FEED THE FUTURE
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Fall Armyworm in Africa:

A GUIDE FOR INTEGRATED PEST MANAGEMENT

First Edition

USAID
FROM THE AMERICAN PEOPLE

CIMMYT
International Maize and Wheat Improvement Center

CGIAR
RESEARCH PROGRAM ON Maize

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Editors

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CIMMYT International Maize and Wheat Improvement Center

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in collaboration with international and national research and development partners

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Preface

The world has seen significant progress in the fight against hunger, undernutrition and extreme poverty, although a lot still remains to be done. At the same time, the emergence and rapid spread of the fall armyworm (FAW; *Spodoptera frugiperda*) in Africa seriously threatens the food and income security of millions of smallholder farmers. Given what we know about the pest's behavior in the Americas and from the early experiences in Africa, shared commitments to reduce poverty and hunger – as expressed by the Sustainable Development Goals, the African Union's Malabo Declaration and G7 – may be difficult to achieve without concerted and intensive actions at all levels. Within a short span of its introduction in Africa, FAW has been confirmed in over 30 African countries and it is likely to become endemic in many. Its major preference for maize, a staple food for over 300 million African smallholder farm families, poses a threat to food security, nutrition and livelihoods.

Given the enormity of the challenge, an effective response requires coordinated action from the broadest possible community – African governments, international and national research institutions, donors, the private sector and civil society. An important foundation for this action must be an understanding of FAW behavior and the management practices that can help smallholder farmers effectively control the pest without damaging human and animal health and the environment. To this end, we convened experts from Africa and around the world in Entebbe, Uganda (Sept 16-17, 2017) to review and identify management options for control of FAW in Africa within an Integrated Pest Management (IPM) framework.

This publication, titled *Fall Armyworm in Africa: A Guide to Integrated Pest Management,* is the result of contributions of dozens of institutions and individuals, to whom we express our deep appreciation. This learning community consisted of experts and practitioners from international and national research and development institutions with extensive experience in pest biology; pest scouting, monitoring and surveillance; biological control; host plant resistance; pesticide risk management; agronomic and landscape management; and IPM strategies. To address the rapid spread of FAW in Africa, we have worked intensively to quickly review and highlight scientifically proven management practices that could be relevant for African farmers, especially smallholders. We intend to revise and release subsequent editions of this FAW IPM Guide, updating the scientific knowledge, management practices, protocols and research findings, as more evidence with regard to efficacy of various FAW management options in Africa emerges.

Our approach to the development of this publication is guided by the Rome Principles developed by leaders at the 2009 World Summit on Food Security to guide urgent action to eradicate hunger. In particular, we seek to work in partnership to:

- Ensure that scientific evidence and knowledge guides recommendations on FAW management practices and policies.
- Foster strategic coordination to align the knowledge, experience and resources of diverse partners, avoid duplication of effort and identify implementation gaps.
- Support country-level engagement and ownership of approaches to ensure assistance is tailored to the needs of individual countries and built on consultation with all key stakeholders.
- Commit to building capacity, focusing on integrated actions addressing policies, institutions and people, with a special emphasis on smallholders and women farmers.

Scope of this FAW IPM Guide

This FAW IPM Guide is designed for use by professionals in plant protection organizations, extension agencies, research institutions, and Governments, whose primary focus is smallholder farmers and the seed systems that support them. The FAW IPM Guide is meant to provide an important foundation for the emergence of harmonized FAW pest management protocols that will continue to be informed by research. The guide is also expected to serve as the basis for a series of cascading technical knowledge dissemination materials and social and behavioral change communications that will specifically target the needs of the smallholder farmers in Africa.

The demand for this FAW IPM Guide is high. Therefore, this first edition is meant to provide practitioners with the IPM foundation to successfully manage FAW in Africa. This includes chapters on FAW Pest Biology and Integrated Pest Management, Host Plant Resistance, Biocontrol, and Agroecological Landscape Management. Importantly, the guide provides protocols for Monitoring and Scouting for FAW in maize fields to assess the level of damage due to the pest and to suggest when interventions are warranted. Because the primary technical intervention, at least in the immediate term, is likely to be treatment with synthetic pesticides, a chapter is included on Pesticide Hazard and Risk Assessment and Compatibility with IPM.

We recognize that some important topics are still in development and may be provided by other avenues in the short term. For example, we do not make specific pesticide recommendations, per se. The use of a particular pesticide is regulated at the country level and therefore varies by jurisdiction. Country recommendations and label directions must be followed when using pesticides. We do, however, provide generic information on what types of chemical pesticides should be avoided, what could be environmentally safer, and how best to assess pesticide hazards and risks. Further, we have not included information on pesticide application since, in many jurisdictions, pesticide applicator training may be a government-regulated activity. Still, our goal for the second edition of the FAW IPM Guide will be to provide a basic outline of that information. In the interim, we have provided guidance from CropLife International, which may prove useful.

Readers of the FAW IPM Guide are encouraged to identify and combine appropriate options from each of the chapters, applying or adapting them as necessary in their local context, in order to develop effective, locally appropriate IPM strategies against FAW. While some chapters in the FAW IPM Guide (*e.g.*, Chapter 2 on FAW Monitoring and Scouting) contain immediately actionable guidance, others (*e.g.*, Chapter 4 on Host Plant Resistance; Chapter 5 on Biological Control and Biorational Pesticides) are aimed primarily for the research community, providing relevant tools and protocols to identify and develop appropriate technologies.

This FAW IPM Guide is intended as a living document, to be updated regularly. While the information compiled in the first edition provides an initial basis for practical decision-making and strategic planning, future editions will reflect the rapidly evolving African experience with FAW, and provide opportunities to expand and refine local IPM approaches in light of new knowledge and tools.

Acknowledgements

This publication on *Fall Armyworm in Africa: A Guide for Integrated Pest Management* is intended as a comprehensive, expert-approved, IPM-based technical guide that can be used as an up-to-date decision support tool for sustainable management of the pest, especially in maize-based cropping systems. Development of such a manual was identified as one of the high-priority interventions by an action plan that emerged out of the Stakeholders Consultation Workshop on Fall Armyworm, organized jointly by CIMMYT, the Alliance for Green Revolution in Africa (AGRA), and Food and Agriculture Organization of the United Nations (FAO), in Nairobi, Kenya (April 27-28, 2017).

CIMMYT, as the main implementing partner, sincerely acknowledges the funding support received from U.S. Agency for International Development (USAID), under the Feed the Future initiative and from the USAID Office of U.S. Foreign Disaster Assistance, to make this publication possible.

This FAW IPM Guide was the result of the contributions of several institutions and individuals. The "seed" for this publication was first sown in a highly productive workshop on "Developing Fall Armyworm Pest Management Field Manual for Africa" (September 16-17, 2017) in Entebbe, Uganda (Appendix 1). The workshop, organized jointly by USAID and CIMMYT, in partnership with FAO, included 60 experts from various international and national research and development partners, as listed below (in alphabetical order): Alliance for Green Revolution in Africa (AGRA); African Union – InterAfrican Phytosanitary Council (AU-IAPSC); Bayer; Brazilian Agricultural Research Corporation (Embrapa); Centre for Agriculture and Biosciences International (CABI); Catholic Relief Services (CRS); Crop Biosciences Ltd; Desert Locust Control Organization-East Africa (DLCO-EA), Ethiopia; FAO; Famine Early Warning Systems Network (FEWS NET); International Center for Insect Physiology and Ecology (ICIPE); International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); International Institute on Tropical Agriculture (IITA); International Maize and Wheat Improvement Center (CIMMYT); Julius Kuhn Institut, Germany; Kenya Agriculture and Livestock Research Organization (KALRO), Kenya; Leibniz Institute, Germany; Ministry of Agriculture, Animal Industry and Fisheries, Government of Uganda; National Agricultural Research Organization (NARO), Uganda; North-West University, South Africa; National Plant Protection Organization (NPPO), Ghana; National Plant Protection Organization (NPPO), Malawi; National Plant Protection Organization (NPPO), the Netherlands; National Plant Protection Organization (NPPO), Nigeria; Oregon State University, USA; Syngenta; University of Florida, USA; University of Lomé, Togo; University of Zimbabwe, Zimbabwe; USAID; United States Department of Agriculture (USDA)-Agricultural Research Service (ARS); Virginia Tech, USA; Zambia Agricultural Research Institute (ZARI), Zambia.

We would like to specially acknowledge the support received from the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) for sponsoring participants from the Leibniz Institute, Julius Kuhn Institut, and the Dutch NPPO, for the Entebbe Workshop.

While developing this FAW IPM Guide, the authors took into account relevant lessons from dealing with FAW in the Americas, recognizing on one hand the inherent differences in the American and African farming contexts and landscapes, and the possible commonalities when it comes to preventive and curative interventions against transboundary pests, including surveillance, monitoring, forecasting and control interventions on the other.

The content of various Chapters in this publication was further refined through collective inputs and interaction with the participants of two Regional Training and Awareness Generation Workshops on Fall Armyworm Management, organized in Harare, Zimbabwe (October 30-November 1, 2017; Appendix 2), and Addis Ababa, Ethiopia (November 13-15, 2017; Appendix 3). Experts in the respective fields also critically reviewed the content of each of the Chapters.

We sincerely thank Tracy Powell for her timely and invaluable editing support, and the CIMMYT Corporate Communications team, especially Gerardo Mejía Enciso, Clyde Beaver, and Genevieve Renard, for kind support in formatting and designing the publication.

List of Acronyms & Abbreviations

AAW	African Armyworm
AGRA	Alliance for Green Revolution in Africa
ARC-RSA	Agricultural Research Council - Republic of South Africa
ARS	Agricultural Research Service
AU-IAPSC	African Union – InterAfrican Phytosanitary Council
BFS	Bureau for Food Security
Bt	*Bacillus thuringiensis*
CA	Conservation Agriculture
CABI	Centre for Agriculture and Biosciences International
CBG	Centre for Biodiversity Genomics
CFTs	Confined Field Trials
CGIAR	Consultative Group for International Agricultural Research
CIMMYT	International Maize and Wheat Improvement Center
cm	centimeter
CML	CIMMYT Maize Line
CNFA	Cultivating New Frontiers in Agriculture
CRS	Catholic Relief Service
Cry	Crystal protein gene
DCA	Dan Church Aid
DLCO-EA	Desert Locust Control Organization-East Africa
DR & SS	Department of Research & Specialists Services
DT	Drought Tolerance
EIAR	Ethiopian Institute of Agricultural Research
EIL	Economic Injury Level
ELISA	Enzyme Linked Immunosorbent Assay
Embrapa	Brazilian Agricultural Research Corporation
EPF	Entomopathogenic Fungi
EPN	Entomopathogenic Nematodes
ET	Economic Threshold
FAO	Food and Agriculture Organization of the United Nations
FAW	Fall Armyworm
FEWS NET	Famine Early Warning Systems Network
FtF	Feed the Future
GEEL	Growth, Enterprise, Employment and Livelihoods program
GEM	Germplasm Enhancement of Maize
GHS	Globally Harmonized System on Classification and Labeling of Chemicals
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GM	Genetically Modified
HHP	Highly Hazardous Pesticide
HPR	Host Plant Resistance
HQ	Hazard Quotient
ICIPE	International Center of Insect Physiology and Ecology
IFAS	Institute of Food and Agricultural Sciences (University of Florida)
IGR	Insect Growth Regulating
IITA	International Institute of Tropical Agriculture
INRA	Institut National de la Recherche Agronomique
IPM	Integrated Pest Management
IPPC	Integrated Plant Protection Center

IRM	Insect Resistance Management
ISABU	Institut des Sciences Agronomiques du Burundi
ISRA	Institut Sénégalais de Recherches Agricoles
JMPM	Joint Meeting on Pesticide Management
KALRO	Kenya Agriculture and Livestock Research Organization
KAVES	Kenya Agricultural Value Chain Enterprises
KEPHIS	Kenya Plant health inspectorate Service
km	kilometer
L	litre
m	minute
MIRT	Multiple Insect Resistance Tropical
mm	millimeter
MOA	Mode of Action
MoA	Ministry of Agriculture
NARO	National Agricultural Research Organization
NGO	Non-Governmental Organization
NPPO	National Plant Protection Organization
OECD	Organization for Economic Co-operation and Development
OP	Organophosphate
OPVs	Open-Pollinated Varieties
OV	Organic Vapor
PIB	Polyhedral Inclusion Bodies
PPE	Personal Protective Equipment
PRM	Pesticide Risk Management
PVC	Polyvinyl chloride
QMS	Quality Management System
RCBD	Randomized Complete Block Design
RH	Relative Humidity
s	second
SAN	Sustainable Agriculture Network
SfGV	*Spodoptera frugiperda* Granulovirus
SfMNPV	*Spodoptera frugiperda* Multiple Nucleopolyhedrovirus
SpexNPV	*Spodoptera exempta* Nucleopolyhedrovirus
spp.	species
SSA	Sub-Saharan Africa
U.S.	United States
USAID	United States Agency for International Development
USDA	United States Department of Agriculture
USDA-ARS	United States Department of Agriculture-Agricultural Research Service
UV	Ultraviolet light
VE	Vegetative-Early
VT	Vegetative-Tassel
WEMA	Water Efficient Maize for Africa
WHH	Welthungerhilfe
WHO	World Health Organization
ZARI	Zambia Agricultural Research Institute

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CHAPTER 01

Integrated Pest Management of Fall Armyworm in Africa: An Introduction

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1. Introduction

1.1. Arrival and Spread of Fall Armyworm (FAW) Across Sub-Saharan Africa (SSA)

Native to the Americas, the fall armyworm (FAW; *Spodoptera frugiperda* (JE Smith); Lepidoptera, Noctuidae) was first reported as present on the African continent in January 2016 (Goergen *et al.* 2016). Subsequent investigations have revealed the pest in nearly all of sub-Saharan Africa (SSA), where it is causing extensive damage, especially to maize fields and to a lesser degree sorghum and other crops. Currently, over 30 countries have identified the pest within their borders including the island countries of Cape Verde, Madagascar, São Tomé and Príncipe, and the Seychelles. The best evidence to date suggests that the FAW type introduced into Africa is the haplotype originating from south Florida (USA) and the Caribbean (see Section 2.6 of this chapter). The location(s), date(s), mode, and number of introductions are not known at present but anecdotal observation and the response of single-gene genetically modified *Bt* maize in South and East Africa suggests it has been present for at least several years. The generally hospitable agroecological conditions for FAW in SSA suggest that FAW will establish as an endemic, multigenerational pest in Africa.

Though new agricultural pests are periodically introduced into the African agricultural environment and pose some degree of risk, a number of characteristic factors make FAW a more devastating pest than many others:

- **FAW consumes many different crops.** FAW is capable of feeding on over 80 different crop species, making it one of the most damaging crop pests. While FAW has a preference for maize, the main staple of SSA, it can also affect many other major cultivated crops, including sorghum, rice, sugarcane, cabbage, beet, groundnut, soybean, onion, cotton, pasture grasses, millets, tomato, potato, and cotton.
- **FAW spreads quickly across large geographic areas.** Like other moths in the genus *Spodoptera*, FAW moths have both a migratory habit and a more localized dispersal habit. In the migratory habit, moths can migrate over 500 km (300 miles) before oviposition. When the wind pattern is right, moths can move much larger distances: for example, a flight of 1,600 km from the southern U.S. state of Mississippi to southern Canada in 30 hours has been recorded (Rose *et al.* 1975).
- **FAW can persist throughout the year.** In most areas of North America, FAW arrives seasonally and then dies out in cold winter months, but in much of Africa, FAW generations will be continuous throughout the year wherever host plants are available, including off-season and irrigated crops, and climatic conditions are favorable. Although the patterns of population persistence, dispersal, and migration in Africa are yet to be determined, conditions in Africa, especially where there is a bimodal rainfall pattern, suggest that the pest can persist throughout much of the year.

1.2. Emerging Impacts Across Africa

Due to its rapid spread and distinctive ability to inflict widespread damage across multiple crops, FAW poses a serious threat to the food and nutrition security and livelihoods of hundreds of millions of farming households in SSA – particularly when layered upon other drivers of food insecurity. In Southern Africa, for example, the 2016-17 FAW outbreak arrived just as households in the region were still reeling from the 2015-16 El Niño-induced drought, which affected an estimated 40 million people.

The potential economic impacts of FAW on agricultural productivity across (and beyond) Africa are substantial:

- Based on an evidence note published by the Centre for Agriculture and Bioscience International (CABI) in September 2017, in the absence of proper control methods, FAW has the potential to cause maize yield losses of 8.3 to 20.6 M metric tons per year, in just 12 of Africa's maize-producing countries. This represents a range of 21-53% of the annual production of maize averaged over a three-year period in these countries. The value of these losses was estimated at between US$2.48 billion and US$6.19 billion.

- Several seed companies in SSA have reported significant damage to their maize seed production fields over the past year, potentially impacting both the availability of seed to farmers over the coming growing seasons and the economic viability of Africa's emerging private seed sector.
- FAW could have serious impacts on regional and international trade. Informal reports indicate that FAW has been intercepted at quarantine points in Africa and Europe, suggesting the potential for phytosanitary trade issues inside and outside of Africa. (However, it must be noted that the pest is also capable of migrating long distances on prevailing winds, so introduction of FAW is also possible via natural migration.)
- Establishment of FAW populations in Africa has broader implications for global agriculture, as it also increases the risk that the pest will further migrate to Europe (possibly via North Africa and Egypt) and Asia (possibly via African countries on the east coast, such as Ethiopia).

In addition to FAW's emerging economic and food security impacts, initial responses to the pest highlight the potential for negative human and environmental health impacts. In particular, extensive, indiscriminate, and unguided use of synthetic pesticides is already being reported anecdotally from several countries in SSA for controlling FAW in farmers' fields. This can result in several critical problems:

- Substantial environmental and human health issues, arising from both the initial application of hazardous chemicals and continued exposure to pesticide residues on consumed produce or in the production environment.
- Damage to populations of natural enemies and predators of FAW and other major African pests, further impeding sustainable management of FAW and other pests.
- Particularly high risk of pesticide exposure for women and children at the farm level, as women primarily manage agricultural operations in Africa.

1.3. The African FAW Response Thus Far

To date, development and implementation of a coordinated, evidence-based effort to control FAW in Africa has faced a number of challenges. In particular, FAW is a recently introduced pest in Africa. Therefore, FAW scouting by farming communities and effective monitoring at the country, regional, and continental levels are limited. In addition to delaying recognition of the pest's movement through Africa, this lack of surveillance, monitoring, and scouting capacity has delayed efforts to determine several key unknowns about FAW populations on the continent and the dynamics of the pest's establishment and spread. The lessons learned from the invasive FAW pest should be identified quickly because they are important for monitoring and interception of future invasive pests.

Beyond the challenges of recognizing and characterizing the presence of FAW in Africa, the lack of validated strategies to effectively manage FAW in an African context also poses challenges. Proven approaches to prevent and avoid FAW are presently limited, and efforts to suppress the pest have largely focused on the application of synthetic pesticides – at times in an indiscriminate manner with high potential to damage human, animal, and environmental health. Furthermore, education, research, and regulatory processes are yet to be scaled up and effectively coordinated across the continent, so as to rapidly disseminate and support emerging best practices for FAW control as they are identified.

FAW is likely to remain a significant agricultural pest across much of SSA for the foreseeable future. It is therefore essential to develop an effective, coordinated, and flexible approach to manage FAW across the continent. Such an approach should be informed by sound scientific evidence, build on past experience combating FAW in other parts of the world, and be adaptable across a wide range of African contexts (particularly for low-resource smallholders). An Integrated Pest Management (IPM) approach (Section 3 of this chapter) provides a useful framework to achieve these goals.

2. FAW Description and Life Cycle[1]

The FAW life cycle is completed in about 30 days (at a daily temperature of ~28°C) during the warm summer months but may extend to 60-90 days in cooler temperatures. FAW does not have the ability to diapause (a biological resting period); accordingly, FAW infestations occur continuously throughout the year where the pest is endemic. In non-endemic areas, migratory FAW arrive when environmental conditions allow and may have as few as one generation before they become locally extinct. For example, FAW is endemic in south Florida (latitude ~28°N) and populates the entire eastern USA each summer by migration.

2.1. Egg Stage

The egg is dome shaped: the base is flattened and the egg curves upward to a broadly rounded point at the apex. The egg measures about 0.4 mm in diameter and 0.3 mm in height. The number of eggs per mass varies considerably but is often 100 to 200, and total egg production per female averages about 1,500 with a maximum of over 2,000. The eggs are sometimes deposited in layers, but most eggs are spread over a single layer attached to foliage (Figure 1A). The female also deposits a layer of grayish scales between the eggs and over the egg mass (Figure 1B), imparting a furry or moldy appearance. Duration of the egg stage is only 2 to 3 days during the warm summer months.

2.2. Larval Stage

The FAW typically has six larval instars. Young larvae are greenish with a black head (Figure 1C), the head turning a more orange color in the second instar. Head capsule widths range from about 0.3 mm (instar 1) to 2.6 mm (instar 6), and larvae attain lengths of about 1 mm (instar 1) to 45 mm (instar 6) (Figure 1D). In the second instar, but particularly the third instar, the dorsal surface of the body becomes brownish, and lateral white lines begin to form. In the fourth to sixth instars the head is reddish brown, mottled with white, and the brownish body bears white subdorsal and lateral lines. Elevated spots occur dorsally on the body; they are usually dark in color and bear spines. The face of the mature larva may also be marked with a white inverted “Y” (Figure 1E) and the epidermis of the larva is rough or granular in texture when examined closely. However, this larva does not feel rough to the touch, as does maize earworm, *Helicoverpa zea* (Boddie), because it lacks the microspines found in the similar-appearing maize earworm. In addition to the typical brownish form of the FAW larva, the larva may be mostly green dorsally. In the green form, the dorsal elevated spots are pale rather than dark. The best identifying feature of the FAW is a set of four large spots that form a square on the upper surface of the last segment of its body (Figure 1E). Larvae tend to conceal themselves during the brightest time of the day. Duration of the larval stage tends to be about 14 days during the warm summer months and 30 days during cooler weather. Mean development time was determined to be 3.3, 1.7, 1.5, 1.5, 2.0, and 3.7 days for instars 1 to 6, respectively, when larvae were reared at 25°C (Pitre and Hogg 1983).

2.3. Pupal Stage

The FAW normally pupates in the soil at a depth 2 to 8 cm. The larva constructs a loose cocoon by tying together particles of soil with silk. The cocoon is oval in shape and 20 to 30 mm in length. If the soil is too hard, larvae may web together leaf debris and other material to form a cocoon on the soil surface. The pupa is reddish brown in color (Figure 1F), measuring 14 to 18 mm in length and about 4.5 mm in width. Duration of the pupal stage is about 8 to 9 days during the summer, but reaches 20 to 30 days during cooler weather. The pupal stage of FAW cannot withstand protracted periods of cold weather. For example, Pitre and Hogg (1983) studied winter survival of the pupal stage in Florida, and found 51% survival in southern Florida, but only 27.5% survival in central Florida and 11.6% survival in northern Florida. This range is approximately between 25.1°N to 30.3°N latitude and represents a January (winter) temperature range of 18-24°C (near Miami, Florida, USA) to 4.5-18°C (near Jacksonville, Florida, USA).

[1]**Source:** John L. Capinera, University of Florida, IFAS Extension, EENY-098 (Capinera 1999)

2.4. Adult Stage

Adult FAW moths have a wingspan of 32 to 40 mm. In the male moth, the forewing generally is shaded gray and brown, with triangular white spots at the tip and near the center of the wing (Figure 1G). The forewings of females are less distinctly marked, ranging from a uniform grayish brown to a fine mottling of gray and brown. The hind wing is iridescent silver-white with a narrow dark border in both sexes. Adults are nocturnal, and are most active during warm, humid evenings. After a preoviposition period of 3 to 4 days, the female moth normally deposits most of her eggs during the first 4 to 5 days of life, but some oviposition occurs for up to 3 weeks. Duration of adult life is estimated to average about 10 days, with a range of about 7-21 days. A comprehensive account of the biology of fall armyworm was published by Luginbill (1928), and an informative synopsis by Sparks (1979). Ashley *et al.* (1989) presented an annotated bibliography. A sex pheromone has been described (Sekul and Sparks 1976).

A. Egg mass placed on stem (left) or leaf (right) at early stage of maize plant

B. Egg mass (left) and larvae hatching three days after oviposition (right)

C. Black-headed larvae emerging out of egg mass

D. Larval growth stages (1 mm to 45 mm)

E. Distinguishing marks on medium to large-sized larvae

F. Reddish-brown pupa

G. Male moth with conspicuous white spot on tip of forewing

Figure 1. Various stages of FAW life cycle (Source: Ivan Cruz, Embrapa).

2.5. Host Range

The FAW has a very wide host range, with over 80 plants recorded, but clearly prefers grasses. The most frequently consumed plants are field maize and sweet maize, sorghum, Bermuda grass, and grass weeds such as crabgrass (*Digitaria* spp). When the larvae are very numerous they defoliate the preferred plants, acquire the typical "armyworm" habit, and disperse in large numbers, consuming nearly all vegetation in their path. Many host records reflect such periods of abundance and are not truly indicative of oviposition and feeding behavior under normal conditions. Field crops are frequently injured, including alfalfa, barley, Bermuda grass, buckwheat, cotton, clover, maize, oat, millet, peanut, rice, ryegrass, sorghum, sugar beet, Sudan grass, soybean, sugarcane, timothy, tobacco, and wheat. Among vegetable crops, only sweet maize is regularly damaged, but others are attacked occasionally. Other crops sometimes injured are apple, grape, orange, papaya, peach, strawberry, and a number of flowers. Weeds known to serve as hosts include bent grass, *Agrostis* ssp.; crabgrass, *Digitaria* spp.; Johnsongrass, *Sorghum halepense*; morning glory, *Ipomoea* spp.; nutsedge, *Cyperus* spp.; pigweed, *Amaranthus* spp.; and sandspur, *Cenchrus tribuloides.*

2.6 FAW Haplotypes

FAW consists of two strains adapted to different host plants. One strain (the "maize strain") feeds predominantly on maize, cotton, and sorghum while the second (the "rice strain") feeds primarily on rice and pasture grasses (Dumas *et al.* 2015a). The two strains are morphologically identical but differ in pheromone compositions, mating behavior, and host range. Matings between the two strains result in viable offspring. Even so, Dumas and co-workers found a significant reduction in mating success in crosses of the two strains, which together with the behavioral and biochemical differences would suggest that the two strains are in a state of sympatric speciation (Dumas *et al.* 2015 a, b; Gouin *et al.* 2017). How this process will evolve in the African context is under investigation (Cock *et al.* 2017, Nagoshi *et al.* 2017). For example, genetic analysis was used to characterize FAW specimens collected from maize fields in the African nation of Togo (Nagoshi *et al.* 2017). Through DNA barcoding, the specimens were found to be primarily of the subgroup that preferentially infests maize and sorghum in the Western Hemisphere. The mitochondrial haplotype configuration was most similar to that found in the Caribbean region and the eastern coast of the United States, identifying these populations as the likely originating source of the Togo infestations. A genetic marker linked with resistance to the *Cry1Fa* toxin from *Bacillus thuringiensis (Bt)* expressed in transgenic maize and common in Puerto Rico FAW populations was not found in the Togo collections. In addition, as stated above, field performance of MON810 single-gene *Bt* maize further suggests that *Bt* resistance alleles may not be present in the FAW population currently in Africa. This needs to be confirmed with further research.

3. An IPM Framework to Control FAW in Africa

FAW is likely to remain a significant agricultural pest across much of SSA for the foreseeable future. It is therefore essential to develop an effective, coordinated, flexible approach to manage FAW across the continent. Such an approach should be informed by sound scientific evidence, build on past experience combating FAW in other parts of the world, and be adaptable across a wide range of African contexts (particularly for low-resource smallholders). An IPM approach provides a useful framework to achieve these goals.

3.1. Principles of IPM

The goal of IPM is to economically suppress pest populations using techniques that minimize harm to the environment, including people. Because of its holistic nature and the need to integrate a variety of techniques and disciplines, IPM should not be viewed as an "off-the-shelf" solution. IPM requires that the farmer or agricultural advisor possess significant agronomic and pest management knowledge to implement an effective program based on local farming conditions. The IPM process is embraced globally by international bodies such as the UN Food and Agriculture Organization (FAO) and the Organization for Economic Co-operation and Development (OECD) and is typically illustrated in the form of a triangle (Figure 2). An effective IPM strategy for control of FAW will employ a variety of integrated approaches including host plant resistance (native and/or transgenic), biological control, cultural control, and safer pesticides, to protect the crop from economic injury while minimizing negative impacts on people, animals, and the environment. Host plant resistance will be reinforced by biocontrol options as they are developed as well as cultural controls within the African context. As in all IPM programs, decisions on pesticide use will focus on the economic trigger elicited when these basic control options fail to limit the pest's damage and on economically viable interventions that pose the lowest risk to human and environmental health.

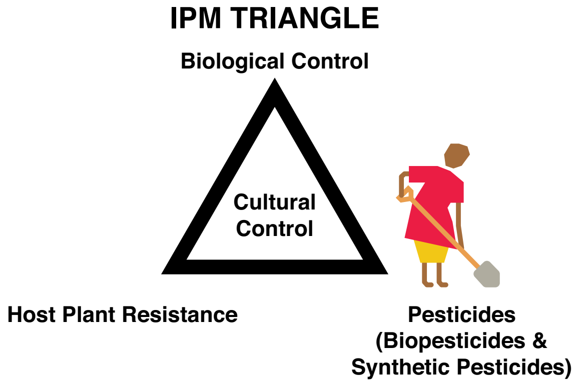

Figure 2. The IPM triangle.

An IPM framework has several key objectives:

- **Prevent or avoid pest infestations** using a combination of environmentally friendly approaches at the field, farm, and landscape scale, such as cultural control, landscape management, host plant resistance, and biological control.
- Implement routine scouting to **identify and respond to** potentially damaging pest infestations when they occur.
- In the event of a pest infestation, **suppress the pests** using a combination of biological, physical, and if necessary, chemical approaches – **leveraging interactions** between complementary approaches in order to maximize control of the pest while minimizing potential risks to human and animal health, the environment, and natural enemies of the pest.
- **Minimize the amount and toxicity** of chemical pesticides applied to achieve control of the pest.
- Provide **scientifically validated, evidence-based choices to farmers** on how to safely and effectively mitigate the potential damage of their crop(s) from a specific pest or combination of pests.
- **Maximize the contributions by all stakeholders**, and **incorporate new, practical findings** as they become available for **continuous improvement.**
- **Manage insect resistance to pesticides** by minimizing their use.

Two very important concepts in IPM are the Economic Threshold (ET) and the Economic Injury Level (EIL). A thorough explanation of the subject is provided by Hunt *et al.* (2009). The main points are summarized here:

- **Economic Threshold (ET)**
  - The density of a pest (or level of injury) at which control measures should be initiated to prevent an increasing pest population from reaching the EIL.
- **Economic Injury Level (EIL)**
  - The smallest number of insects (or amount of injury) that will cause yield losses equal to the insect management costs. At the EIL, the cost of the control is equal to the economic loss resulting from the insect damage.
  - The pest density or extent of crop damage at which a control treatment will provide an economic return.

The EIL is the break-even point between economic loss resulting from the pest and the cost of managing the pest, *e.g.*, equipment, labor, and pesticide costs (Figure 3). Because economic conditions (*e.g.*, commodity market value, management costs) fluctuate, the EIL will fluctuate. The calculation for the EIL is:

$EIL = C/(V \times DI \times K)$,

where

C = Pest management costs,

V = Market value of the commodity,

DI = Yield loss per pest,

K = Pest population controlled.

Note that if management costs (C) increase, then it takes more pests to justify control action, so the EIL increases. Similarly, if market values (V) decrease, then more pests can be tolerated and again the EIL increases.

A good IPM strategy uses a combination of host plant resistance, biocontrol, and cultural control to suppress pest populations below an Economic Threshold (ET). When pest populations exceed the ET, the farmer must take a decision:

- Do nothing and pay in yield;
- Treat (spray) and pay in chemical and labor.

In principle, the EIL calculation variables (C, V, DI, K) and the EIL assessment should be an easy mathematical exercise. In practice, the ET and EIL are difficult to determine and are generally based on multiyear basic research data. For example, commodity prices and pesticide costs are fairly easy to determine but yield loss due to a given pest, the insect's stage of development, the stage of development of the crop, and the agroecosystem the crop is grown in complicate things considerably.

Likewise, the ET, which is normally the 'trigger' for a needed mitigation procedure, is very difficult to estimate because it represents a prediction of when a pest population will reach the EIL. This requires a significant understanding of the crop and agroecosystem as well as the pest's population dynamics. In the case of a new invasive insect pest, estimating those dynamics is very difficult. In the African smallholder context the ET and EIL are even more difficult to calculate because smallholder farmers may rely on their crop for food rather than for sale. Social scientists and anthropologists have techniques for making these comparisons, but that work requires basic research as well.

In practice, true ETs and EILs have not been determined for most crops. Instead, nominal thresholds, herein called Action Thresholds, are calculated based on expert opinion and experience coupled with accurate field scouting assessments. These nominal thresholds are used throughout the IPM community and, while they tend to be conservative, they serve the purpose quite well. Accordingly, given the long history of controlling the FAW in the Americas it is reasonable to use expert opinion to formulate Action Thresholds for FAW in Africa in the short term.

Crucially, the efficacy of an IPM approach arises from complementary interactions between different components of the framework. Proper understanding of these interactions is important for sustainable control of the FAW. For example:

- Cultural practices that promote the growth of healthy plants are important because healthy plants are generally less susceptible to insect and pathogen attack.
- Cultural interventions at the field and farm level (*e.g.,* intercropping, conservation agriculture and its components) generally enhance the biological activity within the cropping system, providing shelter for small-range predators of the pest (spiders, ants, beetles, fungi, and bacteria). In turn, this can help control pest larvae – thereby reducing insect proliferation.
- Creating awareness among farmers on how to identify the FAW and its damage signs in the field through scouting, assessing the pest population and its threat to the crop, and taking

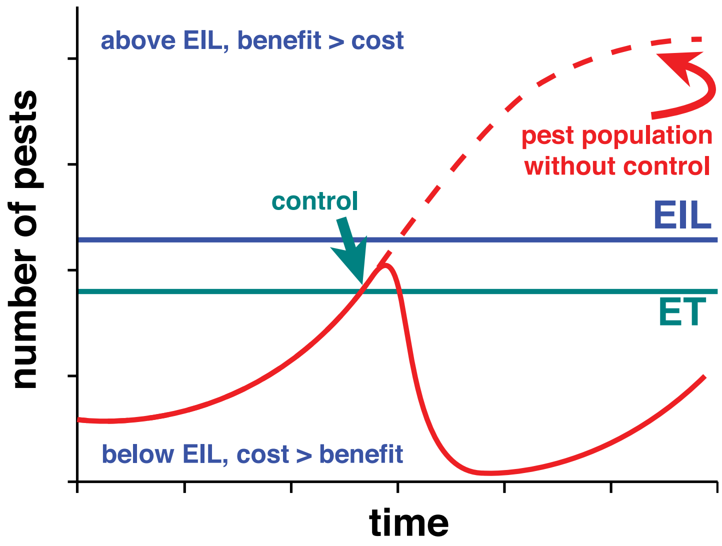

Figure 3. The relationship between pest numbers over time and calculation of the Economic Threshold (ET) and the Economic Injury Level (EIL). Source: Barbercheck and Zaborski (2015).

informed decisions on when and when not to apply a pesticide is critical. Reactive interventions must be used only after proper field scouting for the pest in the field.

- Judicious selection and limited use of pesticides that are low in toxicity and short in environmental persistence is necessary.

It must be recognized that no one specific IPM program will be effective against FAW across all the varied agroecologies in Africa. IPM programs must be context-specific – identifying, adapting, and combining approaches in a manner that is tailored to the specific agroecology, capacities, and socioeconomic context of a given country or farming community.

3.2. Applying the IPM Framework to FAW in Africa

In order to inform development of locally adapted IPM strategies appropriate for Africa, this FAW IPM Guide compiles currently available, scientifically validated strategies to control FAW. Building on the research and field experience of countries that have dealt with FAW for decades, such as the USA and Brazil, the document presents the best management strategies that have either been validated or are in the process of validation in the African context (or, given the relatively nascent state of FAW field experience in Africa, are judged by experts to be appropriate for adaptation to African agroecologies and cropping systems).

Organized according to the key components of an IPM framework, the following five chapters emphasize currently available, practical knowledge and tools to control FAW in Africa:

- Chapter 2: Monitoring, Surveillance, and Scouting
- Chapter 3: Pesticide Hazard and Risk Management
- Chapter 4: Host Plant Resistance
- Chapter 5: Biological Control and Biorational Pesticides
- Chapter 6: Low-cost Agronomic Practices and Landscape Management Approaches

Much of the available evidence on FAW control methods in Africa is preliminary. This is reflected across the chapters, some of which contain more immediately actionable guidance than others or may be aimed at somewhat different audiences depending on the status of available knowledge.

For example, guidance on scouting (Chapter 2) and on pesticide hazard and risk management (Chapter 3) is available to inform near-term, field-level decisions by farmers, extensionists, regulators, and other stakeholders. In contrast, as of publication of this First Edition, researchers are still working to identify and validate levels of host plant resistance in currently available Africa-adapted crop germplasm as well as biological control options. Therefore, Chapter 4 (Host Plant Resistance) and Chapter 5 (Biological Control) offer relatively little practical guidance to inform near-term planting, extension, or technology deployment decisions, and focus instead on providing relevant tools and protocols to help research and development partners identify and develop appropriate technologies (resistant varieties and biological control).

In all cases, this FAW IPM Guide is intended as a living document, to be updated regularly. While the information compiled here provides an initial basis for practical decision-making and strategic planning, future editions will reflect the rapidly evolving African experience with FAW, and provide opportunities to expand and refine local IPM approaches in light of new knowledge and tools.

Therefore, there is an urgent need to generate awareness among the farming communities about the life stages of the pest, scouting for the pest (as well as its natural enemies), understanding the right stages of pest control, and implementing low-cost agronomic practices and other landscape management practices (Chapter 6) for sustainable management of the pest.

At the same time, it is important to introduce, validate, and deploy low-cost, environmentally safer, and effective technological interventions over the short-, medium- and long-term for sustainable management of FAW in Africa, especially keeping in view that a huge majority of African farmers are low-resource smallholders.

CHAPTER 02

Monitoring, Surveillance, and Scouting for Fall Armyworm

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1. Introduction

Monitoring, surveillance, and scouting are critical activities necessary for successful implementation of an effective Integrated Pest Management (IPM) program. Predicting when a pest will be present and then assessing the level and severity of an infestation allows timely mitigation of the problem using the fewest and safest interventions to effectively and economically guard against yield loss while preserving needed ecosystem services and minimizing harm to the environment.

This chapter provides information and context about the role and processes of monitoring, surveillance, and scouting as they relate to an IPM program for fall armyworm (FAW) control in Africa. Additionally, this chapter will provide:

- Monitoring protocols for use of pheromone traps.
- Field scouting protocols.
- Practical guidance on determining whether and when to apply chemical control options, based on monitoring and scouting Action Thresholds.

The chapter content emphasizes field-level knowledge and practices that will be immediately useful to African smallholder and village-level progressive farmers (see Section 1.2), as well as to professional extension personnel developing technical materials to serve these audiences. The chapter may also be of general interest to technical specialists and policymakers interested in the development, implementation, and coordination of broader FAW monitoring efforts at the local, national, regional, and continent-wide scales.

1.1. Definitions

The terms used for monitoring, surveillance, and scouting are not fully standardized across jurisdictions or scientific disciplines. In some cases they are used as synonyms and in others have unique meaning. This can lead to confusion. Therefore, for the purposes of this chapter, the following definitions will apply:

- **Monitoring** denotes an effort to actively track the presence, population, and movement of a pest within a specified geography. Monitoring activities may be organized and implemented at various scales – most typically by governments, through trained technical personnel who systematically gather data to inform policymakers and practitioners about the presence and severity of the pest across a given area. However, more localized measurements, such as data from farmers trained to scout their fields, can also be aggregated and incorporated into broader, formal monitoring schemes. Finally, monitoring also has specific meaning in the context of Insect Resistance Management (IRM), which refers to ongoing, repeated measurement of an insect pest's susceptibility to a particular toxin (e.g., to a conventional pesticide or insecticidal protein expressed in a genetically engineered crop).
- **Surveillance** denotes the informal, passive detection of pest issues as they emerge. In other words, this approach does not actively search for a specific pest; it only notes when a problem occurs. Surveillance is typically performed by farmers at the field and farm level, and assumes no special training or approach. The importance of surveillance should not be underestimated. History shows that farmers in the field are often among the first to identify emerging problems, and when a mechanism exists to collect and track surveillance reports as they arise, the collective feedback of thousands of farmers can provide powerful information about the dynamics of pest infestation.
- **Scouting** refers to an activity conducted according to science-based protocols by a trained individual – typically by a farmer, trained at the farmer field school or extension level, observing his or her own fields for the pest. Scouting allows the farmer to precisely assess pest pressure (e.g., the intensity of FAW infestation) and crop performance in the field. Scouting is typically performed in order to evaluate both the economic risk of pest infestation and the potential efficacy of pest control interventions within the immediate field context, with the goal of informing practical crop management decisions at the individual field and farm level. However, localized scouting data can also be aggregated and incorporated into formal monitoring schemes at broader geographic scales.

1.2. Delivery Pathways to Smallholder Farmers

This FAW IPM Guide describes a variety of products, practices, and knowledge that can be applied to combat FAW in sub-Saharan Africa. The pathways by which these approaches are delivered to smallholder farmers may vary substantially between countries and regions, depending on the availability of formal and informal extension services and the mix of public- and private-sector actors present in a given location. The contents of this FAW IPM Guide are intended to serve as a general resource that can be used by public-sector extensionists, private-sector individuals, development implementing partners, and others to develop locally adapted extension materials. However, ultimately the intended end-user of these technologies is a smallholder farmer. Importantly, many smallholder communities throughout Africa contain a subset of innovative smallholders – typically, but not always, better-educated and better-resourced than their neighbors – who are more likely to act as "early adopters" of new technologies. Throughout this manual, we refer to such smallholders as "village-level progressive farmers." In general, progressive farmers are expected to be the early adopters of the products, practices, and knowledge described in this FAW IPM Guide. Once progressive farmers demonstrate the value of these approaches to their neighbors, subsequent efforts to scale up adoption of FAW control measures are more likely to spread through local communities and achieve broad control of the pest.

1.3. Importance of Monitoring, Surveillance, and Scouting in the African Context

The current African response to FAW has faced several challenges arising from weak monitoring, surveillance, and scouting systems, including delayed recognition of the pest's widespread presence across the continent and lack of information about the dynamics of FAW migration that would allow effective prediction of where infestation might occur next. Perhaps most dangerously for African farmers and rural communities, the spread of FAW has in some cases resulted in indiscriminate spraying of pesticides, often without regard to whether chemical control is necessary or effective within the local context.

In this African context, enacting effective monitoring, surveillance, and scouting systems is a crucial step in implementing an effective IPM strategy at any scale. Such a system is essential not only to provide early warning of FAW infestation and improve understanding of pest dynamics, but also to help farmers determine when – and most importantly, when not – to apply pesticides.

Practical guidance on how to detect FAW, and at what pest threshold to apply chemical control options, promotes more targeted, effective use of pesticides. More targeted and effective use further supports the harmonization of biological, chemical, and cultural control tactics, benefiting both village-level progressive farmers and smallholder farmers in a number of ways:

- Saves money wasted on ineffective chemical treatments.
- Reduces human and animal pesticide exposure in fields, food residues, and the environment.
- Protects natural enemies of FAW, which may also be killed by pesticides.
- Conserves soil and water quality.
- Manages insecticide resistance, helping to maintain the efficacy of existing chemical control options over time.

Such guidance can be particularly crucial for African smallholder farmers, who largely rely on crops such as maize to feed their families or supplement household income, and who often do not have access to the knowledge or tools to apply pesticides in a safe manner.

2. Monitoring for FAW

Regional FAW monitoring is intended to actively track the presence, population, and movement of FAW within a specified geography. This is typically conducted by trained technical personnel at sites throughout a country or region, but can also be conducted at the village and field levels by both smallholder farmers and village-level progressive farmers.

In both cases, monitoring typically relies on pheromone traps erected near fields to trap adult male moths. FAW numbers in the traps are counted, recorded, and used to inform appropriate action (typically reporting the data to appropriate authorities and conducting more intensive, targeted field scouting to inform crop management recommendations and decision making).

2.1. Trap Selection

A pheromone trap is a type of insect trap that uses pheromones to attract (usually) male insects. A pheromone is a chemical secreted by (usually) a female insect to attract males for mating. Pheromones can travel by air very long distances and hence are very useful for monitoring insect presence. Sex pheromones and aggregation pheromones are the most common types of pheromones in use.

Currently there are several different pheromone lures being assessed as well as a variety of trap types. All of these may work, but some pheromone lures also attract a limited number of non-FAW moths, which may cause some confusion.

Based on currently available information, the following traps are recommended:

- For smallholder farms, the Universal Bucket Trap (see Section 2.2.1)
- For regional monitoring, the Heliothis-style Pheromone Trap (see Section 2.2.2)

2.2. Trap Placement and Setup

i. Establish the pheromone trap one month before planting.

ii. Place the trap in or next to the maize field so that the scent of the pheromone is carried across the tops of the plants by the wind.

iii. Hang the trap in a vertical orientation from a long pole (3-4 meters) so that the trap is approximately 1.25 meters off the ground. (See Sections 2.2.1 and 2.2.2 for specific directions on the different trap types.)

iv. When traps are hanging, they should be oriented in the most vertical, straight up-and-down orientation possible, to prevent water from getting in from the side.

2.2.1. Universal Bucket Trap (Figure 1)

i. Attach the pheromone.

— Place the pheromone lure in the compartment in the basket on top of the bucket trap.

— Replace the pheromone lure every four weeks.

— Store extra lures in a freezer.

ii. Insert insecticidal strips.

— Unwrap the insecticidal strip (Vapor-tape) and place it in the trap to kill the moths once they enter the trap. Do not handle the insecticidal strip with bare hands – it is poisonous. Use gloves or some other tool.

Figure 1. Bucket type trap.

— One strip should last for four weeks after which it should be replaced

— Do not store extra strips with food – the strips are poisonous. Place them in a sealed air-tight jar and store in a cool, dark place.

Figure 2. Heliothis-style trap.

2.2.2. Heliothis-style Trap (Figure 2)

i. Attach the pheromone.

— Use a paper clip or a thin piece of wire to pierce the rubber lure. Attach the lure to the string across the bottom of the trap, centering the pheromone below the bottom hole.

— Replace the pheromone lure every three weeks.

— Store extra lures in the freezer.

ii. Check the passageway.

— Make sure that the trap pathway is open from the pheromone up into the funnel (moth-trap).

— Make sure that leaves and tassels do not block entrance to the pheromone trap.

2.3. Trap Monitoring

i. Check and empty the trap every week. To do so, detach the "moth-trap" from the body of the pheromone trap. Turn the moth-trap upside down (Figure 2, right). Live FAW moths may crawl up the sides of the trap.

ii. Pinch the thorax of the moths between your thumb and forefinger to freeze the wing muscles to help identify the FAW moths.

iii. There may be a number of moths other than the FAW in the trap. Sort out and count the FAW moths (Figures 3-4) (wings with white patch near apex of wing; hind wing veins light-colored) and any African Armyworm (AAW) moths (Figure 5) (hind wing veins brown-colored) separately.

iv. As the maize plants grow taller, move the trap up the pole so that the bottom of the trap is always about 30 cm above the plants.

Figure 3. FAW (*Spodoptera frugiperda*) male moth. Yellow arrows indicate key characters.

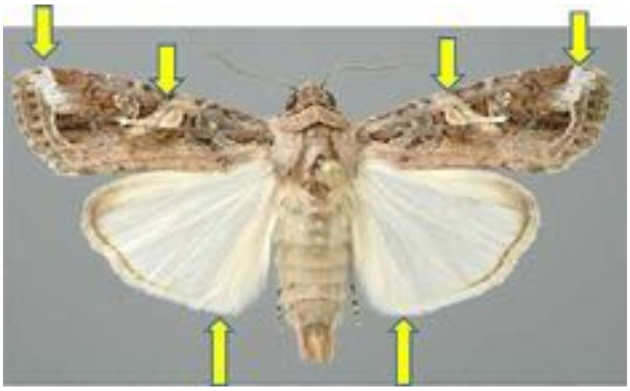

Figure 4. FAW (*Spodoptera frugiperda*) male moth. Yellow arrows indicate key characters. (Source: L. Buss, University of Florida, Bugwood.org).

Figure 5. African Armyworm (*Spodoptera exempta*; AAW) male moth. (Source: Georg Goergen, IITA).

2.4. Data Recording

The following data should be recorded on a scouting form (see Section 5):

- Date of present recording
- Maize growth stage
- FAW moth counts
- African Armyworm (AAW) moth counts (if any)

2.5. Sharing and Use of Monitoring Data

FAW moth count trends from surrounding regions and surrounding countries are highly relevant and should be shared. Continental-level FAW moth counts are being coordinated by a Food and Agriculture Organization (FAO)-organized working group comprising the US Agency for International Development (USAID), the International Maize and Wheat Improvement Center (CIMMYT), the Centre for Agriculture and Biosciences International (CABI), the International Centre of Insect Physiology and Ecology (ICIPE), the International Institute of Tropical Agriculture (IITA), the University of Barcelona, Pennsylvania State University, Lancaster University, and the National Agricultural Research Organization (NARO), Uganda, and other African national research institutions.

Pheromone trap moth counts alone can be misleading. Never base a spray decision on moth counts alone. Remember:

- Moth counts can remain low (less than one moth per trap per day) even during an outbreak. There may be no moths in the field-side trap even though a significant percentage of plants are infested with FAW.

- Moth counts indicate the presence of FAW in the area but do not indicate the level of egg-laying intensity. Scouting is required to determine egg-laying intensity (percent infested plants) (Section 3).
- Do not base spray decisions on moth counts alone. Scout the fields to determine the need to treat.

3. Field Scouting for FAW

Scouting is based on knowledge of the pest and the crop agroecosystem, coupled with an understanding of intervention triggers and mitigation tools.

- Searching a maize field looking for FAW is not without cost. For example, to search a maize field of 50,000 plants at a rate of 5 seconds per plant would cost almost 70 hours in labor.
- To effectively and economically scout a maize field, sampling techniques should be employed.

Based on African and global expert opinion, tentative Action Thresholds that are based on plant growth stage are presented. Over time, the research community will develop more formal Economic Thresholds (see Chapter 1).

- We considered the two categories of farmers described in Section 1.2 – smallholder farmers and village-level progressive farmers – and developed separate Action Thresholds for each of these two groups (Table 1).
- Generally, both smallholder farmers and village-level progressive farmers scout their fields in the same way. In the case of smallholder farmers, extra time may be needed to explain Action Thresholds, sampling, and pesticide use. In addition, more conservative mitigation procedures are recommended for smallholder farmers as they often lack the training and protective equipment to safety and effectively use many pesticides.
- Normally decisions to spray a pesticide are based on the calculated Economic Threshold and Economic Injury Level. We do not have Economic Thresholds based on African country-level estimates, but we do have over 100 years of experience with FAW in the Americas. In this situation, based on Expert Opinion, tentative Action Thresholds that are plant growth stage based should be used.

3.1. Identifying Maize Growth Stages

It is important for a farmer to have a general understanding of the growth stage of their maize crop when scouting, as the stage of development informs a number of relevant factors:

- Canopy density in the field, which in turn informs the scouting pattern used to sample the field.
- The parts of the plant accessible to the insect for infestation, and the amount of time FAW larvae may have to infest the plant after emergence. This in turn informs what part of the plant to inspect during scouting, and what signs of infestation to look for.
- The efficacy of potential chemical control options and amount of time before harvest, both of which impact the recommended Action Threshold before pesticide spray is recommended.

Properly identifying the growth stage helps inform the decision as to whether to treat the maize field and, if so, how. Generally, maize growth stages are divided into Vegetative (V), Tasseling (VT), and Reproductive (R) (Figure 6). The V stage of the maize is defined as the number of maize leaves displaying a leaf collar (Figure 7) and not the total number of leaves on the plant. For example, the maize plant displayed in Figure 7 is in the V3 stage, not the V5 stage!

Maize growth stages

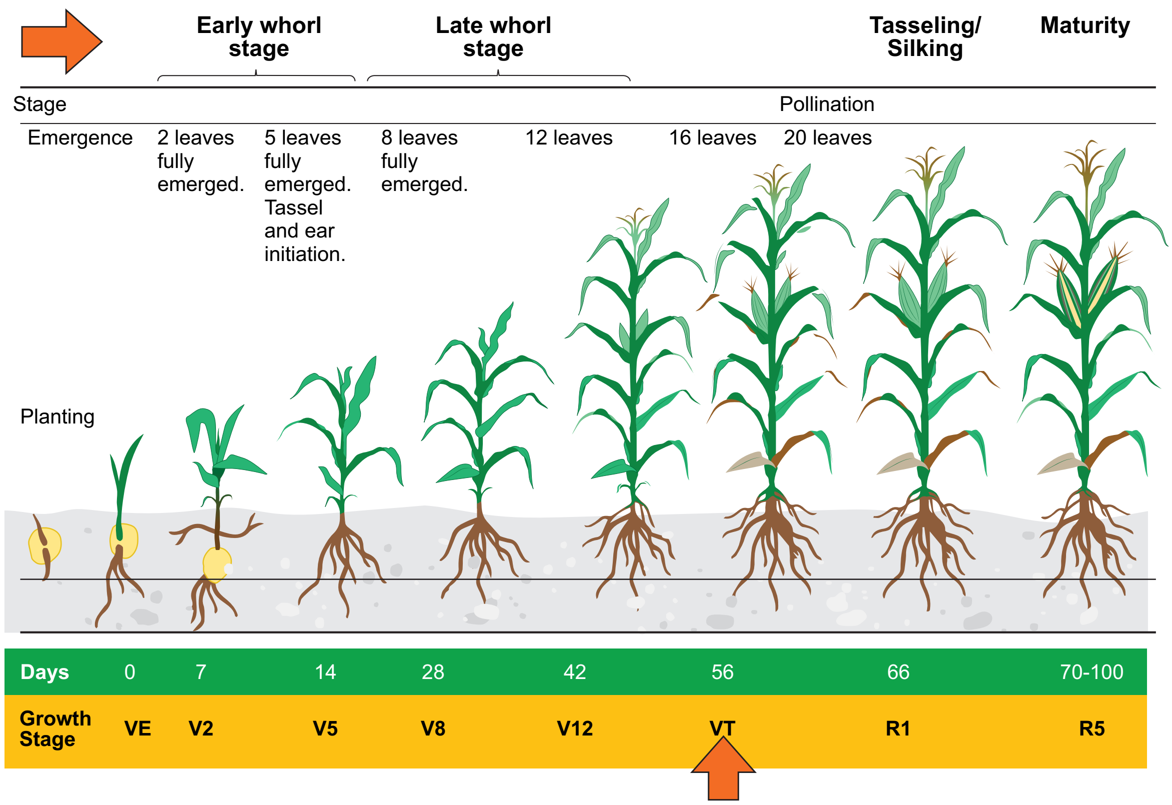

Figure 6. **Maize growth stages (Modified from Clarrie Beckingham, 2007, https://www.dpi.nsw.gov.au/agriculture/horticulture/vegetables/commodity-growing-guides/sweet-corn). Orange arrows indicate critical stages to consider.**

A useful simplification is to call the VE to V6 stages ”Early Whorl,” the V7 to VT stages “Late Whorl,” and the R1 to R3 stages “Tasseling & Silking.” The latter terms are used in the scouting and Action Threshold recommendations.

The growing point of maize is below ground until the end of the Early Whorl stage (about V6)[1], at which point it can be damaged by FAW causing a condition known as ”Dead Heart” (Figure 8). Application of pesticide, if needed, is also easier to target into the whorl at the earlier V stages and also has the advantage that the treatment can more directly and easily control the early instars (first to third) of the FAW. Finally, pesticide exposure is much lower at these early growth stages because the pesticide applicator is not directing the spray overhead.

As the maize plant matures, *i.e.*, post Late Whorl stage (V7 and beyond), it will be progressively more difficult to get uniform applications of pesticide into the whorl. In addition, later-instar FAW larvae (fourth to sixth instars), if present, may block the whorl with frass (insect excreta), suppressing the ability of the pesticide to effectively reach and affect FAW larvae.

At the VT stage the emerging tassel may push the larger FAW larvae out of the whorl. These larvae then frequently move to the growing ear, and frequently bore into the side of the ear.

The first generation of FAW emerging at the V2 stage could complete development, pupate, emerge, mate, and re-infest the maize crop at the maturity stage during the same planting season. In many instances where FAW is endemic, the maize crop can be often seen with overlapping generations of FAW on the same plant.

[1] https://www.agry.purdue.edu/ext/corn/news/timeless/growingpointsgallery.html

Figure 7. V3 stage of the maize plant, to illustrate the progression of growth stages. Note that the V stage is determined by the number of leaves displaying a leaf collar, and not by the total number of visible leaves. (Source: R.L. Nielsen, Purdue University)

Figure 8. "Dead heart" in maize caused by FAW damage (Source: ICIPE).

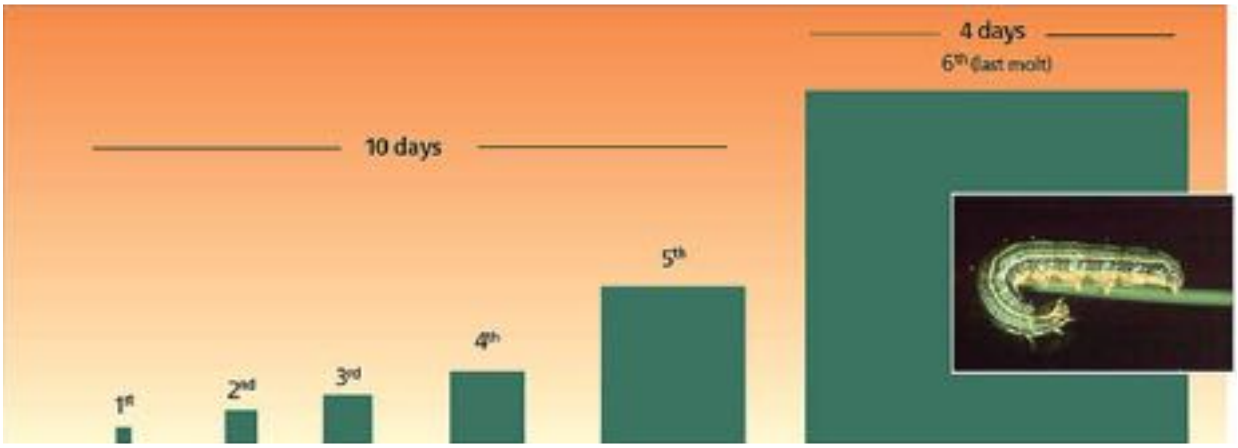

Figure 9. Relative amounts of food eaten by a FAW caterpillar during different growth stages. Note that the caterpillar feeds the most during the last larval stage. (Source: Flanders KL, Ball DM, Cobb PP, Revised May 2017, ANR-1019 Alabama Cooperative Extension System).

3.2. Scouting Protocols

Once the growth stage of the maize has been identified, use the appropriate scouting protocol (see Sections 3.3.2-3.3.4) to sample the field.

The focus of scouting should be on early detection; the smaller the insect, the easier it is to control. Ideally, scouting should begin soon after seedling emergence (VE; Early Whorl). FAW completes its life cycle in 30-40 days and the first generation of FAW larvae generally attacks the seedlings, so fields should be rechecked weekly at the seedling and Early Whorl stages.

In general, scouts should look for signs of FAW egg-hatch and feeding by early-instar larvae, rather than looking for the small FAW larvae themselves. As described below (Sections 3.3.2-3.3.4), such signs include characteristics such as leaf damage, holes in the ear, and frass. Figure 9 is a fair representation not only of the relative amount each FAW larva eats throughout its life span, but also of the relative size of the larvae at different instars. Neonate (freshly hatched) and first-instar larvae are quite small – on the order of 1 mm – and can be difficult to find. However, with a little practice, farmers can become quite adept at spotting even the small pinhole signs of FAW feeding. By the time FAW larvae are big enough to identify without a hand lens, they are difficult to control.

For all scouting protocols, two additional considerations should be kept in mind:

- SAFETY: ALWAYS first determine whether the field has been treated with insecticide and if so, when and with what active ingredient and rate. Pesticides have labeled re-entry criteria, and it is important that scouts not be exposed to hazardous levels of pesticide by scouting in a field that is not safe for re-entry after a recent pesticide application.
- Scouts should always determine if it has rained, and record any rainfall on the scouting form (Section 5). Heavy rain showers can kill the 1st, 2nd, and 3rd instar larvae and even though damage is present in the field, many larvae may have died.

3.3.1. Scouting Patterns

Scouting a maize field involves accurately assessing the level of FAW infestation, usually expressed as a percentage (%) of infested plants. This is done by sampling. Ideally, sampling should be random, but scouting a field in a purely random manner is quite difficult and probably unnecessary. What can be done easily is to scout a field in a semi-systematic manner.
A commonly used approach is the "W" pattern shown in Figure 10. This pattern is particularly easy to follow well up into the Tasseling Stage of the maize crop.

The scout walks into the field about 5 meters (avoiding the border rows of the field is important to avoid the edge effects). The scout then zigzags the field, stopping at 5 different locations. At each of these locations the scout assesses 10-20 plants looking for signs of FAW feeding (described in Sections 3.3.2-3.3.4). The percentage of damaged plants is recorded and the scout moves to the next check point. After assessing 5 locations in the field, the scout determines the percentage of damaged plants for the field and then refers to Table 1 for guidance to determine if mitigation is warranted. These Action Thresholds are used in place of Economic Thresholds (see Chapter 1) when the latter are not available. If the village has Economic Threshold data then by all means they should be used as they are a better guide to mitigation. In lieu of an Economic Threshold, the Action Thresholds presented here, based on the expert opinions of FAW researchers in Africa and the Americas, should serve as accurate guides.

There is nothing prescriptive about the "W" scouting pattern. The scouting pattern might need to be improvised based on the maize growth stage or field shape. For example, densely planted maize at the Tassel Stage or beyond may be difficult to traverse using the "W" pattern. An alternative is to use the "Ladder" pattern shown in Figure 11. In this method, rows A-E are used as alleys to more easily traverse the field in a semi-systematic manner.

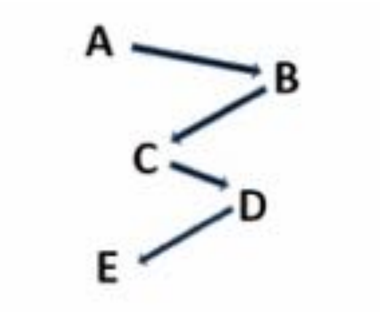

Figure 10. Sample scouting pattern for maize field at the early and late whorl stages.

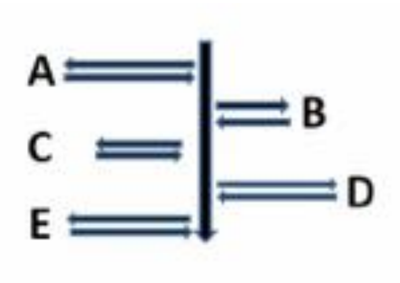

Figure 11. Sample scouting pattern for maize field at the VT and Reproductive stages.

3.3.2. Scouting at the Early Whorl Stage (VE-V6)

i. Upon arrival at the field, especially small fields, stop and quickly do a visual assessment. Sometimes spot infestations in a field can be seen at this stage. Likewise, scan for "hot spots" while moving through the field.

ii. Move through the field quickly. (This becomes easier with experience.) Stop 5 times. Examine a variety of places in the field (but avoid edge rows).

iii. At each stop, examine 10-20 plants. Focus on the newest two to three (2-3) leaves emerging from the whorl as this is where the FAW likes to feed and where FAW moths lay eggs.

iv. In some cases, FAW larvae cut and tear the seedlings (Figure 12). This damage is very similar to cutworm damage. Generally, the offending insect can be found hiding under dirt or debris near the cut plants. Maize stands damaged in this manner may need to be replanted.

Figure 12. Cutting and tearing of plants at the early whorl stage. Damage by FAW at the early growth stage may often be confused with the damage by cutworm.

Figure 13. Early-instar FAW damage on maize leaves in the form of pinholes or small window panes.

v. When the plants are young and the leaf tissues are soft, first-instar FAW larvae produce clusters of pinhole-type damage or small, round "window panes" (Figure 13). Record the number of seedlings (out of 20) that have these types of damage.

vi. Later on, as the leaf tissues mature and become more fibrous and tough, window panes may be scattered and elongated rather than clustered (Figure 14). The width of the window panes reflects the width of the larval head capsule.

vii. Because of the nature of overlapping FAW generations, it may be useful to distinguish between old and fresh damage. For the purposes of scouting, record only fresh damage.

Figure 14. **Early-instar FAW damage on maize leaves in the form of pinholes or small window panes.**

viii. Signs of infested whorls include fresh window panes (in the whorl), FAW larvae, fresh fecal matter (frass), and fresh whorl-feeding-damage.

ix. Whorl-feeding-damage results from damaged-leaves expanding out of the whorl, producing a horizontal series of holes across a "pinch" in the leaf (Figure 15).

x. Record the number of seedlings that have infested whorls and calculate the percent (%) infestation for this scouting location (see Scouting Form in Section 5).

Figure 15. **FAW feeding in the whorl. As the leaf emerges a characteristic "paper doll" cutout pattern emerges. This occurs when larvae feed on the rolled-up leaf in the whorl.**

xi. Now move to the next spot. Examine 10-20 plants. Record the data. Repeat the process a total of 5 times.

xii. After scouting the 5 locations in the field, calculate the total percent (%) infestation across the field. Then refer to Table 1 to determine if the Action Threshold recommends chemical treatment.

- ***<u>Action Threshold: Early Whorl Stage:</u>*** **If 20% (range of 10-30%) of the seedlings are infested, an insecticide application is justified. Many practitioners choose the lower 10% as the Action Threshold. This decision is informed by the availability of safe pesticides, proper equipment, and market value of the maize (see Section 4).**

3.3.3. Scouting at the Late Whorl Stage (V7-VT)

i. Move through the field quickly. Stop 5 times. Examine a variety of places in the field (but avoid edge rows).

ii. At each stop, examine 10-20 plants. Examine the newest three to four (3-4) leaves emerging from the whorl plus the emerging tassel.

iii. Signs of infested whorls include fresh window panes (in the whorl), FAW larvae, frass, and fresh whorl-feeding-damage.

iv. Record the number of plants (out of 20) with fresh window panes or infested whorls.

Figure 16. **Emerging tassel. As the maize plant develops, the tassel will emerge at VT. The emerging tassel will push FAW larvae out of the whorl. Large larvae will migrate to the growing ear axials.**

- ***<u>Action Threshold - Late Whorl Stage</u>:*** **If 40% (range of 30-50%) of the plants are infested, an insecticide application is justified. As noted in Table 1, many practitioners may choose to control FAW at the low end of this range, *i.e.*, 30%. Once better economic data are available the decision will be based on the ET and Economic Injury Level. In the interim, these guidelines, based on expert opinion, should work (see Section 4).**

  » Insecticide applications during the Early and Late Whorl Stages not only reduce foliar feeding by FAW, but also reduce the worm load as tassels begin to emerge (Figure 16).

3.3.4. Scouting at the Tassel & Silk Stage (R1-R3)

i. Move through the field quickly. Stop 5 times. The "Ladder" scouting pattern (Figure 11) may prove helpful at this stage. Examine a variety of places in the field but avoid the edges because of edge effects. At each stop, examine 10-20 plants.

ii. When the tassel emerges, it pushes the FAW larvae out of the whorl. From this point forward, FAW larvae hide in the leaf axils, at the base of the developing ear/cob, and/or in the tip of the ear. (At this stage, there is no whorl left for the FAW larva to hide in.)

iii. Examine every ear and the silks. FAW larvae not only eat through the middle of the ear, but also infest the tip. Examine a leaf immediately above and below each ear.

iv. Record the number of plants with **<u>any</u>** fresh feeding damage, the number of plants that are infested with FAW larvae, and the number of plants that have damaged cobs/ears.

v. Make sure to identify any larvae that are found. The best "field mark" for identifying small FAW is the four-dot square on the eighth abdominal segment (Figure 17).

Figure 17. "Four-dot square" (indicated by arrow) on 8th abdominal segment of FAW.

- **<u>Action Threshold: Tassel & Silk Stage:</u> If 20% (range of 10–30%) of the tasseling plants are infested with FAW or have ear/cob damage (Figure 18), an insecticide application may be justified. <u>See Section 4 for important considerations and cautions about insecticide application at this stage.</u>**

Figure 18. Ear/cob damage caused by FAW larva.

4. Action Thresholds and Recommendations

The following table summarizes the current Action Threshold recommendations.

Table 1. Summary of FAW Action Thresholds. Thresholds are expressed as percentages of plants with typical FAW damage/injury symptoms.

Maize Crop Stage	V Stage	Action Threshold for Smallholder Farmer	Action Threshold for Village-Level Progressive Farmer
Early Whorl Stage	VE-V6	20% (10-30%)	20% (10-30%)
Late Whorl Stage	V7-VT	40% (30-50%)	40% (30-50%)
Tassel & Silk Stage	R1-R3	NO SPRAY Unless low-toxicity & supportive of conservation biological control	20% (10-30%)

The following should be considered when interpreting the Action Thresholds in Table 1:

- Recommendations are presented as the midpoint of the range, *e.g.*, 20% (range of 10-30%).
- Recommendations are presented as Action Thresholds based on expert opinion, including practitioners in Africa and the Americas. These estimates will be revised as Economic Thresholds when data become available. Accordingly, farmers should consult host country extension advisors whenever possible to provide real-time advice on the use of Table 1.
- In some instances, practitioners have chosen the lower (10%) Action Threshold for treating maize at the Early Whorl Stage. In contrast, other practitioners may choose a higher Action Thresholds based on their expertise and the local situation.
- The decision to treat early and at a lower Action Threshold is based on the fact that many smallholder farmers lack Personal Protective Equipment (PPE), proper spray equipment, and knowledge on the safe use of pesticides. Treating at an earlier maize growth stage (pre-VT) may help eliminate situations where smallholder farmers would be spraying overhead at the VT or reproductive stages.
- **We do not recommend that smallholder farmers apply insecticide at or post-VT because it is too dangerous for the applicator and for his or her family.**

Additional safety considerations:

- Safe use of insecticides requires PPE. The poisonous effects of pesticides are not easy to see.
- If sprays are used, effective low-toxicity insecticides exist and should be used when they are available in order to conserve natural enemies of FAW and to limit human exposure to chemicals. See Chapter 3 for more guidance on pesticide use.
- The first edition of this FAW IPM Guide does not address Pesticide Applicator Training. In the interim, please consult country-specific experts. The Trainee Manual: Introduction to Integrated Pest Management (2011), produced by CropLife International, is also a good resource. https://croplife-r9qnrxt3qxgjra4.netdna-ssl.com/wp-content/uploads/2014/04/IPM-Trainee-Manual-2011-update.pdf
- Smallholder farmers and their families are at risk of exposure to highly hazardous pesticides.
- Smallholder farmers are sometimes unaware of insecticide pre-harvest and re-entry intervals. Green ears/cobs of maize that have been recently sprayed must not be used for immediate consumption, as this could present a serious risk of chemical exposure.
- Smallholder farmers should apply control measures early, but based on Action Thresholds (Table 1), when the FAW larvae are small. In addition to being the safest time of application, this timing will reduce the FAW larval load as the plants begin to form ears/cobs.

Keys to integrated, least-toxic control of FAW include early detection and the harmonization of biological, cultural, and chemical control tactics:

- Early detection of FAW infestations requires timely and regular field scouting. Timing may be aided by use of pheromone traps.
- Harmonization of control tactics supports and enhances the impact of natural enemies (see Chapter 5 on Biological Control). When the pest pressure is moderate or low, choose insecticides that are not toxic to beneficial insects. Maize pollen can attract honey bees. Therefore, consider applying insecticides late in the day just before dusk, when honey bees and other pollinators have returned to their hives.
- Smallholder farmers may resort to low-cost control measures that are labor-intensive but nonetheless effective. For example, they may search for egg clusters in the field and crush them with their fingers. They may also search for larvae that can be fed to chickens.
- Many cultural control practices that are too labor-intensive for commercial farmers (*e.g.*, hand picking of larvae) may make sense to smallholder farmers, especially if they have no other means of control and if labor is not an issue.

4.1. Making a Safe Spray/No-Spray Decision – The "Four Steps Repeat" Process

- It is important to look for opportunities to **not** spray chemical pesticides against FAW. The combination of monitoring and scouting gives the most reliable guide to "no-spray" decisions.
- A Four Steps Repeat[2] decision-making sequence should be considered before making a chemical spray decision.
- The four steps sequence uses the following information:
  1. Moth counts at the regional and local scale
  2. The weather forecast (probability of rain)
  3. Systematic field scouting
  4. Action Thresholds

4.1.1. Instructions for the Four Steps Repeat Process

i. Before arriving at the field:

- Check the regional moth counts **(step 1)**.
- Check the weather forecast **(step 2)**.

ii. At the field:

- Check the pheromone trap **(step 3)**.
- Scout the field and apply an Action Threshold **(step 4)**.

If regional and local moth counts are low, and there is very little evidence of FAW infestation in the crop, this is considered as a "double-safe" decision-making environment: (1) There is no FAW in the field; and (2) there are no incoming moths laying eggs in the field.

iii. Repeat:

- In the case of a "yes-spray" decision, come back in 7-10 days. The use of PPE when re-entering the field is essential. It is also important to learn what the re-entry restrictions are for the specific chemical used. Repeat the four steps.
- In the case of a "no-spray" decision, come back in 4-7 days. Repeat the four steps. The number of days is dependent on how close you are to the Action Threshold. If you are close then the shorter 4 day interval is recommended.
- NOTE: In all cases respect the proper re-entry restrictions.

[2]This Four Steps Repeat process is an adaptation of the Five Steps Repeat process developed by Dan McGrath.

4.2. Insecticide Resistance Management (IRM)

- Insecticides, if used appropriately and according to label directions (see Chapter 3), are a safe and powerful tool for controlling insect pests. However, misuse can lead to the insect developing resistance to the active ingredient, besides causing damage to natural enemies and the environment. This is especially important with FAW, as the insect has a long history of developing resistance to insecticides. Therefore, necessary precautions should be taken to avoid development of insect resistance.
- The FAW in tropical climates completes its life cycle in 30-40 days. Avoid treating successive generations of FAW with the same active ingredient.
- Rotate active ingredient with products that have ingredients with different modes of action every 30 days.
- The pesticide label specifies how often and at what rate an insecticide should be applied per season. These instructions are based on research, and are designed to slow down the development of insecticide resistance in the FAW population.
- Apply at the recommended rates, intervals, and seasonal totals, as specified by the label and the instructions.

4.3. Educational Targets

- FAW is a newly introduced insect pest in Africa. Therefore, many farmers are unfamiliar with the pest and need training on pesticide safety and the use of pre-harvest intervals associated with specific insecticides used for FAW control.
- Larger village-level progressive farmers should be informed by regional egg-laying trends, should be aware of how to determine the level of FAW infestation in their maize fields (% infested plants), and apply Action Thresholds in order to reduce costly and unnecessary insecticide applications.
- Smallholder farmers should use the same general approach to decision making based on scouting as the commercial large-scale farmers or seed producers, with the exception that spraying after the VT Stage in the maize crop has to be avoided.
- Agricultural professionals need training to increase their knowledge, self-confidence, skill levels, and willingness to make no-spray decisions when it is safe to skip an insecticide application.

5. Scouting Form

Planting Date: **District:** **Location:** **Your name:**

	Week 1							Week 2							Week 3						
Sampling Date																					
Maize Growth Stage:																					
Dates of rainfall /intensity:																					
Insecticides Applied/Rates/Dates:																					
Pheromone Trap Data	Raise the trap as the maize grows taller. Keep the bottom of the trap 30 cm above the plants.																				
Number of FAW moths:																					
Number of AAW moths:																					
Early Whorl Stage (VE-V6)	**Examine two to three (2-3) newest leaves emerging from the whorl.**																				
Five Stops	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**
#Plants with fresh window panes/ Total																					
#Plants with infested whorls/ Total																					
Late Whorl Stage (V7-VT)	**Examine three to four (3-4) newest leaves emerging from the whorl plus the emerging tassel.**																				
Five Stops	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**
#Plants with fresh window panes/ Total																					
#Plants with infested whorls/ Total																					
Tassel & Silk Stage (R1-R3)	**Examine ear(s) plus leaves and leaf axils at, above, and below the ears.**																				
Five Stops	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**	**1**	**2**	**3**	**4**	**5**	**Sum**	**%**
#Plants with any fresh damage/ Total																					
#Plants with worms/ Total																					
#Plants with damaged ear/cob/ Total																					

Pesticide Hazard and Risk Management, and Compatibility with IPM

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Reviewed by the Western Pesticide Risk Reduction Workgroup (a USDA-funded group of State IPM Coordinators from 14 U.S. Western States and Pacific Island Territories).

1. Introduction

This chapter was conceived at a workshop in Entebbe, Uganda, at which many of the co-authors were participants, with additions from two further Training and Awareness Generation Workshops on Fall Armyworm (FAW) Management in Harare and Addis Ababa.

We have used here several approaches to meet a complex set of needs associated with pesticide management and use against FAW, knowing that pesticides are already being widely distributed to FAW-affected smallholders in Africa who may lack any prior experience with applying them.

We know at this stage of the FAW outbreak in Africa that pesticide use is likely to be justified in some circumstances, but we currently lack sufficient understanding of the situations where pesticide benefits are likely to exceed the risks that they may pose. We are also aware that expertise in efficient pesticide application is limited in many parts of the continent. Ineffective application can result in some pest reduction, but can also cause harm to beneficial insect populations, and could lead to increased pest population pressure and greater damage to crops. It can also result in unacceptable impacts to human health. Finally, the African marketplace for pesticides is complex, with informal pathways for distributing unlabeled materials and limited capacity in regulatory organizations to phase out highly hazardous compounds and replace them with economic, efficacious, and lower-risk chemicals (*e.g.*, De Bon *et al.* 2014; Donald *et al.* 2016; Jepson *et al.* 2014; Pretty and Bharucha 2015).

Later versions of this chapter and associated publications will summarize information about the efficacy of synthetic pesticides and biopesticides from rigorously conducted experiments, review application parameters that maximize efficacy, consider background levels of resistance to some classes of compounds, and quantify risks to human health and the environment that must be considered in the face of limited access by farmers to education and protective clothing.

In this first version, we seek to provide:

1. Information on barriers to and opportunities for integrated pest management (IPM) implementation and effective pesticide management.
2. Accessible and practical IPM guidelines.
3. A discussion of how pesticides can fit within a prototype IPM guideline.
4. Identification of pesticides for which risks to human health and the environment are likely to exceed any potential benefits.
5. A summary of simple steps that may minimize risks for other pesticides.

We have embraced a collaborative and inclusive approach in drafting this chapter that could be broadened still further. We have included university research and extension specialists, pesticide industry technical experts, international agricultural research center scientists, national and regional regulatory officials, agency staff, and policy experts.

This chapter aims to reduce potential pest-related losses by providing critical information about pesticides and how to select them to extension educators and advisors, and to support regulatory authorities with a strong technical platform for pesticide registration decision-making. It will also begin to guide efficacious pesticide use, with minimized risk (economic, health, and, environmental), and in a way that is compatible with IPM (see Chapter 1).

2. Barriers and Opportunities Associated with Pesticides and IPM against FAW

IPM principles, and a broad knowledge base about FAW biology and management from other countries (*e.g.,* Day *et al.* 2017), provide a basis for progress with FAW IPM in Africa. We do, however, perceive a number of barriers to the rapid adoption of IPM with low pesticide risks, and we list these below to guide planning of IPM program development across multiple scales.

2.1. Barriers to IPM Implementation and Effective Pesticide Management

The authors have wide experience in pesticide management throughout Africa and include here a summary of barriers or constraints that might limit the usefulness of this chapter and/or limit the impacts of the information that it, and planned future publications, contain. These should be borne in mind by anyone seeking to use this information so that barriers to effective and low-risk pesticide use can be addressed explicitly.

The barriers fall under four main themes: pesticide regulation and access, pesticide safety capacity, farmer engagement and education, and economics/efficacy data.

2.1.1. Pesticide Regulation and Access

- The lack of a mature, current pesticide market in maize limits experience, knowledge, and access to information at all levels in the system, from farmers to educators and researchers in industry, state institutions, and NGOs. The reason for this historically has been low yield, unstable prices, and lack of affordability of pesticides. This means that the infrastructure for IPM and pesticide use education support in maize must be built from the ground up if pesticide use is widely adopted.
- Large-scale purchase of pesticides by governments can act as a barrier to successful IPM programs. Usually this is undertaken as a short-term solution without the necessary consultations and the tendency is to buy products that are “perceived” to be very effective, but which may not be compatible with IPM or requirements for low health risks.
- Pesticide sale volumes may be too low in some African countries to encourage industrial support for lower-risk chemistries that may themselves require product stewardship if they are to be used efficaciously. Without this support, there will be a tendency for farmers to select highly toxic pesticides that are often inexpensive and easily accessible. This is because highly toxic pesticides can limit pest outbreaks even if they are not applied in an even, calibrated way. These applications are also accompanied by high risks to human health (*e.g.*, Jepson *et al.* 2014), and they impair long-term management of the target pest(s) because they can eliminate natural enemy populations.
- The African marketplace is currently dominated by so called “generic” pesticides, which largely consist of older, more toxic chemistries and which receive limited or no technical support from their manufacturers and distributors.
- There is a lack of post-market surveillance capacity across much of the continent to ensure that only properly registered materials are reaching farmers. This can result in undocumented distribution of hazardous materials that may promote pest outbreaks and also harm human health, wildlife, or domesticated animals (Jepson *et al.* 2014; Donald *et al.* 2016).
- There are some excellent examples of regulatory processes in Africa, including the multi-country system that operates in West Africa (*e.g.*, Jepson *et al.* 2014). There is however, limited capacity to fully implement the laws and procedures that do exist, and the onus is placed upon farmers to manage pesticide risks.

2.1.2. Capacity for Reducing Pesticide Risk

- Personal protective equipment (PPE) may not be compatible with conditions in Africa – and there is evidence that PPE is not available, used, or even marketed (*e.g.*, Williamson *et al.* 2008; Ajayi and Akinnifesi 2007; Jepson *et al.* 2014). This should limit the pesticides that are recommended to those that pose low risks even when used without PPE.
- Choice of application equipment, effective calibration, and timing of application are critical for efficacy. If these are lacking, pesticide use can increase significantly because repeated applications become necessary.

- There is a lack of experience with pesticide container handling and disposal among smallholder farmers. There is a great deal of historical data on the dangers that these containers pose when they are widely available, and this hazard must be part of any pesticide management education program that is undertaken.
- There is low capacity for handling biological control agents and for formulating and handling biopesticides, including botanicals that might provide a low risk alternative to conventional, synthetic pesticides.
- Technical expertise and infrastructural capacity – the key requirements for a safely regulated marketplace – do not always exist. We therefore have concerns about the potential for pesticide misuse and overuse. Acute and chronic health impacts may not always be documented.

2.1.3. Farmer Engagement and Education

- A mechanism is needed to operationalize this material, but it is not immediately apparent how the needs of underserved farmers can be addressed across the large invasion zone of FAW. Farmer Field Schools have the longest and best track record for meeting this need, but multiple modes of education and communication will be necessary.
- The remoteness of some audiences, and of many under-represented groups, limits the potential for more complex education programs to reach them, and for critical information about hazard and risk to have the required impact. Radio and other pathways will need to be employed.
- Subsistence agriculture, as opposed to commercial agriculture, represents a challenging audience for information-intensive IPM programs, yet it is the dominant form of farming exposed to FAW. Important information about pesticide hazards and risks must be presented in ways that are accessible to audiences who have not previously used toxic chemicals or been exposed to the fundamental concepts of IPM (Parsa *et al.* 2014; Pretty and Bharucha 2015; Settle *et al.* 2014).

2.1.4. Economic and Efficacy Data

- There is currently a lack of crop economic data and critical information about pesticide efficacy against FAW that is applicable to different crop-growing regions and agroecologies in Africa. It is not possible at present for anyone to develop and deliver pesticide use recommendations that are locally adapted to reflect the available chemicals, local conditions, and costs.
- The costs of unintended pesticide impacts on human health (*e.g.,* Maumbe and Swinton 2003) are not factored into current assessments of the suitability of certain pesticides in the management of FAW.

2.2. Accessible and Practical IPM Guidelines

IPM programs are successfully adopted and implemented when they have clear goals that include the needs and requirements of the farmers that they are meant to serve.

Example goals include:

1. Implement a sustainable cropping system that minimizes economic (food security), health, and environmental risks.
2. Overcome barriers to IPM adoption.
3. Incorporate new, practical findings when these become available.
4. Maximize the contributions by all stakeholders in the process.

These are typical goals derived from a variety of farming communities in the USA, and in West Africa by Oregon State University, but they can vary with context and the ways in which farmers voice them in different places.

Typically, a farming group will be consulted to determine their desired goals/outcomes that are then translated to fit within the tried-and-tested tenets of IPM:

1. Prevent or avoid significant crop losses using host plant resistance and cultural management (see Chapters 4 and 6), and tolerate sub-economic crop losses.
2. Identify FAW, distinguish it from other maize lepidopteran pests, monitor and scout (see Chapter 2), and respond to potentially damaging FAW infestations at the community and field scales.
3. Suppress FAW and other pests through biological control (see Chapter 5), physically, and if needed, chemically, in response to a locally validated threshold and with low risks to human health and the environment.
4. Undertake the necessary education, research, and regulatory work cooperatively to facilitate progress.

Having clear goals, expressed by farmers, helps to align opportunities for adoption of IPM practices within the context of local farming systems, and it greatly enhances opportunities for IPM uptake and adoption (*e.g.*, Pretty and Bharucha 2015; Settle *et al.* 2014).

Specific challenges to effective IPM in FAW management include:

1. FAW is a novel pest that is still establishing – creating alarm when damage is first seen.
2. Prevention and avoidance options (*e.g*, early planting) are not yet widely practiced in Africa, although there is significant potential for these to be adopted through appropriate education programs.
3. Monitoring and scouting methods have been developed, but these have not been widely distributed. Education and support programs are needed to promote effective monitoring and scouting, as well as interventions.
4. Effective and low-risk pesticides are needed; suppression has focused to date upon highly hazardous pesticides that carry health and environmental consequences, and which can suppress biological control throughout the season.
5. Education, research, and regulatory processes are yet to be scaled up and coordinated.

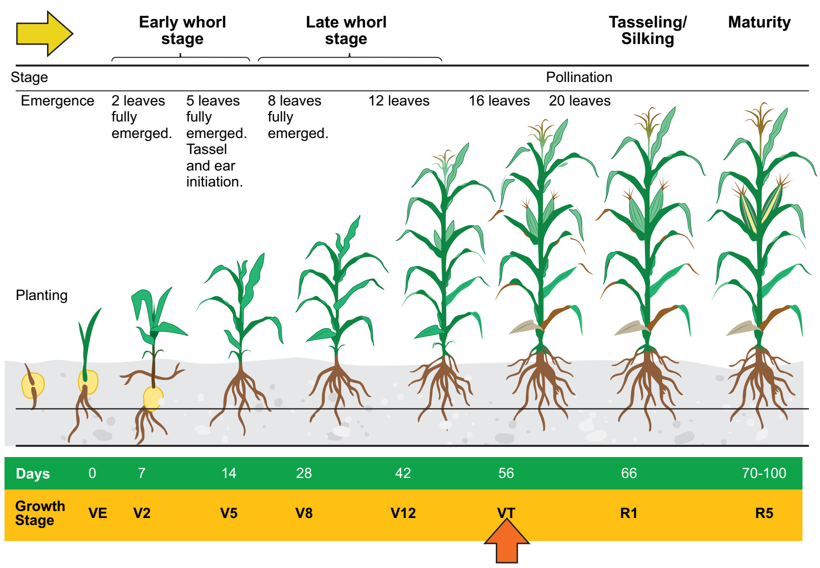
We propose the simple IPM framework below as a major aspect of pesticide risk management (Figure 1). The key criterion of cessation of spraying after the tassel (VT) stage is recommended for smallholder farmers who lack access to training and who also lack adequate PPE. This threshold has an explicit pesticide risk management purpose, because farmer and family exposures to pesticide residues will be high in a mature crop that is tall and envelops people that enter it. Health costs are likely to exceed potential benefits from pesticide applications that, by this growth stage, will lack efficacy with handheld application equipment. It is recognized that progressive farmers with higher levels of training and access to appropriate PPE and spray equipment may choose to treat their fields beyond VT but for the majority of low-resource farmers this is again not recommended. Even for progressive farmers it must be recognized that PPE is not adequate when HHPs, OPs and carbamates are used; so spraying beyond VT only applies to lower risk chemistries.

Given this criterion, the role of any pesticides used before the VT stage is to contribute to maximum suppression of potentially damaging pest populations in a way that complements biological and cultural pest suppression. This relies upon: (1) the use of monitoring and scouting to determine whether or not a treatment is justified, and (2) the capacity to select and source a pesticide that can be applied efficaciously with low risk to human health and the environment. We also highlight here that if broad-spectrum pesticides are applied at an early stage in crop growth, desirable biological control agents may be eliminated from fields for an entire cropping season (Jepson 2007, 2009; Sherratt and Jepson 1993).

Later versions of this chapter and supplementary publications will report the impacts of currently used pesticides on natural enemies of FAW, and will also propose strategies that enable pesticides and natural enemies to complement each other (Jepson 2007). In this first version, we provide initial natural enemy impact assessments only for highly hazardous pesticides.

- Begin scouting at early whorl stage (VE onward)
- Use less hazardous synthetic pesticides, and those only when needed (= beyond specific economic threshold) for:
  - Greater efficacy
  - Lower health risk (less human exposure)
- Pesticide application preferably through trained applicators with appropiate personal protective equipment

Maize growth stages



- Prevent unnecessary pesticide sprays at VT stage onward to avoid risks to human health and natural enemies.
- Pesticide sprays at VT stage onward will have:
  - Low efficacy
  - High human exposure
  - High risk to natural enemies

Figure 1. Possible initial model for IPM against FAW that acknowledges pesticide risks to non-target organisms, including humans; efficacy against the pest; and how both risk and efficacy vary with crop growth stage.

3. Developing Pesticide Data Summaries/ Guidelines and Managing Risks

3.1. Ranking Pesticides for Compatibility with IPM

The IPM criteria matrix (Table 1; modified from Farrar *et al.* 2018) can be used to form the basis for determining which pesticides might be compatible with other IPM tactics, and also minimize the likelihood of unacceptable risks to human health and the environment. If these criteria prove to be widely accepted, then a process can be conducted with partners throughout Africa that screens candidate pesticides to provide a transparent process for classifying pesticides that can lead to more effective management.

The matrix below describes the ways in which proposed pesticide uses could possibly fit into an IPM program. It encompasses a number of specific factors across eight categories: efficacy, economics, non-target effects, resistance concerns, environmental fate, worker risk, compatibility with monitoring, and utility.

Each factor can be assessed through descriptions of affirmative, intermediate, and negative compatibility attributes. Together, the factors described in the IPM criteria matrix integrate the principles of IPM as a systematic method of addressing pest management problems with the pragmatic requirements of economically viable farming in Africa.

Of particular note for FAW is widespread resistance to numerous classes of pesticides, including synthetic pyrethroids, which may be used extensively in Africa (https://www.pesticideresistance.org). This raises the importance of considering resistance in determining IPM compatibility for pesticides. Without a clear understanding of the baseline patterns of resistance exhibited by FAW, IPM alternatives to pesticides should be implemented as widely as possible, and natural enemy activity should be maximized, at first by avoiding brod-spectrum insecticides that are toxic to insect, arachnid and acarine predators, and parasitoids of maize pests, including FAW.

Table 1. IPM Criteria Matrix

Attribute	Affirmative Criteria	Intermediate Criteria	Negative Criteria
Efficacy			
Efficacy	*Data from field trials under similar environmental/climatic conditions demonstrate good efficacy against target pest*	*Data demonstrating efficacy against target pest is from a different set of environmental/ climatic conditions*	*Data from field trials under similar environmental/climatic conditions demonstrate marginal or inconsistent efficacy*
Speed of action and persistence that contribute to efficacy – based on FAW attributes at different crop growth stages, and relative susceptibility of different FAW development stages	*Still to be determined for FAW management in Africa*		
Efficacy level under different pest pressures	*Product effective under high pest pressure*	*Product effective under moderate pest pressure*	*Product only effective under low pest pressure*
Applicability to smallholder agriculture	*Product low risk; application equipment and PPE available*	*Product moderate risk; sprayers and PPE less available*	*Product high risk; effective sprayers and/or PPE less available*
Containers, practicalities for disposal	*Container disposal assured*	*Disposal protocols and training available, but not implemented*	*Disposal and proper container handling not assured*
Regulatory factors and product availability	*Product registered and available*	*Product registered but availability limited*	*Product not registered*
Economics			
Price	*Treatment costs lower than other registered products with equivalent efficacy*	*Treatment costs similar to other registered products with equivalent efficacy*	*Treatment costs higher than other registered products with equivalent efficacy*
Value in overall management	*Total number of applications needed to achieve economic control decreased*	*Total number of applications needed to achieve economic control remains constant*	*Total number of applications needed to achieve economic control increased*
Non-target Effects (See hazard and risk tables below)			
Selectivity – Toxicity to pollinators (honey bees and native pollinators)	*Non-toxic to pollinators*	*Relatively non-toxic to pollinators only if applied during periods when pollinators are not active*	*Toxic to pollinators*
Selectivity – Toxicity to beneficial arthropods	*Non-toxic to beneficial arthropods*	*Non-toxic to some beneficial arthropods; toxic to others*	*Toxic to many beneficial arthropods; likely to result in secondary pest outbreaks*
Selectivity – Toxicity to vertebrates	*Low or no risk to birds, other wildlife, and domesticated animals*	*Intermediate risk to birds, other wildlife, and domesticated animals, or toxic to some and not others*	*Toxic to birds, other wildlife, and domesticated animals*
Selectivity – Toxicity to aquatic life (aquatic algae, aquatic in-vertebrates, or fish chronic risk)	*Non-toxic to aquatic life*	*Intermediate or variable toxicity to aquatic life*	*Toxic to aquatic life*
Post-application movement as vapor or within plant	*Pesticide does not move in plant or movement within plant does not increase risk to pollinators, beneficial arthropods, other beneficial organisms, or non-target organisms*	*Pesticide movement within plant may increase risk to some pollinators, beneficial arthropods, other beneficial organisms, or non-target organisms*	*Pesticide movement within plant increases risk to pollinators, beneficial arthropods, other beneficial organisms, or non-target organisms*

Attribute	Affirmative Criteria	Intermediate Criteria	Negative Criteria
Compatible with cultural pest management practices (for example, resistant varieties, crop rotation, sanitation, vegetation management)	*Use of pesticide is additive or synergistic with cultural pest management practices*	*Use of pesticide does not decrease effectiveness or impede implementation of cultural pest management practices*	*Use of pesticide is not compatible with or decreases the effectiveness of cultural pest management practices*
Resistance Concerns			
Mode of Action (MOA)	*Product has unique MOA for crop/pest combination*	*One or two other pesticides with the same MOA are available for crop/pest combination*	*Several pesticides with same MOA are available for crop/pest combination*
Field evidence or farmer reports of changes in efficacy or evidence of resistance associated with the candidate pesticide	*No field reports of resistance*	*Field reports of resistance, but not validated*	*Validated field reports of resistance, supported by research*
Resistance potential based upon MOA group	*When used according to label instructions, there is low risk of pests developing resistance to the pesticide*	*When used according to label instructions, there is moderate risk of pests developing resistance to the pesticide*	*When used according to label instructions, there is significant risk of pests developing resistance to the pesticide*
Resistance management	*Useful in managing FAW resistance*	*Potentially useful in controlling FAW resistance*	*Not likely to be useful in FAW resistance management because of existing resistance to the active ingredient (a.i.), cross- resistance with a.i.'s with same MOA*
Environmental Fate			
Off-site movement – Drift potential	*Pesticide formulation or application method has little or no potential for drift (e.g., granular formulations or chemigation through drip irrigation lines)*	*Pesticide application method has some potential for drift (e.g., boom sprayer applications)*	*Pesticide application method has potential for drift (e.g., aerial or airblast sprayer applications)*
Off-site movement – Run-off potential	*Pesticide or pesticide application method result in little or no potential for run-off to surface water*	*Pesticide or pesticide application method result in some potential for run-off to surface water*	*Pesticide or pesticide application method result in potential for run-off to surface water*
Off-site movement – Leaching potential	*Pesticide or pesticide application method result in little or no potential for leaching to water groundwater*	*Pesticide or pesticide application method result in some potential for leaching to water groundwater*	*Pesticide or pesticide application method result in potential for leaching to water groundwater*
Persistence of parent and breakdown products	*Relatively short-half life*	*Moderate half-life*	*Long half-life, which increases risk of off-site movement or non-target exposure*
Other IPM Factors			
Worker risk	*Signal word CAUTION / low ipmPRiME* inhalation risk*	*Signal word WARNING / medium ipmPRiME* inhalation risk*	*Signal word DANGER / high ipmPRiME* inhalation risk*
Compatibility with pest monitoring at farm scale	*Tight connection between pest population (or forecast) and economic damage threshold*	*Lack of good data on connection between pest population (or forecast) and economic damage threshold*	*Applications must be made preventatively because of poor relationship between pest monitoring data and forecast*
Preventative applications	Reduces need for additional pest management inputs later		*Increases other pest management inputs*
Evidence from the farm level of potential value of this product	*Compatibility with decision-making guidelines verified*	*Compatibility with decision support guidelines not verified*	*Product not compatible with decision support guidelines*

*Details of ipmPRiME can be found in Jepson *et al.* (2014), and data derived from this tool are presented below.

3.2. Hazard and Risk Classification for Pesticides in Current Use Against FAW, and Suggested Risk Mitigation

We provide here an initial summary of the hazards and risks posed by pesticides that are in current use, or pesticides that have been employed against FAW in other systems. It provides data that are not widely available to IPM educators and scientists and should contribute to design and implementation of initial approaches to IPM that consider risks to human health, the environment, pollination, and natural enemies.

3.2.1. Highly Hazardous Pesticides

Tables 2 and 3 identify those pesticides that have been classified as highly hazardous by the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO). For all of these, it is likely that risks to human health and the environment will exceed any potential benefits in the maize-producing regions of Africa, and their use should be avoided.

Many of these pesticides are in the current marketplace and recorded as being used against FAW (*e.g.*, Day *et al.* 2017).

The FAO/WHO Joint Meeting on Pesticide Management (JMPM), in their 2nd session in October 2008, recommended that highly hazardous pesticides (HHPs) should be defined as having one or more of the following characteristics (see also: http://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/code/hhp/en/):

a. Pesticide formulations that meet the criteria of classes IA (extremely hazardous) or IB (highly hazardous) of the WHO Recommended Classification of Pesticides by Hazard.
b. Pesticide active ingredients and their formulations that meet the criteria of carcinogenicity Categories 1A and 1B of the Globally Harmonized System on Classification and Labeling of Chemicals (GHS).
c. Pesticide active ingredients and their formulations that meet the criteria of mutagenicity Categories 1A and 1B of the GHS.
d. Pesticide active ingredients and their formulations that meet the criteria of reproductive toxicity Categories 1A and 1B of the GHS.
e. Pesticide active ingredients listed by the Stockholm Convention in its Annexes A and B, and those meeting all the criteria in paragraph 1 of Annex D of the Convention (for further information about WHO hazard classes, and the Conventions that contribute to HHP classification see FAO (2014).
f. Pesticide active ingredients and formulations listed by the Rotterdam Convention in its Annex III.
g. Pesticides listed under the Montreal Protocol.
h. Pesticide active ingredients and formulations that have shown a high incidence of severe or irreversible adverse effects on human health or the environment.

The Integrated Plant Protection Center (IPPC) and the Sustainable Agriculture Network (SAN) are the first organizations to have operationalized this definition of HHPs, and use of HHPs has largely been prohibited by the Sustainable Agriculture Standard (SAN 2016) and Pesticide Lists (SAN 2017) in tropical and subtropical fruit, coffee, tea, and cacao production. The designation of HHPs in Tables 2 and 3 is taken from this comprehensive analysis, which has been subject to stakeholder consultations and international peer review in more than 40 countries. Very few exceptions were found that made continued use of HHPs a necessity in any crop, because less toxic and registered efficacious alternatives are nearly always available.

The authors of this chapter argue that HHPs should be eliminated from consideration and use for FAW management, and that alternatives to these pesticides should be employed. This, if implemented, would address a number of the barriers to adoption of effective IPM and pesticide risk management (PRM) cited above, and it would take into account the lack of preparedness and capacity among pesticide users that is one of our greatest concerns.

3.2.2. Pesticides Requiring Risk Mitigation[1]

Of the hundreds of pesticides that remain, after HHPs have been isolated from the list of available products, a number still pose risks to human health and the environment that can be mitigated by some easy-to-adopt practices. The IPPC and the SAN have conducted a comprehensive analysis of pesticide risks, and these are summarized in Tables 2 & 3 below for pesticides that require some form of risk mitigation to reduce these possible impacts. **Please note that the authors, editors, USAID and USAID-supported organizations, including CIMMYT, preparing this document are not recommending the pesticides listed in Tables 2 & 3, but are simply reporting on materials currently in use.** Not detailed herein are the different formulations and combinations in common use which have significant bearing on the differential choices for certified applicators and commercial versus smallholder farmers.

This methodology has also been subjected to international peer review, and similar risk mitigation tables are already in use in approximately one million farm households in the subtropics and across a number of states in the Western USA.

The information provided below is commonly given on pesticide labels in western countries. For African countries, however, detailed label guidance on risk management may not be always provided on the label.

Pesticide risks requiring mitigation in Tables 2 and 3 are categorized as those associated with workers/ bystanders, aquatic life, wildlife, pollinators, and natural enemies. In later versions of this chapter, this range of risks will be expanded to include applicators and workers who re-enter fields after application.

The analysis conducted for these tables is based on the Oregon State University IPPC's state-of-the-science risk assessment tool ipmPRiME (Jepson *et al.* 2014) and a risk model that identifies moderate to high (10% or greater) risk in the following categories:

1. Risk to aquatic life:

   Pesticides qualified for this risk category if one or more ipmPRiME aquatic risk models (aquatic algae, aquatic invertebrates, or fish chronic risk) indicated high risk at a typical application rate.

2. Risk to wildlife or domesticated animals (fowl and mammals):

   Pesticides qualified for this risk category if one or more ipmPRiME terrestrial risk models (avian (bird) reproductive, avian acute, or small mammal risk) indicated high risk at a typical application rate.

3. Risk to pollinators:

   Pesticides were selected based on a widely used hazard quotient (HQ) calculated using the pesticide application rate (in g a.i./ha) and the contact LD_{50} for honey bee (*Apis mellifera*). Values of HQ<50 have been validated as low risk in the European Union, and monitoring indicates that products with an HQ>2,500 are associated with a high risk of hive loss. The HQ value used by SAN is >350, corresponding to a 15% risk of hive loss. The quotient includes a correction for systemic pesticides, which amplify pesticide risks to bees.

4. Risk to bystanders:

   Inhalation risk to bystanders was calculated using the ipmPRiME model for inhalation toxicity (Jepson *et al.* 2014) calculated on the basis of child exposure and susceptibility. This index is protective for workers who may enter fields during or after application, and also for bystanders.

5. Risk to natural enemies:

   The index is based upon published bioassay data, databases including SELCTV held at Oregon State University, natural enemy side-effects test data published by the International Organization of Biological Control, and commercial manuals of side effects. A high-risk, toxic, or hazardous classification is applied in cases where a large proportion (>75%) of the test subjects are killed in biological assays of pesticides applied at field application rate. Our index sought data for three

[1] ipmPRiME provides the source databases and risk assessment models used in development of the 800-compound risk assessment that we refer to. Details of ipmPRiME can be found in Jepson et al. (2014).

important genera of hymenopteran parasitoid biological control agents (*Aphidius* spp., *Encarsia* spp., and *Trichogramma* spp.), a predatory heteropteran bug (*Orius* spp.), and a predatory mite (*Phytoseiulus* spp.). We classified pesticide risk as low if none of these genera exhibited this highest toxicity classification in test data, and as high if any of these genera were highly susceptible.

Tables 2 and 3 should be used to guide initial pesticide selection and mitigation practices (Section 3.2.3) that contribute to risk reduction.

To be effective, these practices must be translated into education programs and media that have a record of leading to behavior change among African farmers. One example of an education program planning, implementation and evaluation process that has been used successfully in West Africa and the USA is provided in Halbleib and Jepson (2016).

3.2.3. Suggested Risk Mitigation Practices

3.2.3.1. Risk mitigation for aquatic life

Use a non-application zone around lake ecosystems (lakes, ponds, and xeric basin ecosystems), river ecosystems (lotic), wetlands (swamps, marshes, wet grasslands, and peatlands), and coastal areas. Establish vegetative barriers and/or use other effective mechanisms to reduce spray drift. The distances below indicate the width of the non-application zone between pesticide-treated crops and aquatic ecosystems:

a) 5 meters, if applied by knapsack sprayers.

b) 10 meters, if applied by motorized sprayers or spray booms.

Suggestions for vegetative barriers:

a) Barriers should be as high as the crop height, or the height of the spray nozzles above the ground, whichever is lower.

b) Barriers should be composed of plants that maintain their foliage all year, but which are permeable to airflow, allowing the leaves and branches to capture pesticide drops.

3.2.3.2. Risk mitigation for wildlife or domesticated animals

Do not apply pesticides within 30 meters of natural habitat or non-crop vegetation; prevent access by domesticated animals, fowl, and mammals after treatment; and do not use crop residues for animal foraging for at least three weeks following application.

3.2.3.3. Risk mitigation for pollinators

a) Use less bee-toxic pesticides if available; and

b) Use a non-application zone around natural ecosystems, establish vegetative barriers, or use other effective mechanisms to reduce spray drift; and

c) Apply only when insect pollinators are not active, or after flowers that attract insect pollinators are managed:

i. Substances should not be applied when weeds are flowering, or until flowering weeds are removed by other means; and

ii. The crop is not in its peak flowering period or at a time of peak attractiveness to bees (*e.g.*, as a source of aphid honeydew or available drinking water).

d) Where beehives are used, temporarily cover these during application, and provide hive bees with a clean water source outside the treated area.

3.2.3.4. Risk mitigation for bystanders

Provide flags or signs to indicate fields that have been sprayed and prevent access to fields by women and children for at least one week after application. Adult men should avoid entering fields for at least five days following application. PPE, including a respirator (with an organic vapor (OV) cartridge or canister with any N, R, P, or 100 series pre-filter), should be worn at the time of application if it is available.

3.2.3.5. Risk mitigation to natural enemies

Pesticides that are toxic to natural enemies should not be used in the early stages of crop development (see initial IPM/PRM guide in Section 2.2). Their use could be minimized by only spot-spraying in areas of high infestation within a field. Sprayers should be calibrated to ensure that excessive doses are not applied.

CAUTION: NO RECOMMENDATION IS IMPLIED BY LISTING PESTICIDES IN THE TABLE BELOW. Pesticides listed here are known to be in use for FAW control. The table provides an assessment of the potential risks posed by the use of these pesticides, based upon the criteria detailed in the chapter and reflected in the column headings.

Table 2. Hazard and risk classification for pesticides known to be in use against FAW in Africa[2].
Red (with black diagonal lines) denotes "Highly Hazardous Pesticide" (HHP), as designated by the WHO Recommended Classification of Pesticides by Hazard, the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), the Rotterdam or Stockholm Conventions, the Montreal Protocol, or evidence for exceptional health or environmental impacts; orange (with black dots) denotes where risk mitigations are needed to avoid unacceptable impacts. The column titled "Labeled for use in (#) African countries" lists the number of African countries approving the listed pesticide for use against FAW. Note that the authors are not providing a recommendation for use of these pesticides or suggesting compatibility with IPM.

Active ingredient	Labeled for use in (#) African countries	HHP criterion	Aquatic life mitigation	Wildlife mitigation	Pollinator mitigation	Bystander inhalation mitigation	Natural enemy toxicity
Abamectin	1						
Acephate	3						
Benfuracarb		Not yet assessed for risk by this process					
Carbaryl	1						
Carbosulfan	1	OBSOLETE STOCK					
Chlorpyrifos	7						
Cyfluthrin							
Cypermethrin	7						
Diazinon	1						
Endosulfan							
Imidacloprid	3						
Lambda-cyhalothrin	5						
Methomyl							
Methyl-parathion	1	OBSOLETE STOCK					
Profenofos	1	Not yet assessed for risk by this process					
Zeta-cypermethrin	1						

[2]http://www.fao.org/3/I8320EN/i8320en.pdf

CAUTION: NO RECOMMENDATION IS IMPLIED BY LISTING PESTICIDES IN THE TABLE BELOW. Pesticides listed here are known to be in use for FAW control. The table provides an assessment of the potential risks posed by the use of these pesticides, based upon the criteria detailed in the chapter and reflected in the column headings.

Table 3. Hazard and risk classification for pesticides not listed above that are labeled for use against FAW in the Americas[3].

Red (with black diagonal lines) denotes "Highly Hazardous Pesticide" (HHP), as designated by the WHO Recommended Classification of Pesticides by Hazard, the Globally Harmonized System of Classification and Labelling of Chemicals (GHS), the Rotterdam or Stockholm Conventions, the Montreal Protocol, or evidence for exceptional health or environmental impacts; orange (with black dots) denotes where risk mitigations are needed to avoid unacceptable impacts; yellow (with white hatches) denotes that the pesticide listed does not pose a risk at commonly applied application rates, but only using the criteria listed above. Natural enemy risks have not been computed for these pesticides yet. The column titled "Labeled for use in (#) African countries" lists the number of African countries approving the listed pesticide for use against FAW. Note that the authors are not providing a recommendation for use of these pesticides or suggesting compatibility with IPM.

Active ingredient	Labeled for use in (#) African countries	HHP criterion	Aquatic life mitigation	Wildlife mitigation	Pollinator mitigation	Bystander inhalation mitigation
Acetamiprid	1					
Alpha-cypermethrin	1					
Azadiractin	2					
Bacillus thuringiensis	2					
Beauveria bassiana	1					
Beta-cyfluthrin	1					
Beta-cypermethrin						
Bifenthrin	1					
Chlorantraniliprole	2					
Chlorfenapyr	1	Not yet assessed for risk by this process				
Chlorfluazuron	1	Not yet assessed for risk by this process				
Chromafenozide		Not yet assessed for risk by this process				
Cyantraniliprole	1	Not yet assessed for risk by this process				
Deltamethrin	3					
Diflubenzuron	1					
Dimethoate	2					
Emamectin benzoate	2					
Esfenvalerate	1					
Ethyl palmitate	1	Not yet assessed for risk by this process				
Etofenprox		Not yet assessed for risk by this process				
Fenitrothion	1					
Fenpropathrin						
Flubendiamide	2					
Gamma-cyhalothrin						
Indoxacarb	3					
Lufenuron	2	Not yet assessed for risk by this process				
Malathion	2					
Maltodextrin		Not yet assessed for risk by this process				
Methamidophos						
Methoxyfenozide						
Novaluron						
Permethrin	1					
Phenthoate		Not yet assessed for risk by this process				
Pyrethrum	1					

[3]www.invasive-species.org/fawevidencenote, pg. 94

Active ingredient	Labeled for use in (#) African countries	HHP criterion	Aquatic life mitigation	Wildlife mitigation	Pollinator mitigation	Bystander inhalation mitigation
Spinetoram						
Spinosad	2					
Sulfur						
Tebufenozide						
Teflubenzuron		Not yet assessed for risk by this process				
Thiacloprid						
Thiamethoxam	3					
Thiodicarb						
Trichlorfon						
Triflumuron	1	Not yet assessed for risk by this process				

3.3. Pesticide Risk Communication

Communicating pesticide health impacts requires considerable expertise (BgVV 2000; OECD 2002). Later versions of this chapter and additional publications will provide guidance on risk communication and farmer education associated with the pesticides used against FAW. The fact of a pesticide being listed as an FAO/WHO HHP is a credible indication of its having unmanageable risks. More specific risk communication procedures will be developed as experience grows within the FAW outbreak.

3.3.1. Communication Summary Notes: Prenatal Exposure to Pesticides

Prenatal exposure to organophosphate (OP) pesticides has been shown to have adverse effects on a baby's nervous system including [a] reduced IQ from chlorpyrifos specifically (ref. 1) and breakdown products that are common to many other OP pesticides (ref. 2); [b] slower mental development and symptoms of pervasive developmental problems at 24 months of age (ref. 3); and [c] decreased length of pregnancy (ref. 4).

1. Rauh *et al.* (2011) Environ Health Perspectives 119(8): 1196-1201.
2. Bouchard *et al.* (2011) Environ Health Perspectives 119(8): 1189-1195.
3. Eskanazi *et al.* (2007) Environ Health Perspectives 115(5): 792-798.
4. Eskanazi *et al.* (2004) Environ Health Perspectives 112(10): 1116-1124.

These references can be downloaded at: **http://ehp.niehs.nih.gov/**

3.3.2. Communication Summary Notes: Pesticide Acute Poisoning

An acute pesticide exposure can result in acute pesticide poisoning, which is an illness or health effect resulting from the exposure and usually developing within 48 hours. The exact symptoms and body systems affected vary depending upon the type and amount of pesticide (Figure 2). The carbamate insecticides such as methomyl, carbaryl, and carbofuran, and the organophosphate pesticides such as chlorpyrifos, methamidophos, diazinon, and dimethoate, have severe effects on the nervous system. Pyrethroid insecticides such as deltamethrin, zeta-cypermethrin, cyfluthrin, and lambda-cyhalothrin may have acute effects on the nervous system but they are less toxic than the carbamates and the organophosphate pesticides.

Suspected poisonings can be reviewed by medical professionals, toxicologists, or pesticide experts, and attributed to pesticides using the following WHO guidelines: Thundiyil *et al.* (2008). WHO Bulletin 86(3): 205–209. http://www.who.int/bulletin/volumes/86/3/07-041814/en/.

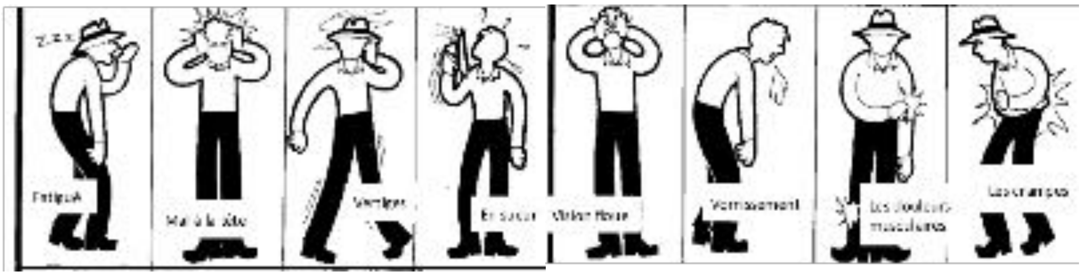


Figure 2. **Graphic used for pesticide education in West Africa – Effects of Acute Pesticide Poisoning. Translation French to English: *Fatigué*= tiredness; *Mal à la tete*= headache; *Vertiges*= dizziness; *En sueur*= sweating; *Vision floue*= blurred vision; *Vomissment*= vomiting; *Les douleurs musculaires*= aching muscles; *Les crampes*= cramps.**

4. Conclusions

The science and technology needed to safely apply pesticides is far more complex than many appreciate. The end user (*i.e.*, the pesticide applicator) determines to a large extent whether or not a given pesticide treatment will be effective, and also the degree to which non-target species including humans will be exposed to unnecessary risks. Applicators often, however, lack basic skills in sprayer servicing, calibration, and field use, and in determining which pesticides to apply and how to apply them, they lack critical information, including from labels, that explains health hazards, volume and mass application rates, restricted entry intervals, and even toxicity information for beneficial species. Pesticide labels also commonly do not refer to risks other than PHI, but if they are referred to at all, they assume that fully serviced and effective PPE is available, which is rarely the case in Africa. To address this problem, a comprehensive, needs-based guide is required that is locally applicable in different locations and contains data currently lacking from other sources. While this guide is in preparation, it is important that applicators at least follow pesticide regulations at the national level. Countries regulate pesticides and their uses (including crop and pest) as well as the applicator requirements for using each pesticide. Compliance with current regulations is one step that can contribute to lower risks and also to more efficacious treatments. Although countries vary in the requirements for pesticide labels, and in the amount of training that is available for applicators, this provides a common starting point that will be widely supported. There currently is no publicly available pesticide applicator manual that would cover the range of jurisdictions in Africa, and their needs. Our plan is to develop a manual in the near future to cover this shortcoming. In the interim, we can advise that pesticide applicators follow the label directions of the pesticide they are using and consult the country-specific agency with the authority to recommend pesticides.

We have deliberately integrated IPM and PRM because (1) these were both parts of the original concept for IPM, which has been tried and successfully tested, and (2) because pesticides can act as barrier to IPM adoption through unintended human health and environmental impacts. Our summary of HHPs and pesticides that require further risk mitigation should contribute to more effective pesticide selection, and at the time of writing, a number of initiatives are underway to acquire further data that can assist the adoption of better and more sustainable IPM practices. This includes efforts by some companies to identify lower-risk and efficacious newer chemistries that may be compatible with IPM.

Regarding synthetic pesticides and biopesticides, it is essential that a number of rigorously constructed experiments provide data on efficacy at different maize growth stages and with different FAW life stages. Without these data, it will be difficult to develop locally specific, low-risk and cost-effective options for farmers.

Finally, pesticide risk communication needs to be taken seriously, given the concerns that we express above about the potential for human health impacts among smallholder maize farmers. The data on pesticide hazards and risk mitigation that we provide are scientifically based and have been subjected to very wide peer review internationally. This information can provide guidance for government and agency purchases of pesticide stocks for emergency use, and can help to prevent some of the costs of employing pesticides as part of an IPM strategy. They can also inform IPM advisors, educators, and researchers about properties of some of the pesticides that are currently in use against FAW. There continues however, to be a need for educational materials that support the decisions made by farmers who may be unaware of the range in hazards and risks that are represented by pesticides in current use.

Knowledge Gaps/Researchable Areas

1. Overcome barriers to IPM adoption that incorporates pesticide use when necessary by:
   a. Using the IPM compatibility tables to review and compare candidate pesticides for use against FAW.

   b. Conducting rigorously designed pesticide evaluation trials that are of a design and scale to allow rigorous and realistic comparison of pesticides. Include both a positive control (a toxic standard known to be efficacious) to validate the trial conditions, and negative controls (water-treated and untreated plots) as the basis for statistical discrimination of results. Monitor natural enemies as well as pests for the whole season, and minimize edge effects that occur when natural enemies migrate from untreated plots into broad-spectrum pesticide-treated plots and artificially enhance their efficacy.

   c. Conducting whole-farm monitoring of likely candidates for recommendation, to ensure that efficacy from experiments translates to the farm.

   d. Developing application parameters and training programs appropriate for the pesticide sprayers that are in use, and for the knowledge and skills level of farmers, to maximize pest exposure, targeting, and efficacy.

   e. Focusing particularly on calibration, volume rates at different growth stages, and additives that may increase efficacy by maximizing coverage and retention.

   f. Conducting assays throughout the infestation zone to evaluate background patterns and levels of pesticide resistance in FAW, and monitor any changes over time. Use this as the basis for design of pesticide resistance management programs that are implemented through effective education and evaluation.

   g. Screening all candidate pesticides for toxicity to key natural enemies of maize pests.
2. Develop effective education programs for IPM adoption that place pesticides in an IPM context.
3. Monitor pesticide acute and chronic health effects, and environmental impacts to ensure proper balancing of the risks and benefits of pesticide use.
4. Integrate economists and social scientists within this research regime to ensure ethical deployment of research data.

Key Messages to Policymakers

Highly Hazardous Pesticides

1. Implement policies for the phase-out and elimination of HHPs from formal and informal marketplaces.
2. Improve labeling of highly toxic pesticides to explain the hazards that are associated with them, particularly for handlers and applicators, and provide restricted entry intervals for field workers that take into account that they may not have access to PPE.
3. Implement policies that establish the process and information pathways for collection and use of field-collected medical data about pesticide acute and chronic impacts.
4. Implement a requirement for pesticide poisoning signs and symptoms to be a part of the education and training of medical personnel, and establish national systems for collecting and reporting poisoning information to regulatory agencies who take this into account during post-marketing review of registered materials.
5. Establish a marketplace for PPE, and develop education programs that generate understanding of the need for, and value of maintaining effective PPE for handlers and applicators.

IPM Compatibility

6. Establish a process to consider IPM compatibility as a criterion of pesticide registration, and which requires regulatory officials and crop protection organizations to work collaboratively to ensure that pesticide recommendations are realistic, practical, and of low risk.

CHAPTER 04

Host Plant Resistance to Fall Armyworm

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1. Introduction

Developing and deploying effective host plant resistance (HPR) is one of the pillars of an effective Integrated Pest Management (IPM) strategy against fall armyworm (FAW). HPR is particularly needed in the African context, where a majority of the farmers are smallholders with limited access to safe and affordable FAW control options.

To facilitate deployment of HPR as part of IPM strategies for FAW management in Africa, this chapter provides:

a. Background information on sources of native and transgene-based germplasm which can potentially offer FAW resistance;
b. FAW insect-rearing and artificial infestation protocols; and
c. A harmonized, reliable, and efficient germplasm screening and rating protocol.

In addressing each of these key topics, this chapter emphasizes practical knowledge intended to accelerate breeders' efforts to identify, evaluate, and integrate FAW resistance traits into maize genetic backgrounds suitable for cultivation in sub-Saharan Africa.

2. Sources of Genetic Variation for Host Plant Resistance to Fall Armyworm

Historically, considerable effort was undertaken in the Americas to breed for FAW resistance, especially in maize. Similar efforts have only been recently initiated in Africa, following the identification of FAW on the continent in 2016 (Georgen *et al.* 2016)[1] . Consequently, **there are presently no Africa-adapted maize cultivars with scientifically validated resistance to FAW.** To address this gap, the International Maize and Wheat Improvement Center (CIMMYT) has accelerated efforts to rigorously screen maize inbred lines, pre-commercial and commercial hybrids, and improved open-pollinated varieties (OPVs) under artificial FAW infestation. Initial results are expected in 2018 and will be communicated through various channels, including future editions of this manual. Once available, these data will indicate the degree of FAW resistance found in currently available African maize varieties and (sub)tropical maize germplasm. In turn, this information will inform both public- and private-sector recommendations regarding which hybrids/varieties to deploy, and breeders' selection of elite germplasm for further varietal development.

Until evidence becomes available to inform recommendations regarding currently available FAW-resistant maize varieties adapted to sub-Saharan Africa, this chapter will focus instead on providing information and tools to maize breeders to facilitate screening and identification of FAW-resistant germplasm, with the intent of supporting implementation of FAW resistance breeding as a core part of African maize improvement programs moving forward.

Maize resistance to FAW, and indeed to other lepidopteran pests, varies along a continuum. The responses of maize germplasm under FAW infestation are measured on the Davis scale (Davis and Williams 1992), which rates the extent of leaf damage or ear damage relative to a susceptible control on a scale of 1 to 9 (explained in detail in Section 3 of this chapter). Responses may range from "highly resistant" (with a score of 1) to "highly susceptible" (with a score of 8-9).

Along this spectrum of susceptibility and resistance, several sources of useful genetic variation have been identified that can provide genetic materials to breeders seeking to improve FAW resistance in (sub)tropical maize germplasm adapted to Africa.

[1] Throughout the chapter, we discuss host plant resistance to FAW using maize as an example, since considerable work has previously been done in maize. However, the principles remain the same for host plant resistance in other annual crops (*e.g.*, sorghum, millets) – although the protocols may need modification depending on the crop species.

Naturally occurring, or "native," resistance has been identified in several maize inbred lines/populations/hybrids, especially in the Americas, where the trait has long been incorporated into conventional breeding programs (described in Section 2.1). Most native resistance in maize is polygenic (based on multiple genes) and quantitative in nature, conferring "partial resistance." Thus, maize varieties with native resistance typically exhibit Davis scores of 3-5 when challenged with FAW.

In addition to such naturally occurring genetic variation, over the past two decades some countries in the Americas have chosen to access transgenic insect-resistance traits to control FAW (described in Section 2.2). Though such products can face additional regulatory, political, and consumer acceptance hurdles, maize varieties carrying lepidopteran-specific transgenes typically provide significant protection against FAW, consistently achieving Davis scores of 1-2.

When designing a crop improvement strategy to introduce FAW resistance traits into Africa-adapted elite germplasm, breeders should consider not only the source and strength of FAW resistance, but also the potential durability of resistance over time. Insect pests such as FAW can evolve to overcome monogenic (based on a single gene) or oligogenic (based on a few genes) resistance, as has been demonstrated particularly in transgenic crop varieties (Huang *et al*. 2014). Breeding efforts against insect pests are therefore a continuous process, with no "finish line" to the perpetual race between the host and the evolving pest. As a general principle, breeding programs should seek to identify, utilize, and ultimately combine multiple resistance traits – whether conventional or, where approved for use, transgenic – in order to improve the durability of HPR.

2.1 Naturally Occurring Genetic Variation for FAW Resistance in Maize

Studies on insect resistance in maize began in the 1900s, when Hinds (1914) demonstrated partial resistance of maize germplasm to corn earworm, *Helicoverpa zea* (Boddie), while Gernert (1917) demonstrated partial resistance to the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), in teosinte × yellow dent maize hybrids in the USA. The first maize varieties with partial resistance to the European corn borer, *Ostrinia nubilalis* (Hübner), were developed by Huber *et al*. (1928), while germplasm with partial resistance to sugarcane borer, *Diatraea saccharalis* (Fabricius), was identified in the 1970s (Elias 1970; Peairs 1977).

Building on this and other work, throughout the 1970s to 1990s, research conducted by CIMMYT in Mexico, Embrapa in Brazil, USDA-ARS (Mississippi), and some universities in the USA led to the identification and development of a number of improved tropical/subtropical maize inbred lines with at least partial resistance to FAW (Table 1).

Although the FAW-resistant germplasm was developed in Mexico, the USA, and Brazil, the diversity of resistant materials identified indicates that ample conventional traits exist to support a medium- to long-term breeding strategy for incorporating FAW resistance into elite, Africa-adapted maize genetic backgrounds. Some of these sources of insect resistance in maize were specifically tested for FAW resistance, while others were tested for resistance to other insect pests but have potential to confer resistance to FAW, as the Mississippi studies demonstrate.

Germplasm with native resistance to FAW described in this section, together with Africa-adapted maize inbred lines, pre-commercial and commercial hybrids, and OPVs, are currently being evaluated by CIMMYT against FAW populations in Africa, to validate and/or identify new sources of resistance in the African context. Conventional maize breeding for host resistance to FAW has also been initiated by the International Institute of Tropical Agriculture (IITA) in West Africa. Moving forward, as results of these screens emerge and validated sources of resistance are found, CIMMYT and IITA, together with national and regional public- and private-sector partners, will ensure that information and resistant germplasm are shared dynamically. Ultimately, the African maize breeding community must make a coordinated and intensive effort to develop elite products that combine resistance to FAW with other desirable and relevant traits for smallholder farmers.

Table 1. Some potential sources of FAW resistance in maize germplasm identified or developed by maize breeding programs in the Americas.

Germplasm	Description	References
Pop. 304; Pop. 392; Pop. FAW-CGA; Pop. FAW-Tuxpeno; Pop. FAW-Non-Tuxpeno	Maize breeding populations developed and used by CIMMYT as sources for deriving several CMLs (CIMMYT Maize Lines) with partial resistance to FAW in Mexico.	Ortega *et al.* (1980); Mihm (1997)
Mp496; Mp701; Mp702, Mp703; Mp704; Mp705, Mp706; Mp707; Mp708, Mp713; Mp714; Mp716	Temperate maize inbred lines with resistance to FAW developed in the USA by USDA-ARS (Mississippi). Of these, Mp496, and Mp701 to Mp708, were derived from Caribbean accessions – Antigua Gp1, Antigua Gp2D, Guadalupe Gp1A, and Republica Dominica Gp1. Mp713 and Mp714 were developed from CIMMYT's Multiple Insect Resistant populations.	Scott and Davis (1981); Scott *et al.* (1982); Williams and Davis (1980, 1982, 1984, 2000, 2002); Williams *et al.* (1990)
B49; B52; B64; B68; B96	Corn-borer-tolerant inbreds generated by Iowa State University, USA, through introgression of Maiz Amargo from Argentina into temperate maize. The most important inbred line among these was B68, which became widely used by the seed industry in the USA.	Walter Trevisan, personal communication
CML121 to CML127	Insect-resistant inbred lines (CMLs) derived by CIMMYT in Mexico, using the USDA-ARS (Mississippi) germplasm.	Gerdes *et al.* (1993)
Three GEM (Germplasm Enhancement of Maize) inbreds	Derived from the introgression of germplasm from Uruguay, Cuba, and Thailand; showed some resistance to FAW in the southern USA.	Ni *et al.* (2014)
CMS14C; CMS23 (Antigua x Republica Dominica); CMS24; MIRT (Multiple Insect Resistance Tropical) race Zapalote Chico, Sintetico Spodoptera, Caatingueiro Spodoptera, and Assum Preto Spodoptera	Since 1975, Embrapa-Brazil identified and described several sources of resistance to FAW in maize, while also investigating the chemical compounds that underlie these native resistance traits.	Walter Trevisan, personal communication
Brazilian maize lines with potential resistance to FAW	In work conducted from 1986 to 1993, Embrapa-Brazil identified potential sources of resistance to FAW based on evaluation of maize accessions in the Brazilian germplasm bank.	Viana and Guimares (1997)

Note: For further information on sources of resistance in CIMMYT maize germplasm, please contact B.M. Prasanna (b.m.prasanna@cgiar.org); for sources of FAW resistance in USDA-ARS (Mississippi) maize germplasm, please contact Paul Williams (Paul.Williams@ars.usda.gov); for sources of resistance in Embrapa maize germplasm, please contact Sidney Parentoni (cnpms.chpd@embrapa.br).

2.2. Transgene-based FAW Resistance in Maize

Deploying transgenic or genetically modified (GM) crop varieties that express lepidopteran resistance genes is another strategy to effectively control FAW damage in maize. The first GM FAW-resistant maize varieties were developed using insecticidal crystal protein genes (*cry*) isolated from *Bacillus thuringiensis* (*Bt*). These traits are the same as those used by the conventional organic pesticide industry. The ingestion of the Cry protein is lethal to larvae of many lepidopteran species, including FAW. Several different *cry* genes are available – *e.g., cry1A, cry1Ab,* and *cry1F* – and have been deployed in commercial *Bt* maize varieties globally for over 20 years. In addition, *Bt* produces another class of lepidopteran-specific proteins termed Vegetative Insecticidal Proteins (VIP). These VIPs are encoded by *vip* genes, the most notable of which is the *vip3A* gene used to confer FAW resistance. Numerous GM maize hybrids, including various combinations of *cry* and *vip* genes, are commercially available in Brazil and North America, where over 80% of the total maize production area is cultivated with *Bt* maize (Horikoshi *et al.* 2016).

Transgenic insect resistance traits confer significantly stronger HPR to FAW than does native resistance. For example, Viana *et al*. (2016) compared the level of FAW resistance exhibited by 32 conventional maize hybrids (derived using inbreds with native resistance to FAW) to the resistance of three transgenic *Bt* hybrids expressing the toxins Cry1F and Cry1A.105+Cry2Ab2 (2B707Hx, AG8088PRO, and DK390PRO). The six best conventional hybrids had Davis scores ranging from 2.8 to 4.1, while the three *Bt* hybrids showed a score of 1; in contrast, the commercial susceptible hybrid control showed a score of 7.

In Africa, *Bt* maize is currently commercially available only in South Africa, where regulatory authorities have overseen multiple approvals, with more than 15 years of deployment of such products. Two GM products are available that provide protection against FAW (ISAAA GM Approval Database):

- The MON810 event, which is intended to control stem borer but also confers partial resistance to FAW, has been cultivated in South Africa since 1997; and
- The MON89034 event, which has demonstrated efficacy for control of both FAW and stem borer, has been cultivated in South Africa since 2010. MON89034 is particularly recommended for FAW control due to its high efficacy against the pest, as well as anticipated durability of control over time due to its incorporation of “stacked” or “pyramided” insect-resistance traits (see Section 2.2.1).

Beyond South Africa, the Water Efficient Maize for Africa (WEMA) project – a public-private partnership to develop and disseminate improved maize varieties appropriate for African smallholders – is currently undertaking development of improved maize varieties with transgenic insect resistance. Under WEMA, the National Agricultural Research Organizations of South Africa, Kenya, Tanzania, Uganda, and Mozambique are testing the performance of MON810 *Bt* and stacked *Bt* + Drought Tolerance (DT) transgenes introgressed into locally adapted African maize varieties[2]. First initiated in 2012, these Confined Field Trials (CFTs) are assessing the safety, efficacy, and performance of transgenic maize in African conditions, and are overseen by country-specific biosafety regulatory authorities.

WEMA’s emerging results are consistent with the performance of *Bt* maize in other countries: When introduced into locally preferred African maize varieties, the MON810 event is demonstrating strong control of stem borers and partial control of FAW in Kenya, Mozambique, and Uganda. An application for approval of MON810 in Kenya is pending finalization, and applications for approvals in other WEMA partner countries are expected to be ready for submission in 2018 – giving African biosafety regulatory agencies the opportunity to evaluate the technology themselves and decide on the safety, efficacy, and performance of *Bt* maize in African environments.

Beyond the availability of effective transgenic FAW resistance traits for maize genetic improvement efforts, WEMA also seeks to explore and address broader issues of African regulatory and stewardship capacity to deploy biotechnology in a manner appropriate for smallholder farmers. To this end, WEMA partners work with biosafety regulators to build capacity and technical expertise, establish functioning regulatory systems, and address questions about the technology from scientists, policymakers, and the general public. WEMA has also piloted the use of royalty-free licensing agreements to seed companies in Africa, in an effort to ensure that improved transgenic varieties are affordable and accessible to the resource-poor smallholders in Africa.

[2] CFTs are also planned in Ethiopia.

2.2.1. Insect Resistance Management (IRM) for *Bt* Maize

Over time, insect pests can evolve to overcome HPR, whether resistance is native or transgenic in nature. However, native resistance is generally more durable, both because it is usually quantitative in nature (with several genes underlying the expression of resistance, making it harder for the pest to "escape" control) and because it is typically less effective at controlling the pest (and therefore exerts less pressure on the pest to overcome HPR). In contrast, the possibility that an insect pest will evolve resistance to the highly efficacious transgenes used in GM crops is a major concern – particularly for early transgenic varieties that rely on expression of a single, highly effective dominant gene (such as *cry1Ab* in MON810 and *Bt11*).

Although a variety of biological and environmental factors influence the risk that an insect will evolve resistance, insect resistance typically emerges when the selection pressure on the insect is exceptionally high – for example, a high degree of monoculture with a GM variety expressing a single resistance gene, coupled with inadequate implementation of an Insect Resistance Management (IRM) strategy. Evolution of FAW resistance to *Cry1F* has been documented in maize in Puerto Rico (Storer *et al.* 2010), the southeastern mainland USA (Huang *et al*. 2014), Brazil (Farias *et al*. 2014), and Argentina (Chandrasena *et al*. 2017).

While the first GM products to market were based necessarily on single genes, a more durable strategy is based on multigene resistance. This invokes the general principle that to maximize trait durability, breeders should combine multiple resistance traits that use distinct mechanisms of action. In the specific context of transgenic crops, this is known as "stacking" or "pyramiding" transgenes – ensuring that two or more genes, preferably with different types of toxic proteins or different modes of action (*e.g., cry* and *vip3A*), are simultaneously expressed in the host plant at high dosage (Horikoshi *et al.* 2016). Studies undertaken in the USA and Brazil suggest that pyramiding multiple transgenes (in the same plant) is more effective in terms of FAW control and IRM than single-gene-based resistance (Huang *et al.* 2014; Horikoshi *et al.* 2016). This also calls for introgression of different transgenic resistance traits (*e.g.,* different *cry* genes or *cry* + *vip3A*) into a maize genetic background that also has native resistance to the insect pest. The biggest advantage of this type of pyramid is that if the pest overcomes the transgenic resistance trait(s), the native resistance of the conventional genetic background (even if partial) can potentially mitigate the infestation until new varieties with more effective resistance are developed and deployed.

To achieve durable control of insect pests such as FAW through deployment of transgenic crop technology, developers have designed and implemented IRM strategies (Siegfried *et al.* 2007; CropLife 2012). These industry-standard protocols ensure that best practices are communicated to stakeholders in a way that ensures the widest possible compliance, as grower compliance is the key mitigating factor in successfully managing resistance. A sound IRM plan varies with the crop and pest combination, but generally considers:

- Rigorous scouting and surveillance for potential development of insect resistance above a baseline level determined prior to introduction of the GM crop;
- Use of multiple resistance traits (both conventional and transgenic) expressed at a high dose; and
- Use of a "refuge" of non-*Bt* maize, of adequate size and design to support a sufficient population of the susceptible target pest (*e.g.*, FAW).

The refuge, a key facet of the IRM plan, ensures that a sufficient population of susceptible insects is available to mate with the few resistant insects that may evolve in the GM-planted areas. This significantly dilutes the frequency of resistance alleles in the insect population, thereby delaying the evolution of insect resistance to the transgene(s).

Though particularly vital in the context of GM maize varieties, ultimately, any FAW-resistant crop variety should be deployed in the context of a broader IPM strategy (see Chapter 1) that seeks to sustainably manage and mitigate the adverse impact of the insect pest.

3. Protocols to Support Breeding for Resistance to FAW

In acknowledgment that FAW has become an endemic, and likely long-term, pest across the African continent, it is imperative that the CGIAR (formerly the Consultative Group for International Agricultural Research), national, and private-sector maize breeding programs initiate and maintain a strong pipeline of elite products that incorporate FAW resistance with other adaptive traits in crops relevant for smallholders in sub-Saharan Africa. To accomplish this, breeders must screen germplasm against FAW – a process that requires adequate amounts of seed for raising plants, an optimal mass-rearing protocol to supply sufficient insects for germplasm screening under artificial infestation (Section 3.1), and a clear protocol to evaluate the responses of the test entries (Section 3.2).

3.1. Protocol for Mass Rearing of FAW Insects

3.1.1. Colony Establishment and Maintenance

A large founder colony of at least 100 larvae should be collected, making sure to sample insects from across a wide geographic range representative of the maize breeding program's target environment. This will ensure genetic diversity. The field-collected insects are reared in isolation from other insects/pathogens to avoid any contamination. Parasitized, diseased, and deformed insects must be discarded (Onyango and Ochieng'-Odero, 1994).

3.1.2. Insect-Rearing Facilities and Conditions

The FAW developmental stages (egg, larva, pupa, and adult; see Chapter 1) differ in their environmental requirements and management, and thus require separate rooms, similar to the stem borer insect-rearing facilities established in some countries in sub-Saharan Africa. (With appropriate modifications, the same facilities can be potentially used for FAW mass rearing, depending on the capacity and objectives of the insectary.) FAW mass rearing requires suitable space for four rooms, namely:

a. Diet preparation and infestation room;
b. Larval development room;
c. Pupal harvesting room; and
d. Moth emergence and oviposition room.

The rearing laboratory is a new habitat for the insects, and should therefore have environmental conditions conducive to their development and effective field performance (temperature 25±1°C; 12:12 light:dark photoperiod; and a relative humidity of 75±5%). The rooms should be kept free from disease, parasites, and predators. Installation of the appropriate equipment in each of the four rooms saves time, increases efficiency, and enhances safety. Further details on the equipment required for FAW insect rearing can be obtained from CIMMYT (Anani Bruce; a.bruce@cgiar.org).

3.1.3. Diet Ingredients and Preparation

Mass rearing of FAW may be done on either a natural diet or a synthetic diet. The protocols for both are outlined below:

3.1.3.1. Natural diet

Castor bean (Ricinus communis L.) is a plant in the Euphorbiaceae family. It is an evergreen robust shrub/small tree that is multiplied by seeds. Certain parts of the castor plant have insecticidal activity and are often used as a natural biopesticide, but the leaves can also be used to support mass rearing of FAW (Cave 2000; Valicente *et al*. 2013; Martínez *et al.* 2015).

Prepare the diet as follows:

i. Collect fresh castor leaves, wash with sodium hypochlorite (5 mL/L), and rinse with water to prevent any contamination.

ii. Cut the leaves into small pieces.

iii. Place 3 neonate larvae in 30ml plastic vials supplied with 4.3g of fresh castor leaf pieces (Figure 1). Alternatively, instead of small vials, up to 300 larvae (first to third instar) can be placed in a 4L plastic jar (Valicente *et al*. 2013).

iv. Replace the leaves every 2-3 days, depending on how long they remain green and fresh.

v. As cannibalism is higher among aged larvae (Chapman *et al*. 1999), especially from the 4th to 6th instars, place the aged larvae in 30ml individual vials.

The FAW larvae on the natural diet usually mature after 15-20 days, with pupation in the last 10 days. FAW larval cannibalism on castor leaves was found to be significantly reduced (almost halved) as compared to rearing on maize-leaf-based natural diet (Valicente *et al.* 2013).

3.1.3.2. Synthetic/artificial diets

The synthetic insect diet is a mixture of nutritive substances including carbohydrates, proteins, fat, minerals, and vitamins. Each fulfills a specific function in the development of the insect and influences the safe shelf life of the constituted diet. Because of FAW's polyphagous nature (capacity to feed on multiple plant species), it can be successfully reared on many diets that have been developed for other insect species – for example, FAW can be successfully mass-produced on maize stem borer diet, as practiced by CIMMYT in Africa.

Several synthetic diets have been optimized by various institutions, including CIMMYT, IITA, the International Centre of Insect Physiology and Ecology (ICIPE), and the Agricultural Research Council (ARC)-South Africa, based on local availability of ingredients. The descriptions below highlight how the synthetic diet for FAW insect mass rearing is prepared at present by CIMMYT in Kenya (Figure 2), ARC in South Africa, and ICIPE in Kenya, based on unpublished protocols (summarized in Table 2). In addition, commercial "multiple species diets" are available in some countries (*e.g.*, http://www.tecinfo.com/~southland/pricelist.html). Some labs also use the Tobacco Budworm diet (Product# F9781B from Frontier Agricultural Sciences; [http://www.insectrearing.com/products/indiets1.html]).

a) CIMMYT diet[3]

Fraction A: Mix all the powdered ingredients except methyl-p-hydroxybenzoate from Fraction A using a plastic spoon, in a clean container under a fume hood. Boil the distilled water, cool it to 60°C, and then mix with the pre-mixed ingredients using a blender for 1 minute. Add methyl-p-hydroxybenzoate (dissolved in 20ml of absolute ethanol) to the mixture in the blender, and then blend for a further 2 minutes.

[3] Adapted from Onyango and Ochieng'-Odero (1994) and Songa et al. (2004).

Tray with FAW-rearing on castor-leaf-based natural diet

FAW larvae feeding on castor leaves

Figure 1. **FAW rearing on castor-leaf-based natural diet.**

Fraction B: Weigh agar powder (Figure 2) in a separate container and then add to cold distilled water in a separate saucepan. Boil while stirring periodically, and then cool to 60°C. Add the ingredients of Fraction B to Fraction A and blend for 3 minutes.

Fraction C: Finally, add 40% formaldehyde to the ingredients of Fractions A and B in the blender and then mix for 3 minutes at room temperature.

b) ICIPE diet

Prepare Fractions A-C as described for the CIMMYT diet, using the ingredients and quantities listed for the ICIPE diet (Table 2).

Weighing the ingredients — *Mixing the ingredients* — *Blending the diet*

Cooking the diet — *Dispatching the diet in vails* — *Diet cooling under the fume hood*

Puncturing the diet — *Diet infestation by FAW neonates* — *FAW larvae feeding on diet*

FAW pupae ready — *Harvesting the FAW pupae* — *Pupae placed in the oviposition cage* — *FAW adult moths in oviposition cage*

Figure 2. Steps in rearing of FAW on an artificial diet.

c) ARC-RSA diet

Fraction A: Mix all dry ingredients in Fraction A well with 1,500ml distilled water in a container.

Fraction B: Boil 1,000ml distilled water, add 7.5g sorbic acid, and stir periodically until the sorbic acid is dissolved. In a separate container, add agar to 1000ml water and mix well. Add agar mix to sorbic acid mix. Boil for 10 minutes. Let Fraction B cool down to 70°C, then add it to Fraction A and mix well with a blender.

Fraction C: Add formaldehyde (40%) to the mix of Fraction A and B. Dissolve Nipagen (3g) in 75ml ether. Add to the mix of Fraction A and B.

Dispense an appropriate volume of the diet into plastic trays, jars, or vials.

Table 2. Three potential diet ingredient options used presently in Africa for rearing FAW.

	Ingredients	a) CIMMYT diet Quantity (g or ml) per 3L diet	b) ICIPE diet Quantity (g or ml) per 3L diet	c) ARC-RSA diet Quantity (g or ml) per 3L diet
Fraction A				
1	Maize leaf powder	75.6g	75.0g	
2	Common bean powder	265.2g	187.5g	
3	Chickpea			250.0g
4	Wheat germ		150.0g	225.0g
5	Brewer's yeast	68.1g		45.0g
6	Torula yeast		32.0g	
7	Milk powder		57.0g	45.0g
8	Ascorbic acid	7.5g	9.0g	15.0g
9	Sorbic acid	3.9g	4.5g	
10	Methyl-p-hydroxybenzoate	6.0g	7.5g	
11	Vitamin E capsules (200 iu)	6.3g		
12	Multivitamin drops		3.0ml	
13	Sucrose	105.9g		
14	Distilled water	1,209.3ml	1,350.0ml	1,500.0ml
Fraction B				
15	Agar (Tech No.3)	37.8g	34.5g	50.0g
16	Distilled water	1,209.3ml	1,200.0ml	1,000.0ml
17	Sorbic acid			7.5g
Fraction C				
18	Formaldehyde 40%	6.0ml	6.0ml	1.0ml
19	Suprapen p (Tetracycline)		7.5g	
20	Nipagen			3.0g
21	Ether			75.0ml

Sources: CIMMYT diet – adapted from Tefera et al. (2011); ICIPE diet – Sevgan Subramanian (ICIPE, Kenya), personal communication; ARC-RSA diet – Erasmus Annemie (ARC-Grain Crops, RSA), personal communication.

3.1.4. Diet Infestation

i. Keep the diet in the fume hood to cool and to allow some chemicals to evaporate.
ii. Create several holes on the surface of the diet in each jar or test tube using a sterilized laboratory plastic rod; this will facilitate larval penetration.
iii. Introduce surface-disinfested black-head eggs or neonate larvae into the holes made in the diet.
iv. Several FAW neonates can be introduced into the same container. However, at the third instar, the larvae need to be transferred to individual vials because of their cannibalistic nature.
v. Close the vials with tight-fitting cotton-wool plugs.
vi. Keep the jars/vials containing the larvae on shelves in the larvae-rearing room under controlled environmental conditions (27±1°C; 65±5% RH; 12:12 light:dark photoperiod).

3.1.5. Management of Larvae and Pupae

i. Monitor larval and pupal development daily to identify problems such as contamination with fungi or insects, and discard any affected diet containers immediately. Begin close monitoring for pupal harvesting 14-20 days after diet infestation, and daily thereafter to avoid moth emergence within rearing jars.
ii. Harvest pupae at once when at least 50% of the larvae have pupated. To harvest, empty the diet from each jar onto a clean tray, and sort and transfer the pupae into a plastic container lined with tissue paper.
iii. Keep larvae that have not pupated by this time in sterilized plastic jars containing clean, moist paper towels until they pupate.
iv. Clean the pupae with a gentle spray of distilled water, and place on tissue paper to drain excess moisture.
v. Transfer the pupae to clean petri dishes (9 cm in diameter) lined with moist tissue paper. Each petri dish can accommodate about 100 pupae.
vi. Place petri dishes in a metal-framed emergence cage (oviposition cage, 45 × 60 × 45 cm), ventilated at the top with fine wire mesh.
vii. Keep the emergence cages at room temperature (25±1°C); 12:12 light:dark photoperiod; and a relative humidity of 75±5%. The humidity can be maintained by placing a plastic cup containing water-soaked cotton wool in the cage at all times.

3.1.6. Management of Moths

i. Line the oviposition cage with a sheet of wax/butter paper. The moths feed on water from a water-soaked wad of cotton wool in a petri dish placed in each cage. Keep about 100 moths in each oviposition cage.
ii. On a daily basis, check each oviposition cage and:
    a) Collect eggs that have been oviposited on wax papers (see 3.1.7).
    b) Remove dead moths from each cage.
    c) Pick and transfer the live moths to a freshly prepared cage containing fresh wax paper and fresh water-soaked cotton wool in a petri dish.
    d) Clean and disinfest the cage for reuse.

3.1.7. Management of Eggs

i. Cut the crumpled waxed papers with eggs laid on them into batches of approximately 50 eggs per batch, using scissors.
ii. Surface-disinfect the eggs (on the waxed paper) by dipping them in 10% formaldehyde for 15 minutes, rinsing them thoroughly using distilled water, and then drying them on filter paper.
iii. Transfer the surface-disinfested egg batches on waxed paper into clean plastic containers.

iv. Keep the plastic containers in the oviposition room and allow eggs to develop for 4-6 days.
v. Maintain a relative humidity of 75±5% in the container by putting a wide plastic dish with water-soaked cotton wool at the bottom of the container.
vi. In about 4-6 days the eggs develop into a black-head stage, which then hatch into neonate larvae after 1-2 days. Both the black-head stage eggs and the neonate larvae can be used for screening of maize genotypes.

3.1.8. Maintaining the Quality of Insects

The ultimate goal of rearing is to obtain insects of acceptable quality. A quality management system (QMS) should therefore be implemented if long-term use of insects is envisioned. The parameters used in determining quality of laboratory-reared FAW include survival rate, developmental period (egg to adult), deformities, reproductive capacity (number of eggs laid, hatchability, sex ratio), growth index (the ratio of percent pupation over mean larval development period), and adaptability under field conditions. The quality of the laboratory-reared insects is monitored periodically against the aforementioned quality parameters (disease-free, and with good reproductive capacity). If the laboratory insect population quality declines below a threshold of at least 300 well-formed, disease-free eggs per female, discard the population, collect a fresh founder colony of wild insects, and repeat establishment of a fresh colony (see Section 3.1.1).

3.1.9. Insectary Disease Management

Insects are living biological organisms and prone to disease when reared en masse in the laboratory. (Polaszek 1998; Songa *et al*. 2004). Insect artificial diets are also suitable for growth of some microorganisms, several types of which are reported to have contaminated insectaries – including bacteria (*Streptococcus* spp., *Serratia* spp., and *Pseudomonas* spp.), fungi (*Aspergillus* spp., *Rhizopus* spp., *Penicillium* spp.), protozoa (*Nosema* spp.), and viruses. Most of these microorganisms are not directly harmful to FAW; however, *Serratia marcescens*, *Nosema* spp., and baculoviruses are pathogenic to insects and may cause an outbreak in an insectary, and other contaminating organisms may nonetheless cause spoilage of the artificial diet or alter biological performance of insects. Sources of microbial contamination in an insectary can include field-collected insects; improper handling of the insects; an insufficiently clean insectary environment; or inadequate sterilization of the containers and diets during preparation, storage, and use. Immediate removal and disposal of contaminated diets and infected insects; proper sterilization of diets, working areas, and utilities; good personnel hygiene; and following recommended occupational safety guidelines (see Section 3.1.10) will minimize microbial contamination in an insectary. Additionally, regular pathological examination of cadavers of larva, pupa, and adults can also aid in early detection and elimination of diseased insects.

3.1.10. Occupational Safety

In addition to observing all standard laboratory safety practices and institutional health and safety policies, particular care should be taken regarding moth scales and toxic fumes when performing these protocols, as these are the primary issues of health concern associated with rearing and maintenance of artificial FAW populations. Moth scales and toxic fumes during sterilization can cause respiratory problems and allergies, while toxic fumes from formaldehyde used in diet preparation can be harmful to human health.

In order to maintain the quality of laboratory-reared insects, avoid microbial contaminants, and minimize potential health hazards to insectary workers, the following practices must be followed rigorously in the insectary:

a. Restrict entry to the insectary only to insectary workers.
b. Use a well-ventilated fume hood for diet preparation to prevent exposure to toxic fumes.
c. All insectary personnel must maintain high personal hygiene.
d. All insectary personnel must wear a laboratory coat, hand gloves, and face-mask (N-95) in the insectary.
e. Prohibit eating, drinking, and smoking in the insectary.

f. Clean all insectary work surfaces daily with germicides and a vacuum cleaner, and periodically fumigate.
g. Remove contaminated diets (including the insects within) and diseased insects, place them in a hot-air oven at 100°C for 2-3 hours, place them in a plastic bag, and then properly dispose of them through a disposal service.
h. Discard any insects that escape from the rearing jar or cage.
i. Install one or more sticky traps in the insectary to capture any moths that escape rearing cages.
j. Control all undesirable insects (other than the reared species).

3.2. Protocol for Screening Maize Germplasm Under FAW Infestation

While germplasm screening can be implemented under high natural infestation of the insect pest, in breeding programs it is particularly important to undertake artificial infestation when screening against insect pests such as FAW. This ensures that pest escapes or feeding preferences do not lead to errors in evaluation of resistance, including the possibility of classifying susceptible genotypes as resistant. The following section provides protocols for both natural and artificial infestation, as well as data collection protocols for rating the resistance of maize germplasm being evaluated under FAW infestation.

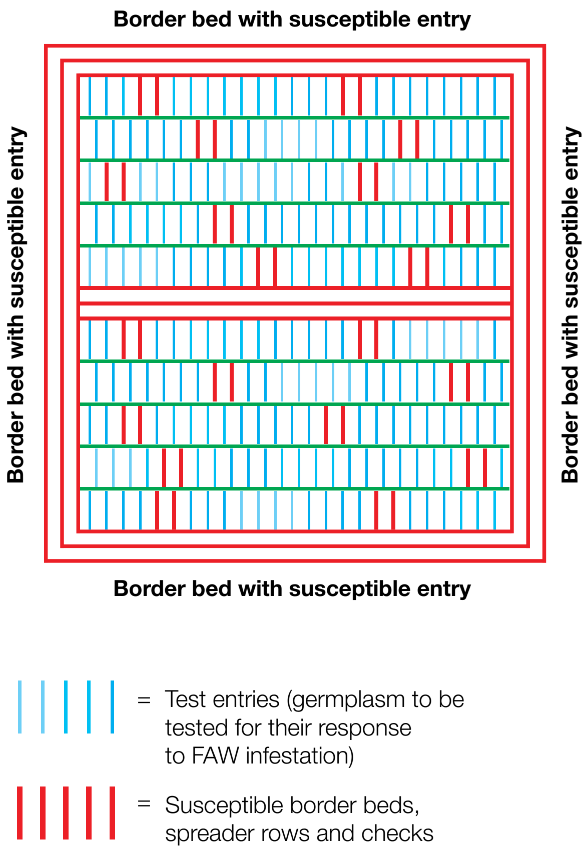

Figure 3. Schematic representation of a field block with susceptible border beds and spreader rows for creating reliable insect pest pressure on test entries under natural infestation. The susceptible check is planted at periodic intervals to ensure the required insect pest pressure.

Additionally, it is important to note that prior, anecdotal experience on other continents indicates that the feeding preferences of insect pests when evaluated in small plots do not necessarily translate to actual resistance under normal field conditions where a single genotype is grown.

3.2.1. Natural Infestation

Natural infestation is usually conducted by selecting an area with a predictable, high level of FAW infestation, commonly referred to as a “hot spot” area. Natural infestation may be used effectively by adjusting planting dates so that the desired growth stage for infestation coincides with peak periods of pest incidence. Uniform infestations are critical for a successful screening program. A well-designed experimental layout can maximize the uniformity of a natural infestation (Figure 3); however, natural infestation makes it difficult to achieve sufficient uniformity in the distribution of the infestation, or to control the level of infestation among the screening materials. This is because the insects are prone to escape, or there may be excessive infestation or differential attraction. Screening under natural infestation, preferably in a randomized complete block design (RCBD), should therefore be used only when resources for rearing insects using artificial diets are not available, and if the population pressure of the insect is nearly stable across seasons. Resistant germplasm selected under natural infestation in small plots should be retested in larger plots, preferably under artificial inoculation, to confirm that the selection was not influenced by insect feeding preferences when multiple germplasm entries are present in small plots.

3.2.2. Artificial Infestation

Artificial infestation is the most reliable method of screening maize genotypes against FAW. To prepare, FAW first-instar larvae (neonates) can be reared in an insect mass-rearing laboratory (see Section 3.1). Maize germplasm entries for the screen should be evaluated in a screen/net-house.

Two weeks after seedling emergence (at the maize V5 stage), infest each of the plants in a row with at least 20 FAW black-head eggs or 10 neonates (first-instar FAW larvae). In the case of FAW larvae, considering their cannibalistic nature, the larvae should be spaced in different nodes on the plant during release. Infestation can be performed manually with a camel hair brush (Figure 4) or a bazooka insect applicator (Tefera *et al*. 2011). It is advisable to infest plants with the insects early in the morning (between 7 and 9 am) or late afternoon (after 4 pm), to avoid exposing the neonates to harsh, sunny conditions that could desiccate the larvae before they are conditioned to the climate and the host. Applying a uniform, sufficient level of insect pressure to each test plant is critical. The level of insect pressure is considered appropriate when the susceptible check is highly affected consistently across the replicates, and at least three-fourth of the plants in a treatment group are infested or show consistent insect damage symptoms (across replicates).

Note: Different protocols may be adapted by different institutions with regard to artificial infestation using FAW neonate larvae in the field for ascertaining germplasm responses. This description highlights the protocol followed by CIMMYT.

FAW egg mass collected on a wax/butter paper from the oviposition cage

FAW neonate larvae emerging from the black egg mass (3-6 days after white egg mass stage)

Newly hatched FAW neonate larvae collected from the black egg mass

Artificial infestation of a maize plant in the field by FAW neonate larvae using a camel hair brush

Figure 4. Artificial infestation of maize plants with FAW after mass rearing.

3.2.3. Data Collection: Rating the Responses of Maize Germplasm

Ratings used in maize FAW screening are primarily based on the degree of plant damage. Data on foliar damage due to FAW infestation should be collected at least two or three times during the crop growth beginning 7-10 days after artificial infestation, and repeated after a 10-day interval. Ear damage and ultimately grain yield data is recorded at the time of harvest.

3.2.3.1. Germplasm rating based on foliar damage by FAW

Foliar damage under FAW infestation should be assessed by scoring each infested plant in a germplasm entry on a 1-9 scale (Davis and Williams 1992), where highly resistant plants are rated with a 1 (no visible damage) and highly susceptible plants with a 9 (completely damaged) (Table 3; Figure 5).

Table 3. **Scale for assessment of foliar damage due to FAW in maize germplasm entries.**

Score	Damage symptoms/description	Response
1	No visible leaf-feeding damage	Highly resistant
2	Few pinholes on 1-2 older leaves	Resistant
3	Several shot-hole injuries on a few leaves (<5 leaves) and small circular hole damage to leaves	Resistant
4	Several shot-hole injuries on several leaves (6–8 leaves) or small lesions/pinholes, small circular lesions, and a few small elongated (rectangular-shaped) lesions of up to 1.3 cm in length present on whorl and furl leaves	Partially resistant
5	Elongated lesions (>2.5 cm long) on 8-10 leaves, plus a few small- to mid-sized uniform to irregular-shaped holes (basement membrane consumed) eaten from the whorl and/or furl leaves	Partially resistant
6	Several large elongated lesions present on several whorl and furl leaves and/or several large uniform to irregular-shaped holes eaten from furl and whorl leaves	Susceptible
7	Many elongated lesions of all sizes present on several whorl and furl leaves plus several large uniform to irregular-shaped holes eaten from the whorl and furl leaves	Susceptible
8	Many elongated lesions of all sizes present on most whorl and furl leaves plus many mid- to large-sized uniform to irregular-shaped holes eaten from the whorl and furl leaves	Highly susceptible
9	Whorl and furl leaves almost totally destroyed and plant dying as a result of extensive foliar damage	Highly susceptible

Source: Modified from Davis and Williams (1992).

The screening method should give distinctly different responses between susceptible and resistant check entries. When such reactions are distinct, moderate resistance in test entries can also be detected. Plant reaction and subsequent damage rating depend on the number of insects per plant, plant vigor, plant age, and environmental factors such as temperature and humidity. The insect population pressure applied should be optimal (typically 20 neonates per plant), so as to unravel genetic variability among the test entries. When the insect population is too high, all entries may appear susceptible. On the other hand, when it is too low, all the entries may appear resistant. Plants that lack vigor because of nutrient deficiencies or other factors, and plants that are extremely young, may also be wrongly rated as susceptible although under optimal conditions they may be resistant/partially resistant.

At physiological maturity, harvest all plants, excluding two border plants from both ends. Shell ears from each plot separately, and take the grain weight at a moisture content of 12-13%.

Figure 5. Rating of maize plants based on foliar damage by FAW.

3.2.3.2. Germplasm rating based on ear and kernel damage by FAW

FAW is not only capable of extensive foliar damage on susceptible germplasm, but also of significant ear/kernel damage when the larvae gain entry into the developing ears. Therefore, germplasm rating under natural/artificial infestation must also consider potential damage caused by the insect on the ears and kernels (Figure 6; Table 4).

Individual ears for each of the germplasm entries are scored at the time of harvest, and the average ear damage score for a germplasm entry is then computed.

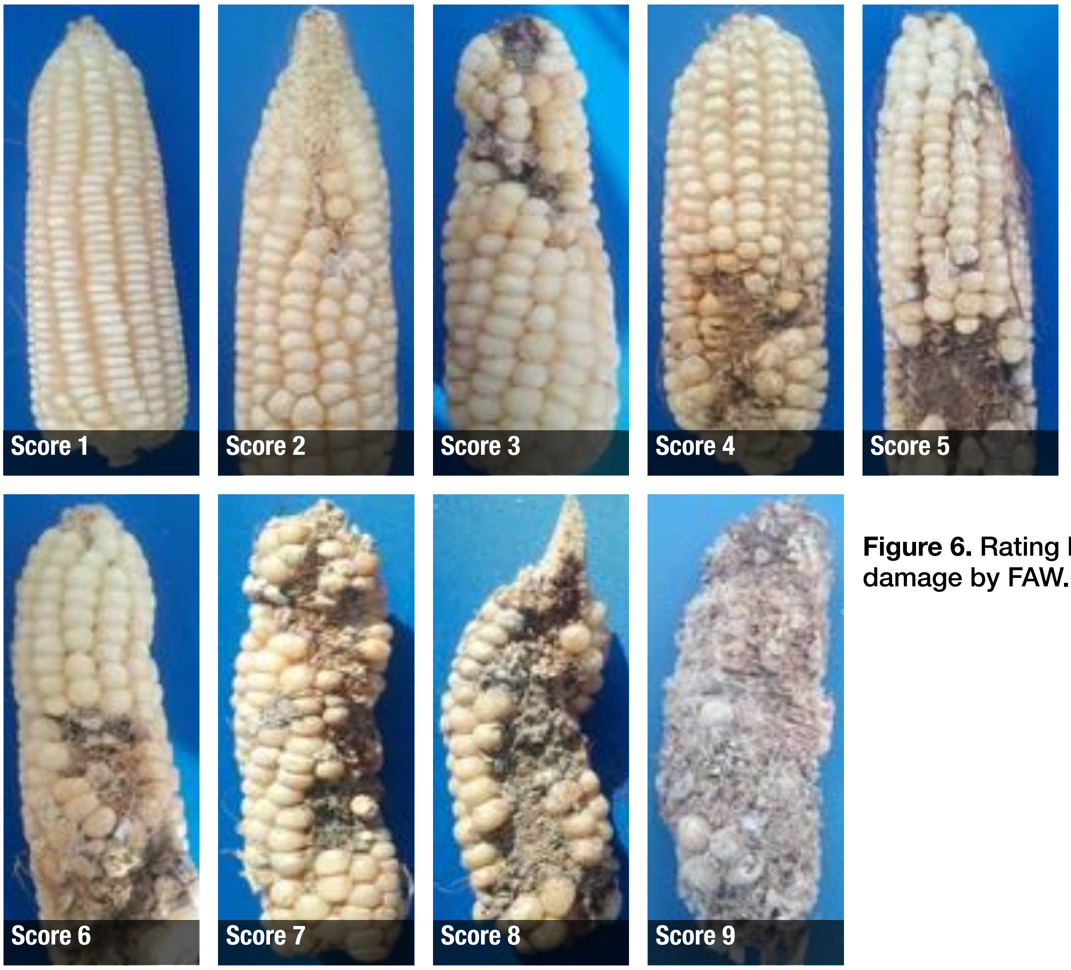

Figure 6. Rating based on ear damage by FAW.

Table 4. Germplasm ratings based on ear and kernel damage by FAW.

Score	Damage symptoms/description	Response
1	No damage to the ear	Highly resistant
2	Damage to a few kernels (<5) or less than 5% damage to an ear	Resistant
3	Damage to a few kernels (6-15) or less than 10% damage to an ear	Resistant
4	Damage to 16-30 kernels or less than 15% damage to an ear	Partially resistant
5	Damage to 31-50 kernels or less than 25% damage to an ear	Partially resistant
6	Damage to 51-75 kernels or more than 35% but less than 50% damage to an ear	Susceptible
7	Damage to 76-100 kernels or more than 50% but less than 60% damage to an ear	Susceptible
8	Damage to >100 kernels or more than 60% but less than 100% damage to an ear	Highly susceptible
9	Almost 100% damage to an ear	Highly susceptible

Source: CIMMYT unpublished protocol.

Note: Breeding programs for FAW resistance have been largely based on leaf-feeding damage rather than ear damage. Although it is useful to also rate the ear damage, for making selection decisions in breeding work, breeding programs will have to determine empirically what relative weight should be given to the leaf-feeding damage rating versus the ear damage rating.

Knowledge Gaps/Researchable Areas

Native resistance

1. Are there already-released African cultivars in maize and other crops with resistance to FAW?
2. Does conventionally derived, FAW-resistant maize germplasm offer resistance to both “rice” and “maize” strains of FAW in Africa (see Chapter 1, Section 2.6)?
3. How can breeders best access and utilize multiple sources of native, trait-based resistance in order to develop broad-based resistance to FAW populations in Africa?
4. Is there a correlation between foliar damage and ear damage, or foliar damage and grain yield?
5. Are there significant differences in maize germplasm in terms of adult FAW preference to oviposit/lay eggs on a given line?
6. How best to improve the resistance rating system using proximal- and remote-sensing tools?
7. What opportunities or technologies exist to accelerate development and deployment of FAW-resistant, Africa-adapted maize varieties (e.g., use of molecular markers, doubled haploid technology)?
8. What relative weight should be given to the leaf feeding damage rating versus the ear damage rating in order to optimize FAW resistance breeding for African farmers?

Transgenic resistance

9. Are the FAW populations in Africa resistant to any of the known transgenes considered for deployment?
10. Devise an Insect Resistance Management strategy relevant for African cropping systems and agro-ecologies.

Key Messages to Policymakers

Native resistance

1. Intensive screening of germplasm in crops that are vulnerable to FAW in Africa needs to be undertaken.
2. Accelerated breeding efforts are required to transfer native resistance from validated sources into diverse, Africa-adapted elite maize products (inbreds/hybrids/OPVs) for deployment to farming communities. Similar efforts are needed in other major crops affected by FAW in Africa.
3. Fast-track release and registration of farmer-preferred, FAW-resistant, conventionally derived hybrids/improved OPVs (with relevant adaptive traits), based on one year of National Performance Trials (instead of 2 years).
4. Need for urgent adoption of policies for harmonized varietal releases across countries/regions, and replacement of highly susceptible varieties with identified resistant varieties.

Transgenic resistance

5. *Bt* maize is an important tool in the toolbox for FAW management.
6. The technology has a proven track record in the Americas, with 20 years of field experience and success. *Bt* maize technology has been one of the most effective tools to control FAW in both the USA and Brazil.
7. The WEMA project has extensively tested *Bt* maize under Confined Field Trials (CFTs) in five (soon to be six) African countries in order to demonstrate safety, efficacy, and yield benefit under African conditions.
8. Some African regulatory agencies have built capacity for science-based decision making to address questions and societal concerns regarding safety, efficacy, and performance of the *Bt* technology.
9. Pyramiding transgenes with different modes of action (*e.g., Cry + Vip3A*) is more effective compared to single-gene deployment, especially in terms of durability of resistance.
10. Proper stewardship is important to ensure durability of the technology and to address insect resistance development.

CHAPTER 05

Biological Control and Biorational Pesticides for Fall Armyworm Management

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1. Introduction

1.1. What are Biological and Biorational Pest Control Options?

In nature, the population of any organism is regulated. It is kept fluctuating within an upper and lower threshold, often below economically damaging levels, due to the actions of biotic regulations (availability of food, parasites, predators, and/or pathogens) and/or abiotic factors (climate and soil factors). Such population regulation is referred to as natural control. However, such natural control when disrupted due to biological, anthropogenic, or climatic factors results in the outbreak of organisms leading to economic damage. Invasiveness of a pest species into new geographies in the absence of biotic regulatory factors often results in the disruption of natural control, leading to devastating outbreaks (*e.g.*, fall armyworm (FAW), *Spodoptera frugiperda* [J.E. Smith]; tomato leaf miner, *Tuta absoluta* [Meyrick]). Anthropogenic changes in crop and pest management practices such as introduction of a susceptible crop/cultivar, monocropping, and irrational use of broad-spectrum pesticides, among others, also often result in disruption of natural control, leading to outbreaks of pest and diseases. Asynchrony in range expansion of pests and their natural enemies due to climate change could also disrupt the natural control.

The best approach to manage such outbreaks is to either revive or establish natural control as much as possible. Biological control primarily focuses on restoring the natural control. Biological control, as defined by Paul DeBach (1964), is the action of living organisms (parasites, predators, or pathogens) introduced by human intervention for regulating the population of another organism at densities less than those that would occur in their absence. Parasitoids are biological agents for which at least one of their life stages is intimately associated with specific life stages of the pest and with greater levels of specificity (*e.g.*, parasitoid species belonging to *Trichogramma* and *Telenomus* parasitizing eggs of insects including FAW). The larvae of parasitoids always kill their host as the outcome of their development. Predators, on the other hand, are never intimately associated with the insect pest, and the pest serves as prey for the predator often with less specificity (*e.g.*, insects such as ladybird beetles, earwigs, and sap-sucking insects such as *Orius* and *Podisus* prey on various life stages of FAW). Entomopathogens include bacteria, fungi, protozoans, nematodes, or viruses that infects and causes diseases in insects (*e.g.*, fungi such as *Metarhizium anisopliae* and *Beauveria bassiana;* viruses such as *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV); and bacteria such as *Bacillus thuringiensis* (*Bt*), and others that are known to infect FAW).

Based on how biological control is undertaken, it can be broadly classified as classical (inoculative) biological control, augmentation (inundative) biological control, and conservation biological control. Classical (inoculative) biocontrol is often undertaken to counter invasive pests; in this method, an exotic species of natural enemies from the region where the insect pest originated and with high level of host specificity is imported and released in the invaded regions. A successful classical biological control results in extensive, continuous, and widespread control of the invasive species (*e.g.*, release of *Cotesia flavipes* for the control of Asian stemborer *Chilo partellus* in Africa). Prior to invasion in Africa, FAW has been prevalent in the Nearctic and Neotropical regions of America for several centuries, associated with several natural enemies. Some of these natural enemies could be potential candidates for classical biological control initiatives in Africa.

An augmentation (inundative) biological control approach involves periodic releases of natural enemies or pathogens, which are either introduced or endemic, to foster biological control or to induce epizootics of pathogens against either invasive or endemic pests. In contrast to the first two forms, conservation biological control involves the manipulation of environment, cropping systems, and practices in a way that favors the natural enemies against the pest. During the process of invasion, invasive species are likely to encounter natural enemies of other species closely related to it. Some of these natural enemies could adapt to the invasive pest, often referred to as “new associations.” It is important to understand that prior to the invasion of FAW, Africa has been home to several lepidopteran pests belonging to the genus *Spodoptera*. African armyworm (*Spodoptera exempta* [Walker]), beet armyworm (*Spodoptera exigua* [Hübner]), and African cotton leafworm (*Spodoptera littoralis* Boisduval) are among the most widely prevalent species with effective natural enemies and entomopathogens enhancing the probability of new associations to establish against FAW. The use of a biocontrol method to control a pest species does not normally affect the performance of other biological agents important in regulating pest populations, although in some cases there is intraguild predation.

The concept of biorational pesticides encompasses pest control products that are efficacious against target pests but are safe to natural enemies and broadly to the environment. Biorational pesticides often refers to products that are derived from natural sources such as botanicals, biopesticides, and others. For this chapter, we will restrict our information on biorationals to botanical pesticides and biopesticides. Integrated use of management options such as biological control and biorational pesticides along with other cultural and host plant resistance is likely to significantly reduce dependence on pesticides for management of pests. In this regard, the focus of this chapter will be to take stock of the diverse biological and biorational pest control options that are available in the native region of FAW and show potential for its management in Africa.

2. Biocontrol-based IPM Strategies for FAW

FAW is native to the Americas and a newly introduced pest species in Africa. As is common with invasive species, most of the naturally occurring biocontrol agents for this pest are not present, or native species have not yet adapted to this new host or prey. Implementation of any IPM strategy in Africa for FAW control should seek to avoid disrupting biocontrol processes that are operational for other pests and those that are adapting to FAW.

Conservation of the diversity and density of natural enemies should be a key focus in such a strategy. A simple way to achieve this is to provide, near the maize area, conditions conducive to survival of natural control agents. Planting crops that provide shelter, alternative food sources, and conditions for multiplication of beneficial species may be key to regulating the FAW population. At the edges of maize cultivation areas, rows of crops such as Mexican sunflower or Crotalaria might be suitable components in landscape management with the goal of increasing the biodiversity of beneficial insects, even those that are not yet associated with FAW. A “Push-Pull” strategy can also be used, in which pest-repellent plant species are intercropped with the main crop to repel (“push”) pests out of the field, which is also surrounded by a border of a pest-attractive species to “pull” both the pest and beneficial insects into it (http://www.push-pull.net/; see also Chapter 6).

The second step in the implementation of a biocontrol-based IPM strategy against FAW is to assess the economic injury levels (EIL); strengthen monitoring, scouting, and surveillance efforts (see Chapter 2); and undertake pest management efforts through inundative release of natural enemies or through application of biorational pesticides, such as botanicals, or biopesticides, especially when the pest density exceeds EIL.

2.1. Advantages of Using Biological Control of FAW in Africa

The smallholder-based maize-production systems in Africa are diverse especially in terms of size, mixed cropping, seasonality, and other characteristics, unlike the large-scale commercial monocropping systems of the Americas. Further, levels of pesticide sprays on maize at present are much lower in Africa than in the other parts of the world. These are ideal conditions for effective conservation of natural enemies and achieving the full benefits of biological control (Herren and Neuenschwander 1991; Macharia *et al.* 2005; Soul-kifouly *et al.* 2016). Biological control, especially classical and conservation biological control, is much cheaper and benefits smallholder production systems in Africa. Further there are no cases of resistance development among FAW to biological control agents. With effective capacity-building initiatives, Africa can take advantage of the available manpower, such as farmers’ associations, to mass-produce and release biological control agents for FAW management in Africa, as with the biological control of millet head miner in Niger and Senegal.

Hence, based on the global experience of managing maize pests, biocontrol will serve as a necessary pillar of the IPM strategy for control of FAW in Africa. However, to harness this potential, it is important to assess the diversity and effectiveness of biocontrol species on the continent to identify new associations. Further, taking stock of the diversity of FAW biological control agents in America, selection of appropriate candidate agents for classical biological control of FAW in Africa based on ecological suitability assessments needs to be undertaken. Effective biorational pesticides that can aid in the management of FAW and conservation of natural enemies need to be identified and promoted. Preliminary assessments of biocontrol species on the continent suggest we should optimize the role of biocontrol in helping to manage FAW (IPM Innovation Lab 2017; https://ipmil.oired.vt.edu/wp-content/uploads/2017/07/Muni-FAW-PPT-1.pdf).

2.2. Inundative Release of a Biological Control Agent against FAW

As mentioned above, *Trichogramma* or *Telenomus* wasps are the best examples of species used in inundative release to control FAW eggs. Unlike pesticide treatments, which must cover the entire plant (whorl or maize ear) to reach the target pest, egg parasitoids may be released at some point in the target area. Once released, the wasps, with extreme search capacity, fly to the plants seeking the pest's eggs. Hence, the releases are made at strategic points ranging from 20 to 40 per hectare (Cruz et al. 2016).

Considering the very short (less than 3 days) longevity of the released female and the fact that a new parasitoid generation occurs 10 days after release, it is necessary to make three releases spaced at 3-day intervals to provide a continual presence of adults in the area. New releases may be necessary if there is a significant increase in the movement of moths into the production area, as indicated by monitoring traps. The inundative release of *Trichogramma/Telenomus* wasps in maize fields does not reduce the populations of other beneficial species. Interspecific competition studies should be done before the introduction of new natural enemies. FAW feeds primarily on leaves but can also use the grain as a food source. Inside the ear, the larvae are protected, making it difficult to use conventional control measures such as pesticide sprays. The presence of FAW in the maize ear results from migration of larvae during tasseling as they are pushed out of the whorl and into and on the ears. Release of *Trichogramma/Telenomus* early in the season helps to suppress FAW migration into the ears.

Synchronization between the presence of FAW egg masses and release of parasitoids in maize is essential to the success of applied biocontrol. Monitoring the arrival of the moths in the target area using pheromone traps (see Chapter 2) is more effective than manually searching for egg masses. The first moth captures signal the arrival of the pest in the area and indicate that oviposition is close.

2.3. Importance of Other Beneficial Insects in the Natural Control of FAW

Considerable biodiversity of beneficial insects exists in maize fields in the Americas and the Caribbean (Molina-Ochoa *et al.* 2003; Cruz *et al.* 2009). The braconid wasp *Chelonus insularis* Cresson is one of the key natural biological control agents (Meagher *et al.* 2016). Like the egg parasitoids, *Chelonus* parasitizes the egg of FAW; however, the FAW eggs hatch into larvae and the parasitoid adult emerges from the FAW larva. Because *Chelonus* is a much larger insect than *Trichogramma/Telenomus* wasps, *Chelonus* is more competitive. The parasitized larvae gradually reduce their food intake, consuming less than 10% of the biomass consumed by a healthy larva (Rezende *et al.* 1994). Therefore, the presence of small larvae in the release area of *Trichogramma* does not necessarily mean a failure in biocontrol of FAW. Rezende *et al.* (1995a,b) provide further information on the role of *Chelonus* in IPM.

In addition to *C. insularis*, several other parasitoid species are also considered important in suppressing populations of FAW larvae (Figueiredo *et al.* 2009). For example, *Campoletis flavicincta* has been extensively used (Matrangolo *et al.* 2007; Matos Neto *et al.* 2004). So far in Africa, *Charops ater* Szépligeti (Ichneumonidae), *Chelonus curvimaculatus* Cameron, *C. maudae* Huddleston, *Coccygidium luteum* (Brullé) (Braconidae), and *Telenomus* spp. (Platygastridae) are egg and larval parasitoids found to be associated with *S. frugiperda* in East and West Africa (Mohamed *et al.* unpublished data; Goergen, unpublished data). Standardization of mass-rearing protocols of these parasitoids on *S. frugiperda* and assessment of their efficiency are ongoing. In addition to the benefits of parasitoids, the presence of insect predators of both eggs and larvae is important to keep the FAW population below the economic threshold level. For example, the predatory earwig *Doru luteipes* (Scudder) lays its eggs inside the maize whorl, the preferred location of FAW (Reis *et al.* 1988), and occurs throughout the maize crop cycle. Nymphs of *D. luteipes* consume 8–12 larvae daily, while in the adult stage they consume 10-21 larvae of *S. frugiperda* daily (Reis *et al.* 1988). Artificial diets for rearing of *D. luteipes* based on insect pupa flour and pollen were found to be equal to FAW eggs (Pasini *et al.* 2007). Several species of earwigs are also frequently observed in the whorl and ears of maize in Africa. Earwigs are frequently assessed as predators of stemborers and aphids in maize in Africa. Among them, *Diaperasticus erythrocephalus* (Olivier) is frequently observed. The predatory potential of these earwigs on FAW eggs and larvae needs to be assessed in detail. Laboratory and field studies with other identified beneficial insects associated with maize pests demonstrate the real possibility of having a sustainable management of maize pests based on biocontrol strategies.

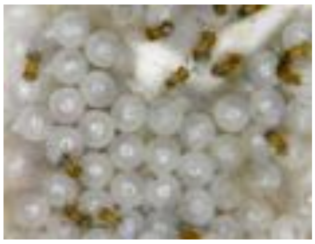
In situations where the presence of biocontrol agents is not yet at the optimal level and where pesticide applications might be required, use of microorganisms such as Baculovirus or *Bacillus thuringiensis* should be considered (Valicente and Cruz 1991; Cruz 2000; Cruz *et al.* 2002; Figueiredo *et al.* 2009; see Section 3.2).

3. How to Recognize Natural Enemies of FAW

3.1. Insects

Table 1 describes the main group of natural enemies associated with FAW to help the farmer identify possible natural enemies of the pest in the different countries where the pest is already present.

Table 1. A summary of parasitoids and predators against FAW.

Scientific Name & Family	Description	Photograph
	FAW Parasitoids	
	Egg Parasitoids	
Trichogramma pretiosum (Riley) (Trichogrammatidae)[a]	• *Trichogramma* species are very small insects, with dimensions <1 mm. • *T. pretiosum* is used in the control of eggs of FAW and *Helicoverpa spp.*	 *Trichogramm*a parasitizing FAW eggs
Trichogrammatoidea armigera (Nagaraja) (Trichogrammatoidea)[b]	• Small insects (< 1 mm) with females bigger than males. • *T. armigera* is used in the control of eggs of *Helicoverpa armigera* and FAW. • *T. armigera* is being mass produced at ICRISAT-Niger Laboratory.	
Telenomus remus (Nixon) (Hymenoptera: Scelionidae)[c]	• Measures 0.5-0.6 mm in length and has a black, shiny body. • Presents high specificity for FAW. Each female parasitizes more than 250 eggs during its life span. • The total development period from egg placement to adult emergence is 10 days.	 *Telenomus remus* adult (left); females parasitizing FAW eggs (right).
	Egg-Larval Parasitoids	
Chelonus insularis Cresson (Hymenoptera: Braconidae)[d]	• Measures about 20 mm in wingspan. • A very competitive parasitoid, usually predominant in maize fields. 91% of natural parasitism found in maize field samples was due to *C. insularis.* • Among the several biological control agents of FAW, it belongs to the most geographically dispersed, common in the USA and throughout South America. *C. insularis* has been found in South Africa and Egypt (CABI). • The parasitized FAW egg hatches, giving rise to a caterpillar, carrying within it the parasitoid. The larval period of the parasitoid has an average length of 20.4 days, close to that of a healthy caterpillar. However, the relationship of leaf consumption between healthy and parasitized caterpillars is 15:1, meaning less damage to the plant.	 Female of *Chelonus insularis* parasitizing FAW eggs (left); two FAW larvae of the same age. The smaller one has been parasitized by the wasp (right).

Scientific Name & Family	Description	Photograph
	Larval Parasitoids	
Campoletis sonorensis (Cameron) (Hymenoptera: Ichneumonidae)[e]	• The insect wingspan is about 15 mm. Third-instar larvae are the most suitable stage for the parasitoid. The total cycle of the parasitoid is around 22.9 days. • The relation of consumption between a healthy caterpillar and a parasitized caterpillar is 14.4:1. Therefore, by parasitizing small-sized caterpillars, in addition to being efficient to cause death of the host insect, the parasitoid greatly reduces leaf consumption by caterpillars. • The skin of the dead FAW caterpillar lies next to the cocoon of the parasitoid, characteristic of this species.	 *Campoletis flavicincta* couple (upper left); female parasitizing FAW larva (upper right).  *C. flavicincta* pupa and remains of a parasitized FAW larva (bottom).
Cotesia icipe (Fernández-Triana & Fiaboe)[h]	• Known to parasitize several species of Spodoptera in Africa, including FAW. • Under laboratory conditions >50% parasitism has been observed on FAW.	 *Cotesia icipe*, seeking FAW larva (Source: Faris Samira Mohamed, ICIPE)
Habrobracon hebetor (Say) (Hymenoptera: Braconidae)[i]	• A small wasp, which has been used against pearl millet head miner, also attacks FAW larvae under laboratory conditions. • These parasitoids are reared in the laboratory at ICRISAT and INRA in Niger, and ISRA in Senegal on *Corcyra cephalonica* larvae, and released in pearl millet fields in Niger and Senegal. • In Africa, this parasitoid is found in Algeria, Burkina Faso, Egypt, Libya, Madagascar, Niger, Senegal, South Africa, Zimbabwe, and Mauritius (CABI).	 *Habrobracon hebetor* parasitizing on FAW larvae
Winthemia trinitatis (Thompson) (Diptera: Tachinidae)[j]	• The female places its eggs in the body of a fifth- and sixth-instar FAW near the head, making it impossible to be removed. The larvae of the parasitoid penetrate the body of the larva, delay pupation, and inflict up to 30% parasitism. • While acting on more developed instars that have already caused damage to the plant, these tachinids contribute to the reduction of future pest generations.	 Tachinid fly *Winthemia trinitatis* laying egg on FAW larva (left) and eggs on the host abdomen (right)

Scientific Name & Family	Description	Photograph
Larval-Pupal Parasitoids		
Archytas marmoratus (Townsend) (Diptera: Tachinidae)[k]	• A solitary larval-pupal parasitoid of several species of Noctuidae (Lepidoptera) including FAW. • Has a complex life cycle that allows it to parasitize a wide range of host larval instars. • The female does not lay the eggs directly on the host, but rather places several of them nearby. The eggs soon hatch and young larvae emerge. Parasitism occurs when these larvae meet a host and penetrate the body of the host. • Since the female of *A. marmoratus* lays several eggs at the same time at several places, the probability of superparasitism is very high. Often 75% of the parasitized larva are superparasitized. Survival of the parasitoid declines significantly if more than four parasitoid maggots are seen in a single host caterpillar. Hence, release rates of *A. marmoratus* need to be optimized to reduce superparasitism rates (Carpenter and Proshold 2000). • Mass-rearing protocols for *A. marmoratus* on corn earworm, Helicoverpa zea (Boddie) and Greater wax moth, Galleria melonella (L.) were standardized (Gross and Johnson 1985; Bratti 1993).	 *Archytas marmoratus*
Lespesia archippivora (Riley) (Diptera: Tachinidae)[l]	• A generalist parasitoid capable of parasitizing at least 25 species of Lepidoptera. • A female can oviposit between 15 and 204 eggs in her life span. • The female oviposits on the back end of the caterpillar. Three instars of *Lespesia archippivora* feed on the host caterpillar and upon maturity the parasitoid emerges out of the larva and pupates in the soil. Adult emerges from the pupa approximately 10–14 days from oviposition.	 *Lespesia archippivora* (Source: CBG Photography Group, Centre for Biodiversity Genomics)

Notes on Egg and Egg-Larval Parasitoids

- The egg parasitoids are considered the most important among the agents of biological control. These species prevent the pest from causing any damage to the host plant. In addition, these parasitoids have been easily reared on a large scale and are therefore commercially available from biofactories in several countries.
- The *Trichogramma* female oviposits inside the egg of its host. Within a few hours its larva emerges and feeds on the contents of the host's egg. The whole cycle of the parasitoid occurs inside the pest egg. Soon after emergence, the adult wasp immediately begins the process of searching for a new egg mass, which continues the multiplication of the species. The total life cycle of the parasitoid is about 14 days.
- 100,000 adult parasitoids per hectare, released at about 40 points, is the recommendation for maize. Field efficiency, rearing ability on a commercial scale, and competitive prices are the main reasons for using *Trichogramma* as the main biological control agent in an inundative release method.
- The presence of scales/hairs over the egg masses acts as a barrier against parasitism by *Trichogramma* spp. This difficulty can be overcome by using a more aggressive parasitoid that is capable of breaking the physical barrier. Therefore, it is essential to know the species/strains present in the agroecosystem when choosing the Trichogramma species to be used for applied biological control of FAW.
- There are 12 species of Telenomus and 27 species of *Trichogramma/Trichogrammatoidea* found in Africa, indicating the adaptability of these genera in the continent.
- A species of *Trichogramma/Trichogrammatoidea* has been collected from the eggs of FAW in Niger. Twenty-four government and private laboratories in Egypt are producing *Trichogramma* spp. and other natural enemies. The Economic Entomology Laboratory at Cairo University is producing *T. achaeae, T. euproctidis, Chrysoperla* sp., *Orius* sp., and coccinellids in large scale for research and distribution. The laboratory is capable of providing training on mass culture of these natural enemies. In 2016, the laboratory trained technicians from Mali and Niger on mass production of Trichogramma spp.
- The use of *Telenomus* in the control of FAW follows the same dynamics as Trichogramma but is used at a quantity of 60,000 insects per hectare. A species of *Telenomus* has been found parasitizing 60% of FAW eggs in Niger (ICRISAT).

Notes on Larval Parasitoids

- *Cotesia marginiventris* has been found in Central African Republic and Egypt (CABI). Incidentally, *C. marginiventris* has been introduced into Cape Verde prior to 1981 where it has established on *Helicoverpa armigera, Trichoplusia ni,* and *Chrysodeixis chalcites* (Lima and van Harten 1985; van Harten 1991).
- Several other species of *Ichneumonidae* larval parasitoids are common in samples taken from FAW larvae in different maize-producing regions in Brazil, indicating their potential for use in biological control programs. For example, *Eiphosoma laphygmae, Ophion flavidus,* and *Colpotrochia* mexicana cause a significant reduction in the food ingestion by the pest, thereby reducing the potential to cause economic losses. In addition to *O. flavidus, Aleiodes laphygmae* (Braconidae), *Meteorus* spp. (Braconidae), and *Euplectrus platyhypenae* (Eulophidae) also associate with FAW larvae (e.g., Meagher et al. 2016).

Notes on Some Pupal Parasitoids

Five species of *Ichneumonidae, Diapetimorpha introit, Cryptus albitarsis, Ichneumon promissorius, Ichneumon ambulatorius,* and *Vulgicheneumon brevicinctor;* two species of *Chalcididae, Brachymeria ovata* and B. robusta; and one eulophid species, *Trichospilus pupivora*, have also been reported on FAW pupae from the USA, Argentina, and Barbados.

Scientific Name & Family	Description	Photograph
	FAW Predator Insects	
Coleomegilla maculata (De Geer) (Coleoptera: Coccinellidae) **Ladybird beetle**[m]	• Adults are 6 mm in length and generally red with six black spots on each elytra. • Females lay clusters of 10 to 20 yellow eggs on the plants. • Both adults and larvae feed on aphids, mites, eggs, and larvae of various insects such as FAW. • Pollen and fungal spores are also important components of this species' diet.	 *Coleomegilla maculata* (adults, eggs, larva and pupa)
Hippodamia convergens (Guérin-Méneville) (Coleoptera: Coccinellidae) **Ladybird beetle**[n]	• Adults are ~6 mm in length and have orange-colored elytra, typically with 6 small black spots on each. • The body section behind the head is black with white margins and two white lines converging. • The females lay clusters of 10-20 yellow-colored eggs on the plants. • The larva grows through four stages.	 *Hippodamia convergens*
Olla v-nigrum (Mulsant) (Coleoptera: Coccinellidae) **Ladybird beetle**[o]	• Adults are initially light in color, and over time, become darker. • Adults come in two different color patterns. The black-colored adult acquires a brilliant black color, while the spots of their elytra become orange. The yellow-straw colored adult shows a slight increase in its tonality and the spots located along its elytra become black. • An efficient predator, both in the larval and adult stages. • The average eggs per oviposition is around 21. The total egg to adult cycle lasts about 20 days.	 *Olla v-nigrum*
Cycloneda sanguinea (L.) (Coleoptera: Coccinellidae) **Ladybird beetle**[p]	• A red insect with no spots on the elytra of adults but two black spots on the clear area of the head. • The female lays her eggs in the host plant, in groups, each containing about 20 yellowish eggs. • The insect passes through four nymphal stages. The larval period lasts for ~8 days. The larvae to adult cycle is ~15 days. • Both the larva and the adult are predators.	 *Cycloneda sanguinea*

Scientific Name & Family	Description	Photograph
Doru luteipes Scudder (Dermaptera: Forficulidae) **Earwigs**[q]	• One of the most important natural enemies of FAW. Bioecological studies with the predator, feeding on FAW larvae, showed that the number of eggs per oviposition is 25-30, with an incubation period of around 1 week. • The nymph stage comprises four instars, ranging from 37 to 50 days. • Adults with sieves at the extremity of the abdomen can live up to 1 year.	 *Doru luteipes*
Euborellia annulipes (Lucas) (Dermaptera: Carcinophoridae) **Earwigs**[r]	• In summer, the incubation period is 7 days. Time from egg until adult emergence is ~60 days. • The newly deposited eggs are oval, of yellowish cream color, 0.95 mm in length and 0.75 mm in diameter. The newly hatching nymphs have white coloration, black eyes, and black or brown abdomen. When they become adults, the initial coloration is white, and then turn dark color. • The insects do not have wings.	 *Euborellia annulipes*
Zelus longipes (L.) *Zelus leucogrammus* (Perty) *Zelus armillatus* (Lepeletier & Serville) (Hemiptera: Reduviidae) **Assassin bug**[s]	• The genus *Zelus* is one of the most common killer bugs in maize. • Average adult length is 1.3-1.9 cm. • Brown or blackish in color, and commonly found in maize fields. • Usually have a long, narrow head with a distinct neck behind the eyes, which are often reddish. • The females lay the eggs in groups on the leaves of the plants or even on the ground. The nymphs resemble an adult but without a wing.	 *Zelus* spp.: adults and egg mass (right, above)
Geocoris punctipes (Say) Hemiptera: Lygaeidae **Big-eyed bugs**[t]	• Small insects (approximately 4 mm in length) occurring in many parts of the world. • Generally considered beneficial because they attack various pests including insects and mites in ornamental and agricultural crops. • Very common predator of *Lepidoptera* species.	 Big-eyed bug *Geocoris punctipes* (Lygaeidae) (upper left); small pirate bug *Orius insidiosus* (Anthocoridae) (lower left); *Nabis* sp. (Nabidae) (right)
Orius insidiosus Say (Hemiptera: Anthocoridae) **Flower bug**[u]	• Predator of small arthropods, such as thrips, mites, whiteflies, aphids, and lepidopteran eggs. • Highly abundant species with the high potential for use in biological control programs.	
Nabis rugosus (L.) (Hemiptera: Nabidae) **Pirate bug**[v]	• Predators of aphids, moth eggs and small Lepidoptera larvae	

Scientific Name & Family	Description	Photograph
Podisus maculiventris (Say) (Hemiptera: Pentatomidae) **Spined soldier bug**[w]	• *Podisus* spp. are found in different ecosystems, with nymphs and adults feeding mainly on *lepidopteran* larvae. • Pricks its prey and injects a toxin that paralyzes it in relatively short time. The prey is killed as its internal fluids are sucked out by the predator.	 *Podisus* spp. (egg mass, nymphs, and adult feeding on FAW larva)
Calosoma granulatum (Perty) (Coleoptera: Carabidae) **Ground beetles**[x]	• A greenish, iridescent beetle (25-30 mm in length). • Mated female lays the eggs on the surface of the soil or slightly below. The immature stage passes through three instars, before pupation in the ground. • Eggs are light yellow. The larval stage is ~12 days. Adult longevity is ~83 days.	 Eggs and pupa (left); adult and larva of *Calosoma* sp. feeding on FAW larva (right)

Note: References provided here are representative for each species.
[a]Buttler and Lopez (1980); [b]Manjunath (1972); [c]Pomari *et al.* (2013); [d]Rezende *et al.* (1995a), Figueiredo *et al.* (2006a); [e]Isenhour (1985); [f]Figueiredo *et al.* (2006b); [g]Jalali *et al.* (1990); [h]Fiaboe et al. (2017); [i]Landge *et al.* (2009); [j]Silva *et al.* (2010); [k]Gross and Johnson (1985); [l]Etchegaray and Nishida (1975); [m]Lundgren *et al.* (2004); [n]Cardoso and Lázzari (2003); [o]Chazeau *et al.* (1991); [p]Cardoso and Lázzari (2003); [q]Choate (2001); [r]Bharadwaj (1966); [s]Cogni *et al.* (2000); [t]Champlain and Sholdt (1967); [u]Coll and Ridgeway (1995); [v]Tamaki and Weeks (1972); [w]Mukerji and LeRoux (1965); [x]Pasini (1995)

3.1.1. Host Suitability Studies

Suitability is defined as the ability of a host to successfully support parasitoid development from egg to adult.

3.1.1.1. Egg parasitoid host suitability

i. Expose 100 eggs to a naïve mated parasitoid female in a glass vial.
ii. After 6 hours of exposure, remove the female parasitoid from the vial and incubate the eggs at 25±1°C and 70±5% RH.
iii. Record data on the following parameters: percentage parasitism, percentage emergence, F1 sex ratio (percentage of females), and developmental time.

3.1.1.2. Host acceptability and suitability for larval parasitoid

i. Select L2-L5 instars for these experiments. Conduct the experiments in the laboratory at 25±1°C, 50–70 % RH, and 12h:12h (L: D) photoperiod.
ii. Use the hand stinging technique, *i.e.*, offer larvae held in a soft forceps to the female parasitoid in a sleeve cage. A host is defined as having been accepted when the parasitoid inserts its ovipositor. Verify oviposition (*i.e.*, egg deposition) later via dissection of a subsample of larvae.
iii. Put the probed larvae individually into glass vials containing artificial diet.
iv. Monitor the fate of both host larvae and parasitoids daily. Only larvae that produce cocoons are considered as suitable. Record the number of hosts that die, produce cocoons that pupate, or form adult moths. In addition, compute parasitoid emergence, total progeny per host larvae, sex ratio (proportion of female progeny), and parasitoid mortality. When neither eggs nor dead parasitoids are found, the larvae are regarded as unparasitized.

3.1.1.3. Host suitability study of pupal parasitoids

i. Expose one- to five-day-old pupae of FAW to a naïve female pupal parasitoid by releasing a mated female into the vial. Stopper the vial with cotton wool to prevent the parasitoid from escaping.
ii. Remove the parasitoid and the pupae after 6 hours. Place all FAW pupae that were exposed to female parasitoids into individual vials to assess host suitability. Stopper the vials with cotton wool and maintain at 25±1°C, 50-70% RH, and 12h:12h (L: D) photoperiod.
iii. Check pupae daily for moth emergence, parasitoid emergence, or pupal mortality. Record the developmental time and sex of adult parasitoids.

3.1.1.4. Host suitability study of FAW predators

i. Place potential predators individually into a petri dish containing moist cotton wool and starve them for 24 hours prior to the experiment.
ii. Offer potential predators, enclosed in a petri dish, either one batch of FAW eggs, 20 first-instar larvae, 10 late-instar larvae (10- to 14-day-old larvae) or five pupae under laboratory conditions (25±1°C and 70±5% RH).
iii. Record prey acceptance and consumption capacity after 24 hours.

3.2. Entomopathogens

3.2.1. Viruses

Among the microbial control agents, virus-based insecticides, which are mostly in the Baculovirus group, have been identified as having the highest potential for development as bioinsecticides due to specificity, high host virulence, and the highest safety to vertebrates (Moscardi 1999; Barrera *et al.* 2011). Two types of Baculovirus have been studied for the control of *S. frugiperda*, namely granulovirus (SfGV) (Betabaculovirus) and multiple nucleopolyhedrovirus (SfMNPV) (Alphabaculovirus). However, SfMNPV has greater potential for use in the management of FAW (Behle and Popham 2012; Gómez *et al.* 2013; Haase *et al.* 2015). SfMNPV is specific to only FAW larvae. Under natural conditions, the pest is infected orally by ingesting the contaminated food (maize leaf). Once ingested, the polyhedral inclusion bodies (PIB) dissolve in the alkaline midgut, releasing the infective virions. These virions infect the midgut epithelium cells and multiply in the nucleus. Further, the virus spreads to the body cavity and infects other tissues such adipose tissue, epidermal, tracheal matrix and even salivary glands, Malpighian tube, and blood cells, causing its death from 6 to 8 days after ingestion. A caterpillar infected with the nucleopolyhedrovirus eats only 7% of the food normally eaten by a healthy caterpillar (Valicente 1988). The symptoms of Baculovirus infection include appearance of blemishes, yellowing of the skin, and decline in feeding. An infected larva moves to the higher parts of the plant and upon death hangs head down, with some prolegs still attached to the plant. The dead larvae are soft, dark in color, and disintegrate easily to release the body fluids rich in polyhedrons which aids in further spread of the virus (Figure 1).

Age of FAW larva at infection, amount of virus ingested, virulence of the virus, and prevailing climatic conditions, especially temperature, humidity, and solar radiation, are key factors that influence the efficacy of the virus and speed of kill. Therefore, these factors have marked effects on the virus action when it is applied in the field. In addition, other factors such as type of spray equipment, formulation used, and time of spray also influence the efficacy of the virus (Hamm and Shapiro 1992; Cisneros *et al.* 2002).

Better efficiency of Baculovirus for the control of FAW is obtained when applied on maize plants at the 6- to 8-leaf stage or 8- to 10-leaf stage with a costal-manual sprayer, using a wettable powder formulation containing the recommended dose of the product (2.5×10^{11} PIB / ha) on newly hatched larvae, applied at one time or at intervals of one week. An evaluation carried out seven days after virus application indicated a minimum larval mortality from 79.2 to 97.2%. In a second evaluation, carried out three days after the second virus application, mortality varied from 86.6 to 100%. Viral efficiency did not vary between the two stages of plant growth. A commercial formulation for FAW NPV, SPOBIOL (prepared by CORPOICA, the Colombian public-private ag research partnership) is available and has been licensed from Certis LLC, a U.S. company (see Section 7 for a method of small-scale production).

It should be considered also that, as the caterpillar develops, it becomes more resistant to virus. Therefore, the newer the larvae, the higher the efficiency of the virus. Hence, it is recommended to apply Baculovirus to larvae of a maximum of 1.5-cm long. Spraying is performed with the same equipment used for the application of a conventional chemical. Particularly for FAW, it is recommended to use a fan nozzle (8004 or 6504). The more uniform the planting, the more efficient the application with backpack or motorized sprayers. Appropriate nozzles to facilitate uniform application with the type or sprayer used need to be considered. Improved formulations of SfMNPV with maize flour and 1% boric acid (Cisneros *et al.* 2002) and microencapsulation (Gómez *et al.* 2013) are effective for the control of FAW.

Despite various developments in terms of *in vitro* multiplication of baculoviruses, large-scale production of baculoviruses as a commercial biopesticide has been based on *in vivo* multiplication in the host insects due to the significantly low cost involved and less technology-intensive nature of production. Factors such as the ability to maintain a diseased colony of the host insect, age of the caterpillar when exposed to the pathogen, temperature at which the infected colony is maintained, concentration of virus inoculum used, nutritional profile of the larval diet, and mechanization/availability of labor are some of the critical factors that govern the efficiency of Baculovirus production (Moscardi 1999; Subramanian *et al.* 2006; Moscardi *et al.* 2011; Paiva 2013). The cannibalistic nature of FAW further adds to the complexity of SfMNPV production. Inoculation of 8-day-old larva with 1×10^7 PIB/ml and maintained at 25°C has been reported to be optimal to maximize the yield of SfMNPV. The cost of the biopesticide product produced is largely dependent on the cost of maintaining a disease-free colony. Use of natural diets such as castor leaves for rearing SfMNPV can greatly reduce the cost of production; however, such a system is largely prone to contamination due to extraneous virus/microsporidians. *In situ* field-level production using infection of field-collected larva has been developed for *Spodoptera exempta* nucleopolyhedrovirus (*Spex*NPV) in Tanzania, Africa. Early outbreaks of the African armyworm are sprayed with potent *Spex*NPV. Diseased insects are harvested, formulated using a kaolin formulation, and used for treatment of subsequent outbreaks (Mushobozi *et al.* 2006).

3.2.2. Entomopathogenic Fungi

Entomopathogenic fungi (EPF) have a broad spectrum of action with the ability to infect several species of insects and different stages, causing epizootics under natural conditions (Alves *et al.* 2008). The fungus spores infect through the integument, multiply in various tissues within the insect body, and kill the insect due to destruction of tissues and by production of toxins. Induction of epizootics depends on climatic factors such as wind, rain, or frequency of contact among the insects. Diseased insects stop feeding, become discolored (cream, green, reddish, or brown), and ultimately die as a hard-calcareous cadaver from which the fungus sporulates. Moisture is essential to the success of fungi as a biological control agent. *Beauveria bassiana, Metarhizium anisopliae*, and *Nomuraea rileyi* are the common fungi with potential uses against insect pests.

Beauveria bassiana has been used in the control of *Spodoptera* (*e.g.*, Fargues and Maniania 1992). Compared to other lepidopteran pests, FAW larvae seem to be least susceptible to *Beauveria bassiana* (Wraight *et al.* 2010). Several fungal isolates belonging to three different genera (*Metarhizium, Beauveria,* and *Isaria*) have been screened for efficacy against second-instar larvae of S. frugiperda at ICIPE, but only one isolate of *B. bassiana* was able to cause moderate mortality of 30% (Akutse et al. unpublished data). Current efforts are underway to screen EPF isolates for efficacy against other life stages of FAW such as adults and eggs.

3.2.3. Bacteria

Among the various biopesticides used for insect control, *Bacillus thuringiensis* (*Bt*) Berliner biopesticides are the most widely used. These are ubiquitous, soil-dwelling, gram-positive bacteria that produce crystal proteins named delta-endotoxins, which are insecticidal. These endotoxins have relative levels of specificity to specific groups of insects. Although there are several commercial *Bt* products available in the market for management of lepidopteran pests, only a few are effective in controlling FAW. Among the various strains of *Bt*, FAW is more susceptible to *Bt aizawai* and *Bt thuringiensis* (Polanczyk *et al.* 2000), and not to *Bt kurstaki*, which is effective against many other lepidopteran pests (Silva *et al.* 2004). Further aspects such as the susceptibility of the endotoxin to UV, inability to reach the pest and induce consumption of the toxins, and high cost of production limit their wide adoption and use. Efforts to screen for effective *Bt* strains against FAW has been ongoing by several research groups. Variations among populations of FAW in their susceptibility to different Cry toxins have also been observed (Monnerat *et al.* 2006), which needs to be considered during the choice of *Bt*-based biopesticides for FAW management in different regions. With the objective of development of Bt-based biopesticides from Africa, 19 Bt strains have been screened against second-instar larvae of FAW at ICIPE. Seven *Bt* strains were recorded highly effective, causing 100% mortality 7 days post-treatment, with lethal time mortality (LT_{50}) values ranging between 2.33±0.33 and 6.50±0.76 days (Akutse *et al.*, unpublished data). Further biological and molecular characterization of these isolates are currently ongoing. Mass production of *Bt*-based biopesticides has been undertaken using fermentation technology, either as liquid or semi-solid or solid-state fermentation (Fontana Capalbo *et al.* 2001). Apart from the Cry toxins, FAW is also susceptible to some of the vegetative insecticidal proteins found in the *Bt* culture supernatants (Barreto *et al.* 1999). Commercial *Bt* biopesticides based on strain *Bt aizawai* are registered and available to a limited extent in Africa. Efficacy of these biopesticides against FAW in Africa needs to be assessed.

3.2.4. Entomopathogenic Nematodes

One of the less explored but promising strategies in biological control is the use of entomopathogenic nematodes (EPNs), especially *Heterorhabditis bacteriophora*, *Heterorhabditis indica*, and *Steinernema carpocapsae.* These have proved to be human- and eco-friendly alternatives to chemical pesticides in controlling many soil-dwelling insect pests including armyworms. It is reported that FAW is very susceptible to these beneficial nematodes at the rate of 23,000 nematodes per sq. ft., to target both young and mature larvae. Beneficial nematodes need to be applied early in the morning or late at night when armyworm larvae are very active and can be easily found by the nematodes. Another advantage of applying nematodes during these timings is the low exposure of the nematodes to UV as they can die instantly if exposed to UV light (Shapiro-Ilan *et al.* 2006).

Similarly, Garcia *et al.* (2008) reported that 280 infective juveniles of *Steinernema* sp. were required to kill 100% of third-instar FAW in petri dishes, as compared to 400 infective juveniles of the *H. indica* nematode to obtain 75% FAW control. It is possible to spray EPNs without significant loss in their concentration and viability, with equipment that produces electrical charges to the spraying mix, and with those using hydraulic and rotary nozzle tips. The concentrations of infective juveniles of *H. indica* and *Steinernema* sp. nematodes were reduced by 28% and 53%, respectively, when hydraulic spraying nozzles that require 100-mesh filtrating elements were used. Furthermore, Molina-Ochoa *et al.* (1999) reported earlier that *Steinernema carpocapsae* and *S. riobravis* are very effective in controlling FAW prepupae. The authors demonstrated that the combination of EPNs and resistant maize silks could enhance the mortality of FAW prepupae and could be used for integrated management of this pest. Negrisoli *et al.* (2010a) reported that several commercial insecticides were compatible with the three species of EPNs including *Heterorhabditis indica*, *Steinernema carpocapsae*, and *Steinernema glaseri* under laboratory conditions. It was also reported that the efficacy of *H. indica* was enhanced against FAW when mixed with an insecticide, Lufenuron (Negrisoli *et al.* 2010b). However, it is critical to study and evaluate the compatibility of insecticides, including biopesticides and EPNs, before recommending their use in an IPM program for FAW.

According to Kaya *et al.* (2006) the African continent provides great potential for occurrence and exploration of EPNs, but only a few countries have been surveyed so far. Extensive work on nematodes has been done on survival, infectivity, and virulence in Egypt and these studies have shown promising results for development and incorporation of EPNs into IPM programs in some cropping systems in Egypt. While some studies reported successful pest management using EPNs, limited field success was achieved against the lepidopteran sugarcane stalk borer, *Eldana saccharina*, in South Africa. The failure was attributed to the cryptic nature of the larvae and frass/sap in the infested sites of the infested stems. Although commercial applications have not yet been reported from Africa, there is a need to delve into active research on EPNs and explore the potential and fitness of EPNs for biological control plans and IPM programs.

3.3. Botanical Pesticides

Plant-derived pesticides are commonly referred as botanical pesticides. A large diversity of plants are known to have insecticidal properties and some of them have been used for the management of FAW in America (Table 2). The botanical pesticides are biodegradable, environmentally safe, less harmful to farmers and consumers, and often safe to natural enemies and hence amenable for use in biocontrol-based IPM strategies. Further, based on the availability of the pesticidal plants in the ecosystem, botanical pesticides could be easily prepared by smallholder farmers.

Table 2. Potential botanical pesticides against FAW, based on studies in America.

Species	Family	Extract	Mode of action	Reference
Neem: Azadirachta indica	Meliaceae	0.25% Neem oil	Larvicidal with up to 80% mortality in the lab	Tavares *et al.* (2010)
Aglaia cordata Hiern	Meliaceae	Hexane and ethanol extracts of seeds	Larvicidal with up to 100% mortality in the lab	Mikolajczak *et al.* (1989)
Annona mucosa Jacquin	Annonaceae	Ethanolic extract from seeds	Larval growth inhibition	Ansante *et al.* (2015)
Vernonia holosenicea, Lychnophora ramosissima, and Chromolaena chaseae	Asteraceae	Ethanol extracts from leaves	Ovicidal	Tavares *et al.* (2009)
Cedrela salvadorensis and Cedrela dugessi	Meliaceae	Dichloromethane extracts of wood	Insect growth regulating (IGR) and larvicidal with up to 95% mortality	Céspedes *et al.* (2000)
Myrtillocactus geometrizans	Cactaceae	Methanol extracts of roots and other aerial parts	Insect growth regulating (IGR), larvicidal, delayed pupation	Céspedes *et al.* (2005)
Long pepper, *Piper hispidinervum*	Piperaceae	Essential oil from seeds	Affects spermatogenesis and hence egg laying	Alves *et al.* (2014)
Melia azedarach	Meliaceae	Ethanolic extracts of leaves	Antifeedent to larva; synergistic with pesticide	Bullangpoti *et al.* (2012)
Jatropha gossypifolia	Euphorbiaceae	Ethanolic extracts of leaves	Antifeedent to larva; synergistic with pesticide	Bullangpoti *et al.* (2012)
Ricinus communis	Euphorbiaceae	Castor oil and Ricinine (seed extracts)	Growth inhibition and larvicidal	Ramos-López *et al.* (2010)

The use of botanicals in pest management is a cultural practice of African smallholder farmers, which could be an arsenal in FAW management. Several plant extracts have insecticidal properties against stemborers infesting cereals in Africa. These include Neem (*Azadirachta indica*), Persian lilac (*Melia azedarach*), Pyrethrum (*Tanacetum cinerariifolium*), Acacia (*Acacia* sp.), Fish-poison bean (*Tephrosia vogelii*), Wild marigold (*Tagetes minuta*), Wild sage (*Lantana camara*), West African pepper (*Piper guineense*), Jatropha (*Jatropha curcas*), Chillies (*Capsicum* sp.), Onion (*Allium sativum, Allium cepa*), Lemon grass (*Cymbopogon citratus*), Tobacco (*Nicotiana* sp.), Chrysanthemum (*Chrysanthemum* sp.), and Wild sunflower (*Tithonia diversifolia*) (Ogendo *et al.* 2013; Mugisha-Kamatenesi *et al.* 2008; Stevenson *et al.* 2017). The efficacy of these botanicals against FAW needs to be quickly assessed and effective botanicals disseminated among maize growers in Africa. Preliminary evidence indicates the insecticidal property of seeds and leaf extracts of Neem, Melia, and Pyrethrum in Africa to FAW, which needs to be further explored.

4. Protocol for Monitoring Biological Control Agents of FAW

Considering that biological control is an important strategy in the management of FAW, and that FAW has likely been in at least some African countries for some time, it is likely that endemic biocontrol species, primarily parasitoids, have already started using FAW as a host. Accordingly, a protocol for the identification of biological control agents of FAW in maize follows below.

4.1 Parasitoids

- This protocol should be carried out preferably for at least three consecutive years, covering municipalities of different regions in each country.
- In each municipality, randomly select three rural properties.
- At each location, identify a maize area of at least one hectare. Choose five sampling points at random and at each point, mark 100 plants and count the number of FAW-damaged plants.
- For each plant, collect all FAW larvae and egg masses, noting the date and place of collection.
- To find the larvae, it is often necessary to open the still-rolled leaves of the plant because that is the insect's preferred feeding location. When the plant is in the reproductive stage, the larva will be found feeding inside the ear.
- In the laboratory, place each egg mass individually in a closed container to prevent the escape of larvae after hatching.
- Use maize leaves washed and dried (in the shade) as a food source for rearing the FAW larvae.
- Change the food in the case of the wilted leaves or when totally consumed.
- If possible, use an artificial FAW diet to rear larvae.
- Daily, observe the presence of newly hatched larvae, considering the incubation period of three to four days; at the end of this period, if there is no egg hatch and eggs are blackened, isolate the remainder of the eggs, and wait for the possible emergence of egg parasitoids.
- Keep neonate larvae in the laboratory for a minimum of 10 days to observe if egg-larval parasitoids are present.
- Keep collected larvae isolated individually to prevent cannibalism.
- Data should include date of collection, location, an estimation of the FAW larval instar at the date of collection. With these data, it is possible to determine the approximate date that parasitism began.
- Monitor the development of the larvae in the laboratory until FAW pupation or until the emergence of parasitoids.
- If the parasitoid species cannot be identified, send it to a specialist for identification (*e.g.*, ICIPE in east and southern Africa; IITA in west and central Africa).

4.2 Predators

Predator insects are generalists and in maize areas they can feed on FAW eggs and or larvae as well as other pest species. Therefore, it will also be important to sample for the presence of predators in the same points of the parasitoids.

Predator sampling can be performed in three ways: (a) Bag the maize whorl with a plastic or mesh bag and immediately remove the leaves for further insect counts and identification; (b) perform sampling with a sweep net; (c) use direct visual observation.

4.3. Entomopathogens

In general, when a FAW larva is infected by a pathogen the larva will change color, increasing in paleness and decreasing movement, especially when touched. However, the best way to identify a diseased larva is when it is already dead. Particularly for FAW larvae infected with Baculovirus (see Section 3.2.1), the dead larvae will generally be observed in the upper parts of the maize plant and will hang upside down. Dead larvae covered with a powdery white or greenish mass suggest fungal infection. Regardless of the symptoms, any larva displaying abnormal behavior should be taken to the laboratory and kept at a low temperature (refrigerator) until the cause of the symptoms is determined.

5. Procedures for Rearing Natural Enemies of FAW in the Laboratory

5.1. Production and Use of Egg Parasitoid *Trichogramma*

Embrapa has an efficient rearing technique for *Trichogramma* that is being passed on to farmers (Cruz *et al.* 2013; Almeida and Cruz 2013; Almeida *et al.* 2013). Artificial rearing of *Trichogramma* has progressed over the last 20 years through the discovery of alternative hosts that support parasitoid development in a manner like that of the preferred host. The use of these alternative hosts is advantageous due to the low cost of rearing, ease of procedures, and high reproduction capacity. Among the insects most used as alternative hosts are stored grain pests or stored flour pests such as *Corcyra cephalonica* (Stainton), *Sitotroga cerealella* Oliver, and *Anagasta kuehniella* (Zeller). This latter species has been the most frequently employed in the production of eggs as alternative hosts for *Trichogramma*, although *Corcyra* is deployed in Niger and Senegal. Known as the flour moth, *A. kuehniella* is a small moth, dark gray in color, with a life cycle lasting around 40 days. One gram of insect eggs is equivalent to 36,000 eggs.

The larval period varies according to temperature, being, on average, 29 days at 27.9°C and 73% RH. The number of larvae per growing container can also affect the duration of development of the flour moth. An increase in the number of larvae leads to a decrease in adult size, increase in cycle length, and mortality.

Pupae exhibit a development period of 8 to 16 days at summer temperatures, which can be lengthy if conditions are adverse. At 30°C and 73% RH, the pupal period is 8 days. Adults have a relatively short life cycle. At 30°C and 73% RH, copulating couples have a much shorter cycle (6 days for females and 7 days for males) than those that do not mate (11 and 10 days, respectively, for females and males).

The laying capacity reaches an average of up to 350 eggs, with 80-90% of eggs produced between the 3rd and 4th days of laying. Usually, eggs are placed shortly after mating and oviposition usually completes two to five days after emergence.

A temperature of 27°C is considered the best for fertility. Females can initiate oviposition 24 to 48 hours after emergence. A 24-hour photoperiod can cause reduction of fecundity, and the viability of eggs from couples where the males were kept under these conditions is less than that of couples where the males were reared in 24-hour darkness. The development from egg to adult, at 28-30°C and 73% RH, lasts about 41 days.

5.1.1. Rearing Procedure for *Anagasta*

Flour-moth larvae are grown on a diet of maize or wheat bran, alone or in equal mixtures, enriched with beer yeast (3%), distributed in 5-L plastic trays, following the procedures below.

5.1.1.1. Container preparation

i. Use plastic trays (10 cm high × 20 cm wide × 30 cm long) with Snap-On caps.

ii. To provide ventilation inside the tray, make a cut (9 cm wide × 19 cm length) on the top of the cover.

iii. To prevent penetration of natural enemies, replace the removed part with fine-woven fabric (organza), fixed with adhesive tape both inside and outside.

5.1.1.2 Diet preparation and set-up of larval rearing vessel

Neither maize nor wheat used in this procedure can be treated with any type of pesticide; therefore, it is essential to observe the provenance of the cereal acquired.

i. Finely grind the grain.

ii. Depending on the milling grit size, sift the material using a 1.5-mm mesh sieve.

iii. After sieving, store the flour of each cereal in an airtight environment to avoid infestations by insects; freezer storage is preferential. Mix the flour with the brewer's yeast in advance, if desired, or immediately prior to use.

iv. Place the food (500 g of maize bran, 500 g of wheat bran, 30 g of beer yeast) evenly inside the plastic tray with a slight compaction to level the diet.

v. On the surface of the diet, spread about 0.20 g of *Anagasta* eggs (about 7,200 eggs), then place the lid and seal it with adhesive tape to prevent the entry of parasitoids.

vi. Keep the trays on shelves in an air-conditioned room (25°C) to allow for good ventilation inside.

5.1.1.3. Construction of oviposition cage

i. Construct the cage using PVC pipe 300 mm in diameter and 25 cm high.

ii. To seal the ends of the cage, use PVC rings (2 cm high) and 0.5-mm nylon mesh.

iii. Glue the mesh to the rings with "araldite" glue.

iv. Use a plastic dish (of the type used under potted plants) as an egg collector.

5.1.1.4. Collection of Anagasta adults

i. After observing the emergence of the first adults of the *Anagasta* (about 40 days), collect them daily by means of a vacuum cleaner. The collection period extends over a period of 15 to 20 days. Adult moth collecting is usually performed in the morning, due to the lower mobility of insects.

ii. Collect insects from about ten trays and transfer them to a plastic bag (20-L capacity). After removing insects from 40 trays, transfer them to the oviposition cage.

5.1.1.5. Obtaining flour-moth eggs

i. After obtaining desired number of adults (about 10,000-12,000 insects), attach the rings to the PVC pipe with crepe tape.

ii. Place the base of the cage within the plastic dish in which the eggs will be collected.

iii. Do not provide any type of food. Maintain adult moths at a temperature of about 25°C and humidity of at least 70%. Adults remain in the cage for 5 days, on average.

5.1.1.6. Egg collection

i. Usually, begin egg collection the day after assembly of the oviposition cage. A lot of eggs will fall directly into the dish. Others will stick to the screen. Therefore, pass a brush over the outside of the screen covering both the top and bottom ring and then knock on the cage to complete removal of the eggs.

ii. Pass the eggs through a 0.50-mm sieve to remove residues such as flour remnants or insect scales. Clean the eggs again with the aid of a thin brush and a cotton pad passed lightly on the eggs.

iii. Measure daily productivity by weighing the eggs, considering an average of 36,000 eggs per gram.

iv. Use the vast majority of eggs to produce the parasitoid and the rest for flour-moth maintenance. Place the eggs inside a plastic tube, without moisture, to prevent them from sticking to each other.

5.1.1.7. Quality control of eggs produced

i. Before assembling the trays for multiplication of the flour moth, evaluate the viability of the eggs. To do this, individualize the eggs, with the aid of a brush, into the holes of a plastic plate (*e.g.*, a 96-well ELISA plate) and then seal the plate with plastic tape.

ii. After six days, on average, count the number of *Anagasta* larvae and determine the viability of the eggs, considering as normal a viability above 75%.

5.1.2. *Trichogramma* Production

There are several systems for the production of *Trichogramma* with *Anagasta* eggs, but they usually follow a basic technique. Initially, moth eggs are placed on rectangular paperboard cards, maintaining an egg-free edge of 1.5 to 2.0 cm along its shorter length. The cards are then placed in plastic or glass containers. For parasitism, a ratio of parasitized to non-parasitized eggs of about 1:15, with a 48-hour exposure period, may be used.

5.1.2.1. Card preparation

i. Cut white-colored cardboard to size 10 × 15 cm.

ii. With the exception of a 2-cm space at one end, cover the entire area with gum arabic glue. First dilute the glue in water (20% glue and 80% water), then spread it evenly over the card with the aid of a sponge.

iii. Immediately distribute eggs uniformly on the glue, avoiding the formation of layers because it impairs parasitism. To facilitate distribution, place the eggs inside a small tube covered by a mesh fabric fine enough to pass only one egg at a time. In addition, place the card at a 45° angle. Record the date of egg distribution.

iv. For better preservation, store the cards in a refrigerator (up to a week) and, if possible, inside Styrofoam boxes. Approximately 25,000 eggs are distributed on each card.

5.1.2.2. Rearing of parasitoids

i. Once the cards with the flour-moth eggs have dried, introduce three to five cards into a 1.6-L plastic or glass container. Inside these containers should already be a card that is totally parasitized and shows the emergence of the first adults.

ii. As food for the *Trichogramma*, use drops of honey free of pesticide residues (eight small droplets, as large droplets can trap miniature wasps) scattered on one wall of the container.

iii. Two days after the first distribution, additional egg cards could be added to the containers.

iv. Seal the containers with PVC film and keep them on shelves. About three to four days after card placement, the parasitized eggs become dark, providing a qualitative evaluation of the rate of parasitism. At that time, remove the cards from the containers and place them, by date of distribution, in other identical containers without adult parasitoids. Usually the rate of parasitism is above 90%. If for some reason the parasitism rate is smaller, eliminate the hatched larvae.

5.1.3. Parasitism Quality Control

For control of parasitism quality, take three 100-egg samples from a card and record the number of parasitized eggs, the wasp emergence percentage, and the sex ratio (number of females divided by the total number of insects emerged). This is important both for the continuity of breeding and for release in the field. Because there is the possibility of having more than one wasp in each parasitized egg, count the number of exit holes in the *Anagasta* eggs to determine viability.

5.1.4. Care in Rearing

To avoid interruption in the insect flow of both the host and the parasitoid, maintain strict control of the asepsis conditions at the breeding sites. After the adult moths have been collected from the flour, place the trays to be discarded in a freezer to avoid contamination in the breeding environment.

During *Anagasta* breeding, care must be taken to avoid the presence of a larval parasitoid (*Habrobracon*), which generally reaches high populations when the trays are not well protected. If these parasitoids occur, discard contaminated trays immediately by placing the material in a freezer for at least 24 hours to kill the contaminating parasitoid.

When hygiene conditions are not adequate and the moth collection exceeds 20 days, a predatory mite can be found preying on *Anagasta* eggs, and, consequently, compromising the parasitoid production. The same procedure used to control *Habrobracon* can be followed for the mite.

5.1.5. Field Release

5.1.5.1. Factors affecting efficiency

The factors that affect the efficiency of the artificially released parasitoid in the field include number of insects released, pest density, *Trichogramma* species, season and number of releases, distribution method, crop phenology, number of other natural enemies in the target area, and climatic conditions.

Number of insects per hectare: The number of insects to be released per unit area varies in relation to the population density of the pest. On average, around 100,000 individuals are released per hectare, which is roughly equivalent to the number of insects on five cards.

Number of releases: Depending on the inflow of the pest in the area, especially in places where the biological imbalance is evident, new releases will sometimes be necessary.

Method of release: To release the parasitoid, there are several methods, but the most recommended is through the release of the adult insect.

i. To release adult insects, use 1.6- to 2-L plastic or glass containers containing three to five 150-cm^2 cards with parasitized eggs. Wrap containers with a black cloth, secured by a rubber band.
ii. A few hours after adult emergence, take the containers to the field.
iii. Intermittently open and close the containers as the site of release is crossed, calibrating the pace of the workers to evenly cover the field.
iv. The next day, bring the containers back to the same location, for distribution of the remaining material that emerged, carefully depositing the cards on the plants at the end. Perform this second release from the opposite direction of that used the first day (e.g., first day – north-south; second day – south-north).
v. When using the technique of carrying the container open all the time, keep the container in a horizontal position, with the mouth facing in the opposite direction from the direction of walking, allowing the insect to jump onto the plants.

Another method of distribution is by placing the card itself before the emergence of adults. When the emergence of the first adults is observed, take the material to the field, distributing it inside the plant whorl.

Release points: The more uniform the release of insects, the better the control efficiency. If parasitoids that are still as pupae inside eggs of *Anagasta* i.e., near emergence, are used then release points should range from 25 to 30 per hectare. In this case, subdivide the cards according to the number of release points and then distribute them at the established points.

Time of release: The distribution of *Trichogramma* in the field should be synchronized with the appearance of the first eggs and/or adults of the pest. Repeat the releases at less than weekly interval, depending on the degree of infestation of the pest eggs. The correct timing of initiation of releases, frequency, and amount used are fundamental factors in ensuring the efficacy of biological control with *Trichogramma*. It is very important to make evaluations before and after the releases, to quantify the behavior of the parasitoid and measure its regulatory action. In this way, one can also make the necessary adjustments. If possible, perform egg distribution at strategic points to determine the rate of parasitism. Otherwise, make this determination by collecting eggs from natural populations of the pest. The efficiency can also be assessed through the damage to maize leaves or ears, using a visual scale of injury.

5.1.6. Precautions during Release

- *Trichogramma* species are phototrophic positive, *i.e.*, they exhibit oviposition activity during the day; therefore, they may be very prone to the toxic effects of nonselective insecticides.
- The efficiency of *Trichogramma* in the field is also affected by climatic conditions. It has been verified, for some species, that relative humidity has no effect on survival and dispersion capacity of the parasitoid in the range of 33 to 92%. Also, the action of the wind, at speeds less than 3.6 m/sec, had no influence on the dispersion of the females. The dispersion rate (cm/min) of the parasitoid, in both sexes, increases at higher temperatures. Males appear to be more sensitive to high temperatures than females, although temperatures below 20°C have reduced dispersal capacity.
- When making the releases, it is essential to consider the direction of the wind, the amount of solar radiation (heat), and the presence of rainfall.

- For greater efficiency of the parasitoid, the reduction or elimination of the use of chemical insecticides is necessary. If pesticide application is required, select less-toxic products and continue releasing the parasitoids two or three days later, increasing dose and frequency, to restore biological balance.
- The integration of releases with other cultural, microbiological, physical, and mechanical measures may increase the overall efficiency of control.

5.2. Production of Egg Parasitoid *Telenomus remus*

For small-scale production, *T. remus* are reared in eggs of FAW, as described in the method below. It is also possible to rear this parasitoid on *Corcyra cephalonica.* Initially, host egg masses are pasted onto rectangular cards, which are placed in plastic or glass containers to allow parasitism to occur. For parasitoid multiplication, a proportion of parasitized to non-parasitized eggs of about 1:5, with a 48-hour exposure period, may be used.

5.2.1. Card Preparation

i. Cut white or black boards to size 10 × 15 cm.
ii. With the exception of a 2-cm space at one end, coat the entire area with “gum arabic” glue, which should be initially diluted with water (20% glue, 80% water) and spread evenly on the paperboard with the aid of a sponge.
iii. Immediately, distribute egg masses of the host evenly over the glue, with the aid of surgical tweezers. Distribute about 60 egg masses (approximately 18,000 eggs) onto each card.
iv. Record the date of egg distribution, to better calibrate the expected adult emergence date.
v. Store the cards in a refrigerator (up to a week) and, if possible, inside Styrofoam boxes. The age of the host can influence the performance of the parasitoid. Experiments conducted with different egg ages when the parasitoid has a choice, show that it prefers oviposition in egg masses of up to 36 hours of embryonic development, although it may, to a lesser extent, parasitize eggs up to 60 hours of age, in a non-choice trial.

5.2.2. Egg Infestation

1. Once cards with FAW eggs are dried (room temperature), introduce six cards (about 100,000 eggs) into a 1.6-L plastic or glass container already containing a card that is totally parasitized and a day or less from adult emergence.
2. As food for the parasitoid adults, scatter drops of honey (eight small drops, as large droplets can trap the tiny wasps) on a wall of the container.
3. Seal the containers with plastic film and keep them on shelves. About three to four days after card placement, the parasitized egg becomes dark, providing a qualitative way to evaluate the rate of parasitism. When that occurs, remove the cards from the containers and place them, by date of distribution, into other identical containers without adult parasitoids.

Usually the rate of parasitism is above 90%. If, for some reason, the parasitism rate is lower and larvae hatch from the host, remove them by means of a brush or transfer the parasitized card to another container.

Both temperature and relative humidity can also influence the performance of the parasitoid, especially when it is less than 70%.

5.3. Production of *Chelonus* spp.

The establishment of a small colony of *Chelonus* can be initiated with parasitized eggs or larvae of FAW or from parasitoid adults collected in the field.

i. In the laboratory, keep the collected insects in rooms with little temperature oscillation (optimum is 25±2°C). Soon after emergence, place adults in oviposition cages. Maintain parasitized FAW larvae individually on artificial or natural diet until adult emergence. If using artificial diet, do not use anti-contaminants.

ii. Place five couples of *C. insularis* in an oviposition cage (a transparent container such as glass or plastic pot, for example, with a 1.6-L capacity) containing a food source composed of 10% sugar solution, enriched with 0.1% of ascorbic acid. This solution can be previously prepared (kept in the refrigerator) and offered by means of a cotton dental roll introduced into plastic cups (50 ml) and fitted into a hole made in the middle of a polystyrene lid or another lid type.

iii. Cover the oviposition cage with a fine mesh fabric for ventilation. Keep insects in a lab room with an average temperature of 25±2°C, relative humidity of 70±10%, and a 12-hour photoperiod for one day to allow mating.

iv. After the mating period, replace the food three times per week. Also, offer daily, for a week, about three batches of FAW with less than 24 hours of embryonic development. In case of death of the female parasitoid, add another to the container if available. After each period of parasitism, remove the parasitized FAW egg masses and individualize them in plastic cups containing artificial diet, noting the date of parasitism.

v. Place the cups in Styrofoam stands and keep them on shelves under the same environmental conditions as the *C. insularis* adults. Seven days after hatching, individualize the parasitized larvae to avoid cannibalism, keeping them within the rearing container until the appearance of parasitoid adults, usually 30 days after parasitism. The parasitoid pupation occurs inside the diet. At the time of adult emergence, record the sex of each individual and initiate a new generation. Sex separation of *C. insularis* can be performed through the antenna, which is markedly longer in males.

Apparently, there is no pre-oviposition period for *C. insularis*; the mean incubation period is about 1.8 days. The larval period varies from 17 to 23 days, with an average of 20.4 days; the mean pupal period is 6.2 days. The average duration of the total cycle is 28.6 days. The average longevity of mated females is, on average, 11.6 days, with a maximum of 18 and a minimum of 5 days.
The number of parasitized eggs and the longevity varied greatly from female to female, and the parasite capacity is reduced considerably near death. The highest rate of parasitism occurs when females are three days old, with a maximum of 92.2 and a minimum of 48.1 eggs parasitized on that day. In the interval between the 3rd and 6th day, the females had a 72% to 80% parasitism rate.

Although the food consumption of a parasitized larva is much lower than that of a normal larva, it is not possible to reduce the amount of food because the diet will dry out, causing high mortality.

5.4. Production of *Campoletis flavicincta*

The same rearing procedures for *Chelonus* are used to rear *C. flavicincta* but with this species the artificial diet is complete; that is, it is prepared with anti-contaminants.

i. After separation by sex, which is facilitated due to the exposed female ovipositor, place five couples of *C. flavicincta* in an oviposition cage in acclimatized rooms at 25±2°C, relative humidity of 70±10% and photophase of 12 hours, for a period of five days for mating.

ii. After the mating period, replace the adult food source three times per week. Each day for one week, offer about 150 three-day-old FAW larva to the parasitoid. After each 24-hour parasitism period, individualize the parasitized larvae in plastic cups containing diet. Keep insects on shelves under the same environmental conditions as the *C. flavicincta* couples.

iii. The first pupae of the parasitoid usually appear eight days after the individualization of the larvae. Three days after the appearance of these first pupae, eliminate non-parasitized larvae and compute the number of insects parasitized. Seven days after this period, the emergence of adults begins. Unlike *Chelonus*, whose pupa occurs within the diet, the *Campoletis* pupa usually occurs in the higher parts of the breeding recipient. The total cycle of the parasitoid is, on average, 22.9 days: 14.5 days from egg to pupal period and from 7.3 days for completion of pupal period. Parasitized larvae live about a week less than healthy caterpillars.

iv. As the food consumption of a parasitized larva is only 16.9% of the consumption of a normal larva, it is possible to use only one-third the amount of food used by a larva without parasitism.

6. Actions Complementary with Biological Control

6.1. Classical Biological Control implemented by Government Intervention

FAW has been researched for many years in the Americas. Notably in Brazil, there are many agents of natural biological control of the pest of both eggs and larvae. In addition to their demonstrated efficiency under field conditions, technologies for laboratory rearing already exist. Considering the relative similarity in terms of soil and climatic conditions, careful introduction of these biological control agents is highly promising to keep the pest at acceptable population levels and, especially, avoiding the application of chemicals, particularly under smallholder farming. Moreover, given the technical and institutional capacity of many African countries, government incentive is very important in pest mitigation now and in the future. In addition to being a sustainable solution to the pest, it certainly provides an opportunity for exchanges of experience and continued knowledge among countries with so many partnerships already existing in other areas of common interest.

Although there is much knowledge about FAW, especially in the Americas, it is important that researchers make local surveys of natural enemies and then generate necessary evidence on efficacy, selection, mass production, and release of the most effective natural enemies. When gaps exist, emphasis should be given on classical biocontrol for species with proven efficiency against FAW, including *Telenomus remus, Trichogramma pretiosum, Chelonus insularis,* and *Cotesia marginiventris*, following appropriate guidelines, including proper environmental assessment of such introductions.

To achieve effective impact, governments should be willing to invest in mass rearing and large-scale releases, and farmers should be involved in all processes. In fact, the involvement of farmers is critical. As an initial incentive, governments could provide for free effective natural enemies of FAW to the farmers to do their own release and appreciate the effect of the technology on the pest.

6.2. Using Traps with Female Pheromone for Monitoring and Making Decisions

The effectiveness of the biological control of FAW is directly related to the synchronization of the presence of the pest with the presence of the beneficial insect.

When traps are placed at the time of planting (see Chapter 2), the moth catch indicates that the pest has reached the farmer's area and soon the female will begin oviposition. That is, the trap will indicate to the farmer that the pest is present, but it is still not causing damage because there are no larvae yet.
The presence of eggs is the indicator to use, for example, the parasitoid *Trichogramma* or *Telenomus*. The continued capture of moths in the trap suggests that the farmer should continue to observe the plants for the presence of larvae. Larvae up to 12 mm (usually 10 days after the first catch of moths in the traps) can be efficiently controlled either by beneficial insects or through biopesticides such as *Metarhizium, Beauveria, Baculovirus, Bacillus thuringiensis,* fungi, or plant extracts such as Neem products, after local evaluation against the pest. That is, the farmer should use only biopesticides that are compatible with natural biological control. However, success only will be achieved when spraying the products directly into the maize whorls.

6.3. Awareness of Farmers Regarding the Benefits of Biological Control

A great difficulty in establishing a culture of biological control in rural areas is the lack of knowledge on how to recognize and separate insect pests from beneficial insects. There is a need for empowerment of these farmers by showing them that beneficial insects are those that feed on the pests that attack the crops and those that are essential in agricultural production as pollinators, such as bees.

Brochures (with good photographs), videos, and training courses (with sufficient time for field visits) will be useful to help raise the awareness of the farmer and his/her family about the importance of biodiversity of beneficial insects.

Using the photos provided in this FAW IPM Guide and gradually updating them with new photos of biological control agents found locally in Africa against FAW will provide an important resource for continuous training of the farmers. This should be coupled with an open-access database of natural enemies of FAW identified across the African continent.

6.4. Suggestions for Continued Training of Rural Extension Agents and Farmers

- Train farmers and extension people to identify/collect eggs masses that have turned dark (egg masses become dark three days after parasitism) and ship them to Ministry personnel for identification, remembering that local parasitoids could be better than foreign species.
- Provide materials for farmers to collect parasitized eggs.
- Remind farmers and extension people that FAW lays eggs in masses, never isolated, and that each egg mass may contain up to 300 eggs, usually covered with scales.
- Farmers should be aware that by avoiding the use of chemicals on their property, they will contribute to maintain natural biological control agents. But it is important to use strategies that favor the increase of these beneficial insects not only on the individual farmer's property but also throughout the entire community.
- Encourage farmers to manage habitats and use conservation agriculture to augment naturally occurring parasitoids and predators (see Chapter 6).

7. Establishing Small-Scale Biofactories for Regional Use of FAW Biological Control Agents

7.1. Small-Scale Production of Baculoviruses Infecting FAW

Since 1984, Brazil has been researching entomopathogens for the control of FAW, especially with Baculovirus (see Section 3.2.1). Here, a simple method is provided to produce Baculovirus in a small or medium-size biofactory that can be applied in African countries where the pest is already established, as described in several Embrapa publications (Valicente and Tuelher 2009; Valicente *et al.* 2010).

7.1.1. Obtaining Baculovirus-Infected Larvae

Baculovirus-infected larvae can be obtained in the field (Figure 1) from maize plants or purchased from other sources, such as in laboratories where Baculovirus is already grown.

Figure 1. FAW larva killed by Baculovirus on the maize plant (left); dead FAW larvae showing integument rupture (right).

7.1.2 Formulation of Baculovirus Wettable Powder

The formulation of the Baculovirus in wettable powder is carried out in three steps: selection and collection of larvae, maceration, and drying.

7.1.2.1 Selection and collection of larvae

i. Use tweezers to collect larvae killed by Baculovirus infection, selected by color and external appearance, and store them in clean containers.
ii. If there is time, dead larvae may be processed and formulated immediately. Usually a larva killed by Baculovirus has a ruptured integument, making it difficult to collect the insect (Figure 1). For this reason, dead larvae may be placed in the freezer before being collected.

7.1.2.2. Maceration of larvae and incorporation of kaolin clay

i. Macerate the dead larvae using a standard or industrial blender, with a small amount of water, just enough to spin the blender blades. The larvae should be ground in the blender for approximately 10 minutes without interruption.
ii. During blending, incorporate an inert agent (kaolin clay), which acts as a filler and aids in drying the product in the wettable powder formulation. Kaolin clay is inert (does not react with other elements) at widely varying pH and temperature and it often exists in nature as a free element.

The farmer may utilize the Baculovirus macerate provided that the material from the blender is suitably filtered to remove any impurity that may cause nozzle clogging when applied in the field.

7.1.2.3. Drying of Baculovirus formulated in wettable powder

1. Place the larvae/inert mixture in trays (Figure 2) that have been washed and cleaned with 70% alcohol.
2. Dry the material in the laboratory with a forced-air jet. After three to four days, all material will be dry (Figure 2).
3. Crush the dry material using a grinder (Figure 3).
4. Package the material in transparent plastic bags (Figure 3) or bags of aluminum-laminated paper (coffee packaging).


Figure 2. Baculovirus wettable powder preparation. Distribution in tray (left); Mixture of Baculovirus and kaolin clay, completely dry (right).


Figure 3. Milling and packaging. Milling of the Baculovirus wettable formulation (left); Baculovirus wettable packaging for application on one hectare of maize crop (right).

7.1.2.4. Stability of FAW Baculovirus formulated in wettable powder

Storage conditions may affect Baculovirus infectivity. Thus, the shelf life of a biological product must be determined so that it can be used safely, obtaining the desired control efficiency. The efficiency of the Baculovirus was verified with the use of two different inert materials: kaolin and zeolite. After one year of storage, there was no decrease in the control efficiency of FAW larvae and no significant difference between the evaluation times or inert materials used in the formulation.

CHAPTER 06

Low-Cost Agronomic Practices and Landscape Management Approaches to Control FAW

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1. Introduction

In addition to host plant resistance, biological control, and judicious application of chemical pesticides, a number of low-cost cultural practices and landscape management options can be implemented as part of an effective Integrated Pest Management (IPM) strategy against Fall Armyworm (FAW). Such approaches can be particularly relevant to smallholders who lack financial resources to purchase improved seed, pesticides, or other relatively expensive agricultural inputs (Wyckhuys and O'Neil 2010; Stevenson *et al*. 2012).

While there is a range of experience applying cultural and landscape management practices to control other pests in Africa (Martin *et al*. 2016;, Pumariño *et al.* 2015;, Stevenson *et al*. 2012), there is still considerable uncertainty about how effective such approaches will be against FAW, and these knowledge gaps require additional research. Many of the measures recommended in this chapter therefore represent general agroecological best practices for pest control – though where indicated, emerging evidence suggests efficacy against FAW in Africa, particularly for the "Push-Pull" intercropping approaches.

This chapter will focus on cultural and landscape management practices suitable for maize-based farming systems common in most parts of sub-Saharan Africa, with additional reference to agroforestry interventions.

1.1. Principles of Agroecological Control

Agroecological approaches apply knowledge about the complex interactions between organisms and their environment to suggest management options that reduce the frequency and intensity of pest infestation and minimize the damage inflicted by pests on crops. In the context of FAW control in Africa, such approaches typically focus on farmers' cultural practices or landscape management options that achieve the following:

Improve plant health to better withstand pest attack. Increasing plant health, for example through improved soil management and crop nutrition, can ensure that plants develop well before pest damage significantly affects yield-defining components (*e.g.*, leaf area). Healthy plants can also invest more in defense (Chapin 1991), thereby increasing the likelihood of escaping serious damage.

Figure 1. Diverse landscapes provide shelter and perches for preying birds, parasites, and predators that can potentially mitigate the damage by FAW (Source: Frédéric Baudron, CIMMYT).

Optimize timing of crop planting and rotations to escape pest pressure. Manipulating the timing of host plant development relative to pest presence (*e.g.*, early planting, crop rotations). Such approaches work by creating asynchrony between the pest and critical crop growth stages.

Create sustainable local ecosystems that are inhospitable to the pest and attractive to its predators and parasitoids. Intercropping or crop rotations with crops that are not preferred by the pest can help repel FAW. Some intercrops, particularly those producing natural insecticides (*e.g., Tephrosia*) or repugnant semiochemicals (*e.g., Desmodium*), repel the adult female moths, reducing the number of eggs laid on host plants. Conversely, creation of sustainable ecosystems (*e.g.*, through surface crop residue retention) that attract and conserve natural enemies of FAW, including generalist predators (*e.g.*, spiders, ants, or birds) and parasitoids, can contribute to enhanced pest predation and parasitism that controls FAW populations. In particular, increasing habitat diversity at the landscape scale (*e.g.*, through the preservation or cultivation of patches of natural vegetation, tree cover, or hedgerows) can increase the abundance of insectivorous birds and bats. The effect of these voracious and highly mobile pest predators depends on the availability of suitable habitat within the field (*e.g.,* suitable perches or roost sites) and across the broader landscape (Figure 1).

The benefits of cultural and landscape management approaches often arise from the interplay of ecological factors across a range of spatial scales – from plot to field to farm to landscape – that disrupt and control the pest at multiple stages throughout its life cycle (Veres *et al.* 2013; Martin *et al.* 2016) (Figure 2). For example, cultural practices such as intercropping, companion cropping, conservation agriculture, and agroforestry may simultaneously improve the health of the crop, provide shelter and alternative food sources for natural enemies, and reduce the ability of FAW larvae to move between host plants.

Cultural and ecological management options are highly compatible with host plant resistance and biological control approaches. Indeed, laboratory experiments have demonstrated that evolution of insect resistance to pest-control measures can be delayed or prevented in the presence of natural enemies (Liu *et al.* 2014). However, indiscriminate spraying of toxic pesticides often adversely affects these natural enemies, reducing benefits from biocontrol (Meagher *et al*. 2016) and potentially increasing the population of secondary pests (Tscharntke *et al*. 2016).

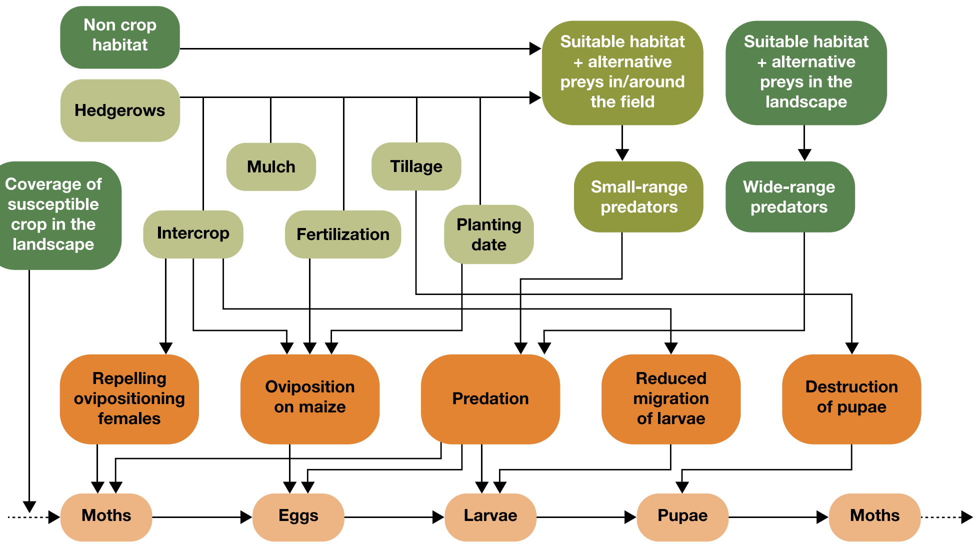


Figure 2. Cultural and landscape management approaches implemented at various spatial scales interact to help control FAW throughout the pest's life cycle. (Source: Frédéric Baudron, CIMMYT).

1.2. Cultural Practices and Landscape Management Approaches in an African Smallholder Context

Although agroecological concepts broadly inform any IPM approach to pest management, they can be particularly relevant in the design and implementation of low-cost management approaches for smallholder farmers in particular, because such farmers may not have access or financial capital to purchase pesticides, improved seed, or other relatively costly inputs on which the chemical-control or host-plant-resistance elements of an IPM approach are typically based. Because most of these cultural and landscape management practices rely on labor rather than financial capital, they may be more accessible for smallholders.

At the plot, field, and farm scale, cultural interventions are typically implemented by smallholder farmers, ideally with guidance from extensionists, development implementing partners, or other knowledgeable experts. Although individual farmers and practitioners may also implement landscape-level interventions, landscape-scale approaches typically also require involvement of communities, governments, or other organizing bodies to coordinate action across a sufficient scale to achieve impact on pest populations.

2. Cultural and Landscape Management Options

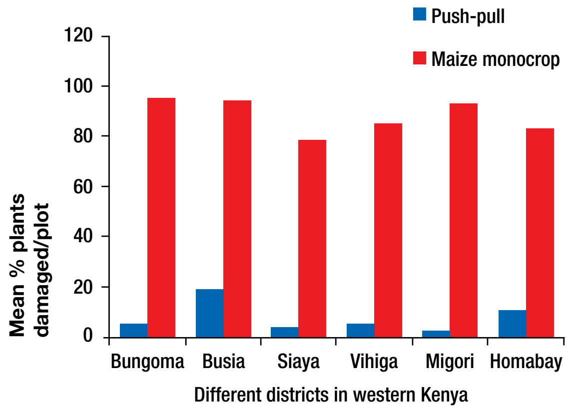
2.1. Recommended Practices to Control FAW

Based on a review of available evidence, the following low-cost cultural practices and landscape management options are currently recommended for control of FAW. With the exception of the "Push-Pull" approach, for which experimental evidence exists to suggest efficacy against FAW in an African context (Section 2.1.1), many of these measures represent generic best crop and landscape management practices for pest control, and have not been specifically validated for FAW in Africa (Section 2.1.2). It is also worth noting that, while these approaches are highlighted due to their low financial cost, in many cases they may require a substantial investment of labor to implement, and are therefore not completely without cost.

2.1.1. "Push-Pull" Companion Cropping

In the "Push-Pull" companion cropping strategy, farmers protect cereal crops from pest damage by intercropping them with pest-repellent ("push") plant species (*e.g., Desmodium* spp.), surrounded by a border pest-attractive trap ("pull") plant species [usually grasses such as napier grass (*Pennisetum purpureum* Schumach.) or *Brachiaria* spp.] (Table 1). In one recent study conducted across East Africa, farmers who fully implemented the Push-Pull approach reduced FAW infestation and crop damage by up to 86%, with a 2.7-fold increase in yield relative to neighboring fields that did not implement the approach (Midega *et al.* 2018) (Figure 3). Though implementing Push-Pull requires initial financial costs to establish the companion plants, costs gradually reduce in subsequent seasons. Furthermore, beyond controlling FAW and other stemborer pests, Push-Pull has also been reported to reduce *Striga* infestation, increase nitrogen and soil humidity, and most importantly, provide a suitable environment for the proliferation of predators and parasitoids of FAW (Khan *et al*. 2010). However, achieving the benefits of the Push-Pull approach depends heavily on proper establishment and management of the companion plants, and is therefore highly knowledge and labor intensive.

Extension materials including videos, radio storylines, brochures, and farmer training materials have been developed in multiple languages to support dissemination of the Push-Pull approach, and are available at www.push-pull.net.



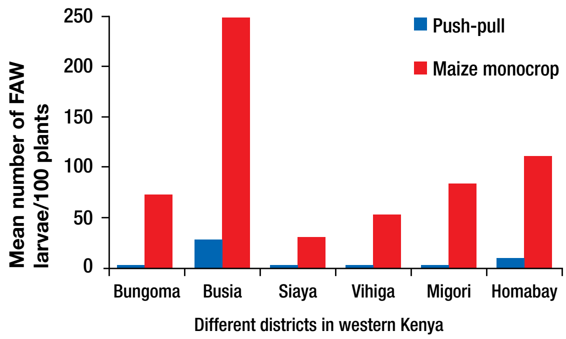


Figure 3. Effect of Push-Pull technology on FAW. (Source: Midega *et al.* 2018)

2.1.2. General Best Practices for Cultural Control and Landscape Management

In addition to the Push-Pull companion cropping strategy cited above, a number of other cultural and landscape management practices have demonstrated some degree of success in managing insect pest populations in various agricultural systems. Ongoing and future research will be necessary to determine the specific efficacy of these approaches against FAW within the African context, and thus provide clearer guidance regarding the relative benefit of smallholders' investment of money and/or labor to implement these approaches. However, current evidence is adequate to recommend them as general best practices (Table 1).

In some cases these approaches may be undertaken directly by individual smallholders, ideally with technical guidance from extensionists, agro-dealers, or other experts. In other cases – particularly for landscape-scale interventions – the approaches suggested here require coordinated action at the village or community level, or even by policymakers, in order to achieve sufficient scale to impact pest populations.

Table 1. Recommended cultural and landscape management options for control of FAW in Africa.

Method	Description	Effectiveness	Financial cost	Relevant actors	Scientific evidence and further information
Planting at the recommended/ optimal time	Do not delay planting. Take advantage of planting with the first effective rains, as FAW populations build up later in the crop season.	Evidence from research with other maize stem borers shows that early/timely planting has higher chances of escaping pest infestation, compared to delayed planting.	Low	Extensionists, farmers	Gebre-Amlak *et al.* (1989); Van den Berg and Van Rensburg (1991)
Plant nutrition	Adequate nutrient supply through mineral fertilizer, use of fertilizer trees and nitrogen-fixing legume crops, organic manures, or compost support healthy plant growth.	Good fertilization reduces plant damage by increasing plant health and defenses against pests, but damage may increase with excessive nitrogen application.	Medium: if additional input purchase is required	Extensionists, farmers, agro-dealers	Altieri and Nicholls (2003); Morales *et al.* (2001); Rossi *et al.* (1987)
Intercropping with compatible companion crops or fertilizer trees	Plant additional crops in strips, rows, or stations between the main crop (e.g., pigeonpea, cassava, sweet potatoes, cowpea, beans, pumpkins, or fertilizer trees [*e.g.*, *Tephrosia, Gliricidia,* or *Faidherbia albida*]) (Figure 4).	Likely to be more effective either when non-host plants are used (e.g., cassava or fertilizer trees) or when crop diversity may interrupt egg laying, and can increase the diversity of beneficial organisms including natural enemies of the pest. For example, *Tephrosia* is a source of natural insecticides and may reduce egg laying.	Low: often a traditional practice.	Extensionists, farmers, plant nurseries	Pichersky and Gershenzon (2002); Landis *et al.* (2000); Coolman and Hoyt (1993)
Conservation agriculture (CA)	Combined use of no-tillage, residue retention, and rotation increases and diversifies biological activity of macro-(spider, beetles, ants), meso-(fungi), and microfauna (bacteria). These practices also lead to improvement of soil health, which contributes to more vigorous growth of the crop.	Effective, if all principles of CA are applied and continued for some time. Unlike other pests, FAW cannot be controlled by burning of crop residues. **Note:** CA can reduce plant access to nitrogen if this is limiting, which might reduce the health and vigor of plants and increase pest attack rates. This can be avoided by addition of fertilizer or by intercropping with fertilizer trees (e.g., CA with agroforestry).	Medium: some specific tools and inputs may be required for establishing effective CA systems.	Extensionists, farmers, agro-dealers	All (1988); Tillman *et al.* (2004); Rivers *et al.* (2016)

(Continued on page 94)

(continued from page 93)

Table 1. Recommended cultural and landscape management options for control of FAW in Africa.

Method	Description	Effectiveness	Financial cost	Relevant actors	Scientific evidence and further information
Increased groundcover	Cover crops like mucuna, lablab beans, jack bean, sunnhemp, etc., contribute to plant species diversity that enhances biological activities and provides shelter for natural enemies (spiders, beetles, ants).	Use of a range of cover crops can be effective as trap crops, as repellent crops that interrupt egg laying and larval development, and as shelter for natural enemies.	Medium: availability of seed and suitability of the cover crops.	Extensionists, farmers, communities, policymakers (landscape scale)	Altieri *et al.* (2012); Bugg *et al.* (1991); Hoballah *et al.* (2004); Ratnadass *et al.* (2011); Meagher *et al.* (2004); Wyckhuys and O'Neil (2007)
Hedgerows and live fences	Complex cropping systems influence interactions of biota and increase effectiveness of parasitoids. Provides extra-field diversity and habitats for natural enemies to proliferate and contribute to control of the pest (birds, spiders, ants) Planting of live fences or hedgerows, maintenance of uncultivated areas, reduced weeding in part or all of the crop, planting of other crops or fruit trees in neighboring fields.	Fields close to hedgerows are usually less infested with pest due to biological control agents (birds) activities.	Medium to high: extra land may be required for establishing hedgerows.	Extensionists, farmers, communities (landscape scale)	Veres *et al.* (2013); Landis *et al.* (2000); Martin *et al.* (2016); Marino and Landis (1996); Wyckhuys and O'Neil (2007)
Enhance agroforestry systems at landscape level	Plant trees/shrubs between maize especially neem, *Tephrosia, Gliricidia, Faidherbia albida*, etc., to enhance diversity for natural enemies (beneficial insects and birds).	Long-term intervention to create biodiversity and biological pest control – can be very effective once trees are established.	Medium: land needs to be shared with main crops.	Extensionists, farmers, policymakers, communities (landscape scale)	Wyckhuys and O'Neil (2006); Wyckhuys and O'Neil (2007); Hay-Roe *et al.* (2016); Ratnadass *et. al.* (2011)

Note: Table adapted from CABI Evidence Note (2017).

Figure 4. Potential intercropping options for mitigating FAW damage. (Source: Christian Thierfelder, CIMMYT).

2.2. Practices that Need Further Research Evidence

The following practices need further research evidence before they can be widely recommended for management of FAW in Africa, especially in the smallholder context:

- **Application of sugar water to maize foliage.** Though in some cases this practice has been recommended, efficacy, practicality at scale, and cost have to be established.
- **Placement of ash/sand/soil/chili powder in maize whorls.** Though all of these practices are being tried by some smallholders in Africa, additional research evidence is required on the efficacy and scalability, as well as the mechanism behind their possible effect on FAW.
- **Deep tillage.** Tillage can kill pupae in the soil. However, soils are normally tilled before FAW arrives in a field; tilling may therefore cause more harm than good, by reducing biological activity and increasing soil degradation while contributing relatively little to FAW control due to asynchronous timing of the intervention with the pest population cycle. Its effect is therefore inconclusive and should be investigated further.

Knowledge Gaps/Researchable Areas

Goal: Establish a solid evidence base regarding the control- and cost-effectiveness of agroecological and cultural pest control options for the management of FAW in Africa.

1. How does planting date affect the incidence and abundance of FAW, and resultant damage to crops?
2. How does conservation agriculture affect the incidence and abundance of FAW, and resultant damage to crops? What are the mechanisms?
3. How does the presence of companion plants (intercrops and the Push-Pull system) affect the incidence and abundance of FAW, and resultant damage to crops? What are the mechanisms: (i) reduced movement of pest larvae, (ii) reduced oviposition rates, or (iii) increased predation and parasitism?
4. How does habitat diversity (including tree cover) at field, farm, and landscape scales affect the incidence and abundance of FAW, and resultant damage to crops? What are the mechanisms?

Key Messages to Policymakers

1. Increase diversity at the farm, field, and landscape levels. The Zambian Government has recently released a policy on diversification which could be examined by other African Governments.
2. Malawi is promoting agroforestry as a solution to land degradation; this could possibly be linked to pest control efforts.
3. Link National and Regional Task Forces with the global FAW development partners for effective advocacy and implementation.
4. Given emerging evidence for positive impacts of Push-Pull on FAW mitigation, this technology could be considered for some level of scale-up in Africa. This is a key focus of the technology transfer unit at ICIPE, in partnership with the National Agricultural Research Systems and African governments. For access to training and dissemination materials and other information, please visit www.push-pull.net.

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Appendices

Appendix 1. List of Participants of the Workshop for Developing Fall Armyworm Pest Management Field Manual for Africa (September 16-17, 2017; Entebbe, Uganda).

	Name	Institution	Country
1	Georg Goergen	IITA	Benin
2	Tchoromi Ghislain Tepa-Yotto	IITA	Benin
3	Ana-Paula Mendes	USAID	Brazil
4	Ivan Cruz	EMBRAPA	Brazil
5	Abdel Fattah Amer Mabrouk	AU-IAPSC	Cameroon
6	Dave Hodson	CIMMYT	Ethiopia
7	Felege Elias	DLCO-EA	Ethiopia
8	Dietrich Stephan	Julius-Kühn Institut	Germany
9	Jöerg Wennmann	Julius-Kühn Institut	Germany
10	Stephan Winter	Leibniz Institute DSMZ	Germany
11	Ebenezer Aboagye	NPPO	Ghana
12	Allan Hruska	FAO	Italy
13	Anani Bruce	CIMMYT	Kenya
14	B.M. Prasanna	CIMMYT	Kenya
15	David Onyango	CABI	Kenya
16	Emily Kimathi	ICIPE	Kenya
17	Francis Ndeithi	Syngenta	Kenya
18	Hugo De Groote	CIMMYT	Kenya
19	Ivan Rwomushana	ICIPE	Kenya
20	Joseph Kibaki Miano	Bayer	Kenya
21	Lilian Gichuru	AGRA	Kenya
22	Margaret Mulaa	CABI	Kenya
23	Muo Kasina	KALRO	Kenya
24	Nicholas Davis	CIMMYT	Kenya
25	Tracy McCracken	USAID	Kenya
26	Vongai Kandiwa	CIMMYT	Kenya
27	Donald Kachigamba	NPPO	Malawi
28	Ernst Neering	NPPO	Netherlands
29	Malick Ba	ICRISAT	Niger
30	John Abah Obaje	NPPO	Nigeria
31	Johnnie van den Berg	North-West University	South Africa
32	Abdullahi D. Khalif	FEWS NET	South Sudan
33	Felix Dzvurumi	FAO	South Sudan
34	Francis Nkurunziza	Catholic Relief Service (CRS)	South Sudan
35	Wilfred Mushobozi	Crop Bioscience Ltd.	Tanzania
36	Komi Agboka	University of Lome	Togo
37	Ambrose Agona	NARO	Uganda
38	Godfrey Asea	NARO	Uganda
39	Mathew Abang	FAO	Uganda
40	Stephen Byantwale	Ministry of Agriculture, Animal Industry and Fisheries	Uganda
41	Daniel McGrath	Oregon State University	USA
42	Joseph Huesing	USAID	USA
43	Paul Jepson	Oregon State University	USA
44	Regina Eddy	USAID	USA
45	Muniappan Rangaswamy	Virginia Tech	USA
46	Rob Meagher	USDA-ARS	USA
47	Robert Beiriger	Univ. of Florida	USA
48	Yene Belayneh	USAID	USA
49	Isaiah Nthenga	Zambia Agricultural Research Institute	Zambia
50	Christian Thierfelder	CIMMYT	Zimbabwe
51	Joyce Mulila-Mitti	FAO	Zimbabwe
52	Peter Chinwada	University of Zimbabwe	Zimbabwe

Appendix 2. List of Participants of the Regional Training and Awareness Generation Workshop on Fall Armyworm Pest Management in Southern Africa (October 30 - November 1, 2017; Harare, Zimbabwe).

	Name	Institution	Country
1	Georg Goergen	IITA	Benin
2	Kuate Sebua	MoA	Botswana
3	Tamuka Magadzire	FEWS NET	Botswana
4	Ivan Rwomushana	CABI	Kenya
5	Margaret Mulaa	CABI	Kenya
6	B.M. Prasanna	CIMMYT	Kenya
7	Nicholas Davis	CIMMYT	Kenya
8	Saliou Niassy	ICIPE	Kenya
9	David Wangila	Monsanto	Kenya
10	Francis Ndeithi	Syngenta	Kenya
11	Anderson Chikomola	MoA, Irrigation, & Water Development	Malawi
12	George Lungu	MoA, Irrigation, & Water Development	Malawi
13	Tonny Harris H. Maulana	MoA, Irrigation, & Water Development	Malawi
14	Samuel Njoroge	ICRISAT	Malawi
15	George Vilili	USAID Ag Div Project	Malawi
16	Fenton Sands	USAID Malawi Mission	Malawi
17	Martin Banda	USAID Malawi Mission	Malawi
18	Aderito Lazaro	Dept. of Plant Protection, MoA	Mozambique
19	Antonia Vaz Tombolane	Dept. of Plant Protection, MoA	Mozambique
20	Domingos Cugala	Eduardo Mondlane University	Mozambique
21	Moses Muchayaya	Empreza de Comercializacao Agricola Lda	Mozambique
22	Alfredo Novela	World Food Program	Mozambique
23	Ravi Moustache	National Biosecurity Agency	Seychelles
24	Jan Van Vuuren	Bayer	South Africa
25	Bellah Mpofu	Feed the Future Southern Africa Seed Trade Project	South Africa
26	Patricia Rwasoka-Masanganise	USAID Southern Africa	South Africa
27	Takele Tassew	USAID Southern Africa	South Africa
28	Tomas Rojas	USAID Southern Africa	South Africa
29	Jeromy McKim	USDA APHIS Southern Africa	South Africa
30	Marius Boshoff	Villa Crop Protection	South Africa
31	Barry Pittendrigh	Michigan State University	USA
32	Julia Bello-Bravo	Michigan State University	USA
33	Dan McGrath	Oregon State University	USA
34	Paul Jepson	Oregon State University	USA
35	Joseph Huesing	USAID	USA
36	Regina Eddy	USAID	USA
37	Sabeen Dhanani	USAID	USA
38	Rob Meagher	USDA-ARS	USA
39	Simasiku Nyambe	Disaster Management and Mitigation Unit	Zambia
40	Anthony Chapoto	Indaba Agricultural Policy Research Institute	Zambia
41	Christabel Chengo-Chabwela	Indaba Agricultural Policy Research Institute	Zambia
42	Shadreck Mwale	MoA	Zambia
43	Harry Ngoma	USAID	Zambia
44	Gilson Chipabika	Zambia Agriculture Research Institute	Zambia
45	Tinomuonga Hove	ActionAid	Zimbabwe
46	Rob Fisher	AgDevCo	Zimbabwe
47	Augustin Musomera	CARE	Zimbabwe
48	Tafadzwa Moliba	Christian Aid	Zimbabwe
49	Christian Thierfelder	CIMMYT	Zimbabwe
50	Cosmos Magorokosho	CIMMYT	Zimbabwe
51	Taswell Chivere	CNFA	Zimbabwe
52	Khumalo Ncomulwazi	DCA	Zimbabwe
53	Fortune Sangweni	DR & SS	Zimbabwe
54	Josephine Ngorima	DR & SS	Zimbabwe
55	Providence Mugari	DR & SS	Zimbabwe
56	Richard Rwafa	DR & SS	Zimbabwe
57	Tafadzwa Makanza	DR & SS	Zimbabwe
58	Kudzai Mutowo	Environmental Management Agency	Zimbabwe
59	Mark Benzon	Fintrac	Zimbabwe
60	Meynard Chirima	Fintrac	Zimbabwe
61	Conrad Murendo	ICRISAT	Zimbabwe
62	Kennedy Mukonyora	IRC	Zimbabwe
63	Prisca Myagweta	LEAD Trust	Zimbabwe
64	Scarlet Chamambo	Plan International	Zimbabwe
65	Peter Chinwada	University of Zimbabwe	Zimbabwe
66	Adam Silagyi	USAID Zimbabwe	Zimbabwe
67	Herold Ngwenya	WHH	Zimbabwe
68	Abraham Muzulu	World Vision	Zimbabwe
69	Lilian Zheke	World Vision Enterprise	Zimbabwe

Appendix 3. List of Participants of the Regional Training and Awareness Generation Workshop on Fall Armyworm Pest Management in Eastern Africa (November 13-15, 2017; Capital Hotel, Addis Ababa, Ethiopia).

	Name	Institution	Country
1	Georg Goergen	IITA	Benin
2	Alexis Mpaweninmana	Institut des Sciences Agronomiques du Burundi (ISABU)	Burundi
3	Eustache Cimpaye	National Plant Protection Departement	Burundi
4	Longin Nzeyimana	Reseau Burundi 2000	Burundi
5	Leif Davenport	USAID/Burundi	Burundi
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