmax 25 EC Decis, Decitab	
	28	III	Lambda-Cyhalothrin	Kenya [107]	Duduthrin Karate	
	3A		Teflubenzuron+Cypermethrin	Malawi [105]	WormAtak EC	
			Gamma- cyhalothrin	Kenya [108]	Vantex 60 CS	
Ryanodine Receptor Modulators	28	III	Flubendiamide	South Africa [106] Malawi [105] Kenya [108]	Belt 480 SC Belt 480 SC Belt 480 SC	
		U	Chlorantraniliprole	South Africa [106] Kenya [108]	Coragen 20 SC, Prevathon, Mythic FN SC Coragen 20 SC	
		5A	U	Spinetoram	South Africa [106]	Delegate 250 WG
					Kenya [108]	Radiant 120 SC
Nereistoxin analogue	14	U	Cartap hydrochloride	South Africa [106]	Ag-Tap 500	
Combinations of pesticide classes						
Avermectin+Diamide	6 and 28	II	Abamectin+Chlorantraniliprole	Kenya [108]	Voliam Targo 063	
Benzoylureas+Avermectin	15 and 6	III	Lufenuron+Emamectin benzoate	South Africa [106]	Denim Fit	
				Malawi [105]	Proclaim Fit	
				Sudan [109]	Denim Fit 50%	

Pesticide class	IRAC Group	WHO classification	Active ingredient(s)	Country of registration	Pesticide brand examples
Benzoylureas+Oxadiazine	15 and 22A	U	Novaluron+Indoxacarb	South Africa [106]	Plemax
Carbamate+Pyrethroids	1A and 3A	-	Benfuracarb+fenvalerate	South Africa [106]	Oncol Super 220 EC
Organophosphates+Pyrethroids	1B and 3A	II	Profenofos+Cypermethrin	Uganda [104]	Roket, Agro-Cypro, Supa Profenofos, Hitcell
			Pirimiphos methyl+Deltamethrin	Malawi [105]	Ecotex 0.5 GR
				Zimbabwe [110]	Ecotex 0.5 GR
			Cypermethrin+Chlorpyrifos	South Africa [106]	Cyferfos 500 EC
			Zambia [107]	Cyclone 505 EC	
Pyrethroids+Neonicotinoids	3A and 4A	III	Lambda Cyhalothrin+Thiamethoxam	Uganda [104]	Striker, Engeo
Diamide+Neonicotinoid	28 and 4A	-	Chlorantraniliprole+Thiamethoxam	Zambia [107]	Fortenza DuoA
				Zimbabwe [110]	
Diamide+pyrethroid	28 and 3A	-	Chlorantraniliprole+Lambda cyhalothrin	South Africa [106]	Ampligo
				Zambia [107]	
Spinosyn+Benzoylureas	5 and 18		Spinetoram+methoxyfenozide	South Africa [106]	Uphold 360 SC
Spinosyns+Diamide	5 and 28	U	Spinetoram 75+Flubendiamide 100	Sudan [109]	Belt extra 175 OD
Biopesticides					
Microbial disruptors of insect midgut membrane	II	U	<i>Bacillus thuringiensis</i>	South Africa [106]	Delfin, Florbac WG
			<i>Beauveria bassiana</i>	South Africa [106]	Eco-Bb

Table 2.
Selected chemical pesticides registered for control of the Fall armyworm in Africa.

and Organophosphates are the most used (**Table 2**), followed by Avermectins, perhaps because of their availability and lower prices. Combination of different classes of pesticides are also on the market (**Table 2**). The combinations help increase the effectiveness, target spectrum, and reduce the speed with which pesticide resistance can develop. Pesticides shown in **Table 2** below are approved and recommended by the respective African governments to control FAW. To date, several African countries do not have an official register for approved pesticides for control of the FAW. This may be in part due to the failure to test chemical pesticides for their efficacy. Nonetheless, we provide a review of research efforts towards use of chemical pesticides to control the FAW in Africa.

The rapid adoption of pesticides by farmers in Africa was mostly due to the distribution of free pesticides by the governments. Free distribution proved ineffective in most countries because;

1. Distribution was not matched with adequate training of farmers on proper pesticide usage.
2. Most of the distributed pesticides were not effective as they were never evaluated to determine the suitable application rates for the different agroecologies within the continent [2, 40]. This resulted in indiscriminate spraying by farmers.
3. Farmers' negative perceptions on use of pesticides because they believe the latter are not effective in controlling the FAW [51, 96, 97].
4. Recommendations by governments of cheap chemical pesticides known to have developed resistance to FAW elsewhere. For example, Organophosphates and Pyrethroids-Pyrethrins pesticides to which FAW is reported to have developed resistance in the Americas (Prassana, 2018; Day et al., 2017; Yu, 1992; Yu, 1991; Yu, 1982; Giraud et al., 2015; Flagel et al., 2018). The above has resulted in indiscriminate application of pesticides by farmers causing fears of likely resistance development in the near future [43, 51]. Although, there are no reports of development of pesticide resistance in FAW in Africa, there is evidence of samples of the pest from Kenya, Malawi and Uganda possessing mutations associated with resistance to organophosphates and carbamates [22, 23].
5. Furthermore, effectiveness of pesticide use in Africa is hindered because many of the countries in Africa lack listings of registered (government approved) pesticides for control of the FAW [91].

7. The future FAW management in Africa

The current invasion of the fall armyworm (FAW) in sub-Saharan Africa (SSA) and other parts of the world threatens food and nutrition security of many nations, and also poses challenges in the attainment of a number sustainable development goals (SDGs) including SDGs: 1 (no poverty), 2 (zero hunger), 3 (good health and wellbeing, 8 (decent work and economic growth) and 12 (protecting life on earth). Without sustainable management of this invasive pest, farmers' efforts in increasing cereal productivity, most especially smallholder farmers in nations that rely on maize as a staple crop, will be futile. The previous sections provided detailed information on the biology and ecology of the FAW, and current management practices for curtailing damage and associated yield losses [98–103]. Like most invasive insect pests,

FAW management across the continent, has relied primarily on the use of pesticides and cultural interventions, but with minimal efforts on an IPM approach. In view of the pest status, threat posed to food and nutrition security, and the grave health and environmental footprints of indiscriminate use of pesticides, the need to formulate effective and sustainable management approaches is dire. This calls for formulation of an effective Pest Management Plan (PMP) at the national and regional levels. The plan should consider International Plant Protection Convention (IPPC) policies, the Pesticides and Toxic Substances Regulations, the Plant Pests and Diseases Regulatory Acts and, Environmental and Social Management Frameworks (ESMF). The components of such a plan may include: i) periodic scouting and review of FAW damage and impact to cereal productivity, ii) identification of interactions between FAW and other cereal insect pests belonging to the same family and consequential impact on productivity, iii) exploration of alternative ways of FAW management, with emphasis on environmentally friendly and socially acceptable approaches, and iv) identification of concerns related to pesticide use and recommendation of measures for enhanced public and occupational health and safety.

7.1 Interventions for sustainable management of fall armyworm in Africa

In planning for effective FAW management in the future, the following should be considered at national or regional levels;

7.1.1 Research

Sufficient knowledge or data is a prerequisite for developing any sound action plan and management decision. According to FAO (2016), institutional capacity, effective policies and an enabling environment are key ingredients for the transformation and growth of the agricultural sector in the face of climate change. A lot of effort has been put in understanding the ecology of FAW and possible management practices, but much remains to be done. Equally important is the need to understand FAW behavior in the face of climate change. Thus, future FAW management will require generation of data that can be used for developing predictive models for determining future hotspots/outbreaks and decision-making. Addressing issues of pesticide resistance, will require proper planning, implementation of research activities, monitoring and evaluation, safeguards compliance, and regional engagement.

7.1.2 Collation and dissemination of research outputs

In addition to research, future FAW management should focus on effective dissemination of proven technologies, while leveraging on existing dissemination systems such as extension services of the Ministries of Agriculture and mass communication channels. Regional and/or continental exchange of information, knowledge and technologies will be key to managing this transboundary pest. Currently, however, the national dissemination systems in most African countries are not only weakened by poor research-extension linkages, but by low human capacity; lack of information and communication materials on recommended technologies; lack of harmonization of information packaging; inappropriate packaging of extension messages; limited use of mass communication channels; and inadequate training. Incorporating unique and modern approaches to transfer knowledge across the value chains, e.g., using training of trainers (TOT) approach, use of videos on social media platforms, radios, promoting strategic dialog and/or effective communication for knowledge transfer will play a critical role in sustainable management of FAW.

7.1.3 Capacity building

Currently, most scientists, extension officers and farmers lack knowledge on pest identification, economic impact assessment and management strategies. Capacity building interventions through scientific short and/or long-term trainings, as well as upgrade of research infrastructure (e.g., functional laboratories, greenhouses, containment facilities that can handle GMO materials) and information technology and knowledge management system are required to address the knowledge gaps for sustainable management of FAW on the continent. At grass-root level, hands-on trainings on FAW scouting, identification, safe use of pesticides and ecologically based integrated pest management strategies should be implemented through farmers' field schools. Furthermore, government bodies like the Environmental Management Agencies, Agrochemical Associations, etc.) in different countries should take an active role in building the capacity of extension officers and farmers on good pesticide use and putting in place an effective monitoring system to ensure that only registered pesticides are being distributed to farmers, and that the formulations are maintained in their registered state (without re-formulation).

7.1.4 Enhanced coordination of stakeholders

Across the continent, the response to FAW outbreak by key actors (e.g., national governments, research scientists and regional bodies like FAO) was loosely coordinated. Moving forwards, regional and national government leaders should focus on ensuring that all essential FAW task forces and management coordination functions are effectively carried out.

7.1.5 Effective policy implementation

In most sub-Saharan Africa (SSA) countries, agricultural policies put emphasis on agricultural productivity, with the promotion of pesticide use to address the perennial low productivity placed among top pest management intervention strategies. Legislations on management of Plant Pests and Diseases that is often enforced by the Phyto-sanitary Services Department under the Ministry of Agriculture and The Pesticides and Toxic Substances Regulations (PTSR) do exist across the continent. Unfortunately, issues of improper and unsafe use of chemicals due to inadequate enforcement of regulations and lack of compliance to safety measures pose a serious threat to the ecosystem. Therefore, through the participation of key players (i.e., right institutional structures, systems and set of skilled personnel), the implementation of effective and targeted regulatory policies for improving agricultural sector, e.g., those that support subsidies, grants and tax credits, risk mitigation, market access, purchase of surplus produce from farmers must be strengthened, and applied in future FAW management plans.

While the African Union, through her Comprehensive African Agricultural Development Program has formulated strategies to improve agricultural productivity at regional level, FAW management plans are currently embedded within national agricultural and food security strategic plans but not at regional level. Thus, attempts to transform the African agriculture sector should focus on preparedness to respond to pest threats, specifically invasive transboundary pests like FAW and migratory locusts that the continent has witnessed recently. Such a preparedness plan should include, but not be limited to i) investments in proper policies, pest and disease management, extension and infrastructure, and ii) effective coordination of available resources for pest and disease management.

Addressing the FAW constraint in sub-Saharan Africa requires policy dialog and policy harmonization on key areas that affect the management of the pest at national and regional levels. For instance, issues of IPs/patents for new technologies, harmonization and operationalization of the pesticide regulatory system, implementation of biosafety regulations, etc. should be addressed at the regional level. Approved pesticides for FAW control at regional and national levels must comply with guidelines of the International Plant Protection Convention (IPPC) on Phytosanitary Measures for pest surveillance, risk identification, reporting and management and complement the recently published IPPC Guide to Pest Risk Communication. Equally such harmonized policies should support other global voices, such as The Stockholm and the Rotterdam Conventions that advocate for use of non-Persistent Organic Compounds (POPs), the Pesticide Action Network (PAN) and the Sustainable Agriculture Network (SAN). For example, the Pesticide and Toxic Substance Regulations, which advocates for using pesticides with: i) negligible adverse effects on humans and domestic animals in the treated areas; ii) effectiveness against the target species; iii) minimal effects on non-target species, especially damage to natural enemies, and the environment in general; iv) avoidance of pesticide resistance and resurgence, should be borne in mind during such policy dialogs and harmonization.

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