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## A GUIDE FOR INTEGRATED PEST MANAGEMENT


**Editors**

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CIMMYT International Maize and Wheat Improvement Center

CGIAR RESEARCH PROGRAM ON Maize

in collaboration with international and national
research and development partners


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**CIMMYT – The International Maize and Wheat Improvement Center** – is one of the centers under the Consultative Group on International Agricultural Research (CGIAR) and is the global leader in publicly funded maize and wheat research and related farming systems. Headquartered near Mexico City, CIMMYT works with hundreds of partners throughout the developing world to sustainably increase the productivity of maize and wheat cropping systems, thus improving global food security and reducing poverty. CIMMYT leads the CGIAR Research Programs on Maize and Wheat and the Excellence in Breeding Platform. The Center receives support from national governments, foundations, development banks, and other public and private agencies. For more information, visit www.cimmyt.org.

**The CGIAR Research Program on Maize (MAIZE)** is an international collaboration led by CIMMYT and the International Institute of Tropical Agriculture (IITA) that seeks to mobilize global resources in maize R&D to achieve greater impact on maize-based farming systems in Africa, South Asia, and Latin America. The MAIZE strategy draws upon learning and experiences obtained through decades of extensive partnerships with national and international research and development partners, including both public and private institutions, and farming communities. For more information, visit www.maize.org.



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**September 2021**

# Foreword

In my capacity as Chief Scientist for the U.S. Agency for International Development's (USAID) Bureau for Resilience and Food Security, I have encountered few pests as alarming as the Fall Armyworm (FAW). This pest is at once invasive, able to attack multiple crops, and, in maize, it can be challenging to control. Native to the Americas, FAW is capable of long-distance movement, accelerating its spread across vital farming systems where it was heretofore unknown. My greatest concern is the threat it poses to maize, which is a food security and economic mainstay to countless millions of farm families and a vital food for hundreds of millions of low-income consumers. In a very short time, FAW has become a major threat across much of Africa and Asia and, because of its migratory nature, could one day also reach Europe.

FAW's emergence in Asia is a high concern given that the region contributes approximately 30% of global maize supplies, which are now at risk. Smallholder farmers are especially vulnerable, having limited access to the tools, technologies, and management practices that are necessary to sustainably manage the pest. As a novel threat, FAW also poses challenges to local governments and agricultural research systems, which must quickly monitor the pests' spread and provide the farming communities with effective control options. The upward trend in global temperatures exacerbates the situation as it increases the range and seasonal activity of insect pests. Associated losses in crop yield and quality are met, in turn, with efforts to increase production through expansion. This requires the use of more land and other natural resources, which in turn increases the global carbon footprint. Uncontrolled infestations also pose major food safety threats.

This publication on *Fall Armyworm in Asia: A Guide for Integrated Pest Management* offers to a broad range of public and private stakeholders – including national plant protection, research, and extension professionals – evidence-based approaches to sustainably manage FAW. The Guide is the result of contributions of dozens of institutions and individuals, to whom we express our deep appreciation. In particular, I want to acknowledge our long-standing collaboration with CIMMYT, and the FAW R4D International Consortium it coordinates, to build the evidence and systems needed to guide safe, effective pest control strategies. I also applaud the UN-FAO Global Action for FAW Control and the dozens of partners it has convened in helping generate a strategic and effective response to the FAW threat. Given the enormity of the challenge, an effective response requires coordinated action from the broadest possible community – governments, research institutions, donors, the private sector, and civil society. I hope this document provides the knowledge critical to meeting the FAW challenge and look forward to expanding our partnerships with many of you as we exchange knowledge, innovations, and experience and move forward in the fight against fall armyworm.

**Rob Bertram**
USAID Chief Scientist
Bureau for Resilience and Food Security

# Preface

The discovery and rapid spread of the fall armyworm (FAW; *Spodoptera frugiperda*) in Africa (since 2016) and in Asia (since 2018) seriously threatens the food security and livelihoods of millions of resource-constrained smallholders and their families. Within a short span of its incursion in Asia in mid-2018, FAW has spread to over 15 countries on the continent. Similar to the situation in Africa, the pest is likely to become endemic in many countries due to the conducive environment. FAW's major preference for maize, a crop that serves as food, feed, and fodder, and provides income to millions of smallholders in Asia, is indeed a major concern.

Soon after the outbreak of the pest in India in 2018, USAID, CIMMYT, and the Fall Armyworm Research-for-development (R4D) International Consortium, comprised of several international and national partners, have organized a series of workshops and stakeholder consultations in several countries across Asia, including Bangladesh, Nepal, and India. Governments in Asia have also quickly responded to the challenge and set up National FAW Task Forces to rapidly mobilize actions to mitigate FAW damage. Several public- and private-sector institutions in Asia have organized massive campaigns to bring awareness about the diagnosis and management of FAW. There is an increasing understanding that the pest needs to be sustainably managed, along with other maize pests, using an integrated pest management (IPM) strategy, without damaging human and animal health and the environment.

Similar to our approach in formulating the FAW Technical Guide for Africa in 2018, 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. We have sought to work in partnership to:

- Ensure that scientific evidence and knowledge guides recommendations on FAW management practices and policies in both Africa and Asia.
- 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 key stakeholders.
- Commit to building capacity, focusing on integrated actions addressing policies, institutions, and people, with a special emphasis on smallholder farmers, including women and youth.

## Scope of this FAW IPM Guide for Asia

This FAW IPM Guide is designed for use by professionals in private and public 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 Asia.

In order to inform development of locally adapted IPM strategies appropriate for Asian farmers, this FAW IPM Guide compiles currently available, scientifically validated strategies to control FAW. The document presents the best management strategies that have either been validated or are in the process of validation in the smallholder farmer context, as judged by experts to be appropriate for adaptation to Asian agroecologies and maize-based cropping systems.

Based on the key components of an IPM framework, the following seven chapters emphasize currently available, practical knowledge and tools to control FAW in Asia:

- Chapter 1: Fall Armyworm in Asia: Invasion, Impacts, and Strategies for Sustainable Management
- Chapter 2: Fall Armyworm Scouting, Action Thresholds, and Monitoring
- Chapter 3: Pesticide Application, Safety, and Selection Criteria for Fall Armyworm Control
- Chapter 4: Host Plant Resistance in Maize to Fall Armyworm
- Chapter 5: Biological Control for Fall Armyworm Management in Asia
- Chapter 6: Agroecological Management of Fall Armyworm in Asia
- Chapter 7: Communications Framework for Integrated Pest Management of Fall Armyworm in Asia

Much of the available evidence on FAW control methods in Asia is still preliminary but is based, in part, on experiences with smallholder farmers in different countries in Asia. It is important to note that while the FAW is a new pest to Asia, it is not a new pest to agriculture. Practitioners and farmers in the Americas from Brazil to Canada have been managing FAW successfully for over 100 years. What works and what does not work is largely known to both smallholders and production agriculturalists. Nonetheless, there are still significant challenges for Asia. The available FAW management knowledge needs to be disseminated, acquired, and actioned. As with IPM in any country, the approaches need to be contextualized for farmers to reflect their particular circumstances. This manual is meant to serve as a guide in that process. 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 application and choices (**Chapter 3**) is available to inform near-term, field-level decisions by farmers, extensionists, regulators, and other stakeholders. In addition, breeders have identified and validated sources of native genetic resistance to FAW in currently available maize germplasm adapted to Africa and Asia, and both conventionally bred and genetically modified (GM) FAW-resistant varieties are available in some countries (**Chapter 4**). The use of biocontrol as a component of IPM for FAW is well understood from experience in the Americas; **Chapter 5** (Biological Control) describes the research being done in this area in India and Bangladesh. The manual also covers important topics related to agronomic and landscape management approaches (**Chapter 6**) for FAW control. As these chapters illustrate, there is a wealth of information on control of FAW from around the world, and there is an urgent need to communicate this knowledge to different stakeholders in Asia (**Chapter 7**).

We are deeply grateful for the insights from the FAO Global Action Plan on Fall Armyworm, especially the Technical Steering Committee, which includes a cohort of global multi-disciplinary experts with strong commitment and intensive engagement in implementing IPM-based FAW management in Africa and Asia. While the information compiled here provides an initial basis for practical decision-making and strategic planning, further guidance will come from the rapidly evolving experiences in both Asia and Africa, which will provide opportunities to expand and refine local IPM approaches in light of new knowledge and tools. 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 Asia, especially for the benefit of resource-constrained smallholders in the region. We call on Asian governments, the global private sector, universities and international research centers, foundations and civil society organizations, and other development partners to join us in combating the impact of this pest.

**B.M. Prasanna**
**Joseph E. Huesing**
**Virginia M. Peschke**
**Regina Eddy**

# Acknowledgements

This publication on *Fall Armyworm in Asia: A Guide for Integrated Pest Management* is intended as a comprehensive IPM-based technical guide that can be used as an up-to-date decision support tool for sustainable management of the pest, especially in the maize-based cropping systems in Asia.

Development of a comprehensive IPM-based manual was identified as one of the high-priority interventions during the Stakeholders Consultation Workshop on Fall Armyworm Management in Asia, organized jointly by USAID, CIMMYT, ICRISAT, CGIAR Research Program on Maize (MAIZE), and CGIAR Research Program on Grain Legumes and Dryland Cereals (GLDC), at ICRISAT, Hyderabad, India (May 1-3, 2019).

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 CGIAR Research Program on Maize (MAIZE), to make this publication possible.

This publication is the result of contributions of experts from several institutions to whom we express our deep appreciation. While formulating various chapters in this manual, the authors considered relevant lessons from dealing with FAW in both Asia and Africa, recognizing on the one hand the inherent differences in the Asian and African farming contexts and landscapes, and on the other hand the possible commonalities when it comes to interventions against transboundary pests like FAW.

We express our sincere gratitude to the following colleagues who have critically reviewed various chapters in the manual, and provided valuable inputs for their improvement: Buyung Hadi, Anne Sophie Poisot, and Puyun Yang (FAO); Mark Edge (Bayer); Clint Pilcher, Imre Mezei, and Melissa Willrich Siebert (Corteva); Andrew Ward, Keith Jones, Christoph Neumann, D'Arcy Quinn, and Langewald Juergen (CropLife/IRAC); Robert Meagher (USDA-ARS, Florida); and Roger Day (CABI).

We sincerely thank the CIMMYT Corporate Communications team, especially Marcelo Ortiz, Eliot Sanchez, and Marcia MacNeil, for their kind support in formatting and designing of the publication.

# List of Acronyms & Abbreviations

| | |
|---|---|
| **AATF** | African Agricultural Technology Foundation |
| **AChE** | Acetylcholinesterase |
| **AICRP** | All India Coordinated Research Project |
| **AIRN** | Agricultural Input Retailer Network (Bangladesh) |
| **ANGRAU** | Acharya N.G. Ranga Agricultural University (Hyderabad, India) |
| **ASEAN** | Association of Southeast Asian Nations |
| **AT** | Action Threshold |
| **BARC** | Bangladesh Agricultural Research Council |
| **BARI** | Bangladesh Agricultural Research Institute |
| **BC** | Backcross |
| **BHEARD** | Borlaug Higher Education for Agricultural Research and Development |
| **BIPM** | Biocontrol-based IPM |
| **BMGF** | Bill and Melinda Gates Foundation |
| ***Bt*** | *Bacillus thuringiensis* |
| **BWMRI** | Bangladesh Wheat and Maize Research Institute |
| **CABI** | Centre for Agriculture and Biosciences International |
| **CAGR** | Cumulative annual growth rate |
| **CESAS** | Cost, efficacy, safety, accessibility, and scalability |
| **CGIAR** | Consultative Group for International Agricultural Research |
| **CHPRRU** | Corn Host Plant Resistance Research Unit (USDA-ARS) |
| **CIMMYT** | International Maize and Wheat Improvement Center |
| **CML** | CIMMYT Maize Line |
| ***COI*** | *cytochrome oxidase subunit I gene* |
| **CPD MARD** | Crop Protection Department of the Ministry of Agriculture and Rural Development (Vietnam) |
| ***cry*** | Crystal protein gene from *Bacillus thuringiensis* |
| **CSISA** | Cereal Systems Initiative for South Asia |
| **DAE** | Department of Agricultural Extension (Bangladesh) |
| **DAC&FW** | Department of Agriculture, Cooperation and Farmers Welfare (India) |
| **DH** | Doubled haploid |
| **DOAE** | Department of Agricultural Extension (Myanmar)* |
| **DT** | Drought tolerance |
| **EAC** | East African Community |
| **EIL** | Economic Injury Level |
| **Embrapa** | Brazilian Agricultural Research Corporation |
| **EPN** | Entomopathogenic nematode |
| **ET** | Economic Threshold |
| **EUA** | Emergency Use Authorization |
| **FAO** | Food and Agriculture Organization of the United Nations |
| **FARM** | Fostering Agricultural Revitalization in Myanmar |
| **FAW** | Fall armyworm |
| **FGD** | Focus group discussion |
| **FPA** | Fertilizer and Pesticide Authority (Philippines) |
| **GAP** | Good Agricultural Practices |
| **GLDC** | CGIAR Research Program on Grain Legumes and Dryland Cereals |
| **GLP** | Good laboratory practices |
| **GLS** | Gray leaf spot |

* The military government changed the country's name to "Myanmar" when it took power in 1989. The U.S. government continues to use the name "Burma" because it believes that any change of the name of a country should be a decision for its people. Internationally, both names are recognised.

| | |
|---|---|
| **GM** | Genetically modified |
| **GWAS** | Genome-wide association study |
| **h** | Hour |
| **ha** | Hectare |
| **HDTS** | High-Density Trapping System(s) |
| **HHP** | Highly hazardous pesticide |
| **IAL** | Ispahani Agro-Limited (Bangladesh) |
| **ICAR** | Indian Council of Agricultural Research |
| **ICIPE** | International Center of Insect Physiology and Ecology |
| **ICRISAT** | International Crops Research Institute for the Semi-Arid Tropics |
| **IFAD** | International Fund for Agricultural Development |
| **IFDC** | International Fertilizer Development Center |
| **IGP** | Indo-Gangetic Plains |
| **IIMR** | Indian Institute of Maize Research |
| **IITA** | International Institute of Tropical Agriculture |
| **IP** | Infested plants |
| **IPM** | Integrated Pest Management |
| **IRAC** | Insecticide Resistance Action Committee |
| **IRM** | Insect Resistance Management |
| **IRMA** | Insect Resistant Maize for Africa |
| **ITS** | Internal transcribed spacer |
| **IW** | Infested whorls |
| **JNCASR** | Jawaharlal Nehru Centre for Advanced Scientific Research (Bangalore, India) |
| **KALRO** | Kenya Agriculture and Livestock Research Organization |
| **KII** | Key informant interview |
| **KVK** | Krishi Vigyan Kendra (Farm Science Center in India) |
| **L** | Liter |
| **LC** | Lethal concentration |
| **LDTS** | Low-Density Trapping System(s) |
| **MAIZE** | CGIAR Research Program on Maize |
| **MARD** | Ministry of Agriculture and Rural Development (Vietnam) |
| **MBR** | Multiple Borer Resistant |
| **MEL** | Monitoring, Evaluation and Learning |
| **MOCC** | Ministry of Climate Change (Pakistan) |
| **MIRT** | Multiple Insect Resistance Tropical |
| **MMT** | Million metric tons |
| **MNFS&R** | Ministry of National Food Security and Research (Pakistan) |
| **MOA** | Mode of Action |
| **MoA** | Ministry of Agriculture |
| **MSSRF** | M.S. Swaminathan Research Foundation (India) |
| **MSU** | Michigan State University (USA) |
| **MTD** | Moths per trap per day |
| **NARS** | National Agriculture Research System |
| **NBAIR** | National Bureau of Agricultural Insect Resources (India) |
| **NBC** | National Biosafety Committee (Pakistan) |
| **NCBI** | National Center for Biotechnology Information (USA) |
| **NCL** | National Chemical Laboratory (Pune, India) |
| **NGO** | Non-Governmental Organization |
| **NPIC** | National Pesticide Information Center |
| **NPPO** | National Plant Protection Organization |
| **NPV** | Nucleopolyhedrovirus |

| | |
|---|---|
| **NTO** | Non-target organism |
| **OB** | Occlusion bodies |
| **OECD** | Organization for Economic Co-operation and Development |
| **OPVs** | Open-Pollinated Varieties |
| **OV** | Organic Vapor |
| **PEUA** | Pesticide Emergency Use Authorization |
| **PHI** | Pre-Harvest Interval |
| **PPD** | Plant Protection Division (Myanmar) |
| **PPE** | Personal Protective Equipment |
| **PPRI** | Plant Protection Research Institute (Vietnam) |
| **QTL** | Quantitative Trait Locus |
| **R1–R5** | Reproductive stages of maize |
| **REI** | Restricted Entry Interval |
| **RACI** | Responsible, Accountable, Consulted, Informed |
| **RH** | Relative humidity |
| **RIB** | Refuge-in-a-bag |
| **SAAO** | Sub-Assistant Agricultural Officer |
| **SABC** | South Asia Biotechnology Centre |
| **SAWBO** | Scientific Animation Without Borders |
| **SAU** | State Agricultural University (India) |
| **SDS** | Safety data sheet |
| **SEM** | Scanning electron microscopy |
| **SfMNPV** | *Spodoptera frugiperda* multiple nucleopolyhedrovirus |
| **SFW** | Small, fresh windowpanes |
| **SLI** | Self-limiting insect technology |
| **SMART** | Specific, Measurable, Achievable,Realistic, and Time-bound (goals) |
| **SNP** | Single-nucleotide polymorphism |
| **SpfrNPV** | *Spodoptera frugiperda* nucleopolyhedrovirus |
| **SSA** | Sub-Saharan Africa |
| **SSR** | Simple sequence repeat |
| **TEM** | Transmission electron microscopy |
| **TLB** | Turcicum leaf blight |
| ***Tpi*** | *Triosephosphate isomerase* gene |
| **UAHSS** | University of Agricultural & Horticultural Sciences, Shivamogga |
| **UAS** | University of Agricultural Science |
| **UASB** | University of Agricultural Sciences, Bangalore |
| **UK** | United Kingdom |
| **US$** | United States dollars |
| **USA** | United States of America |
| **USAID** | United States Agency for International Development |
| **USDA-ARS** | United States Department of Agriculture-Agricultural Research Service |
| **USDA-FAS** | United States Department of Agriculture-Foreign Agricultural Service |
| **UV** | Ultraviolet |
| **VAAS** | Vietnam Academy of Agricultural Sciences |
| **V1–V12** | Maize vegetative stages |
| **VE** | Vegetative-Early stage |
| ***vip*** | *Vegetative insecticidal protein* gene from *Bacillus thuringiensis* |
| **VT** | Vegetative-Tassel stage |
| **WHO** | World Health Organization |
| **WP** | Wettable powder |
| **YAU** | Yezin Agricultural University |

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CHAPTER 01

# Fall Armyworm in Asia: Invasion, Impacts, and Strategies for Sustainable Management

B.M. Prasanna[1*], Joseph E. Huesing[2], Virginia M. Peschke[3], Rodney N. Nagoshi[4], Xiangping Jia[5], Kongming Wu[6], Y Andi Trisyono[7], Tek Tay[8], Alison Watson[9], Roger Day[10], Regina Eddy[11].

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# 1. Introduction

## 1.1. Arrival and Spread of Fall Armyworm (FAW) in Asia-Pacific[1]

Native to the Americas, the fall armyworm (*Spodoptera frugiperda*; FAW) was officially reported outside the Americas for the first time in West Africa in January 2016 (Goergen *et al.* 2016). When and where it first arrived on the continent is unknown (Schlum *et al.* 2021), as is the number of introductions. By January of 2018, FAW was reported in over 40 African countries (Figure 1). FAW has been found in every country of sub-Saharan Africa except Lesotho, possibly because of its high elevation (Njuguna *et al.* 2021). In the Asia-Pacific region, FAW incidence was first reported in the southern state of Karnataka, India, in May 2018 (Sharanabasappa *et al.* 2018; Shylesha *et al.* 2018), and subsequently in all the maize-growing states in the country (Suby *et al.* 2020). Yemen, Bangladesh, Myanmar (Yee *et al.* 2019), China (Jiang *et al.* 2019; Jing *et al.* 2020; Sun *et al.* 2021), and Thailand also reported FAW outbreaks in 2018[2]. In 2019, FAW was reported by several countries, including Sri Lanka (Perera *et al.* 2019), Nepal (Bajracharya *et al.* 2019), the Philippines (Navasero *et al.* 2019), Vietnam (Hang *et al.* 2020), and Indonesia (Trisyono *et al.* 2019). In 2020, Australia, South Korea, Cambodia, Papua New Guinea, Timor Leste, New Caledonia, Jordan, Syria, and United Arab Emirates formally reported the outbreak of the pest (Figure 1).

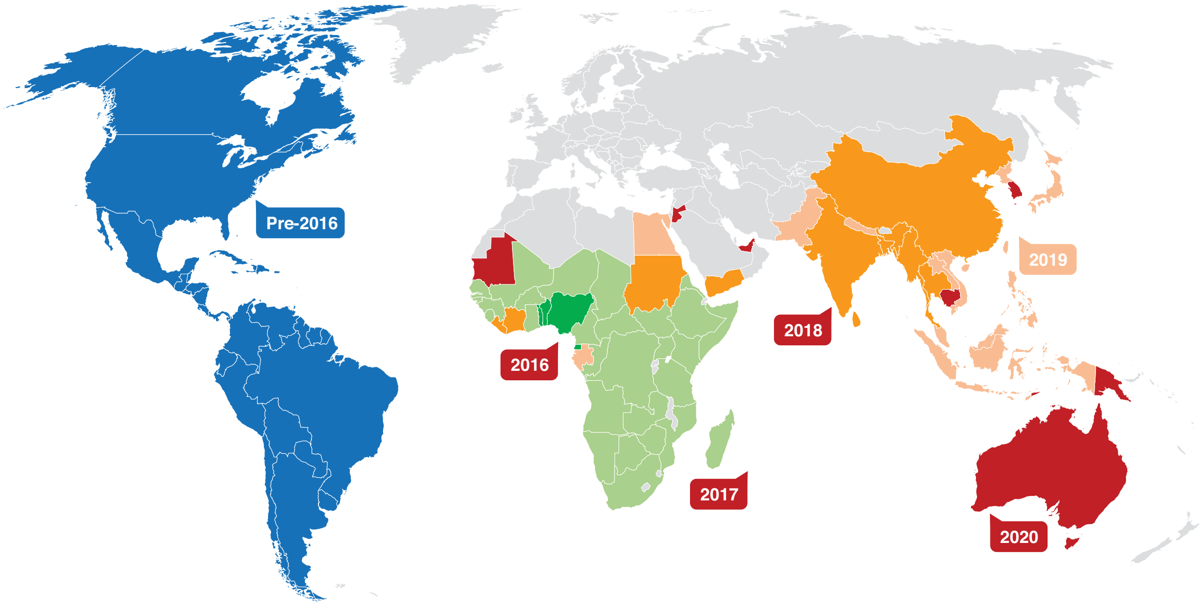


**Figure 1.** Global distribution of FAW, based on the published reports, and information presented in Centre for Agriculture and Biosciences International (CABI) Invasive Species Compendium (https://www.cabi.org/isc/datasheet/29810; accessed on January 2, 2021). Note that there could be some discrepancies in years of informal reports of the pest versus formal reporting through the Food and Agriculture Organization of the United Nations (FAO) and/or CABI in some of the countries.

The temporal spread of FAW within several countries in the Asia-Pacific region has been documented over the last two years. Through an extensive study of migration patterns and biometeorological processes, Wu *et al.* (2019) elucidated the population dynamics of FAW in the Yangtze River Valley located in Central China and comprising 11 provinces. The authors highlighted the importance of the Yangtze River Valley as the source of migrant FAW colonizing Northern China during May to July. They also proposed that the migration of FAW between the Yangtze River Valley (*i.e.*, middle and northern subtropical zones of China) and the tropical and southern subtropical zones of China would form a circuit due to the advance and retreat of the prevailing southerly winds.

[1] The Asia-Pacific region includes East Asia, South Asia, Southeast Asia, and Oceania (https://en.wikipedia.org/wiki/Asia-Pacific).

[2] https://www.ippc.int/en/countries/thailand/pestreports/2018/12/first-detection-of-fall-army-worm-on-the-border-of-thailand/

The rapid emergence and distribution of FAW populations in Asia highlights two important facts: (1) similar to Africa and the Americas, the pest can spread quickly across large geographic areas within a limited timeframe, through natural and/or trade-assisted migration; and (2) the FAW populations can persist throughout the year in the conducive tropical/subtropical climates of Asia. Thus, FAW has now become a global problem, posing a serious threat to the food and nutrition security and livelihoods of hundreds of millions of farming households in both Africa and Asia.

## 1.2. FAW Host Range and the Potential Impact on Maize in Asia

FAW incidence has been reported on several crops in Asia, including maize (field/sweet/waxy), sorghum, sugarcane, wheat, rice (very limited), millets, ginger, soybean, tomato, cotton, cabbage, groundnut, banana, pasture grasses, and green amaranth. However, similar to the situation in Africa, FAW has caused major economic damage mostly to the maize crop across Asia, followed by sorghum and sugarcane (to a limited extent).

In Asia, maize is the third most important cereal after rice and wheat. The maize area in Asia is about one-third of the global maize area of 197 M ha. However, five countries in Asia (China, India, Indonesia, the Philippines, and Pakistan) account for 90% of the area under maize cultivation on the continent. Compared to 2013, when China's maize area was around 33.5 M ha, in 2019 the harvested maize area in China reached 41.28 M ha (FAOSTAT 2021), exceeding the maize area on the entire African continent. It must be noted that 80-85% of the maize-growing area in China is temperate, while the rest is subtropical. The temperate maize-growing areas are not conducive for FAW to survive in the severe winter months, unlike the subtropical areas. The maize-growing areas in North Korea, South Korea, and Japan are also temperate. However, it must be noted that FAW does not diapause, and has a strong capacity for multigenerational seasonal migration (with potential to cause damage) in areas that may be unsuitable for year-round persistence of the pest (Westbrook *et al.* 2019; Niassy *et al.* 2021; Maino *et al.* 2021; Zhou *et al.* 2021a,b).

India is the second largest maize-growing country in Asia, with an estimated maize area of 9.03 M ha in 2019. Maize in India is grown predominantly under tropical/subtropical conditions. India's maize production rose from 11.15 million metric tons (MMT) in 2002 to 27.7 MMT in 2019 (FAOSTAT 2021). In the Indian context, no fewer than 15 million smallholder farmers are engaged in maize cultivation, generating employment for more than 650 million person-days at farming. Out of a total production of 27.7 MMT in 2019, 14.8 MMT (53.4%) was estimated to be used as poultry feed, 7 MMT (25.2%) as food, 1.8 MMT (6.5%) for industrial uses (especially starch), 1.5 MMT (5.4%) for ethanol production, and the remaining 9.5% for other purposes (USDA-FAS GAIN Report 2019).

Indonesia is the third largest maize-growing-country in Asia. Maize is the second most important food crop in Indonesia. The harvested area and yield have both been increasing during the last several years. The harvested area in 2014 was 3.84 M ha with the national yield averaging 4.95 tons/ha, while in 2019 the harvested area reached 5.64 M ha with the national yield 5.44 tons/ha (BPS 2021; FAOSTAT 2021). This trend may continue due to high demand for animal feed.

The Philippines is the fourth largest maize-growing country in Asia. Maize occupies the third largest area in the country, next to rice and coconut. Approximately 600,000 Filipino farmers are estimated to depend on maize as a major source of their livelihoods (Department of Agriculture, 2020). In 2019, maize was cultivated on an area of 2.52 M ha with a total production of 7.98 MMT, and an average yield of 3.17 tons/ha (FAOSTAT 2021). About three-fourths of the harvested area is under yellow maize, which accounts for approximately 50% of livestock mixed feed. The genetically modified (GM) yellow maize, first released in the Philippines in 2002, presently occupies 460,000 ha in the country (Alvarez *et al.* 2021). White maize is mostly consumed as food by about 14 million Filipinos, although part of it is processed into industrial starch (Anderson and Yao 2003).

Maize is Pakistan's third most important cereal in both area and production. In 2019, maize area, production, and productivity in Pakistan was 1.41 M ha, 7.24 MMT, and 5.12 tons/ha, respectively (FAOSTAT 2021). Over 95% of maize production in Pakistan occurs in two provinces *viz*., Punjab and Khyber Pakhtunkhwa (KPK), although in recent years maize production has also been increasing in the traditionally non-maize growing provinces like Sindh and at limited scale in Balochistan. Approximately 30-40% of the maize area is covered with hybrids, mostly in the Punjab province, and about 60-70% covered with open-pollinated varieties (OPVs), mostly in the KPK province. The use of maize as food is decreasing and the poultry industry has emerged as the major driver of maize sector in Pakistan, utilizing at present around 60% of the total production. The wet milling industry uses around 25% and the balance goes for human consumption and silage making (Ali *et al.* 2020).

In Nepal, maize is the second most important crop after rice in terms of area, production, and yield. In 2019, maize was cultivated on an area of 0.94 M ha with a total production of 2.65 MMT, and an average yield of 2.82 tons/ha (FAOSTAT 2021). About 72% of maize area is in the mid hills, followed by the *Terai* (19%) and high hills (9%). In the hills of Nepal, more than 86% of the maize production is used for human consumption while in the *Terai* (lowland), 80% of the maize production is used for poultry and animal feed (Gurung *et al.* 2011). Nepal predominantly cultivates OPVs of maize, while hybrid maize covers only 10% of the total maize area in the country (Kandel 2021).

Maize is the second most important cereal crop in Bangladesh (FAO 2021). Although the cultivated area under maize (0.45 M ha) and production (3.56 MMT) are significantly lesser than those of rice, average yield is the highest in South Asia (8 tons/ha). The maize sector in the country is growing rapidly. In 2020, maize saw an increase of 9.3%, far outstripping the growth of all other cereals. In Bangladesh, the National Seed Policy identifies five crops, namely, rice, wheat, jute, potato, and sugarcane, as 'notified' (controlled) crops, and thus, their import and distribution are subject to stringent regulations (Chowdhury and Ullah, 1995). Because maize is a non-notified crop, the private-sector companies are able to invest in improved maize seed delivery in the country.

FAW moths were found to have invaded China, possibly from Myanmar, in December 2018 (Sun *et al.* 2021). Apart from Xinjiang, Qinghai, Liaoning, Jilin, and Heilongjiang, during the first year of invasion, FAW spread quickly throughout China (Jiang *et al.* 2019). The pest spread through 26 provinces in 2019 and 27 in 2020, damaging 1.125 and 1.278 M ha of crops, respectively. Maize was the most severely affected crop, although FAW damage was also seen on sugarcane, wheat, and other crop plants. Faced with the severe challenge of FAW, China established a national coordination mechanism to prevent damage from the pest. In a short time, the crop yield loss was reported to be controlled to within 5% of the total production in both years (Zhou *et al.* 2021b).

Unlike in Asia, maize is not a major crop in Oceania, with only 81,084 ha of harvested area in 2019. Of this, Australia alone covers 58,949 ha. Although the hectarages are small, the risk to maize crops on island nations impacts their resilience disproportionately. On the other hand, sorghum is grown on a significant area (550,279 ha in 2019) in Australia (FAOSTAT 2021) and could be potentially vulnerable to FAW if appropriate management practices are not adopted. Sorghum is also cultivated on more than 5 M ha in Asia. India leads the sorghum area in Asia with about 4 M ha (in 2019), followed by China (750,000 ha), Pakistan (199,026 ha), and Myanmar (160,619 ha) (FAOSTAT 2021).

Robust estimates of the economic impacts of FAW in the countries affected by the pest in Asia are crucially needed. There are reports available on the extent of the impact of FAW, especially on the maize crop, from a few countries in Asia. In Xundian county, northeastern Yunnan, China, farmers' dependence on pesticides to manage FAW was reported to have significantly affected farming revenue (Yang *et al.* 2021). In India, the cumulative data published by the Department of Agriculture Cooperation and Farmers Welfare, Government of India, on 25 June 2019 indicated that Karnataka had the largest area affected with FAW (211,300 ha), followed by Telangana (24,288 ha), Maharashtra (5144 ha), and others (Rakshit *et al.* 2019). FAW was reported to have caused economic damage to maize crops in several states in India during the rainy and post-rainy seasons of 2018 and 2019 (Suby *et al.* 2020). Mayeeet al. (2021) reported that the FAW invasion in India has negatively impacted the poultry industry, which led the Indian Government to import 130,000 tons of maize in 2019.

FAW is considered as a potential threat to the sugarcane crop, which is grown in several countries across Asia. FAW infestation on sugarcane in China was reported for the first time by Liu *et al.* (2019b). FAW feeding has been reported on sugarcane fields in the states of Tamil Nadu (Srikanth *et al.* 2018), Karnataka (Matti and Patil 2019), and Maharashtra (Chormule *et al.* 2019). Song *et al.* (2020) reported serious incidence of FAW on sugarcane, which is the main cash crop in Guangxi, China. The authors indicated control of the pest by pesticides applied by drones. The available evidence shows that FAW does attack sugarcane; however, it is not clear to what extent the infestation has resulted in economic damage.

It is important to emphasize that the economic impact of FAW is not only represented by the yield loss caused to the affected crop. There are potentially significant impacts incurred by the associated additional management costs in the field, such as through increased labor or new research, extension, and training demands. An increase in the use of pesticides can also represent a substantial cost to the farmers. A recent study (Yang *et al.* 2021) examining the response of farmers to FAW in the Yunnan province in China showed that the full cost of pesticide-based crop protection increased from US$81 per hectare per crop season in 2018 to US$276 in 2020. The study also showed that at the FAW infestation levels present, some farmers were applying, on average, as many as 6.4 pesticide applications per crop season in 2020. This underscores the need for implementing an effective Good Agricultural Practices–Integrated Pest Management (GAP-IPM) approach to FAW control in Asia.

## 1.3. Maize Market Segments in Asia vis-à-vis FAW Incidence and Potential Impacts

Understanding the purpose for which a crop is cultivated by farmers, and thereby the economic value of the produce, is particularly important for devising appropriate management regimes for the control of a pest such as FAW. In this section, we describe the diverse market segments of maize in Asia, and thus, the types of farmers who grow maize for enhanced incomes and livelihoods.

- **Maize as an animal feed:** Animal feed is the largest end-use segment for maize in Asia with ~70% of the total volume used by the feed industry. Yellow/orange maize constitutes 60-65% of the poultry feed. Demand for maize is being further fuelled by population growth and increasing inclination towards higher protein consumption in the form of meat and eggs. Around 60% of the total maize production in China is utilized for animal feed production and only 10% is utilized for human food, seeds, and other purposes. In India too, animal feed accounts for about 60% of the maize consumption: poultry feed accounts for 47% of total maize consumption, while livestock feed accounts for 13%. The Indian poultry industry (specifically eggs and poultry meat) is growing at a cumulative annual growth rate (CAGR) of around 6-9%, creating a huge demand for maize. Therefore, any significant reduction in maize production due to FAW and/or other biotic/abiotic threats could have a cascading effect on the feed industry, and consequently on maize prices.
- **Maize as food:** Unlike sub-Saharan Africa, where maize is a major staple food, consumption of maize as food in Asia is relatively limited. Nevertheless, there are several areas in the highlands and tribal regions of South and Southeast Asia (*e.g.*, Nepal, Bhutan, India, southern China, southwestern Bangladesh, Indonesia, and the Philippines) where maize is used as a staple food (Prasanna 2014). In general, in urban areas, maize consumption as a staple food continues to be low. In India, food consumption accounts for 20% of maize consumption, with direct consumption being 13% and processed foods accounting for 7% of total maize consumption (FICCI 2018).

  There is an increasing interest of urban consumers in Asia for speciality maize, in addition to a rising popularity of multi-grain flour in countries such as Bangladesh. Specialty maize, including fresh maize, sweet corn, baby corn, and waxy maize, is consumed in many Asian countries, and the production happens especially in the peri-urban areas with good market access. Sweet corn differs from normal field maize, both genetically and morphologically, with the kernels having a high sugar content (25-30%). Sweet corn is harvested when the kernels are immature and are in the milky stage. Since FAW attacks not only the vegetative stage but also the developing ears, sweet corn growers need to be cautious in protecting the crop before it is harvested.
- **Maize for industrial products:** Apart from feed, industrial application of maize is a crucial end-use segment, as maize is used for making an array of industrially important products, including starch, biofuel, food additives, and sweeteners. For instance, in India, the non-food industrial products account for 20% of maize use. Starch is the most important product in this category, accounting for 14% of the total maize use. The remaining 6% is accounted for by exports and other industrial non-food products (FICCI 2018).
- **Hybrid maize seed production market:** Maize hybrid seed markets are rapidly growing in Asia, offering opportunities to farmers in certain pockets to serve as "contract producers" for the seed companies. For example, in India the private seed companies for maize in particular are located in Andhra Pradesh, Telangana, Karnataka, and Maharashtra, where progressive farmers have turned into seed producers on a contract basis and entire stretches of villages have been converted into "Seed Production Hubs" and "Seed Production Villages" (FICCI 2018).

# 2. FAW Life Cycle

The FAW life cycle, and its various stages—egg, larval, pupal, and adult—have been described in detail by Huesing *et al.* (2018), which was based on Capinera (1999). These stages are illustrated in Figure 2. A few aspects of the FAW life cycle are of particular importance when considering scouting and control of this pest:

- FAW generally has six larval instars, rarely more than seven. The $1^{st}$- and $2^{nd}$-instar larvae are easiest to control, whereas larger larvae ($4^{th}$-$6^{th}$ instar) are more difficult—the larvae have more mass and they tend to feed in the whorl where they are better protected. For that reason, scouting procedures and control recommendations (see **Chapters 2 & 3**) are based on larval size, which is estimated by the feeding patterns on the plant, as well as on the percentage of infested plants.
- FAW can have overlapping generations on the same plant, complicating scouting and its control.
- As described above (Section 1.2), FAW feeds on numerous hosts although in Africa and Asia the economic damage is mostly reported on maize and sorghum. In addition, the moths are capable of migrating hundreds of kilometers, particularly when the wind is favorable.

As FAW is a pest of tropical origin and the pest does not go into diapause, temperature plays a critical role in its migration and persistence. Du Plessis *et al.* (2020) analyzed the effects of temperature on the development of FAW. The study revealed that the development rate of FAW increased linearly with increasing temperatures between 18°C and 30°C and that larval survival was the highest between 26°C and 30°C. The optimal range for egg, larval, and egg-to-adult development was between 26 and 30°C. The optimum temperature with the fastest larval development rate and lowest mortality was at 30°C. These data indicate that FAW populations may not be able to develop and persist in certain geographical regions in Asia where temperatures typically decrease to below these thresholds, especially during the winter months (Du Plessis *et al.* 2020).

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-brow pupa

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

**Figure 2.** Various stages of FAW life cycle. (Note: A detailed figure showing the sizes of FAW larvae at various stages is presented in **Chapter 2**.) Photo credits: A-D; F-G: Ivan Cruz (Embrapa); Reproduced from FAW-Africa IPM Manual); E: Anani Bruce (CIMMYT).

# 3. Molecular Comparison of FAW Populations in Africa and Asia

An understanding of the molecular characteristics of FAW populations in various parts of the world can help researchers to understand introduction and migration patterns, predict host plant preferences, understand issues of pesticide resistance, and design management practices against the insect. Key findings on FAW populations in Asia are described in this section.

## 3.1. FAW Strains and Host Preference

FAW consists of two strains adapted to different host plants: the "corn/maize strain" (C-strain) that feeds predominantly on maize, cotton, and sorghum, and the "rice strain" (R-strain) that feeds primarily on rice and pasture grasses (Prowell *et al.* 2004; Dumas *et al.* 2015a). The two strains are morphologically identical, so their identification is based on a small number of genetic markers, with polymorphisms in the mitochondrial *cytochrome oxidase subunit I* (*COI*) and Z-chromosome-linked *triosephosphate isomerase* (*Tpi*) genes most commonly used. The efficacy of *COI* and *Tpi* as strain markers was determined empirically by analysis of multiple sites in the Americas that consistently showed significant differences in the frequencies of certain haplotypes in FAW collected from different host plants (Prowell *et al.* 2004; Nagoshi 2010; Murúa *et al.* 2015). The *COI* and *Tpi* genes can segregate independent of each other, so the observation in Western Hemisphere populations of about 80% agreement between the strain markers indicate that successful matings are mostly limited to within-strain pairings (Nagoshi *et al.* 2018). Strain differences in the nocturnal timing of mating activity (Pashley *et al.* 1992; Schöfl *et al.* 2009, 2011) and reduced fertility in interstrain hybrids (Kost *et al.* 2016) between males of the rice mtCOI strain mating with the females of the maize mtCOI strain were suggested as possible factors leading to interstrain mating avoidance. However, laboratory studies show that mating between the strains can produce viable and fertile hybrid offspring (Pashley and Martin 1987; Dumas *et al.* 2015a; Kost *et al.* 2016), and there is evidence for the existence of interstrain hybrids in field populations (Nagoshi *et al.* 2017a; Nayyar *et al.* 2021). Furthermore, recent whole-genome analyses identified significant interstrain matings in native populations of FAW (Yainna *et al.* 2020; Tay *et al.* 2020). These observations are consistent with suggestions that the two strains are in the process of sympatric speciation (Prowell *et al.* 2004; Dumas *et al.* 2015a,b; Gouin *et al.* 2017), and are currently displaying only partial reproductive isolation driven by differences in host range and mating behaviors.

## 3.2. Genetic Characteristics of FAW in Africa and Asia

The FAW in Africa exhibits four distinctive genetic features: (1) Genetic variation of FAW populations is much reduced in Africa compared to those in the Americas when assessed by comparisons to a highly variable *Tpi* intron segment (Nagoshi *et al.* 2019b). This is consistent with what would be expected if the introduction into Africa was recent and involved a relatively small invading population. (2) Only a single variant has been found in Africa of the *Tpi* haplotype group that identifies the R-strain, and this variant appears to be extremely rare or absent in Western Hemisphere populations (Nagoshi *et al.* 2018). (3) The *COI* strain marker is generally not in agreement with *Tpi* in the African FAW. Specifically, the majority of specimens in most Africa locations carry the R-strain *COI* haplotype together with the C-strain *Tpi* haplotype, creating an ambiguous strain identity. Overall, the R-strain *Tpi* haplotype is rare in Africa, observed in no more than 10% of the hundreds of African specimens examined (Nagoshi *et al.* 2018, 2019b). Because all the specimens tested to date were from C-strain host plants (maize, sorghum) and so are probably of that strain, it appears that *COI* is no longer an accurate marker of strain identity for the FAW found in Africa. It has been speculated that this dissociation of the *COI* and *Tpi* markers could be explained by interstrain hybridization occurring early in the invasion period, thereby mixing the *COI* and *Tpi* markers, with the hybrid form retaining a C-strain host range (Nagoshi *et al.* 2019b). Additional evidence comes from whole-genome analysis showing extensive introgression between the rice and maize strains in the invasive FAW populations in Asia (Zhang *et al.* 2019; Yainna *et al.* 2020; Tay *et al.* 2020), and in Africa (Yainna *et al.* 2020; Tay *et al.* 2020). Yainna *et al.* (2020) noted that invasive FAW populations could have arrived as hybrids to their new invasive ranges, and such hybrids could have been from the existing hybrid populations in the Americas. (4) The great majority of the African FAW populations that carry a C-strain *COI* haplotype contain a variant that is predominantly found in only the Caribbean and Florida (Nagoshi *et al.* 2017b, 2019b). This variant is a minority, but still substantial, constituent of the C-strain populations that overwinter in Texas and Mexico and is rarely observed in South America.

The FAW in central and eastern Asia are similar to those from Africa with respect to these genetic features. FAW from Africa, India, Myanmar, and southern China share the same limited genetic variation and the same haplotypes, consistent with a common and recent origin for these populations (Nagoshi *et al.* 2019a, 2020). Collections from India, Myanmar, and China displayed the same disagreement in strain markers as observed in Africa, with most specimens carrying the R-strain *COI* and the C-strain *Tpi* haplotypes. The R-strain *Tpi*R haplotype was only rarely observed, and the single type of variant found was identical to that which is so far unique to Africa. The predominance of the R-strain *COI* haplotype in India was observed by Swamy *et al.* (2018) in a survey of maize and sorghum fields from six states. In a recent study, Nayyar *et al.* (2021) investigated 190 FAW samples from different regions in India for strain identity and polymorphism on the basis of partial mtCOI gene sequences. The study revealed the presence of interstrain hybrid haplotypes of rice and maize strains in India, and a recent and common origin for invasive FAW populations in Asia and Africa, with no evidence for multiple introductions of FAW populations to India. When specimens from India, Myanmar, and China were found that carried the C-strain *COI* haplotype, they all were of the variant associated with the Caribbean and Florida (Nagoshi *et al.* 2019a, 2020).

Zhang *et al.* (2019) describe similar results for FAW from China based on an extensive study of 318 populations sampled from 131 counties and cities of 13 provinces. The strain markers showed disagreement similar to that found in Africa, with more than 96% carrying the R-strain *COI* haplotype while all specimens carried the C-strain *Tpi* haplotype. In a subsequent study, Zhang *et al.* (2020) undertook genome-wide resequencing of 103 samples (collected across 16 provinces). The study confirmed that all the Chinese FAW sampled carried the C-strain *Tpi* haplotype and have a genetic background dominated by the American C-strain-specific single-nucleotide polymorphisms (SNPs). These observations together with the unique sequence of the single R-strain *Tpi* variant found in Africa led these authors to suggest that the American R-strain FAW may not have invaded Africa or China. Liu *et al.* (2019a) did find one specimen from Guangdong province in China with the R-strain *Tpi* haplotype. Genetic analysis found it to be identical to the variant found in Africa, further supporting the link between the African and Asian FAW populations.

In summary, the current data indicate that FAW in the Eastern Hemisphere is predominated by an interstrain hybrid population as defined by genetic criteria, but that is behaviorally of the C-strain with respect to host plant usage. The continued linkage of the *Z*-chromosome *Tpi* marker to this strain-diagnostic phenotype despite evidence of significant genetic introgression between strains suggests that sex-linked genes may have a predominant role in determining FAW strain identity.

## 3.3. Resistance to *Bt* and Other Insecticides

FAW in the Western Hemisphere has evolved resistance to a number of insecticides, with large regional differences in the traits expressed (see for example Gutiérrez-Moreno *et al.* 2019). Efforts are ongoing to determine the insect resistance status of the FAW now in the Eastern Hemisphere and involve genomic approaches to identify resistance alleles as well as laboratory and field bioassays to test for resistance phenotypes. Boaventura *et al.* (2020) provide genetic evidence that organophosphate and carbamate pesticides are likely to be compromised in Kenya FAW and found no evidence for the presence of a mutation associated with resistance to the Cry1F *Bt* protein. Botha *et al.* (2019) reported that FAW in South Africa exhibited only moderate susceptibility to the *Bacillus thuringiensis* (*Bt*) toxin Cry1Ab but was highly susceptible to Cry2Ab2.

Similar results are being observed with FAW from China. The studies of Zhang *et al.* (2020) included analysis of genes related to synthetic pesticides and *Bt* protein resistance. The authors found mutations resulting in amino acid substitutions in acetylcholinesterase (AChE) that are associated with resistance to organophosphates in about 70-75% of 280 FAW samples (276 samples from China), but they did not detect mutations associated with resistance to *Bt* proteins. As expected, laboratory bioassays of two inbred FAW strains from Yunnan province showed increased resistance to some organophosphate and pyrethroid pesticides. A single-location field experiment in Yunnan province showed good control of FAW by maize expressing the *Bt* toxin Cry1Ab, but the authors did not identify the line that was evaluated or its expression level, so it is difficult to make general conclusions.

Comparable results on resistance to synthetic pesticides were reported by Gui *et al.* (2020), who assembled a complete chromosome-level genome of a male FAW (SFynMstLFR) from Yunnan province in China, and compared resequencing results of the populations from America, Africa, and China. A total of 22,201 genes were predicted in this genome. The expansion of the cytochrome P450 gene family in FAW was found to be closely related to detoxification and tolerance to pesticides. Transcriptome analysis of 23 pesticide treatments revealed several candidate target genes. Strain identification of 163 individuals collected from the Americas, Africa, and China showed that both maize and rice strains were found in the American populations, while only the maize strain was found in the Chinese and African populations. Based on this whole-genome analysis, the study suggested that FAW populations that invaded China most likely originated from Africa, and not directly from the Americas. These studies demonstrate that whole-genome analysis can provide better insights into the genes controlling FAW host range and dispersion, which in turn could lead to more effective tools/approaches for FAW management.

## 3.4. Need to Monitor the Evolution of FAW Strains

The FAW populations from Africa, India, and south-eastern Asia exhibit a number of genetic traits that include low haplotype variation, shared haplotypes at all locations, a similar disagreement between *COI* and *Tpi* markers, and a unique R-strain *Tpi* haplotype variant. These findings are consistent with a single or small number of introductions in West Africa followed by rapid eastward dissemination into south-eastern Asia, a pattern that also reflects the temporal sequence of detections. How this rapid dispersion occurred remains to be elucidated and there are some regions that appear to be particularly conducive to long-range natural migrations (see for example Wu *et al.* 2019). Of significance is the growing body of evidence that the R-strain is not yet present in the Eastern Hemisphere, at least not in substantial numbers, which reduces the number of crops at high risk of consistent FAW infestations. However, given the apparent rapidity by which FAW can spread across the hemisphere, it is important to remain vigilant and keep monitoring for the presence of the R-strain, or of new (possibly hybrid) variants that could significantly impact rice, millet, and other R-strain preferred crops.

There is evidence from multiple studies that the FAW strains in Africa and Asia carry alleles for resistance to organophosphates and other chemical insecticides. As of this writing, however, there is little evidence for the presence of *Bt* resistance alleles in these populations. As with host range, it is important to continue monitoring for evidence of FAW populations developing resistance to *Bt* proteins.

# 4. Good Agricultural Practices–Integrated Pest Management (GAP-IPM) Framework for FAW Control in Asia[3]

FAW is now an endemic pest across much of Africa and Asia and it is therefore essential to develop an effective GAP-IPM approach, based on farming practices, to manage this pest across Asia. 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 agroecological contexts (particularly for low-resource smallholders). The GAP-IPM approach provides a useful framework to achieve these goals.

[3] Note: This section on IPM is substantially based on Huesing et al. (2018) from Fall Armyworm in Africa: A Guide for Integrated Pest Management.

## 4.1. Good Agricultural Practices (GAP)

GAP are key to a robust maize crop and are complementary to IPM. Soil health, comprising conservation of soil microbiological life, a balanced mix of organic matter and/or fertilizer containing nitrogen, phosphorus, and potassium, and a properly adjusted soil pH, will support a robust stand of maize. A robust stand is better able to meet the yield potential of the maize variety planted and is better able to withstand stresses. A robust stand of maize also aids in conservation biocontrol by reducing the number of times a field needs to be treated with pesticides. Note that "GAP" as used in this manual (e.g., https://cropforlife.com/list-of-agricultural-practices/) should not be confused with GAP related to food safety (e.g., https://www.ams.usda.gov/services/auditing/gap-ghp).

## 4.2. Principles of IPM

The goal of IPM is to economically suppress pest populations using techniques that support a healthy crop, minimize the use of pesticides, and minimize harm to people and the environment. 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 and agricultural advisor possess significant agronomic and pest management knowledge to implement an effective program based on local farming goals and conditions. The IPM process is embraced globally by international bodies such as FAO and the Organization for Economic Co-operation and Development (OECD) and is typically illustrated in the form of an IPM pyramid, based on GAP (Figure 3). 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 control within the Asian 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.

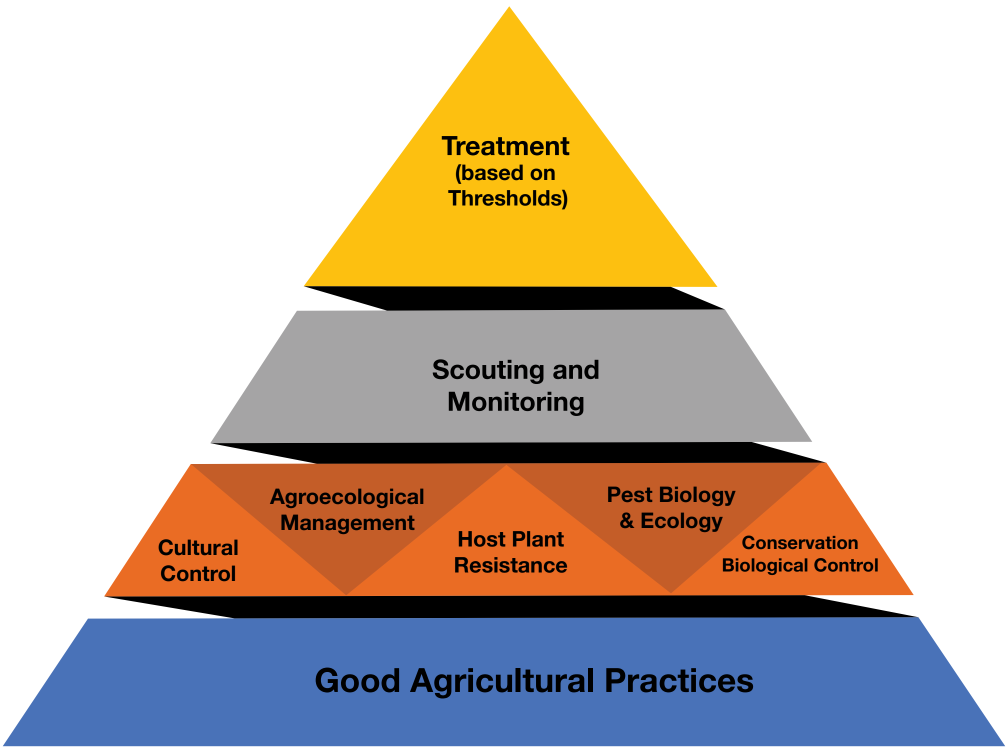


**Figure 3.** A conceptual illustration of IPM (modified from Naranjo 2011; Naranjo *et al.* 2020). “Treatment” may include pesticides (biopesticides and/or environmentally safer synthetic pesticides), augmentative biocontrol, mating disruption, sterile male insect release, etc. (see **Chapter 3**). These treatments may be used either alone or in combination, as appropriate, based on the farmer’s access to technologies and an IPM package informed by the CESAS (Cost, Efficacy, Safety, Accessibility, Scalability) model (Section 5).

An IPM framework for control of FAW in maize 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 (especially timing of planting), landscape management, and host plant resistance, all supporting conservation biological control.
- Implement routine scouting to **identify and respond quickly** to pest infestations when they occur.
- In the event of a pest infestation exceeding the Action Threshold (see Section 4.4), **suppress the pests** using as efficacious and low-toxicity pesticides as possible, to minimize the potential risks to human and animal health, the environment, and the natural enemies of the pest.
- Provide **scientifically validated, evidence-based choices to farmers** on how to safely and effectively mitigate the potential damage to their crop(s) from a specific pest or combination of pests. Cost, efficacy, and safety (environmental and human) should be evaluated for each option.
- **Minimize the amount and toxicity** of chemical pesticides applied to achieve control of the pest.
- **Incorporate new, practical findings** as they become available for continuous improvement.
- **Manage insect resistance to pesticides** by minimizing their use and using recommended Insecticide Resistance Action Committee (IRAC) Mode of Action (MOA) rotations.

## 4.3. Economic Threshold and Economic Injury Level

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 Stern *et al.* (1959), and 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.

**It is only worth treating your maize crop when the cost of the pest control treatment is less than the value of the crop saved by the treatment.**

### 4.3.1. Calculation of Economic Injury Level

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 4). 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 = Proportion of the pest population controlled.

Note that if management costs (C) increase, then it takes more pests/pest damage to justify control action, so the EIL increases. Similarly, if market values (V) decrease, then more pests/pest damage 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 the 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 costs 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 may vary significantly from place to place in a given country, which means that individual farmers may need to make adjustments in their own calculations based on the price they receive for maize and the local costs of technologies. (See Section 7.1.5 of **Chapter 3** for examples of cost-benefit calculations.) Yield loss due to a given pest also varies depending on the insect's developmental instar, the stage of development of the crop, the crop's overall health (influencing its ability to compensate for foliar damage), and the agroecosystem in which the crop is grown. Also, while data on the efficacy of some technologies are robust because the same product is used globally by thousands of farmers in many countries, efficacy data for some technologies are at best an estimation. Moreover, efficacy for some technologies may vary under different conditions, including environmental conditions and farmer's management expertise. EIL calculations also typically do not take into account the costs to human health and the environment, nor do they factor in the potential loss of natural enemies of the pest.

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 biology and population dynamics. In the case of a new invasive insect pest, estimating those dynamics is very difficult. However, in the case of FAW, which has been a pest in the America for decades, this information is readily available.

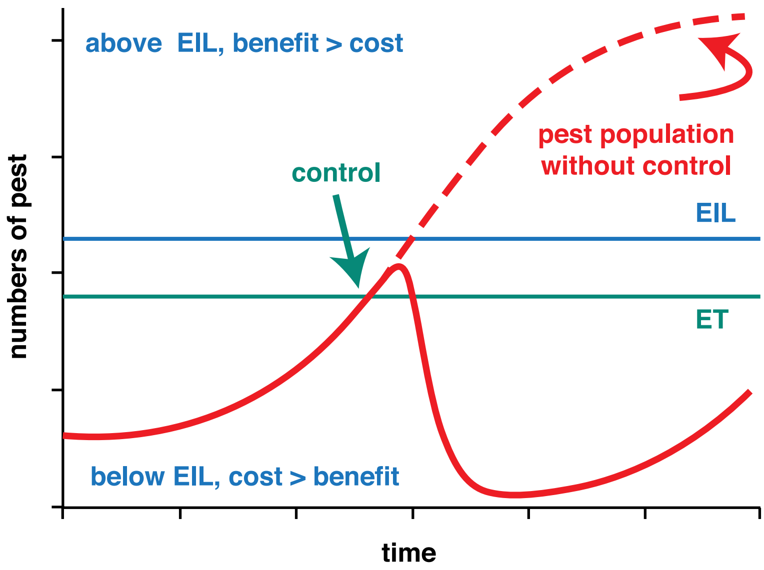


**Figure 4.** The relationship between pest numbers over time and calculation of the Economic Threshold (ET) and the Economic Injury Level (EIL). Figure credit: Ed Zaborski, University of Illinois; from Barbercheck and Zaborski (2015).

## 4.4. Action Thresholds

In practice, ETs and EILs have not been determined for most crops. Instead, nominal thresholds, herein called **Action Thresholds (ATs)**, are calculated based on experimental results, expert opinion, and experience. These nominal thresholds are used throughout the IPM community to support farmers' decision-making. Accordingly, given the long history of controlling the FAW in the Americas, it is reasonable to use expert opinion to formulate ATs for FAW in Asia in the short term. In addition to the density of the pest and/or level of damage, which form the basis of ATs, farmers also consider the overall health of the crop and current growing conditions (crop stage, soil moisture, weather, etc.). See **Chapter 2** for more information on use of ATs to make treatment decisions.

## 4.5. Summary of the IPM Approach

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:

- GAP that promote the growth of healthy plants are important because healthy, robust plants are generally less susceptible to insect and pathogen attack and may better withstand such attacks.
- 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 (*e.g.*, spiders, ants, earwigs, beetles, fungi, and bacteria) or parasitoids (*e.g., Trichogramma* spp., *Telenomus* spp., etc.). In turn, this can help control pest larvae—thereby reducing pest proliferation.
- Creating awareness among farmers on how to identify FAW damage in the field through scouting, assessing the pest population and its threat to the crop, and taking 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.
- Pesticides should be selected judiciously and used only when necessary, as part of a holistic IPM strategy. Pesticide attributes such as environmental safety, selectivity, and environmental persistence should be considered in the decision-making process (see **Chapter 3**).

It must be recognized that no one specific IPM package will be effective against FAW across all the varied agroecologies in Asia. 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.

# 5. Use of the CESAS Model to Evaluate Technologies for Use in IPM Packages in Asia

There is a wide range of proven techniques and technologies available for control of FAW and other lepidopteran maize pests (Table 1), although these are not equally accessible to farming communities across Africa or Asia. To assist farmers and extension advisors in selecting/promoting appropriate technologies, it is important to provide information on a range of technologies or approaches that have been transparently evaluated according to five specific criteria: cost, efficacy, safety, accessibility, and scalability (CESAS). To that end, Table 1 provides an example of an evaluation framework of such an assessment, as explained in further detail below.

- ***Costs*** should include not only the direct cost to the farmer of a technology or a management practice but also the indirect cost of implementation, such as labor, equipment, etc. to the farmer, as may be applicable, in addition to the opportunity costs. Cost distortions that may be created when technologies are subsidized or require ongoing donor support or government investments are factored into the scalability column. Importantly, costs determine the **affordability** of a technology to resource-constrained smallholders, whether in Africa or in Asia.

- In terms of ***efficacy***, most practitioners do not recommend mitigation technologies that result in less than 80% FAW larval mortality and many do not even recommend mitigations that result in less than 90% larval mortality. Regardless of the level of mortality, practitioners rarely recommend interventions that have not demonstrated efficacy determined based on crop yield data. This is very important because research assessments are frequently based on differences in damage ratings (*e.g.*, the Davis scale), or % parasitism (used when evaluating parasitoids). These research assessments often do not readily translate into farm-level control of FAW.
- The ***safety*** of a technology to humans, animals, and the environment is an important consideration. For example, several broad-spectrum insecticides could be available in the market to farmers at a low cost, but could be quite detrimental to the ecosystem, including humans, animals, and natural enemies of the target pest (which may result in a lower level of conservation biocontrol). **Chapter 3** provides information on the safety profiles of a number of insecticides and the importance of using appropriate personal protective equipment (PPE).
- ***Accessibility*** is important because farmers are frustrated when they hear about solutions but are unable to access the technology. Regulatory frameworks are important, and the regulators need to be supported with robust data for decision-making. At the same time, this process needs to be predictable and transparent and avoid needless delays. The provision for use of an Emergency Use Authorization (EUA) is particularly important for invasive pests (Suguiyama *et al*. 2020).
- ***Scalability*** is an often-overlooked criterion, not only for specific technologies but also for IPM packages as a whole. There are many technologies that can be made to work if enough time, resources, and expertise are committed to the task. However, history has shown that control options that are exceedingly complex, costly, and dependent on long-term funding commitments are not scalable across countries and certainly not across time.

***Acceptability*** is an important element in the success of technology transfer. Ultimately, it is farmers who decide on the technology to use, and they should be provided with the best information to inform their decisions. Ideally, recommendations should be based on empirical evidence and consider the weight of evidence (gathered through robust studies) before any technology or a combination of technologies is widely recommended to farming communities. Farmers' indigenous knowledge can also be recommended once validated.

While all five components of the CESAS framework are important in assessing the potential combination of technologies or management practices for FAW control, it is important to keep in view the human, animal, and environmental ***safety*** criterion in the IPM context. Resource-constrained smallholders frequently lack the protective equipment and training to mitigate the technology risks. In Table 1, technologies with lower scores are, relatively speaking, less hazardous for farmers and are more likely to be compatible with conservation biological control. Technologies with higher scores would need some mitigation to ensure full human, animal, and environmental compliance. The technologies listed in Table 1 are discussed in more detail in **Chapter 3** (Pesticides), **Chapter 4** (Host Plant Resistance), **Chapter 5** (Biocontrol), and **Chapter 6** (Agroecology).

Supporting farmers and/or extension advisors to select/promote appropriate technologies for FAW control is likely to require much more than awareness creation or information on the advantages, disadvantages, and safety of various technologies/approaches (discussed in **Chapter 7**). It is also important to consider farmers' decision-making behavior with regard to the adoption of new technologies, including factors such as age, gender, wealth, experience, risk tolerance/aversion, attitudes, and beliefs.

**Table 1.** A potential framework for considering appropriate combinations of technologies for IPM-based FAW control in maize.

| S. No. | Technology | IPM tactics | Efficacy[1] | Safety | | Cost of product (US$)[4] per hectare to the farmer | | | Accessibility | | Scalability[6] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | User safety (Scale: 1-3)[2] | Environmental risk / Compatibility with biocontrol (Scale: 0-3)[3] | Purchase price to farmer (Single treatment) | Purchase price to farmer (Over a crop season) | Other costs to the farmer | Policy requirement | Infrastructure/ Supply chain (Scale 1-3)[5] | Scale: 1-3 |
| 1 | **FAW-resistant maize varieties (native genetic resistance)** | **Host plant resistance** | Good | Not Applicable (N/A) | 0 | N/A | $42-90 | N/A | Regulated | 1 | 1 |
| 2 | **FAW-resistant maize varieties (transgenic)** | **Host plant resistance** | Excellent | N/A | 0 | N/A | $140-206 | N/A | Regulated | 1 | 1 |
| 3 | **Intercropping with compatible crops** | **Agroecology** | Fair to Good | 1 | 0 | N/A | Variable | Planting an additional crop | Some companion crops regulated | 1 | 1 |
| 4 | **Push-Pull system or habitat diversification at the farm level** | **Agroecology** | Good | 1 | 0 | N/A | Variable | Planting additional crops | Some companion crops regulated | 1 | 2 |
| 5 | **Augmentative biocontrol using *Trichogramma* spp.** | **Biological control** | Fair to Good | 1 | 0 | $3.00-3.25 | $13-15 | Labor | Regulated | 3 (Biofactory; Logistics) | 3 |
| 6 | **Augmentative biocontrol using *Telenomus remus*** | **Biological control** | Fair to Good | 1 | 0 | $10-12 | $46-50 | Labor | Regulated | 3 (Biofactory; Logistics) | 3 |
| 7 | ***Bt* spray (Commercial)** | **Biopesticide** | Fair to Good | 1 | 0 | $28 | $110 | Labor, Sprayer, PPE, Cold Chain | Regulated | 2 | 1 |
| 8 | **Azadirachtin – Neem spray (Commercial)** | **Biopesticide** | Fair to Good | 1 | 0 | $32 | $96 | Labor, Sprayer, PPE | Regulated | 1 | 1 |

*(Continued on page 16)*

(Continued from page 15)

**Table 1.** A potential framework for considering appropriate combinations of technologies for IPM-based FAW control in maize.

| S. No. | Technology | IPM tactics | Efficacy[1] | Safety | | Cost of product (US$)[4] per hectare to the farmer | | | Accessibility | | Scalability[6] |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | User safety (Scale: 1-3)[2] | Environmental risk / Compatibility with biocontrol (Scale: 0-3)[3] | Purchase price to farmer (Single treatment) | Purchase price to farmer (Over a crop season) | Other costs to the farmer | Policy requirement | Infrastructure/ Supply chain (Scale 1-3)[5] | Scale: 1-3 |
| **9** | **Baculovirus/ SfMNPV spray (Commercial)** | **Biopesticide** | Good | 1 | 0 | $ 12-15 | $60-90 | Labor, Sprayer, PPE | Regulated | 2 | 1 |
| **10** | **Spinosad** | **Pesticide** | Excellent | 1 | 1 | $35 | $70 | Labor, Sprayer, PPE | Regulated | 1 | 1 |
| **11** | **Emamectin benzoate** | **Pesticide** | Excellent | 3 | 2 | $7.50-8.00 | $15-16 | Labor, Sprayer, PPE | Regulated | 1 | 1 |
| **12** | **Chlorantraniliprole** | **Pesticide** | Excellent | 1 | 0 | $32 | $66 | Labor, Sprayer, PPE | Regulated | 1 | 1 |
| **13** | **Lambda-cyhalothrin** | **Pesticide** | Fair to Good | 3 | 2 | $11-12 | $22-24 | Labor, Sprayer, PPE | Regulated | 1 | 1 |

**NOTE:** This table modifies an earlier USAID analysis, which was expanded by CIMMYT, USAID, and the FAO Global Action on FAW Control: Technical Committee in 2020. It appears as Tables 1 and 2 in *FAW Secretariat, Global Action for FAW Control (2020) General Guidelines for Developing and Implementing Regional IPM Strategy for Fall Armyworm Control in Demonstration Countries*. The **Chapter 1** authors have further updated the table based on emerging evidence and consultations with technology developers. In addition to using new evidence for refining the ratings, two of the rating scales have been recalibrated/harmonized to allow all dimensions to be evaluated via a 3-point vs a 4-point scale. This revised table reflects only the views of the **Chapter 1** authors; it may not reflect the views of the institutions with whom they are affiliated or the FAO Global Action for FAW Control: Technical Committee as a whole. The authors will update the information in this table at regular intervals as further evidence emerges.

## Footnotes:

**(1) Efficacy:** Ratings: Fair: 50-70% efficacy; Good: 70-90% efficacy; Excellent: >90% efficacy.
**Assessments for Efficacy, Safety, and Compatibility with Biocontrol** are derivative works of Jepson PC, Murray K, Bach O, Bonilla MA, Neumeister L (2020) Selection of pesticides to reduce human and environmental health risks: a global guideline and minimum pesticides list. Lancet Planet Health 4: e56-63. https://doi.org/10.1016/S2542-5196(19)30266-9. The efficacy ratings for biopesticides and synthetic pesticides in the above table were modified to align with those in Table 1 of **Chapter 3** of this manual.
**IPM measures in this table are meant to be used in combination (*e.g.*, resistant seed + intercropping + *Bt* spray). Thus, a lower level of efficacy for a single measure should NOT be used as a standalone decision-making guide on implementing the IPM measures.**

**(2) User safety,** as measured in terms of the personal protective equipment (PPE) needs, is rated as follows: Level 1 is the minimum level of protection needed while level 3 is the maximum requirement. The requirements for each level of protection are: 1 – Lower-risk pesticides requiring single-layer PPE; 2 – Lower-risk pesticides requiring single-layer PPE, plus eye and/or respiratory protection; and 3 – High-risk pesticides requiring double-layer PPE, plus eye and/or respiratory protection.

**(3) Environmental risk/Compatability with biocontrol** was assessed using a 4-point scale considering environmental risk assessments conducted on aquatic organisms, terrestrial animals, and pollinators where a risk would require some kind of mitigation. A risk of 0 was assigned when no risks were observed in any of the three categories, while a risk of 3 was assigned when risks were determined in all three categories. It is important to note that frequently risk (even high risk) can be mitigated through a variety of approaches. Accordingly, an effective technology carrying some risk could still be a viable option if there is a reasonable means to mitigate the risk. The current environmental animal assessment includes birds, mammals, fish, and aquatic invertebrates. Future assessments will include direct effects on non-target terrestrial invertebrates. Regarding compatibility with biocontrol, honeybee (a pesticide-sensitive species of Hymenoptera) serves as a conservative surrogate for parasitoids, most of which are also Hymenoptera. Honeybee is also a good surrogate for predatory arthropods owing to its extreme sensitivity to pesticides. The aquatic sensitivity test, which includes an assessment on aquatic invertebrates, can serve as a surrogate for other predatory invertebrates. See Table 1 of **Chapter 3** of this manual for additional details on environmental risks for specific pesticides and suggested mitigation techniques.

**(4) Costs:** The costs reflected in the table were obtained through multiple (unpublished) sources in Asia. However, some of the costs, especially related to agroecological management, biopesticides, and synthetic pesticides, could be variable in different countries. The scale is as follows: 1 – green; <100 US$/ha/crop season; 2 – yellow; US$100-200/ha/crop season; 3 – red; US$ >200/ha/crop season.

**(5) Infrastructure/Supply chain** rating scale: 1 – requires no special storage and/or cold chain conditions; 2 – requires special storage and/or cold chain conditions; 3 – requires special storage and/or cold conditions as well as infrastructure such as transportation.

**(6) Scalability**: For technologies with commercialization potential (*e.g.*, FAW-resistant varieties, augmentative release of biocontrol agents), if the private sector is already producing and offering a product for sale (realizing the need for addressing regulatory issues), then we can consider that technology fully scalable (a score of 1). If the technology requires a significant logistics stream (*e.g.,* cold chain), then the potential for scaling over poorly developed rural areas is diminished; also, if the technology is considered too complex by the farming community, widespread adoption may be a challenge (a score of 2). Finally, if the technology requires infrastructure and maintenance investment from the public sector then the potential for scaling is greatly diminished (a score of 3).
For certain management practices (*e.g.,* agroecological tactics), it is essentially knowledge and practice that we are trying to scale; thus, scalability can be divided into geographical/socioeconomic applicability and diffusion speed. Diffusion speed is determined by (i) availability of prior knowledge on the intervention across the target region, including locally tailored options; (ii) complexity of the intervention—how difficult is it to educate farmers for adoption; (iii) cost–benefit, including co-benefits to the farmer; (iv) scope of integrating the intervention into ongoing development initiatives, such as climate-smart agriculture. Locally tailored options that are relatively simple with co-benefits to farmers and ongoing development initiatives are scored as 1. Options that are relatively complex and thus needing some outreach efforts with non-obvious co-benefits for farmers are scored as 2. Options that require community-level agreement and need certain investment to incentivize adoption are scored as 3.

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CHAPTER 02

# Fall Armyworm Scouting, Action Thresholds, and Monitoring

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# 1. Introduction

This chapter describes several methods for detection of FAW and the use of the FAW incidence data in making treatment decisions (which may sometimes include the decision not to treat). FAW incidence (pest pressure) is one component of the decision-making process. Risk of crop loss is the result of the interaction between pest pressure, plant growth stage, and environmental conditions.

Scouting is covered first because scouting can be readily done by farmers and most directly affects their treatment decisions. Monitoring data complement field-level scouting data and inform crop management decisions. Detailed background information on these topics is followed by protocols for scouting and pheromone trap setup. The information in this chapter should be immediately useful to agricultural professionals (extension, development organization, and private-sector personnel) who advise smallholder farmers, as well as to village-level progressive farmers. It may also be of general interest to technical specialists and policymakers who develop and coordinate local, national, and regional FAW management programs.

We recognize that not all smallholder farmers will formally scout their maize fields. But we recommend that even smallholder farmers use a simplified scouting method to assess the risk of crop damage by FAW before making a control decision. Introducing farmers to scouting protocols, Action Thresholds, and decision support tools such as monitoring provides them with valuable crop management information and will help them develop the skills to more effectively manage pests. Cost-effective management of FAW requires that pest management decision makers consider the pest pressure, the maize growth stage, and the weather, regardless of whether they formally scout their fields.

Finally, we recommend that researchers and pesticide regulators who test the efficacy of interventions for FAW control use a standardized scouting protocol (see **Chapter 3**) in addition to rating plant damage and yield. Scouting data used in combination with a plant damage rating system and yield data provides a more robust assessment of efficacy.

# 2. Definitions

Terms used for monitoring and surveillance are not standardized across jurisdictions or scientific disciplines (FAO.IPPC 2016; McGrath *et al.* 2018). In some cases, the terms are used as synonyms and in others they have unique meanings. For the purposes of this chapter, the following definitions 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 with their own pheromone traps, can also be aggregated and incorporated into broader, formal monitoring schemes. Finally, monitoring also has a specific meaning in the context of Insect Resistance Management (IRM), which refers to ongoing, repeated measurement of an insect pest population's susceptibility to a particular toxin (*e.g.*, to a pesticide or a specific insecticidal protein expressed in a genetically engineered crop variety).
- ***Surveillance*** denotes the informal, passive detection of pest presence and other issues. Surveillance is typically performed by farmers at the farm level and assumes no special training or approach. The importance of surveillance should not be overlooked. 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, this can lead to more rapid response to invasive pests. The collective feedback of thousands of farmers can provide powerful information about the dynamics of pest infestation. One lesson learned from the FAW management campaign in Africa was that many farmers had observed FAW before it was officially reported by scientists. In the future, there will be new pests arriving in farming areas and it is critical that pest control specialists in each country better integrate farmer observations to more effectively manage emerging pests.
- ***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 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. As noted above, however, localized scouting data can also be aggregated and incorporated into formal monitoring schemes at broader geographic scales.

# 3. Scouting for FAW in Maize

Cost-effective maize integrated pest management (IPM) programs are built on a foundation of good agricultural practices, good-quality (and preferably pest-resistant) seed and, only if needed, conservative use of pesticides. When implemented correctly, IPM lowers pest pressure through conservation biological control, which conserves natural enemies (McCravy 2008; see **Chapter 5**). It is important to scout maize fields on a regular basis to assess the risk of crop loss due to FAW and other pests. If egg-laying pressure is high and the weather is favorable to FAW, additional control measures may be needed to prevent unacceptable crop loss. Proper scouting should also provide farmers with the information necessary to avoid treatments that are not economically justified.

- ✓ **One of the fastest ways to reduce the use of insecticide** and control the cost of FAW management is to use scouting and Action Thresholds to eliminate unneeded insecticide applications.

Farmers frequently ask, “When can I skip an insecticide application without putting my crop at risk?” This chapter will answer that question, providing practical information based on field experience in Africa, the Americas, and Asia. Here, we will explore the following topics:

- ✓ Field scouting, including protocols for detecting FAW larvae of different sizes
- ✓ Guidance on what pesticide application methods to use based on FAW larval size and the growth stage of the maize plants
- ✓ Guidance on when it is advisable to use an effective, low-toxicity insecticide even though it may be more expensive than other options
- ✓ Monitoring systems for FAW
- ✓ Risk assessment data that support “no action” decisions (moth counts and weather forecasts)
- ✓ Strategic combinations of materials and methods that improve the efficacy of control tactics and reduce the cost of FAW management (see Section 8, FAW Management Scenarios)

## 3.1. Surveillance and Simplified Scouting

There are three approaches to assessing the risk of crop loss due to FAW in a maize field, which are referred to in this manual as *surveillance*, *simplified scouting*, and *formal scouting*. All three approaches are useful depending on the situation, the management goals of the farmer (*e.g.,* maximum grain yield, silage quality, reduction of input costs), and the level of scouting experience. The first two can be done easily by most farmers while formal scouting generally requires some amount of more formal training.

### 3.1.1. Surveillance

The most informal type of assessment, surveillance, gives an overall sense or first impression of what is going on in the field, and what signs to look for during more formal field scouting. *Signs* are indicators such as feeding scars on maize leaves that provide indirect evidence that FAW is present. When farmers or their advisors arrive at a maize field, they typically spend a few minutes looking around for signs of FAW (and other pests, diseases, and weeds). Information on FAW instar and severity can be quickly obtained by breaking open a few plants and taking note of the plant growth stage (see Section 3.2, Maize Growth Stages).

In some cases, surveillance is a sufficient level of assessment for the farmer to determine whether there is a pest problem in that field. There is, however, a natural sampling bias associated with surveillance because the eye is drawn to FAW “hot spots” (parts of the field that contain a heavy FAW infestation). Sampling bias during surveillance can lead to an overestimate of risk and unnecessary insecticide applications. Thus, we recommend that the farmer or advisor conduct a brief surveillance coupled with scouting, which represents a more systematic approach to risk assessment.

### 3.1.2. Simplified Scouting

To reduce bias while keeping the time and cost reasonable, scouting is based on sampling techniques. If one were to examine every plant in a one-hectare maize field (as many as 60,000 plants per hectare) at a rate of 5 seconds per plant, it could cost about 83 hours in labor. In contrast, the scouting instructions below recommend visiting five representative field locations per hectare and examining 10 plants per location to determine the average percentage infestation in the field. This should take no more than 15 minutes.

A simplified and useful scouting procedure is described in the training video "How to Identify and Scout for the Fall Armyworm" (https://sawbo-animations.org/708) by Scientific Animations Without Borders (SAWBO; Bello-Bravo *et al.* 2018). Simplified scouting reduces sampling bias and may reduce insecticide use. To perform simplified scouting:

- ✔ Check the field in five representative locations ("stops"). Examine 10 plants at each stop.
- ✔ Record the number of plants (out of 10) that are infested with FAW.
- ✔ Calculate an average of the FAW infestation level across the five stops.
- ✔ If an average of 2-4 plants out of 10 (20-40%) are infested with FAW in the field, consult a local Extension Officer (see Section 5, Action Thresholds).

Simplified scouting is sufficient in many cases, especially when farmers and their advisors are first learning about FAW. After the first growing season, farmers and their advisors are often ready to use a more detailed scouting method. Formal scouting follows the instructions above, but adds two additional procedures: (1) distinguishing between small and large larvae during the vegetative growth stages; and (2) evaluating the risk of yield loss caused by damage to the tassel (which reduces pollen shed and can lead to reduced kernel set and misshapen ears) or to the developing ear, especially when FAW egg laying is high and the weather is favorable to FAW (see Section 7, Decision Support Tools).

Assessing the size of the FAW larvae during vegetative growth is important because it influences spray timing, application method, and insecticide choice (see Section 8, FAW Management Scenarios). During later stages of crop growth, there is a narrow window of opportunity to control large FAW larvae, especially after initial tassel and ear emergence when they can cause substantial yield loss (see Section 4, Formal Scouting).

## 3.2. Maize Growth Stages

When scouting a maize field, it is important to have a general understanding of the crop growth stage. Maize growth stage does influence the scouting procedures (see Section 4, Formal Scouting) because it determines where to search, what to search for, and which Action Threshold to use (Section 5).

Maize growth stages are divided into the Vegetative (V), Vegetative Tassel (VT), and Reproductive (R) stages. The "V" stage of a maize plant is defined as the number of leaves that have a visible "collar". The maize plant below (Figure 1) has three leaves with visible collars. There are no visible collars on the fourth and fifth leaves. Therefore, this plant is at the V3 stage. Note that determining the maize V-stage precisely is not important. Mistaking a V4 plant for V3 or V5 will not affect your management decision.

The maize vegetative stages are subdivided into the early-whorl (V1-V6) and late-whorl plant (V7-V12) stages (Figure 2). Seedlings are sensitive to foliar feeding by FAW (red arrow at left in Figure 2). In addition, neonate larvae from eggs laid during the seedling stage grow into large larvae that can attack the growth point two weeks later. First tassel (VT) marks the end of the vegetative growth stages and is the stage at which the maize tassel is emerging from the whorl. There are six reproductive (R) stages, R1 (silking) to R6 (physiological maturity) (Nielsen 2019; Larson 2020). It is important to scout carefully after tassel emergence (red arrow at right in Figure 2) and during early ear development (VT-R2). R2 (blister stage) is often referred to as the "brown silk" stage, and its midpoint is about 10 days after silking (Larson 2020).

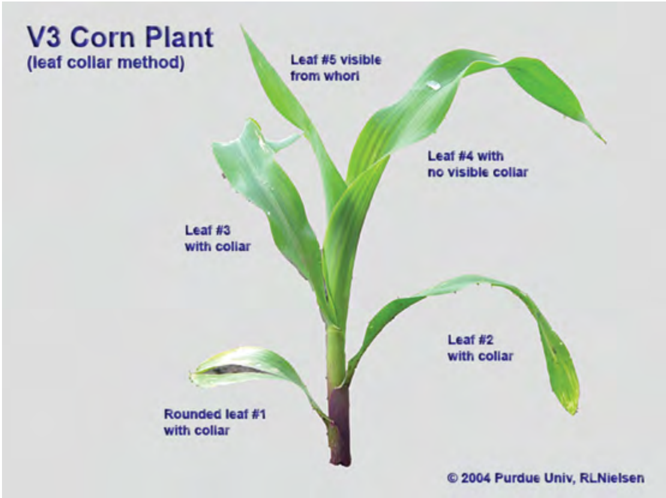



**Figure 1.** The maize plant displayed here has three (3) leaves with visible collars. There are no visible collars on leaves four and five. Therefore, this plant is at the V3 stage. Photo credit: R.L. Nielsen (Purdue University, USA).

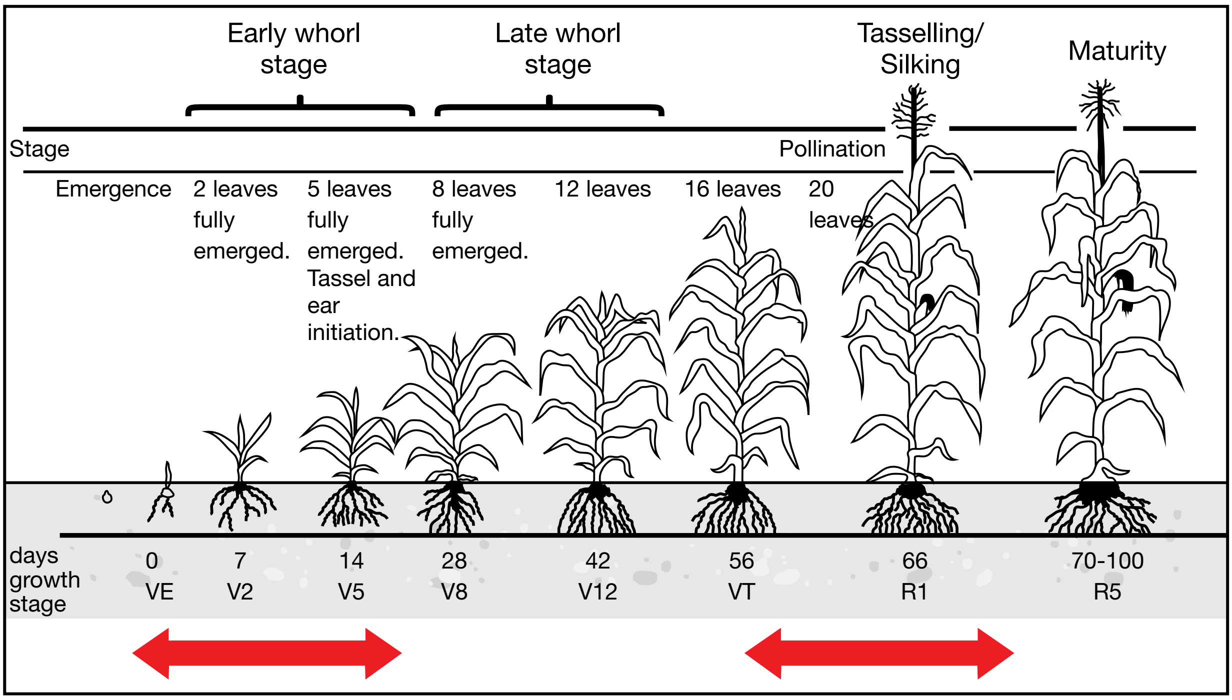



**Figure 2.** Vegetative (V) and Reproductive (R) stages of maize. (Adapted from Beckingham 2007).

The seedlings (VE-V6) are more vulnerable (red arrow at left) to foliar feeding by FAW than the late-whorl-stage plants (V7-V12).

Risk of crop loss due to FAW (red arrow at right) is high during early ear development (VT-R2).

# 4. Introduction to "Formal Scouting"

A step-by-step scouting protocol and data worksheet are provided in Section 9. The next few sections provide more detail on the principles and rationale underlying the recommended scouting procedures. Box 1 describes several abbreviations and terms used throughout this chapter.

**BOX 1. Terms Used in Scouting**

**Percentage of Infested Whorls (%IW)** – the percentage of plants with FAW larvae in the whorl.

**Percentage of plants with Small, Fresh Windowpanes (%SFW)** – a windowpane is an area of the leaf that the FAW fed upon but was unable to penetrate fully. Early-instar FAW larval mandibles are not able to fully penetrate the leaf surface and leave a thin, translucent layer of tissue that resembles a windowpane when held up to the sun. (The Davis Scale refers to these as pinholes; see **Chapter 3**, Section 7.1.2.)

**Percentage of Infested Plants (%IP)** – the percentage of plants infested by FAW. Includes plants with larvae, regardless of size, as well as those with any signs of fresh feeding.

**Search arena** – The area of the maize plant being searched (*e.g.*, the whorl).

**Search target** – The insect or sign being searched for (*e.g.*, small or large FAW larvae).

**Selective spray** – A pesticide application made either to a specific part of a field, to specific plants within the field, or to a specific part of the maize plant. This is generally done when it is clear that just a small number of plants are infested with larvae. The selective spraying described in this chapter is done by walking the entire field but applying the insecticide only to infested plants.

## 4.1. When to Scout

- Begin scouting when the maize plants are small, soon after emergence. Seedlings are vulnerable to foliar feeding; in addition, FAW sometimes acts like a cutworm, shearing the young seedling at its base. Continue scouting preferably every 7 days but no longer than every 14 days. The best time to apply control measures is at egg hatch when the larvae are small and before they move into the whorl.
- Check the fields carefully after initial tassel emergence and during early ear development. If the weather is favorable to FAW and there are larvae at the base of the developing ears, the risk of crop loss is high. Apply control measures before the larvae penetrate the husk of the developing ear.
- Scout after an insecticide application (following the insecticide label field re entry interval). It may be necessary to re-treat surviving larvae with a selective spray directed at the whorls. The advantage of selective sprays is that they may reduce pesticide use. The disadvantage is that it is possible to miss some infested plants, thus reducing the efficacy of the treatment.
- Scout after a heavy rainstorm. Heavy rainstorms can kill most of the small FAW larvae. Consider delaying a spray decision if rainstorms are likely because a spray might not be needed after a heavy rainstorm. In equatorial climates (tropical), a series of well-timed rainstorms can substantially reduce crop loss associated with FAW, even when egg-laying pressure is high.

## 4.2. Scouting Patterns

The first step when scouting maize is to choose one of the two basic scouting patterns. In each pattern, sampling is conducted in five representative locations per hectare. Use the "W" scouting pattern when the maize plants are small (Figure 3). Zigzag through the field, stopping and examining plants at five different locations (A-E in Figure 3).

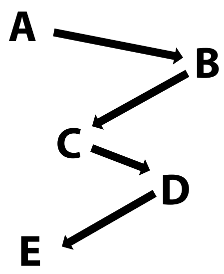



**Figure 3.** Use the "W" scouting pattern when plants are small. Each of the letters represents a sampling location within the field.

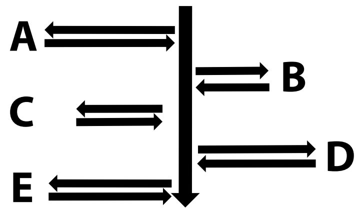



**Figure 4.** Use the "Ladder" scouting pattern when plants are tall. Each of the letters represents a sampling location within the field.

Use the "Ladder" scouting pattern when the maize plants are tall (Figure 4). Start at the beginning of the middle row. Walk several paces; turn right, stop, and sample. Return to the middle row. Walk several paces; turn left, stop, and sample. Return to the middle row. Repeat until five different and representative locations in the field have been examined (A-E in Figure 4).

## 4.3. Where and What to Look for During the Vegetative Stages

During the vegetative stages, focus observations on the newest three or four leaves emerging from the center of the whorl (a "whorl" is an arrangement of leaves in the center of the plant when looking at it from the top; see Figure 5). Focusing on the whorl will increase the chances that the feeding damage being observed is "fresh" damage, *i.e.*, indicative of actively feeding larvae.

**Figure 5.** Whorl of a healthy maize plant. Arrow indicates center of whorl.
Photo credit: Anani Bruce (CIMMYT).

Although one will occasionally encounter FAW egg clusters and larvae, they are usually well-hidden and not so easy to find. It is rare to see 1$^{st}$- and 2$^{nd}$-instar larvae (Figure 6). Therefore, during the vegetative stages, look for signs of feeding (described below) rather than eggs or larvae themselves.

Learn to distinguish between the signs of small versus large larvae. Small FAW larvae feeding on the leaves are exposed and more physiologically susceptible to insecticides. Large larvae in the whorl are protected from exposure to insecticides and are more physiologically resistant to insecticides than small larvae. Low-toxicity insecticides (*e.g.*, some microbial or botanical insecticides) are much more effective on small larvae than on larger larvae. Control options for large larvae are more limited. Although large FAW larvae are not generally found on newly emerged maize, it is possible for FAW larvae to enter the field from weeds or a neighboring crop.

## Key points

✓ **Target the control of FAW when the larvae are small.**

✓ **Control the FAW larvae before they move into the whorl.**

The FAW life cycle is summarized in **Chapter 1** and described in detail by Capinera (2020).

### 4.3.1. Small Larvae—Signs of Feeding

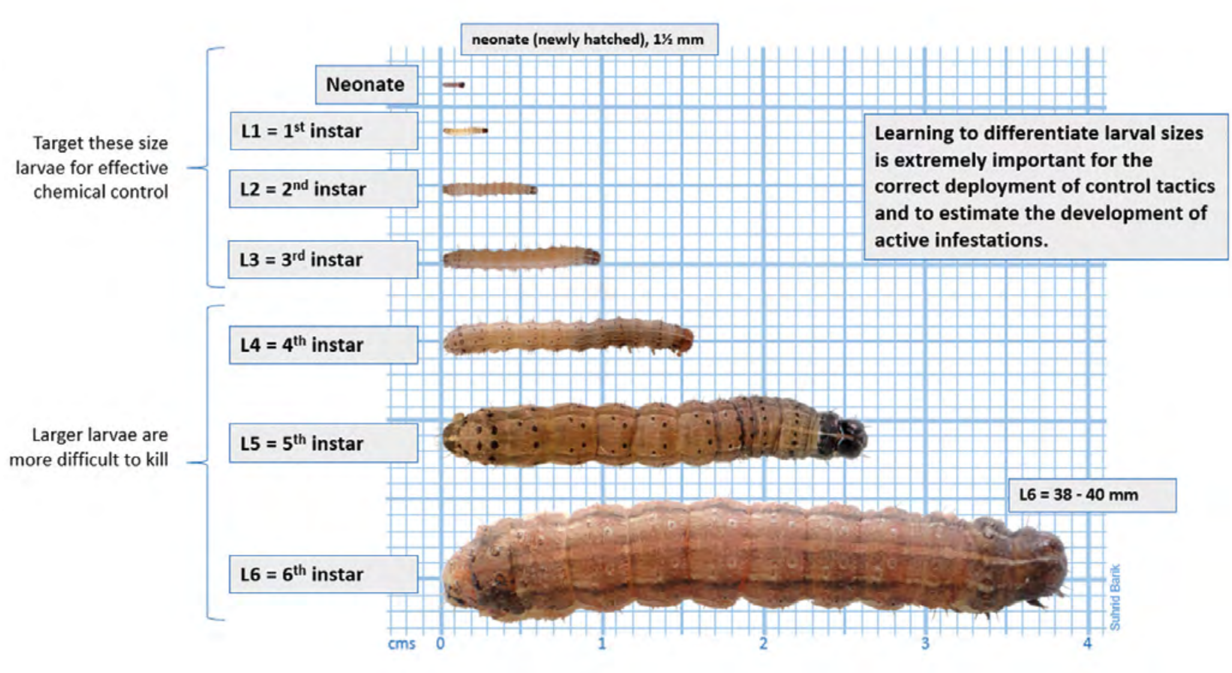



**Figure 6.** FAW instars (illustrated to scale). Image credit: Suhrid Barik, Corteva.

FAW eggs are laid in clusters. Egg hatch results in clusters of small larvae that in turn feed on leaves, causing clusters of small, sunken, transparent pits or windowpanes (Figures 7 and 8). Small, fresh windowpanes (SFW) indicate egg hatch and the presence of small larvae. If the indicated percentage of plants (see Section 5, Action Thresholds) has clusters of SFW, consider applying control measures.

The feeding pattern depends on the maize variety (level of resistance) as well as the crop maturity and leaf texture. When the leaves are young and tender, small larvae produce small, round windowpanes (about 1.0 mm in diameter; Figure 8). As the leaves get older and more fibrous, small larvae produce small, elongated windowpanes (about 1.0 mm in width; Figure 9).

### 4.3.2. Large Larvae–Signs of Feeding

Third-instar FAW larvae move down into the whorls. Larger FAW larvae (4th, 5th, and 6th instar) take up residence in the whorl and produce a variety of feeding signs: scraping, cutting and tearing, fecal pellets (frass), and a pattern sometimes called the whorl-feeding sign (Figures 10-14). For the purpose of scouting, all signs of feeding by large FAW larvae are recorded under a single heading: infested whorls (%IW).

**Figure 7.** Egg hatch results in a cluster of small larvae. Photo credit: Anani Bruce (CIMMYT).

**Figure 8.** Feeding by small larvae results in clusters of small round windowpanes that are about 1.0 mm in diameter. Photo credit: Dan McGrath.

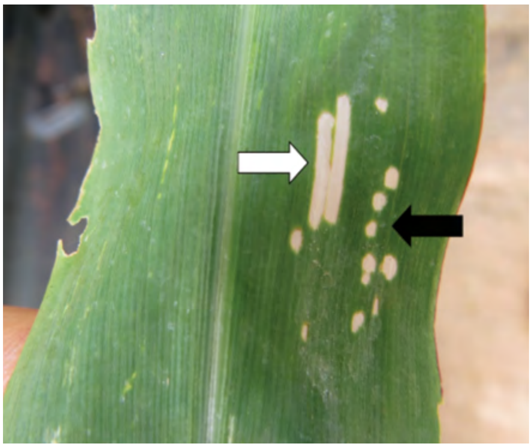


**Figure 9**. As the leaves mature and become more fibrous, the small windowpanes become more elongated (white arrow), about 1.0 mm in width. Black arrow shows round windowpanes made earlier on leaf. Photo credit: Dan McGrath.

By the time FAW larvae are three centimeters (3 cm) in length (Figure 10), they will complete their life cycle soon. These larvae will leave the maize plants and form their pupae in the soil. When they emerge from the pupae (referred to as eclosion), the moths fly up into the air and are scattered across the landscape by the wind. Controlling 6$^{th}$-instar larvae, therefore, may be a waste of time and resources. Try to time pest management actions so that treatments are applied when the larvae are small (during instars 1-3 of larval development).

**Figure 10.** The most useful field mark for large larval identification is the "four dots in a square" pattern on the eighth (8$^{th}$) abdominal segment (arrow). However, by the time FAW larvae are large enough to identify without a hand lens, they are difficult to control. Photo credit: Anani Bruce (CIMMYT).


**Figure 11.** Feeding by large larvae produces a sign called scraping (left). Feeding by small larvae produces clusters of small, round windowpanes (right). Photo credit: Dan McGrath.

**Figure 12.** Cutting, tearing, and fresh fecal pellets (frass) indicate the presence of large FAW larvae. Photo credit: Dan McGrath.

**Figure 13.** Damaged leaves expanding out of the whorl produce a series of holes across a "pinch" in the leaf. This is called the whorl-feeding sign. Photo credit: Dan McGrath.

**Figure 14.** The whorl-feeding sign (arrow) indicates the presence of large FAW larvae. Photo credit: Anani Bruce (CIMMYT).

## 4.4. Where and What to Look for During the Reproductive Stages

When the tassel first becomes visible (Figure 15), the search arena (where to look) and the search target (what to look for) both change. Examine the base of the developing ears and the leaf axils above and below the ears. Look for larvae, regardless of size, and any signs of fresh feeding. In other words, during the reproductive stages (after tassel/ear emergence), scout to determine the percentage of FAW-infested plants (%IP). Base the %IP on the discovery of any larvae regardless of size and any sign of fresh feeding.

**Note:** The reason to use this more conservative measure (%IP) is that if FAW attacks the ears, the risk of crop loss is significantly higher.

When the tassel emerges, it pushes the FAW larva(e) out of the whorl. The larvae then migrate to the base of the developing ears and the leaf axils above and below the ears (Figure 16). Eggs that hatch during tassel formation produce large larvae in about two weeks, right about the same time that the ears are filling.

There is a brief period after tassel emergence and during early ear development, *i.e.*, before the FAW larvae penetrate the husks, when application of an effective, low-toxicity insecticide can significantly reduce yield loss. At this plant growth stage, use of a low-toxicity insecticide is particularly important because of the risk to the applicator and the length of time to harvest; see **Chapter 3**. The frequency of ear damage depends on weather conditions and egg-laying pressure. If egg-laying pressure is high at first tassel emergence and the weather conditions are favorable for FAW (warm and dry), the risk of ear damage is high (see Section 7, Decision Support Tools).

FAW larvae sometimes enter the developing ears from the tip. Most of the time, however, FAW larvae either damage the base of the ear or bore through the husk and eat the developing kernels (Figure 17).

**Figure 15.** When the tassel emerges, it pushes the FAW larvae out of the whorl. The larvae then migrate to the base of the ears and the leaf axils above and below the ear. Photo credit: Anani Bruce (CIMMYT).

**Figure 16.** When scouting after tassel emergence, gently pull the developing ear away from the stem. Look for larvae at the base of the ears and in the leaf axils above and below the ears. Photo credit: Syed Nural Alam (Bangladesh).

**Figure 17.** After tassel emergence, the FAW larvae attack the developing ears by boring through the husk. Photo credit: Dan McGrath.

### Key points

- ✓ **Scout the maize crop carefully before first tassel emergence and again between the first tassel (VT) and R2 stages.**
- ✓ **Control the FAW larvae <u>before</u> they penetrate the husk and enter the developing ear.**

# 5. Action Thresholds

There are several types of pest management thresholds including Detection, Economic, and Action Thresholds. All three are useful depending on the goals of the farmer. These concepts are described in detail in **Chapter 1** and are briefly summarized here.

If the mere presence of FAW in a maize field triggers pest control actions, we refer to this as a *Detection Threshold.* In general, use of Detection Thresholds is not advised because they will tend to overestimate the risk to the crop. An *Economic Threshold* is a formal, research-based tool that is used to evaluate the risk of economically significant crop loss, taking into account the pest population, the cost of the control measures, and the value of the crop. While a formal Economic Threshold for FAW may not be available, crop advisors have a good working knowledge of the factors typically used in calculating Economic Thresholds and can use that information to help farmers make management decisions.

An *Action Threshold* is an estimate of the Economic Threshold. It is based on impartial information but informed by practical experience and expert opinion. The Action Thresholds discussed below are based on consensus among most pest management specialists familiar with grain yield and infestation data for FAW in maize in the Americas, Africa, and Asia. For example, recent research at the International Maize and Wheat Improvement Center (CIMMYT) in Eastern Africa shows that under natural, low to moderate FAW damage levels, the yield loss of open-pollinated varieties (OPVs), FAW-tolerant hybrid maize, and FAW-susceptible hybrid maize was between 36% and 57% in the absence of chemical control. Use of hybrid maize in the absence of chemical control doubled yields relative to the OPVs (Prasanna 2019). Similarly, Britz (2020), using artificial infestation of maize plots with 3rd-instar larvae, studied the relationship between FAW infestation level and yield loss and determined that initial infestation levels of 10, 20, 40, and 100% at the V4 stage resulted in yield losses of approximately 16, 34, 49, and 74%, respectively (Britz (2020) and Johnny van den Berg, personal communication).

**Table 1.** Relationship between FAW infestation level and maize yield loss (Britz 2020), and potential yield protection by insecticide treatment.

| | | 1 ton/ha scenario | | | 3 ton/ha scenario | | |
|---|---|---|---|---|---|---|---|
| Initial Infestation level (%) | Yield loss (%) | Loss from 1 t/ha field (kg) | Protected yield in kg (assuming 90% efficacy) | Value of protected yield (@US$0.21/kg) | Loss from 3 t/ha field (kg) | Protected yield in kg (assuming 90% efficacy) | Value of protected yield (@US$0.21/kg) |
| 10 | 16 | 160 | 144 | $30.24 | 480 | 432 | $90.72 |
| 20 | 34 | 340 | 306 | $64.26 | 1020 | 918 | $192.78 |
| 40 | 49 | 490 | 441 | $92.61 | 1470 | 1323 | $277.83 |
| 100 | 74 | 740 | 666 | $139.86 | 2220 | 1998 | $419.58 |

Yield loss data from Britz (2020) and Johnnie van den Berg (personal communication)
Cost of maize = 15 Rupees per kilogram ($0.21 USD/kg)
One rupee = 0.014 USD (Feb 16, 2021)

An herbicide-tolerant maize hybrid, DKC78-35R, was used in this trial (Johnnie van den Berg, personal communication). Plants of this hybrid take between 68 and 78 days to 50% tassel and have relative maturity of 120 to 148 days. The inherent level of lepidopteran resistance in this hybrid is unknown (https://www.cropscience.bayer.africa/za/en-za/products/seeds/product-detail-template.html/dkc78-35r-east_west.html).

In Table 1, the data from Britz (2020) are used to illustrate calculation of an Economic Threshold for a particular variety and commercial value of maize, and how it can be used to support an Action Threshold. By estimating the potential loss of yield from a field at a particular level of infestation, one can calculate the cost of that damage. In turn, one can determine whether that loss is more than the cost of a pesticide treatment being considered (the Economic Injury Level; see **Chapter 1**). These calculations also show that for a higher-yielding field, the benefit of a pesticide treatment becomes evident even at relatively small infestation levels. The data are consistent with the Action Thresholds provided below in Table 2. Additional calculations that include costs of actual pesticide treatments are provided in **Chapter 3**, Section 7.1.5. A method for estimating yield by sampling within small plots (crop cutting) is available from the One Acre Fund (https://oneacrefund.org/documents/291/Maize_Yield_Measurement_2018_One_Acre_Fund.pdf).

The FAW Action Thresholds serve two purposes: (1) deciding when to act to prevent unacceptable crop loss, and, equally important, (2) deciding when *not* to act—when one can skip an insecticide application without putting the crop at risk.

Depending on the value of the maize crop, partial FAW control may be sufficient because some crop loss may be economically acceptable.

✓ **The presence of FAW in a crop does not necessarily mean that spraying of a pesticide is economically justified.**

Table 2 describes our recommended plant-age-based Action Thresholds, which are described in more detail in the following sections. During the vegetative stages, Action Thresholds are based on percentages of plants with specific FAW damage/injury signs associated with small (%SFW) versus large (%IW) larvae. During the reproductive stages, thresholds are based on %IP.

Ideally, Action Thresholds would be calculated for each maize variety and possibly confirmed in different world areas. In the absence of a formally calculated economic injury level, the Action Thresholds in Table 2 provide guidance for grower decisions. Section 5.3 describes several factors that can be used to adjust

Action Thresholds for a particular situation. In **Chapter 3,** Section 7.1.5 illustrates cost-benefit calculations for two different yield scenarios and provides instructions for performing these calculations given the expected efficacy of a particular treatment.

**Table 2.** Action Thresholds based on maize growth stage, FAW feeding signs, and larval size.

| Maize growth stage and feeding sign | Growth stage | Plant-age-based Action Thresholds based on larval size | | Action |
|---|---|---|---|---|
| Seedling (early whorl) based on percentage of plants with SFW or IW | V1-V6 | 20% (10-30%) with SFW or IW<br><br>SFW indicate small larvae (1st & 2nd instars); IW indicate large larvae (4th, 5th, & 6th instars) | | If 20% or more of the plants have SFW or IW, consider treating (see recommendations below for different larval sizes) |
| Late-whorl-stage plant based on percentage of plants with SFW or IW | V7-V12 | 50% (40-60%) with SFW or IW<br><br>SFW indicate small larvae (1st & 2nd instars); IW indicate large larvae (4th, 5th, & 6th instars) | | If 50% or more of the plants have SFW or IW, consider treating (see recommendations below for different larval sizes) |
| Tassel and early ear development based on %IP | VT-R2 | IF SPRAYING AT THIS STAGE, USE PRODUCTS WITH LOW HUMAN TOXICITY AND ONLY IF THE RECOMMENDED PPE IS AVAILABLE.* | 20% (10-30%)<br><br>Percent infested plants | If %IP is 20% or more, and appropriate pesticides and PPE are available, consider treating (see recommendations below) |

SFW, small, fresh windowpanes; IW, infested whorl; %IP, percent infested plants; PPE, personal protective equipment
* Particular caution must be taken during late sprays owing to the height of the plants and the risk of applicator exposure.

## 5.1. Action Thresholds for the Vegetative Stages (Before Tassel Emergence)

During the vegetative stages, use the scouting procedure (as in Section 9.1) to estimate the percentage of plants infested by FAW and the predominant size of the larvae. Before making a spray decision, consider the environmental conditions. A heavy rainstorm, for example, will kill most of the small larvae. If a heavy rainstorm is expected, delay the spray decision until after the rainstorm. Scout again after the rainstorm.

Seedling (early whorl stage = VE-V6):

20% (range 10-30%) of plants have SFW (small, fresh windowpanes) and/or IW (infested whorls)

- If the field exceeds the Action Threshold and most larvae are small (detected as SFW), apply a recommended foliar broadcast spray (see **Chapter 3**).
- If the field exceeds the Action Threshold and most larvae are large (detected as IW), apply a selective spray directed into the whorl of the infested plants.
- If the field exceeds the Action Threshold and both small and large larvae are detected, there are multiple overlapping generations of larvae. It may be necessary to apply a recommended broadcast spray to control the small larvae, re-scout the field, and follow up with a selective spray directed into the whorl to re-treat the large larvae that survived the first insecticide application (see Section 8, FAW Management Scenarios). NOTE: Do not re-enter the field sooner than the re-entry interval listed on the label.

  Note: This approach "resets the larval developmental clock" by killing both older and younger larvae. Thus, the next spray decision can be made based on the density of small larvae. This is the ideal situation because small larvae are easier to control.

Late-whorl-stage plants (V7-V12) are more resilient and better able to compensate for FAW leaf damage. Therefore, the plant-age-based Action Threshold is higher (less conservative) during the late-whorl plant stage than during earlier stages. It should be noted that FAW feeding on tassels and pollen can cause significant damage to maize kernel set in the developing ears.

Late-whorl-stage plant (V7-V12):

50% (range 40-60%) for SFW (indicating small larvae) and/or IW (indicating large larvae)

As the late-whorl plant stage comes to an end, scout carefully. Check the regional moths counts, if available. Check the weather forecast, if available. Watch out for the combination of high moth counts (high egg-laying pressure) and warm, dry weather. If necessary, apply an insecticide to reduce the number of larvae infesting the whorls as the maize plants begin to tassel at the end of the late-whorl plant stage.

## 5.2. Action Threshold for the Reproductive Stage (After Tassel Emergence)

After tassel emergence, the situation and the scouting protocol change (see Section 9.2). The plant-age-based Action Threshold is set lower (more conservative) during the reproductive stage because if FAW larvae are present during early ear development, the risk of crop loss is high.

The decision to apply a pesticide spray on developing ears is based on the %IP. In other words, if there are larvae at the base of the developing ears (regardless of size) or any signs of fresh feeding, the risk of crop loss is high.

Tassel and early ear development to brown silk stage (VT-R2):

20% (range 10-30%) based on %IP

A well-timed rainstorm can kill most of the FAW larvae (if small), significantly reducing the risk of ear damage. Moth counts and the weather forecast are particularly useful when making an ear-spray decision (see Section 7, Decision Support Tools).

- ✓ **If the weather is warm and dry and moth counts are high at tassel formation, check carefully for FAW at the base of the developing ears and the leaf axils above and below the ears.**

## 5.3. Factors Affecting Action Thresholds

As noted in the introduction to this section, the Action Thresholds presented here are based on worldwide experience, including from Asia, and provide a starting point for the decisions farmers in Asia need to make now. For crop advisors and others wanting to provide more tailored advice to farmers, the following factors can influence Action Thresholds and should be considered:

- A key variable is the maize variety's performance under insect pressure. Typically, that information is available from the seed dealer. For example, farmers planting maize varieties that do not carry resistance to FAW would generally use the lower value in the action threshold range while farmers planting maize varieties known to be tolerant to FAW would use the higher end of the range. See **Chapter 4** for more information on host plant resistance.
- Moth counts may give an indication as to the overall FAW pressure in the area (see Section 6).
- Heavy rainfalls can reduce the incidence of FAW (see Section 5.3.1).

### 5.3.1. Action Thresholds and the Weather

Risk of crop loss due to FAW depends on pest pressure, the maize plant growth stage, and the weather. It is widely known that FAW is sensitive to low temperatures. In addition, small FAW larvae immediately after egg hatch are highly sensitive to rainstorms that dislodge and destroy them (Varella *et al.* 2015).

Scouting and an action threshold may indicate high pest pressure, but a spray decision should also take into consideration the weather patterns and the probability of a rainstorm. If egg-laying pressure is high during the seedling stage, for example, one might decide to apply a control measure on the basis of %SFW. However, a well-timed rainstorm can kill most of the FAW larvae (if small), significantly reducing the risk of crop loss regardless of egg laying pressure. The same is true of ear damage. Heavy rainstorms during tassel and early cob formation can significantly reduce the risk of ear damage. This is particularly true in tropical (equatorial) climates where rainstorms can occur on a regular basis throughout the maize growing season. Ear damage is less common in tropical climates. Ear damage is more common in temperate climates and highly variable in subtropical climates.

- ✓ **Consider the probability of a rainstorm before making a spray decision. If infestation is close to the lower end of the Action Threshold range and rain is imminent, the farmer might choose to delay spraying and re-scout the field a few days after the rain event.**

# 6. Monitoring and Pest Population Dynamics

## 6.1. Introduction

Monitoring provides a higher-level view of pest populations in a geographic region and can be organized at various scales. FAW monitoring systems vary a great deal from country to country. The approach used depends, in part, on where the country stands in terms of FAW colonization (Section 6.2). Some countries in Asia are in the early stages of colonization while Africa has been dealing with the FAW since 2016 or earlier. In the Americas, FAW is an endemic pest of maize.

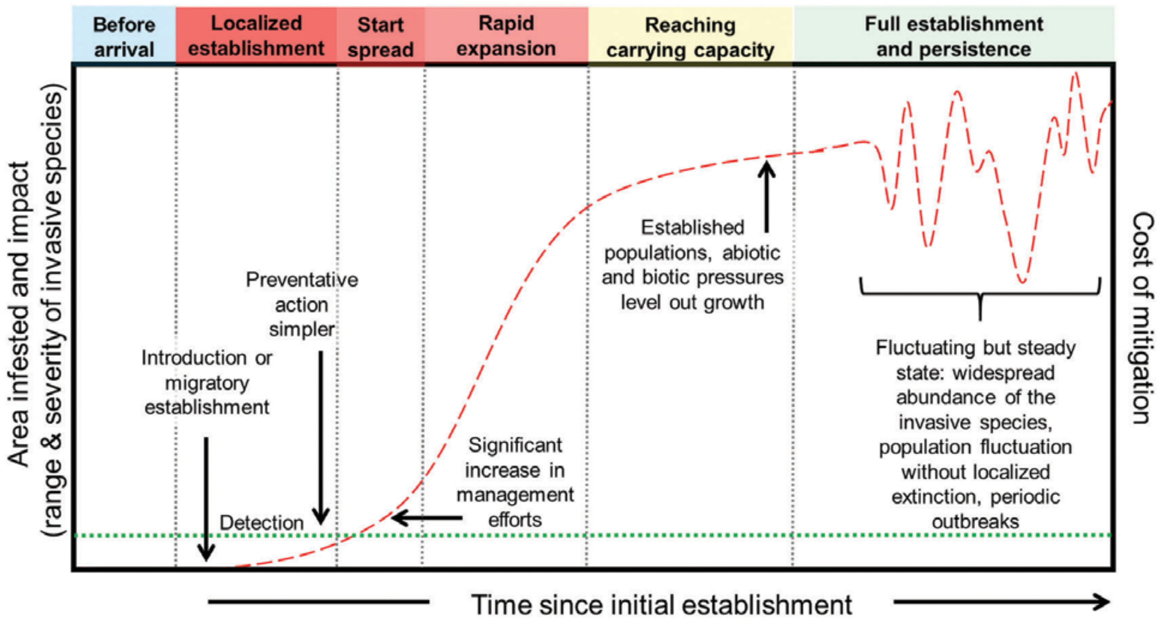
There are two styles of pheromone-based FAW monitoring systems. The most common system, the High-Density Trapping System (HDTS), uses a high density of traps, perhaps thousands, across a country. The HDTS is primarily used to detect the arrival and spread of FAW, often with the hope that new infestations can be discovered early and eradicated to prevent establishment of the new pest. An HDTS may also be used as an educational platform, alerting farmers that FAW has arrived and engaging the farming community in learning about the new pest. On the downside, HDTSs are expensive to establish and maintain; for example, lures must be regularly replaced (see trap descriptions in Section 10). In addition, the traps often capture species other than FAW. It should be noted that the skill level needed to accurately identify a FAW moth in the traps and to recognize contaminating moth species is considerable.

The other system, the Low-Density Trapping System (LDTS), uses a lower density of traps, often on the order of one or a few per thousands of square kilometers. In the USA, LDTSs are used to detect changes in the level of FAW egg-laying pressure from year to year and within a growing season, although moth counts are not always indicative of the number of larvae in the field. The LDTS is used to provide pest management decision support for farmers and their advisors and to detect populations as they migrate into new areas each season (see Section 7: Decision Support Tools). LDTSs are much less expensive to establish and maintain than HDTSs. In addition, an LDTS is usually managed by a university or other institution, where there are likely to be experts and equipment (*e.g.*, microscopes) to facilitate identification of FAW and other pests found in the traps.

## 6.2. Stages of Colonization

Following introduction into a new region, FAW populations expand according to a normal population colonization curve (Figure 18). Early during the colonization process, FAW infestations may be small and scattered. The first arrival of FAW often goes unnoticed. Delayed detection is usually due to a lack of systematic and comprehensive sampling to detect invasive species. Failure to listen to surveillance reports from farmers is also a factor. As described elsewhere in this manual, FAW's arrival in Asia was both anticipated and detected relatively early, and India's decision to make detection public allowed many countries to begin monitoring for FAW before its arrival to pre-emptively prepare response plans that could be rapidly implemented.

In the years immediately following introduction or migration of FAW into a given area, its establishment is localized, and the pest is most effectively controllable. Following an initial generation(s) in the localized establishment stage, as the population begins to spread, egg-laying pressure can be quite high. Farming communities suddenly realize the full potential of FAW and put a great deal of pressure on their Ministry of Agriculture to "do something." This is generally when governments establish HDTS networks, though because of the rapid growth of the pest population, this is also when management efforts to mitigate FAW will significantly increase in terms of cost and effort. Such a period of rapid expansion was observable following FAW's arrival in India—within two years, FAW had been detected as far to the east and south as Indonesia (Gustianingtyas *et al.* 2021). Given FAW's high range of dispersal (Day *et al.* 2017), and despite individual countries' efforts to mitigate FAW's impact on a preemptive basis, this rapid spread was not overly surprising.




Stages of invasive species management

| Preven-tion | Early control (if possible) | Containment (if possible) | Reaching carrying capacity | Full establishment and persistence |
|---|---|---|---|---|
| • Pre-emptively raise aware-ness of stake-holders<br>• Moni-toring and surveill-ance | • Implement early and aggressive control measures<br>• Attempt to contain populations before migration (may not be feasible for highly mobile species such as FAW) | • Raise public awareness<br>• Scouting<br>• Work to slow speed of spread<br>• Begin IPM regimes | • Intensify IPM regimes and underscore the importance of conservation biological control<br>• Continued population monitoring | • Ensure IPM approaches are supported and implemented<br>• Continue to underscore the importance of conservation biological control and cultural management<br>• Make use of weather forecasting to aid in IPM and pesticide application decisions |

**Figure 18.** Colonization curve describing the pattern of insect arrival and localized establishment, rapid expansion (exponential growth), and full establishment (at carrying capacity) common to FAW and many other invasive species. Prevention and containment may not be possible for highly migratory pests such as FAW. Source: Timothy Krupnik (CIMMYT).

After several years, abiotic (climate, weather, wind patterns) and biotic factors (availability and concentration of preferred host plants, host plant resistance, density-dependent insect diseases, and natural enemies) begin to regulate and shape the dynamics of the FAW population. The ecosystem approaches the carrying capacity for the species and the population begins to stabilize, though periodic or localized outbreaks are still possible (Koffi *et al.* 2020). The eventual steady-state population level for FAW across Asia is unknown at this time, but in the tropical and subtropical areas of the Americas the FAW is a persistent yearly pest requiring annual control. Regardless of the specific phase of the pest in a given region, the aim of a FAW invasive species management program is to move as quickly as possible to integrate the pest into an IPM framework for maize.

Despite the importance of monitoring, especially in the early stages of a pest invasion, enthusiasm for maintaining HDTS networks often falters after a few years. Many farmers (and system actors as a whole) experience “pest alert fatigue.” International development groups eventually withdraw their support for pheromone traps because supplies and the personnel to maintain them are exceedingly expensive. At this point, governments either abandon monitoring altogether or shift to a more cost-effective LDTS (see Sections 6.3-6.6). Emphasis shifts from monitoring of an invasive pest to decision support for management of an established endemic seasonal pest.

## 6.3. Low-Trap-Density Monitoring of FAW in North America

Experience in the Americas and Africa has shown that LDTS networks can accurately detect regional moth count trends that are useful to pest management decision makers. Once established in a region, FAW egg-laying pressure varies from year to year. The University of Kentucky, USA, provides an LDTS example that demonstrates typical FAW population dynamics in a temperate maize-production area. The example is based on a single pheromone trap, continuously maintained by the University of Kentucky Entomology Department for 14 years (Figure 19). For reference, Kentucky has a land area of approximately 104,658 km$^2$ (about 2/3 the size of the country of Bangladesh, which has a land area of 148,470 km$^2$).

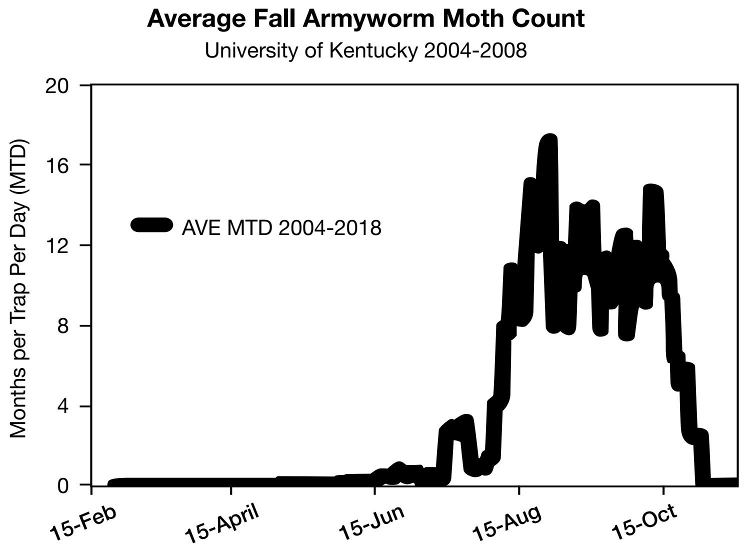



**Figure 19.** Average number of moths per day, Kentucky USA. The average moth count on a given calendar date was based on data collected from 2004 to 2018. Graph produced by Dan McGrath using data obtained from https://ipm.ca.uky.edu/faw (University of Kentucky College of Agriculture, Food and Environment 2020).

In Kentucky, migratory FAW moths begin to arrive each year in mid-July. The moths are carried north by the wind from endemic populations further south in states of Florida and Texas. Moth counts peak in Kentucky in September and October, late in the North American maize-growing season. This is why *Spodoptera frugiperda* is called the “fall” armyworm: in North America, where it was first observed, FAW arrives in the Fall season. As the weather turns cold in November, the population dies out.

The total number of FAW moths captured each year in Kentucky varies (Figure 20). In years with very low insect pressure, fewer than 100 moths were captured over an eight-month period (approximately 230 days), which is less than 0.44 moths per trap per day (MTD; Figure 21). In high-pressure years, close to 2,000 moths or even more were caught over an eight-month period, which is about 8.7 MTD or more (Figure 22).

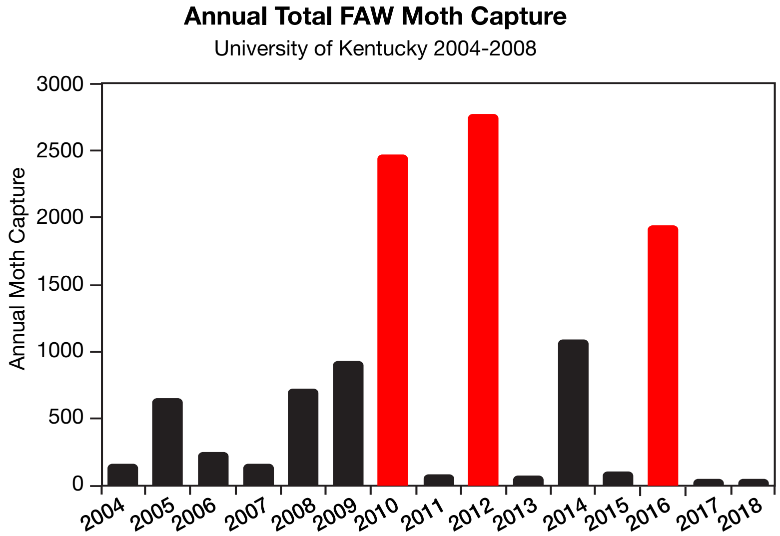



**Figure 20.** Total FAW moths captured in each year from 2004 to 2018, Kentucky, USA. Red indicates high FAW pressure.

Graph produced by Dan McGrath using data obtained from https://ipm.ca.uky.edu/faw (University of Kentucky College of Agriculture, Food and Environment 2020).

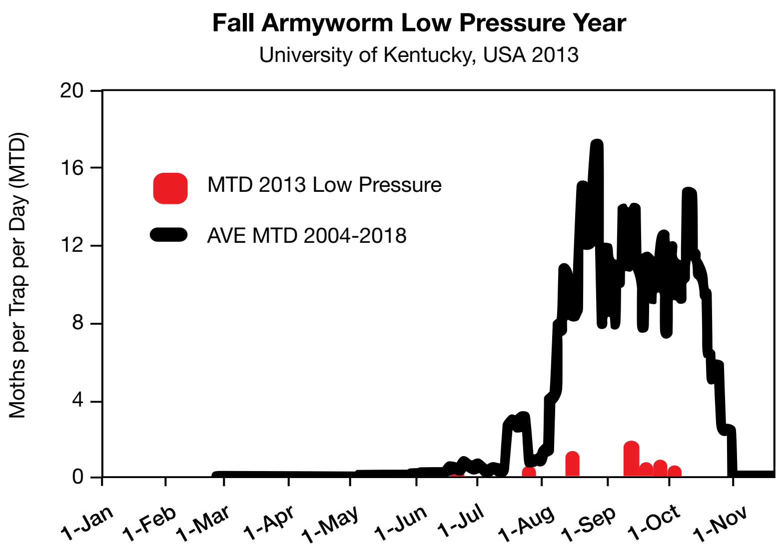



**Figure 21.** FAW moth counts during 2013 (red columns), a low-pressure year, University of Kentucky, USA. Graph produced by Dan McGrath using data obtained from https://ipm.ca.uky.edu/faw (University of Kentucky College of Agriculture, Food and Environment 2020).

Regional monitoring systems using LDTS networks are used throughout North America to report fluctuations in FAW populations from year to year (http://www.pestwatch.psu.edu). Using these decision support tools provides opportunities to significantly reduce insecticide use in low-pressure years.

## 6.4. Low-Trap-Density FAW Monitoring in Ghana and Moths Per Trap Per Day (MTD)

Regional FAW LDTSs were pilot tested in four maize production areas of central and northern Ghana during 2017. The Brong Ahafo region covers 39,557 km$^2$ (15,273 mi$^2$) and has a subtropical climate. At the beginning of the 2017 growing season, 10 extension officers in the Brong Ahafo region each chose one maize field in their area, set up a *Heliothis*-style pheromone trap (see Section 10), began

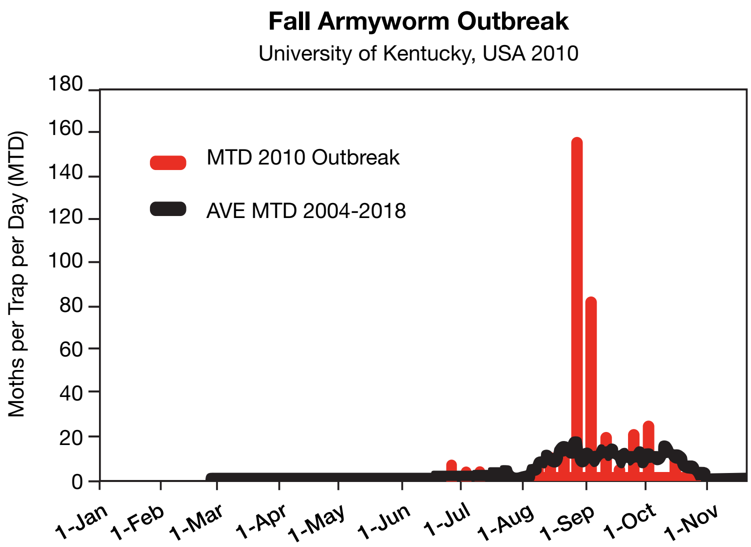



**Figure 22**. FAW moth counts during 2010 (red columns), a high-pressure year, University of Kentucky, USA. Graph produced by Dan McGrath using data obtained from https://ipm.ca.uky.edu/faw (University of Kentucky College of Agriculture, Food and Environment 2020).

scouting the field about once per week, and reported the data to a regional coordinator. The average regional moth count (Figure 23) was based on the 10 sampling sites.

Across the monitoring sites and throughout the maize season, the trap-check interval varied from 6 to 12 days. In order to calculate the regional average daily moth count, the total number of moths in a trap was divided by the days since the trap was last checked and reported as the MTD. (When reported on a regional basis, the MTD is also called the regional moth count.) As in North America, current experience suggests that MTDs in the range of 0.1-0.2 are low pressure while MTDs of 1.0 and above are high pressure. Further research is needed to establish nuances within these ranges, but this rough guideline should aid practitioners in their spray/no-spray decision-making process.

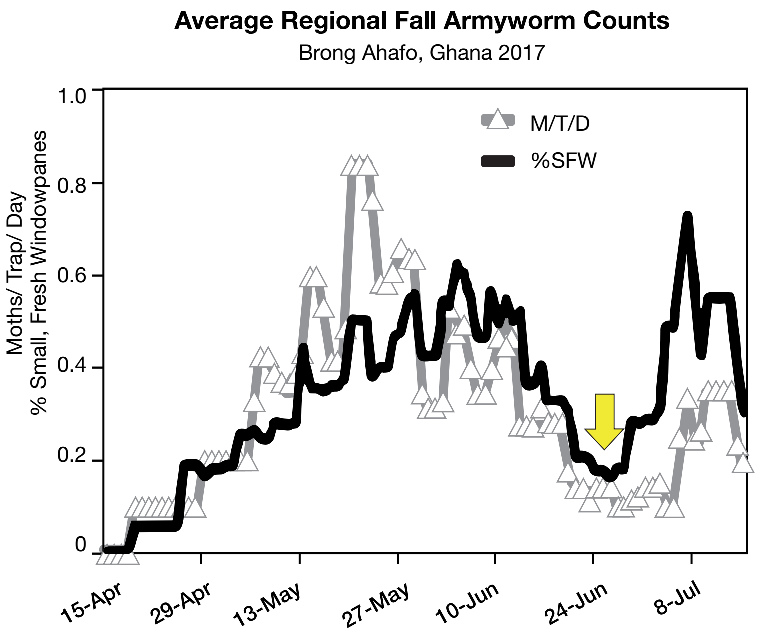



**Figure 23.** Average numbers of moths per trap per day (MTD) and frequencies of small, fresh windowpanes (SFW) collected from 10 monitoring sites in the Brong Ahafo Region of Ghana, 2017. For SFW, values indicate the proportion of plants with SFW (*e.g.*, 0.4 = 40% of plants had SFW). Adapted from McGrath and Ahlidza (2018).

In Brong Ahafo, the moth count rose steadily at the beginning of the rainy season as maize fields were planted. In late June, there were heavy rainstorms and moth counts declined (yellow arrow in Figure 23). The moth count tapered off as the rainy season came to an end and the maize was harvested.

As shown in Figure 23, average regional MTD counts, which indicate egg-laying pressure, were correlated with SFW percentages, which indicate egg hatch. Thus, the field scouting data appeared to validate the MTD data.

The average regional moth counts in the Brong Ahafo approached 1.0 MTD in late May. Maize fields that were planted in early to mid-April had 70% cob damage at harvest (McGrath and Ahlidza 2018). Maize that was planted in May and tasseled in June had very little cob damage. The LDTS network (one trap per 3,995 km$^2$) was sufficient to detect regional FAW moth count trends.

## 6.5. Low-Trap-Density Monitoring in Ethiopia

Low-density monitoring systems were also pilot tested in Ethiopia in four maize-producing regions during 2018 and 2019. Results below are from the Amhara Region, a subtropical maize-production area that covers 154,709 km$^2$ (59,734 mi$^2$). Sixteen Ethiopian extension officers established and maintained universal bucket-style pheromone traps (see Section 10) and reported moth counts on a weekly basis to a regional coordinator.

FAW moth counts in the Amhara rose slowly at the beginning of the rainy season as farmers began to plant maize (Figure 24). Moth counts peaked in mid-November and began to taper off as the maize was harvested and the rainy season came to an end.

In early January of 2019, the average regional moth count (yellow arrow in Figure 24) fell below 0.3 MTD. Field scouting confirmed that egg-laying pressure was low (McGrath and Chali 2019). Large (6$^{th}$ instar) FAW larvae from an earlier egg-laying period infested about 5% of the maize plants, which were in the V8 stage (late-whorl stage). This was consistent across several fields in the area.

Based on field scouting data and an Action Threshold and supported by the average regional moth count, farmers were advised to (1) scout their fields to confirm the low level of infestation and (2) look for opportunities to reduce insecticide use. We pointed out that only 5% of the plants were infested with 6$^{th}$-instar larvae, and that the large larvae were within hours of pupation. Most of the farmers decided to spray anyway, but they only treated the infested plants using a selective spray, directing the spray nozzle into the whorl of the infested plants. This may have reduced the volume of insecticide applied.

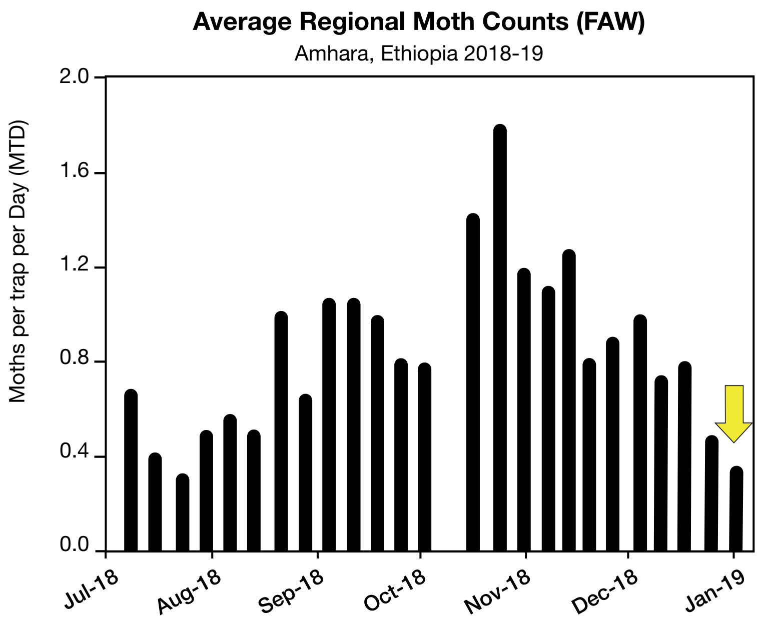



**Figure 24**. Average FAW moths per trap per day (MTD) in the Amhara Region of Ethiopia during 2018-19. Adapted from McGrath and Chali (2019).

The LDTS network in Ethiopia (one trap per 7,700 km$^2$) was sufficient to detect FAW moth count trends on a regional scale. Low egg-laying pressure was confirmed by field scouting. The combination of scouting data and moth count data was useful to the farmers, because they were considering a no-spray decision (see Section 8.3).

## 6.6. Low-Trap-Density Monitoring in Asia

Governments across Asia now recognize the widespread presence of FAW, and many have established pheromone trap networks to track the arrival and spread of FAW in their countries. Hundreds of farmers and extension officers are engaged in these projects.

Figure 25 shows the rise and fall of moth counts (based on pheromone trap captures) and the rise and fall of plants with clusters of SFW (based on field scouting) across Bangladesh during the Rabi (winter) maize-growing season of 2019-2020 (that particular Rabi season was unusually cold for Bangladesh). The average moth and windowpane counts were based on observations of more than 750 fields maintained by the Department of Agricultural Extension in the primary maize growing areas of the country. Averages from three traps per monitoring site were used to calculate a mean per site. Trap density was therefore three per monitoring site over an area of approximately 1,564 km$^2$ (293 mi$^2$). All data are available and open-source at the website: https://faw-monitor.firebaseapp.com/.

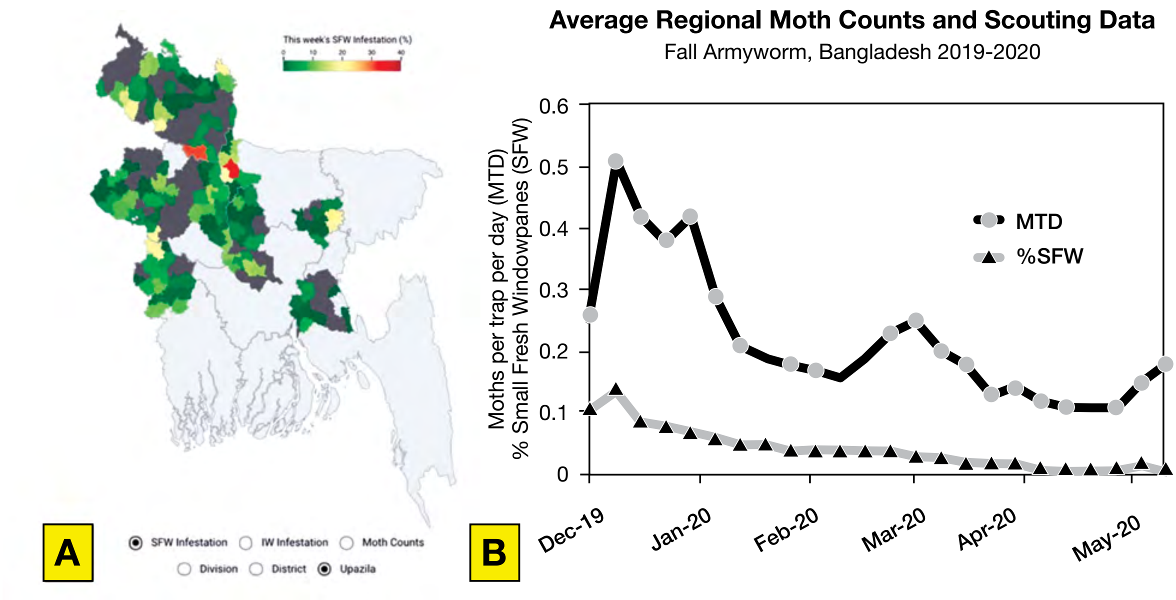



**Figure 25.** (A) Areas monitored for FAW in Bangladesh. (B) Average moth counts and frequencies of plants with small, fresh windowpanes during the 2019-2020 Rabi Season in Bangladesh. MTD, moths per trap per day; %SFW, percentage of small, fresh windowpanes. Source: Department of Agricultural Extension and CIMMYT, Bangladesh, available at: https://faw-monitor.firebaseapp.com/

The average MTD and the average %SFW told the same story. At the beginning of the Rabi planting season of maize (late November), egg-laying pressure was moderate. Moth counts peaked in December at about 0.5 MTD (3-4 moths per week). The percentage of plants with small larvae (based on SFW) approached the Action Threshold for seedling maize, but both moth and windowpane counts tapered off as the season progressed. By the time the maize plants began to tassel (mid-January), moth counts were low, at or below 0.2 MTD (less than one moth per day). At harvest, which begins in late March, there was essentially no cob damage. This is good news, as it indicates that sometimes insect pressure is low enough not to require aggressive treatment.

The trapping effort by the Bangladesh Extension officers indicates that there may be times in the future when FAW egg-laying pressure is low and farmers should consider reduced insecticide use. There may be times when more environmentally friendly, moderately effective materials and methods would be an appropriate and safe choice including microbials (*e.g.*, *Bacillus thuringiensis* serovar *kurstaki*), botanicals (*e.g.*, Neem oil), and biological control agents (*e.g.*, *Spodoptera frugiperda* nucleopolyhedrovirus). However, the maize crop must be checked carefully at first tassel emergence. If egg-laying pressure is high and the weather is warm and dry at that stage, switch to a highly effective, fast acting, low-toxicity insecticide.

Once FAW has become established, Asian countries may consider restructuring their monitoring systems to use a less expensive LDTS strategy. Average regional moth counts could serve as an important decision support, especially for farmers who are looking for opportunities to reduce pesticide use and control the cost of FAW management.

## 6.7. Monitoring for Changes in Resistance or Host Range

As detailed in **Chapter 1**, FAW exists as two strains, Corn/Maize-strain (C-strain) and Rice-strain (R-strain), which have identical morphology but differ in genetic characteristics and host preferences. Current evidence indicates that FAW in Asia is behaving as a C-strain with respect to host preference, and that the R-strain found in America may not have invaded Africa or Asia. Nevertheless, it will be important to investigate any instances of FAW feeding on millet, rice, or other crops preferred by R-strains.

Evidence from several studies (see **Chapter 1**) indicates that FAW in Africa and Asia carry alleles for resistance to synthetic pesticides. There is currently little evidence for the presence of resistance to *Bt* proteins in FAW from Africa or Asia, but this too requires continued monitoring.

# 7. Decision Support Tools

With training and experience, farmers or their advisors can scout a planting of maize, apply an Action Threshold, and make an informed pest management decision without moth counts or a weather forecast. Moth counts (see Section 7.1) and weather forecasts (Section7.2) should, therefore, be considered supplemental "decision support tools". The following sections explain how these decision support tools can be used in conjunction with field scouting data.

## 7.1. Moth Counts

Moth captures (in pheromone traps) indicate egg laying and may be the first indication that FAW is present. The presence of high moth counts should certainly prompt careful field scouting if it is not already being done on a regular basis. Moth counts (egg laying) and clusters of SFW (egg hatch) are highly correlated (see Section 6, Monitoring).

There is a narrow window of opportunity (a few days) to effectively control FAW damage after egg hatch and before the larvae move into the whorl. Once FAW larvae mature and move into the whorl, control options are limited. Moth counts can prompt timely field scouting and timely intervention, *i.e.*, when the larvae are small (1$^{st}$ and 2$^{nd}$ instar).

There are several potential sources of moth count data including local (field-side), area-wide (village or neighborhood), regional, and even national sources. Local or field-side trap counts are useful, but it may not be economically feasible for every farm, much less every planting, to have its own pheromone trap. Average regional moth counts, where they are available, can provide an accurate assessment of FAW egg-laying pressure.

It takes a few years before one can be confident in interpreting the moth counts for a given area. Keep historical moth count records and review this information at the end of each maize-growing season. Farmers and advisors who do this will grow more confident in the ability to discern whether moth counts are above or below average.

Based on experience so far with FAW in Africa, Asia, and the Americas, we can offer the following estimates as a starting point for interpreting average regional moth counts.

- ✓ **If the average regional moth count is 1.0 MTD or higher (seven moths per week or higher), the FAW egg-laying pressure is relatively high. Confirm this with field scouting.**
- ✓ **If the average regional moth count is 0.2 MTD or lower (approximately one moth per week), FAW egg-laying pressure is relatively low. Confirm this with field scouting.**

The high moth count guidance may seem low (1.0 MTD). Unlike many other lepidopteran insects, FAW moths rarely show up in pheromone traps in large numbers. One moth per day or seven moths per week is a significant number of FAW moth captures.

In addition, keep in mind that this advice is based on average regional moth counts. FAW moth density is usually patchy (uneven) across the landscape. The regional average integrates across high, medium, and low moth count patches. When the average moth count in a region rises above 1 MTD, regular scouting is necessary because a FAW outbreak is likely.

- ✓ **Average regional FAW moth counts will remain relatively low, even during an outbreak. One or more moths per day is significant.**
- ✓ **If both moth counts (MTD) and scouting data (%SFW) are low, look for opportunities to avoid or minimize insecticide use.**
- ✓ **If traps are improperly placed, such as being covered in tall maize, there may be no moths in the field trap even though a significant percentage of plants are infested with FAW. A poorly maintained or poorly placed trap produces misleading results. Under these conditions, field-level trap counts may be poorly correlated with field damage.**

Moth counts support no-spray decisions by increasing the confidence of farmers (or their advisors) in their scouting data. If the percentage of maize seedlings with %SFW is low and moth counts are low, a farmer may be more comfortable making a no-spray decision.

Average regional moth count trends prior to and during the growing season, if they are available, support community-based FAW management decisions.

- ✓ **High moth counts should prompt preparation for FAW control including, if time permits, the procurement of insecticide-treated seed.**
- ✓ **If one is using a short-residual botanical insecticide (*e.g.*, neem), high moth counts should prompt preparation of spray solution.**
- ✓ **If the farming community is practicing area-wide mating disruption, high moth counts should prompt area-wide deployment of FAW pheromone dispensers.**

## 7.2. Weather Forecasts

A heavy (and well-timed) rainstorm will kill most of the small 1st- and 2nd-instar FAW larvae feeding on the leaves. Rainstorms, however, do not control large FAW larvae established in the whorls.

In rainfed (non-irrigated) maize culture, FAW damage depends on the sequence of planting and rainfall. When rain moistens the soil at the beginning of the season, farmers often plant maize. What happens next is critical. In tropical areas where there are regular heavy rainstorms throughout the maize-growing season, FAW damage may be insignificant. FAW damage is sometimes heavier in subtropical maize-producing areas when the weather is dry and warm as the maize begins to tassel. If the weather is dry during the late vegetative stage, the risk of ear damage is higher.

The weather forecast, if available, should be considered when assessing risk of crop damage in a FAW-infested field. If rain is forecast or storm clouds are gathering on the horizon, consider delaying an insecticide application decision. Scout the field again following a rainstorm. The field may require only a selective spray (directed at the whorl) to control larvae that survived the rain, or may not need a spray at all.

## 7.3. Four-Step Risk Assessment with Decision Support

If moth counts and a weather forecast are available, use them. This is especially important when trying to reduce insecticide use.

An experienced individual should be able to scout a field (one hectare, five stops) in about 15 minutes and make a well-informed spray decision. Risk assessment with decision support takes four steps.

Before reaching the field …

1) Check the average regional moth count (if available)
2) Check the weather report (if available)

Upon arriving at the field…

3) Check the pheromone trap (if available)
4) Scout the field (see Section 9) and apply an Action Threshold

- ✓ Following a yes-spray decision, scout again in 7-14 days (after the label re-entry interval).
- ✓ Following a no-spray decision, shorten the scouting interval.

# 8. FAW Management Scenarios

The following scenarios are based on field experience in Africa and Asia. They are not meant to be prescriptive; rather, they are designed to give the practitioner a sense of how to apply field scouting data and decision support in making a pest management decision.

Good agricultural practices (GAP) do make a difference. They produce a more resilient, fast-growing maize crop that can better compensate for foliar feeding. Yield loss associated with foliar feeding by FAW is more prevalent when soil fertility is low (Clavijo 1984). Good soil fertility does not, however, prevent ear damage. Regardless of how well the crop is growing, scout fields carefully after first tassel emergence and during early ear development.

Once a farmer has made the decision to apply an insecticide, the choice of insecticide and the application method are based on the size of the larvae (small vs. large) and the maize growth stage (early vs. late). The following descriptions provide some general guidance. Details on pesticide efficacy and safety are presented in **Chapter 3**.

**Foliar broadcast** sprays are a relatively expensive application method because the active ingredient is applied across the entire field. A broadcast application with an effective insecticide will control small FAW larvae, but is unlikely to control large FAW larvae once they are established in the whorl. The most effective approach for controlling FAW in maize is to control the larvae before they move into the whorl.

If the %SFW is high and the %IW is low, a broadcast application should work.

**Selective** sprays directed at the whorl only treat the visibly infested plants. In some cases, this may reduce the volume of pesticide applied per hectare. Farmers should choose the most effective insecticide(s) they can afford, when they are trying to control large larvae.

**Tassel or ear** sprays are rare and should be based on careful scouting. Tassel and ear sprays may be required less often in tropical locations where heavy rainstorms occur throughout the production season. Risk of ear damage is the highest when the weather is warm and dry (no rain) and the average regional moth count (egg-laying pressure) is high.

If FAW larvae are discovered at the base of the ears, risk of yield loss is high. The risk of applicator exposure, particularly through the skin, is also high because the maize is tall. Choose a low-toxicity insecticide that is highly effective on FAW (*e.g.*, chlorantraniliprole, spinosad, spinetoram, emamectin benzoate). These insecticides are relatively more expensive than older insecticides, but they are a good value when a tassel or ear spray is needed.

The risk of applicator intoxication depends on insecticide choice, the height of the maize plants, use of personal protective equipment (PPE), and applicator practices. If the appropriate level of PPE is not available (see product label and **Chapter 3**), it is recommended to hire a professional spray service provider.

We recognize that FAW moth counts and weather forecasts are not widely available to smallholder farmers. Farmers who do have access to such information should use it, but farmers can successfully control FAW even without those data.

- ✓ In one of the case studies below, moth counts were used as a decision support for a farmer who was considering a no-spray decision.
- ✓ In another case study, rain clouds observed on the horizon were used, in part, to support a delay-spray decision.

## 8.1. Scenario One: High Cash-Value, No Scouting Data

Under most circumstances, calendar-based spray schedules are discouraged, but under exceptional circumstances, they might be considered. For example, under FAW outbreak conditions, a farmer growing a high-value maize crop (such as a seed company growing a hybrid maize seed production field) may be justified in using a calendar-based spray schedule. Plan on applying six insecticide sprays at a 14-day interval starting two weeks after planting and continue until brown silk (R2). Rotate the chemical family based on mode of action [MOA] (see Insecticide Resistance Action Committee [IRAC] recommendations in **Chapter 3**, Pesticides) every two sprays. A six-spray program using a rotation of effective insecticides will control cob damage even during an FAW outbreak (McGrath and Ahlidza 2018).

This is an aggressive and expensive spray program that might be used in a maize seed production field operated by a commercial seed company. It is possible that less than six applications will be needed. Scout the field and use an Action Threshold prior to each application.

- ✓ Timely and sequential application of effective insecticides at a 14-day interval keeps resetting the FAW "developmental clock" and enables treating the FAW population when the larvae are small. The insecticide applications are, therefore, more likely to be effective.
- ✓ As the plants move into the reproductive stage, it is important to reduce the possibility of FAW larvae moving to the base of the developing ears.
- ✓ Rotate the chemical families every 30 days (about every two sprays) to slow down the development of insecticide resistance.

## 8.2. Scenario Two: Moderate Cash-Value, Seedling Stage

**Scouting Data:**

- Maize growth stage: V2
- %SFW: 14%
- %IW: 0%
- Average regional moth count: Not available

**Field Notes:** "good moisture and soil fertility, plants growing well"

In this case, the maize plants were at the seedling stage (VE-V6). Field scouting showed that FAW egg-laying pressure was moderate; 14% of the plants had clusters of SFW. Few, if any, larvae had advanced to the 3rd or 4th instar. None had moved into the whorl.

- ✓ Remember that SFW are indicative of FAW egg hatch and the presence of small larvae.

This maize planting with 14% SFW was not quite at the seedling Action Threshold of 20% (Table 2). However, the Action Threshold is a range from 10% to 30% depending on the risk perception of the farmer or advisor. No moth count data were available, so the farmer did not know if the egg-laying pressure was rising or falling.

A conservative decision would be to apply a recommended foliar insecticide as a broadcast spray to kill the small FAW larvae before they move into the whorls. However, soil fertility was high and the plants were growing well (field notes). A weather forecast was not available, but rain clouds were gathering on the horizon and it looked like a heavy rainstorm was coming. The farmer decided to delay their decision and scout the field again after the rainstorm.

- ✓ Heavy rainstorms may kill most of the small FAW larvae (1st and 2nd instar) feeding on the leaves.
- ✓ Less than total FAW control during the vegetative stages may be acceptable because some crop loss at this plant stage may be economically acceptable.

## 8.3. Scenario Three: Moderate Cash-Value, Late-Whorl Plant Stage

**Scouting and Moth Count Data:**

- Maize growth stage: V9
- %SFW: <1%
- %IW: 21%
- Average regional moth count 0.1 MTD

**Field Notes:** "mostly 6th instar FAW larvae were observed"

In this case, the maize plants were waist-high and in the late-whorl stage (V7-V12). Egg-laying pressure was low based on field scouting (<1% of plants with SFW). The farmer (or their advisor) had access to the regional FAW moth count. The moth count was also low, a second confirmation that egg-laying pressure was low.

Twenty-one percent (21%) of the maize plants had IW. The 6th-instar larvae were from a previous egg-laying period, a residual population (survivors) following an earlier insecticide application.

- ✓ Remember, FAW has six larval instars. The first and second instar larvae feed on the leaves. The 3rd instar moves into the whorl. The fourth, fifth, and sixth instar occupy the whorl and sometimes come out to feed at night.
- ✓ Remember, the signs of feeding by large FAW larvae include scraping, cutting and tearing, frass, and the whorl-feeding-sign (Section 4.3.2). For the purpose of field scouting and application of an Action Threshold, all signs of feeding by large FAW larvae are recorded as IW.

A planting of maize with 21% IW is not at the Action Threshold for late-whorl-stage plants (30-50%; see Table 2).

- ✓ Remember that large, rapidly growing maize plants can tolerate and compensate for a significant amount of foliar feeding. As a result, the plant-age-based Action Threshold is higher (less conservative).

The whorl damage in a few of the plants was severe. The farmer was alarmed and prepared to spray the field again. Upon examination, the scout found that the majority of the whorl feeders were large, 6th-instar FAW larvae. FAW Action Thresholds often exclude larvae that are greater than three centimeters long (>3.0 cm), because it is not cost effective to control them (Figure 10). They are within days of pupation. At the V9 stage, first tassel is a few days away. The scout advised the farmer to skip this insecticide spray but keep scouting. The farmer rejected the advice and sprayed anyway. However, the farmer decided to selectively spray rather than spray the whole field. The farmer applied a spray directed at the whorl, spraying only the infested plants.

## 8.4. Scenario Four: Moderate Cash-Value, Cob Stage

**Scouting Data:**

- Maize growth stage: VT to R1
- %IP: 30%
- Average regional moth count: Not available

  **Field Notes:** "A lot of plants have FAW larvae at the base of the developing ears. The larvae have not yet begun to penetrate the husks."

In this case, the maize plants were in the reproductive stage after first tassel. Thirty percent (30%) of the plants were infested with FAW. Based on %IP (Table 2), the Action Threshold for ear-stage maize is 20% (10-30%). There were FAW larvae at the base of the developing ears, but they had not yet begun to penetrate the husks. The weather was warm and dry.

- ✓ Remember, scouting after tassel emergence is focused on the discovery of any larvae or any sign of fresh feeding (%IP).
- ✓ Remember, if there are FAW larvae at the base of the developing ears, the risk of crop loss is high.

Since the applicator's risk of exposure to insecticide is high when the maize plants are tall, the farmer chose to use a highly effective and low-toxicity insecticide (chlorantraniliprole). Although it was expensive, the farmer thought it was a good value.

The farmer hired a local spray service provider who wore a complete set of PPE. The applicator directed the spray at the ears and the leaf axils above and below the ears.

## 8.5. Scenario Five: High FAW Pressure, Subsistence Farmers

For smallholder farmers growing maize to feed their families, the crop has significant value. Subsistence farmers, however, may be cash poor, and pest control can be a significant input cost. Smallholder farmers often ask, "Can I get away with just one FAW spray?" The answer is, "It depends." The decision should be based on field scouting and an Action Threshold.

In an emergency, smallholder subsistence farmers may purchase a small amount of a recommended, less expensive FAW insecticide available in the market. However, cheap insecticides tend to be older ones for which generic versions are available (Haggblade *et al.* 2021). Many of these less expensive insecticides tend to be highly toxic to people and only moderately effective on FAW.

- ✓ It is especially important that the subsistence farmer scouts the field when the plants are small. Seedlings are vulnerable to foliar feeding. FAW seedling damage can depress yield if good agronomic practices are not followed.
- ✓ It is equally important to treat the field while the FAW larvae are small. Small larvae are more susceptible to insecticides. Apply the insecticide when the larvae are small, before they move into the whorl.

In terms of applicator safety, when the maize plants are small, the applicator can walk down an alley and reach across the closest maize row, spraying the next row over to their side. This prevents them from walking through wet, recently sprayed foliage.

A percentage of the larvae may survive the less effective insecticide and move into the whorl. Although late-whorl-stage maize plants can tolerate more foliar feeding than seedling maize, and thus have a higher Action Threshold, most farmers should focus on controlling FAW when the larvae are small rather than wait for the appearance of large FAW larvae and damaged plants. It is very difficult to control large larvae buried in the whorls.

In many cases, depending on the weather and the egg-laying intensity, one or two sprays will be sufficient. Heavy rainstorms kill many of the 1st- and 2nd-instar FAW larvae. However, the farmer should take a careful look at the base of the developing ears between the first tassel (VT) and brown silk (R2) stages. If there are larvae at the base of the developing ears, the risk of significant crop loss is high. Farmers should consider using an effective, lower-toxicity insecticide to protect the ears (*e.g.*, 5% emamectin benzoate).

**Example: One- or Two-Spray Program:**

- **One broadcast spray at the seedling stage, based on field scouting and an Action Threshold using %SFW.**

  Ignore the large larvae and their dramatic feeding signs during the late-whorl plant stage. It is difficult and expensive to control the large larvae anyway.

- **One spray on developing ears using a highly effective, low-toxicity insecticide based on field scouting and an Action Threshold using %IP.**

  If the weather is favorable to FAW (dry and warm) and the egg-laying pressure (moth count) is high, expect some yield loss.

# 9. Protocol: Scouting a Maize Field for FAW

## 9.1. Scouting Instructions – Vegetative Stages

*See Section 4.3 for detailed descriptions and photos.*

Upon arriving at a field, make a preliminary assessment (surveillance):

- ✓ Determine whether the field has been recently sprayed with pesticide. If yes, check the re-entry interval before proceeding into the field.
- ✓ Determine the growth stage of the maize plants.
- ✓ Determine which insect pests and what size larvae are present.
- ✓ Determine which signs of insect feeding are present.
- ✓ Note whether there has been a heavy rainfall recently.

**Step One:** Choose a scouting pattern.

Use the “W” scouting pattern when the maize plants are small. Zigzag through the field, stopping and examining plants at five different locations within the field (A-E in Figure 3).

Use the “Ladder” scouting pattern when the maize plants are tall. Start at the beginning of the middle row. Walk several paces; turn right, stop, and sample. Return to the middle row. Walk several paces; turn left, stop, and sample. Return to the middle row. Repeat until five different and representative locations in the field have been examined (A-E in Figure 4).

**Step Two:** Walk into the field and begin scouting about 5 meters from the edge, avoiding the border rows. Move through the field at a steady, moderate pace.

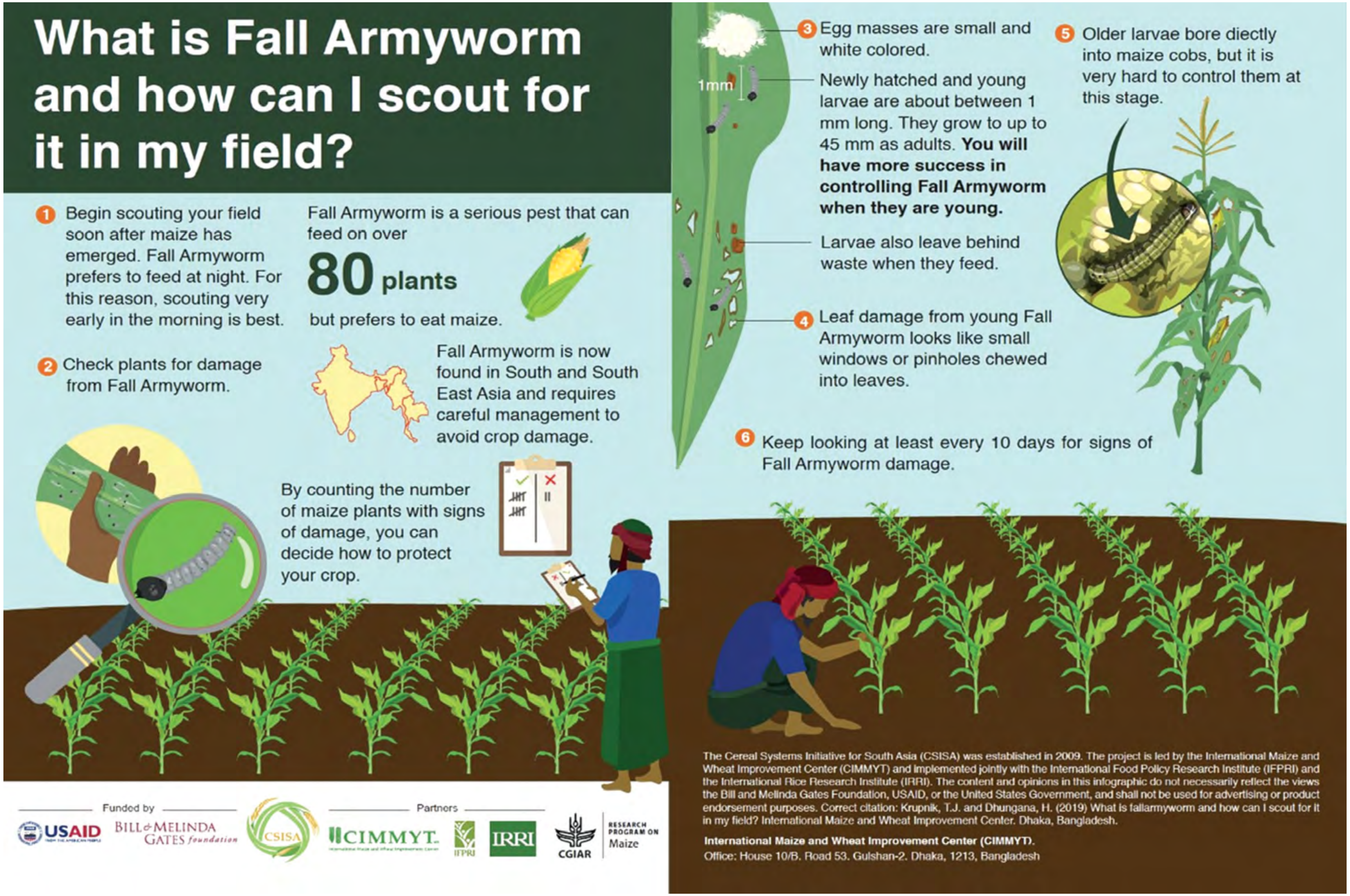



**Figure S1**. First pages of an infographic providing a brief summary of scouting procedures for growers. Source: CIMMYT, Bangladesh (Krupnik and Dhungana 2019). See **Chapter 7** for links to this and other FAW infographics in English, Bangla, and Lao.

**Step Three:** Stop and examine 10 plants in a row.

- ✓ Focus the search (search arena) on the newest three to four (3-4) leaves emerging from the whorl.
- ✓ Record the number of plants (out of 10) that have small, fresh windowpanes (SFW) and/or signs of fresh feeding by large larvae, indicating infested whorls (IW).
- ✓ Note which kind of feeding (SFW or IW) is more prevalent. The feeding sign, SFW or IW, is a clue to the size of the FAW larvae infesting the plant.

**Step Four:** Move to the next stop. Examine 10 plants **in a row**. Record the number of plants (out of 10) that have SFW or IW. Repeat the process at five locations per hectare.

**Step Five:** After examining five different locations per hectare, exit the field. Obtain two data points per field:

1) The percentage of plants that have SFW or IW.

2) The most common kind of feeding (SFW or IW).

**Step Six:** Make a spray decision based on the plant-age-based Action Threshold (see Section 5, Action Thresholds), the size of the larvae, and the weather. If most of the larvae are small and a rainstorm is expected, consider delaying your decision. Scout the field again the day after the rainstorm.

## 9.2. Scouting Instructions – Reproductive Stages

*See Section 4.4 for detailed descriptions and photos.*

**Step One:** Use the ladder pattern to scout the field. Enter in the middle of the field (middle alley).

**Step Two:** Walk into the field about 5 meters (to avoid the field-edge effect). Turn right and walk several paces perpendicular to the middle row. Stop and examine 10 plants **in a row**.

- Gently pull the developing ear away from the stem and examine the base of the ear.
- Briefly examine the leaf axils above and below the ears.
- Record the number of plants (out of 10) that have any larvae (regardless of size) or **<u>any sign</u>** of fresh feeding.

**Step Three:** Walk back to the middle. Walk several paces down the middle row. Turn left and walk several paces perpendicular to the middle row. Stop and examine 10 plants in a row.

**Step Four:** Walk back to the middle row. Walk several paces down the middle row. Turn right. Repeat the process at five locations per hectare.

**Step Five:** Exit the field. Calculate the percentage of infested plants (%IP). Use a plant-age-based Action Threshold to make a spray decision (see Section 5, Action Thresholds).

See Figure S1 for an example of an infographic summarizing scouting procedures.

**FAW Scouting Worksheet**

**Location**________________________ **Planting Date:**_______________ **Pheromone Trap Type:**____________________
**Name:** ____________________________________ **Phone**: ________________________________

| **Moth Trap & Weather Data** | **Scouting #___** | | | | | | | **Scouting #___** | | | | | | | **Scouting #___** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Today's date: | | | | | | | | | | | | | | | | | | | | | |
| Date last checked: | | | | | | | | | | | | | | | | | | | | | |
| Days since last checked: | | | | | | | | | | | | | | | | | | | | | |
| FAW moth count: | | | | | | | | | | | | | | | | | | | | | |
| FAW moths/trap/day (MTD): | | | | | | | | | | | | | | | | | | | | | |
| Average Regional FAW (MTD): | | | | | | | | | | | | | | | | | | | | | |
| Maize growth stage: | | | | | | | | | | | | | | | | | | | | | |
| Insecticide Application (Date): | | | | | | | | | | | | | | | | | | | | | |
| Rainstorm (Date): | | | | | | | | | | | | | | | | | | | | | |
| Rainstorm Forecast (yes/no): | | | | | | | | | | | | | | | | | | | | | |
| **Field Scouting Data** | **Vegetative (V1-V12): Examine the three to four (3-4) newest leaves emerging from the whorl.** | | | | | | | | | | | | | | | | | | | | |
| Five Stops | A | B | C | D | E | Sum | %SFW + IW | A | B | C | D | E | Sum | %SFW + IW | A | B | C | D | E | Sum | %SFW + IW |
| #Plants w/ small windowpanes (SFW) or infested whorls (IW): | | | | | | | | | | | | | | | | | | | | | |
| Most common sign (SFW or IW): | | | | | | | | | | | | | | | | | | | | | |
| **Field Scouting Data** | **Early Reproductive (VT-R2): Examine, tassel, base of cobs, & leaf axils above and below the cobs.** | | | | | | | | | | | | | | | | | | | | |
| Five Stops | A | B | C | D | E | Sum | %IP | A | B | C | D | E | Sum | %IP | A | B | C | D | E | Sum | %IP |
| #Plants w/larvae or any feeding: | | | | | | | | | | | | | | | | | | | | | |

| **Notes:** | | | |
|---|---|---|---|

Vegetative Stages (VE-V12): SFW (Small, Fresh Windowpanes = egg hatch & small larvae); IW (Infested Whorls = scraping, cutting, tearing, frass, & whorl-feeding sign = large larvae).
Early Reproductive Stages (VT-R2): %IP (Percent Infested Plants = any larvae plus any sign of fresh feeding)

# 10. Protocol: Pheromone Trap Setup and Maintenance for a Low-Density Network

## 10.1. Introduction

The most cost-effective way to produce a FAW moth count is to establish and maintain a low-density pheromone trap network (see Section 6). It is not necessary to establish a pheromone trap on every farm, much less every field. The purpose of the low-density trap network is to detect high and low egg-laying intensity and inform pest management decisions.

Most of the time, we think of pheromone trap networks as an early-warning system, detecting pest outbreaks and generating “pest alerts.” It is equally important, however, to detect low-pressure periods and provide decision support when a farmer is considering a no-spray decision. When a farmer or farm advisor scouts a field and finds that the FAW larval counts are low, average regional moth counts validate and support the no-spray decision. There are few larvae in the field and few incoming moths, so no insecticide is necessary. The farmer or advisor should check the field again the following week.

## 10.2. Instructions for Setup and Maintenance

Establish pheromone traps at least one month before planting maize. Place the traps in or next to the maize fields so that the scent of the pheromone is carried across the tops of the plants by the wind.

As the wind blows through and around a pheromone trap, it picks up and carries the scent downwind. The length of a pheromone plume is 50-100 meters, though plume length varies according to the pheromone chemistry and other factors (Adams *et al.* 2017). The male FAW moth follows the scent-trail or “plume” back to the trap. The length of the pheromone plume determines, in part, the effectiveness of the trap and the area that is sampled.

Hang the trap from a long pole (3-4 meters). For seeding maize, start with the trap approximately 1.0 meter off the ground. As the plant grows taller, raise the trap so that its base is always 30 centimeters above the top of the plants (Figure S2).

**Figure S2.** As the maize plant grows tall, raise the trap up so that the base of the trap is always above the top of the plants. Photo credit: Dan McGrath.

Although some manufacturers claim that their lures "work" for several months, all lures lose strength over time. As a result, moth counts diminish over time. This can mislead a pest manager, suggesting that moth counts are low or declining when, in fact, they are not. The details of each type of trap use vary, but for most types, lures should be replaced every three to four weeks and stored in a freezer until use.

Trap maintenance is important. If the scout fails to replace the pheromone lure every 3-4 weeks, the trap attracts fewer moths as the lure loses strength. If the scout fails to raise the trap as the plant grows taller, the pheromone is not carried downwind across the top of the plant and the trap attracts fewer moths. If the plant plugs, blocks, or buries the trap, fewer FAW moths can access the trap. Note that poor maintenance leads to false and misleading moth counts.

## 10.3. Pheromone Trap Styles

There are a variety of pheromone traps that can be used for monitoring FAW populations. When choosing a trap, consider not only the cost, but also the durability of the trap. Consider the strength and weakness of the trap (Figures S3-S8). Some inexpensive pheromone traps are disposable after one use. Other more expensive traps can be used for five to twenty (5-20) years.


**Figure S3.** Delta traps are inexpensive and disposable. The male FAW moths are attracted to the lure and get stuck on the sticky bottom board. The sticky bottom has to be replaced when choked with dead moths or dust, sometimes as often as once per week. This raises the maintenance cost. Photo credit: T. Tefera, B. Sisay & J. Simiyu (*icipe*, Addis Ababa, Ethiopia).

**Figure S4.** Funnel traps are inexpensive, and the bags are disposable. The moths are attracted to the lure at the top of the funnel, then flutter down and are trapped in the bag. The biggest weakness of this trap is that the moths knock their wing-scales off in the bag. This makes it much more difficult to identify the FAW moths. Photo credit: Sharanabasappa Deshmukh (UAHS-Shivamogga, India).

To use a universal bucket trap (Figure S6), unwrap the insecticidal strip and place it in the bottom of the trap. Do not handle the strip with bare hands: use gloves or some other tool. An insecticide strip should last for three to four months after which it should be replaced. If the moths are still alive, fluttering around, and knocking off their wing-scales when you check a bucket trap, the insecticide strip may need to be replaced. Do not store extra insecticide strips with food. Place them in a sealed airtight jar and store in a cool, dark place.

**Figure S5.** Water traps are relatively inexpensive. They can be reused for a couple of seasons. The moths are attracted to the lure hanging above soapy water, then flutter down and drown. The water removes wing-scales, making moth identification difficult. It is challenging to adjust the height of the water trap, keeping it above the plants. Many farmers put the traps on the edge of the field. Photo credit: Tim Krupnik (CIMMYT).

**Figure S6.** Universal bucket traps are moderately expensive, but they can be reused for about 5 years. The moths are attracted to the lure suspended above the funnel, then flutter down into a dry chamber below. Inside the chamber is an insecticide strip. The moths die rapidly and retain their wing-scales., which helps with identification. Insecticide strips must be replaced every 3-4 months. This increases maintenance costs. Photo credit: T. Tefera, B. Sisay & J. Simiyu (*icipe*, Addis Ababa, Ethiopia).

**Figure S7.** Heliothis net traps are expensive but they can be reused for 5-10 years. The male moths are attracted to the lure suspended at the bottom of a large opening, then flutter up into a small funnel where they are trapped.

Because of the size and design of the trap, the traps are more sensitive than most other trap types. They detect moths even when the population density is low. These are one of the most popular traps in the USA for monitoring insect pests in maize fields. Photo credits: Dan McGrath.

**Figure S8.** Hartstack wire-mesh traps are expensive, but they can be reused for 15-20 years. They detect moths even when the population density is low. These are one of the most popular traps in the USA for low-density pheromone trap networks and regional monitoring systems.

The moths are attracted to the lure suspended at the bottom of a large opening. They fly up into a trap at the top. Wing-scales are preserved, making it easier to identify the FAW moths.

Photo credit: Copyright and Courtesy of Purdue University and Kira Albright.

## 10.4. Checking the Trap

FAW pheromone lures will attract the target moth species, *Spodoptera frugiperda*, but may also attract closely related moth species. It is important, therefore, to identify and count both the FAW moths and any contaminating moth species when checking a trap. Do not just count the moths in the trap and assume all those trapped are FAW moths.

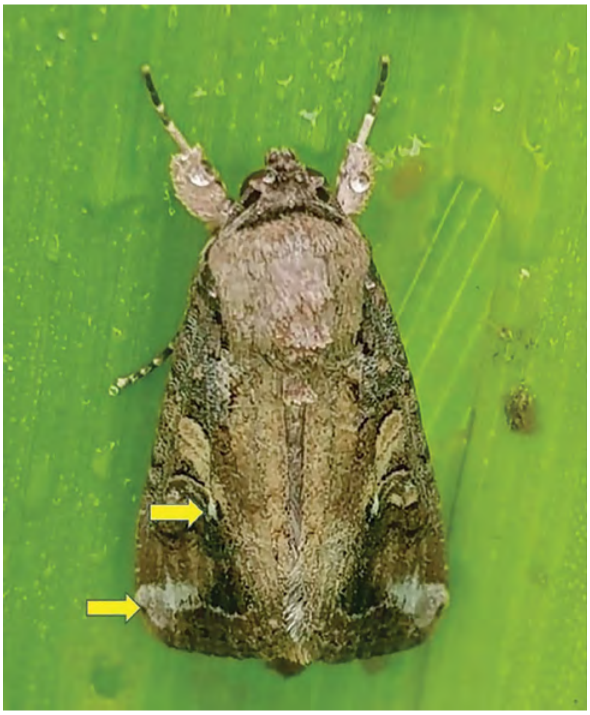


**Figure S9**. Male *Spodoptera frugiperda* (FAW) moths have a wingspan of 32 to 40 mm. In the male moth, the forewing is shaded gray and brown, with triangular white spots at the wing tip and near the center of the wing. Photo credit: B.M. Prasanna (CIMMYT).

If the FAW moths have blown in on the wind from another location, they will be damaged and hard to identify. Likewise, if the FAW moths have lost their wing-scales in the pheromone trap, they will be difficult to identify. Use "partial" field identification marks and body size to identify FAW (Figure S9). Look for field identification marks that should not be there, to eliminate contaminating moths (*i.e.*, moth species with field marks that do not occur on FAW moths).

- ✓ Check and empty the trap every week.
- ✓ Live moths may crawl up the sides of the trap. Pinch the thorax of the moths between your thumb and forefinger to freeze the wing muscles.

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CHAPTER 03

# Pesticide Application, Safety, and Selection Criteria for Fall Armyworm Control

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# 1. Introduction

The fall armyworm (FAW) has been effectively managed in the Americas for decades using a Good Agricultural Practices–Integrated Pest Management (GAP-IPM) approach. GAP-IPM uses a combination of the control methods described in this manual, including host plant resistance, cultural control, biological control, and pesticides. This chapter will provide and summarize information about the efficacy of pesticides (both synthetic and biopesticides) from rigorously conducted experiments, review application parameters that maximize efficacy, and discuss insect resistance management (IRM)*. The chapter also quantifies the risks to human health and the environment that must be considered in the face of limited access by farmers to education and personal protective equipment (PPE).

This chapter is organized as follows:

1. Pesticide selection information, including efficacy, human and environmental safety and risk mitigation, cost, and availability.
2. A table summarizing pesticides in current use against the FAW, classified by hazard, requirement for risk mitigation, and efficacy against the pest.
3. Examples of pesticide scenarios for risk mitigation and resistance management.
4. A summary of new and alternative pesticide technologies.
5. A supplement describing efficacy testing principles, including a protocol based on Good Laboratory Practices (GLP).
6. A summary of new and alternative pesticide technologies. A supplement describing backpack sprayer calibration and pesticide dilution, including sample calculations.
7. A supplement describing the Insecticide Resistance Action Committee (IRAC) pesticide classification system.

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

The information presented here is intended to focus on the needs of smallholder farmers and the people who advise them. It is necessary to acknowledge, however, that smallholder farmers are not a monolithic group. On one end of the spectrum are resource-constrained smallholder farmers managing 0.5 to 1.0 hectares of land. Their primary goal is to feed their families, and they have a very small budget for FAW management or other agricultural technologies including fertilizers and improved seed. However, these farmers are also increasingly involved in agricultural market economies, especially in Asia. They may also use some degree of mechanization, grow improved varieties, and seed at a plant population that is appropriate for the variety and rates of fertilizer they may apply. In some cases, especially in South Asia's Indo-Gangetic Plains and in South-East Asia's Deltas, some farmers also have access to irrigation. These farmers, who generally and widely access markets for maize, may use pesticides that derive from the formal marketplace, and frequently have access to backpack sprayers or foggers. They may also hire pesticide applicator service providers, or apply pesticides directly, to protect their investment in the crop and in general would be willing and able to spend more on crop protection, including purchase of low-cost protective clothing if available. Access to education and training associated with pesticides and their use can be limited throughout this spectrum of farmers.

# 2. Pesticide Selection Criteria

Selection of pesticides for use against FAW requires a balance of efficacy, cost, safety, environmental risk, and availability. In the context of an IPM program, pesticides are only used when the pest population reaches the Action Threshold (see **Chapter 1**), thus minimizing the overuse of pesticides and supporting conservation biocontrol. Today, there are a number of modern, low-toxicity, low-environmental-risk insecticides, both synthetic and biopesticides, that are highly effective against FAW. The problem is that these insecticides are normally more expensive than older products and some are not widely available in many developing countries. The sections below discuss each of these aspects of pesticide selection, including ways to mitigate the issues of cost and availability.

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* The term "Insecticide Resistance Management" is more often used when referring to insecticides, whereas "Insect Resistance Management" is more often used when referring to genetically modified crops containing insecticidal proteins. For the purposes of this manual, we have used "Insect Resistance Management", though the terms are interchangeable.

## 2.1. Efficacy

The relative potency of an insecticide against FAW can be determined in the laboratory, but efficacy in the field is more complex. In the field, efficacy depends in large part on application timing and technique. The plant growth stage (vegetative versus reproductive), the size of the larvae (small versus large), and the larval feeding behavior (leaf, whorl, tassel, or ear) at or soon after application determines the impact of an insecticide treatment on FAW. In addition, efficacy depends on the appropriate insecticide dilution, application rate, and application parameters including nozzle selection and spray placement. The following sections summarize important principles for efficacy testing and describe some of the factors affecting the efficacy of a pesticide treatment.

### 2.1.1. Efficacy Testing

Because of the complex interaction between FAW and maize, as well as the variation inherent in all field experiments, it is important for pesticide registrants, regulators, and extension researchers to use sound scientific practices when conducting efficacy testing. We recommend using procedures similar to the principles outlined for GLP to ensure that the resulting conclusions and recommendations are scientifically sound. In the context of testing for pesticide efficacy, such testing should include clear identification of the materials being tested (test substances) and the controls (control substance) as well as the maize varieties being used for testing, statistically sound experimental design, assessment of insect size/stage and percent infestation, etc. Section 7 (Supplement 1) expands on these principles and provides an example of a GLP-like protocol for a pesticide efficacy trial.

Similarly, farmers trying a new pesticide or other control method on their own farms should consider the factors that affect pesticide efficacy when drawing conclusions. For example, many treatments that might be effective and appropriate for small larvae (*e.g.*, neem [from *Azadirachta indica*], *Bacillus thuringiensis* [*Bt*]) will appear to be ineffective if tested on large, whorl-feeding larvae.

### 2.1.2. Spray Timing

When considering the efficacy of materials and methods for FAW control in maize, it is important to know the size and maturity of the FAW larvae when the treatments are applied. The size and maturity of the larvae determine (1) their feeding location, (2) their exposure to the treatments, (3) their physiological tolerance to insecticides, and (4) their exposure to rainstorms.

Small (1$^{st}$ and 2$^{nd}$ instar) FAW larvae feed on the leaves, where they are exposed and vulnerable to insecticide applications, natural enemies, and rainstorms. Small larvae are physiologically more susceptible to insecticides than large larvae. Small larvae are also more susceptible to rainstorms than large larvae. Heavy rain may knock the small larvae onto the ground, where they die.

Large (4$^{th}$, 5$^{th}$, and 6$^{th}$ instar) FAW larvae mainly feed in the whorls and the leaf axils (after first tassel) where they are more protected from insecticide applications, natural enemies, and rainstorms. Large larvae are physiologically more tolerant to insecticides than small larvae. Rainstorms have little impact on large larvae protected in the whorls and the leaf axils.

As described below (Section 2.2.1), spray timing also affects applicator safety. Treatment of small plants is safer for the applicator, who does not need to reach overhead and is not surrounded by tall and wet foliage.

### 2.1.3. Application Method

Optimal use of a pesticide requires that the recommended rate is applied to the crop at the right time. Too little might result in poor efficacy and may also promote resistance; too much is a waste of money and potentially increases operator exposure and hazard. Sprayer calibration is required to ensure that the intended dose of pesticide is being applied. A protocol for backpack sprayer calibration and calculations for pesticide dilution are provided in Section 8 (Supplement 2).


**Figure 1.** Example of guidance for purchasing legally registered, authentic pesticide products. Modified, with permission, from CropLife India.

## 2.1.4. Insecticide Quality

It is important that only legally registered insecticide be used on a farmer's crop. The pesticide must be properly labeled and purchased whenever possible in a sealed, unopened container. The pesticide should be used within any 'use by' dates indicated on the package. It is best if the pesticide is purchased from a licensed dealer with a reputation for selling legally registered products. Given that illegal and counterfeit pesticides are made and distributed by criminals with the intent to deceive farmers, it is of utmost importance that farmers are provided training and awareness on how to avoid buying and using illegal/counterfeit pesticides (Figure 1).

## 2.1.5. Insecticide Resistance

FAW has a short life cycle, about 30 days at 25-27°C. As a result, FAW populations have the potential to rapidly develop insecticide resistance, thus rendering previously useful pesticides ineffective. In a study from China, Zhang *et al.* (2020) discovered FAW populations with resistance to organophosphate and pyrethroid insecticides. This was not unexpected since FAW populations in the Americas carry resistance to these two insecticide classes. Consistent with observations made in Africa, however, the insect was still sensitive to a *Bt* (*Cry1Ab*) maize variety in a single-location field experiment. Although there is little current evidence for resistance to *Bt* toxins in FAW in Asia, this has not been studied in detail, and it is important to watch for any evidence of such resistance.

There are several ways to slow down the development of insecticide resistance:

- Read and follow the product label directions. The label may require the applicator to limit the number of applications and the total amount of material applied per season.
- Do not apply insecticides with the same group classification number to successive generations of FAW (see Section 9 [Supplement 3], IRAC Classification). Rotate between insecticides with different group classification numbers about every 30 days (every two sprays) within the same season.

Examples of insecticide rotations for FAW control are given in Section 4.2.

## 2.2. Safety

There are two main components to pesticide safety: human health risks and environmental risks. Some pesticides are so toxic to humans that if they are used at all, they should only be applied by professional applicators and not by smallholder farmers, even if PPE is available. In other cases, human health risks can be managed by a combination of good application technique, protective clothing (PPE), delayed reentry into crop fields after treatment, and avoiding pesticide use when the crop is close to harvest. Pesticides may also pose risks to aspects of the environment including aquatic life, terrestrial life (mammals and birds), and pollinators, and these impacts, if not excessive, may be limited by using a variety of mitigation practices (Jepson *et al*. 2020). Pesticide registrants also look at the possible effects of pesticides on parasitoids and other natural enemies of pests, which can also be mitigated (see Section 2.2.2.4).

To capture these various hazard and risk categories within a single classification scheme, Jepson *et al.* (2020) developed a system that takes all of these factors into consideration, with the intent of identifying lower-risk pesticides. Highly Hazardous Pesticides (HHPs) have been defined by the joint FAO-WHO meeting on Pesticide Management (JMPM) (FAO and WHO 2016). This is a broad classification that includes acute and chronic human health hazards, environmental hazards such as ability to magnify pesticide concentrations through food chains, and also evidence of severe impacts that arise from use. Any one of eight criteria can result in HHP classification; Jepson *et al*. (2020) listed this group, along with a guideline that enables alternative pesticides to be selected (see supplementary material in Jepson *et al.* 2020). There are other pesticides that may be toxic to humans and also the environment, where risk management or mitigation is possible. Jepson *et al.* (2020) list these, with recommended mitigation measures. Finally, there are hundreds of compounds that do not pose significant hazards, or excessive risks to health or the environment if used correctly, and with a lower level of PPE.

We use this classification system in our tables below, arguing that lower-risk and efficacious materials are more appropriate in a smallholder setting.

### 2.2.1. Safety to Humans

**There is widespread agreement around the world that we need to phase out and eliminate the use of HHPs (including many organophosphate, carbamate, and pyrethroid insecticides).** Unfortunately, these older, highly toxic insecticides are still widely available and used by low-resource farmers because they are inexpensive and legally available in many countries (Jepson *et al.* 2014, 2020; Haggblade *et al.* 2021).

As with efficacy, safety is determined not only by the pesticide itself but also by the way in which it is used. For example, if it is clear that maize ears are at risk (based on pheromone trap moth captures, field scouting, and an action threshold), use of insecticide products such as chlorpyrifos or methomyl is not recommended because they are too toxic to applicators and to farm workers who may enter fields after application has taken place. When the maize plant is tall, risk of applicator exposure is high because the applicator will be moving through foliage that is wet with insecticide, and also exposed directly to spray drops and pesticide vapor. Many smallholder farmers do not have access to PPE, and although PPE is becoming more affordable, some farmers who do not use PPE still indicate that affordability is an issue. For these reasons, the risk to applicators and their families is too high for many broad-spectrum insecticides.

To reduce risk to the applicator while obtaining control of FAW, farmers and applicators should consider using a modern, highly effective, less-toxic insecticide such as chlorantraniliprole, emamectin benzoate, or spinetoram. These three lower-toxicity insecticides are highly effective against FAW. They also represent three different modes of action and can be used in rotation to slow down the development of insecticide resistance (see Section 4.2).

### *2.2.1.1. Personal Protective Equipment (PPE)*

Pesticide product labels should provide details on what PPE is required to safely handle the product. PPE requirements vary according to active ingredients and formulation and so the label provides key guidance for the product user. In cases where the label is difficult to understand or does not have the necessary information, the advice in this manual may serve as a guide. Level 1 PPE is the minimum level of protection needed by applicators for all insecticide uses, while level 3 is the maximum requirement for products of up to moderate toxicity. The requirements for each level of protection are listed in Section 3 and Jepson *et al.* (2020). Even for low-toxicity pesticides, basic protective coverings such as shoes and socks, long pants, long-sleeve shirts, and particularly gloves are recommended (*e.g.,* see Figure 2). Chemical-resistant gloves are needed because the hands may be a primary route of pesticide exposure and uptake.

Please note that for certain HHPs, PPE may not be sufficient to prevent applicators from being exposed to doses of pesticides that can be toxic. We have noted these materials in Table 1.


**Figure 2.** General illustration of personal protective equipment (PPE) used in pesticide application. Always check the pesticide label for specific PPE requirements. In particular, some pesticides require use of a respirator, eye protection, and/or an additional layer of chemical-proof clothing when handling or applying. Figure credit: CropLife International (2016).

#### *2.2.1.2. Restricted Entry Interval (REI) and Pre-Harvest Interval (PHI)*

In addition to the protection used during pesticide application, the user needs to consider the amount of time, or interval, after which it is safe to re-enter the field, and after which it is safe to harvest or consume the product. All pesticides decay in concentration on the plant and soil over time, and ultimately, deposits pose lower risks to farm workers and consumers if time is allowed to elapse before the field is visited after spraying, or if harvesting is delayed. These intervals are referred to as the restricted entry interval (REI) and pre-harvest interval (PHI), respectively, and they are listed on many pesticide labels. They are intended to protect field workers carrying out basic tasks such as weeding, irrigation, or scouting, and consumers, who may be exposed to pesticide residues on harvested ears.

Labels in some regulatory jurisdictions have tended to underestimate the time that is required to elapse before it is safe to re-enter fields (Jepson *et al*. 2014). This is because farm workers and farm family members spend longer periods working the fields than risk assessments take into account, and they are, therefore, more exposed to pesticide deposits than these calculations consider. We have also found that pesticide exposure may be higher because farm workers may have bare arms and legs while in the field, and the toxicity of the pesticide to individuals may also be higher if they have lower-than-average body weight. In combination, these factors can increase the risks of a toxic effect.

PHI is intended to protect consumers by allowing for pesticide residue decay in the field before the harvested crop is stored or processed for consumption. Although pesticide residues may dissipate in storage, and be lost during cooking, the PHI minimizes the risk that humans will consume a dose that could be toxic. This is particularly important in locations where maize forms an important part of the diet, particularly for infants and children and those who may be susceptible because of low body weight or health cofactors. PHI is particularly important also where pesticide sprayers are not properly calibrated—a situation that is common in Asia and Africa—and application rates in the field may be higher than the labeled rate. In these circumstances, a longer delay before harvest may be recommended to allow residues to dissipate as much as possible.

**Regardless of the pesticide used, farmers or applicators should mark fields that have been treated (*e.g.*, with signs or flags) and prevent access to the field prior to the specified reentry period for the pesticide used.**

## 2.2.2. Safety to the Environment

While human safety is paramount, environmental safety is also an important consideration when choosing a pesticide. Fortunately, there are a number of practices that can be used to mitigate some of the most detrimental effects of pesticides when they are otherwise a good choice for farmers. These general practices are listed below, and specific examples are given in Section 4.1. Please note that these apply to specific pesticides, and to field application by hydraulic sprayers. They are always supplementary to the pesticide label, which will also include risk management requirements.

The following suggested risk mitigation practices are substantially based on Jepson *et al.* (2018), from *Fall Armyworm in Africa: A Guide for Integrated Pest Management*, and Jepson *et al.* (2020), where a list of pesticides requiring mitigation is provided.

#### *2.2.2.1. Risk mitigation for aquatic life*

Use a no-pesticide-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 if they are not specified on the label:

a) 5 meters, if applied by knapsack sprayers.

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

Avoid spraying pesticides when it is windy as a general practice, and especially if near bodies of water.

Suggestions for vegetative barriers (*e.g.*, hedgerows, live fences, or other intentionally cultivated plants adjacent to or surrounding cropped fields):

a) Barriers should be at least 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.

### 2.2.2.2. 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.

### 2.2.2.3. Risk mitigation for pollinators

a) Use pesticides, if available, that are less toxic to bees and other insect pollinators (see pesticide selection guideline published with Jepson *et al.* 2020).

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

c) Apply only when insect pollinators are not foraging on the field, or after flowering plants 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.

   ii Substances should not be applied when the crop is 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 with impermeable sheets (*e.g.*, plastic sheeting) or move them during application, and provide hive bees with a clean water source outside the treated area for at least 24 hours following application.

### 2.2.2.4. Risk mitigation for natural enemies

A persistent challenge in pest management is the lack of compatibility between some pesticides and biological control agents, or natural enemies (Croft and Brown 1975; Croft 1990). It is important to recognize the trade-offs that exist between pest damage, pesticide use, and predation or parasitism of the pest. Both pesticides and natural enemies can increase pest mortality and limit yield loss, but this joint benefit can be cancelled if broad-spectrum pesticides are used that eliminate predation and parasitism, even for a short time. At worst, this can increase yield loss, and elicit pest outbreaks if the pesticide is not effective against the pest, or if it has short-lived effects on the pest and natural enemies are delayed in their recovery (Sherratt and Jepson 1993; Halley *et al.* 1996).

Insecticide resistance has been documented in FAW, and this is predominantly associated with use of the organophosphate, carbamate, and pyrethroid insecticides that have dominated the response to this invasive species in maize. Unfortunately, these classes of pesticide are universally toxic to most kinds of natural enemy and use of them against FAW limits predation and parasitism, and yet fails to suppress pest damage.

Farmers and pesticide applicators can maximize the contribution that all pest management tactics, including both pesticides and natural enemies, make to FAW suppression by:

1. Only using pesticides when crop yield is threatened (**Chapter 2**).
2. Avoiding use of organophosphate, carbamate, and pyrethroid insecticides that are not effective against FAW, and toxic to natural enemies.
3. Applying pesticides at the correct dose-rate, to maximize their effectiveness against the pest, and limit their toxicity, and the duration of impacts, against natural enemies (*e.g.*, Longley and Jepson 1997). Sprayers should be calibrated to ensure that excessive doses are not applied (see Section 8.2).

Farmers should also consider steps that conserve natural enemies (**Chapter 5**), which limit the need to use pesticides at all, and minimize early sprays, so that predators and parasite populations have an opportunity to build up.

## 2.3. Cost

As described in previous sections, the new, lower-risk insecticides recommended for FAW control can come at increased cost, which might be prohibitive for smallholder farmers. However, growers and pesticide applicators can control the cost of these newer pesticides by using them as part of an integrated program. A cost-effective IPM program incorporates host plant resistance (**Chapter 4**), biological control (**Chapter 5**), and cultural control (**Chapter 6**), and also decision-making that determines the need for pesticides. Scouting for signs of the pest and monitoring of egg-laying pressure (optionally using pheromone traps) can help the grower to determine when and if pesticide treatments are required (**Chapter 2**).

In some cases, off-patent but effective pesticides can be obtained at relatively low cost. For example, emamectin benzoate and *Bt* preparations are currently being sold in small packets corresponding to the amount of product needed for a single backpack sprayer batch. Another economical choice is neem, which is effective against small larvae if proper quality is ensured. The use of a commercial-grade neem spray is encouraged over homemade preparations if the commercial product is available and affordable.

Section 7.1.5 (Supplement 1) provides examples of how information on pesticide efficacy can be combined with cost information to inform treatment decisions.

## 2.4. Availability

It is urgent that smallholder farmers have ready access to modern insecticides with favorable efficacy and safety profiles. The following mechanisms would ensure that the products are available to farmers and handled responsibly in the marketplace.

### 2.4.1. Regional Regulatory Harmonization, Pesticide Emergency Use Authorizations, and Enforcement

Even for smallholder farmers, pesticide use is increasing at a dramatic rate (Haggblade *et al.* 2021). In most countries, pesticides must be registered for use on specific crops (*e.g.,* maize), and against specific pests such as the FAW. The normal registration process typically takes about two years to complete, typically driven by the need for regulatory review of product efficacy trials over multiple seasons. The sudden arrival of a new invasive pest can create significant challenges for regulators since products that can control this pest will not be labeled for use against the pest and may or may not be registered for use on the crop (Suguiyama *et al.* 2020). The unavailability of approved pesticides to control particular pests can result in farmers using off-label pesticides to control the pest. Two policy options can greatly accelerate the labeling of pesticides for use against new invasive pests: (1) regional harmonization of pesticide laws and regulations; and (2) use of pesticide emergency use authorizations (PEUAs).

Regional harmonization of the pesticide review and approval process, exemplified by the East African Community (EAC), allows a block of countries to use common guideline processes for pesticide approval and to share the burden of pesticide data review. This both lowers the cost of registration and expedites the approval process (see EAC Harmonized Pesticide Guidelines for Efficacy Trials). PEUAs allow regulators to give preference to known registered products and safer pest control alternatives, such as biopesticides (Suguiyama *et al.* 2020). Unfortunately, PEUAs were not widely used in the FAW mitigation campaign in Africa.

Finally, a critical function of the regulatory authorities is enforcement of pesticide regulations post approval (Haggblade *et al.* 2021). Enforcement includes ensuring that fake/fraudulent and banned highly hazardous materials are removed from sale, and perpetrators prosecuted.

# 3. Summary of Efficacy, Safety, and Environmental Hazards of Pesticides in Use Against FAW

Table 1 lists pesticides in use in Africa and Asia against FAW and assesses human and environmental risk using the process described in Jepson *et al.* (2018). Included are also literature assessments of efficacy as well as the IRAC Group classification. An expanded version of this analysis was prepared for publication under a USDA FAS and USAID contract (see Jepson *et al.* 2020).

Nine pesticides in the table are classified as HHPs. Fourteen are classified as low risk, but two of these (spinosad and spinetoram) require mitigation for pollinator hazards (see Section 4.1). A further 30 are neither HHPs nor low risk and require mitigation of human or environmental risks. Note that of the 14 low-risk compounds, four have been documented to have excellent (E) efficacy against FAW. The narrow diversity of modes of action for these low-risk pesticides is such that selection pressure on the insect population, leading to insecticide resistance, needs to be addressed as part of an IRM plan. Also note that the entomopathogenic bacteria and viruses in this list will have low toxicity to natural enemies, and that they are highly compatible with IPM programs that use non-pesticide management tactics.

**Table 1.** Pesticides used for control of FAW (*Spodoptera frugiperda*) in Africa and Asia.

**KEY** (see Jepson *et al.* 2020 supplementary materials for full description and a more detailed summary of PPE requirements).

Overall Risk Levels:

HHP: **Red** = Highly Hazardous Pesticide (HHP) (human and/or environmental hazards). The HHP designation occurs when a categorical threshold is passed in any one or more of eight categories encompassing risk to humans and or/the environment.

Low Risk: **Green** = low risk to human health and the environment

Human Risk:

Inhalation Risk: **Orange** = a requirement for applicator or bystander risk mitigation.

PPE level:

- #: HHPs for which acute and/or chronic risks may be too high for PPE, engineering, and behavioral mitigations to be sufficient for smallholder farmer use (see Jepson *et al*. [2020] supplementary materials)
- 3: High-risk pesticides requiring double-layer PPE, plus eye and/or respiratory protection
- 2: Lower-risk pesticides requiring single-layer PPE, plus eye and/or respiratory protection
- 1: Low-risk pesticides requiring single-layer PPE

Environmental Risk:

Aquatic (including aquatic algae, aquatic invertebrates, and fish), Terrestrial Animal (including birds and mammals), and Pollinator (including honeybee). Risks indicate requirements to mitigate negative impact of pesticides on aquatic wildlife, terrestrial wildlife, and pollinators, respectively. Details of these analyses and options for risk mitigation are provided in Jepson *et al.* (2020) supplementary materials.

Efficacy:

P, F, G, E, and ? indicate Poor (<50% control), Fair (50-70%), Good (70-90%), Excellent (90%+), and Unknown, respectively. Bracketed efficacy values in table indicate that efficacy rating is provisional and based upon mode-of-action group rather than field evidence.

MOA (IRAC group): See Section 9 for more information on IRAC groups.

| Pesticide Active Ingredient | HHP | Low Risk | Human Risk | | Environmental Mitigation Required | | | Efficacy[†] | MOA (IRAC Group) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Inhalation Risk | PPE (1-3) | Aquatic Risk | Terrestrial Animal Risk | Pollinator Risk | | |
| Abamectin | | | | 3 | * | | * | P | 6 |
| Acephate | | | | 3 | | * | * | F-G | 1B |
| Acetamiprid | | | | 2 | * | | | (P) | 4A |
| Alpha-cypermethrin | | | | 3 | * | | * | F-G | 3A |
| Azadirachtin (neem) | | * | | 1 | | | | F-G | UN |
| *Bacillus thuringiensis* | | * | | 1 | | | | F-G | 11A |
| Beauveria bassiana | | * | | 1 | | | | P | UNF |
| Benfuracarb | | | | 3 | * | * | * | P-F | 1A |
| Beta cyfluthrin | * | | | # | * | | * | F-G | 3A |
| Beta cypermethrin | | | | 3 | * | | * | F-G | 3A |
| Bifenthrin | | | | 2 | * | | * | F-G | 3A |
| Carbaryl | | | | 3 | * | * | * | P-F | 1A |
| Carbofuran | * | | * | # | * | * | * | P-F | 1A |
| Cartap hydrochloride | | | | 3 | * | | * | ? | 14 |
| Chlorantraniliprole | | * | | 1 | | | | E | 28 |
| Chlorpyrifos | | | * | 3 | * | * | * | F-G | 1B |
| Cyantraniliprole | | * | | 1 | | | | E | 28 |
| Cyfluthrin | * | | | # | * | | * | F-G | 3A |
| Cypermethrin | | | | 3 | * | | * | F-G | 3A |
| Deltamethrin | | | | 3 | * | | * | F-G | 3A |
| Diazinon | | | * | 3 | * | * | * | P | 1B |
| Dichlorvos/DDVP[‡] | * | | * | # | * | * | * | P | 1B |
| Diflubenzuron | | | | 3 | * | * | | F-G | 15 |
| Dimethoate | | | * | 3 | * | * | * | F | 1B |
| Emamectin benzoate | | | | 3 | * | | * | E | 6 |
| Fipronil | * | | | 2 | * | * | * | ? | 2B |
| Fenvalerate | | | | 3 | * | | * | F-G | 3A |
| Fenitrothion | | | | 3 | | * | | P | 1B |
| Flubendiamide | | * | | 1 | | | | G | 28 |

| Pesticide Active Ingredient | HHP | Low Risk | Human Risk | | Environmental Mitigation Required | | | Efficacy† | MOA (IRAC Group) |
|---|---|---|---|---|---|---|---|---|---|
| | | | Inhalation Risk | PPE (1-3) | Aquatic Risk | Terrestrial Animal Risk | Pollinator Risk | | |
| Gamma cyhalothrin | | | | 3 | * | | | F-G | 3A |
| Imidacloprid | * | | | 1 | * | | * | P | 4A |
| Indoxacarb | | | | 2 | | | * | E | 22A |
| Lambda-cyhalothrin | | | | 3 | * | | * | F-G | 3A |
| Lufenuron | | | | 2 | * | | * | E | 15 |
| Malathion | | | | 3 | | | * | P | 1B |
| *Metarhizium anisopliae* | | * | | 1 | | | | P | UNF |
| Methomyl | * | | | # | * | * | * | G | 1A |
| Methoxyfenozide | | * | | 1 | | | | F-G | 18 |
| Novaluron | | | | 2 | * | | | F-G | 15 |
| Pirimiphos-methyl | | | * | 3 | * | * | * | (P) | 1 |
| Profenofos | | | * | 3 | * | * | * | (P) | 1 |
| Pyridalyl | | | | 2 | * | | | ? | UN |
| Pyrethrum | | * | | 1 | | | | F-G | 3A |
| Pyriproxyfen | | * | | 1 | | | | P | 7C |
| SfMNPV§ | | * | | 1 | | | | G | 31 |
| Spinetoram | | * | | 1 | | | * | E | 5 |
| Spinosad | | * | | 1 | | | * | E | 5 |
| Teflubenzuron | | | | 2 | * | | | F-G | 15 |
| *Tephrosia vogelii* | | * | | 1 | | | | ? | UNE |
| Thiamethoxam | * | | | 1 | | | * | P | 4A |
| Thiodicarb | | | * | 3 | * | * | * | (P) | 1A |
| Trichlorfon | * | | | # | | | | (P) | 1B |
| Triflumuron | | | | 2 | * | * | * | (F-G) | 15 |

Source: Updated from Jepson *et al.* (2018)

† Materials in the fair to good category (F-G) may be effective against small larvae only. Spray timing is critical. These pesticides may require multiple applications in an outbreak.

‡ DDPV = 2,2-dichlorovinyl dimethyl phosphate

§ SfMNPV = *Spodoptera frugiperda* multiple nucleopolyhedrovirus. These viruses occur in nature and can be used as uncharacterized isolates. In commercial use, *e.g.,* Fawligen (*Spodoptera frugiperda* MNPV-3AP2), a specific isolate is registered for use by farmers.

# 4. Application of Available Pesticides

When a FAW outbreak is detected, growers should use the least toxic, most effective, most environmentally friendly materials and methods available. During a severe FAW outbreak, the insecticide choice depends, in part, on egg-laying pressure, the weather, and the growth stage of the maize. For example, if the maize tassels are starting to emerge, the weather is warm and dry, and FAW egg-laying pressure is high, the risk of later ear damage and significant crop loss is consequently also high. When risk of crop failure is imminent, the use of an on-farm manufactured botanical insecticide is not recommended because it may not be sufficiently effective. On the other hand, use of a highly toxic synthetic insecticide is also not warranted because there are lower-risk options, particularly when the maize plants are tall.

The following examples show how some of the modern, lower-risk pesticides described in Table 1 can be applied in real-world situations for control of FAW. These examples describe methods for use that mitigate risk to non-target organisms (and are also less costly) and suggest several possible insecticide rotations for IRM.

For all pesticides, be sure to follow the label requirements for REI and PHI (Section 2.2.1.2). The latter is particularly important to consider when a pesticide is being applied as a leaf axil or ear treatment.

## 4.1. Examples of Pesticide Selection and Risk Mitigation

Emamectin benzoate is highly cost-effective on FAW (Babendreier *et al.* 2020), but some formulations of emamectin have an $LD_{50}$ approaching 1500 mg/kg (moderately toxic). A product-appropriate level of PPE is still required.

Although spinetoram and spinosad are of low toxicity to humans, they are highly toxic to honeybees (*Apis mellifera*) and other pollinators when they are directly sprayed. However, the dry deposits of spinosad are of low toxicity to the visiting bees 3 hours after application with a low-volume or ultra-low-volume sprayer (Mayes *et al.* 2003). Similar results have been obtained for spinetoram, as documented in the manufacturer's EPA registration (Nick Simmons, Corteva Agriscience, personal communication). Therefore, the application method and application timing need to be taken into account in order to mitigate risk to pollinators. For example, prior to tassel emergence, control flowering weeds to prevent attracting honeybees into the maize. When the tassels start to emerge, if the crop is at risk, apply insecticides early in the morning, before the honeybees become active, or apply the insecticide at dusk, when fewer bees are in the field. There are also other approaches for minimizing injury to bees when using spinetoram or spinosad.

- When controlling large FAW that are deep within the whorl tissues, add a spray adjuvant (a surfactant or other additive that improves performance of the pesticide treatment), as recommended by your pesticide dealer or extension agent, to the tank, walk down the row, and insert the spray nozzle into the whorl of the infested maize plants. Directing the spinetoram or spinosad into the whorl or leaf axils reduces the hazard to the honeybees. It is unnecessary and expensive to flood the whorl. Only a very short spray (squirt) is required in order to obtain the rate of pesticide application that the manufacturer recommends, and which pesticide regulators have approved. It is easy to exceed this rate if a longer spray is applied to each whorl, and this can be hazardous to the plant, the applicator, and non-target organisms including predators and parasites.

See Section 2.2.2.3 for other practices to reduce injury to honeybees.

## 4.2. Examples of Season-Long Insect Control Programs

The following examples are provided to illustrate the process of making insect control decisions throughout a growing season. These examples are based on programs that were used in actual field situations and are not intended to be prescriptive, but rather to show what an insect control program could look like. At each stage of plant growth, treatment decisions should be based on insect size, insect pressure, efficacy, and safety. As the season progresses, safety concerns become more important because as the plants grow, the risk of applicator exposure to the pesticide increases. A different class of insecticide is used at each step to reduce the likelihood of developing resistance in the FAW population.

### 4.2.1. Example #1

- **During the early vegetative stage, one or two broadcast sprays with lambda-cyhalothrin based on scouting and an action threshold.**

Lambda-cyhalothrin is in the insecticide chemical family known as the pyrethroids (IRAC Group 3A; see Section 2.1.5 and Section 9). It is only moderately effective on small FAW larvae, and there is evidence for resistance to some pyrethroid insecticides in FAW in Asia (Zhang *et al.* 2020). Base the action threshold on the percentage of plants with small, fresh windowpanes (%SFW); see **Chapter 2,** Scouting, for details on scouting metrics and action thresholds.

Lambda-cyhalothrin is fairly toxic; wear appropriate PPE. Spray two rows to your side rather than in front of yourself. Do not spray straight ahead and then walk through the wet foliage.

Lambda-cyhalothrin is a broad-spectrum insecticide; it can kill many of the natural enemies of FAW. Use it sparingly and only if absolutely needed. Establish spray refuges on the edges and corners of your fields (see **Chapter 6**, Agroecology).

A significant number of FAW larvae will survive the lambda-cyhalothrin application and move into the whorls. You may need to re-treat the surviving larvae (see below).

It is extremely important that dose rates are not increased to compensate for poor efficacy, because this drives increases in resistance, increases costs, and has very limited benefit relative to increased risks to operators and beneficial insects.

- **One selective spray directed at the whorls with indoxacarb based on scouting and an action threshold.**

Base the action threshold on the percentage of plants with infested whorls (%IW). Indoxacarb is in the insecticide chemical family known as the oxadiazines (IRAC Group 22A) and is highly effective against FAW.

To selectively spray against FAW only in plants where the pest is present, walk along the rows and only treat the plants that are visibly infested (signs of large larvae). Direct the spray into the whorl of the infested plants.

As the maize plants grow taller, it makes sense to switch to indoxacarb because it is a lower-risk insecticide. But as with all insecticides, PPE is recommended.

If the larval load and/or the FAW egg-laying pressure is high when the tassels start to emerge, and the weather is favorable to FAW (warm and dry), scout your maize carefully. You may need an ear spray (see below).

- **One low-toxicity ear spray with chlorantraniliprole based on scouting and an action threshold.**

Chlorantraniliprole is in the insecticide chemical family known as the diamides (IRAC Group 28) and is highly effective against FAW. Direct the spray at the base of the ears and the leaf axils above and below the ears.

Base the action threshold on the percentage of infested plants (%IP). Switch to this more conservative (more sensitive) search target after tassel, because if there are small larvae at the base of developing ears, risk of significant crop loss is high.

There is a narrow window of opportunity to protect the ears between first tassel (VT) and brown silk (R3). In order to be effective, it is important to reduce the number of FAW larvae at first tassel and/or spray the ears before the larvae penetrate the husk.

When the tassels are starting to emerge, the maize plants are tall and the risk of applicator exposure to pesticide spray and residues is high. Chlorantraniliprole is a low-toxicity insecticide, but as with any pesticide application, basic PPR should be worn.

Chlorantraniliprole is expensive. However, if FAW larvae are present at the base of the ears, a highly effective, low-toxicity insecticide represents a good value.

## 4.2.2. Example #2

- **During early vegetative stages, one or two broadcast sprays with *Bacillus thuringiensis* (*Bt*) based on field scouting and an action threshold.**

*Bacillus thuringiensis* (*Bt*) is in the insecticide family known as the microbial disrupter (IRAC MOA Class 11A). It is moderately effective on small FAW larvae. Base the action threshold on %SFW.

*Bacillus thuringiensis* is a low-toxicity insecticide, but the applicator should wear PPE.

A significant number of FAW larvae may survive the *Bacillus thuringiensis* application(s) and move into the whorls. It may be necessary to re-treat the surviving larvae. Use a more effective insecticide for the re-treatment and apply a selective spray directed into the whorl (see below).

- **Selective spray directed at the whorl with emamectin benzoate based on scouting and an action threshold.**

Emamectin benzoate is in the insecticide chemical family known as the avermectins (IRAC Group 6). It is highly effective against FAW. For the selective spray, base the action threshold on %IW.

Emamectin benzoate is considered a lower-risk insecticide, but it is moderately toxic and the applicator should wear PPE.

If the FAW larval load and/or the FAW egg-laying pressure are high and the weather is favorable to FAW (dry and warm), scout the maize carefully. It may be necessary to apply an ear spray (see below).

- **One highly effective, <u>low-toxicity</u> ear spray with spinosad based on scouting and an action threshold.**

Spinosad is in the insecticide chemical family known as the spinosyns (IRAC Group 5). It is highly effective against FAW. (The field experience on which this example is based involved spinosad. Spinetoram was not available at the time but could be used in the same way.) Direct the spray at the base of the ears and the leaf axils above and below the ears.

Base the action threshold on %IP. Switch to this more conservative (more sensitive) search target after tassel, because if there are small larvae at the base of developing ears, risk of significant crop loss is high.

There is a narrow window of opportunity to protect the ears between the start of tassel emergence (VT) and brown silk (R2). In order to be effective, it is important to decrease the number of larvae present at first tassel. Spray the ears <u>before</u> the larvae penetrate the husk.

At the start of tassel emergence, the maize plants are tall and the risk of applicator exposure is high. Spinosad is a low-toxicity insecticide, but the applicator should still wear PPE.

Spinosad is expensive. However, if there are FAW larvae at the base of the ears, a highly effective, low-toxicity insecticide represents a good value.

Spinosad has low toxicity to most natural enemies of FAW but it is toxic to honeybees. Control weeds to prevent them from flowering and attracting bees into the maize. Apply the insecticide early in the morning when it is cooler and bees are less active. Establish spray and tillage refuges on the edges of the fields (see **Chapter 6**, Agroecology).

# 5. Other Pesticidal Approaches

## 5.1. Seed Treatment

This chapter has focused on use of foliarly applied pesticides, but pesticide can also be delivered via a seed treatment applied by the seed provider. Risk to applicators is a function of hazard (toxicity) and exposure, so risk can be mitigated by reducing exposure. Use of seed treatments can reduce exposure of humans and some non-target species to a pesticide while increasing exposure to plant-feeding pests during early seedling growth. But care must be taken to ensure that the selected pesticide controls FAW or other important maize pests, and that protection from these pests is needed between planting and approximately 3 weeks post-emergence. The effectiveness of the seed treatment wanes as the pesticide degrades and as the plant grows, so these are only useful against early-season infestations, when spray application is not efficient because plants are small. A publication by the International Seed Federation and CropLife International provides guidance on stewardship and safety when using seed treatments; see https://croplife.org/wp-content/uploads/2019/01/Stewardship-Guidelines-on-Seed-Treatment-and-Handling-of-Treated-Seed_Final-1.pdf.

## 5.2. Alternative Insecticides and Whorl Treatments

The use of non-synthetic chemical and alternative insecticides that are 'homegrown' has been promoted as an 'agroecological' means to control FAW in smallholder farming systems in Africa, and more recently in Asia (FAO 2018; FAO and PPD 2020). Such methods include spraying maize with sugar and molasses solutions, as well as the application of fish soup to maize. Considering the former two options, only one peer-reviewed study by Zalucki *et al.* (2002) evaluated the effectiveness of sugar solutions, finding that 10-20% solution sprays can attract Hymenoptera such as ants, and other predators and parasitoids. There is no evidence that this is a cost-effective means of controlling FAW. There is also no scientific evidence that fish soup can be used to mitigate FAW.

Farmers in Africa and Asia have also been advised that they can apply sand, sawdust, burned rice husks, and ash in maize whorls to control FAW (FAO and PPD 2020). Traditional agricultural techniques that are easily accessible to farmers are desirable, provided that they are effective in terms of cost and pest control. But as with fish soup and sugar sprays, formal studies evaluating these treatments are rare, and often come with negative results. Babendreier *et al.* (2020), for example, found that neither ash, nor sand, nor soap treatments effectively reduced FAW larval populations or crop damage. Moreover, the density of maize plantings in Asia, especially when hybrids are grown under irrigated conditions, can easily exceed 66,000-80,000 plants $ha^{-1}$; this is considerably denser than under the rainfed conditions in Africa where populations are often below 50,000 plants $ha^{-1}$ (Thierfelder *et al.* 2015). As a result, suggestions that farmers apply sand or ash in whorls may increase labor demand and costs, in addition to being ineffective. Suggestions to hand-pick and crush eggs or larvae are also unlikely to be economically viable, and the labor costs have been shown to be considerable (see Section 7.1.5.3). In addition, this type of labor falls disproportionately on women and children. In all cases, these approaches need to be assessed using the CESAS model outlined in **Chapter 1.**

Even though many of the whorl treatments being used by or suggested to farmers are ineffective, there are others that could potentially be both highly effective and relatively low in cost. One example is a spinosad phagostimulant whorl treatment described by Williams *et al.* (2004). This is a mixture of spinosad insecticide with maize flour, maize starch, and oil in a granular formulation that could be applied to the whorl or leaf axils of infested plants. The maize flour is a feeding attractant. As a result, the spinosad is effective at a gram or less of active ingredient per hectare (Williams *et al.* 2004). A whorl/leaf axil treatment containing corn flour and powdered sugar has also been tested for application of *Bacillus thuringiensis* strains (Tamez-Guerra *et al.* 1998). To our knowledge, spinetoram has not yet been tested in this type of method. Use of phagostimulant whorl treatments is an approach that warrants further applied research for both efficacy and for any possible negative effects on pollinators, but this use of pesticides is currently unapproved and should NOT be used by farmers today. Commercial availability of such a method for use with a given pesticide would require the participation of the pesticide producer because it would require changes to the label. Nevertheless, this type of method seems worthy of further development because of the need to make safe, highly effective products more accessible and affordable to smallholder farmers.

## 5.3. Pheromone-based Mating Disruption Technologies for FAW Control*

A semiochemical is a chemical released by an organism that affects the behavior of other individuals. The term "semiochemical" is derived from the Greek word *semeion*, meaning "signal". Insects often produce semiochemicals conveying specific chemical messages that modify the behavior or physiology of other individuals. These messages may communicate location or food source, induce mating, enable escape from natural enemies, avoid competition, or overcome natural host defense systems (El-Shafie and Faleiro 2017). Pheromones are powerful semiochemicals produced by insects—*e.g.,* sexual pheromones are released by female insects to attract a male. Sexual pheromones can be synthesized artificially and can be used in various ways for insect population control.

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* Disclaimer: Mention of specific companies and brand names in this section is not intended as any form of endorsement of particular commercial products over others, but only for the purpose of providing some examples of mating disruption technologies that are in the marketplace.

Mating disruption technology protects a crop by preventing a specific insect pest from effectively reproducing in the field. One of the mating disruption technologies for FAW control is the ***Pherogen™ dispenser SpoFr***, commercialized by Provivi, a company based in the USA. The technology uses a synthetic version of a sex pheromone that the female moths of FAW emit in nature to attract the males for mating. The synthetic pheromone is released into the field by dispensers, creating an invisible cloud saturating the air with an overabundance of the pheromone.). The pheromone cloud confuses the male moths and they cannot find the females with which to mate (Figure 3). This results in the reduction of the pest population without actually killing the insects.

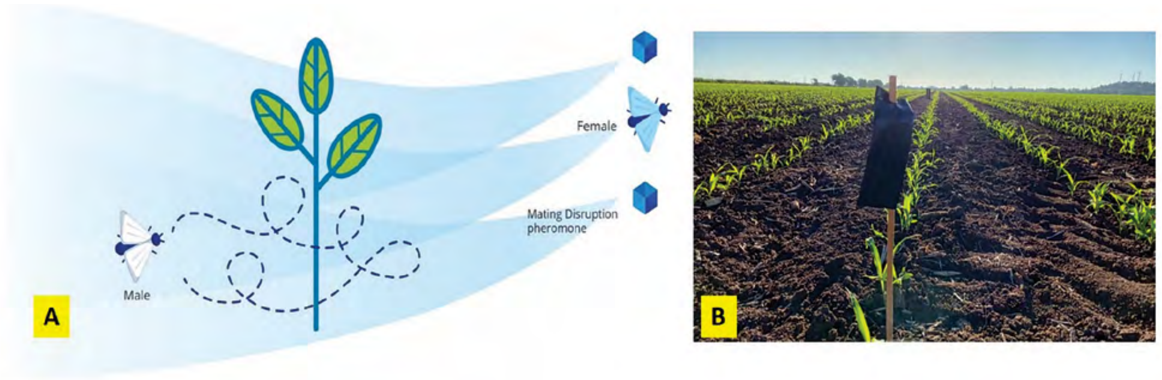


**Figure 3. (A)** An illustration of mating disruption due to the release of a synthetic sex pheromone. **(B)** Pheromone dispensers in a maize field. Figure credit: Juan Lombana (Provivi, USA).

Studies undertaken in Kenya by Provivi, in partnership with the *Centre for Agriculture and Biosciences International* (CABI), showed that the pheromone-based mating disruption technology offered protection of the maize crop from FAW for over 90 days with 90% or more mating disruption, and led to significant reduction in the number of insecticide sprays for FAW control (Juan Lombana, Provivi, personal communication). The Pherogen™ Dispenser SpoFr has been registered for FAW control in Mexico (in 2020) and Kenya (in 2021), while efforts are ongoing to register the product in Indonesia, Thailand, and China (Jarett Abramson, Provivi, personal communication). In Kenya, the cost of 36 pheromone dispensers per hectare to the farmer (enough for one season) is currently US$ 50-55.

Species-specific mating disruption pheromones offer several advantages: (1) The pheromones are a natural part of the insect's biology; (2) The technology is non-toxic to humans and is environment-friendly as it does not affect non-target organisms; and (3) Insects do not develop resistance to the semiochemicals, unlike pesticides.

Another example of pheromone-based FAW control technology is the ***CREMIT™ technology*** of ATGC Biotech, a company based in Genome Valley, Hyderabad, India. ATGC Biotech has developed three different pheromone-based technologies for FAW management, in partnership with Indian institutions, namely, Jawaharlal Nehru Centre for Advanced Scientific Research (JNCASR), Bangalore; ICAR-NBAIR, Bangalore; National Chemical Laboratory (NCL), Pune; University of Agricultural Sciences (UAS), Raichur; and Acharya N.G. Ranga Agricultural University (ANGRAU)—Hyderabad. The three novel pheromone delivery systems (natural and biodegradable) are: (1) CREMIT-T (tablet-based diffusers; Figure 4A), (2) CREMIT-SM (wax-, microcapsule-, and nanolipid-based diffusers; Figure 4B), and (3) CREMIT-P (a nanocarbon- and nanolipid-based water-dispersible wax emulsion system amenable for different application methods in the field for season-long control; Figure 4C).


**Figure 4. (A)** Tablet dispensers; **(B)** Nanolipid microcapsule film under electron microscopy; **(C)** Nanocarbon- and nanolipid-based water-dispersible emulsion system.
Figure credit: Markandeya Gorantla (ATGC Biotech, Hyderabad, India).

Evaluation of the CREMIT-T, CREMIT-SM, and CREMIT-P delivery platforms in collaboration with various institutions in India showed that the efficiency in FAW mating disruption could be up to 95% in a maize crop, with a yield difference between 14.67% and 23.15% in the treated fields above that obtained with farmer's practice (with 4 to 5 insecticide applications). A total of two applications at a specific interval are required to get season-long protection (Markandeya Gorantla, ATGC Biotech, personal communication). Season-long controlled-release FAW pheromone dispensers for monitoring and mass trapping of FAW males were successfully developed and evaluated by ICAR-NBAIR and JNCASR, Bangalore. Installation of funnel traps with controlled-release FAW pheromone dispensers helps to trap FAW moths (~50 to 60 per trap per week; Figure 5) as compared to 20-25 adult moths/trap/week with silicone/rubber septa lures and could be effectively used for reducing FAW populations in the field (Kesavan Subaharan and N. Bakthavatsalam, ICAR-NBAIR, personal communication). The CREMIT technology also uses the "lure and kill" strategy by combining a pheromone-based lure with an insecticide, thus eliminating the FAW moths that contact the source point. Costs per hectare of CREMIT products are currently US$42 for CREMIT-T, US$48 for CREMIT-SM, and US$32 for CREMIT-P. Each cost listed here reflects the total cost of the two applications per product that are required each season.

**Figure 5.** Mass trapping of FAW male moths using FAW nanolure technology.
Figure credit: Figure credit: Kesavan Subaharan (ICAR-NBAIR, Bangalore, India) and Kittur Mutt (UAS VC Farm, Mandya, India).

Like most other pest management strategies, pheromone-based mating disruption technologies need to be adopted within the context of an IPM program (Welter *et al.* 2005). This is because while pheromones disrupt mating in the fields, they do not stop gravid (egg-carrying) females from entering the fields to lay eggs. Moreover, as FAW is a highly mobile pest, sometimes with high pest population densities, pheromone-based mating disruption technologies could have better efficacy when done at the community and regional levels rather than at an individual farm level (with a village having patchwork of treated and untreated fields). By having community- and regional-level collaboration on IPM, the expansion of a pest population (through gravid females) can also be diminished. As with other technologies, mating disruption technologies need to be assessed using the CESAS model outlined in **Chapter 1**.

## 5.4. Self-Limiting Insect Technology*

First conceived in the 1930s, the use of the sterile insect technique (SIT), in which sterile insects are released into wild populations to suppress insect pest populations, is a proven insect pest management intervention (Shelton *et al.* 2020). The most successful example of this approach was the radiation-based SIT campaign in the Americas against the screwworm (*Cochliomyia hominivorax*), a livestock pest, which resulted in its eradication from the USA and much of Central America and the Caribbean.

However, the use of radiation to produce sterile insects has several limitations: for example, radiation treatments can reduce male mating fitness. The UK-based company Oxitec has used the tools of biotechnology to overcome these limitations and developed their male-selecting, self-limiting insect (SLI) genetic system to produce and mass-release male-only cohorts of the target pest species. Their approach uses colonies of genetically engineered insects carrying a transgene that confers female-specific mortality in the juvenile life stages, providing a means to mass-produce males. Once released into the field, the males find and mate with the females of the particular pest. Unlike the radiation-based SIT males, the males produced by the SLI approach retain the same reproductive fitness as the wild-type males and thus are competitive at mating.

Under the SLI approach, the female progeny of these released males cannot survive to adulthood because they are carriers of the male-selecting, self-limiting gene. With inundative releases of the self-limiting males, which mate with wild-type females, the number of females in the next generation is reduced, leading to population suppression. In addition to suppressing the wild pest population as a whole, SLI can also be used to suppress unwanted alleles in the pest. For example, in areas where pest populations have become resistant to *Bt* toxins, release of *Bt*-susceptible SLI males into the *Bt*-resistant pest population would result in the lowering of the pest population's *Bt* resistance allele frequency, which could help maintain the efficacy of *Bt* maize germplasm.

Oxitec has used the SLI approach to produce male-sterile insects of several insect pest species, most notably the diamondback moth (*Plutella xylostella*) in New York, USA, and a mosquito species (*Aedes aegypti*) in Key West, Florida, USA. In April 2021, Oxitec obtained approval from the Brazilian government's regulatory agency CTNBio for use of their Friendly™ FAW product to manage FAW in Brazil (https://www.oxitec.com/en/news/oxitec-receives-landmark-biosafety-approval-for-new-fall-armyworm-control-solution). The product is now in the pilot stage for scaling and eventual commercialization. As with other technologies, SLI needs to be assessed using the CESAS model outlined in **Chapter 1**.

# 6. Conclusions

Pesticides are an often-necessary set of tools for controlling FAW and other lepidopteran pests of maize, and should be chosen to support conservation biological control. Users need to be aware of potential hazards to people and the environment and should always use pesticides as part of IPM and IRM programs. This includes an awareness of efficacy and safety, as well as the need for insecticide rotation as part of a resistance management plan. PPE should be used when applying pesticides. An understanding of when pesticide application is necessary and cost-effective, versus when it can be delayed or skipped altogether, is important. This chapter provides important information on pesticide application methods and safety, as well as a table summarizing pesticides in current use in Africa and likely to be used in Asia against the FAW, classified by hazard, requirement for risk mitigation, and efficacy against the pest. Users are encouraged to consult appropriate experts as needed when making pesticide choices and treatment decisions.

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* Disclaimer: Mention of a specific company and a brand name in this section is not intended as any form of endorsement of particular commercial product, but only for the purpose of providing a specific example of mating disruption using a self-limiting technology.

# 7. Supplement 1: Efficacy Testing

## 7.1. Efficacy Rating Systems

There are several rating systems used to evaluate insecticide efficacy including the Davis Leaf Damage Score (Davis *et al.* 1989, 1992), larval density (larvae per plant or larvae per plot), and yield. The authors suggest that researchers experiment with additional rating systems that take into account (1) moth counts (which indicate egg-laying pressure), (2) plant growth stage (vegetative, first tassel, and reproductive), (3) density of small and large larvae, and (4) weather conditions before and after application of treatments.

### 7.1.1. Tracking Larval Size

Evaluation of the distribution of larval sizes is tedious work and requires good technical understanding. It requires sorting the larvae according to instar by measuring their head capsule size. It is arguable, however, that doing so would add resolution power to an efficacy test. It might help to identify which insecticides are effective on both small and large larvae. An alternative to direct measurement, however, is to use the feeding patterns on the plant to estimate larval size.

FAW moths lays their egg in clusters, mostly in the whorls and on the underside of the leaves. When the egg batches hatch, they produce clusters of tiny larvae. Small larvae produce clusters of tiny "windowpanes," little pits in the leaves where the larvae have eaten away the green leaf mesophyll but have not penetrated through the translucent epidermis (Figure S1). These are particularly evident if the leaf is held up to the light.

**Figure S1.** Egg hatch produces clusters of small FAW larvae (left). In turn, small larvae produce clusters of small, fresh windowpanes (right). Small, fresh windowpanes indicate the presence of small larvae. Photo credits: left, Anani Bruce (CIMMYT); right, Dan McGrath.

Small larvae feeding on the leaves are exposed and vulnerable to natural enemies and insecticide applications. Many insecticides are less effective on large FAW larvae.

As the larvae mature and increase in size, they move into the whorl. Large (4$^{th}$, 5$^{th}$, and 6$^{th}$ instar) larvae produce a variety of feeding signs including scraping, cutting, tearing, fecal pellets (frass), and a series of holes across a pinch in the leaves (see **Chapter 2**). All of these feeding signs indicate the same thing: large larvae feeding in the whorls.

Figure S2 shows the percentage of maize plants that have clusters of small, fresh windowpanes (%SFW) versus the percentage of plants with infested whorls (%IW) during an insecticide efficacy trial at the Agricultural and Horticultural Research Station, Kattalagere, University of Agricultural and Horticultural Sciences, Shivamogga, India, in 2019. Data from this trial (Deshmukh *et al.,* unpublished) are used in this chapter to illustrate several principles about insect efficacy testing and to provide examples of cost–benefit analysis for insect control products. This discussion is not intended to advocate for or against any specific product.

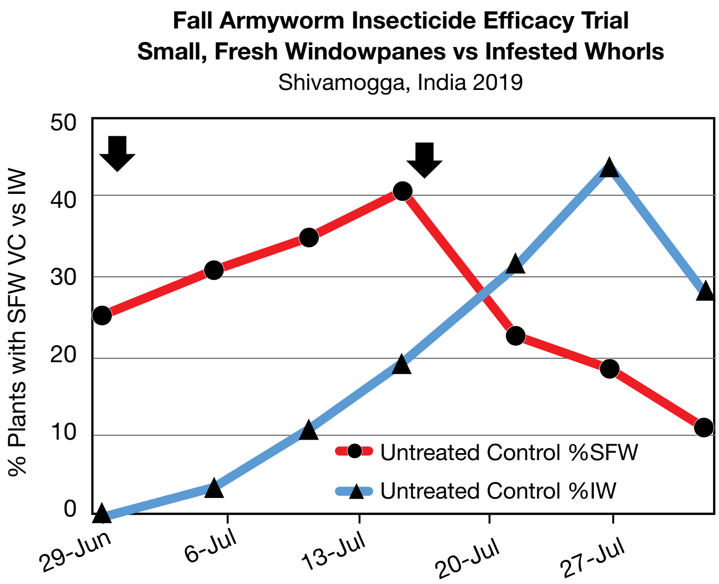


**Figure S2.** Plants with small, fresh windowpanes (%SFW, red line) and plants with infested whorls (%IW, blue line) during an insecticide efficacy trial, Shivamogga, India 2019. Black arrows indicate insecticide applications.

The percentage of plants that had small, fresh windowpanes, presumably caused by small larvae (red line), rose and then fell. During this efficacy trial, it appears that FAW egg-laying pressure declined late in the trial. By the time the plants began to tassel, egg-laying pressure was low. This could explain why there was essentially no ear damage at harvest. As a result, the efficacy of the insecticides was tested only on the basis of their ability to control foliar feeding. We did not learn anything about the ability of the insecticides to control ear damage.

The %IW (blue line) first rose and then began to fall like a second wave, following the first wave of small larvae (red line). These two waves probably indicate the same larvae progressing through development stages. As the large larvae matured, the majority left the maize plant to pupate in the soil prior to first tassel.

Detailed descriptions of scouting using %SFW and %IW are given in **Chapter 2**. Briefly, scout the field and the experimental plots on a weekly basis to determine the %SFW, an indication of egg hatch and the presence of small (1st and 2nd instar) larvae. Determine the %IW, which indicates the presence of large (4th, 5th, and 6th instar) larvae. In addition to the weekly scouting, always scout to determine the density of small and large larvae the day prior to an insecticide application and for two weeks following the application. One month prior to starting an efficacy test, establish and maintain a minimum of three FAW pheromone traps in the area. Check them once per week and calculate the average moths per trap per day (MTD). Average moth counts (based on pheromone trap captures) indicate egg-laying pressure. Keep good records of weather conditions throughout the experiment.

## 7.1.2. Davis Leaf Damage Score*

The Davis Leaf Damage Score (Davis *et al.* 1992) is widely used around the world. Leaf damage is scored by visual observation using a rating scale of 0-9. The following list describes the scale for rating 7 days after infestation from Davis *et al.* (1992), which also describes a scale for rating 14 days after infestation.

* **Chapter 4** (Host Plant Resistance) describes use of a modified Davis scale at CIMMYT for evaluation of maize germplasm against FAW under artificial infestation, taking into consideration both foliar damage and ear damage (see Prasanna *et al.* 2018 for details). CIMMYT's rating scale of 1-9 for foliar damage is based on the 0-9 scale provided by Davis *et al* (1992) but modified for consistency with similar scales used for evaluating maize germplasm against diseases/insect-pests in CIMMYT maize breeding programs. Even in cases where a 0-9 scale is used, it might be modified to meet the needs of a specific program (Toepfer *et al.* 2021). Thus, researchers should clarify the scale they have used (and the plant and leaf stage(s) at which the plants were assessed) when presenting or publishing work.

0 - No visible damage.

1 - Only pinhole lesions present on whorl leaves.

2 - Pinholes and small circular lesions present on whorl leaves.

3 - Pinholes, small circular lesions and a few small elongated (rectangular shaped) lesions of up to 1.3 cm (1/2") in length present on whorl and furl leaves.

4 - Small elongated lesions present on whorl leaves and a few mid-sized elongated lesions of 1.3 to 2.5 cm (1/2" to 1") in length present on whorl and/or furl leaves.

5 - Small elongated lesions and several mid-sized elongated lesions present on whorl and furl leaves.

6 - Small and mid-sized elongated lesions plus a few large elongated lesions of greater than 2.5 cm (1") in length present on whorl and/or furl leaves.

7 - Many small and mid-sized elongated lesions present on whorl leaves plus several large elongated lesions present on the furl leaves.

8 - Many small and mid-sized elongated lesions present on whorl leaves plus many large elongated lesions on the furl leaves.

9 - Many elongated lesions of all sizes on whorl and furl leaves plus a few uniform to irregular shaped holes (basement membrane consumed) eaten from the base of the whorl and/or furl leaves.

The Davis Leaf Damage Score is particularly useful in a trial where the plant/insect interaction is “staged,” *i.e.*, where the plants are inoculated all at once with larvae at the same stage of development. Some researchers use a criterion of 20% of plants having Davis scale 3 damage, focusing on the new leaves, as a method for assessing when to repeat a pesticide application (Imre Mezei, Corteva, personal communication). (This effectively targets 20% plants with small larvae, as does the use of 20%SFW; see Box 1).

**BOX 1. Relationship Between Davis Scale and Larval Size**

Immediately after egg hatch, 1st- and 2nd-instar FAW larvae form clusters of small, round windowpanes (pinholes) (Davis Scale 1-2). The 3rd instar moves into the whorl, where the FAW larvae produce small, increasingly elongated windowpanes that reflect the size of their head capsules (Davis Scale 3-5). As the larval size increases even more, the larvae begin to cut and tear apart the leaves (Davis Scale 6-9), creating a distinct pattern referred to as the whorl-feeding sign (see **Chapter 2**, Figure 13).

In general, foliar damage scoring may be more useful as a part of assessment of maize germplasm responses to FAW infestation in breeding programs (see **Chapter 4**) than for assessment of pesticide efficacy, particularly when older plants and tissues are being assessed. The leaf damage scale does not take into account the changing susceptibility of the plants to FAW damage based on plant growth stage (seedling, mature plant, tassel, and developing ears), nor the behavior of the larvae (leaf, whorl, or ear feeding), which influences their exposure to the insecticides, nor the changing susceptibility of the larvae to the insecticides. For example, seedlings are more sensitive than older vegetative plants, so foliar feeding at the seedling stage leads to greater yield loss than feeding at the late-whorl stage. Foliar feeding can lead to significant crop loss, but feeding on the tassels and the developing ears can lead to crop failure.

When one tries to use the Davis Scale to test the efficacy of an insecticide in the field, especially on older plants, the results can be confusing. The Davis Scale works with young seedlings because as the plant emerge from the soil and the moths begin to lay eggs, these first eggs are laid across a relatively uniform stand of plants. The first cohort of larvae progress in an orderly manner through their developmental stages. If egg laying is continuous, however, as the plants mature it becomes increasingly difficult to separate treatments using the Davis Leaf Damage Scale (Figure S3). Continuous egg laying results in overlapping generations of FAW and a mixture of larval sizes and associated behaviors (leaf, whorl, tassel, and ear feeding). For most researchers, the presence of overlapping generations blurs the efficacy data and makes it difficult to separate treatments, especially late in the maize cropping cycle. For example, in the later part of this efficacy trial, lambda-cyhalothrin appeared to work as well as the other insecticides whereas it appeared less effective at earlier stages.

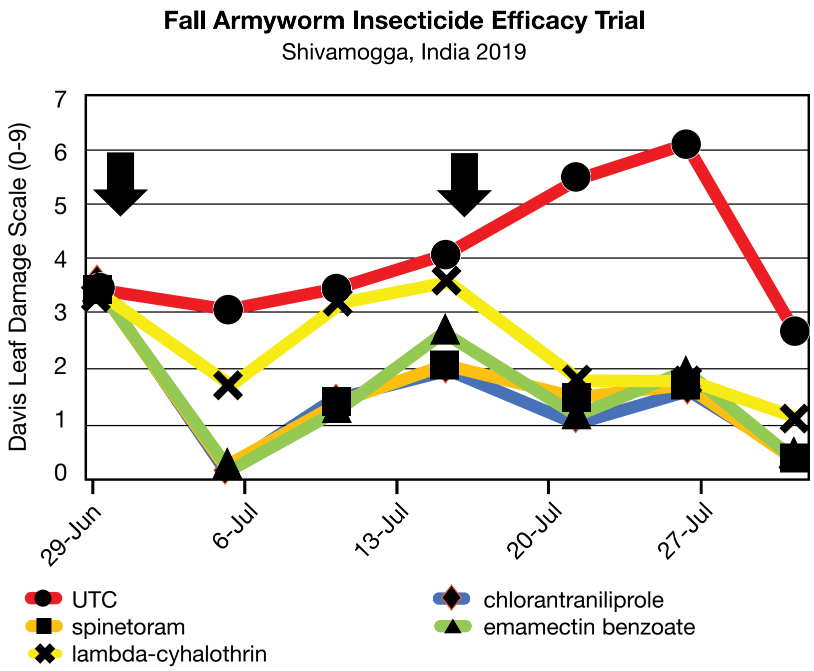


**Figure S3.** The Davis Scale (modified from Davis *et al.* 1992 by Deshmukh *et al.*)* became less effective at separating treatments as the maize plants matured and FAW generations overlapped. Black arrows indicate insecticide applications. UTC refers to untreated control.

* Scale as modified by Deshmukh *et al*: 0 - No visible leaf damage; 1 - Only pinhole damage on leaves; 2 - Pinhole and shot hole damage to leaf; 3 - Small elongated lesions (5-10 mm) on 1-3 leaves; 4 - Midsized lesions (10-30 mm) on 4-7 leaves; 5 - Large elongated lesions (>30 mm) or small portions eaten on 3-5 leaves; 6 - Elongated lesions (>30 mm) and large portions eaten on 3-5 leaves; 7 - Elongated lesions (>30 mm) and 50% of leaf eaten; 8 - Elongated lesions (30 mm) and large portions eaten on 70% of leaves; 9 - Most leaves with long lesions and complete defoliation observed

## 7.1.3. Percentage of Plants with Small, Fresh Windowpanes (%SFW)

In India, a team of researchers (Deshmukh *et al.* unpublished) tested a simple scouting protocol to determine the relative percentage of maize plants with small versus large FAW larvae along with the Davis Leaf Damage Scale. This allowed comparison of the two rating systems on the same plants in the same efficacy trial. The %SFW and %IW before and after application of the insecticides were tested as potential measures of insecticide efficacy.

The %SFW provides a rough estimate of the density of small larvae, whereas %IW provides a rough estimate of the density of large larvae. The scouting methodology is not as accurate as measuring head capsule size, and it has other weakness. The %SFW, however, appeared to separate treatments better than the Davis Leaf Damage Scale (Figure S3), especially as the maize plants matured and the FAW generations began to overlap later in the cropping cycle (Figure S4).

In Figure S4, it appears that lambda-cyhalothrin may not be as effective at controlling FAW as the other insecticides in the trial. If a result such as this is observed, it is important to ask whether it is due to resistance in the FAW population to the pyrethroid family of insecticides. Chlorantraniliprole, spinetoram, and emamectin benzoate appear to be equally effective at controlling small larvae, based on %SFW before and after application.

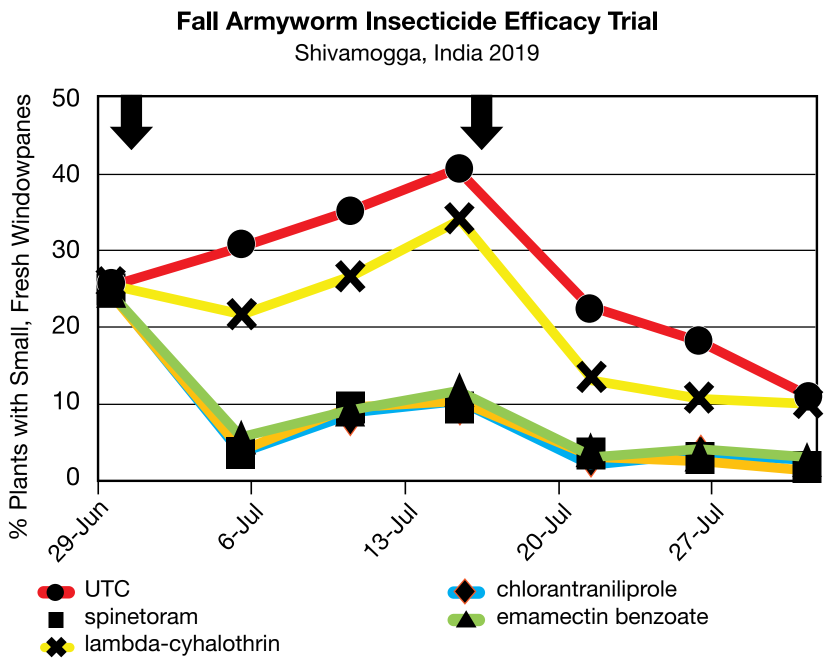


**Figure S4.** Prior to tassel emergence, the percentage of plants with small, fresh windowpanes (%SFW) was a useful measure of relative insecticide efficacy. Black arrows indicate insecticide applications. Black arrows indicate insecticide applications. UTC refers to untreated control.

The team (Deshmukh *et al.* unpublished) also evaluated the merits of chlorantraniliprole used alone or in combination with lambda-cyhalothrin based on the percentage of plants with clusters of small, fresh windowpanes before and after application of the insecticides. As expected, the mixture of 4.6% lambda-cyhalothrin and 9.3% chlorantraniliprole (35 g a.i./ha) was not as effective as 18.5% chlorantraniliprole (37 g. a.i./ha) (Figure S5) but provided substantial control at a lower cost (see Section 7.1.5). The toxicity of the mixture is greater than that of chlorantraniliprole, however, because lambda-cyhalothrin is considerably more toxic than chlorantraniliprole.

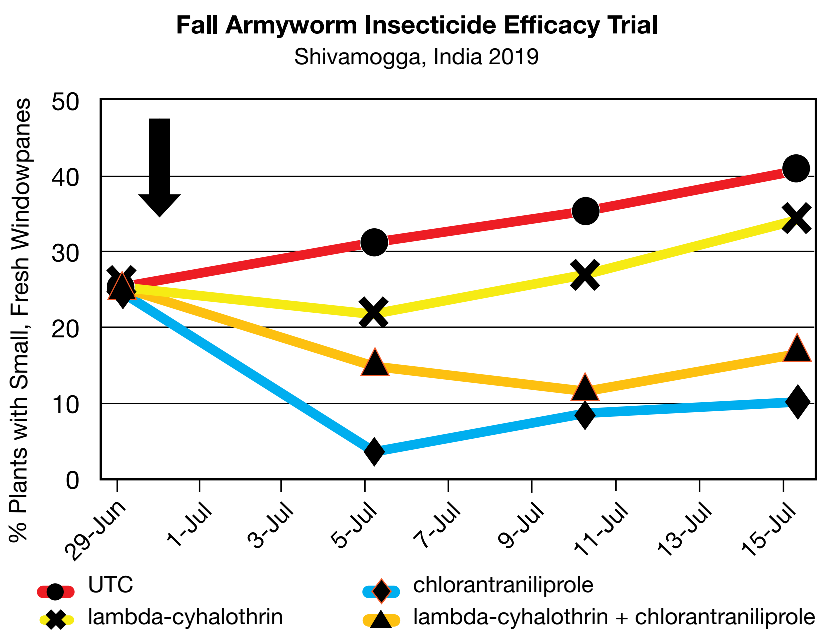


**Figure S5.** When assessed on the basis of %small, fresh windowpanes, a mixture containing 4.6% lambda-cyhalothrin and 9.3% chlorantraniliprole was less effective than 18.5% chlorantraniliprole but still more effective than 5% lambda-cyhalothrin. Black arrow indicates insecticide application. UTC refers to untreated control.

### 7.1.4. Conclusion—Efficacy Testing Methods

Yield is the primary measure of insecticide efficacy, but the number and size of larvae needs to be understood throughout an efficacy trial, particularly at the time(s) of pesticide application. Several methods are available for assessing the number and size of larvae such as percent infestation, the Davis scale, etc. These rating systems have a long track record. In addition, we suggest that researchers experiment with additional measures. The %SFW before and after insecticide applications, for example, may add resolution power, especially when insecticide efficacy trials are conducted in the field with naturally occurring infestations of FAW. The critical issue is the need to take into account the relative vulnerability of small vs. large larvae to many insecticides. We also suggest that researchers document and report average moth counts and field scouting data (especially the relative proportion of small and large larvae) prior to and immediately following the application of treatments. This may help to improve the resolution power of the traditional rating systems. Finally, we suggest that researchers document rainstorms and weather data in general. Rainstorms kill small larvae and should be taken into account during an efficacy trial.

### 7.1.5. Use of FAW Insecticide Efficacy Data to Inform A Cost–Benefit Assessment

The decision to treat a field infested with FAW or other pests is largely based on economics—will the cost of the treatment result in a level of yield protection to justify its use? In IPM, this portion of the assessment is captured in the Economic Injury Level (EIL) and the Economic Threshold (ET) (see **Chapter 1**). In addition to labor, the key variables include the cost (value) of maize seed, the cost of the treatment (*e.g.,* the pesticide), the efficacy of the treatment, and the value of the maize crop saved from loss to the pest. With these variables, a cost-benefit assessment can be performed. One very important point is that it is assumed that the farmer will treat the field in a manner consistent with the specifications of the pesticide. This aspect is discussed at length in the preceding sections.

Using the data from the efficacy trial described above, we present here an example of how practitioners can use these data to help inform management decisions. Please note that these data are unpublished and their use here is only to provide an illustration of the decision-making process for pest treatment cost and benefit. In addition, pesticide costs and maize prices can vary considerably from country to country. Nevertheless, the analysis shown here illustrates an approach to assessing the value of a treatment being considered.

The five pesticides tested in the efficacy trial were lambda-cyhalothrin (efficacy rated as fair to good for FAW control), chlorantraniliprole (efficacy rated as excellent), spinetoram (efficacy rated as excellent), and emamectin benzoate (efficacy rated as excellent), and a mixture of lambda-cyhalothrin and chlorantraniliprole. As mentioned above, chlorantraniliprole, spinetoram, and emamectin benzoate appear to be equally effective at controlling small FAW larvae, based on %SFW (Figure S4). On this basis, the mixture of lambda-cyhalothrin and chlorantraniliprole had intermediate effectiveness (Figure S5), and lambda-cyhalothrin was the least effective.

Tables S1 and S2 present the efficacy and yield data for the pesticides used in the FAW efficacy trials under two different yield scenarios. Included in the tables are variable costs of the pesticide product, the cost of maize, the total maize yield, and the maize yield protected by the treatments. In this assessment we assumed that the labor cost variable was the same across treatments. Based on these calculations, estimates of the return on investment in terms of value of maize protected and cost of treatment in terms of maize yield are given.

**Table S1.** Data from an efficacy trial (Deshmukh *et al.*, unpublished), with a maximum yield of 5.7 t/ha, used to illustrate calculations of FAW treatment costs and benefits using insecticides.

| Treatment | Formulation (g a.i./ ha) | Yield (kg/ ha) | Yield protected (kg/ha) | Cost of treatment (per ha) | Market value of 1 kg seed (US$) | Value of protected yield | Net return (Value protected – Cost of treatment) | Yield (kg) needed to pay for treatment |
|---|---|---|---|---|---|---|---|---|
| Lambda - cyhalothrin 5 EC | 25 | 4533 | 1560 | $11.76 | $0.21 | $327.60 | $315.84 | 56 |
| Spinetoram 11.7 SC | 30 | 5680 | 2707 | $73.50 | $0.21 | $568.40 | $494.90 | 350 |
| Chlorantraniliprole 18.5 SC | 37 | 5560 | 2587 | $88.67 | $0.21 | $543.20 | $454.53 | 422 |
| Emamectin benzoate 5 SG | 12.5 | 5553 | 2580 | $15.40 | $0.21 | $541.80 | $526.40 | 73 |
| Chlorantraniliprole 9.3% + Lambda-cyhalothrin 4.6% ZC | 35 | 4933 | 1960 | $56.87 | $0.21 | $411.60 | $354.73 | 271 |
| Untreated control (UTC) | - | 2973 | | | $0.21 | | | 0 |

Formulation indicates grams a.i./ha for each application. Each treatment was applied twice.
Calculations were performed using unrounded values.

**Table S2.** Data from an efficacy trial (Deshmukh *et al.*, unpublished), with yields proportionately adjusted to a maximum yield of 2 t/ha, used to illustrate FAW control costs and benefits using insecticides.

| Treatment | Formulation (g a.i./ ha) | Yield (kg/ ha) | Yield protected (kg/ha) | Cost of treatment (per ha) | Market value of 1 kg seed (US$) | Value of protected yield | Net return (Value protected – Cost of treatment) | Yield (kg) needed to pay for treatment |
|---|---|---|---|---|---|---|---|---|
| Lambda - cyhalothrin 5 EC | 25 | 1596 | 549 | $11.76 | $0.21 | $115.35 | $103.59 | 56 |
| Spinetoram 11.7 SC | 30 | 2000 | 953 | $73.50 | $0.21 | $200.14 | $126.64 | 350 |
| Chlorantraniliprole 18.5 SC | 37 | 1958 | 911 | $88.67 | $0.21 | $191.27 | $102.60 | 422 |
| Emamectin benzoate 5 SG | 12.5 | 1955 | 908 | $15.40 | $0.21 | $190.77 | $175.37 | 73 |
| Chlorantraniliprole 9.3% + Lambda-cyhalothrin 4.6% ZC | 35 | 1737 | 690 | $56.87 | $0.21 | $144.93 | $88.06 | 271 |
| Untreated control (UTC) | - | 1047 | | | $0.21 | | | 0 |

Formulation indicates grams a.i./ha for each application. Each treatment was applied twice.
Calculations were performed using unrounded values.

### *7.1.5.1. Cost–benefit analysis assuming yields >5 t/ha*

The data presented in Table S1 are the data recorded in the efficacy trial (Deshmukh *et al.,* unpublished), here termed the 5.7 t/ha data. The highest-yielding treatment, spinetoram, was taken as the optimal possible yield at 5.7 t/ha (5680 Kg/ha actual). Note that it is possible the yield could have been higher in the absence of FAW, but for illustrative purposes it was used as the baseline. Based on the data, all insecticide treatments produced an adjusted positive economic return on investment ranging from $315.84 to $526.40 per hectare in the 5.7 t/ha scenario.

At the low end of the net return per hectare, the lambda-cyhalothrin treatment, which is rated as fair to good in terms of efficacy (Table 1), produced a protected yield of 1560 kg/ha at a cost of $11.76/ha, with a net return of $315.84 (Table S1). To pay for the treatment, the protected yield needed would be a minimum of 56 kg/ha, which was easily met by the 1560 kg/ha protected yield.

The spinetoram treatment, which is rated as excellent in terms of efficacy, produced the highest level of protected yield (2707 kg/ha) at a cost of $73.50/ha. The value of the protected yield was $568.40 with a net return of $494.90. To pay for the treatment, the protected yield needed would be a minimum of 350 kg/ha, which was easily met by the 2707 kg/ha protected yield. Similarly, the chlorantraniliprole treatment provided excellent control but at a cost higher than that of the other options ($88.67/ha).

The emamectin benzoate treatment, which is rated as excellent in terms of efficacy, produced a protected yield of 2580 kg/ha at a cost of $15.40/ha. The value of the protected yield was $541.80 with a net return of $526.40. To pay for the treatment, the protected yield needed would be a minimum of 73 kg/ha which was easily met by the 2580 kg/ha protected yield attained.

At about two-thirds the cost of the chlorantraniliprole (18%) treatment was the mixture of chlorantraniliprole (9.3%) and lambda-cyhalothrin (4.6%), which had efficacy intermediate between the components (Figure S5). This product produced a protected yield of 1960 kg/ha at a cost of $56.87/ha. The value of the protected yield was $411.60 with a net return of $354.73. To pay for the treatment, the protected yield needed would be a minimum of 271 kg/ha, which was easily met by the 1960 kg/ha protected yield.

These data show the range of options for choosing a treatment for FAW control. Factors a farmer might consider for choosing a treatment include up-front costs, economic benefit, availability, and safety of the product. All treatments produced a respectable return on investment. The low-end efficacy treatment of lambda-cyhalothrin yielded about 20% less than the spinetoram treatment but the cost to the farmer was low at $11.76/ha. Nevertheless, the farmer would have realized a net return of $315.84/ha. At the other extreme, a farmer choosing spinetoram would have had an initial cost of $73.50/ha but a net return of $494.90/ha. The best value was emamectin benzoate, which cost only $15.40/ha but yielded a net return of $526.40.

### *7.1.5.2. Cost–benefit analysis assuming yields ~2 t/ha*

Generally, smallholder farmers in the stress-prone rainfed environments in India obtain maize yields in the range of 1-3 t/ha. Accordingly, we extrapolated the data from the 5.7 t/ha trial into a 2 t/ha scenario (Table S2). It is assumed that the costs of the treatments, including labor, are approximately the same in a 2 t/ha field as they are in a 5.7 t/ha field.

At the low end of the net return per hectare, the lambda-cyhalothrin treatment produced a protected yield of 549 kg/ha at a cost of $11.76/ha, with a net return of $103.59. To pay for the treatment, the protected yield needed would be a minimum of 56 kg/ha which was easily met by the 549 kg/ha protected yield—a nearly 10-fold difference.

The spinetoram treatment produced a protected yield of 953 kg/ha at a cost of $73.50/ha. The value of the protected yield was $200.14 with a net return of $124.64. To pay for the treatment, the protected yield needed would be a minimum of 350 kg/ha which was easily met by the 953 kg/ha protected yield—a nearly 3-fold difference. Similarly, the chlorantraniliprole treatment provided excellent control but at a cost higher than that of the other options ($88.67/ha). Given an expected maximum yield of 2 t/ha, the value of the protected yield is about 2-fold that of the treatment cost.

The emamectin benzoate treatment produced a protected yield of 908 kg/ha at a cost of $15.40/ha. The value of the protected yield was $190.77 with a net return of $175.37. To pay for the treatment, the protected yield needed would be a minimum of 73 kg/ha which was easily met by the 908 kg/ha protected yield—over a 12-fold difference.

The mixture of chlorantraniliprole and lambda-cyhalothrin produced a protected yield of 690 kg/ha at a cost of $56.87/ha. The value of the protected yield was $144.93 with a net return of $88.06. To pay for the treatment, the protected yield needed would be a minimum of 271 kg/ha which was met by the 690 kg/ha protected yield—a 2.5-fold difference.

As in the example for the 5.7 t/ha scenario, all of the treatments produced a respectable return on investment. However, given the much lower yields in the 2 t/ha scenario, the ratios of extra income to treatment cost are much lower. For example, in the low-yielding (2 t/ha) scenario, the chlorantraniliprole treatment had a much narrower level of return, only 2-fold, than in the 5 t/ha scenario, where it was 6-fold. The same was true of the spinetoram treatment. As in the 5 t/ha scenario, the emamectin benzoate produced good yield protection at a low price and with over a 12-fold margin. Even if the total expected profit is higher for a more expensive product, a farmer with little cash available to risk might choose a lower-cost product with an acceptable yield benefit.

### 7.1.5.3. Cost–benefit calculations

The following equations provide several methods to calculate the costs and benefits of a pesticide treatment. Equations 1-3 consider only the purchase price of the applied product, but as noted below, other costs such as labor (Equations 4-5) need to be considered. As above, these examples use US$, which can be replaced with any currency:

**1. To determine the net return (US$/ha) from a treatment:**

| | | | | |
|---|---|---|---|---|
| ________ kg/ha | minus (–) | ________ kg/ha | = | ________ kg/ha |
| Yield of treated area | | Yield of untreated control | | Yield protected by spray |

| | | | | |
|---|---|---|---|---|
| ________ kg/ha | × | US$________ | = | US$________ |
| Yield protected by spray | | Cost of grain per kg | | Value protected by spray (per ha) |

| | | | | |
|---|---|---|---|---|
| US$________ | minus (–) | US$________ | = | US$________ |
| Value protected by spray (per ha) | | Cost of treatment (per ha) | | Net return (per ha) from treatment |

**2. To determine the amount of yield protection required to pay for a treatment:**

| | | | | |
|---|---|---|---|---|
| US$________ | ÷ | US$________ | = | ________ kg/ha |
| Cost of treatment (per ha) | | Cost of grain (per kg) | | Yield protection (in kg/ha) needed to pay for treatment |

### 3. To determine the rate of return of the cost of treatment:

| | | | | |
|---|---|---|---|---|
| US$________ | ÷ | US$________ | = | ________-fold |
| Value protected by spray (per ha) | | Cost of treatment (per ha) | | Rate of return |

Typically, the cost of a treatment is focused on the cost of the applied product, but other costs need to be considered. For many pesticide products, the cost of the sprayer and PPE must be considered, thought both are typically used for multiple applications.

An under-considered but very important cost is that of labor. The examples below estimate the cost, in hours, of a spray treatment vs. a plant-by-plant treatment such as hand-crushing of eggs.

### 4. To determine the labor cost (hours) of a spray treatment:

| | | | | | | |
|---|---|---|---|---|---|---|
| ________ ha | × | 10,000 | ÷ | _______ m | = | ________ m |
| Field size hectares | | Size of 1 ha in square meters | | Distance between rows (meters) | | Meters of row in the field |

| | | | | |
|---|---|---|---|---|
| ________ m | ÷ | 4,828 | = | ________ h |
| Meters of row in the field | | Speed (meters/hour) assuming typical walking pace of 3 miles/hour | | Hours to spray field |

For a 1-ha field with row spacing of 2.5 feet (0.76 m), this calculation indicates that the field would require approximately 2.7 hours to spray at a typical walking pace.

### 5. To determine the labor cost (hours) required for a treatment applied to plants individually (*e.g.*, egg crushing):

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| ________ha | × | _____ | × | _____ s | ÷ | 3600 | = | ________ h |
| Field size | | Number of plants per hectare | | Number of seconds per plant | | Number of seconds per hour | | Hours to treat field |

For a 1-ha field planted at a density of 60,000 plants per hectare, and a treatment requiring 5 seconds per plant, the field would require 83 hours to treat.

## 7.2. Sample Protocol for GLP-Like Efficacy Trial

The following is an example of an efficacy protocol for a maize FAW trial, illustrating the key principles of such a trial. Researchers should adapt this example to their own objectives and circumstances.

1. PROJECT TITLE

Efficacy of [name of PESTICIDE a.i.] on Maize for Control of Fall Armyworm

2. JUSTIFICATION AND OBJECTIVES

The Fall Armyworm (FAW; *Spodoptera frugiperda*; Noctuidae; Lepidoptera) is a pest of the Americas recently introduced into Africa and Asia. The purpose of this efficacy and crop safety trial is to determine the level of control provided by [PESTICIDE a.i. (PRODUCT NAME)].

3. INSTITUTIONAL RESEARCH COORDINATOR

________________________________________ ________________

NAME (Date)

Project Headquarters ADDRESS

Phone: XXXXXXXXX FAX: XXXXXXX, e-mail: XXXXXXX

4. TEST SYSTEM/CROP

Maize (*Zea mays*) shall be used as the test crop. The maize variety and source shall be provided.

5. TEST/CONTROL SUBSTANCE

Use the products/formulations listed in Section 9 of this protocol. It is very important that the test and control substances are accurately described. The Field Research Director (FRD) will communicate with the industry representatives on the protocol to ensure that the appropriate amount of test substance is ordered. Upon receipt, document the lot/batch number. Store the test substance in a secure, clean, dry area at temperature ranges noted in the product label or Safety Data Sheet..

Chain of Custody (CoC): It is important that the Chain of Custody of the Test Substance (the new pesticide being tested) and the Control Substances (the control pesticide(s)) be maintained and documented.

6. TEST SYSTEM DESIGN

EXPERIMENTAL DESIGN

Each test site will typically consist of a minimum of four replicates of each treatment using an appropriate statistical design. NOTE: The Randomized Complete Block Design (RCBD) is the most commonly used experimental design for pesticide trials, but other designs may be used. The RCBD is used here for illustrative purposes.

In addition to the pesticide test substance, an untreated control and a treatment that includes a registered insecticide commonly used by local growers for control of FAW insects will also be included in this experiment.

The starting point for the experiment varies depending on the experimental protocol and could be based on days after planting, pest number and size, etc. To initiate a trial based on pest number and size, a researcher might start the trial based on observing a particular percentage of plants with SFW (see **Chapter 2**) or percentage of plants at Davis scale rating 0-3 (Imre Mezei, Corteva, personal communication). For trials that are based on a fixed spray schedule rather than on larval size/number, a pre-spray evaluation to determine the pre-existing pest level is useful to compare the impact of the application.

As noted above, an experiment would typically have at least four replicate blocks per treatment, with experimental plots consisting of 10 rows, each 5 m long, with 0.8 m between rows with a 40 to 50 seed planting density. Seedlings may later be thinned to 34 plants per row. The experimental plot should be surrounded with a buffer area (*e.g.*, six rows). In many pesticide efficacy control trials, plastic sheeting may be used to reduce pesticide drift between plots. Alleys should be established between experimental blocks. To prevent the small larvae from ballooning across plots within the blocks, at least two guard rows (additional rows of maize) should be planted between the plots. The guard rows serve only as a separation and buffer between the experimental plots; no data are collected from them. Generally, in pesticide evaluation, both the plot and the adjacent guard rows are sprayed with the test product, even though only the center rows are evaluated. In the case of FAW, however, the risk of this approach is that small larvae in the control (untreated) plots can balloon into adjacent plots if the guard rows surrounding the controls are untreated. This can be addressed by first applying the test treatment to each plot, leaving the negative control plots untreated, and then spraying the guard rows separating the plots with an appropriate low-toxicity insecticide such as chlorantraniliprole (Figure S6).

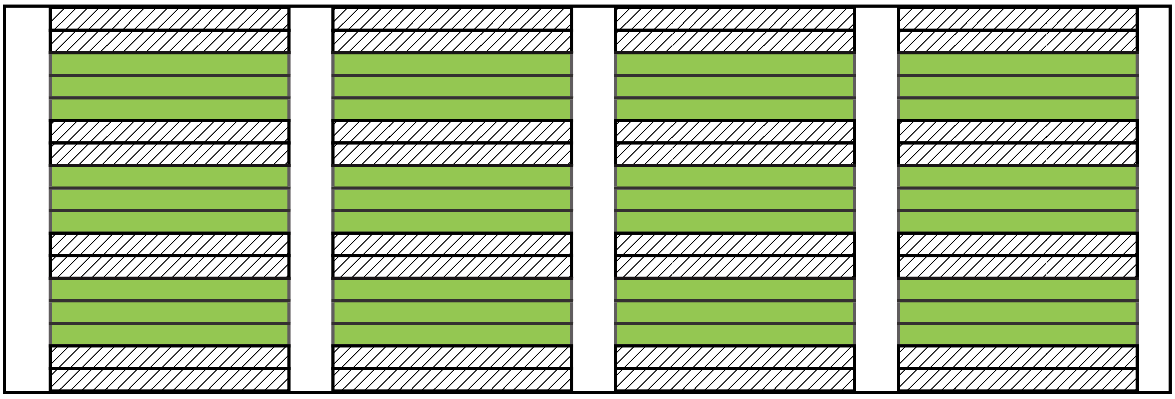

**Figure S6.** Sample plot map showing an experiment consisting of four blocks separated by alleys (represented by vertical boxes). The number of rows per plot may vary depending on the practitioner. In this illustration, each block contains three plots of three rows each (green) surrounded by guard rows. Within each block, treatments should be assigned randomly to the plots. Guard rows are shown as hatched rectangles.

## TREATMENT TYPES

### A. Natural Infestation

Natural infestation refers to the situation where the trial is planted and allowed to become infested with FAW naturally. This is the least controlled type of trial because the researcher has no control on when and with what intensity the infestation will occur. Indeed, it is possible that no infestation will occur.

### B. Artificial Infestation

Artificial infestation uses FAW reared in a laboratory on artificial diet (Mihm 1983). Briefly, the hatching larvae are mixed into a maize grit mixture and the neonates are inoculated onto the maize plants using an inoculation device (Mihm 1983; Davis 2019). The inoculator is calibrated to deliver a precise number of neonates onto the plant. Single or multiple applications of neonates can be made depending on the protocol. Generally, 12 to 24 hours after inoculation the pesticide can be applied. If performed under nethouse conditions, the researcher can exclude other non-FAW lepidopteran from the trial.

## TRIAL EVALUATION

The trial field should be scouted before the pesticide treatment is applied and then at least once a week thereafter. Reentry should consider the label and Safety Data Sheet (SDS; formerly the MSDS) reentry interval, safety precautions, and needed personal protective equipment (PPE) (FAO and WHO 2015; NPIC 2020; UN 2019).

Pest pressure should be evaluated throughout the trial. Measures that might be used include the following:

- Davis (0-9) scale. See description in Section 7.1.2.
- Percentage of Infested Plants (%IP). The percentage of plants infested by FAW regardless of larval instar. The larval instar should be noted as accurately as possible.
- Percentage of Plants with Infested Whorls (%IW). The percentage of plants with FAW larvae in the whorl should be recorded. The larval instar should be noted as accurately as possible.
- Percentage of Plants with Small, Fresh Windowpanes (%SFW). The percentage of plants with SFW should be recorded.
- Moth counts.

NOTE: The % infestation is an important assessment measure because it is the basis for the Action Thresholds (AT) used in many IPM programs (McGrath *et al.* 2018). The problem with the % infestation measure is that it does not typically distinguish between small and large larvae. In an efficacy trial, however, larval size is important to determine. Large larvae embedded in the whorl are more resistant to insecticides. The efficacy of a given insecticide will look very different depending on whether the plant is infested with large, small, or a combination of large and small larvae.

7. TEST SITE SELECTION

Select a test site that is appropriate for growing maize. Try to select sites that are uniform and avoid field edges. Site should be planted and maintained using Good Agricultural Practices (GAP).

8. TEST SUBSTANCE APPLICATION

The test substance will be applied in the manner described in Section 9 of this protocol. Adequate pressure, volume, and equipment will be used to cover leaves and penetrate the crop canopy.

9. TREATMENTS:

**This table is an illustration only.** Rates and application should be appropriate to the pesticide being tested.

| TRT # | Product (formulation) | Rate of active ingredient per hectare | Rate of product per hectare | Application placement and timing | Spray volume range |
|---|---|---|---|---|---|
| 1 | Untreated | N/A | N/A | N/A | N/A |
| 2* | Test pesticide 1 | XX g a.i./ha | XX ml | Chosen according to the experimental design of the trial** | 800-1200 L/ha (Volume will be dependent on plant size and amount of foliage present.) |
| 3* | Test pesticide 2 | XX g a.i./ha | XX ml | | |
| 4* | Test pesticide 3 | XX g a.i./ha | XX ml | | |
| 5*** | Any commercial product registered for use by local growers | Consult label | Consult label | Foliar directed. Follow local label rate and use directions | |

* Consult the label to determine appropriate rate (g a.i./ha) for testing.
** Application placement and timing will depend on the type of treatment being tested (spray, whorl/axil treatment, etc.) and on the residual activity of the test product.
*** Use a locally registered product commonly used by growers. Follow label directions for rate and application timing.
NOTE: All plots should be maintained using GAP (*e.g.,* weed and disease control, fertilizers, etc.) to maintain a vigorous crop, except that no other insecticides should be used except the experimental treatments. (If an insecticide is absolutely needed, try to use specific products for those other arthropod pests to avoid causing effects on the target pest of the experiment.) The insecticide treatments are applied to their assigned plots.

10. INSECT EVALUATIONS and STATISTICAL ANALYSIS

Some researchers find that a direct assessment of larval instar is useful in assessing efficacy. For example, one might record initial insect counts prior to first and second application, and then at 7, 14, and 28 days after each application, or at an appropriate time to assess efficacy. Such counts require destructive sampling (at least 10/plot) at each evaluation time point and should include the numbers of small ($1^{st}$-$3^{rd}$ instar) and large ($4^{th}$-$6^{th}$ instar) larvae as well as the total.

Conduct appropriate statistical analysis on the data, including level of significance, coefficient of variation, Least Significant differences, mean separation, to determine if significant differences exist in insect control between treatments. Consult a statistician for the final design.

If it is important for the study to understand the prevalence and number of non-target organisms (NTOs; *e.g.*, parasitoids), consider including that as part of the design. If NTOs are included in the study, clear endpoints are necessary to justify the cost and labor.

11. STATISTICAL ANALYSIS

There are many different statistical analysis packages available. PROC ANOVA and Tukey's multiple rank test ($P < 0.05$) can be used to compare among treatments. Software such as SAS/STAT (SAS version 9.0; SAS Institute, Cary, North Carolina) can be used to analyze the percentage of plant injury and the damage ratings (*e.g.*, Davis Scale). Some regulatory agencies specify which statistical packages are acceptable for data analysis.

12. SUPPLEMENTAL CROP TREATMENTS

The integrity of the study will be protected by managing pests (insects, diseases, weeds) causing significant damage to the test crop. Only registered maintenance pesticides will be used at label rates. Try to use specific products for other pests to avoid causing effects to the target pest of this experiment with the secondary products used. Document all supplemental crop treatments used by the farmer.

13. FIELD DOCUMENTATION AND RECORD KEEPING

All operations, data and observations, appropriate to this study will be recorded directly. A report will be written in a style appropriate for publication in a scientific journal and include an Introduction, Materials and Methods, statistically analyzed data in a table or graph within a Results and Discussion section. Any and all publications shall contain an Acknowledgement section stating (if appropriate), "This research was supported (or partially supported) by the XXXX." It is recommended that at a minimum, collect and maintain the following raw data:

- Test site information
- Plot maps
- Information regarding calibration, and use of application equipment
- Treatment application data
- Crop maintenance pesticides and cultural practices
- Meteorological/Irrigation records

Keep detailed records of weather conditions including: temperature, precipitation and/or irrigation, and relative humidity with a minimum of high, low, and average daily temperatures. Keep in mind that risk of crop loss depends on egg-laying pressure, the maize growth stage, and environmental conditions. If there are a series of well-timed heavy rainstorms during the efficacy trial, neither the level of egg-laying pressure nor the level of infestation may be a predictor of yield loss. In some climates, rainstorms provide substantial control of FAW. Other information to record includes: soil-type or soil-less media, application equipment, irrigation (type and frequency), and plant growth stage at application and data collection dates. Content of reports must be sufficient for a reader to fully understand how the experiment was conducted.

Photographs often illustrate experimental design, site conditions, and impacts of treatments very well. You are encouraged to include a picture or two of the location where the experiment is sited. It is highly encouraged that pictures illustrating treatment effects are taken if and when these impacts are visually apparent.

If different application methods or evaluations are made, please clearly specify differences in the final report and explain reason for change.

14. PROTOCOL/MODIFICATIONS

Consult with the Research Coordinator regarding desired changes in this protocol prior to occurrence.

15. FIELD RESEARCH REPORT/ARCHIVING

A short summary of one to two pages will be submitted to the study sponsor. Statistical analysis of the data is required. Copies of the data from each evaluation should also be provided. The results will include summaries of statistically analyzed data showing the levels of significance, coefficient of variation, Least Significant differences, mean separation. Compare results over seasons for multiple season trials. The FRD will send the report and evaluation data to the appropriate leadership, and a copy to your regulatory authorities.

16. FIELD PERSONNEL

| Trial ID# | FRD | Address | E-mail |
|---|---|---|---|
| XX-1 | Name[1] | See Below | Name@gmail.com |
| XX-2 | Name[2] | See Below | Name@gmail.com |
| XX-3 | Name[3] | See Below | Name@gmail.com |
| XX-4 | Name[4] | See Below | Name@gmail.com |

[1] Country 1: NAME, Department, Institution.

List of abbreviations

| | |
|---|---|
| a.i. | active ingredient |
| AT | Action Threshold |
| CoC | Chain of Custody |
| IP | Infested Plants |
| IW | Infested Whorls |
| FRD | Field Research Director |
| GAP | Good Agricultural Practices |
| GHS | Global Harmonized System |
| IPM | Integrated Pest Management |
| IW | Infested Whorls |
| PPE | Personal Protective Equipment |
| FRD | Field Research Director |
| MSDS | Material Safety Data Sheet |
| NPIC | National Pesticide information Center |
| PPE | Personal Protective Equipment |
| RCBD | Randomized Complete Block Design |
| SFW | Small Fresh Windowpanes |
| SDS | Safety Data Sheet (formerly MSDS) |
| UN | United Nations |

# 8. Supplement 2: How to Calibrate a Backpack Sprayer Using the Measured-Amount Approach

## 8.1. Introduction

There are many ways to calibrate a pesticide sprayer. Most calibration strategies are designed for boom sprayers mounted on tractors. The following method is recommended for smallholder farmers using a small handheld or backpack sprayer. Whether one is working with a tractor or a backpack sprayer, one needs to operate the sprayer at a consistent groundspeed, pressure, and nozzle height.


**Figure S7.** Backpack sprayers. (Left) Sprayer with electric pump to maintain constant pressure. Photo credit: Sharanabasappa Deshmukh. (Right) The sprayer is operated by an applicator on a maize field with proper PPE. Photo credit: Tim Krupnik (CIMMYT).

The calibration method described below can be summarized in five steps:

1) Add a measured amount of water to the spray tank.
2) Spray until you run out of water.
3) Measure the length and width of the area you sprayed.
4) Calculate the area sprayed per measured volume.
5) Calculate the area sprayed by the sprayer when full.

Knowing the area covered by the spray volume in a full tank, a smallholder farmer can estimate the portion of a hectare covered by that volume. By multiplying the fraction of a hectare covered by the sprayer times the product rate (given on the product label), the farmer can calculate how many milliliters (or grams) of product to add to the tank.

Fraction of hectare covered by total sprayer volume × Product label rate = mL (or g) product to add to the tank.

- ✓ **Tip:** In some cases, the product rate is expressed as "the bottle" or "the sachet" per hectare. In other words, if the bottle contains 250 ml of product, the rate would be 250 milliliters per hectare or "one bottle per hectare." If you are spraying less than one hectare, you will need to use a fraction of the bottle and the rate will be in milliliters per hectare.

These steps for calibration and preparation of spray solution are given in detail below.

If the smallholder farmer lacks confidence handling fractions, then the farmer should calculate the area covered by one spray batch and provide that information to the local pesticide-kiosk operator. Together, they can calculate how much product to put into the spray tank.

If neither the smallholder farmer nor the local pesticide-kiosk operator is confident in handling fractions, the farmer should consider using methods of pest control other than insecticides. This is especially true if the insecticides are highly toxic.

## 8.2. Sprayer Calibration

### Materials

- Sprayer with appropriate spray nozzle (the nozzle that will be used to treat the field)
- Measuring cup (or plastic bottle of known volume)
- Measuring tape (or cord/rope/string of known length)
- Water

*NOTE: No pesticide is used during calibration!*

### Instructions

1) Lay out a long measuring tape (50-100 meters). Alternatively, cord, rope, or string can be used but the length of the cord must be known.
2) Fill the spray tank only with water, close the lid, and bring the tank to full pressure. DO NOT USE PESTICIDE.
3) Hold the nozzle above the ground at the height you will use while spraying. Hold the nozzle as still as possible.
   - ✓ **Tip:** To maintain a consistent nozzle height, tie a string to the end of the nozzle wand. The string should be approximately the same length as the distance from the nozzle to the ground. Suspend a small weight (nut, bolt, rock) from the end of the string to maintain a consistent nozzle height by keeping the weight at a constant distance from the ground while spraying. Note that the weight should not touch the ground but should be suspended just a bit above the ground.
4) Stand still and spray until there is a wet mark on the ground. This mark reveals the width of the spray band.
5) Measure the width of the spray band.
   - Example: The spray band is 75 centimeters (0.75 meters) wide.
6) De-pressurize the spray tank and dump out all of the water.
7) Add a measured amount of water to the spray tank. Note that the spray tank does not need to be full.
   - Example: Add 2 liters of water.
   - Do not add pesticide.
8) Close the lid, put the sprayer on your back, and bring the tank up to pressure.
9) Begin spraying as you walk down the tape from one end to the other.
   - Maintain the same pace, pressure, and nozzle height throughout the walk.
     - ✓ **Tip:** To bring a manual sprayer up to full pressure, pump the handle until you feel resistance. When you cannot pump any more due to resistance, the pressure is at full pressure. Every few steps, pump the handle to keep the sprayer at full pressure.

10) When you get to the end of the tape, stop spraying, turn around, start spraying, and walk back down the tape to where you started.
    - Maintain the same pace, pressure, and nozzle height as before.
11) When you get to your original starting point, stop spraying, turn around, start spraying, and walk down the tape again.
    - Keep track of how many times you walk up and down the tape.
    - Each trip (in either direction) represents one time.
        - ✓ **Tip:** At the end, you must add the number of trips plus one partial trip down the tape measure. For example: If the tape is one hundred meters long, and you walk up and down five and one-quarter times, then the total distance walked would be 500 meters plus 25 meters, which equals 525 meters.
12) Continue walking up and down the tape until the sprayer is empty.
    - Note where you on the tape measure and measure (or estimate) the distance walked after last turning around.
13) Add up the total distance you walked before the sprayer was empty.
    - Example: The farmer used a tape measure 100 meters long. The farmer walked along the tape measure 4¼ times before the sprayer was empty. Thus, the total distance walked was 425 meters (Figure S8).

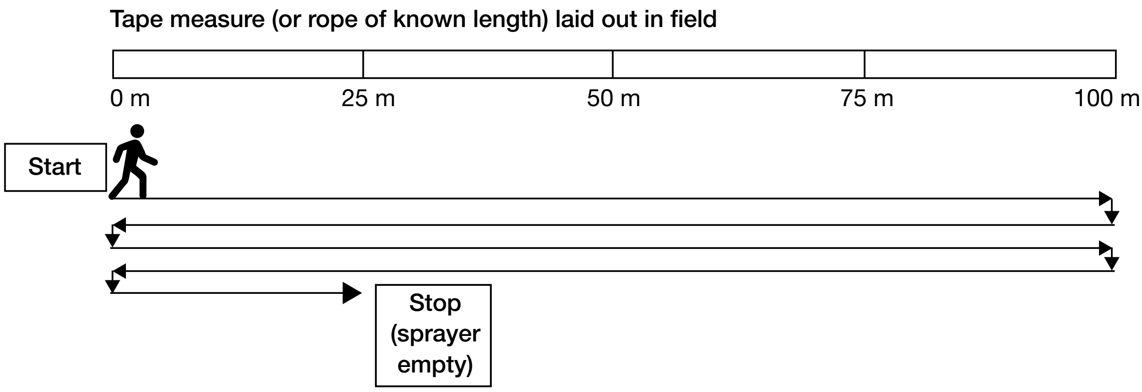


**Figure S8.** Use of tape measure for sprayer calibration. The applicator fills the sprayer tank with a measured amount of water and sprays the ground while walking up and down the length of the tape measure until the sprayer is empty. The applicator must count the number of passes up and down the field, including partial passes, to arrive at the total length walked. In this example, the total distance is 425 m ([4 x 100 m] + 25 m).

14) Calculate the area covered with the measured amount of water as follows:
    - Multiply the width of the spray band by the total length sprayed.
    - In this example, 2 liters of spray solution covers an area 0.75 meters wide times 425 meters long, which equals an area of 319 m$^2$.

| ________ m | | ________ m | | ________ | | ________ m$^2$ |
|---|---|---|---|---|---|---|
| **Width of spray band (in meters)** | **×** | **Length of tape measure or string (in meters)** | **×** | **Number of passes (in either direction), including partial passes** | **=** | **Area covered by test spray volume (in square meters)** |

15) Calculate the total area covered by the sprayer tank when full.

- In this example, 2 liters of spray solution covered an area of 319 m$^2$.
- Therefore, the amount covered by 1 liter of solution is 319 m$^2$ divided by 2, which equals 160 m$^2$.
- If the backpack sprayer holds 16 liters of spray solution when full, the 16-liter spray batch would cover 16 times 159 m$^2$, which equals 2,552 m$^2$ (or approximately 2,550 m$^2$).

| ________ m$^2$ | ÷ | ________ L | = | ________ m$^2$/L |
|---|---|---|---|---|
| **Area covered by test spray volume (in square meters)** | | **Volume used for sprayer test (in liters)** | | **Area covered by one (1) liter of spray** |

| ________ m$^2$/L | × | ________ L | = | ________ m$^2$ |
|---|---|---|---|---|
| **Area covered by one (1) liter of spray** | | **Volume held by sprayer (in liters)** | | **Area covered by full sprayer (in square meters)** |

A similar description of sprayer calibration, with photographs, is available in Withrow-Robinson (2020a).

## 8.3. Preparation of Insecticide Using Data from Sprayer Calibration

The insecticide product label prescribes a rate expressed in milliliters of product per hectare (for liquid products) or grams of product per hectare (for dry products).

- Example: The label prescribes 250 milliliters (ml) of product per hectare.
- A hectare has an area of 10,000 m$^2$.

However, a small sprayer does not cover an entire hectare.

1) To obtain the area covered by the 16-liter sprayer used in the examples here, divide 2550 m$^2$ (the area covered by one 16-liter spray batch) by 10,000 m$^2$/hectare. This calculation gives a result of 0.255 hectares per spray batch.
   - In other words, one spray batch in this example covers about one-quarter of a hectare.

| ________ m$^2$ | ÷ | **10,000 m$^2$/ha** | = | ________ ha |
|---|---|---|---|---|
| **Area covered by sprayer (in square meters)** | | | | **Number of hectares per spray batch** |

2) To calculate the amount of product to add to the 16-liter spray batch, multiply the product rate times the fraction of a hectare covered by one spray batch.
   - In the example here, (250 ml of product per hectare) times (0.255 hectares per spray batch) equals 64 ml of product per spray batch.

| ________ | × | ________ ha | = | ________ |
|---|---|---|---|---|
| **Product rate (in grams or milliliters)** | | **Number of hectares per spray batch** | | **Amount of product to add to each spray batch (in grams or milliliters)** |

3) To prepare the spray solution (using the quantities in our example above):

- Add a total of 16 liters of water to the spray tank.
- Add a total of 64 ml of product to the spray tank.
  - ✓ **Tip:** (1) Add half of the water you need for the application. (2) Add a measured amount of product. (3) Rise the measuring cup and add the rinse water to the tank. Rinse and add three times. (4) Add the remaining water needed.
  - ✓ **Tip:** Studies have shown that most pesticide exposures occur during mixing to the hands. Wear gloves.
  - ✓ **Tip:** Follow PPE requirements for the pesticide as specified on the label and as given in Table 1. **Remember that following label directions for use of a pesticide is a legal requirement.**
- Close the spray tank, mix, bring up to pressure, and spray (while maintaining a consistent pace and pressure and holding the nozzle at a consistent height above the ground).
  - ✓ **Tip:** To maintain a steady and consistent pace, choose a song or melody with an appropriate tempo. Sing the song (to yourself) while you maintain a steady pace.

An illustrated example of mixing pesticide for a backpack sprayer is available in Withrow-Robinson (2020b).

# 9. Supplement 3: IRAC Classification

## 9.1. Use of the IRAC MOA Classification System

The IRAC MOA* Classification system is described here for those individuals who are likely to be farmers, pest control advisors for farmers or extension scientists. For people in those groups, the information here will make sense as they likely have been exposed to the system already. Others will likely find it useful to consult with more knowledgeable experts to address questions.

Table 1 (Section 3) contains the IRAC classifications for pesticides described in this chapter. For more information on these pesticides, or on others not listed there, IRAC provides several helpful web pages:

- The IRAC Mode of Classification Online (https://irac-online.org/modes-of-action/) provides a means for searching chemical names, modes of action, or chemical class.
- A poster showing structures of insecticides in each category can be downloaded from https://irac-online.org/mode-of-action/. This poster is available in several languages including English, Chinese, and Japanese.

## 9.2. Use of Groups and Sub-Groups**

- Alternations, sequences or rotations of compounds between MOA groups reduce selection for target site resistance.
- Applications are arranged into MOA spray windows defined by crop growth stage and the duration of one pest generation.
- Several sprays of a compound may be possible within each spray window, but successive generations of a pest should not be treated with compounds from the same MOA group.
- Local expert advice should always be followed with regard to spray windows and timing.

* Mode of action is abbreviated in this section as "MOA" for consistency throughout the manual, although it appears as "MoA" in the cited material.
** Modified from text on English-language IRAC Mode of Action Classification poster, available from https://www.irac-online.org/documents/moa-structures-poster-english/?ext=pdf.

- Groups in the classification whose members do not act at a common target site are exempt from the proscription against rotation within the group. These are all the UN groups: UN, UNB, UNE, UNF, UNM, UNP & UNV.
- Sub-groups represent distinct structural classes which have the same mode of action.
- Sub-groups provide differentiation between compounds that may bind at the same target site but are structurally different enough that risk of cross-resistance is lower than for close chemical analogs.
- Rotation between sub-groups should be considered only when there are no alternatives, and only if cross-resistance is not known to exist, following consultation with local expert advice. Generally, this approach is not sustainable, and alternative options should be sought.

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CHAPTER 04

# Host Plant Resistance in Maize to Fall Armyworm

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**Note:** Throughout the chapter, we discuss host plant resistance to FAW using maize as an example, since considerable work has been done on maize. However, the principles of host plant resistance remain the same in other major crops (*e.g.*, sorghum, millets) affected by FAW.

# 1. Introduction

Host plant resistance, in the context of resistance to insect pests, was originally defined as "the collective heritable characteristics by which a plant species may reduce the probability of successful utilization of that plant as a host by an insect species" (Beck 1965). It is indeed a central component of the integrated pest management (IPM) strategy to control the fall armyworm (FAW) (Prasanna *et al.* 2018), and comprises:

- **Native genetic resistance:** Identifying/developing germplasm with resistance to an insect pest; and
- **Transgenic resistance:** Using a gene (or genes) from an external source(s) (other than the recipient plant species) to make the host plant resistant to an insect pest.

FAW-tolerant/resistant varieties, whether derived through native genetic resistance or through a transgenic approach, provide a practical and economical way to minimize crop losses due to the pest. Improved maize varieties with genetic resistance to FAW will effectively complement other IPM interventions (Riggin *et al.* 1992, 1994). Seed-based technologies such as host plant resistance are not only easily disseminated and readily adopted by farmers due to their visible benefits, but will also require far fewer applications of pesticides than FAW-susceptible varieties, thus saving smallholder farmers resources (financial and labor), while mitigating negative environmental impact.

When designing a breeding strategy to introduce FAW resistance traits into elite maize 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 for insect-pest resistance is, 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, to improve the durability of host plant resistance (Prasanna *et al*. 2018).

Prasanna *et al.* (2018) presented a comprehensive review of host plant resistance to FAW, especially in maize (FAW IPM Guide For Africa). This included information on potential sources of resistance to FAW in maize germplasm identified or developed earlier by maize breeding programs in the Americas, and detailed protocols for (a) mass rearing of FAW and (b) screening germplasm under artificial and natural FAW infestation. These will not be repeated in this chapter. Here we will (a) provide an update on progress with regard to breeding for native genetic resistance to FAW in maize; (b) highlight the status with regard to deployment of genetically modified (GM) maize (specifically *Bt* maize) in Asia for the control of FAW, and the need for implementing a well-coordinated insect resistance management (IRM) strategy in Asia; and (c) suggest possible next steps for making host plant resistance an integral component of an IPM-based strategy for sustainable management of FAW in sub-Saharan Africa (SSA) and Asia.

# 2. Breeding for Native Genetic Resistance to FAW

## 2.1. FAW Resistance in CIMMYT's Tropical Maize Germplasm

The International Maize and Wheat Improvement Center (CIMMYT) has a wealth of diverse genetic resources in maize, including improved germplasm for an array of traits (*e.g.,* high yield, drought tolerance, heat tolerance, nitrogen use efficiency, disease resistance, etc.) relevant for smallholders in Africa, Asia, and Latin America. In addition, the maize germplasm bank at CIMMYT-Mexico (https://www.genebanks.org/genebanks/cimmyt/) holds over 28,000 accessions that provide a rich platform for identifying genetic resources for client-preferred traits. Throughout the 1970s to 1990s, research conducted at CIMMYT in Mexico (Mihm 1997) revealed that there is genetic variation and potential to support breeding for native genetic resistance to FAW insect-pests of maize, including stem borers, FAW, and post-harvest pests (weevils and large grain borer).

The work done at CIMMYT-Mexico led to development of two major populations—Multiple Insect Resistant Tropical (MIRT) and Multiple Borer Resistant (MBR)—that served as the foundation for deriving improved tropical/subtropical maize inbred lines with at least partial resistance to FAW. CIMMYT's insect-resistant maize populations were derived primarily from the Caribbean maize germplasm and Tuxpeño landrace accessions from Mexico (Mihm 1997). Most native resistance in maize to FAW is polygenic (based on multiple genes) and quantitative in nature, conferring "partial resistance". The quantitative or polygenic nature of native genetic resistance also offers the opportunity to minimize selection pressure on FAW and prevents emergence of new resistant strains.

CIMMYT and partners in Africa have utilized the insect-resistant maize populations and inbred lines from Mexico and developed elite maize germplasm with resistance to other lepidopteran stem borer pests, including the European corn borer (*Ostrinia nubilalis* Hbn.), the African stem borer (*Busseola fusca* Fuller), and the spotted stem borer (*Chilo partellus* Swinhoe) (Beyene *et al.* 2012; Murenga *et al.* 2015; Tefera *et al.* 2016a,b). Some of these insect-resistant materials have the potential to offer resistance against FAW, which is also a lepidopteran pest.

***FAW mass rearing:*** The CIMMYT team, together with the Kenya Agricultural and Livestock Research Organization (KALRO), adopted and further optimized the USDA-ARS-based FAW mass-rearing protocol at KALRO-Katumani, for a steady supply of neonate larvae for artificial infestation of maize germplasm in screenhouses. This is important for identifying reliable sources of resistance to the pest. A colony of FAW was established and maintained at KALRO Insectary at Katumani, Kenya, on artificial diet as described by Prasanna *et al.* (2018). The larvae and pupae were originally collected from Kiboko (02°21'S, 037°70'E, 945 m.a.s.l.) and Machakos (01°57'S, 027°25'E, 1568 m.a.s.l.) in the eastern part of Kenya. The FAW rearing facility at the Katumani Center has the capacity to supply 500,000-800,000 neonates per year, which are used for germplasm screening experiments under artificial infestation at Kiboko, Kenya.

***Artificial infestation of maize plants in screenhouses:*** A screenhouse complex (with 13 screenhouses, each 1000 $m^2$) was established by CIMMYT at KALRO Research Center at Kiboko, Kenya, in 2017-2018, for intensive screening of maize germplasm against FAW under artificial infestation (Figure 1), and for identifying and developing promising FAW-tolerant inbred lines and hybrids. Each screenhouse can accommodate 245 maize rows of 3 m length. Similar screenhouse facilities are being established by CIMMYT at Hyderabad, India.

**Figure 1.** Screenhouse complex established by CIMMYT at KALRO Research Center at Kiboko, Kenya, for screening maize germplasm under artificial FAW infestation.

The neonates produced in the laboratory are used for artificial infestation of maize plants in the screenhouse. To infest a plant, a camel-hair brush is used to pick the neonates from a container and put them in different nodes of maize plants to avoid cannibalism (Figure 2) (Prasanna *et al.* 2018). Infestation is carried out either early in the morning (7-9 am) or in the evening (4-6 pm) to allow the neonates to acclimatize to the environment since sudden changes of conditions may desiccate the neonates, especially if infestation is done during dry, hot conditions. Based on optimization experiments, the CIMMYT team at Kiboko, Kenya, typically uses five (5) neonates for infesting inbred lines at the V5 stage (three weeks after planting), and seven (7) neonates for infesting hybrids at the V3 stage (two weeks after planting).

**Figure 2.** Infestation of a maize plant with FAW neonates using a camel-hair brush.

***Data recording:*** When identifying germplasm with native genetic resistance to FAW, it is important to consider not only the foliar damage score but also the ear damage score, as FAW larvae can cause significant ear/kernel damage by burrowing into the developing ears. CIMMYT uses a 1-9 scale (Prasanna *et al.* 2018), which is a modification of the Davis *et al.* (1992) 0-9 scale, for assessing maize germplasm against FAW under artificial infestation for the foliar damage. At physiological maturity (harvest), the CIMMYT team also assesses the ear damage of the maize germplasm due to FAW on a 1-9 scale, as described by Prasanna *et al.* (2018). In addition, other parameters including percentage ear rot and number of exit holes per ear, are also recorded. The average score of foliar and ear damage rating, besides grain yield and other parameters are considered for final rating of the germplasm.

Starting in 2017, the CIMMYT maize breeding program in Kenya implemented intensive efforts to identify and develop maize germplasm with tolerance/resistance to FAW. FAW-tolerant maize germplasm developed earlier at CIMMYT-Mexico as well as inbred lines, open-pollinated varieties (OPVs), and hybrids developed by CIMMYT in Africa through the Insect Resistant Maize for Africa (IRMA) project were some of those that were screened. Between 2017 and 2020, over 6,000 maize genotypes, including 3,000 inbred lines and 3,000 hybrids/OPVs from diverse sources were screened under artificial FAW infestation in the screenhouse complex at Kiboko. The work has led to identification of some promising FAW-tolerant/resistant* inbred lines, especially from the MBR and MIRT germplasm backgrounds, with low foliar and ear damage scores.

The **FAW-tolerant/resistant CIMMYT maize inbred lines** include CML71, CML124, CML125, CML338, CML333, CML334, CML338, CML370, CML372, and CML574. Since 2018, FAW-tolerant/resistant CIMMYT Maize Lines (CMLs) have been disseminated to 92 institutions in 34 countries globally, including an array of National Agricultural Research and Extension Systems (NARES), advanced research institutes (ARIs) and commercial seed companies (Table 1). The FAW-tolerant/

**Table 1.** Global dissemination of CIMMYT-developed FAW-tolerant/resistant CMLs since 2018 (until August 2021).

| Type of Institution | Africa | Asia | Latin America | North America* | Europe | Australia | Total |
|---|---|---|---|---|---|---|---|
| NARES/ARIs/Universities | 14 (11) | 9 (6) | 14 (5) | 3 (2) | 1 (1) | 2 (1) | **43 (26)** |
| Commercial seed companies | 11 (7) | 10 (6) | 22 (4) | 2 (1) | 4 (3) | | **49 (21)** |
| **Total** | **25 (13)** | **19 (9)** | **36 (6)** | **5 (2)** | **5 (3)** | **2 (1)** | **92 (34)** |

Note: Figures in parentheses indicate number of countries.
*Mexico is included under Latin America.

* In the context of insect pests, "resistance" is the capacity to minimize the damage through mechanisms such as antibiosis and/or antixenosis, while "tolerance" is the ability to restrict the economic damage even in the presence of the pest (outside/inside the host). Resistance to an insect pest, thus, may involve a combination of antibiosis, antixenosis, and/or tolerance (Painter 1958). Earlier studies evaluating FAW-resistant maize germplasm showed that the mechanisms contributing to native genetic resistance in these materials could be quite varied: for example, some lines showed higher levels of metabolites such as silk maysin and terpenoids, while some lines have morphological traits (*e.g.*, very tight husk cover) that minimize the ear damage by FAW. As of now, we do not have firm evidence whether the promising inbreds/hybrids developed recently at CIMMYT can be considered as "resistant/tolerant" to FAW, as we still do not know the underlying mechanisms; this requires further studies. Therefore, in this chapter, we have used the term "FAW-tolerant/resistant hybrids".

resistant CMLs can be potentially utilized as trait donors in breeding programs of partner institutions that are aiming to develop FAW-tolerant maize cultivars suitable for local environments. These CMLs can be sourced through a Standard Material Transfer Agreement (SMTA) from CIMMYT Genebank at Mexico. Several national maize breeding programs in Africa and Asia have initiated breeding programs for development of FAW-tolerant cultivars (*e.g.*, Matova *et al.* 2020; Kasoma *et al.* 2020), especially utilizing sources of native genetic resistance developed and disseminated by CIMMYT.

Besides the promising CMLs mentioned above, the CIMMYT team in Africa has also identified over the last two years several promising inbred lines (materials under development) in both yellow- and white-kernel backgrounds, with tolerance/resistance to FAW for both foliar and ear damage as well as combining ability for grain yield under FAW artificial infestation. For example, based on the data from germplasm screening during 2017-2018, several crosses were made among the promising FAW-tolerant/resistant lines, from which progenies were selected and intercrossed to increase the frequency of favorable resistance alleles. Doubled haploid (DH) lines were developed from F1, F2, and backcross (BC) source populations that showed promising levels of resistance to FAW. In 2019-20, a total of 2733 DH lines were produced from different source populations. In 2020, a set of 1400 DH lines were screened against FAW under artificial infestation at Kiboko (Figure 3), leading to identification of new lines with resistance to FAW. Such lines are being used to make new single-cross and three-way hybrids for further evaluation in 2021 and beyond.

**Figure 3.** Variability for FAW foliar feeding under artificial infestation in a screenhouse at Kiboko, Kenya (2019-2020). The figure shows a FAW-resistant doubled haploid (DH) line (left), developed from a MIRT population, side-by-side with a FAW-susceptible DH line (right).

**Development of FAW-tolerant maize hybrids with high yield potential and other agronomic and adaptive traits:** Based on results from screening of a large collection of inbred lines from different genetic backgrounds during 2017-2018, the CIMMYT team in Kenya formed single-cross and three-way-cross hybrids. In 2018, a set of 197 single-cross hybrids were developed and evaluated under artificial FAW infestation. The best FAW-tolerant/resistant single crosses have been used (a) as female parents to develop three-way hybrids, (b) to make narrow-based synthetics, and (c) as source populations for DH induction to develop new FAW-resistant lines. In 2019, 88 three-way hybrids showed genetic variation for grain yield under various conditions and FAW damage parameters. Hybrids with MBR and MIRT backgrounds were among those that showed a combination of low ear damage and good grain yield across various conditions. In 2019-2020, over 500 hybrids, including single- and three-way crosses, were tested across different management conditions, including screening at Kiboko under artificial FAW infestation. Stage-gate advancement of promising maize hybrids with native genetic resistance is implemented by considering both foliar damage and ear damage scores below specific thresholds (≤5.0 and <3.0 Davis scores, respectively), in addition to significantly higher grain yield than the FAW-susceptible commercial checks. On average, the FAW-tolerant pre-commercial maize hybrids produced 47% to 77% higher grain yield than the FAW-susceptible commercial checks.

## 2.2. FAW-tolerant Elite Maize Hybrids for Africa

Based on the results of on-station screenhouse trials against FAW (under artificial infestation) conducted at Kiboko during 2017-2019, the CIMMYT maize team in Africa further evaluated in 2020 a set of eight promising white-grained hybrids (four early-maturing and four intermediate-maturing) against four widely used commercial hybrids (two early- and two intermediate-maturing) as checks under different management conditions. The experimental conditions and the main findings are summarized below:

- **"No-choice" trial under FAW artificial infestation in screenhouses in Kiboko, Kenya:** Each entry was planted in 40 rows in a separate screenhouse compartment ("no-choice"), and each plant infested with seven FAW neonates 14 days after planting. Foliar damage was assessed 7, 14, and 21 days after infestation. Ear damage due to FAW in each plot was also recorded, in addition to grain yield and other agronomic parameters. Significant differences were observed between three FAW-tolerant hybrids (FAWTH2001, FAWTH2002, FAWTH2003) and the commercial benchmark hybrid checks at the vegetative and grain-filling stages and at harvest (Figure 4). In the FAW artificial infestation trial, the three FAWTH hybrids yielded 7.05 to 8.59 t/ha while the commercial checks yielded 0.94 to 1.03 t/ha.

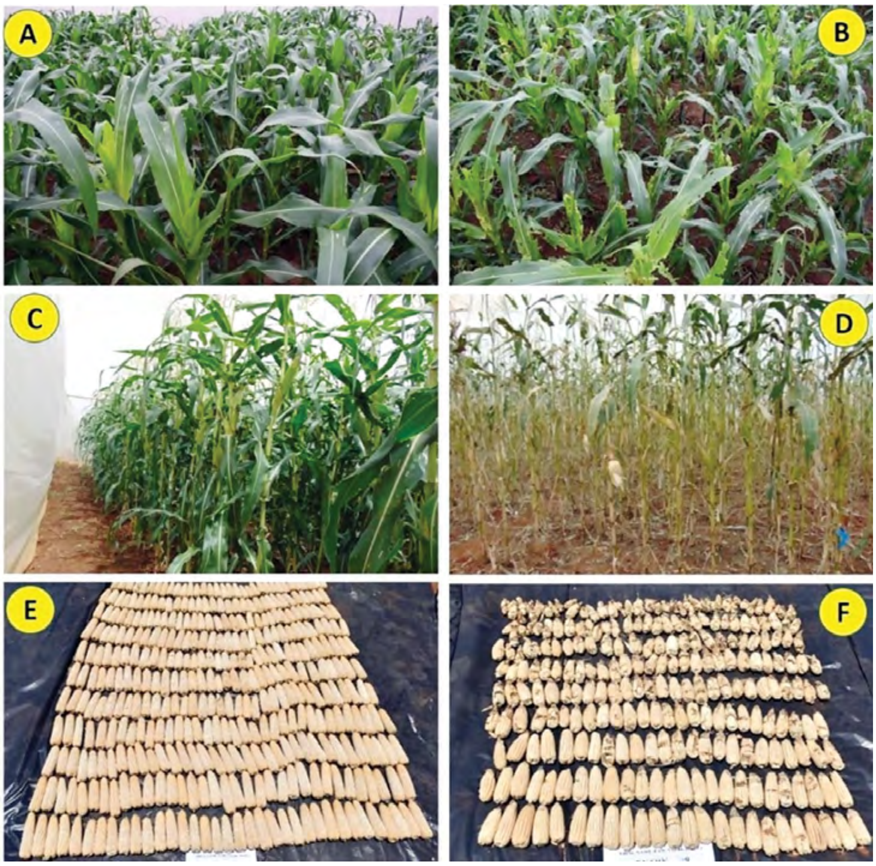


**Figure 4.** Responses of CIMMYT-derived FAW-tolerant hybrids (left) versus susceptible commercial checks (right) at the vegetative stage (**A & B**) and at the reproductive stage (**C & D**), after artificial infestation of FAW under "no-choice" conditions in screenhouses at Kiboko, Kenya. Note the difference in the yield of a FAW-tolerant hybrid (**E**) versus one of the susceptible commercial hybrid checks (**F**), as well as the extent of damage caused by FAW to the ears of the susceptible check (visible as blackish spots with no grains in the ears).

- **On-station trials in East Africa**: The trials, including the eight test entries and four commercial checks, were conducted at six locations in Kenya during the maize cropping season in 2020. The purpose of these regional trials was to collect data on agronomic performance across a range of environments. Entries were evaluated for their performance under managed drought stress, managed low-nitrogen stress, and artificial inoculation for Turcicum leaf blight (TLB) and Gray leaf spot (GLS) diseases. The three-way cross CIMMYT test hybrids and their parents were also characterized on-station for their seed production characteristics, including maximum flowering time difference between parents and single-cross female parent seed yield. In addition to the above, the eight test entries with FAW tolerance were also evaluated in regional on-station trials (comprising a total of 58 entries) at 28 locations in Kenya and Tanzania. No significant differences were observed between the three selected FAWTH hybrids and the commercial checks for grain yield and other important traits evaluated under optimum conditions, managed drought stress, low-nitrogen stress, and TLB and GLS disease pressure. The three selected FAWTH hybrids recorded excellent synchrony in terms of flowering between the female and male parents, and very good female parent seed yield.
- **On-farm trials in Kenya**: The eight test hybrids and four commercial checks were evaluated under farmers' management conditions (without any insecticide spray) at 16 on-farm sites in Kenya. Each entry was planted in 20-row plots, and data were recorded on natural FAW infestation. Foliar damage was assessed 7, 14, 21, 28, and 35 days after germination together with insect incidence. Ear damage and percent ear damage were also recorded, as well as grain yield and other agronomic parameters. There were significant differences in terms of foliar damage ratings between the FAWTH hybrids and the commercial checks. For ear damage, the differences were not statistically significant. The grain yields did not vary significantly under natural infestation in the on-farm trials because of the very low incidence of FAW at most sites.

Based on the stage-gate advancement process, including rigorous review of the complete set of on-station and on-farm trial data (described below), the three promising FAW-tolerant elite maize hybrids (FAWTH2001, FAWTH2002, FAWTH2003) were announced by CIMMYT in December 2020 (https://www.cimmyt.org/news/announcing-cimmyt-derived-fall-armyworm-tolerant-elite-maize-hybrids-for-eastern-and-southern-africa/) for partners, especially in SSA.

**Note:** Native genetic resistance to FAW in maize is partial, though quite significant in terms of yield protection under severe FAW infestation, as compared to the susceptible commercial checks. Sustainable control of FAW is best achieved when farmers use host plant resistance as part of an IPM program, including good agricultural practices, pest scouting (**Chapter 2**), and judicious use of safer-use pesticides (**Chapter 3**) only when needed to encourage conservation biological control.

## 2.3. FAW Resistance in IITA's Tropical Maize Germplasm

Considering the importance of FAW as an emerging major pest of maize in West Africa, the International Institute of Tropical Agriculture (IITA) began screening genotypes under naturally occurring FAW infestation in 2016, and later under artificial infestation with FAW larvae, to identify tolerant synthetics, hybrids, and inbred lines from existing adapted germplasm. Among the 365 yellow and 212 white lines screened at IITA, 13 yellow and 20 white lines exhibited minimal damage symptoms and had well-filled ears under severe natural infestation. As cyclical/recurrent breeding methods have been used to accumulate desirable genes for resistance to FAW (Welcker 1993; Welcker *et al.* 1997), equal quantities of seeds of the self-pollinated ears from each of the white and yellow lines were used to form balanced bulks, which were planted to form a white synthetic (AWSYN-W) and a yellow (AWSYN-Y) synthetic. After one generation of recombination, the two synthetics were improved using an S1 selection scheme under artificial infestation with FAW larvae.

A modest FAW rearing facility has also been established at IITA for artificial infestation and has been further upgraded with support from the Consultative Group for International Agricultural Research (CGIAR) Research Program MAIZE to enable screening large numbers of inbred lines under artificial infestation. The IITA maize team has screened more than 20 stress-tolerant and provitamin A–enriched synthetics, about 60 drought-tolerant and *Striga*-resistant hybrids being tested in regional trials, and more than 200 advanced stress-tolerant maize inbred lines, all under FAW natural infestation in the screenhouse. Some promising synthetics and hybrids were tested in multiple locations under natural FAW infestation to confirm their performance. These materials are suitable candidates for extensive field testing under both natural and artificial infestation to identify the best products for further testing and sharing with partners. To boost the levels of resistance to FAW in adapted germplasm, several FAW-resistant inbred lines from the USA have also been introduced as donors and backcrosses have been made (Abebe Menkir, IITA, personal communication).

## 2.4. FAW Resistance in Temperate Maize Germplasm

The USDA-ARS Corn Host Plant Resistance Research Unit (CHPRRU) in Mississippi, USA (https://www.ars.usda.gov/southeast-area/mississippi-state-ms/crop-science-research-laboratory/corn-host-plant-resistance-research/) has a long history of conducting research on native genetic resistance to FAW especially within temperate maize germplasm. During the late 1980s and throughout the 1990s, USDA-ARS and CIMMYT (Mexico) collaborated extensively on developing maize germplasm with resistance to FAW damage in Mexico (Williams and Davis 1997). USDA-ARS researchers developed protocols for infesting maize plants with neonates and evaluating the resulting damage, and thus identified temperate maize inbred lines with resistance to FAW (*e.g.*, Mp705) (Williams and Davis 1984, 2002; Prasanna *et al*. 2018). Several maize inbred lines (Mp496, Mp701, Mp704, Mp706, and Mp708) developed at USDA-Mississippi were based on CIMMYT maize germplasm, especially Caribbean-based, as source populations. In addition to USDA-ARS, temperate maize germplasm with native genetic resistance to FAW has been developed by Embrapa-Brazil, University of Florida, USA, and the Germplasm Enhancement of Maize (GEM) project (Prasanna *et al*. 2018).

## 2.5. Genomic Analysis of Resistance to FAW in Maize

There is still a lot to learn about the genetic architecture of native genetic resistance to FAW in maize, although a few studies carried out in recent years have given some insights. Brooks *et al.* (2007) used 91 simple sequence repeat (SSR) markers on 213 $F_{2:3}$ families and detected quantitative trait loci (QTLs) on chromosomes 1, 2, 6, 7, and 9. Womack *et al.* (2018) evaluated 231 $F_{2:3}$ families from the cross of Mp704 (resistant) × Mo17 (susceptible) and genotyped with both SSR and single-nucleotide polymorphism (SNP) markers. This study revealed QTLs in chromosome bins 1.09, 2.08, 3.08, 6.02, 7.04, 8.03, 9.03, 10.02, and 10.04. Womack *et al.* (2020) developed a bi-parental mapping population, comprising 243 $F_{2:3}$ families from the cross Mp705 (resistant) × Mp719 (susceptible), and evaluated this population for FAW leaf-feeding damage under artificial infestation over 3 years in the USA. QTL analyses led to identification of two major QTLs in bins 4.06 and 9.03 that together explained 35.7% of the phenotypic variance over all environments. The QTL identified in bin 9.03 co-located with a previously identified QTL associated with resistance to leaf-feeding damage in maize by FAW and other lepidopteran insects, while the QTL in bin 4.06 is a new source of resistance to FAW leaf-feeding damage identified in this study. Badji *et al.* (2020) evaluated a set of 316 tropical maize lines under natural insect pressure for FAW in Uganda and identified 14 SNPs through genome-wide association study (GWAS). These SNPs are distributed on all chromosomes except chromosomes 6 and 7. Several FAW resistance QTLs discovered in earlier studies (Brooks *et al.* 2005, 2007; Womack *et al.* 2018) co-localized with 6 of the 14 SNPs reported by Badji *et al.* (2020).

The CIMMYT team in Africa recently undertook GWAS and joint linkage association mapping on a set of 285 lines and about 485 DH lines developed from seven FAW-tolerant lines. These lines were evaluated for their responses to FAW artificial infestation at Kiboko, Kenya, in 2017 and 2018. Foliar damage was scored 7, 14, and 21 days after artificial infestation on a modified Davis scale (1-9) (Prasanna *et al.* 2018). Ear damage was also rated on a 1-9 scale, based on the protocol described by Prasanna *et al.* (2018). All the screened lines were genotyped with the DArTseq genotyping-by-sequencing platform (Diversity Arrays Technology/DArT). A set of 20,000 SNPs were used for association mapping on 285 lines, and around 1000 SNPs were used on DH populations, for linkage and joint linkage association mapping. The study revealed a very weak and non-significant correlation between foliar and ear damage scores. GWAS revealed 22 SNPs significantly associated with foliar damage, distributed on all 10 chromosomes. Only one SNP, *S4_186497220* on chromosome 4, was significantly associated with ear damage. Seven SNPs distributed on chromosomes 4, 5, 7, 8, and 9 were significantly associated with grain yield under FAW infestation.

Even though there were no common SNPs identified across the GWAS panel used by CIMMYT and that by Badji *et al.* (2020), several markers were consistently present in the same bins on chromosomes 8, 9, and 10. QTLs on chromosome 4 (17.28 Mb and 183.82 Mb) and chromosome 9 (at 8.05 Mb) are consistent with bi-parental population-based QTL mapping in the CIMMYT study, as well as earlier studies (Womack *et al.* 2018, 2020). These regions appear important for developing markers for resistance to foliar damage by FAW.

In CIMMYT's GWAS panel, ridge regression–based genomic prediction correlations were 0.61, 0.53, 0.31, and 0.30 for early foliar damage, late foliar damage, ear damage, and grain yield, respectively, under FAW artificial infestation. In contrast, prediction correlations as high as 0.69 to 0.71 were reported for foliar damage (under FAW natural infestation) in a set of 316 lines by Badji *et al.* (2021). Overall, considering both foliar and ear damage, the role of specific QTLs on chromosomes 4 and 9 needs further investigation, while genomic prediction could possibly play an important role in improving native genetic resistance to FAW.

# 3. Transgenic Resistance to FAW

Deploying transgenic or genetically engineered/modified (GE/GM) maize hybrids that express lepidopteran resistance genes is an important component of an IPM strategy to effectively control FAW. FAW-resistant transgenic maize hybrids typically have insecticidal crystal protein genes (*cry* genes) and/or *vip* genes encoding vegetative insecticidal proteins (Vip), isolated from a soil bacterium, *Bacillus thuringiensis* (*Bt*). Numerous transgenic maize hybrids, with various combinations of *cry* (*cry1Ab, cry1F, cry1A.105 + cry2Ab2*) and *vip* (*vip3A*) 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; ISAAA 2019).

## 3.1. *Bt* Maize Status in Africa

In Africa, *Bt* maize is currently being commercialized only in South Africa, where regulatory authorities have overseen multiple approvals, with more than 15 years of deployment of such products. Kenya is presently undertaking national performance trials of MON810 (*cry1Ab*)-based *Bt* maize hybrids. In South Africa, *Bt* maize hybrids expressing the *cry1Ab* gene (MON 810) and the *cry1A.105+cry2Ab2* genes (MON 89034) have been planted on over 1.62 million hectares, comprising 71% of the total maize area (ISAAA 2017). After the documentation of FAW invasion into Africa during early 2016, it has been included as a target pest of MON 89034 (Botha *et al.* 2019). MON 89034 is particularly recommended for FAW control due to its high efficacy against the pest, as well as the resistance management value of "pyramided" insect-resistant *Bt* genes expressing the Cry1A.105 and Cry2Ab2 proteins. The MON 810 maize event, which has been cultivated in South Africa since 1997 and is intended to primarily manage the larval feeding damage caused by stem borers (*e.g., Chilo partellus*, *Busseola fusca*), confers partial resistance to FAW.

Beyond South Africa, under the TELA® Maize project the National Agricultural Research Organizations of Kenya, Ethiopia, Nigeria, Tanzania, Uganda, and Mozambique are testing the performance of *Bt* and stacked *Bt* + Drought Tolerance (DT) transgenes introgressed into Africa-adapted maize genetic backgrounds. The TELA Maize Project is a public-private partnership led by the African Agricultural Technology Foundation (AATF) working towards the release of transgenic drought-tolerant and insect-protected (TELA®) maize hybrids, in partnership with Bayer, CIMMYT, and National Agricultural Research System (NARS) institutions in Ethiopia, Kenya, Mozambique, Nigeria, South Africa, Tanzania, and Uganda.

## 3.2. *Bt* Maize Status in Asia

In Asia, *Bt* maize is currently grown in the Philippines and Vietnam, and *Bt* maize events are approved in Pakistan. The primary target pests are the Asian corn borer (*Ostrinia furnacalis* Guenée) in the Philippines, Vietnam, Indonesia, and China, and the maize stem borer (*Chilo partellus* Swinhoe) in Pakistan. Other secondary target pests include the common cutworm (*Spodoptera litura* Fabricius), the corn earworm (*Helicoverpa armigera* Hübner), and FAW. The experiences with *Bt* maize in different Asian countries are discussed in more detail below.

**Philippines:** The cultivation of *Bt* maize in the Philippines began with the approval of the insect-resistant event MON 810 in 2002. This was followed by approvals of Bt11 in 2005, MON 89034 in 2010, TC1507 in 2013, and MIR162 in 2018. Insect-resistant event MIR162 contains the *vip3Aa20* gene, which encodes the insecticidal protein Vip3Aa20; Bt11 expresses the Cry1Ab protein; and TC1507 expresses the Cry1F protein. In 2019, commercial products with these insect resistance events were estimated to occupy over 45% (0.66 million hectares of the total 1.415 million hectares) of the yellow maize hectarage (USDA-GAIN 2020a).

FAW invaded the Philippines in mid- to late-2019 with nearly 8000 hectares affected, mostly conventional maize, in the regions of Cagayan Valley, Soccsksargen, Northern Mindanao, and Zamboanga Peninsula, as of June 2020 (Department of Agriculture (DoA), Philippines; https://www.da.gov.ph/da-allots-p150m-to-help-farmers-control-fall-armyworm/). Currently, the list of products approved for the control of FAW in maize from the Fertilizer and Pesticide Authority (FPA) of the Department of Agriculture (DoA) in the Philippines includes MON 89034 and TC1507 × MON 810. The FAW-resistant hybrids include DK8719S, DK8899S, DK9118S, DK9132S, DK9919S, DK6919S, DK6999S, P3530YHR, P3774YHR, P4097YHR, and P4124YHR.

**Vietnam:** *Bt* maize has been commercialized in Vietnam since 2015. In 2019, *Bt* maize occupied 92,000 hectares, which was about 10.2% of the total crop) (Crop Protection Department of the Ministry of Agriculture and Rural Development: CPD MARD, Brookes and Dinh 2021). The approved *Bt* maize hybrids include stacked events, *viz.*, MON 89034 × NK603 and Bt11 × GA21. *Bt* maize hybrids carrying MON 89034 × NK603 include DK9955S, DK6919S, DK8868S, DK6818S, and CP501S; those carrying Bt11 × GA21 include NK66 BT/GT, NK67 BT/GT, NK4300 BT/GT, and NK7328 BT/GT (Brookes and Dinh 2021).

After the invasion of FAW in Vietnam in 2019, the pest was reported to have affected 35,000 hectares. However, in 2020, there was a reduction in heavily affected areas as well as an increase in planting of insect-resistant *Bt* maize hybrids (USDA-GAIN 2020b; Figure 5). One of the *Bt* maize hybrids, DK6919S, planted by farmers of Nghi Xuân, Hà Tĩnh province, was resistant to FAW, and reportedly led to an increased yield of 5.5-6.0 tons/hectare as compared to conventional varieties/hybrids (https://www.sggp.org.vn/giong-ngo-dk-6919-s-cho-nang-suat-cao-tren-vung-dat-nghi-xuan-660427.html [in Vietnamese]).

**Pakistan:** Currently, conventional maize is grown on 1.4 million hectares in Pakistan, with an increase in area from 1.0 to 1.4 million hectares in the last two decades. The production also has increased from 1.7 to 7.2 million metric tons due to the introduction of elite genetics and improved agronomics (http://www.fao.org/faostat/en/#home). The evaluation of GM maize events started in 2009 in Pakistan, and the approval of stacked GM maize expressing insect resistance and herbicide tolerance traits for


**Figure 5.** (A) FAW-damaged conventional (non-*Bt*) maize hybrid in Vietnam with extensive foliar damage; (B) *Bt* maize (MON 89034) hybrid expressing Cry1A.105 and Cry2Ab2 proteins with no FAW damage. *Note: Bt* maize (MON 89034) planted in the field is a blend containing 5% non-*Bt* seed. (Source: Bayer Crop Science, Vietnam).

commercial cultivation was given by the National Biosafety Committee (NBC) of the Ministry of Climate Change (MOCC) in 2016. The products approved include MON 89034 × NK603, MON 810 × NK603, TC1507 × NK603, and TC1507 × MON 810 × NK603. As part of the regulatory requirement for varietal registration by the Federal Seed Certification and Registration Department, Ministry of National Food Security and Research (MNFS&R) in 2017-18, field performance trials of GM maize hybrids were conducted. Commercialization of biotech maize in Pakistan will happen once MNFS&R registers the tested GM hybrids. Other products being tested include Bt11 × GA21 and Bt11 × MIR162 × GA21.

**Other countries in Asia**: *Bt* maize is undergoing testing and approval processes in Indonesia and China. Events with insect resistance genes such as *cry1Ab*, *cry1F*, *cry1A.105*, *cry2Ab2*, and *cry1b-cry2Aj fusion* are in various stages of the approval process. In January 2021, China's Ministry of Agriculture and Rural Affairs granted a biosafety certificate for *Bt* maize event DBN9501 (*vip3Aa-19*), developed by Beijing Dabeinong Technology Group, conferring resistance to FAW. A biosafety certificate was granted in January 2020 to "double-stacked 12-5" (*cry1e* + *cry1Ab-cry2Aj*) maize, which was co-developed by Hangzhou Ruifeng Biotech Co. Ltd. and Zhejiang University. In a recent study, Li *et al.* (2019) demonstrated that the FAW population invading China is highly susceptible to the commonly used Cry1, Cry2, and Vip3 proteins, with the highest susceptibility to Vip3A, Cry1Ab, and Cry1F. In another study, Zhang and Wu (2019) showed that pyramided events DBN3608 and DBN3601 (Cry1Ab + Vip3A) have high resistance to FAW. Recent publications from China (Li *et al.* 2020, 2021) highlighted the need to deploy pyramided events in China as an effective strategy for delaying resistance evolution in target pests, including FAW to *Bt* maize.

## 3.3. Field-evolved *Bt* Resistance in FAW

The first case of documented field-evolved resistance to *Bt* maize in FAW was for Cry1F-based maize hybrids in Puerto Rico (Storer *et al.* 2010, 2012a). Several factors were central to the evolution of FAW resistance in Puerto Rico, including the island setting, which limited insect migration; the tropical climate conducive to year-round cultivation of maize; and drought conditions in 2006/2007, which reduced the availability of alternative hosts for FAW (Storer *et al.* 2010). Subsequently, field resistance to Cry1F maize was detected in the southeastern USA (Niu *et al.* 2013; Huang *et al.* 2014) and in the Brazilian state of Bahia, three years after being deployed in Brazil (Farias *et al.* 2014a). A significant decrease in susceptibility to Cry1F was detected in FAW across Brazil between 2010 and 2013, especially in areas with intensive maize production and high adoption of *Bt* technologies (Farias *et al.* 2014b). Low compliance with non-*Bt* structured refuge recommendations was one of the root causes for resistance to Cry1F in Brazil (Farias *et al.* 2014b).

Bernardi *et al.* (2015) detected partial cross-resistance among Cry1 proteins in FAW, meaning that the Cry1F resistance conferred some resistance to Cry1A.105 and Cry1Ab. However, no significant cross-resistance was found between Cry1F and Cry2Ab2. MON 89034 maize (expressing the Cry2Ab2 and Cry1A.105 proteins) in combination with appropriate management practices continues to provide effective control of FAW in Brazil (Bernardi *et al.* 2015). Omoto *et al.* (2016) documented the evolution of field-relevant Cry1Ab *Bt* resistance in FAW in Brazil, potentially due to either direct selection from the use of MON 810 and/or cross-resistance to Cry1F.

The use of *Bt* maize hybrids with less-than-ideal IRM fit (*e.g.*, less-than-high-dose expression, components of *Bt* pyramids with cross-resistance to other *Bt* proteins in the landscape) combined with low compliance with the structured refuge recommendation seems to be a common theme across the resistance cases with FAW in South America (Farias *et al.* 2014a; Chandrasena *et al.* 2017). A consequence of these is a reduction in the number of effective modes of action to manage FAW. However, the deployment of MIR162 (Vip3Aa20) maize represents an effective new mode of action added to the maize cropping system to counter FAW.

## 3.4. Insect Resistance Management (IRM) for *Bt* Maize

The primary threat to the sustainable use of *Bt* maize is the selection for resistance in the target pests. It is important to note that, to date, there is no evidence that *Bt* resistance alleles were transferred from the Americas to Africa and Asia with the current invasive FAW population (see also **Chapter 1**). This evidence includes the fact that MON810 performed as expected across Africa. However, good stewardship practices encourage deploying the best IRM strategies regardless. Therefore, proactive

IRM programs are needed to delay resistance in the FAW populations. A sound IRM plan varies with the crop and pest combination, but generally considers:

1) Lowering the frequency of resistance alleles/genes in the insect population, which can be accomplished via an effective dose or high-dose expression of *Bt* proteins in *Bt* maize.
2) Providing refuge plants for the target insect pest to reduce selection pressure.
3) Ensuring "redundant killing" with products expressing two or more proteins that provide multiple modes of action against the targeted insect pests.
4) Rigorous scouting and surveillance for potential development of insect resistance above a baseline level determined prior to introduction of the GM crop.

For *Bt* maize, the critical components of an IRM strategy are the refuge strategy and refuge compliance, which drive the durability of the product. The refuge ensures that a sufficient population of susceptible insects is available to mate with the few resistant insects that may evolve in the *Bt* maize-planted areas. This significantly dilutes the frequency of resistance alleles in the insect population, thereby delaying the evolution of insect resistance to the *Bt* traits. Refuge plantings are recommended for use with all *Bt* maize products.

In addition, the latest generations of *Bt* maize express at least two *Bt* proteins for FAW control with unique modes of action. These products, known as *Bt* pyramids, are characterized by more robust insect protection and improved IRM value (Horikoshi *et al.* 2016; Roush 1998; Storer *et al.* 2012b). Studies undertaken in the USA and Brazil suggest that pyramiding multiple transgenes (in the same plant) is more effective in terms of FAW control 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, preferably one with native genetic 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 maize hybrids with more effective resistance are developed and deployed.

The new generation of *Bt* maize technologies with multiple modes of action, together with the implementation of IRM strategies that are more dependent upon manufacturing and less dependent upon grower behavior, can mitigate the risk of resistance. Seed blends (with *Bt* and non-*Bt* seeds mixed in the seed bag), sometimes referred to as refuge-in-a-bag (RIB), offer one such solution to enhance IRM in *Bt* crops. Seed blends are a widely adopted refuge deployment strategy for dual-gene *Bt* maize products registered for use against FAW, such as MON 89034 and TC1507 × MON 810 in the Philippines and Vietnam. In contrast, the current requirement for single-gene products in these countries is a 10% structured refuge. RIB may not be without risk, as some entomologists are concerned that the RIB approach may lead to resistance development in some above-ground pests, such as FAW. The Insecticide Resistance Action Committee (IRAC) published detailed guidelines on IPM and IRM for FAW control based on South African maize conditions (https://irac-online.org/documents/ipm-irm-for-fall-armyworm-in-s-african-maize/?ext=pdf).

Although products with two or more distinct modes of action, effective dose of *Bt* protein expression, refuge compliance, and scouting/surveillance are key components of an IRM strategy (Head and Greenplate 2012; Storer *et al.* 2012b), there are other components that influence the overall success of IRM. These include:

a. Resistance monitoring programs, which can be laboratory-based (pure protein or plant tissue-based) or field-based, that help us understand resistance development.
b. Farmer surveillance reporting systems that allow technology providers to receive feedback on performance-related issues.
c. Education and training programs on the importance of IRM and other measures for farmers and relevant stakeholders.
d. Remedial measures to address any unexpected damage caused by target pest(s).
e. Pest management plans for secondary pest management.

# 4. Host Plant Resistance for FAW Management in Africa and Asia: Critical Gaps

- An array of FAW-tolerant/resistant germplasm in diverse genetic backgrounds needs to be developed and deployed for both Africa and Asia. A major obstacle to breeding crop varieties with FAW resistance using conventional breeding is the low frequency of resistant genotypes in germplasm collections. Therefore, it is imperative both to widen the search for sources of native genetic resistance to FAW and to discover, validate, and ultimately deploy genomic regions conferring resistance to FAW using either marker-assisted breeding or genomic selection, as appropriate, depending on presence/absence of major haplotypes conferring resistance to FAW.
- It must be noted that farming communities need elite crop varieties with not only FAW tolerance/resistance, but also a package of other traits relevant for that specific agroecology or market segment, including high yield, abiotic stress tolerance, disease resistance, nutrient and water use efficiency, nutritional enhancement, etc. Often the sources of genetic resistance to FAW may not be directly useful as elite parental lines of commercial hybrids/varieties. Therefore, intensive and accelerated breeding efforts are required to transfer native resistance from validated sources of resistance into diverse, Africa-adapted and Asia-adapted elite maize products (inbreds/hybrids/OPVs) for deployment to farming communities. Similar efforts are needed in other major crops, such as sorghum and millets, affected by FAW in Africa and Asia.
- Lack of adequate investment in accelerated and intensive breeding for native genetic resistance to FAW in Africa and Asia is hampering progress by the international agricultural research centers and national partners to come out with solutions for FAW management based on host plant resistance. This needs to be urgently addressed.
- Another important gap that needs urgent attention is the stacking of transgenic insect-resistant traits with native genetic resistance. This could generate significant synergistic value, ensuring sustainable yield protection from pests such as FAW.
- Deploying improved maize varieties with genetic resistance to FAW (native or transgenic) has great potential to reduce the use of pesticides by farmers. Studies should be done to empirically quantify the reduction of pesticide use together with the increase in resilience and productivity that comes with deployment of host plant resistance.

# 5. Priorities/Next Steps

1. In terms of native genetic resistance to FAW, the proposed priorities are:
   a) Varietal release and widespread deployment of “first-generation” white maize hybrids with FAW resistance, developed recently by CIMMYT and now available to partners, especially in SSA; these hybrids can also be potentially tested in Asian countries where white maize varieties are grown and consumed by local populations.
   b) Fast-tracked introgression of sources of native genetic resistance to FAW into Africa- and Asia-adapted germplasm, and release of next-generation products with native genetic resistance to FAW in Africa and Asia.
   c) Discovery/validation of genomic regions for resistance to FAW in maize using appropriate populations and exploring the possibility of genomic prediction for developing novel Africa-adapted/Asia-adapted FAW-tolerant/resistant maize varieties.
   d) Strengthening the capacity of NARS institutions in Africa and Asia in breeding for resistance to FAW along with other important adaptive and agronomic traits relevant for the smallholders.
2. Regarding transgenic resistance to FAW, the priorities are:
   a) Accelerated testing and deployment of *Bt* maize with proven efficacy, biosafety, and environmental safety with appropriate support from policy makers and regulatory authorities.
   b) Pyramiding transgenes with different modes of action (*e.g.*, *cry* + *vip* genes), instead of single-gene deployment, as a part of IRM strategy.
   c) Implementing IRM and proper stewardship wherever *Bt* maize varieties have been deployed in Africa and Asia, to ensure sustainable protection against the pest.

# 6. Conclusions

Sustainable control of FAW is best achieved when farmers use host plant resistance as part of an IPM strategy, together with good agricultural practices, pest scouting, biological control, agro-ecological management, and judicious use of safer-use pesticides. Intensive efforts are being made in Africa by CIMMYT and partners to identify, validate, and develop elite maize germplasm with native genetic resistance to FAW. These efforts need to be further accelerated and intensified in both Africa and Asia to derive elite tropical/subtropical germplasm suitable for different agroecologies and market segments. Such products must combine FAW resistance with other desirable and relevant traits for resource-constrained smallholder farmers in the target geographies.

*Bt* maize varieties carrying lepidopteran-specific transgene(s), wherever released in Africa and Asia, can become an important tool in the IPM toolbox for FAW management. Bringing the benefits of *Bt*-based solutions for FAW management more extensively into Africa and Asia would, however, require overcoming the current regulatory, political, and consumer acceptance hurdles. In countries where *Bt* maize is already being commercialized, it is important to devise and implement a well-coordinated regional IRM strategy. Synergies also need to be explored between native genetic resistance and *Bt* maize for offering better and sustainable host plant resistance options to the farming communities.

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CHAPTER 05

# Biological Control for Fall Armyworm Management in Asia

**CASE STUDY: INDIA**

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**CASE STUDY: BANGLADESH**

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# 1. Overview

Biological control, as mentioned in **Chapter 1**, is an important pillar of integrated pest management (IPM). The various components of IPM are not meant to act independently, and in some cases, for example with the use of parasitoids and predators, extra precautions may be needed when using pesticide applications. This is especially true in maize, where an IPM program must address several pests and not just the fall armyworm (FAW; *Spodoptera frugiperda* (J.E. Smith)). Biological control should be integrated into an IPM program with a clear understanding of its interactions with the other components of the IPM crop strategy such as habitat manipulations, host plant resistance, and pesticide use practices (Figure 2 in **Chapter 6**, Agroecology) (Orr 2009). In this chapter, biological control efforts for management of FAW are discussed using two case studies—India and Bangladesh. The principles and protocols could be applicable across the FAW-affected countries in Asia. A summary of the current status of biocontrol worldwide and issues regarding its adoption can be found in Barratt *et al.* (2018).

## CASE STUDY: INDIA

# 2. Introduction

Increased international trade has resulted in a continuous influx of alien arthropod species globally. In the last 13 years, India has formally recorded the entry of 17 invasive insect pests, including the fall armyworm (FAW; Gupta *et al.* 2017; Shylesha *et al.* 2018; Selvaraj *et al.* 2020). The scientific community, in collaboration with other stakeholders including farming communities, has succeeded in tackling these invasive pests using an IPM framework, which includes classical biological control (*i.e.*, the introduction of a new predator/parasitoid of an exotic pest to a new location where the pest has invaded) as well as augmentative biocontrol (the rearing and release of biocontrol agents as a treatment). A central goal of IPM is conservation biological control, which seeks to minimize harm to biocontrol agents occurring naturally in the cropping system. Finally, an increased demand for use of less-toxic pesticides, and in some cases a demand for biointensive pest management (BIPM) approaches (Anitha and Parimala 2014; Dufour 2001; Prakash and Rao 2017; Ranga Rao *et al.* 2007), is a driving force for greater use of biocontrol options where they are cost-effective and efficacious.

The focus of research at the Indian Council of Agricultural Research–National Bureau of Agricultural Insect Resources (ICAR-NBAIR), Bengaluru, India, was to search for indigenous natural enemies of FAW and to develop, promote, and deploy validated sustainable BIPM technologies against FAW. During 2018-19, 22 indigenous natural enemies of FAW were identified from infested fields, which comprised 13 parasitoids, five predators, and four microbials. This information on indigenous natural enemies is of paramount importance in designing conservation or augmentation biological control strategies for management of FAW, particularly because of the regulatory restrictions on bulk import of biopesticides.

Further, systematic studies were taken up to identify those bioagents that are amenable for multiplication and field utilization against FAW. Instead of testing the available commercial biopesticides, those potential bioagents/biopesticides available at the NBAIR macrobial (parasitoids and predators) and microbial repositories were evaluated against FAW—initially through laboratory trials to identify the best agents, which were followed by field testing in different agroecological zones of the country. Three egg parasitoids and one egg-larval parasitoid were observed to be amenable to rearing and release. Two exotic parasitoids, *Trichogramma pretiosum* Riley and *Telenomus remus* Nixon (which had been imported into India several decades ago and were already available in the insectary at NBAIR), which have proven to be efficient bioagents in Latin American (Figueiredo *et al.* 2015) and African trials, were evaluated against FAW. It was also interesting to record that *T. remus,* which was imported and released several decades ago to target *Spodoptera litura* (Fabricius) in India and which had never been recorded in release and recovery studies, was now observed to parasitize FAW eggs in nature. The indigenous species *Trichogramma chilonis* Ishii was also recorded as a dominant parasitoid of FAW eggs in nature.

A total of six microbials—one strain of *Metarhizium anisopliae,* one strain of *Pseudomonas fluorescens*, two strains of the entomopathogenic nematode *Heterorhabditis indica* from the NBAIR microbial repository, and two microbials isolated from infected field-collected FAW larvae, which included a strain of *S. frugiperda* nucleopolyhedrovirus (SpfrNPV) and a strain of *Bacillus thuringiensis* (*Bt*)—were identified for final large-scale field trials. These were validated in the fields in different parts of the country in collaboration with the All India Coordinated Research Project on Biological Control. A BIPM strategy was developed that comprised nano-based pheromone traps for monitoring and mass trapping, egg parasitoids for targeting the egg stage of the pest, and microbials to target the early and late larval stages.

# 3. Indigenous Natural Enemies of FAW Reported from Indian Maize Fields

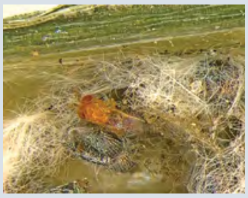
Molina-Ochoa *et al.* (2003) reported approximately 150 species of parasitoids and parasites of FAW, which belonged to 14 families—nine in the Hymenoptera, four in the Diptera and one in the Nematoda—throughout the Americas and the Caribbean Basin. Ichneumonids and braconids were the most diverse families in Hymenoptera. The Tachinidae was the most diverse family among the parasitoids, with 55 species.

In July 2018, when FAW was first reported in India, an extensive search was made for the presence of indigenous natural enemies. As expected, a number of such parasitoids and predators were found. Shylesha *et al.* (2018) have documented natural parasitism by parasitoids (Table 1), namely, the egg parasitoids *Telenomus* sp. (Platygastridae) and *Trichogramma* sp. (Trichogrammatidae), the egg-larval braconid parasitoid *Chelonus* spp., the gregarious larval parasitoid *Glyptapanteles creatonoti* (Viereck) (Braconidae), the solitary larval parasitoid *Campoletis chlorideae* Uchida (Ichneumonidae), and an indeterminate larval-pupal Ichneumoninae parasitoid.

Gupta *et al.* (2019) reported *Cotesia ruficrus* (Haliday) as a larval parasitoid of FAW in the maize fields of Karnataka, Tamil Nadu, Rajasthan, Uttar Pradesh, Punjab, and Meghalaya. Gupta *et al.* (2020a, b) additionally reported *Chelonus formosanus* Sonan and *Coccygidium transcaspicum* (Kokujev), respectively, from FAW.

Two parasitoids, namely, *Phanerotoma* sp., and *Coccygidium transcaspicum* (Table 1), which were found associated with FAW, were less frequently encountered than *T. remus*, *Trichogramma chilonis*, *Chelonus formosanus*, *Chelonus* spp. (see Section 5.3.3), *Campoletis chlorideae* Uchida, and *Cotesia ruficrus. Forficula* sp. (Dermaptera: Forficulidae) (Table 1) was also observed feeding on FAW larvae in some of the fields that were free from insecticidal spray.

**Table 1.** Parasitoids and predators reported on FAW in India.

| Scientific name | Biological attribute | Photograph | Collection locality | Reference(s) |
|---|---|---|---|---|
| *Telenomus* sp.# Hymenoptera: Platygastridae | Egg parasitoid |  | Karnataka and Tamil Nadu | A |
| *Trichogramma* sp.## Hymenoptera: Trichogrammatidae | Egg parasitoid |  | Karnataka | A |
| *Chelonus formosanus* Sonan Hymenoptera: Braconidae | Egg-larval parasitoid |  | Karnataka; Telangana | B |
| *Coccygidium transcaspicum* (Kokujev) Hymenoptera: Braconidae | Larval parasitoid |  | Karnataka; Telangana | C |

| Scientific name | Biological attribute | Photograph | Collection locality | Reference(s) |
|---|---|---|---|---|
| *Cotesia ruficrus* (Haliday)<br><br>Hymenoptera: Braconidae | Larval parasitoid |  | Karnataka; Tamil Nadu; Rajasthan; Uttar Pradesh; Punjab; Meghalaya | D |
| *Glyptapanteles creatonoti* (Viereck)<br>Hymenoptera: Braconidae | Larval parasitoid |  | Karnataka | A |
| *Campoletis chlorideae* Uchida<br>Hymenoptera: Ichneumonidae | Larval parasitoid |  | Karnataka | A,E |
| *Eriborus* sp.<br>Hymenoptera: Ichneumonidae | Larval parasitoid | | Karnataka | E |
| *Odontepyris* sp.<br>Hymenoptera: Bethylidae | Larval parasitoid | | Tamil Nadu | E |
| *Phanerotoma* sp.<br>Hymenoptera: Braconidae | Larval parasitoid |  | Karnataka | F |
| *Exorista sorbillans* (Wiedemann)<br>Diptera: Tachinidae | Larval parasitoid | | Karnataka | E |
| *Forficula* sp.<br>Dermaptera: Forficulidae | Predator |  | Karnataka | A,E |
| *Harmonia octomaculata* (Fabricius):<br>Coleoptera: Coccinellidae | Predator | | Karnataka | E |
| *Coccinella transversalis* Fabricius<br>Coleoptera: Coccinellidae | Predator | | Karnataka | E |
| Indeterminate Ichneumoninae<br>Hymenoptera: Ichneumonidae | Larval-pupal parasitoid |  | Karnataka | A |

Source of all photos in Table 1: Ankita Gupta, ICAR-NBAIR.
# Reported in Shylesha *et al.* (2018) as *Telenomus* sp.; now identified as *Telenomus remus* Nixon
## Reported in Shylesha *et al.* (2018) as *Trichogramma* sp.; now identified as *Trichogramma chilonis* Ishii
References (for discovery on FAW in India): A: Shylesha *et al.* (2018); B: Gupta *et al.* (2020a); C: Gupta *et al.* (2020b); D: Gupta *et al.* (2019); E: Sharanabasappa *et al.* (2019); F: Present report.

## 3.1. Natural Field Parasitism Rates in Various Countries

A number of natural enemies of FAW including parasitoids, predators, and pathogens have been reported from African countries (Huesing *et al.* 2018) and Latin America (Molina-Ochoa *et al.* 2003). From African countries, *Cotesia icipe* Fernandez-Triana & Fiobe (Hymenoptera: Braconidae) was the major parasitoid recorded in Ethiopia, with a parasitism rate of 37.6% (Sisay *et al.* 2018). Another braconid, *Coccygidium luteum* (Brullé), was found parasitizing over 20% of larvae found in Ghana and Benin (Agboyi *et al.* 2020; Koffi *et al.* 2020). *Chelonus curvimaculatus* Cameron (Hymenoptera: Braconidae) was the only egg-larval parasitoid recorded in Kenya, with a 4.8% parasitism rate; however, *Chelonus bifoveolatus* Szépligeti was a dominant parasitoid in West Africa (Agboyi *et al.* 2020; Koffi *et al.* 2020). In 2018, six species of egg and larval parasitoids were recovered with *C. icipe* being the dominant larval parasitoid, with percentage parasitism ranging from 16% to 42% in the three surveyed countries. In Kenya, *T. remus* (Hymenoptera: Scelionidae) was the dominant egg parasitoid, causing up to 69.3% parasitism as compared to only 4% by *C. curvimaculatus.* Pomari *et al.* (2013) reported that a ratio of 0.165 female *T. remus* parasitoids per FAW egg can be recommended to be released in maize since this release rate resulted in ≥80% parasitism. In Latin America, inundative releases of *T. remus* resulted in 90% parasitism, providing control of FAW (Cave 2000; Ferrer 2001).

*Telenomus remus* was originally imported into India and field-released several decades ago for the management of *S. litura* (Sankaran 1974). Parasitism of FAW eggs by *T. remus* was recorded in Karnataka, Maharashtra, and Telengana states in India (Navik *et al.* 2021; ICAR-NBAIR 2020). *Trichogramma chilonis* parasitism was recorded in Karnataka and Maharashtra (Navik *et al.* 2021; ICAR-NBAIR 2020). Parasitism by *T. chilonis* in the early stage of FAW invasion in 2018 ranged from 1.08% to 1.20%; however, in the following year (2019-20), parasitism by *T. chilonis* increased and ranged from 2.28% to 20% in different localities of Karnataka. In Maharashtra, the parasitism rate by *T. chilonis* ranged from 7.5% to 18%. Parasitism by *T. remus* was 1.0% to 7% during 2018 and 1.2% to 8% during 2019-20 in Karnataka. Both parasitoids were observed to parasitize eggs in the same egg mass, indicating their complementarity. In India, laboratory studies at ICAR-NBAIR indicated 100% parasitism by *T. remus* on FAW eggs. *Telenomus remus* was observed to be the dominant parasitoid when both *T. pretiosum* and *T. remus* were released together.

## 3.2. Parasitism Potential of *Trichogramma* Species against FAW

Laboratory screening of field-collected *Trichogramma chilonis* and lab-reared *T. pretiosum*, *T. chilonis*, and *Trichogrammatoidea armigera* indicated that field-collected and lab-reared *T. chilonis* and lab-reared *T. pretiosum* could provide high rates of parasitism (74%, 69%, and 67%, respectively) (ICAR-NBAIR 2020; Om Prakash Navik, unpublished data).

# 4. Entomopathogens

## 4.1. Entomopathogenic Fungi

Attempts were made to record the microbial pathogens infecting FAW in different maize-growing areas in India. The aim was to identify potential entomopathogens and further develop alternative pest management strategies using microbials. *Metarhizium rileyi* (=*Nomuraea rileyi*) was observed to cause epizootics (Figure 1A) with around 10-62% infection in natural field situations in different locations in the states of Karnataka (Shivamogga, Chikkaballapur, Hassan, Davanagare, Chitradurga, and Bangalore districts) (Shylesha *et al.* 2018; Mallapur *et al.* 2018), Andhra Pradesh (Anantapur, Visakhapatnam, and Vijayanagaram districts), Telangana (Ranga Reddy and Medak districts), and Maharastra (Ahmednagar, Pune, and Solapur districts).

Two strains of *Metarhizium rileyi* were isolated from FAW cadavers collected from Chikkaballapur and Anantapur (designated NrSf-4 and NrSf-5, respectively). Molecular characterization was done using the internal transcribed spacer (ITS) region and the sequences were deposited at NCBI GenBank (accession number MN602591). *Beauveria felina* has been found to cause natural infection (Figure

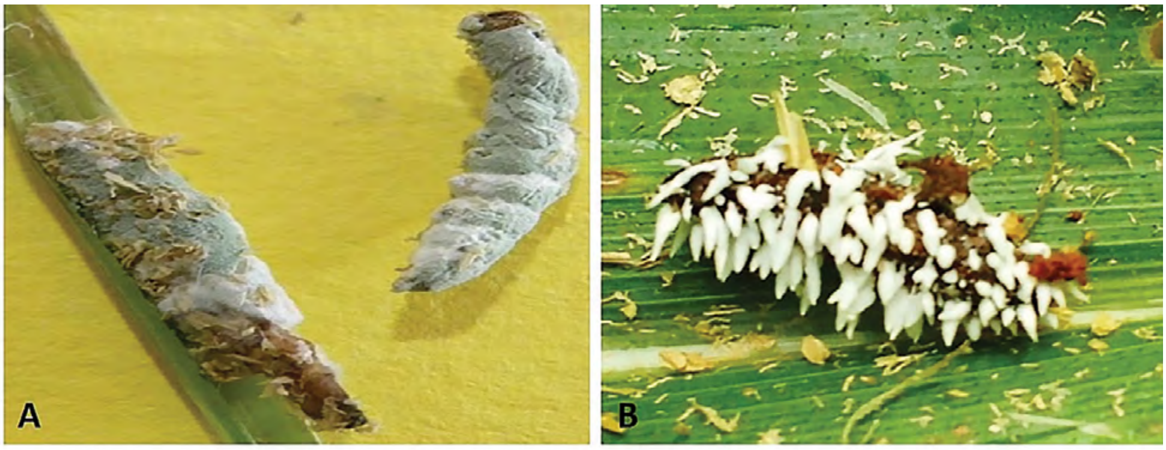



**Figure 1.** (A) Epizootics of *Metarhizium rileyi* on FAW; (B) natural infection of *Beauveria felina* on FAW.

1B), recorded as around 30% infection in Chikkaballapur, Karnataka (ICAR-NBAIR 2020). The organism has been isolated, molecular characterization was done using the ITS region, and the sequences were deposited at NCBI GenBank (accession number MN833071).

ICAR-NBAIR holds a repository of promising isolates of entomofungal pathogens. After initial laboratory studies, field evaluations of *Beauveria bassiana* (ICAR-NBAIR Bb-45) and *Metarhizium anisopliae* (ICAR-NBAIR Ma-35) were carried out against FAW during the *rabi* (winter) season in 2018 and the *kharif* (monsoon) season in 2019 (Bangalore and Chikkaballapur in Karnataka) and at Anakapalle in Andhra Pradesh during *rabi* 2018. Three foliar sprays @ 5 g/L (talc formulation containing $1 \times 10^8$ spores/g) were applied at 15, 30, and 45 days after maize germination. The results indicated that ICAR-NBAIR Ma-35 and ICAR-NBAIR-Bb-45 could cause 50-80% reduction in pest damage. Field evaluation against FAW in Dharwad district of Karnataka resulted in 58-62% pest reduction 15 days after spraying (Mallapur *et al.* 2018). The Bb-45 and Ma-35 isolates have been field-tested so far in different maize-growing areas of India covering an area of 40 hectares in Karnataka, Andhra Pradesh, Telangana, Tamil Nadu, Maharashtra, and Orissa during the *rabi* and *kharif* seasons of 2018 and 2019.

## 4.2. Entomopathogenic Bacteria

### 4.2.1. *Bacillus thuringiensis*

*Bacillus thuringiensis* Berliner (*Bt*) is a bacterium that forms insecticidal proteins and other toxins, and is used as a biopesticidal spray. Most *Bt* crystal (Cry) toxins are specific to lepidopteran insects, and *Bt* strains with activity against FAW can be found all over the world. For example, *Bt aizawai* HD 68 and *Bt thuringiensis* 4412 have shown 80% and 80.4% mortality, respectively, against FAW in laboratory studies (Polanczyk *et al.* 2000). de Souza *et al.* (2009) identified *Bt (israelensis* type) showing toxicity to FAW ($LC_{50}$ of 76.58 μg $cm^{-2}$). Monnerat *et al.* (2007) isolated three indigenous *Bt* isolates from Brazil showing higher toxicity ($LC_{50}$ of 18-25 ng $cm^{-2}$) against FAW. Similarly, Cerqueira *et al.* (2016) isolated four indigenous isolates from Brazilian soils having $LC_{50}$ of 44-108 ng $cm^{-2}$ against FAW. At ICAR-NBAIR, researchers have succeeded in identifying an effective indigenous *Bt* isolate, NBAIR-BT25, and further developing it into a formulation for FAW management (Figure 2). This isolate has been submitted to GenBank as MN327970 (AICRP-BC 2020). In a replicated trial in Orissa, a combination of *Trichogramma* sp. releases to target the egg stage followed by NBAIR-BT25 sprays to target the larval stage resulted in a green cob yield of 16.05 t/ha, significantly higher than that of the untreated control (8.14 t/ha) and comparable to that obtained with emamectin benzoate (17.54 t/ha) (AICRP-BC 2019). (Green cob yield includes the wet weight of cob + kernels + husks sold as "sweet corn" for human consumption, which would be higher than typical yields of dried corn used for grain.) The percentages of plant damage in these three treatments followed the expected trend, *i.e.*, more damage was associated with lower yield. Additional testing will be required to confirm these effects.

Note that uncharacterized strains (*i.e.*, for which the specific insecticidal protein(s) are unknown) cannot be commercialized in most jurisdictions, but *Bt* formulations active against FAW can be obtained commercially in many world areas. Care must be taken to ensure that commercially available products are authentic. In India, ICAR-NBAIR is evaluating indigenous *Bt* strains with the goal of commercialization. More information on use of *Bt* and its characteristics relative to those of other pesticides can be found in **Chapter 3**. Genetically modified (GM) maize expressing one or more *Bt* proteins is also available in some countries (see **Chapter 4**).

**Figure 2.** Dead larvae observed after foliar application of NBAIR-BT25.

### 4.2.2. *Pseudomonas fluorescens* Strain NBAIR-PFDWD against FAW

*Pseudomonas fluorescens* is well-known for plant-growth-promoting effects that improve crop health and increase agricultural production, and it exhibits potent insecticidal activities along with fungicidal activities (Flury *et al.* 2016). The *Pseudomonas fluorescens* group of bacteria is very diverse, and it comprises members that form part of the beneficial rhizosphere microbiota that cooperates with the plant to act against pests and diseases (Venturi and Keel 2016). Loper *et al.* (2016) reported the identification of additional insect pathogenicity factors of a representative insecticidal pseudomonad, *P. protegens* Pf-5, in an oral infection model against dipteran and lepidopteran insects. In our study, *P. fluorescens* strain NBAIR-PFDWD exhibited potential insecticidal activity against FAW in *in vitro* bioassays. Different dosages of NBAIR-PFDWD were tested, and 100% mortality of FAW was observed at a dosage of $10^8$ colony-forming units (CFU)/ml within 72 h after treatment. An increase in dosage (to $2 \times 10^9$ CFU/ml) of this strain led to 100% mortality in 48 h.

Under field conditions, a talc-based formulation of NBAIR-PFDWD was sprayed on FAW-infested hybrid maize at ICAR-NBAIR, Yelahanka campus, Karnataka. Treatments were initiated after the observation of more than 80% FAW infestation on 25-day-old hybrid maize seedlings. Four post-infestation sprays (20 g/L of water) at weekly intervals effectively controlled FAW infestation under field conditions. One hundred percent recovery of the hybrid maize plants was observed, suggesting that the treatment promoted plant growth as well as removing the insects. This NBAIR-PFDWD strain could effectively manage FAW infestation on maize under field conditions.

## 4.3. Entomopathogenic Viruses

SpfrNPV belongs to the family Baculoviridae, a family of viruses that are recognized for controlling insect pests in an efficient and environmentally sustainable manner. Baculoviruses are reported to be highly specific, virulent, and safe to non-target organisms (Moscardi 1999; Fuxa 2004; Barrera *et al.* 2011). Worldwide, different isolates of SpfrNPV have been used for biological control of FAW, with efficacies higher than 80%, demonstrating its potential to control the pest (Martínez *et al.* 2012; Behle and Popham 2012; Gómez *et al.* 2013). A commercial formulation of SpfrNPV called CORPOICA was developed in Colombia for the biological control of FAW (Villamizar 2015). Fawligen is another commercial baculovirus-based biopesticide produced by AgBiTech, USA, and released into the market for the management of FAW (https://www.prnewswire.com/news-releases/agbitech-and-upl-enter-distribution-agreement-for-baculovirus-insecticide-products-for-africa-300991442.html).

Surveys were conducted by NBAIR in maize fields of Chikkaballapur (Karnataka), Coimbatore, and Jolarpettai (Tamil Nadu) and diseased FAW larvae, which were showing characteristic viral infection symptoms, were collected (Figure 3). Naturally NPV-infected larvae were observed in the field with characteristic infection symptoms of hanging from the leaves, eventually oozing viroid particles and fluids. Observation of discharged body fluid of diseased larvae under a phase-contrast microscope revealed numerous spherical particles resembling occlusion bodies (OBs) of baculovirus, especially SpfrNPV (Figure 4). OBs of nucleopolyhedrovirus were extracted from the diseased larvae by differential centrifugation. The OBs were enumerated using a Neubauer's hemocytometer and mounted on a phase-contrast light microscope at 10× and 40× magnification.

**Figure 3.** Diseased FAW larvae showing characteristic viral infection symptoms.

Under scanning electron microscopy (SEM), the OBs of SpfrNPV appeared as tetrahedral shapes (Figure 5A). Transmission electron microscopy (TEM) of the OBs revealed the tetrahedral-shaped occlusion body, with a size of 1.64 µm (Figure 5B) (Sivakumar *et al.* 2020).

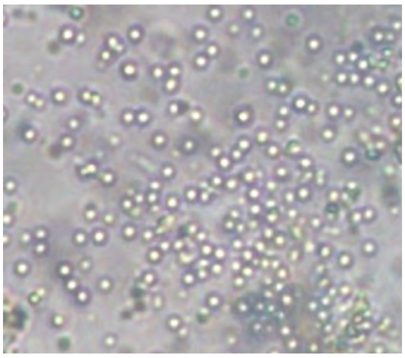


**Figure 4.** Light micrograph of body fluid obtained from diseased FAW larvae showing nucleopolyhedrovirus occlusion bodies (OBs).

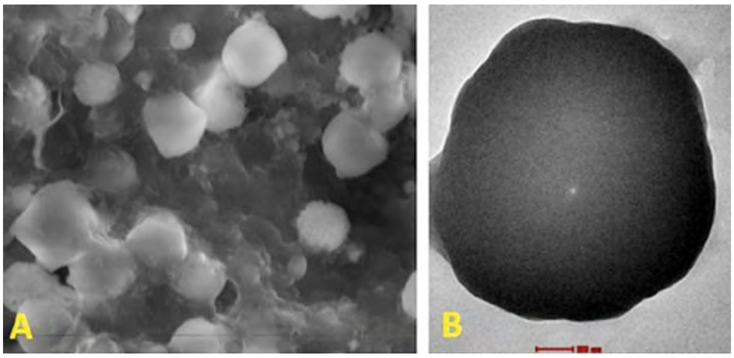



**Figure 5.** Scanning (A) and transmission (B) electron micrographs of tetrahedral occlusion bodies of *S. frugiperda* NPV.

Field experiments were conducted by NBAIR in farmers' fields in the Chikkaballapur district of Karnataka to evaluate the bioefficacy of SpfrNPV NBAIR1 (ICAR-NBAIR 2020). Field data revealed that a prophylactic spray of aqueous suspension of SpfrNPV NBAIR1 twice @ 3 ml/L, at a concentration of $1.5 \times 10^{12}$ polyhedral occlusion bodies (POBs)/ha, on the 20$^{th}$ and 35$^{th}$ day after sowing reduced the FAW infestation by 80.4% during the *rabi* season and 68-72% during the *kharif* season and increased yield and general growth of the maize plants (G. Sivakumar, personal communication). Thus, for the first time, a new virulent indigenous novel isolate of NPV associated with FAW was recorded from India and evaluated against FAW. This product is in the process of being commercialized.

## 4.4. Entomopathogenic Nematodes

A less explored but promising biocontrol strategy is the use of entomopathogenic nematodes (EPNs) for management of lepidopteran pests and root grubs. EPNs belonging to the families Steinernematidae and Heterorhabditidae are ubiquitous generalist parasites of several economically important insect pests. They are symbiotically associated with the bacteria *Xenorhabdus* spp. and *Photorhabdus* spp. When these bacteria are released into the insect hemocoel, they cause septicemia and death of the insect in 24-48 h (Kaya and Gaugler 1993). EPNs have a great potential as biological control agents against agricultural and horticultural insect pests because of their wide host range. Furthermore, they can be easily mass-produced, formulated, and applied as biopesticides (Kaya and Gaugler 1993). The effects of different application technologies were evaluated, with focus on the appropriate concentration, viability, and efficiency of infective juveniles of the nematodes *Heterorhabditis indica* Poinar, Karunakar and David and *Steinernema* sp. (IBCB-n6) to control FAW on maize plants. It was reported that the efficacy of *H. indica* was enhanced against FAW when mixed with an insecticide, lufenuron (Negrisoli *et al.* 2010). Viteri *et al.* (2018) reported that when *S. carpocapsae* was used in combination with chlorantraniliprole or spinetoram, this combination caused more than 90% mortality in 5$^{th}$-instar larvae of FAW in 72-h in laboratory tests.

### 4.4.1. Application of EPNs for FAW Management

Four isolates of EPNs were examined for their efficacy against FAW in maize fields at the research farm of ICAR-NBAIR, located at Yelahanka, Bengaluru, during *kharif* and *rabi* 2018-19. Based on the lethal concentration (LC) values obtained, time and method of application were standardized. Consolidated results indicated that prophylactic application of a wettable powder (WP) formulation of *H. indica* at 15 days after plant emergence reduced FAW infestation by 65-72% during *kharif* and 58-64% during *rabi*, compared to 45-65% in maize treated with emamectin benzoate. The relatively high FAW incidence in the maize treated with emamectin benzoate indicates that this treatment did not perform as well as expected based on global experience (see **Chapter 3**), which might be due to application timing, application technique, or possibly the development of insecticide resistance. Yields per plant were on par in EPN-treated and insecticide-treated plants. Due to plant mortality and stand/m$^2$, significant differences in productivity were observed in treated and untreated maize. Field trials on EPN doses, efficacy in combination with conventional insecticides, and formulations of EPN against FAW (*kharif* 2019-20) indicated dose-dependent control of FAW larvae with an optimum dose of 4-6 kg ha$^{-1}$ either in the form of WP or granular formulation of *H. indica* NBAII Hi101. Split doses and combination of *H. indica* with emamectin benzoate at split doses could reduce the infestation by 80-88%. A field study on application of WP formulations of EPN on the maize whorl indicated that WP formulations of EPN reduced FAW populations by 60-72% and produced plant growth and yield comparable to emamectin benzoate and chlorpyriphos sprays, both in *kharif* and *rabi*. Another field trial in Pachora, Maharashtra, in black cotton soils demonstrated that application of a WP formulation of EPN to the plant root zone in combination with whorl application in the first fortnight followed by split dose 30 days later prevented secondary infestation of field populations.

ICAR-NBAIR researchers demonstrated and validated the delivery of EPN to whorls using WP formulations that reduced FAW populations to approximately 60-72% of the original in maize and sustained plant growth and yield comparable to emamectin benzoate and chlorpyrifos sprays at experiments done at four Krishi Vigyan Kendras (KVKs; “Farm Science Centers”) in Telangana, six in Tamil Nadu, three in Maharashtra, and four in Karnataka. The area covered under the supply of WP of *Heterorhabditis indica* NBAII Hi101 provided to farmers, KVKs, AICRP centers, etc., for the management of FAW was about 58 ha, whereas 112 ha was covered through supply of WP of *H. indica* NBAIIH38. Training was imparted to 165 farmers, KVK workers, and trainers and the technology was commercialized by several companies. The technology for WP formulation of EPNs developed at ICAR-NBAIR is available for commercialization.

## 4.5. Biointensive Pest Management (BIPM) Trial

A combinatorial efficacy trial was evaluated in farmer's fields during the *rabi* and *kharif* seasons (2018-2019), which comprised installation of controlled-release FAW pheromone traps (developed by ICAR-NBAIR), four releases of the egg parasitoid *T. pretiosum*, two sprays of neem oil, and one spray each of two indigenous microbial biopesticides: *Bt* (NBAIR-BT25) and *M. anisopliae* (NBAIR Ma-35). There was a significant reduction in egg masses (76% and 71.64%) and larval population (80% and 74.44%) at 60 days after treatment during the *rabi* and *kharif* seasons, respectively. This was accompanied by an increase in maize cob (ear) yield compared to the farmers' fields, where 6-7 sprays of emamectin benzoate 5% SG were applied (Varshney *et al.* 2020). As in the experiments with EPN (Section 4.4.1), the emamectin benzoate treatment did not reduce larval infestation as well as expected, though the reasons are unclear. While the major challenge lies in making the biocontrol agents available to farmers, this module needs to be validated in larger areas under different agroecological regions of the country, with replicated yield comparisons to highly effective treatments and modifications in the components of the module based on regional requirements. In addition, the cost-benefit ratio of such a treatment regime needs to be assessed.

The results of a study by Amala *et al.* (2020) in India indicate that maize-legume intercropping with a border crop of napier grass can be very effective in managing FAW, as it could significantly reduce the pest population and increase the abundance of natural enemies. It would be important to evaluate the effects of these treatments on yield and whether the above "push-pull strategy" can be integrated into the combination of treatments described above. Additional information on agroecological control of FAW can be found in **Chapter 6**.

# 5. Protocols for Mass Production of Natural Enemies under Laboratory Conditions

## 5.1. Mass Production of Egg Parasitoids *Trichogramma* and *Telenomus*

*Trichogramma* species used for management of FAW are mass-produced on eggs of laboratory host *Corcyra cephalonica*. *Telenomus remus* can be easily mass-produced on eggs of FAW and *S. litura*. In Africa, rearing of both these parasitoids for targeting FAW was initiated in the International Center of Insect Physiology and Ecology (*icipe*) in 2019 with support from the United States Agency for International Development (USAID) Feed the Future Innovation Lab for Integrated Pest Management, through the "Rice, Maize, and Chickpea IPM for East Africa" project. *Trichogramma* cultures were initiated at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) facility in Niger in 2015, and both FAW and *Telenomus* cultures were initiated in 2018 (Kenis *et al.* 2019). In Colombia, many private sugarcane plantations maintain small insectaries for production of trichogrammatids. During the 1990s, there were 30 commercial mass-production facilities for parasitoids and predators in Colombia, but by 2000 the number had decreased to nine (Van Lenteren and Bueno 2003). The live-insect repository at the NBAIR, Bangalore, India, holds 130 live-insect cultures, which are multiplied and maintained year-round. Pest cultures such as *C. cephalonica, S. litura, Helicoverpa armigera* (Hübner), and FAW; parasitoid cultures such as *Trichogramma* spp., *T. remus, Goniozus nephantidis* (Muesbeck), and *Chelonus* spp.; predators such as *Chrysoperla zastrowi sillemi* Esben-Peterson and *Cryptolaemus montrouzieri* Mulsant; and some species of anthocorid predators and predatory mites are maintained in the repository.

ICAR-NBAIR supplies parasitoids, predators, and microbials to farmers (primarily for rice, coconut, vegetables, maize, and sugarcane) free of charge. In India, there are very few commercial entities producing parasitoids and predators. The major role of NBAIR is to provide start-up cultures to government and private-sector labs and units, who in turn supply farmers. ICAR-NBAIR also trains officials from government departments and private units to mass-produce macrobials and microbials, as availability of biocontrol agents is a major concern in India.

One of the challenges facing producers of parasitoids is the need for rapid distribution and use following production. As mentioned below (Section 5.3.1), ICAR-NBAIR has developed a cold-storage method for *Trichogramma* that allows storage for up to 3 months, which could provide satisfactory adult emergence, longevity, and parasitism (Ghosh and Ballal 2017).

## 5.1.1. Mass Production of Host Insects

### *5.1.1.1. Rearing of tobacco caterpillar Spodoptera litura (Fabricius) (Lepidoptera: Noctuidae)*

*Spodoptera litura* (Fabricius) is a polyphagous pest attacking tobacco, cole crops, castor, cotton, sunflower, tomato, pigeon pea, and other crops and is distributed throughout India. The adult moth has a longevity of 10 to 24 days. Eggs are laid in batches on tender leaves and are covered with scales. The caterpillars are about 3.7 cm long and pale greenish brown in color with dark markings. A black ring encircling the body is present at both ends. The egg, larval, and pupal stages last for 3-4, 18-20, and 9-10 days, respectively. The pupation occurs in soil.

Male and female pupae of *S. litura* can be distinguished by the distance between the genital and anal pores, which in females is more than twice that in the males. In addition, in the female pupae, on either side of the genital pore, a `V' shaped depression or fold extending up to the tenth segment is visible (Figure 6).

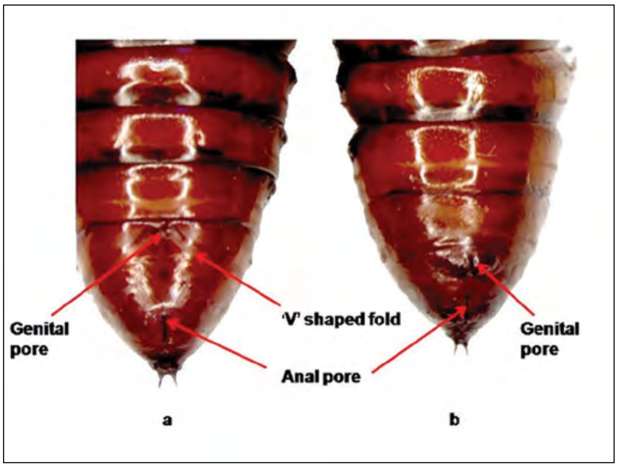



**Figure 6**. Spodoptera litura pupae: (a) female; (b) male.

*Spodoptera litura* is the most suitable host for multiplying *Telenomus remus.* The rearing protocol for this host insect has been standardized. The oviposition cage is a plastic container with a ventilated lid (Figure 7).

1. Line the inner wall and roof of the container with ordinary paper.
2. Release moths @25 pairs/container. Moths will lay eggs on the paper lining.
3. Collect eggs by cutting out portions of the lining where eggs are laid, and place the eggs in glass vials with cotton plugs. Eggs hatch in 3 to 4 days.
4. Group-rear the initial larval stages on bunches of castor leaves or on semi-synthetic diet (Section 5.1.2) in ventilated plastic boxes. These boxes can be conveniently stacked in racks to save space.
5. After 1 week, transfer the larvae to individual vials of semi-synthetic diet or multicellular larval rearing trays.

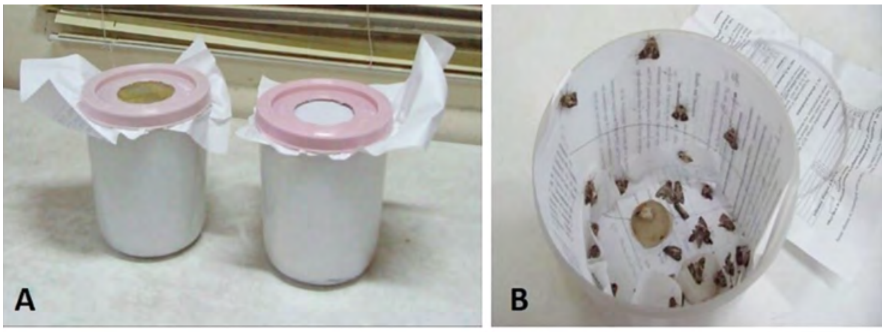



**Figure 7.** *Spodoptera* egg-laying cage.

### 5.1.2. *Spodoptera litura* Diet Preparation

Ingredients for the four diet parts are given in Table 2.

1. Mix 390 ml of water with part A of the diet. Run blender for 2 minutes.
2. Boil part B in 390 ml of water. Add this to part A in blender. Run blender for 1 minute.
3. Add part C and run blender again for 1 minute.
4. Add part D and run blender for a minute. Pour the diet into sterilized glass vials before the diet cools.
5. Transfer one larva to each tube and plug tube tightly with cotton wool.
6. After 20-25 days, collect the pupae formed inside the vials.
7. Sterilize pupae in 0.1% sodium hypochlorite solution and dry before placing into adult emergence cages.

**Table 2.** Composition of the semi-synthetic diet used for rearing *S. litura.*

| Part | Ingredients | Quantity |
|---|---|---|
| A | Chickpea (Kabuli gram) flour | 105 g |
| | Methyl para hydroxy benzoate | 2 g |
| | Sorbic acid | 1 g |
| | Yeast tablets | 10 g |
| B | Agar | 12.75 g |
| C | Ascorbic acid | 3.25 g |
| | Multivitaplex | 2 caps |
| | Vitamin E | 2 caps |
| | Streptomycin sulphate | 0.25 g |
| D | 10% formalin | 5 ml |

## 5.2. Mass Multiplication of *Corcyra cephalonica*

The rice meal moth, *Corcyra cephalonica* Stainton (Lepidoptera: Pyralidae) is a host insect highly amenable to rearing because of its adaptability to varied rearing conditions and its positive influence on the progeny of the natural enemies. *Corcyra cephalonica* is used as an alternative host to mass-multiply natural enemies such as trichogrammatid egg parasitoids, several braconids, and anthocorid and chrysopid predators. *Corcyra* can be mass-multiplied throughout the year in all the ecological zones of India at 28 ± 2°C and 65 ± 5% relative humidity (RH).

The eggs are oval and measure 0.5 × 0.3 mm. Full-grown larvae are creamish white with a brown head and prothoracic tergite and well developed prolegs on abdominal segments 3-6 and 10. The last-instar larva spins a closely woven, very tough, double-layered cocoon in which it develops into a dark-brown pupa. Adults are greyish-brown with thin vague lines of darker brown color along the wing veins. The males are smaller than the females. The pre-oviposition period is 2 days. Egg laying mainly occurs during the night and more eggs are laid on the second and third days after emergence, though oviposition continues throughout the adult lifespan. The incubation period is 2-3 days. Optimum conditions for larval development of *C. cephalonica* are 28-30°C and 70% RH. Under these conditions, the developmental period from egg hatch to adult emergence is 26-27 days. Males generally have 7 larval instars and females have 8 instars.

## 5.2.1. Mass Production of *Corcyra* in the Laboratory

Table 3 provides a list of the chemicals and equipment needed for raising *Corcyra*. Methods are described in the following sections.

**Table 3.** Materials required for mass production of *Corcyra*.

| | |
|---|---|
| Coarsely milled bajra (pearl millet) grain | Ground nut (peanut) (*Arachis hypogaea*) kernels |
| Yeast | Streptomycin sulphate (Ambystrin) |
| Honey | Vitamin E capsules (Evion) |
| Storage racks | Formaldehyde (2%) |
| Wooden rearing box | Vacuum cleaner (used as a suction pump) |
| Oviposition drums | Sulphur (WP) |
| Enamel tray | Face masks |
| Detergent | Mesh (see details in protocol) |
| Filter paper | Cotton wool |
| Thread | |

### *5.2.1.1. Preparation of rearing boxes*

*Corcyra* is reared in a rectangular rearing box (15 × 30 × 45 cm) made of 10-mm-thick plywood. The lid is provided with six ventilated holes (1 $cm^2$), covered on both sides with brass mesh of 100 mesh size (Figure 8). The boxes used for *Corcyra* multiplication are thoroughly cleaned with 0.5% detergent, rinsed, and dried. Whenever the boxes are emptied after a cycle of rearing, they have to be cleaned, preferably with 2% formaldehyde solution.

**Figure 8.** *Corcyra* rearing box.

### 5.2.1.2. Preparation of rearing medium and rearing of Corcyra

1. Coarsely mill the required quantities of bajra grains (each grain broken into 3-4 pieces).
2. Heat-sterilize the broken grains at 70°C for 1 h to eliminate residual populations of stored product insects such as *Rhizopertha dominica*, *Sitotroga cerealella*, *Tribolium castaneum*, and fungal contaminants. Cool the grains (in the shade or under a fan) in a clean area.
3. Transfer the grains to the rearing box @ 2.5 kg/box. Add 75 g of groundnut seed powder, 5 g of yeast powder, 0.7 g of streptomycin sulphate (Ambystrin), and 0.125 cc of *Corcyra* eggs (~2000 eggs). One cc of eggs contains approximately 16000-18000 eggs.
4. Place the inoculated boxes on racks at room temperature. Write the date of inoculation in each box. The larvae that hatch out in 3-4 days begin to feed on the fortified bajra medium. At this stage, light webbings are noticed on the surface of the medium. As the larvae grow, they move into the medium. During this period, the boxes and their contents should not be disturbed.
5. Moths emerge 40 days after inoculation and emergence can continue even up to 2 months. Collect moths daily using a suction pump (modified vacuum cleaner) and transfer to an oviposition drum (Figure 9A). Workers involved in the collection of moths should wear masks to avoid inhalation of scales (Figure 9B). The oviposition drums are made of plastic, with a wire-mesh base to enable collection of eggs. The walls of the drums have two vents (ventilation holes) opposite each other that are covered with wire mesh (Figure 9C). The lids of the drums have slots for introducing the moths and one vent with mesh for providing adult feed. The oviposition drums holding the moths are maintained for 4 to 7 days for egg collection, after which they are emptied and cleaned for the next cycle of use.
6. Provide the adults with honey solution as feed, which is prepared by mixing 50 ml honey with 50 ml water and 5 capsules of vitamin E (Evion). Store the prepared feed in the refrigerator until use. Soak a piece of cotton wool in the honey solution, attach it to a thread, and hang it from the lid inside the drum. The moths lay loose eggs in large numbers.
7. To minimize the risk of inhalation of scales in the culture rooms, place the oviposition drums on sheets of filter paper placed in enamel trays, which trap the scales effectively. Place sets of oviposition drums in a well-ventilated area. Every morning, lift up the oviposition drums and gently clean the wire-mesh base from the outside using a brush so that the eggs and remnants of scales and insect parts settled on the mesh are collected along with those on the filter paper. Pass the eggs through 15-, 30-, and 40-mesh sieves to remove scales. Quantify the eggs using a measuring cylinder. Retain some eggs for building up the host stocks; the rest can be used for natural enemy production.
8. For *Trichogramma* production, expose eggs to ultraviolet (UV) rays (30 W UV tube) for 45 minutes at a distance of 2 feet.


**Figure 9.** (A) Moth collection device; (B) moth collection using suction pump; (C) oviposition cage.

#### *5.2.1.3. Precautions during Corcyra rearing*

1. Line the doors and windows of the *Corcyra* production rooms with 60- to 100-size brass mesh to prevent entry of *Habrobracon* (= *Bracon*) *hebetor* (Say), which can completely destroy the culture.
2. Note the date of charging in each *Corcyra* box to enable the staff to initiate collection of moths on the correct day.
3. Dispose of the contents of rearing boxes after complete emergence.
4. Clean boxes properly before reuse.
5. Spray the rearing boxes with Dicofol and dry them before use to prevent mite infestation.
6. Use a light trap for monitoring *Habrobracon* infestation.

## 5.3. Production of Egg Parasitoids

### 5.3.1. Production of Trichogrammatids

1. As described above (Section 5.2.1.2), treat the eggs of *C. cephalonica* with UV rays for 45 minutes (to prevent hatching) and then glue them uniformly onto a card (15 × 10 cm) within a marked area of 12 × 8 cm. Gently remove the excess eggs from the cards by using a brush. Allow the cards to dry before exposing to parasitoids.
2. Expose the eggs to adult female *Trichogramma* in a tube (2.5 ×15 cm) or in plastic covers. If cards with unparasitized eggs are exposed to female parasitoids in tubes, small card strips (1.5 ×10 cm) are used and the egg-to-female ratio should be 8:1. If large cards (15 × 10 cm) are exposed in polythene covers, the eggs-to-female ratio should be 30:1, allowing the females to parasitize till mortality. One nucleus card of *Trichogramma* can be used to parasitize six additional cards. Provide a mixture of 50% honey and vitamin E (see Section 5.2.1.2 for preparation) in a soaked cotton swab as feed for the adults. Remove the parasitized cards ("tricho cards") after 2 days. Parasitized *Corcyra* eggs turn black on the 5$^{th}$ day after exposure, which indicates parasitization of the eggs.
3. Prepare 6-day-old parasitized cards for shipment or field release. Staple each parasitized card in such a way that the eggs do not rub against each other and get damaged. Twenty or more tricho cards can be packed in each polythene bag depending on the size of the bag. Provide a fine honey streak on the inner side of polythene bag as feed for adults that may emerge in transit. A technology has also been developed for long-term storage of tricho cards for up to 3 months through diapause induction (Ghosh and Ballal 2017). Tricho cards can be stored for shorter durations in a normal refrigerator at 10°C for up to 21 days.

#### *5.3.1.1. Release of trichogrammatids into the field*

1. Cut each tricho card into 16 pieces. Staple each piece onto the under-surface of a leaf, so that the eggs are not exposed directly to sunlight.
2. Perform releases at weekly intervals as long as pest eggs are available in the field.
3. Initial release of trichogrammatids could be timed based on pheromone trap catches or visual observation of the target pest.

### 5.3.2 Production of *Telenomus remus* (Scelionidae: Hymenoptera)

*Telenomus remus* (Figure 10) is primarily produced on the eggs of the tobacco caterpillar, *S. litura,* which is the preferred host. It can also parasitize eggs of *S. exigua*, *Helicoverpa armigera*, *Plusia signata, Agrotis segetum, Agrotis biconica, Agrotis ipsilon, Mythimna loreyi, Trichoplusia ni, Achaea janata,* and *Corcyra cephalonica*. Out of the total production of eggs, about 90% are utilized for *T. remus* production, the rest for continuation of the host culture. The ideal conditions for rearing of *T. remus* are 26-27°C and 60-70% RH. The protocol below describes use of *S. litura* as the host.

**Figure 10.** *Telenomus remus*.

#### *5.3.2.1. Materials required*

The materials include *S. litura* egg masses (Section 5.1.1.1), nucleus culture of *Telenomus remus*, cards, test tubes, polythene bags, scissors, stapler, water-soluble gum, honey solution (50%), and a refrigerator.

#### *5.3.2.2. Protocol*

*Telenomus remus* males have filiform antennae and short abdomens whereas females have clubbed antennae and longer and wider abdomens with the ovipositor clearly visible under a 10× hand lens. The males emerge before the females.

1. Pair the adults for 24 h for mating.
2. After a pre-oviposition period, confine the adult females in 25 × 150 mm glass tubes. Stick a small piece of cotton swab soaked with 50% honey solution on the inner side of the glass tube as feed for the adult parasitoids.
3. Glue ~6000 freshly laid (0-24 h old) *S. litura* eggs onto a thick paper card (10 × 2 cm) and expose to 100 parasitoids for 24-48 h for parasitization. On the 3$^{rd}$ and 4$^{th}$ days, 3,000 eggs may be provided, and on the 5$^{th}$ day, 1500 eggs may be provided. The parasitized eggs turn black in 4 to 5 days. Remove larvae hatching from unparasitized eggs from the card.
4. Transfer cards carrying only parasitized eggs into fresh, clean tubes for the emergence of the parasitoids. The adult parasitoids emerge in 9 to 10 days from the date of parasitization and can be used for field release. Retain 10% of the adults for continuation of the cultures.

### 5.3.3. Rearing of *Chelonus* spp. (Egg-Larval Parasitoid)

*Chelonus* spp., egg-larval parasitoids, were recorded frequently from field samples collected from different districts of Karnataka since March 2018, when the incidence of FAW was initially reported across the country. The parasitoid specimens were processed for identification (both morphological and molecular) and the genus was confirmed as *Chelonus* spp. There appeared to be two different species of *Chelonus*: one small and arrhenotokous (Figure 11A), one large and arrhenotokous (Figure 11B). (In arrhenotokous species, unfertilized eggs develop into males.) The insect in (B) has been identified as *Chelonus formosanus,* first reported from India (Gupta *et al.* 2020a). Species-level identification of (A) is in progress. Adults of *Chelonus* spp. can be reared by allowing them to parasitize the eggs of natural hosts such as FAW and *S. litura,* or the laboratory host, *C. cephalonica*. Adult longevity varied from 2 to 7 days. The developmental period was 20 to 25 days on natural host and 25 to 50 days on *C. cephalonica*. The parasitism rate was 10 to 19.4%. Adult emergence was 45 to 57.5% from cocoons reared on natural host and 85 to 98% from those on *C. cephalonica*. Successful rearing on *C. cephalonica* eggs enabled field evaluation of *Chelonus* spp. against FAW. Field trials are in progress.


**Figure 11.** Two different species of egg-larval parasitoid *Chelonus* spp. recorded on FAW in Karnataka, India: (A) *Chelonus* sp., (B) *Chelonus formosanus*.

# 6. Conclusion

Indian agriculture is facing a variety of challenges, which include climate change and onslaughts by invasive pests. Researchers have realized that management strategies, particularly biological control practices, have to be tailored to adapt to these challenges within an IPM framework. In addition, all management strategies have to be based on the understanding of the genetic diversity of the pest. The Indian research team at ICAR-NBAIR, which identified FAW through molecular characterization when it first invaded India in 2018, went on to analyze the genetic diversity of FAW in India two years after the initial introduction. Apart from the ancestral rice and corn strain haplotypes, 14 novel haplotypes unique to India, as well as inter-strain recombination, were recorded. The study also suggested that the invasive FAW populations in Asia and Africa have a common origin and that the FAW population in India might be undergoing expansion (Nayyar *et al.* 2021). Details on additional studies of FAW strain biology are provided in **Chapter 1**.

The identification of promising indigenous macrobials and microbial isolates and development of a nano-based pheromone technology culminated in the development and validation of a BIPM module. The major challenge faced in adoption of this approach by farmers is the availability of macrobial and microbial biocontrol agents. Commercial entrepreneurs have to be trained to mass-rear egg parasitoids and EPNs, which are exempt from registration. The efficacy of the indigenous microbial isolates discovered by NBAIR has been evaluated in the lab and field and the production protocols have been developed. NBAIR is in the process of generating toxicology data and preparing the regulatory dossiers, which can then be provided to the private sector for commercialization. Other important challenges include the complexity of obtaining and applying biocontrol agents at the proper time and the need to assess the cost-benefit ratio for treatments being considered.

**Areas for further research, development, and commercialization**

- Tracking the future evolution of FAW with respect to pesticide resistance and host range.
- Assessment of the efficacy of different management options on FAW in India.
- Comparative performance of the egg parasitoids and their competitive/complementary interactions.
- Comparative efficacy of the indigenous microbial isolates to target the larval stage of FAW infesting different crop stages.
- Evaluation of the BIPM module in different agroecological zones of the country.
- Large-scale validation of habitat manipulation strategies in farmers' fields and their integration within the BIPM module.
- Ensuring commercial availability of biocontrol agents for the farmers to effectively tackle FAW.
- Cost-benefit analysis of treatments using the CESAS (cost, efficacy, safety, accessibility, and scalability) model described in **Chapter 1**.

**CASE STUDY: BANGLADESH***

# 7. Introduction

Fall armyworm (*Spodoptera frugiperda*; FAW) was recorded in November 2018 for the first time in Bangladesh and since then has spread throughout the country. Infestation at the vegetative stage of maize was estimated at 40 to 50% while ear damage was estimated at around 23-30% in the summer maize (BWMRI 2020). An effective IPM strategy for this devastating pest is very much essential to minimize the maize production losses. Until now famers have depended mainly on synthetic chemical pesticides to combat the pest. However, to control the FAW, in an environmentally sustainable, socio-economically acceptable manner, IPM strategies are very much needed. Fortunately, FAW has been effectively controlled in the Americas for over 100 years so the goal in Bangladesh is to adopt these proven approaches to the Bangladesh farming system. Such strategies may include augmentative/inundative (periodic release of natural enemies against the target pest) biocontrol and use of technologies that support conservation biological control (*e.g.,* manipulation of environment and agronomic practices in a way that favors natural enemies).

# 8. Promising Biocontrol Agents against FAW in Bangladesh

Several studies have been initiated in Bangladesh to characterize natural enemies of FAW along with development of methods for their bioassay testing, standardizing of mass production, and field trials. Several biocontrol agents, such as larval parasitoid *Habrobracon* (= *Bracon*) *hebetor* (Say) and egg parasitoid *Trichogramma* spp., are being used as a component of an IPM package against different insect pests. Several public and private companies are also undertaking mass-rearing of different biological control agents and making them available to the farming communities on a limited scale. As FAW is a recently introduced pest in the country, limited work has been done on its biological control. So far, several predators including earwig (*Euborellia annulipes* Lucas) and ladybird beetle (*Coleomegilla maculate* De Geer), and several parasitoids including *Trichogramma* sp., *Telenomus remus, H. hebetor, Chelonus* sp., *Campoletis chlorideae*, etc., have been identified as effective biocontrol agents against FAW in the country.

## 8.1. Efficiency of *Habrobracon hebetor* as a Larval Parasitoid of FAW

*Habrobracon hebetor* is a medium-sized wasp that is parasitic on later instars of larvae lacking seta (hairs on their body) of a wide range of insect pests. Female *Habrobracon* first inject venom and thus paralyze host insect larvae. As little as one part of venom in 200 million parts of host blood (hemolymph) was sufficient to cause permanent paralysis and death of insect larvae, and one female *Habrobracon* can paralyze 500-1000 larvae. Female *Habrobracon* then lay their eggs on the paralyzed host larvae; the emerging *Habrobracon* larvae multiply therein and thus destroy the pest. In Bangladesh, *Habrobracon* is considered as an effective parasitoid and it is being successfully and commercially applied to control of many devastating pests such as *Prodenia* caterpillar (*Spodoptera litura*), tomato fruit worm (*Helicoverpa armigera*), tea looper (*Biston suppressaria*), etc. Laboratory and field efficacy studies against FAW larvae were undertaken by Bangladesh Agricultural Research Institute (BARI) in collaboration with the Centre for Agriculture and Biosciences International (CABI).

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### 8.1.1. Laboratory Study

Laboratory studies were carried out in the IPM laboratory of the Entomology Division, BARI, Gazipur, during December 2019 to evaluate the efficacy of *H. hebetor* as a larval parasitoid of FAW larvae. Five 4$^{th}$-instar larvae of FAW and one pair of adult *H. hebetor* were placed in a test tube (replicated 10 times). Adult *B. hebetor* females sting the FAW larvae and inject venom inside their body by inserting the ovipositor, which paralyzes the larvae and lead to death (Figure 12). After 24 hours of exposure, all the host larvae were transferred to Petri plates. It was recorded that 100% of the FAW larvae were killed. All the larvae became black, dead and dry within 24 h after *H. hebetor* venom injection. However, no *H. hebetor* emerged from the dead FAW larvae due to desiccation of the dead host. The dry-matter content of FAW larvae is less than that of other insect larvae, and the water content is high. For that reason, the larvae killed due to parasitization by *H. hebetor* dried up very quickly. Thus, it can be concluded that *H. hebetor* can kill FAW larvae efficiently, but no new *H. hebetor* will be released from those larvae. For effective results, inundative release of *H. hebetor* should be considered.


**Figure 12.** (A, B) Stinging and injecting venom of *B. hebetor* on FAW larva; (C) dead and dry larvae of FAW after 24 hours.

### 8.1.2. Field Study

An efficacy study of *H. hebetor* against FAW was carried out in the maize fields of farmers in Shibganj, Bogra, during June-July 2019. *Habrobracon hebetor* were applied at a rate of 800-1200 adults per ha (one jar contained 800-1200 adults, costing US$3.00). Releases of *H. hebetor* were done at 15-day intervals. The study was replicated three times in a disperse manner (200 m distance from one replication to another). Many dead larvae were recorded in the treated areas due to the venom injection by the parasitoid. FAW larval populations were reduced by 32-45% in the treated areas. Use of this organism in IPM management approaches with other technologies for effective control of FAW needs further evaluation, particularly in terms of yield protection.

## 8.2. Mass-Rearing Protocol for *H. hebetor*

BARI-Bangladesh has developed and validated a unique mass-rearing protocol for *H. hebetor* (Figure 13) which has been commercialized by a private company, Ispahani Agro Limited. Late-instar (5th-6th instar) wax moth (*Galleria mellonella*) larvae were used as the host of *H. hebetor*. First, a parent stock of wax moth was developed in honeycomb in glass jars. First- to second-instar larvae of wax moth were released into the artificial diet (made with proprietary proportions of wheat flour, maize flour, milk, animal fat, sugar, and yeast and autoclaved at 125°C and 1.5 PSI for 70 minutes). When the larvae attained full growth length (18-20 days later), they were transferred into a plastic bottle (200 larvae /bottle) containing a corrugated paper sheet. The full-fed larvae took position on the corrugated paper sheet for pupation. After pupation, 40 adult *H. hebetor* (30 female and 10 male) were released into the plastic bottle with a honey cube for their food. The open end of the jar was closed with black cloth. The wax moth larvae and *H. hebetor* were then kept in racks for 8-10 days for parasitism, egg laying, pupation and adult emergence of *H. hebetor*.


**Figure 13.** Mass-rearing protocol for *H. hebetor*. (A) Parent stock of wax moth larvae; (B) artificial diet for wax moth larvae; (C) full-grown larvae on the diet; (D) full-grown larvae put in plastic jar with a corrugated paper sheet; (E) parasitization of *H. hebetor* in the dark; (F) adult *H. hebetor* ready to use in the field.

## 8.3. Efficiency of *Trichogramma evanescens* Westwood and *Trichogramma chilonis* as Egg Parasitoids of FAW

*Trichogramma* are minute wasps that are parasites of lepidopteran insect pests. This species is considered as an effective egg parasitoid against many insect pests and is used worldwide in biocontrol-based pest management. The *Trichogramma* lays its eggs in the host insect eggs, and multiplies therein, thus preventing hatching of host insect larvae. In Bangladesh, it is commercially used against many destructive insect pests such as eggplant shoot and fruit borer (*Leucinodes orbonalis*) and tomato fruit worm (*Helicoverpa armigera*), among others.

Laboratory efficacy studies of two species of *Trichogramma* for activity against FAW eggs were undertaken by BARI in collaboration with CABI. The study was undertaken in the IPM laboratory of the Entomology Division, BARI, under controlled conditions at a temperature of 25±2°C, relative humidity (RH) of 60±5% to evaluate the efficacy of two species of egg parasitoids—*Trichogramma evanescens* and *T. chilonis*. FAW eggs were collected from a laboratory-reared population of 24-h age. Approximately 100 eggs were glued onto light blue-and-white paper (10 × 1.5 cm) with gum acacia diluted in distilled water. The paper strips with FAW eggs were kept in test tubes. Then, 10 pairs of laboratory-reared 24-h-old female wasps of *T. evanescens* or *T. chilonis* were released inside the test tubes containing FAW eggs and allowed to parasitize on the eggs for 24 h (Figure 14).

The parasitism rates of *T. evanescens* and *T. chilonis* on FAW eggs after 24-h exposures were 56% and 47%, respectively, and the adult emergence rates were 89% and 92%, respectively. Parasitoid egg-to-adult duration was 10 days for both parasitoids.

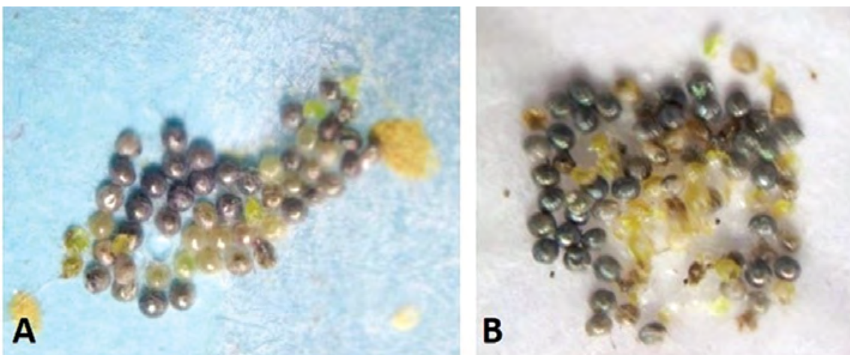


**Figure 14.** Parasitization of FAW eggs by Trichogramma species.
(A) FAW eggs parasitized by *T. evanescens*; (B) FAW eggs parasitized by *T. chilonis.*

## 8.4. Mass-Rearing Protocol for *Trichogramma* and its Hosts *Corcyra cephalonica* and *Sitotroga cerealella*

Easy and cost-effective mass-rearing is very important for augmentative biocontrol using an egg parasitoid such as *Trichogramma*. Mass-rearing of *Trichogramma* is generally done on eggs of rice meal moth, *Corcyra cephalonica*; however, it is not very cost effective. Therefore, the BARI team developed a cost-effective mass-rearing protocol of *Trichogramma* sp. on *Sitotroga cerealella* eggs, which has been commercialized by a private company, Ispahani Agro Ltd. in Bangladesh.

To rear *S. cerealella*, 5 kg wheat flour can be poured into boiling water and cooked for 2-3 minutes. Then the treated wheat is placed in steel trays (50 cm × 60 cm), each tray containing 2.5 kg and 1 gm of *S. cerealella* eggs and kept untouched for 5-6 days. After that, around 100-150 ml water per kg wheat flour is added and mixed properly with gentle stirring. After 22-25 days, the infested wheat with *S. cerealella* larvae is put into a mass-rearing chamber for adult emergence.

From the insect mass-rearing chamber, thousands of *S. cerealella* adults were collected and kept in a glass cylinder with the opening covered by 32-gauge mesh net. Adults were kept in the cylinder for one day for mating and subsequent egg laying. On the following day the eggs laid on the wall of the cylinder were brushed off and then sieved to collect fresh eggs. The adults and their body parts and scales were removed from the eggs by holding the cylinder near an exhaust fan to obtain the fresh eggs. Five grams of fresh eggs of *S. cerealella* were then put in a long, moist glass cylinder (glass cylinders were moistened by keeping them inside a freezer for few minutes) and the eggs were spread over the cylinder. A vial containing 1 g of eggs parasitized with *Trichogramma* was then placed inside the glass cylinder. The glass cylinders were then kept continuously in fluorescent light at 25.0±2.0°C for 9-11 days (Figure 15). Within 9-12 days, parasitism of almost all eggs of *S. cerealella* had occurred. The duration of the egg stage of *Trichogramma* spp. within the host egg was 1-2 days, larval stage 5-6 days, pupal stage 3-4 days (total 9-12 days). The parasitized eggs can also be collected and kept in desiccators at 3-4°C and 75-85% RH for 1-1.5 months.

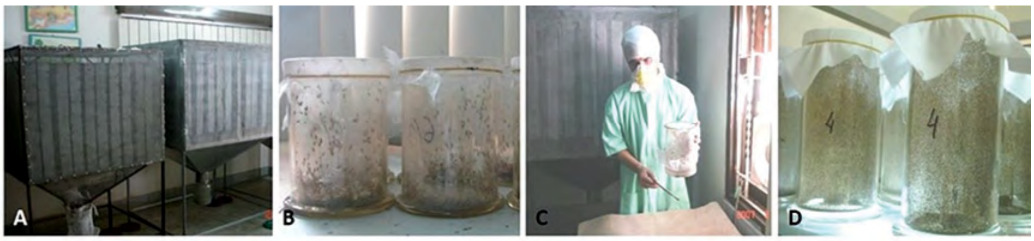


**Figure 15.** Mass-rearing protocol for host insects of *Trichogramma* parasitoids. (A) Mass-rearing chamber for host insects; (B) egg laying of host insects in glass cylinders; (C) collection of host eggs; (D) parasitization of host eggs.

## 8.5. Augmentative Biological Control for FAW Management

Table 4 provides a summary of the current status of augmentative biocontrol in Bangladesh. This information is also likely to be useful for other countries in subtropical Asia where FAW has become a problem.

**Table 4.** Status of augmentative biological control against FAW in Bangladesh.

| Specific biological control agent identified against FAW | Institution(s) involved | Stage of development (Proof-of-concept / Piloting / Scaling) | Efficacy (= % crop yield protected from the loss due to FAW) |
|---|---|---|---|
| *Habrobracon hebetor* (larval parasitoid)<br><br>Commercial name: I-bracon | BARI and Ispahani Agro Ltd. | Scaling for different destructive insect pests; proof-of-concept for FAW | Laboratory efficacy 100%; Field efficacy: 32-45%. Data on percent crop yield protected was not obtained |
| *Trichogramma evanescens* and *T. chilonis* | BARI and Ispahani Agro Ltd. | Scaling for different destructive insect pests; proof-of-concept for FAW in the laboratory has been done | Laboratory efficacy 47-56%; Field efficacy: not yet done. Data on percent crop yield protected was also not obtained |

Cost analysis of *Bracon hebetor* was undertaken by Ispahani Agro Limited, one of the primary private companies involved in the commercialization of the biocontrol agent in Bangladesh (Table 5).

**Table 5.** Cost analysis of *Habrobracon hebetor* as a biocontrol agent in Bangladesh.

| Item | Cost (in US$) | Remarks |
|---|---|---|
| ***Mass-rearing of the biological control agent (I-Bracon)*** | **2.35 × 4 = 9.4** | Application: 1 Jar for 15 Days and 4 Jars in a crop season per hectare |
| Personnel (Technicians/Skilled helpers) | 0.71 × 4 = 2.84 | Seasonal cost |
| Infrastructure/Facilities | 0.71 × 4 = 2.84 | Seasonal cost |
| Supplies & expendables (*e.g.*, diet, cages etc.) | 0.94 × 4 = 3.76 | Seasonal cost |
| ***Transport (including cold chain, where relevant) and distribution through local dealers*** | **0.47 × 4 = 1.88** | Seasonal cost |
| ***Augmentative release of the biological control agent in the farmers' fields*** | **0.12 × 4 = 0.48** | Seasonal cost |
| **TOTAL** | **11.76/Crop Season** | |

# 9. Areas for Further Research, Development, and Commercialization

- The following topics are key areas for future research that—if well positioned with private partners—could aid in commercial availability of biocontrol agents to assist farmers in an IPM response to FAW.
- Regular field surveys to identify effective predators and egg and larval parasitoids of FAW.
- Evaluation of efficacy of field predation/parasitization of different predators and parasitoids against FAW.
- Development of cost-effective mass-rearing protocols for newly identified parasitoids, especially *Trichogramma pretiosum* and *Telenomus remus.*
- Development of IPM strategies against FAW with biological control as one of the major components.
- Storage, transport, and field application of different biocontrol agents for cost-effective management of FAW.
- Cost-benefit analysis of treatments using the CESAS (cost, efficacy, safety, accessibility, and scalability) model described in **Chapter 1**.

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# CHAPTER 06

# Agroecological Management of Fall Armyworm in Asia

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# 1. Introduction

Following its discovery in Africa in 2016 and the significant impact that it had across Africa (Day *et al.* 2017), the 2018 arrival of fall armyworm (FAW; *Spodoptera frugiperda* J.E. Smith) in Southern India raised alarm of the risk for crop losses across Asia (Sun *et al.* 2021; ASEAN 2020). Farming systems and cropping patterns are, however, considerably different in Asia than in Africa. These differences are likely to have implications for the ways in which FAW interacts with the crops grown by farmers and the intensity and extent of pest damage that results. Some of the largest generalizable differences between the two continents include the predominance of rice (*Oryza sativa*) as a staple crop that is usually grown at least once a year in Asia as a result of the region's monomodal monsoon rain pattern. Maize, which is the introduced FAW biotype's preferred host crop (see **Chapter 1**), can be grown throughout the year in different parts of Asia, and is often (but not always) rotated with rice. Maize is predominantly grown during the monsoon season in South Asia. In the farming systems of the Indo-Gangetic Plains (IGP) that span India, Nepal, Pakistan, and Bangladesh, maize is also increasingly grown using irrigation in the winter season following the summer rice crop (Timsina *et al.* 2011), although in parts of the IGP where monsoon-season rainfall is not excessive and soils are well drained, maize can also be grown in the summer. Across the Himalayan foothills and in the more mountainous environments of South East Asia, maize is grown as a primary crop during the monsoon season after the onset of sufficient rainfall (Gerpachio and Pingali 2007). Much of the maize produced in the Himalayas is open-pollinated, subsistence oriented, and low-input, while the hybrid maize cultivated in South Asia tends to be grown with more inputs as a cash crop sold to the animal feed industry (Timsina *et al.* 2011). In South East Asia's mountainous areas, maize is also commonly included in slash-and-burn farming systems that replace primary forests (Mertz *et al.* 2009). Irrigated or flood-retreat maize is also grown as a cash crop in Asia's riverine deltas.

The ways in which FAW interacts with maize and the rich diversity of cultivated and uncultivated species in Asia's agroecosystems is the subject of this chapter. Agroecology is a scientific discipline and approach to farm and cropping systems design that encourages the purposeful use of biological diversity and ecological interactions among species and their environment (Nicholls and Altieri 2016; Pretty 2003). Manipulation of the factors influencing biodiversity and ecological processes are prioritized to support productive, resource-conserving, and resilient farm management practices that minimize negative environmental and socioeconomic impacts (Altieri 1999). With a focus on providing practical and actionable advice for extension services, and following a review of invasive species biology as it pertains to FAW, this chapter focuses on the applicability of agroecological methods to manage FAW in Asia's diverse farming systems.

# 2. FAW Source-Sink Relationships and Life History

FAW is a highly mobile species and can migrate from one region to another depending on the intensity and direction of the wind for dispersal (Day *et al.* 2017). This positively affects the species' ability to find host plant resources and quality habitat (which ecologists refer to as 'sinks') throughout the calendar year. In Asia, sinks can take the form of maize crops, which are grown throughout the calendar year, though sinks can also be alternative host species that allow FAW to mature following egg hatch and to disperse following pupation. These locations, therefore, become FAW population 'sources' that can, following migration, colonize new areas with patches of maize (Figure 1).

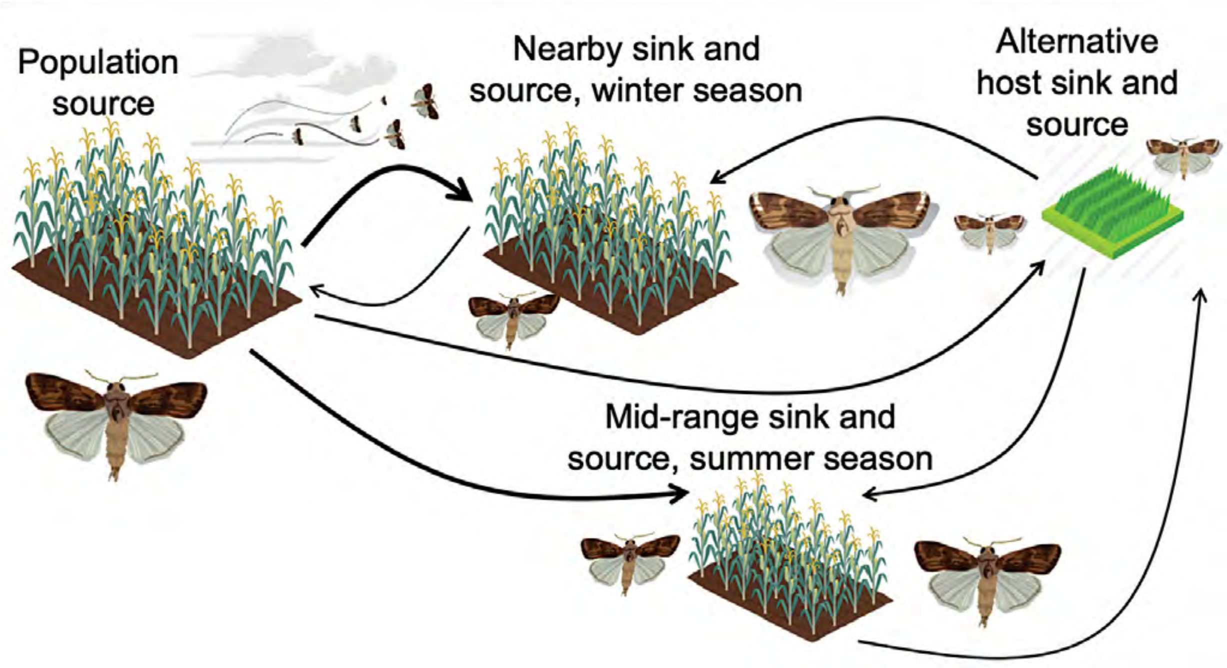


**Figure 1.** Source–sink relationships between FAW and its habitat that permit year-round population maintenance and growth in Asia.

Combined with the traits of FAW that make it highly adaptable to multiple environments (Table 1), FAW is a particularly challenging pest from an agroecological point of view.

**Table 1.** Characteristics associated with FAW that affect its status as an invasive pest species.

| Trait | What does this mean? | Why is this a concern for management of FAW? |
|---|---|---|
| Polyphagous | FAW can eat over 80 species of plants, but prefers maize as its host (Capinera 2002) | FAW can survive and reproduce on a large number of alternative host plant species even if maize is not present in the environment. |
| High fecundity | FAW reproduces and grows very rapidly. Adult female months can lay 1,500-2,000 eggs within their lifetime (Capinera 2002) | FAW populations can increase very rapidly; multiple generations can occur in a single maize crop. |
| High dispersal range | When aided by the wind, adult moths can migrate several hundred kilometers in a single night (Early *et al.* 2018) | FAW can spread over large areas in a very short time. In Asia, FAW can easily migrate between areas in which maize is grown in the monsoon and winter seasons, sustaining the FAW metapopulations. |
| Wide adaptability | FAW is adapted to many environments (sinks) in which it can flourish (Day *et al.*, 2017) | Because FAW is polyphagous and can disperse over large areas, it can survive and reproduce, with population sinks becoming sources within a short time. |

Longer-term management requires an understanding of the numerous ways in which lepidopteran pests such as FAW interact with their environments at each stage of their lifecycle (Figure 2) to aid in the design of ecologically based approaches to enhance pest mortality through a variety of mechanisms at the crop, field, field margin, and landscape levels. These management interventions can be targeted at the specific stages of the FAW lifecycle when the potential for reducing crop damage to specific fields is the greatest.

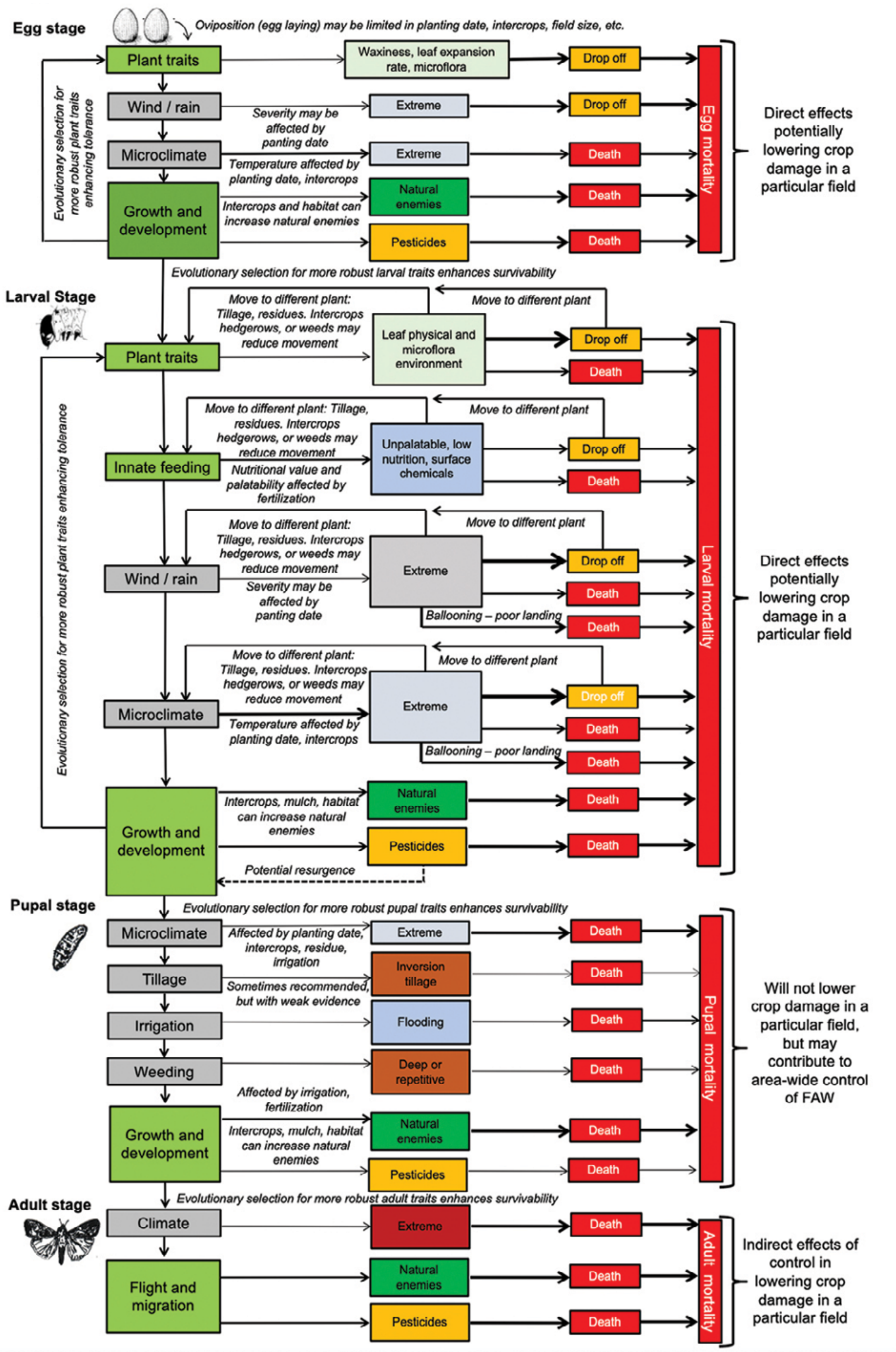


**Figure 2.** Biotic and abiotic interactions affecting FAW development and mortality during each major stage of its lifecycle. Thicker arrows indicate potentially stronger effects. "Natural enemies" refers to a range of predators, parasitoids, and pathogens that may limit FAW populations. Adapted and expanded following Zalucki *et al.* (2002).

As a lepidopteran pest, FAW undergoes progressive maturation after egg hatches to the neonate and subsequent larval instars. Management of FAW at these stages of the lifecycle is more likely to reduce damage to a particular crop field in which FAW is observed, as management interventions will limit the species' ability to hatch and/or feed on the crop. Once the larvae drop from the host plant and bury into the soil to pupate, management options affecting crop damage in specific fields become more limited. This is because after emergence from the soil as an adult, FAW takes flight to find mates and migrate to other fields that can be even hundreds of kilometers away (Early *et al.* 2018). Some of the management techniques that are sometimes advised by extension services are to reduce pupal density within fields (for example tillage, weeding, or irrigation) and are therefore less likely to reduce damage by inducing FAW mortality. This is not to imply that these actions are not useful; rather, they may indirectly improve crop growth and affect yield, while also potentially contributing to area-wide FAW control by limiting the ways in which particular maize fields become sources of FAW spread to new areas. Once FAW reaches the adult stage, farmers' options for FAW control are generally limited to efforts aimed at reducing egg laying in their fields (Harrison *et al.* 2019).

# 3. Principles of Agroecology and Pest Management

Achieving the long-term regulation of FAW populations and limiting damage to crops requires knowledge of the FAW life cycle in the context of a multi-pronged approach that utilizes ecological complexity to achieve pest suppression by maximizing beneficial biological interactions between FAW and other plant, insect, fungal, and vertebrate species (Harrison *et al.* 2019). Agroecosystems include the interactions and ecological processes between all non-living and living components of ecosystems that support agricultural production. Agroecological approaches also entail an understanding of the evolution of pests and their natural enemies, as well as applying their population dynamics to pest management (Karlsson Green *et al.* 2020). They aim at enhancing the diversity of species that play functional roles in increasing productivity, stability, and resilience through enhanced biological interactions that generate ecosystem services including pest regulation (Bottrell and Schoenly 2018). Agroecological methods also aim to enhance nutrient flows and recycling (*e.g.*, through the use of manures, recycling of crop residue, etc.) to improve crop and soil health, while also minimizing losses of nutrients to the environment in ways that can cause pollution (Figure 3).

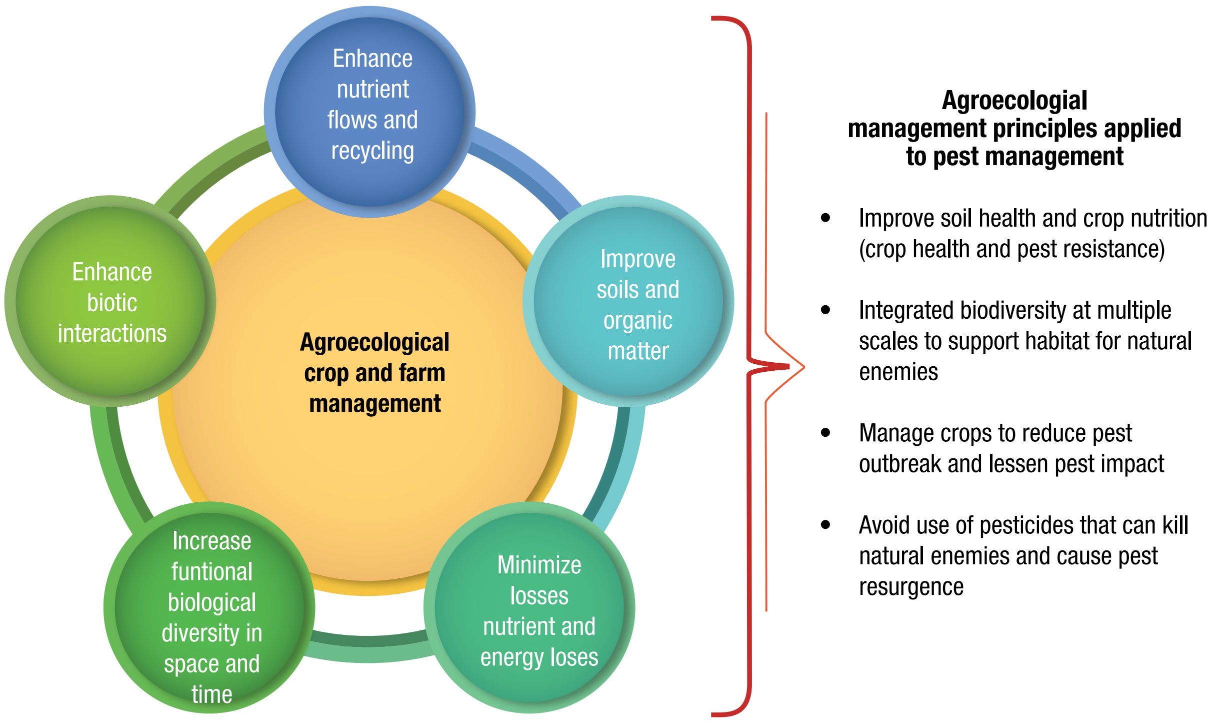


**Figure 3.** Principles of agroecological crop and farm management and their application in pest management.

Applied to the management of pests—including invasive species—agroecological approaches prioritize efforts to:

- increase soil organic matter, provide habitat to ground-dwelling predators, and provide balanced nutrition to crops (Alteri and Nicholls 2003);
- purposefully integrate biodiversity into the farming system, with emphasis on provision of habitat for natural enemies (Nicholls and Altieri 2004; Altieri and Letourneau 1982; Letourneau 1987; Landis *et al*. 2000); and
- manage crops and agricultural landscapes in ways that reduce the risk of pest outbreak, such as by increasing plant health, using tolerant or resistant cultivars, planting at times of the year when pest pressures are likely to be lower, or by reducing pest populations during critical and susceptible stages of the crop growth cycle (Pretty and Bharucha 2015).

Agroecological approaches within the IPM framework seek to minimize the use of pesticides, and, where possible, use the least-toxic product possible to encourage conservation biocontrol and avoid damaging human and environmental health (see also **Chapter 3**). This point is particularly relevant because pesticides—especially those that are broad-spectrum and kill both pests and natural enemies—can adversely cause the resurgence of pests when naturally occurring populations of predators and parasitoids are killed (Tscharntke *et al.* 2016; Meagher *et al.* 2016; van Huis 1981). These functional groups—which are beneficial to farmers—are often more affected by pesticide sprays than the target pest itself (Karlsson Green *et al.* 2020).

# 4. Biological Interactions, Agroecology, and Pest Management at Differing Scales

Farmers require multiple methods—'baskets' of options—to respond to the threat that FAW poses in Asia. The following sections describe agroecological considerations and opportunities to manage FAW as an invasive species at the plant and crop scale, the field scale, within and around crop field margins, and at the landscape level.

## 4.1. Plant and Crop Scale

Plants have multiple methods of defense against pests. In the case of FAW, host plant resistance mechanisms affect the egg and larval life stage, though they can also be deployed to limit oviposition, especially through mating disruption technologies. The architecture of plants (and also their configuration in crop fields) can modify the microclimate in ways that may be less favorable for the egg, neonate, and later-instar larval survival (Harrison *et al.* 2019). Pests survive by consuming and deriving their nutrition from the crops they attack. Crop varieties with native genetic resistance can be bred that have more 'hairy' leaves (called trichomes) that can limit palatability (Wiseman and Davis 1979). In addition to their toughness, leaves can also have surface waxes and can emit chemicals that can reduce pest attack. The former quality can also cause eggs to poorly attach after oviposition and drop off the plant, causing mortality (Zalucki *et al.* 2002) (Figure 2). Digestibility can also be lowered through breeding for the accumulation of phytochemicals or metabolites that can reduce pest development and survival (Constabel and Kurz 1999). Pests may also be controlled by the leaf macrofloral environment, for example if fungal species that limit egg or larval development are present or can be manipulated in ways that affect survivability (He *et al.* 2021).

CIMMYT has been undertaking systematic studies on native genetic resistance to FAW in Africa, including identification of sources of resistance to the pest. These FAW-tolerant inbred lines are now being used in breeding programs by public and private sector institutions in Asia (*e.g.*, in India), although Asia-adapted FAW-tolerant improved maize varieties are yet to be deployed. *Bt* maize varieties (expressing one or more FAW resistance proteins from *Bacillus thuringiensis*) are being commercialized in the Philippines and Vietnam (host plant resistance is discussed in detail in **Chapter 4**). The development of resistance to *Bt* toxins is also a concern as observed in other countries where both crop species and varietal monocultures are common (Midega *et al.* 2006; Huang *et al.* 2014). Studies examining other non-target ecological effects of *Bt* transgenes in agroecosystems producing maize (cf. Lang and Otto 2010; Wolfenbarger *et al.* 2008) have been implemented so far only in the Philippines and Vietnam in Asia; multi-year and multi-location studies across on insect resistance management would be useful.

## 4.2. Crop Field Scale

### 4.2.1. Land Preparation and Crop Establishment

FAW may come into contact with the soil during its early neonate and larval stage if it drops off of the plant as a result of the leaf physical or chemical environment, or during extreme weather events (Figure 2). First-instar FAW larvae also disperse from plant to plant by ballooning in a process called 'phototaxis' (Rojas *et al.* 2018), in which larvae emit silk from their bodies that is caught by the wind. This facilitates ballooning and dispersal from plant to plant. Larvae that fail to intercept other plants, or that are knocked off maize leaves due to extreme weather events will fall to the soil. Once on the soil, they will attempt to access other plants, though they may be predated or die from exposure on the soil surface before finding a new host plant. Studies of soils in Brazil also demonstrated that soils may contain bacteria such as *Bt* that can cause larval mortality (Ramierez-Rodriguez and Sanchez-Peña 2016). Soil is also abrasive to young larvae, which lack well-developed exoskeletons, and may cause injury and death (Harrison *et al.* 2019).

FAW also pupates in the soil at 2- to 8-cm depth (Capinera 2002). For these reasons, some FAW pest management guidelines suggest inversion tillage to expose pupae to natural enemies and higher temperatures at the soil surface (ASEAN 2020; GoN 2019), but the effectiveness of this technique is questionable. Tillage may indeed mechanically kill pupating FAW or expose them to natural enemies, though after emergence as an adult, FAW will fly up and migrate to other areas, often over considerable distances (Early *et al.* 2018; Sparks 1979). This means that destruction of pupae by tillage may limit a particular field's strength as a source of FAW, though tillage itself will have no direct effect on the subsequently planted maize crop. In addition, parasitoids can also lay eggs in pupae by ovipositing through the tunnel larvae dig into the soil (Capinera 2002); such soil structures may be destroyed by tillage events, inadvertently limiting this ecosystem service.

Oviposition by FAW may, however, actually be lower in the early stages of maize growth in no-till systems where crop residues are retained as mulch (All 1998), as shown in Figure 4. In Zimbabwe, Baudron *et al.* (2019) observed that zero-tilled maize fields in which residues were maintained lowered FAW attack. Evidence from North and Central America showed similar results (Clark *et al.* 1993; Rivers *et al.* 2016). In addition to limiting FAW oviposition, this effect is likely the consequence of the ways in which an undisturbed soil environment with mulch—which modifies the soil microclimate and enhances habitat for a diversity of insects—can facilitate increased densities of predatory spiders, ants, and beetles. Residue mulch may also impede the movement of larvae from plant to plant during ballooning, and/or if larva drop off the plant and attempt to transit to a new host (Harrison *et al.* 2019). Mulching also increases soil biological activity, which over time can increase soil carbon status that positively affects the retention and supply of nutrients and crop health; from a practical standpoint, however, mulches can also transfer plant diseases and hence should be used carefully (Rodríguez-del-Bosque and Salinas-García 2008). Conversely, zero-tilled and mulched fields have also been associated with higher soil moisture conditions in arid environments that create improved maize vegetative growth that can also increase oviposition (Kumar and Mihm 2002). Despite these concerns, evidence from South Asia indicates that zero-tillage with mulch can maintain yields (Gathala *et al.* 2015), though it may take several years for yield increases to be observable. Farmers should therefore be carefully apprised of the potential trade-offs associated with zero-tillage and mulching as a mechanism of pest control, so that they may make appropriately informed pest management decisions.

**Figure 4.** Large zero-tilled maize field in eastern China. Note the vegetational strips permitted to grow after each 10th maize row, and the field's proximity to hedgerows and tree cover. These structures may assist in reducing FAW oviposition and movement between plants when the crop is young, in addition to facilitating control by natural enemies. Photo: Tim J. Krupnik (CIMMYT).

## 4.2.2. Early Planting

Early or timely planting is often advised as a low-cost, relatively easy to implement, and agroecologically sound method of reducing the risk of FAW attack in maize (Harrison *et al.* 2019). Farmers may escape from FAW damage if they plant early and the crop develops to maturity before pest pressure builds up during the season. FAW development and the number of generations that may attack maize is at least partly controlled by temperature (Early *et al.* 2018). Winter maize in Asia, particularly in subtropical and tropical areas, can be established as an irrigated crop and can enable farmers to avoid rapid pest development and attack as maize matures during cool winters. Similarly, FAW attack is likely to be higher during the warmer monsoon season. Systematic research on these topics is not yet done in Asia; therefore, some caution should be exercised when advising farmers to go for early planting. This is because of the implications of FAW's large dispersal and migration range. Moreover, most maize in Asia is grown during the monsoon season, while there are pockets of winter-grown maize (particularly in Bangladesh and the region's deltas) that could, at least in principle, serve as sources of FAW dispersal in the monsoon season. As such, further research is needed to assure this advice is indeed sound, although timely planting does tend to be a fundamental tenant of good agronomy.

Early establishment of maize in the winter season is, however, complicated by the time necessary to harvest the preceding rice crop and for fields to dry out enough to become trafficable for land preparation and planting. Farmers in high-monsoon rainfall areas may have fields that stay wet too long to facilitate early planting; conversely, for those that have well-drained fields, high-yielding and short-duration rice varieties are increasingly available and can be used to accelerate maturation and harvest, thereby increasing opportunities for planting early-maturing maize, effectively altering the cropping sequence. Reduced tillage and mechanized seeding can also help accelerate maize establishment (Krupnik *et al.* 2018). In the summer season, farmers with access to irrigation who grow maize may wish to consider a starter irrigation, if possible, to establish the crop rather than waiting for monsoon rains to commence. For those without irrigation, sub-seasonal (~1 month in advance) and seasonal (3+ months in advance) rainfall forecasts can also assist farmers in being fully prepared so they may plant immediately after the first rainfall.

## 4.2.3. Nutrient and Organic Matter Management

Poor and unbalanced application of fertilizers without sufficient attention to soil organic matter management can lead to increased pest damage (Harrison *et al.* 2019). For extension agencies advising farmers on FAW management, this means that efforts should be focused on assuring that farmers are equipped with both the resources and the knowledge to provide adequate and balanced plant nutrition for healthy crop development, which can in turn improve resistance to pest attack. Considering FAW management, fertilization will affect two of the three categories of plant resistance described by Painter (1951), including pest preference and tolerance of plant damage without significantly affecting growth. Indirectly, 'healthy' and well-fertilized crops may also affect antibiosis, as the production of some of the plant secondary metabolites are linked to nitrogen availability.

Maize is considered as a "heavy feeder", meaning that it requires high levels of nutrients. Poorly fertilized crops tend to experience higher levels of FAW attack (Harrison *et al.* 2019). Conversely, because nitrogen from overly large doses of urea application can cause a surge in excess nutrient availability in the crop, pests may find crops nutritionally attractive, thereby increasing attack. As such, rational rates of nutrients should be applied that are neither poor nor excessive. The release of nutrients from organic materials is slower (Alteri and Nicholls 2003) and can be coupled with fertilizers to sustain plant growth over time. Soils higher in organic matter also tend to be associated with higher populations of ground-dwelling predators. Similarly, the application of compost and organic matter can also create habitat for detritivores (organisms that decompose plant residues) that can serve as alternative prey for predators, hence helping to maintain their population when FAW or other pests are not available as a food source (Landis *et al.* 2000; Thomson and Hoffmann 2007; Nicholls and Altieri 2004).

It is also important to note that many of the soils in subtropical and tropical Asia–especially in upland environments–are acidic (von Uexküll and Bosshart, 1989; Hossain *et al.* 2021; von Uexküll and Mutert, 1995). In sorghum, Gardner and Duncan (1982) found increased FAW foliar damage on acidic soils. This effect was due to the retarded rate of sorghum growth in more acidic soils with pH below 5.4, in which plants remained in the vegetative and whorl development stage longer than on neutral soils. This extended duration during the critical stages is conducive for FAW attack, affecting crop performance. Comprehensive studies on the implications of soil pH on FAW damage in maize are still lacking. Corrective actions to overcome soil acidity in Asia are likely to assist in crop growth more generally in addition to potentially mitigating FAW attack.

## 4.2.4. Water Management

Land area devoted to irrigated winter maize in the eastern IGP of South Asia is growing (Timsina *et al.* 2011). Because FAW pupates in the soil, flood irrigation could potentially aid in drowning and reducing populations before they emerge as adults. Similarly, in lowland environments of Asia where winter maize is rotated with summer rice, seasonal flooding at the landscape scale may reduce overall FAW populations. Research is needed to confirm whether these hypotheses do indeed result in FAW pupal suppression, although it should be noted that such strategies are unlikely to reduce the incidence of FAW in the particular fields to which irrigation is applied. This is because following pupation, FAW adults migrate in order to reproduce and then oviposit in other fields (Early *et al.* 2018; Sparks 1979).

## 4.2.5. Intercropping and Relay Cropping

Intercropping, in which two or more crops are grown in the same field at the same time, is common in Asia (Yadav *et al.* 2020). Intercropping is also a widely studied agroecological pest management tool (Trenbath 1993). Diversification of species within the crop field creates environments that encourage higher populations of natural enemies, which in turn can reduce the pest incidence (Nicholls and Altieri 2004; Andow 1991), including FAW (Altieri 1980). Four major mechanisms can be identified that improve pest control in intercrops. First, they can (1) reduce the ability of adult females to identify and lay eggs in the crop (Ampong-Nyarko *et al.* 1994). This may be achieved by the emission of plant volatiles that repel egg-laying females so they cannot locate the host crop (Khan *et al.* 2010; Pichersky and Gershenzon 2002). Intercrops can also (2) reduce the movement of larvae between host plants within the crop (by disrupting ballooning in a similar way as described for mulch) (Päts and Ekbom 1994). They can also (3) improve crop growth through the modification of the microclimate, and by (4) attracting and creating habitat for natural enemies (Midega *et al.* 2006; Landis *et al.* 2000; Yadav *et al.* 2020). In particular, maize intercropped with pulses (legumes) has been shown to reduce pest damage (Rwomushana *et al.* 2018). The specific intercrop species that are 'best-bet' for reducing FAW attack in Asia have yet to be formally determined, as research in a range of countries is ongoing. However, early candidate intercrops that appear to have some benefits include cowpea (*Vigna unguiculata),* pigeon pea (*Cajanus cajan*), and soybean (*Glycine max*), although horticultural and spice crops are also gaining popularity, as discussed below.

Intercropping can also result in trade-offs that can increase pest damage, if not carefully managed. For example, Baudron *et al.* (2019) observed that pumpkin-maize intercrops that maintained a closed canopy across the field may act as 'bridges', allowing FAW larvae to disperse between maize plants to avoid the environmental and predation risks they may otherwise encounter if moving along the soil surface. This is especially an issue with GM maize when the crop is planted as part of a refuge-in-a-bag (RIB) approach.

These points are important, as maize is intercropped with a wide range of species in Asia that are understudied from the perspective of pest management and FAW in particular. In South Asia, farmers commonly incorporate horticultural crops such as red amaranth (*Amaranthus cruentus*) or even spices such as coriander (*Coriandrum sativum*) in maize fields, growing them as an understory with increased levels of fertilization applied to boost growth (Figure 5). In comparison to pulses, which may be picked multiple times during the season as an intercrop, these alterative intercrops are harvested early, well before maize reaches advanced vegetative stages. Coordinated research is urgently needed to examine the efficacy of different intercrop configurations on FAW control in Asia.

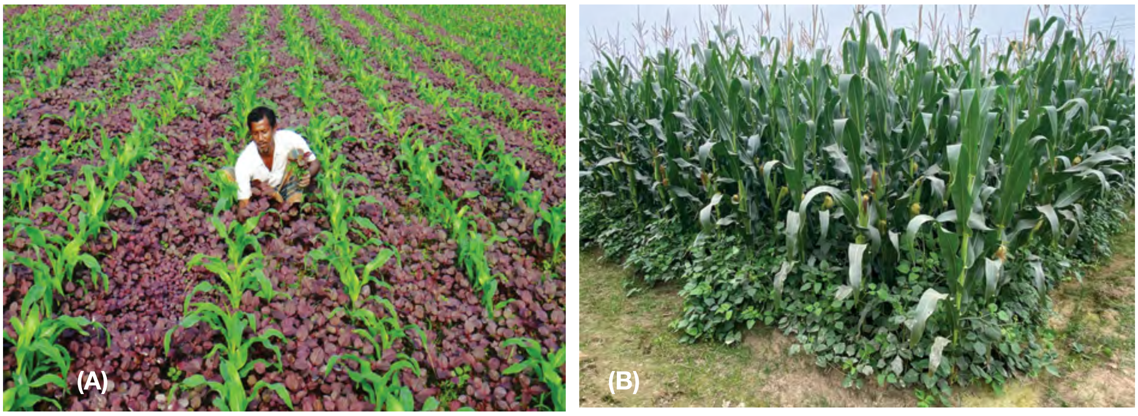


**Figure 5.** (A) A farmer in Bangladesh, harvesting red amaranth as a leafy vegetable from an intercrop with maize. Photo: D.B. Pandit (CIMMYT). (B) A maize–cowpea intercrop growing under experimental conditions to evaluate crop performance and rates of FAW damage in Dinajpur, Bangladesh. Photo: Tim J. Krupnik (CIMMYT).

## 4.2.6. Push-Pull Systems

The push-pull system is a type of intercropping developed and popularized in East Africa to control lepidopteran pests, including stem borers and FAW (Hailu *et al.* 2018; Midega *et al.* 2018). In these systems, maize is intercropped with a 'push' crop such as *Desmodium* spp. that repels FAW oviposition through its production of plant volatiles, while fields are surrounded with a 'pull' species such as napier grass (*Pennisetum purpureum* Schumach.), which is commonly grown in South Asia as a fodder for livestock, or brachiaria (*Brachiaria* spp.), among other species. These border-planted species are meant to attract and trap lepidopteran pests (Harrison *et al.* 2019). Further information can be found at http://www.push-pull.net.

A recent study (Midega *et al.* 2018) indicated that FAW damage can be significantly reduced, and maize yields increased, in East Africa if farmers carefully implement push-pull in their fields. Research to evaluate the performance and applicability of push-pull systems has commenced in

India, Nepal, and other Asian countries. Push-pull systems require initial investments by farmers and a significant change in crop management practices, *i.e.*, planting and maintaining borders of attractant 'pull' species, that should be considered in any and all experimental comparisons with other pest control methods (Harrison *et al.* 2019). The lack of evidence on the effectiveness of push-pull systems in Asia therefore indicates that it should be cautiously advised to farmers, with clarification of the potential costs they may incur in management of the system. As with all technologies, their use should be evaluated using the CESAS model of cost, efficacy, safety, accessibility and scalability as outlined in **Chapter 1**.

### 4.2.7. Refugia to Limit Resistance and Encourage Biological Control

Refugia are parts of fields or agricultural landscapes in which crops are not sprayed with pesticides and are planted adjacent to transgenic crops (Cerda and Wright 2004). Refugia may also be natural areas within or adjacent to agricultural fields in which non-crop habitat is maintained. In the former case, refugia are intended to provide microhabitats in which pests such as FAW can develop and disperse without selecting for resistance to pesticides or *Bt* crops. This is because individuals dispersing from refugia subsequently mate with members of their species that may have escaped from the effects of pesticide application or transgenic control due to their higher level of resistance. By doing so, the selection of resistant populations of pests can be slowed, as the frequency of alleles conferring resistance will be diluted by alleles conferring susceptibility from populations dispersing from refuges (Karlsson Green *et al.* 2020).

Similarly, refugia can also provide habitat to natural enemies. Following spray events, both arthropod and vertebrate natural enemies can disperse into fields and control surviving pests. Gras *et al.* (2016), for example, showed how birds can affect lepidopteran larval and adult pest control as they disperse from trees and forests and patrol adjacent agricultural areas. Large-range aerial predators such as bats also play a role in predating adult FAW moths while in flight (Gras *et al.* 2016; Maine and Boyles 2015). Farmers in Bangladesh commonly erect bird perches by pushing small tree branches into the soil in rice fields to encourage pest suppression; similar approaches could be applied to maize, although FAW's nocturnal feeding habit and ability to hide within maize whorls may limit the ability of many birds to retrieve worms. Further research on this potential mechanism of pest suppression is needed.

Structured refugia may not be necessary in highly diverse agricultural landscapes where farm sizes are small and farmers cultivate a wide diversity of crops, for example in Bangladesh, or in parts of Nepal and Eastern India, and in Indonesia. However, in landscapes dominated by monocultures of maize and in which pesticides are widely used, for example, in parts of China, or in the western IGP, refugia can be used within agroecosystems to slow resistance and conserve natural enemies. Research on the role of refugia in the maintenance of these ecosystem services is currently very limited in Asia.

### 4.2.8. Weeds and Weeding

Although weeds are themselves considered as a type of "pest" by most farmers, they can also support natural enemy populations (Bàrberi *et al.* 2010). So long as weeds do not seriously compete with the crop, Penagos *et al.* (2003) suggested that their presence within fields may provide habitat to natural enemies that assist in maize pest control. Yet because FAW can consume a variety of plant species beyond maize—with a preference for grasses —pest managers often advise farmers to clean their fields and field margins of grassy weeds, as they could also support FAW (Moraes *et al.* 2020). During the cropping season, and within cropped fields, Baudron *et al.* (2019) also confirmed that frequent weeding reduced FAW in agroecosystems where gramineous weed flora dominated. In addition to reducing habitat for FAW, frequent manual or mechanical weeding (including earthing-up prior to in-season irrigation) may also have some effect on reducing the survival of pupae in the soil, while also reducing crop–weed competition and improving yield. This hypothesis needs to be further tested, especially in the Asian context.

Sedges or broadleaved weeds between maize rows may reduce the ability of first-instar FAW larvae to balloon and move between plants, while also supporting populations of natural enemies (van Huis 1981). Non-grassy weeds may assist in controlling FAW, although extension services advising farmers to use these tactics must be very clear to avoid significant levels of weed growth that may compete with the crop. Despite these questions, no studies considering interactions between FAW and weeds have yet been conducted in Asia. Combined with the wider availability of chemical herbicides in Asia relative to Africa's more input constrained farming systems, information on the potential effects of weeds as ecological components of maize systems subjected to FAW pressure are currently inferred from studies outside the continent. Systematic research is, therefore, needed to address this gap and provide integrated weed and arthropod pest management advice that conserves natural enemies while also reducing FAW survivability.

## 4.3. Field Edges and Farm Margins

Farm sizes in Asia tend to be relatively small (less than 2 hectares). Fields are often separated by walking paths or bunds that separate fields. The integration of trees into farming systems and homesteads is also relatively common. Agroecological management systems work to leverage these structures and their function in agroecosystems to benefit of farmers.

For example, bunds and field margins can be planted to species that provide habitat and food sources for natural enemies that can enter fields and control pests, potentially including FAW (Harrison *et al.* 2019). Parasitoids that rely on nectar for survival can be encouraged by cultivating flowering plants in these areas. Where farmers cannot afford to plant new species, they may manage field margins and bunds through the selective removal of species that compete with nectar-producing plants, thereby encouraging their growth (Bàrberi *et al.* 2010). Live fences, windbreaks, and hedgerows between fields can also provide habitat to beneficial insects that can disperse into fields and control pests (Aluja *et al.* 2014), in addition to potentially limiting the ability of ballooning FAW larvae to transit between fields (Harrison *et al.* 2019).

Theoretically, these agroforestry structures can also provide connectivity within farm landscapes, allowing populations of natural enemies to build and disperse across these habitats and then move into farmers' fields. Agroforestry structures can also encourage birds and bats that can predate pests in cultivated fields (Maas *et al.* 2016), though Tscharntke *et al.* (2016) pointed out that birds and bats also consume and do not discriminate between pests and natural enemies. Bats are, however, well-known to provide ecological services in the form of adult FAW moth control during flight (Maine and Boyles 2015; Boyles *et al.* 2011); as such, bats play an important role in overall population regulation of FAW and may be encouraged as a line of defense against invasion. Most studies have focused on how agroforestry can increase populations of natural enemies, although studies linking agroforestry, natural enemy populations, FAW, and crop yields are lacking in Africa (Harrison *et al.* 2019), and also in Asia.

## 4.4. Agroecological Management at the Landscape Level

Beyond fields and field margins, agroecological approaches also consider management at the landscape level. Theoretically, more complex and diverse agricultural landscapes offer more habitat for arthropod and vertebrate natural enemies that can move within and between fields to facilitate pest control, while also maintaining natural enemy populations over time (Harrison *et al.* 2019). Forest patches may be similarly important in maintaining populations and pest control services (Maas *et al.* 2016; Boyles *et al.* 2011). Young forests located in proximity to maize fields with a diversity of successional plant species that provide habitat to natural enemies have been linked to moderate FAW control (Wyckhuys and O'Neil 2009). On the other hand, Harrison *et al.* (2019) noted that evidence for the effects of landscape diversity on FAW control in the Americas is inconsistent, and that no research on this topic has been conducted in Africa. Similarly, studies on the interactions of FAW with landscape diversity and complexity in Asia are lacking, though the complexity of landscapes in Asia and Africa make this a compelling area of study (Figure 6).


**Figure 6.** Satellite images of 2.25-km$^2$ areas demonstrating the diversity in agricultural landscapes in (A) United States, (B) rural Zimbabwe, and (C) Nepal. Note the increasing complexity in Zimbabwe and Nepal relative to the United States, and the corridors and patches of forest visible in the Nepal landscape.

From a practical standpoint, there is some likelihood that farmers in Asia—at least in more complex landscapes with smaller fields and patches of forest and agroforestry systems—are benefitting in some way from the ecological service of pest control, in addition to the other products and services produced by diverse vegetation in the landscape. Maize in South East Asia's mountainous areas is often grown in fields cleared during slash-and-burn agriculture (Mertz *et al.* 2009), though the maintenance of forest patches near cleared fields can increase the prevalence of natural enemies in ways that benefit farmers (Boyles *et al.* 2011). Communities and policymakers should therefore be apprised of the potential benefits of landscape diversity and the maintenance of forests and may be encouraged to maintain them, though the practicality of such advice from the standpoint of agricultural extension services may be limited. These changes require higher-level policy action, and the time and resources to affect change at the political as well as at the community level.

# 5. Conclusions: What We Know and What We Still Need to Know for Effective Extension

Agroecological management of pests, including FAW, aims at enhancing the diversity of species in agricultural systems that interact and function to enhance productivity, resilience, and stability through the flow of ecosystem services. In other words, agroecological management of pests like FAW should focus on building and maintaining habitat for natural enemies like arthropod predators, parasitoids, and even vertebrate predators. Many of the agroecological management practices described in this chapter are easily compatible with agronomic best practices that can aid in pest management. From the standpoint of managing FAW as a newly invasive species in the context of Asia's farming systems, it is useful to reflect on and conclude which practices may or may not be most applicable for farmers in Asia. The points below summarize the key agroecological principles and highlight their applicability as a part of a 'basket' of options for sustainable FAW management.

- **Encourage ecological awareness and understanding:** Agroecology is knowledge intensive and requires efforts to raise awareness and understanding of the principles described in Section 3 of this chapter. Extension agents and farmers should be encouraged to learn about agroecology and the interactions between species in agricultural systems in the context of hands-on learning within the field. Learning should also focus on a solid understanding of FAW and the numerous abiotic and biotic interactions that this pest species has with its environment at each phase of the life cycle. This will help equip farmers and pest managers with more sophisticated information to make increasingly comprehensive and relevant intervention decisions.
- **Crop-pest interactions:** Although crops can be bred in ways that improve their capacity to tolerate/resist insect-pests like FAW, studies supporting the use of particular maize varieties as being more tolerant to FAW have not yet been conducted in Asia. As such, advising farmers to use particular varieties against FAW in Asia is premature at this time. Moreover, efforts on host plant resistance need to be intensified in Asia, similar to what is being done in Africa by organizations like CIMMYT (see **Chapter 4**).

- **Land preparation and crop establishment:** Available scientific evidence points to positive FAW suppression when farmers practice zero-tillage and maintain mulches on the soil surface. The reasons for these outcomes are complex, but are likely related to the provision of habitat for natural enemies that aid in reducing the impact of FAW. While some countries and organizations are advising tillage to control pupal build-up in the soil, this approach is likely to be only effective in the context of area-wide efforts to manage FAW because FAW migrates to new areas after emergence. The recycling or addition of organic matter to the soil also improves soil quality, though it may take time for farmers to experience significant yield benefits when transitioning into zero-tillage systems. Where residues are not widely used as fuel or feed, they can be relatively easily left in fields to aid in maintaining natural enemies and ground-dwelling predators.
- **Timely planting:** Although there is no documented evidence at this time that early planting in Asia can assist in reducing FAW attack, the principle of timely planting makes sound ecological sense and is likely to be advantageous to farmers. This approach suggests that when farmers establish their maize crops in a timely manner, they can potentially escape from the risk of pest attack as temperatures and pest populations build up in both the monsoon and winter seasons. In rainfed areas, farmers can benefit from sub-seasonal and seasonal rainfall forecasting to help them prepare for planting immediately after the first sufficient rain event. In areas where farmers can access ground or surface water, they may consider using a starter irrigation, if possible, to advance establishment of the crop. In cropping systems where monsoon-season rice is rotated with winter maize and soils can be drained, farmers can consider using higher-yielding but short-duration rice varieties as well as mechanized maize establishment to advance cropping.
- **Soil and nutrient management:** Poor soil fertility and unbalanced application of fertilizers, including both under- and over-application of nitrogen without sufficient attention to soil organic matter management can lead to increased pest damage. There is considerable scientific evidence for the benefits of balanced fertilization on pest and FAW control. Extension services should focus on the resources and knowledge to provide adequate and balanced plant nutrition for healthy crop development, which in turn can aid in pest management. In addition, farmers can and should be generally advised to retain residues as mulch and/or to apply organic matter to the soil. This can enhance habitat for natural enemies that can aid in FAW control.
- **Intercropping:** Maize is commonly grown in association with other crops in Asia. Evidence from Africa and the Americas indicates that intercropping with cowpea, pigeon pea, and soybean can reduce oviposition of FAW on maize, while also increasing habitat for natural enemies. Intercropping can also reduce FAW ballooning dispersal from plant to plant, though intercrops should be carefully designed to avoid contiguous canopy cover that might enable larvae that have fallen off maize plants to move to another maize plant without landing on the soil and thus risking mortality..
- **Encourage refugia:** In relatively non-complex agricultural landscapes in which maize is grown, for example in the Mekong or Ayeyarwady Deltas, or in the western IGP, refugia can assist in maintenance of natural enemies. In Asian countries where *Bt* maize is now being grown to control FAW, such as in the Philippines and Vietnam, the use of refugia has to be rigorously practiced to delay the evolution of FAW and other lepidopteran pest populations developing resistance to *Bt*. Refugia can also be useful in landscapes where *Bt* crops are not used, but where insecticide pressure is high, to slow resistance and help manage pest resurgence.
- **Increase biological diversity at field edges and farm margins:** Bunds and field margins can be planted to species that provide habitat and food sources for natural enemies that can enter fields and control pests, potentially including FAW. Agroforestry structures such as live fences, windbreaks, and hedgerows between fields can also provide connectivity and habitat natural enemies that can disperse into fields and control pests.
- **Encourage biologically diverse and habitat-rich landscapes:** Theoretically, more complex and diverse agricultural landscapes can offer more habitat for arthropod and vertebrate natural enemies. These organisms can move within and between fields to facilitate pest control, while also maintaining natural enemy populations over time. Similarly, agricultural fields located near forests may potentially benefit from the ecosystem service of pest control by predators or parasitoids that disperse from within forests and search for prey or egg-laying sites. Agricultural communities and policymakers should therefore be apprised of the potential benefits of landscape diversity and the maintenance of forests and may be encouraged to maintain them.

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# CHAPTER 07

# Communications Framework for Integrated Pest Management of Fall Armyworm in Asia*

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* The information on communications framework and principles described in this chapter is substantially based on CABI (2019), Framework for Strategic Communication during Pest Outbreaks: Learning from fall armyworm.

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# 1. Background

Early May 2018 in Karnataka, India, researchers under the jurisdiction of the University of Agricultural and Horticultural Sciences, Shivamogga (UAHSS), encountered an exotic pest feeding in the maize fields. Identified as *Spodoptera frugiperda* (FAW) by the UAHSS, followed by the University of Agricultural Sciences, Bangalore (UASB) and the Indian Council of Agricultural Research–National Bureau of Agricultural Insect Resources (ICAR-NBAIR), the pest was reported in India/Asia for the first time (Sharanabasappa *et al.* 2018). Soon thereafter the FAW adult moths were reported in various states across India. Shortly after this, reports of FAW began to emerge in Sri Lanka, Bangladesh, Myanmar, and a number of countries in South and South East Asia (see **Chapter 1**). In response, and in some cases as pre-emptive action, both public and private agencies rallied to provide the necessary support to maize farmers to mitigate the damage to the maize crop.

Because FAW was formally reported in West Africa in 2016 (Goergen *et al.* 2016) and subsequently reported throughout Africa soon thereafter, the arrival of FAW in Asia was not surprising; several of the Asian nations were prepared for the outbreak (BOX 1). The successful control of FAW in the Americas for over 100 years, combined with experiences from Africa, meant that appropriate control options and recommendations were already available (see **Chapter 3**). FAW, with its voracious appetite, would have had devastating effects on food production if the knowledge of how to control FAW from the Americas had not been deployed in various pest management, extension, and communication strategies. Communications to create enhanced awareness on FAW among the farming communities—its identification, behavior, signs of damage, and appropriate and rational management strategies at the farm, national, and regional levels—became the need of the hour. In particular, it was necessary to provide information to smallholder farmers, whose knowledge of the pest was very limited. Several countries in Asia have addressed the threat posed by FAW through communications and sharing of cross-sectoral knowledge developed with the assistance of stakeholders, including representatives from the government, international organizations, the private sector, and non-governmental organizations (NGOs) (*e.g.*, BOX 2).

The coordinated efforts to communicate to key agricultural policy makers, development organizations, and extension partners are a priority in order to brace farmers for the detrimental effects of invasive species such as FAW. Because of the speed at which FAW can colonize new areas and affect farmers' fields, systems need to be in place that pre-emptively prepare for invasion, while offering stakeholders—including but not limited to farmers—appropriate and affordable integrated pest management (IPM) options that are at once easy to understand and to implement. At the same time, it is crucial that such efforts place emphasis on utilizing communications strategies and methods that are well designed and consider their target audiences, as the same type and level of technical information is not likely to be needed by different groups. In other words, the design of communication materials and methods for policy makers, the private sector, and farmers should be distinct, well planned, and targeted.

**BOX 1. Response to Early Warnings of FAW**

Before FAW made entry into Asia, the Centre for Agriculture and Biosciences International (CABI), through its experience of working in Africa on FAW and looking at the predictability maps it had produced with the University of Exeter, sent an alert to National Plant Protection Organizations (NPPOs) of all its Plantwise countries (11 in total) on the possible future invasion of the pest. After learning of the pest, some countries including India, Bangladesh, and Myanmar called for high-level task force planning meetings under senior leadership of Ministries of Agriculture (MoA) and National Agriculture Research Systems (NARS) to deliberate on the current status of the pest and possible interventions. CABI organized the first regional conference on FAW in Nepal in November 2018, where NPPOs from South and South East Asian countries participated along with other international partners such as the International Maize and Wheat Improvement Center (CIMMYT) and the Food and Agriculture Organization of the United Nations (FAO). CABI apprised the partners on the spread, kinds of damage, and possible proven tools that could be explored for intervention in Asia. In 2019, CIMMYT organized two regional workshops with support of the United States Agency for International Development (USAID)—one in Hyderabad and the other in Nepal—to provide hands-on experience via field trips within the workshops to strengthen the understanding of representatives from ministry, research, extension, and private-sector stakeholders from several countries in Asia on FAW management. National-level workshops were held in Myanmar in early and late 2019 initially to create awareness among the stakeholders and to assess the different organizations' efforts toward addressing FAW and the gaps identified to form recommendations for future activities.

Coordinated early pre-emptive efforts were made to raise awareness and prepare for the possible invasion. In particular, the Indian Council of Agricultural Research (ICAR) sounded the alert for the region once FAW was identified. The first high-level meeting under the chairmanship of the Secretary of the Department of Agricultural Research and Extension (DARE) and the Director General of ICAR was held on August 20, 2018. This was followed by a coordinated action involving the central bodies and state departments of agriculture, which was closely coordinated by the ICAR-Indian Institute of Maize Research, Ludhiana (Rakshit *et al.* 2019; Suby *et al.*2020). As such, pre-emptive efforts to coordinate FAW activities commenced in Bangladesh even before FAW was able to migrate and invade, with USAID and CIMMYT convening stakeholders to initiate appropriate policy and strategies in September of 2018. This timely action enabled early efforts to fight back against FAW, with numerous public meetings, trainings, and activities put into place through to the end of 2019.

### BOX 2. USAID Mission-Sponsored Events and Activities for Addressing FAW in Asia*

**Burma:**** USAID held the first inclusive stakeholder meeting on FAW (March 2019). USAID worked with the MoA (Department of Agriculture [DOA]/Plant Protection Division [PPD]) to develop simplified guidelines for FAW control. These guidelines were used by the MoA as well as USAID (through the International Fertilizer Development Center [IFDC]) to train over 100 input retailers in the major maize-growing areas and helped these retailers establish demonstration plots with five rounds of monitoring (measure infestation, use an action threshold, use recommended control products). The *Bt* spray was an effective control agent. A crop cut (small yield test) from ~60 farmers (trained and control) found that control farmers had an ~8% lower yield. Michigan State University (MSU) and DOA/PPD collaborated to identify, via DNA analysis, the FAW haplotypes present (Nagoshi *et al.* 2020). USAID communicated with both Corteva and Syngenta to register new effective FAW control products with PPD. Spinetoram (Corteva) was registered for use in October 2019.

**Bangladesh:** Alongside initiatives undertaken by the government, USAID/Bangladesh and MSU's Borlaug Higher Education for Agricultural Research and Development (BHEARD) supported the 'Fighting Fall Armyworm in Bangladesh' activity, which is led by CIMMYT, to support the public and private sector to achieve more effective FAW mitigation. The key achievements of the project so far include the intensive training of 735 government officials (31% of whom were women) on FAW IPM. A smaller subset of master trainers also engaged in regular monitoring of FAW in farmers' fields and coordinated their own trainings. In sum, these actions resulted in 187,000 farmers receiving structured IPM advice on FAW. Other important USAID-sponsored communication projects include the production of educational materials (video and print) in Bangla and other languages, as detailed in BOX 9 and BOX 13. In a synergistic activity co-supported by the CIMMYT-led Cereal Systems Initiative for South Asia (CSISA), the project assisted in the development of technical materials and a rapid one-day awareness raising training for agricultural input dealers in 10 major maize-growing districts of Bangladesh. These trainings (described in BOX 9) were deployed by partnering with the Agricultural Input Retailer Network (AIRN) in Bangladesh. The Fighting FAW activity has provided consistent support to two Bangladesh national companies, Ispahani Agro-Limited (IAL) and Syngenta Bangladesh Ltd., through 50-50% cost share partnership agreements, to raise awareness and stimulate market demand for biological pesticides and biocontrol agents against FAW. The two companies trained a total of 1,187 pesticides dealers/retailers from nine major maize-growing districts and also provided hands-on training to 1,041 service providers. It also aided in efforts to fast-track registration of a biological pesticide for FAW and a low-toxicity seed-treating agent against FAW. This was achieved through raising awareness of FAW National Task Force members and lobbying the Plant Protection Wing of the Department of Agricultural Extension, and by working closely with the Bangladesh Agricultural Research Institute to accelerate field trials demonstrating the efficiency of those products in FAW control.

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* Information provided by Matt Curtis, Feed the Future Coordinator, USAID Burma, and Mohammad Sayed Shibly, USAID Bangladesh.

** The military government changed the country's name to "Myanmar" when it took power in 1989. The U.S. government continues to use the name "Burma" because it believes that any change of the name of a country should be a decision for its people. Internationally, both names are recognised.

# 2. Importance of Gender-responsive Communication

Communication strategies that fit within broader pest response plans in countries affected by FAW are important to ensure that the information dissemination to stakeholders—especially to farmers—is as relevant, as science-based, and as harmonized as possible. This avoids mixed messaging and confusion that can hinder rapid and appropriate response efforts.

Information dissemination and messaging should be (a) timely, (b) developed in a participatory manner, (c) considerate of social equity and gender issues (especially in the types of information and method of dissemination chosen), (d) cognizant of target audiences and easy to understand, (e) action-oriented, (f) generated by credible organizations, and (g) shared in such a way that builds trust among end-users, particularly farmers. To ensure interaction and mutual understanding between farmers, extension workers, scientists, and policy makers, these general characteristics should be prioritized.

Gender must be taken into account when considering the type of information and method of dissemination. For example, if diagrams or pictures show farmers in the field, they can be women (and not just men). Certain times during the day may be more suitable for radio/TV programs for reaching women than others. In some Asian countries, it is not uncommon to see that women farmers will only visit plant clinics and seek advice if they can talk to a woman advisor (Figure 1).

**Figure 1.** Communications through woman extension officers is particularly important and effective in reaching out to women farmers in some of the Asian countries. Photo credit: CABI/FAO Bangladesh.

Policy makers and response team managers need accurate and timely data and evidence to evaluate complex issues, explore multiple options, and propose the most suitable solutions for securing resources and providing the necessary technical support. The relevance of the messages to the context is also crucial, as essential messages on pest management can fail to meet their purpose when they are communicated in inappropriate formats or through inaccessible channels. As noted above, the information exchanged or disseminated must be specifically tailored to the intended audiences (CABI 2019). Good communication strategies, methods, and systems can in turn reduce information overload, mitigate conflicting messages, avoid duplicative or inefficient efforts, and ultimately positively influence farmers' decision-making processes by orienting them towards rational and data-driven pest and agroecosystem management.

# 3. Communication Planning Framework

Communications planning is a central aspect of any invasive pest response campaign. It is especially critical with invasive pests because of the pest's novelty to affected farming communities, and in some cases, such as the FAW, the speed with which the pest can migrate and infest new areas. The ability to quickly provide accurate information to a wide range of stakeholders is important not only for managing the pest but also to address responses that are not science-based and that may in some cases create hazards. In addition, resources to fund information dissemination are likely to be limited, necessitating a well-planned strategy. It is perhaps also worth noting that while effective communications could best be accomplished through a national or regional coordinated framework, experience has shown that this likely will be a significant challenge. However, broad coordination and stakeholder buy-in to messaging is preferred whenever and to the extent possible.

Communication planning can be divided into five distinct phases (CABI 2019):

- Information and communication needs assessment
- Communication strategy formulation
- Implementation
- Evaluation
- Revision

**Information and communication needs assessment:** Understanding the information needs of the diversity of stakeholders impacted by a new invasive species will help guide the strategy for quickly and efficiently compiling the information, formatting it for distribution, and identifying the mechanisms for dissemination. The assessment should be holistic and cover the broad demographics of stakeholders, including but not limited to gender, language, and cultural attributes, as well as socioeconomic groupings. The assessment should also address mechanisms, *e.g.*, radio and internet, as means for disseminating information across a wide range of options. Budgetary and technology constraints should also be assessed.

It is critical to understand that in many cases, invasive species, such as FAW, were already well-studied and successfully managed at their point of origin. In many ways this helps to simplify the needs assessment because a solid baseline already exists that can inform the context of the needs assessment in the pest's new environment. Nevertheless, one must recognize that the socioeconomic contexts and the technology landscape at the point of origin of FAW (the Americas) are quite different from those of newly infested countries, such as those in Asia.

**Communication strategy formation:** Once the needs assessment is complete, the next step is to use the results to develop a communications strategic plan. The plan should outline the goals and objectives of the strategy, the operational plan for meeting those goals, the messages, and the target audiences. The plan should also provide for a means of monitoring and evaluation as well as taking into consideration the lessons learned over time. Accordingly, the plan should contain the following elements:

- Goals and objectives of the strategy
  a. The characteristics represented by the acronym SMART—Specific, Measurable, Achievable, Realistic, and Time-bound—can be used to guide drafting of goals and objectives.
- An operational plan including activities, scheduling, cost, scope, and implementation
  a. Clearly articulate who is Responsible, Accountable, Consulted, and/or Informed (RACI).
  b. Milestones and critical path elements should be identified.
  c. A timeline for implementation, including milestones, is required.
- Specific messages to be developed and disseminated
  a. A review process should be included to ensure information is accurate and science-based.
- Identification of target audiences, with particular attention to cultural, educational, gender, and institutional aspects
- Communications channels/means/technologies
- A monitoring and evaluation process for course correction and lessons learned

The remainder of this manual describes approaches and examples from early experience with FAW in Asia. Section 4 describes further aspects of planning. Sections 5 and 6 describe communications for two specific groups: those who support farmers (Section 5) and the farmers themselves (Section 6).

# 4. Communication Approaches to Raise Awareness of FAW Management Strategies in Asia

With the progressive addition of new countries reporting FAW invasion, a number of approaches to contain and manage the pest emerged and began to be popularized by different organizations. Because Asia is reasonably well-connected through various intergovernmental platforms and by a number of international research and development organizations focused on agricultural productivity and pest management, relative harmonization—or at least broad sharing of information and learning on management strategies and communication approaches—has not been overly difficult. Importantly, international organizations including CIMMYT, FAO, USAID, and CABI all had a pivotal role in working with their respective national counterparts since 2018 (BOX 1 and BOX 2). Strong and early response actions were taken in several countries, including India, Bangladesh, China, Myanmar, and Vietnam, some of which provide the case studies in this chapter. Some of the actions taken across the region to raise preparedness among stakeholders by creating awareness of the signs of FAW infestation and feeding and its management are described below. We focus on steps that can be used as communication strategies with examples of relevant lessons and learning that have come out of these actions, which can assist in streamlining communication approaches in the case of emerging and future threats.

## 4.1. Planning Process and Levels

The National Planning System architecture consists of three levels of planning: strategic, operational, and tactical.

### 4.1.1. Strategic Level

- Strategic-level planning sets the context and expectations for operational planning and emergency response. This planning is generally the responsibility of a National Task Force, which includes stakeholders from all relevant departments, *e.g.,* research, extension, and Information and Communication Technology (ICT).
- Stakeholder engagement and commitment are crucial at the onset of the outbreak and in the long-term management of the pest.
- Development communication principles applied to outbreak communication include dialogue, consensus, participation, and ownership (CABI 2019).

### 4.1.2. Operational Level

Operational-level planning provides the tasks and resources needed to execute the strategy, *e.g.*, through National Task Forces. The major responsibilities of the Task Force include the following:

- Establish collaboration on best approaches to devise and implement IPM of FAW, appropriate to the geographical distribution of the pest.
- Coordinate implementation of harmonized strategies to reduce crop yield losses caused by FAW.
- Lower the risk of further spread of FAW to new areas.

Examples of National Task Forces are given in BOX 3.

**BOX 3. Operational-Level Planning**

**India**

To provide an actionable plan, appropriate plant resistance, pesticidal, cultural, and biocontrol measures were identified by ICAR-Indian Institute of Maize Research (ICAR-IIMR), NBAIR, and All India Coordinated Research Project (AICRP) on Maize centers, to specifically target FAW. Government authorities also opted for *ad hoc* approval of certain insecticides to accentuate the protective measures available to the farmers. A High-Power Committee (HPC) was constituted in August 2018, which is jointly chaired by the Secretary (Department of Agricultural Cooperation & Farmers Welfare) and Secretary (Department of Agricultural Research and Education) to review the status and recommend appropriate strategies. Various sub-committees have also been constituted in the state of Karnataka, Maharashtra, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, Telangana, Bihar, and Rajasthan, which are headed by the Director/Commissioner of Agriculture or Principal Secretary of the respective state. Periodically the HPC reviewed the progress of the pest and discussed possible measures to contain the spread and damage by the insect. A package of practices to control FAW as developed by ICAR-IIMR in collaboration with ICAR-NBAIR was disseminated to all stakeholders through the Directorate of Plant Protection, Quarantine & Storage (DPPQS), departments of agriculture, and State Agricultural Universities.

**Bangladesh**

A National Task Force has been formed in Bangladesh under the stewardship of the MoA. Its members consist of all relevant stakeholders from research (Bangladesh Agricultural Research Council [BARC], Bangladesh Wheat and Maize Research Institute [BWMRI], and Bangladesh Agricultural Research Institute [BARI]), extension (Department of Agricultural Extension [DAE]), and international organizations such as FAO and CIMMYT. The task force meets every month to review activities undertaken for FAW awareness and management and endorses proposals regarding communication, strategies, and inputs for FAW management to provide a harmonized approach across the country. In this context, the task force has issued fast-track registration to two important environmentally friendly inputs to manage the pest on an emergency basis.

**Vietnam**

Cognizant of the threat to maize production, Vietnam's Ministry of Agriculture and Rural Development (MARD) through the Plant Protection Department took numerous proactive measures. These initiatives included the timely detection of FAW; issuance of technical prevention and control guidance; establishment of collaborations with international organizations and the private sector; training programs for key stakeholders including farmers, officials of plant protection, and extension and crop production departments; temporary approval of insecticides; and successful demonstration of *Bacillus thuringiensis* (*Bt*) genetically modified maize resistant to FAW as a part of IPM solutions (USDA 2019).

### 4.1.3. Tactical Level

Tactical-level planning addresses how to apply resources to complete the operational tasks within a given time frame, and takes place primarily at a local level.

- Information addressed to farmers, advisory services, national and local leaders, media, and agro-input dealers must be relevant, appropriate, timely, and tailored to their specific needs.
- Understanding the information and communication needs of all stakeholders will help in the selection of the most appropriate tools and resources necessary to design, implement, and evaluate a communication strategy.

All three levels of planning involve the whole community. Through the three levels of the planning process—strategic, operational, and tactical—planners develop an understanding of threats, hazards, risks, and capabilities, which assist them in the development of plans and planning products that are based on mission, purpose, and stakeholders' needs.

## 4.2. Use of an Iterative Approach

During pest outbreaks such as FAW, farmers, agricultural supply chain providers and traders, and the general public rely heavily on rapid and consistent information that will enable them to adequately respond to the pest outbreak. Outbreaks are not linear events, so the communication plan will have to be adapted to the changing scenarios. In most cases, it is better to modify an existing plan rather than develop a new one that will have to be changed shortly thereafter.

The following elements are necessary to devise an appropriate and timely strategy:

### 4.2.1. Understanding of Farmer Needs

The climate of uncertainty during pest outbreaks generates confusion, disorientation, and misunderstandings among farmers and the services that support them. Communicating with farmers and the public on a regular basis not only ensures a smooth coordination of response efforts but also helps in reducing distress, encouraging public support, and increasing the perceived effectiveness of containment measures.

There is an urgent need to integrate ways to get feedback from farmers so that the communication work feeds into learning. Thus, it is important to establish communication channels in which there are more direct interactions with farmers on a regular basis. More dialogue will lead to clarity of knowledge and practice among farmers and will enable them to learn from extension workers the latest developments in FAW management and whether the approaches that they have adopted are appropriate. See BOX 4 below for examples of how such practices are being instituted to obtain better understanding of farmers' perceptions of FAW.

**BOX 4. Training of Extension Agents and Communication with Farmers**

CABI Plantwise has been instrumental in South Asia in promoting IPM practices through dissemination of action-based knowledge to farmers, thus enhancing IPM adoption and utilization for optimum results. This comprises capacity building of extension officers—whether governmental or from NGOs, the private sector, etc.—in building their skills for field diagnosis and giving good recommendations. Through this network of plant clinics, the pest management advisors are also able to detect new pests in the clinics from samples brought by farmers for diagnosis.

In 2019, 60 new knowledge centre (KC) managers were trained as pest management advisors in the Nay Pyi Taw area of Myanmar, with support of the International Fund for Agricultural Development (IFAD)-funded FARM (Fostering Agricultural Revitalization in Myanmar) project. The major objective of this activity was to train pest management advisors on how to create awareness of FAW and its management options. Plantwise clinics submitted farmer queries to the Plantwise online management system.

It was evident that in 2019 FAW was the major issue among the maize queries (74 out of 112). In parallel with Plant Clinic activity, which aims at advising farmers on pest and disease issues, the KCs have been supported by learning platforms that can help smallholder farmers, field technicians, rural shopkeepers, and local communities to upgrade their knowledge on plant health issues. In 2019, the first learning plot was set up at KC#31 (Figure 2), with farmers reporting significant challenges when growing maize in the first months after detection of the FAW, which has since extended its spread throughout the country.

**Figure 2.** Visit of learning plot at KC#31 on FAW- 8 Oct 2019. Photo credit: CABI.

## 4.2.2. Bringing Research from Lab to Field through Communication

Results from ongoing research, such as pesticide efficacy trials and landscape and cultural management options, should be readily available to extension service providers in formats that are easily accessible and understandable to non-technical audiences. This will enable extension agents to disseminate technical information to farmers who are on the front line of managing the pest outbreak.

The geographic spread of FAW is so vast that effective communication methods are needed that can reach large numbers of people across countries and continents. For example, by employing digital tools, it is possible to connect practitioners regardless of distance (see BOX 5). This may result in bringing new technologies to be tested or applied to a new pest in-country in a time-appropriate manner (see BOX 6).

**BOX 5. FAW Research Collaboration Portal**

In order to accelerate efforts to manage FAW, CABI established a "Fall Armyworm Research Collaboration Portal" (https://faw.researchcollaborationportal.org/) that brings together FAW researchers and encourages open working and collaboration across the global research community. The portal aims to identify and develop a global network of researchers working on FAW research and management, and to increase collaboration via an online resource where participants can share research data, insights, and outputs. A steering committee drawn from leading FAW research groups, including CIMMYT, defined the scope of the portal, including various host plant resistance, biocontrol, agro-ecological management, and environmentally safer pesticides.

**BOX 6. Promoting Novel Technologies through Effective Communication**

***Bt* maize as a part of IPM solutions: Vietnam**

To manage FAW effectively, Vietnamese agriculturalists implemented FAW management strategies focused on farmer education, use of pesticides, *Bt* maize technologies, biocontrol, maintaining plant diversity on farms, and habitat management. Moreover, FAW-effective insecticides were assumed to be the first line of defense, with careful guidance on temporary use as many of these chemicals were yet to be approved. The country's acceptance of biotechnological advancements, with the approval of *Bt* maize back in 2015, also supported the fight against FAW. Vietnam approved the commercial cultivation of *Bt* maize including single- and double-gene *Bt* along with herbicide-tolerant varieties, then targeted to control lepidopteran pests such as Asian maize stem borer (*Ostrinia furnacalis*) and provide effective management of weeds. *Bt* maize technology was certified for biosafety by Vietnam's Ministry of Natural Resources and Environment as well as food-feed safety and hybrid registration by the MARD, Government of Vietnam. In the past four years, Vietnam significantly increased cultivation of biotech maize. For more information on use of *Bt* crops to control FAW in Asia, see **Chapter 4**, Host Plant Resistance.)

## 4.2.3. Content Development and Updating

- Content development workshops bring people together to contribute to key messages, thus avoiding conflicting messaging.
- In order to be effective, technical information must be translated and adapted into local languages, using expressions and idioms that farmer communities can relate to (CABI 2019).
- An approach that has been used effectively in the response to the FAW outbreak has been the development of "technical briefs", which are developed collaboratively by bringing stakeholders together to debate knowledge available on pest identification, monitoring, and management, and factor in the latest research outcomes, taking account of licensing and availability of inputs and farmer insights on management approaches (CABI 2019; FAO 2018, 2019).

### 4.2.4. Web-based Resources on FAW Management

Another significant development that contributed to effective dissemination of FAW-related information was development of several FAW-focused websites, which serve as repositories for relevant information and communication resources. A few examples are listed below.

- The CABI Fall Armyworm Portal (Fall Armyworm (FAW) Portal | CABI) has relevant news, research publications, practical extension materials, videos and other communication resources on FAW.
- The websites of Project Safal (https://www.fallarmyworm.org.in) and CABI Plantwise Knowledge Bank (Plantwise.org | Knowledge Bank Home) also support farmers and other plant health stakeholders with relevant information on FAW management.
- The Grow Asia website (Fall Armyworm Control | Grow Asia) facilitates regional responses, especially in the Association of Southeast Asian Nations (ASEAN) countries, to outbreaks of FAW through its Action plan (ASEAN Action Plan on Fall Armyworm Control | Grow Asia Exchange).
- Another website that supports the FAW Action plan in South East Asia is Sustainable Agriculture | ASEAN FAW Action Plan | Singapore.
- CIMMYT's FAW site: https://www.cimmyt.org/tag/fall-armyworm/
- FAO's Global Action Plan on FAW: http://www.fao.org/fall-armyworm/resources/en/
- SAWBO (Scientific Animation Without Borders): https://sawbo-animations.org/708
- Training modules on FAW management: https://agritraining.co.za/fall-armyworm-faw-free-learning-modules/ (see Section 5.3).
- Feed the Future Tools to Combat Fall Armyworm (on Agrilinks): https://agrilinks.org/post/feed-future-tools-combat-fall-armyworm-africa (see Section 5.3).

In addition to the above, open-access portals like YouTube also host useful information on identification and management of FAW.

## 4.3. Evaluation to Support Improvement of the Communication Strategy

The communication strategy should be complemented by a Monitoring, Evaluation and Learning (MEL) Framework (BOX 7; CABI 2019). This framework is used to assess whether activities are consistent with the strategy that has been communicated, whether they are having the desired effect, and whether any adjustment is needed. Evaluation starts from the beginning: given the dynamic nature of an outbreak, activities need to be constantly assessed and refocused if necessary. Reviewing the strategy frequently will help in understanding whether activities are successful and on track or need to be changed. Therefore, planning for the communication activities should be done in conjunction with identification of the variables to be monitored. Focus group discussions and key informant interviews are the tools through which communication can be evaluated. The practices in use by farmers and other stakeholders and their level of awareness will demonstrate how effective the communication strategy has been.

**BOX 7. Farmer Focus Groups**

CABI in Bangladesh conducted a rapid rural appraisal in seven subdistricts of four districts using focus group discussion (FGD) and key informant interview approaches during November 2019. Through eight FGDs conducted at eight villages in five upazilas in three districts, 166 maize farmers provided information on their awareness and preparedness to manage FAW. Most of the farmers said that the pesticide sprays they were using were only partially effective against FAW infestations in maize, and they expressed appreciation for guidance and support in management of FAW. The highest proportion of the respondents appreciated guidance on pesticide usage (88%), which was followed by diagnosis of FAW (11%), cultural practices (11%), hand picking of larvae (10%), and pheromone trap use (6%).

# 5. Communication with Intermediaries who Support Farmers

Keeping farmers and the public informed on a regular basis not only ensures a smooth coordination of response efforts but also helps in reducing distress, encouraging public support, and increasing the perceived effectiveness of containment measures (CABI 2019). As described in the following sections, there are several key groups of intermediaries who need to be considered during these efforts.

## 5.1. Government-Sector Influencers

These key individuals influence decision-making processes at the local and national levels during the management of a pest outbreak. Their capacity building, participation, and actions are important as a part of an effective communication strategy reaching out to the farmers with appropriate information. See BOX 8 for examples of action-oriented steps taken to mobilize these functionaries.

### BOX 8. Mobilization of Extension Agents and Other Influencers

**India**—Following the reporting of FAW in India, cross-sector strategic communication and management activities were initiated at the national level by the Central IPM centers of the Department of Agriculture, Cooperation and Farmers Welfare (DAC&FW), State department of agriculture, Krishi Vigyan Kendras (KVKs) in different states, scientists and researchers from State Agricultural Universities (SAUs), AICRPs on Maize and Biocontrol, pesticide companies, CABI, South Asia Biotechnology Centre (SABC), NGOs, and other key stakeholders in the community. In the process, ICAR through its two research institutes, ICAR-IIMR and ICAR-NBAIR, provided technical inputs to the DAC&FW, who implemented the package of practices (POPs) through its network of IPM centers. ICAR institutes and AICRPs, along with SAUs and KVKs, played a crucial role in awareness creation and information dissemination. As of November 2019, since the reporting of FAW in India, ICAR institutes with their coordinating networks organized 589 major training programs across the country, benefitting over 15,000 personnel (Rakshit *et al.* 2019). Field visits were undertaken and biocontrol agents were distributed by NBAIR and its AICRP Centres for the management of FAW. Twenty-eight awareness programs were organized by NBAIR in coordination with AICRP Biocontrol centres, benefitting 3903 personnel. In addition to this, ICAR-KVKs have been actively involved with state functionaries and NGOs in organizing awareness programs on FAW management. A total of 407 training programs were conducted on awareness of FAW by KVKs in Zone X under the Agricultural Technology Application Research Institute (ATARI), Hyderabad. The community-based participatory efforts distilled down to educating farmers in effective IPM strategies to reduce damage in a sustainable manner. An initial baseline survey done by CABI jointly with UASB revealed that farmers were quite acquainted with FAW and its occurrence, and they relied heavily on the advice of agro-dealers.

**Bangladesh** has a network of over 10,000 front-line extension agents, each of which make rounds every two weeks to farmers' groups or producer's clubs; thus, working with the extension department can be a powerful mechanism by which farmers are provided with information on FAW management. Working with the FAW Task Force, CIMMYT developed curricula for intensive three-day field trainings of Department of Extension staff on the principles of IPM to control FAW. These curricula were based on the principles of the fact sheet and infographics described in BOX 9, and were developed to assure a healthy mix of intensive classroom training with field exercises. The Appendix to this chapter provides a summary of the key concepts included in the trainings.

Between October and November of 2019, 366 extension staff were trained using these approaches, in addition to six delegates from Nepal. The effectiveness of the training was assessed by giving participants (a) a pre-test before trainings, (b) a post-test at the conclusion of the trainings, and (c) telephone surveys during which 241 of the same trainees were asked the same post-test questions, in addition to several new questions about FAW management, six months after the trainings were completed. There were two key take-home results: (a) In the months following the trainings, 129 extension agents voluntarily arranged farmer field days at which they discussed conservation biological control and demonstrated how to most safely apply insecticides and maintain spray refuges to maintain natural enemy presence in fields. (b) Although most extension agents passed on their knowledge informally during their regular rounds of interacting with farmers, seven Sub-Assistant Agricultural Officers (SAAOs) organized 22 additional formal batch trainings in their respective working areas.

These efforts resulted in 721 lead farmers receiving advanced FAW training (246 farmer participants were women). A total of 168 extension staff provided detailed customized advice to farmers on FAW management, giving direction on when and where to spray in FAW-infested maize fields. In sum, SAAOs advised farmers 1,231 times. In addition, and more importantly, 216 extension staff scouted fields and advised farmers to not apply pesticides 3,613 times. All extension staff indicated that they used their learnings and had conveyed IPM advice to farmers for controlling FAW during their regular rounds of meetings with farmers and in farmers' groups and clubs. On average, follow-up survey data indicated that SAAOs shared FAW IPM advice with a total of 74,132 farmers (~307 farmers per extension agent on average), among which 22% were women.

**Burma***—USAID partnered with IFDC to provide extension services in FAW-affected areas. The IFDC extension team prepared a training manual, information posters, and pamphlets in May 2019. IFDC liaised with the PPD to ensure consistency in delivery of technical information sharing. The Implementing Partner then conducted FAW retailer trainings in Pindaya, Aung Ban, Nyaung Shwe, and Taunggyi Township of Southern Shan State at the end of May 2019. From this group, they selected 12 demonstration field schools in six townships with input retailers who were willing to lead in demonstration field schools. These demonstration field schools started with an initial training in June 2019, followed by five rounds of scouting through August 2019. Sample plot harvesting in demonstration field schools and random farmers' crop cuts (small yield tests) were completed during October 2019. IFDC produced a second edition of the training manual during September 2019 and started retailer training for the Delta Region, at Maubin, Zalun, and Letpadan Township. During October 2019, they established six demonstration field schools and regular scouting in five townships. Scouting was continued until November 2019, when the activity ended.

## 5.2. Agro-dealers and Other Input Providers

A communication strategy considers a specific crop protection problem not just as the outcome of a crop–pest interaction but also within the context of the local agricultural system. Agro-dealers form a significant part of the extension system because most of the time they are the first point of contact for the farmers seeking advice. Hence, it is important that dealers have the right information. Consistent information can reach the agro-dealers if they are trained under one umbrella, which can be their network in the country. See BOX 9 for the trainings that were undertaken in Bangladesh.

**BOX 9. Agricultural Input Dealers and the Private Sector—Bangladesh**

Farmers in Bangladesh get the vast majority of their pest management advice from pesticide dealers. Although many IPM programs eschew work with pesticide companies and their dealers, activities in Bangladesh embraced the reality that working with these groups is crucial in reaching farmers with appropriate information. Without engaging with the private sector—and village-level insecticide dealers in particular—farmers are likely to be given inappropriate advice to spray potentially dangerous insecticides that may not even be effective against FAW.

To this end, CIMMYT initiated work with AIRN to develop FAW IPM training materials—with emphasis on the moral hazards of selling dangerous and ineffective insecticides and business models for less toxic products—and plans to reach input dealers at a large scale. Between March and April of 2019, 755 input dealers were trained by AIRN. Follow-up telephone surveys of a subsample of 259 input dealers were conducted three months later, after the maize season had ended. Out of the 259 respondents, 54% gained at least basic and initial knowledge on IPM. Out of the 140 dealers who developed a basic knowledge of IPM, 125 (89%) provided IPM or pesticide-oriented messages to farmers. The types of information provided by these dealers to farmers depended on their learned competencies from trainings, and included information on identification of FAW, FAW biology, scouting, IPM techniques, pesticide safety, and basic concepts of economic thresholds. Dealers retained this information, as evidenced in post-training studies, but heterogeneously (Figure 3).

In mid-2019, shortly after the formal formation of the FAW Task Force, a "fact sheet" was developed cooperatively among task force members with recommendations for IPM techniques to control FAW. Information on the fact sheet was generated through review of scientific literature, research conducted

* Information provided by Matt Curtis, Feed the Future Coordinator, USAID Burma.

in Bangladesh, the FAW infographics (described below), and experiences from other countries. Using nationally approved messaging on FAW, and based on learnings from the first round of trainings of input dealers described in Figure 3, a second round of training by AIRN was conducted in January-February of 2020 with another 1,000 additional input dealers trained, each of whom had been strategically selected as key dealers operating in locations with intensive maize cultivation. Follow-up surveys of the latter trainings found that each of the retailers trained by AIRN master trainers reached at least 50 farmers with information on FAW management. In this way, an estimated 52,000 farmers benefited from enhanced advice on FAW management. These results underscore the importance of strong monitoring and evaluation efforts in training and communications programs in order to adjust curricula and improve messaging based on participant's retention of knowledge.

In addition to efforts to directly train input dealers and communicate key messages on IPM to control FAW, CIMMYT and USAID contacted key pest control product companies, and the National FAW Task Force was convened by USAID and CIMMYT at the US Embassy in Dhaka on August 5, 2019. During this meeting, pesticide companies willing to take part in multi-day field trainings on FAW management were identified. Nine companies received intensive 2-day residential trainings in October of 2019. Follow-up surveys of each company revealed that they had all taken subsequent action to further communicate the messages received during the trainings.

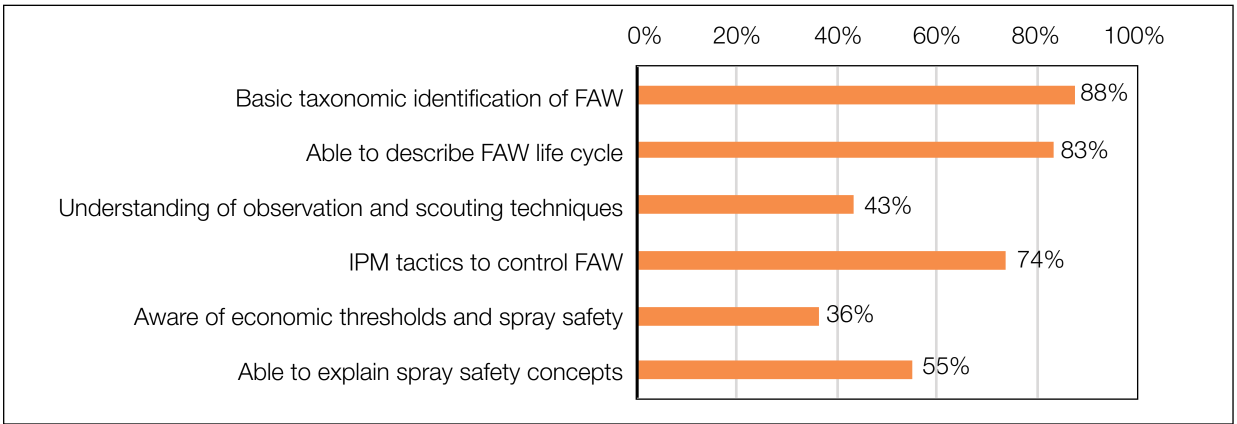


**Figure 3.** Technical competencies of insecticide input dealers following rapid 1-day trainings on integrated FAW management in Bangladesh when activities started in 2019 (data are from a survey of 259 dealers trained). (Figure credit: Tim Krupnik, CIMMYT).

## 5.3. Resources for Training the Trainers and other Reference Materials

USAID has prepared or funded several freely available web-based resources useful for training of extension agents and others involved in training farmers on FAW (BOX 10).

**BOX 10. USAID-Sponsored Web Resources**

Agrilinks (https://agrilinks.org/) is part of the US Government's Feed the Future initiative that addresses the root causes of hunger, poverty, and undernutrition, and establishes a lasting foundation for change. Feed the Future strengthens the capacity of communities and governments to manage FAW through a range of IPM strategies that protect people and the environment (https://agrilinks.org/post/feed-future-tools-combat-fall-armyworm-africa). The FAW portion of the site houses the FAW IPM Guide for Africa (Prasanna *et al.* 2018) in several languages and will be the home for the FAW IPM Guide for Asia as well.

Agri-Training (https://agritraining.co.za/), an effort funded by USAID and implemented by Land O'Lakes Venture37, provides a set of seven freely available modules covering various aspects of FAW identification and control (https://agritraining.co.za/fall-armyworm-faw-free-learning-modules/). These modules are designed as resources for individuals responsible for training smallholders. The modules include presentations that the trainer can use directly for training sessions as well as presentations and other materials for the trainer's own education.

# 6. Communication with Farmers

The strategy for communication with farmers should employ a multimedia, multi-channel approach that will allow for information to reach farmers across the country. The strategy must be informed by the socioeconomic status and communication capabilities of the target farmers. Range, transmission method or device (radio, TV, mobile phones, print, Internet, face-to-face), interactivity, and cost are just some of the considerations that the strategy must carefully consider when choosing the channel(s) to use.

For example, the sheer number of farmers in Bangladesh—who number over 60 million—makes it an extreme challenge to reach them with effective information on FAW. For this reason, initial efforts in Bangladesh focused on the development of easy-to-understand informational graphics (infographics) that could be mass-printed and distributed to farmers (Figure 4). Other communication strategies and examples are highlighted in the following sections.

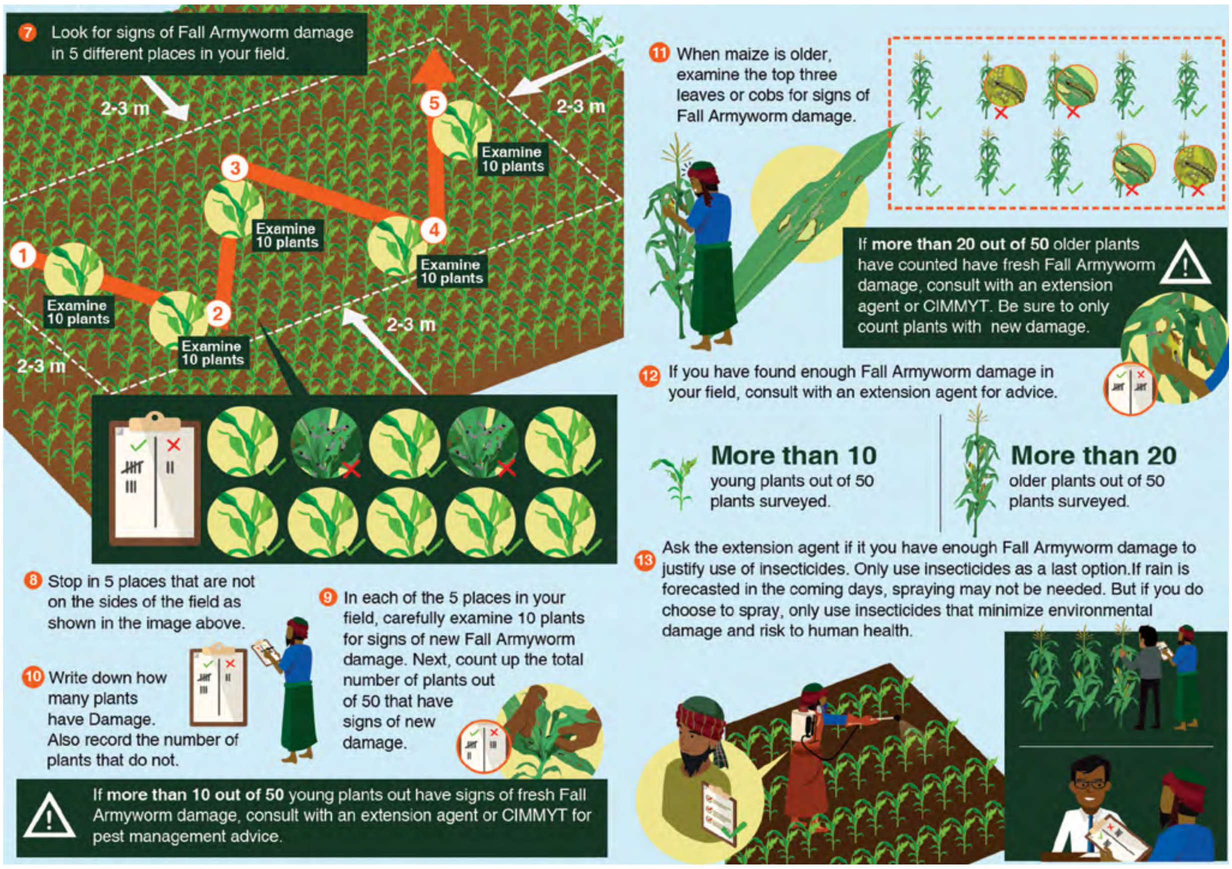


**Figure 4.** Pages from one of four pocket-sized infographics developed in English, Bangla, and Lao (Krupnik and Dhungana 2019a-d). This infographic describes how to scout fields for FAW damage and make spray or no-spray decisions. Over 500,000 infographics have been printed and distributed to farmers across maize-growing areas in Bangladesh.

## 6.1. Community-Based Field Training

Community-based field training is ideal but has limited reach. It is most effective with small audiences since it entails direct, face-to-face interactions. The quality of the communication is very high since it allows audience feedback in terms of questions and comments, stimulates discussions, and enables active participation. Further awareness can be raised by mass extension campaigns, plant health rallies, and use of mass media (see BOX 11).

Surveys to determine the types of information needed, followed by meetings and workshops covering those topics, are effective methods of creating need-based awareness.

**BOX 11. Community-Based Training: Some Examples**

In **Myanmar**, CABI intensified its support for managing FAW and building awareness given that FAW presence was confirmed in early 2019. On the request of the Deputy General of the Department of Agriculture, a large awareness program was organized that targeted more than 650 farmers in four key states and regions. The awareness meetings on FAW in Shan State (Taunggyi and Lashio) reached 236 farmers and extension staff, including 77 women and 159 men. There was considerable interest by farmers and extension staff as the majority confused FAW with other local armyworms, and its biological features were unknown. Most farmers and staff learned during the awareness program to identify the key morphological features of the pest and to diagnose FAW. Further in April 2019, PPD and CABI visited Ayeyarwady Region, Tatkone, Kayah State, and Sagaing Region and met with 421 farmers and extension staff, including 168 women and 253 men. Meetings were organized in each location with two key objectives: (1) to inform farmers regarding the key features of FAW and (2) to spread awareness of methods for FAW management.

**India** – From September 2018, ICAR-IIMR along with ICAR-NBAIR and AICRP-Maize initiated large interface meetings and training programs for extension workers, agriculture development officials, and farmers. These initial efforts, which helped to create widespread awareness, have been documented by Rakshit *et al.* (2019). Subsequently, a massive grassroots project, Safeguarding Agriculture & Farmers against FAW (Project SAFFAL), was launched in March 2019 by SABC, supported by FMC Corporation. Project SAFFAL was equipped with grassroots awareness programs, mobilization and engagement of government stakeholders, direct farmer training, and technology-based communication elements delivered through a dedicated web portal, www.fallarmyworm.org.in. The web portal walked the user through a rich database of information such as informational posters in different regional languages, IPM plans, consolidated data on FAW research, and other rich sources of information on FAW. Moreover, a dedicated FAW network comprising volunteer scientists, researchers, and experts in the field was made available to help farmers through an interactive expert network on the FAW website (Mayee *et al.* 2021). Similar web portals on FAW are managed by FAO (www.fao.org/fall-armyworm/en) and CABI (www.cabi.org/ISC/fallarmyworm) wherein information on FAW is being hosted and updated periodically. Project SAFFAL relied on animated videos on FAW, webinars with SAUs & KVKs, online media, and digital technologies to relay messages and meet the informational needs of key stakeholders including smallholder farmers during the COVID-19–induced pandemic in 2020. The project activities, both physical and webinars, traversed the Indian landscape while reaching 10 major maize-growing states. They included 15 awareness programs involving 35 public-sector institutions, providing direct training to almost 15,000 maize farmers and indirectly reaching out to almost 300,000 farmers, extension officials, and other key stakeholders on FAW management.

## 6.2. Remote Communication – Role of Mass Media

Mass media approaches are most suitable for reaching large audiences. They include:

- Print media – national, regional, and community newspapers, magazines, newsletters, posters, leaflets, booklets, and flyers.
- Broadcast media – announcements and interactive programs on FM radio and TV. When using this tool, proper messaging is vital to complementing the government's overall efforts to effectively manage and mitigate the effects of the pest outbreak.
- Video shows – especially those conducted in villages and in rural marketplaces – can be an effective tool to reach farmers with training information. Video shows are compelling and attractive, and when combined with an opportunity for farmers to ask questions and receive answers from experts after showing technical videos, these events can effectively double as informal training sessions.

Regardless of the medium used, the messages should be accessible and easy to understand but also validated for quality. It is important to ensure that the voices of farmers are represented in the messages. Messages should provide accurate and verified information on incidence and abundance of pests, the resultant damage to crops, and safe and effective control measures. See BOX 12 and BOX 13.

**BOX 12. Mass Media Strategy – India**

In India, following the FAW outbreak, different information, communication, and educational activities around IPM strategy were organized. These included regular meetings among stakeholders; continuous surveys, trainings, and sensitization of different stakeholders (589 countrywide training programs as of October 2018); distribution of pheromone traps and lures; distribution of extension folders, leaflets, and pamphlets; and dissemination of information through social media, radio, TV talks, and language-specific posters and audio-visuals. Moreover, the informational power of print media and newspapers was also harnessed by different stakeholders.

In collaboration, the different initiatives by Government agencies, NGOs, and private agencies addressed the farmer's informational needs in a targeted manner. The efforts appealed to the different information delivery channels, reaching the farmers through mass media, customized information material, demonstrations, active helplines, and expert networks. The active engagement of farmers and their demonstrated efficiency in controlling an exotic pest upon the first instance of infestation showed the efficient relay of information. Indian farmers also exhibited the tendency to actively uptake information when relayed effectively through different channels accessed by them regularly. Additionally, the regular assessment of conditions through surveys also facilitated the adjustment of recommendations.

Among the many valuable Government- and NGO-led initiatives, some of the key developments were the following:

- Awareness through educational programs for farmers in conjunction with Agri-University scientists, KVKs, NGOs, and agricultural department officers.
- Field visits and on-the-farm awareness programs.
- Workshops and training program for retailers, Agri-department & extension officials.
- Farmers' Advisory on FAW management in vernacular languages.
- Posters, video clips, pamphlets, and technology capsules on IPM of FAW in vernacular languages.
- Extension bulletins and online videos in all predominant Indian languages.
- ICAR-IIMR collaborated with CIMMYT, USAID, and MSU on translation of the SAWBO video on FAW identification, scouting, and management into different Indian languages (Hindi, Punjabi, Gujarati, Telugu, Kannada, Tamil, Odia, Bengali, Manipuri, Mizo, and Naga).
- Distribution of pheromone traps, lures, and safety kits to large numbers of farmers.
- FAW-dedicated website, maize expert network, eSAP (Electronic Solutions against Agricultural Pests), WhatsApp groups, and helpline for farmers.
- UAHSS developed a video clip on the present status of FAW, its identification, biology, and management in the Kannada language.

Moreover, the support from various international organizations was also extended to the farming communities in collaboration with Government agencies in the battle against FAW.

**BOX 13. Mass Media Strategy – Bangladesh**

CIMMYT has partnered in Bangladesh with various institutions, including the NGO Agricultural Advisory Society (AAS), for more than eight years to conduct mass media campaigns and rural video shows on a variety of topics. Shortly after FAW was identified in Bangladesh, CIMMYT and AAS developed plans to translate the SAWBO video on FAW identification and scouting (https://sawbo-animations.org/708) to suit the farming context in Bangladesh. This video, which uses cartoon-style information to explain FAW to farmers and train them on how to scout fields and make spray or no-spray decisions, was shown across key maize-growing areas of Bangladesh. Between February and April of 2019, 13,057 maize farmers had participated in 238 video show trainings across the country. After the formation of the FAW National Task Force and acceleration of efforts to respond to the FAW outbreak, CIMMYT and AAS resumed this activity in late 2019 and early 2020. These efforts reached 130,000 additional farmers throughout much of the maize-growing areas in Bangladesh through village and road-side video shows.

## 6.3. Digital Technology

Digital tools are quite flexible in terms of message delivery. In addition, they are relatively inexpensive, allow interactivity, and can distribute messages to vast audiences rapidly and efficiently. Such tools connect field agents and experts so that there is effective and timely flow of information, knowledge, and expertise. Tambo *et al.* (2019) evaluated the unique and combined effects of three complementary ICT-based extension methods – interactive radio, mobile SMS messages, and village-based video screenings – on farmers' knowledge and management of FAW in Uganda. The study concluded that: (a) participation in ICT-based extension campaigns significantly increases farmers' knowledge about FAW and stimulates the adoption of agricultural technologies and practices for the management of the pest; (b) exposure to multiple campaign channels yields significantly higher outcomes than exposure to a single channel, with some evidence of additive effects; and (c) among the three ICT channels, radio has greater reach, video exerts a stronger impact on the outcome measures, and greater gains are achieved when video is complemented by radio. Although the study was done in Uganda, the results also hold potential relevance to communications on FAW management in Asia. Farmers who have access to smartphones can readily obtain free, accurate training and information on FAW (BOX 14).

A few elements have to be kept in mind while using these tools for creating awareness.

- Integration of these tools can enable smallholder farmers or those who work with them to recognize and take effective action against the pest.
- Offline mobile communication technologies and applications are cheap and can be used by farmers in areas with poor Internet connectivity.

**BOX 14. Cellphone-Accessible Training for Farmers**

As described in previous sections, the SAWBO platform (https://sawbo-animations.org/home/) provides freely accessible video animations on numerous educational topics. These animations are designed for low-literate learners and are often narrated in multiple world languages. The animation on identification and scouting of FAW (https://sawbo-animations.org/708) has been narrated in over 35 languages through the help of ICAR-IIMR (BOX 12) and many others.

For farmers and farm advisors with access to smartphones, two app-based courses, FAW Seedling Scout and FAW Cob Scout, have been developed by USAID FTF and are available on the Learn.Ink platform (Figure 5). The courses are freely available at https://m.learn.ink/feedthefuture/courses.

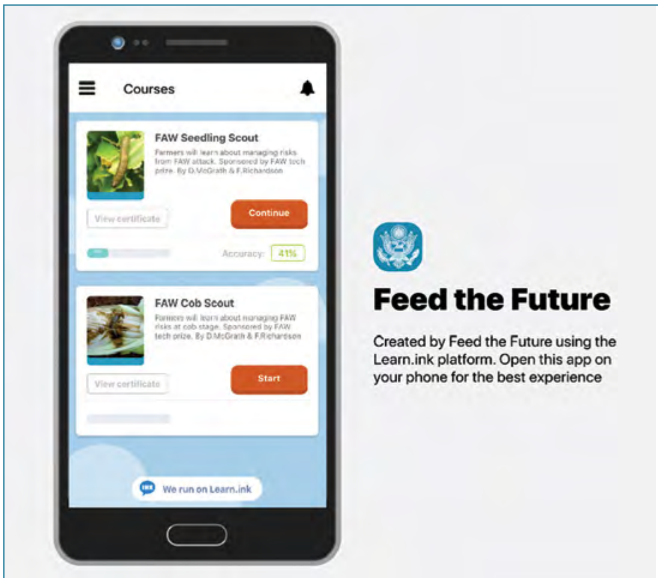


**Figure 5.** Illustration of Feed the Future FAW courses available on the Learn.ink platform. These can be accessed from a smartphone or computer at https://m.learn.ink/feedthefuture/courses. Photo credit: Learn.ink.

# 7. Conclusion

An efficient coordination and communication system can support FAW management while mitigating its social, economic, and environmental impacts. Development of a communication framework with the aim of providing a set of guiding principles and tools to assist the respective governments with country-level communication strategies for FAW and other major pests should be considered seriously by all countries affected by FAW. Through this framework, governments will gain a better understanding of the communication and other issues that must be considered when preparing a FAW preparedness plan and communication strategy. The FAW Communications Framework should be considered as a work in progress and should be periodically updated to reflect more recent developments and current practices in communications on invasive pests.

# 8. Acknowledgements

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## Appendix: Example of a Training Schedule on FAW Management

**Key elements of a three-day, hands-on FAW management training course used for training the trainers within the Department of Agricultural Extension (October-November of 2019) in Bangladesh.**

| Day | Topic | Details | Location and time required |
|---|---|---|---|
| 1 | Pre-test | Multiple choice pre-test | • Classroom; 40 minutes |
| | FAW Introduction | • Identification, background<br>• Monitoring system introduction | • Classroom; 40 minutes |
| | Scouting Introduction | • Why is scouting important? | • Classroom; 20 minutes |
| | FAW management overview | • Introduction to IPM | • Classroom; 40 minutes |
| | General field reconnaissance | • Participants explore fields | • Field; 15 minutes |
| | Sex pheromones | • Learning to place and measure FAW in traps with expert guidance | • Field; 15 minutes |
| | Simplified FAW scouting | With expert guidance:<br>• Damage assessment<br>• V stages in maize<br>• Data recording | • Field; 1 hour |
| | Advanced scouting | With expert guidance:<br>• Search Targets<br>• Action Thresholds<br>• Moths/Trap/Day<br>• 3rd Risk assessment<br>• Management recommendation | • Field; 1 hour |
| | Debrief Field Training | • Discuss field learnings | • Classroom; 1 hour |
| | Field scouting case study | • Groups present their management decisions | • Classroom; 1 hour |
| 2 | Day 1 review | • Recap and Q&A | • Classroom; 1 hour |
| | FAW Biology | • Use live specimens | • Classroom; 45 min |
| | Monitoring methods | • Introduction to ICTs in FAW monitoring | • Classroom; 1 hour |
| | Detailed scouting review | • Different action thresholds | • Classroom; 1 hour |
| | Advising farmers | • Participatory role playing | • Classroom; 30 min |
| | Ecology and pest management | • Principles of ecological control of pests | • Classroom; 45 min |
| | Bio-control | • Augmentative and conservation | • Classroom; 45 min |
| | Chemical control | • Focus on safe and low-toxicity options | • Classroom; 45 min |
| | Monitoring with tablets | • Learning how to enter monitoring data into tablets | • Classroom; 1.5-2 hours |
| | Planning for day 3 | • Planning for advanced field scouting | • Classroom; 45 minutes |
| 3 | Field reconnaissance | Trainees train new extension staff, farmers without expert assistance:<br>• Why is scouting important | • Field; 45 minutes |
| | Trap demonstration | Trainees train new extension staff, farmers without expert assistance:<br>• Trap set up and monitoring | • Field; 30 minutes |
| | Video showing | Trainees train new extension staff, farmers without expert assistance:<br>• Showing SAWBO video on mobiles | • Field; 45 minutes |
| | Simplified Scouting | Trainees train new extension staff, farmers without expert assistance:<br>• Topics from Day 2 | • Field; 1 hour |
| | Data entry into tablets | Trainees train new extension staff, farmers without expert assistance:<br>• Full field damage and population assessment | • Field; 1 hour |
| | Debrief and learning | • Observations on field experience | • Classroom; 1-2 hours |
| | Building an IPM program | • Components of area-wide IPM program in practice | • 1 hour |
| | Next season planning | • Action plans developed | • Classroom; 1 hour |
| | Post-test | • Multiple choice post-test | • Classroom; 20 minutes |
| | Award ceremony | • Recognition of best students | • Classroom; 30 minutes |

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CIMMYT International Maize and Wheat Improvement Center

CGIAR RESEARCH PROGRAM ON Maize

in collaboration with international and national research and development partners


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