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.

			Human Risk		Environmental Mitigation Required				
Pesticide Active Ingredient	**HHP**	**Low Risk**	**Inhalation Risk**	**PPE (1-3)**	**Aquatic Risk**	**Terrestrial Animal Risk**	**Pollinator Risk**	**Efficacy[†]**	**MOA (IRAC Group)**
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.

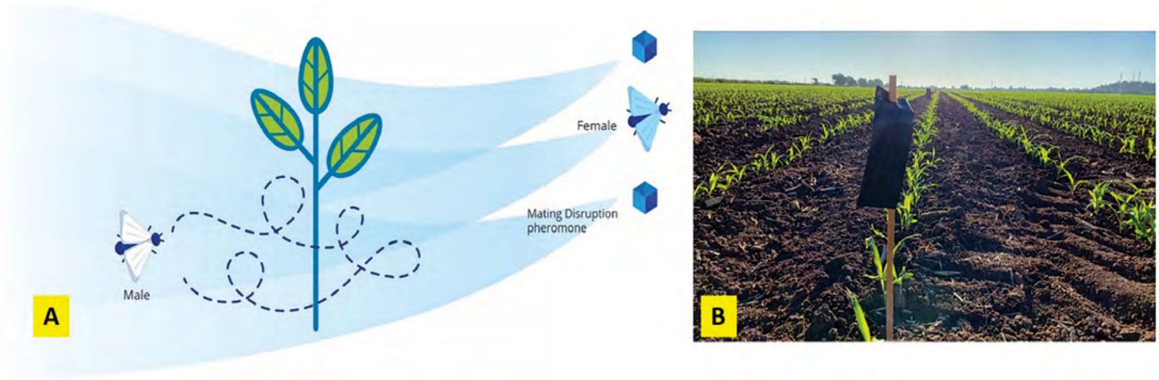

Figure 3. (A) An illustration of mating disruption due to the release of a synthetic sex pheromone. **(B)** Pheromone dispensers in a maize field. Figure credit: Juan Lombana (Provivi, USA).

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.

* 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 (4th, 5th, and 6th 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.

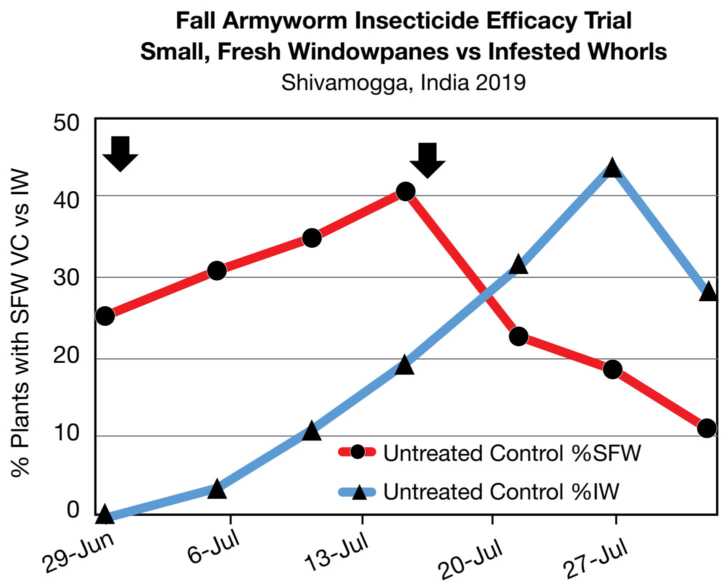

Figure S2. Plants with small, fresh windowpanes (%SFW, red line) and plants with infested whorls (%IW, blue line) during an insecticide efficacy trial, Shivamogga, India 2019. Black arrows indicate insecticide applications.

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.

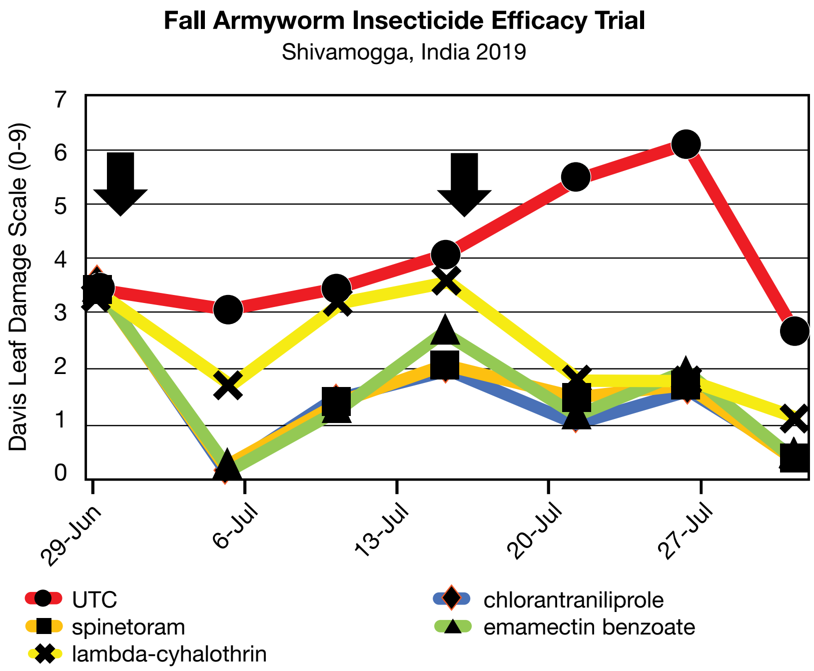

Figure S3. The Davis Scale (modified from Davis *et al.* 1992 by Deshmukh *et al.*)* became less effective at separating treatments as the maize plants matured and FAW generations overlapped. Black arrows indicate insecticide applications. UTC refers to untreated control.

* 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.

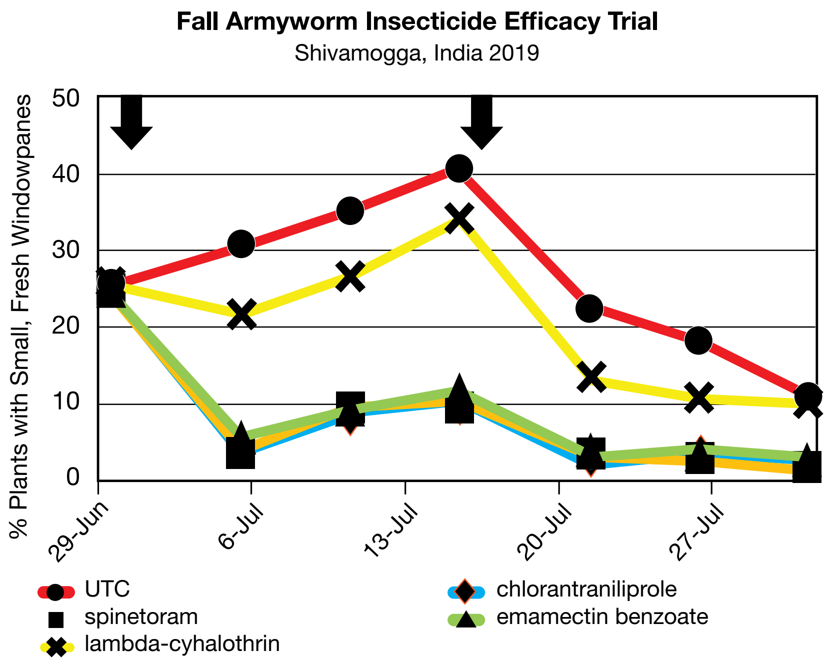

Figure S4. Prior to tassel emergence, the percentage of plants with small, fresh windowpanes (%SFW) was a useful measure of relative insecticide efficacy. Black arrows indicate insecticide applications. Black arrows indicate insecticide applications. UTC refers to untreated control.

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.

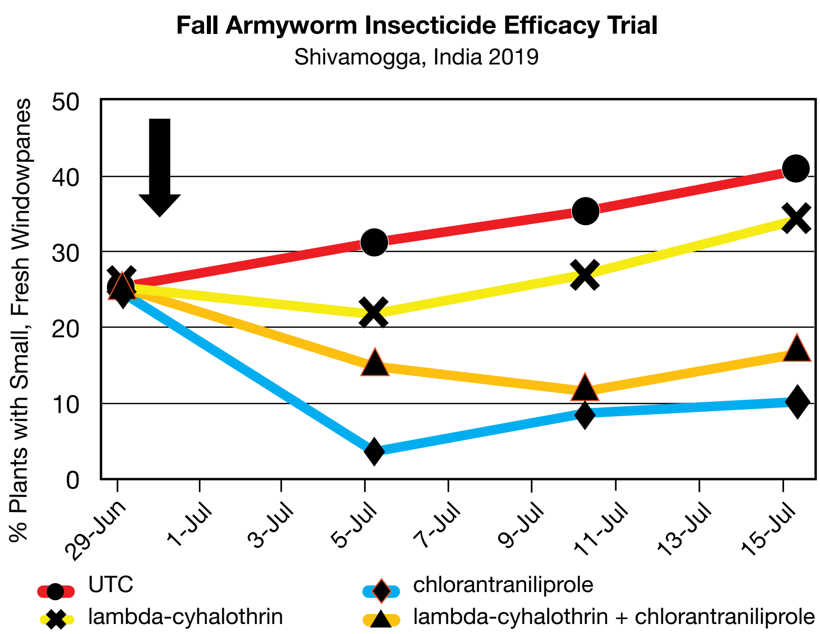

Figure S5. When assessed on the basis of %small, fresh windowpanes, a mixture containing 4.6% lambda-cyhalothrin and 9.3% chlorantraniliprole was less effective than 18.5% chlorantraniliprole but still more effective than 5% lambda-cyhalothrin. Black arrow indicates insecticide application. UTC refers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

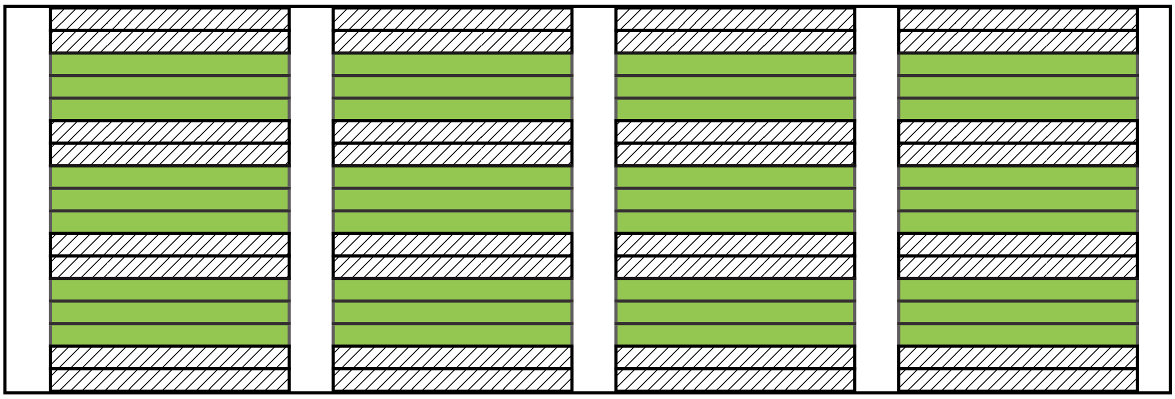

Figure S6. Sample plot map showing an experiment consisting of four blocks separated by alleys (represented by vertical boxes). The number of rows per plot may vary depending on the practitioner. In this illustration, each block contains three plots of three rows each (green) surrounded by guard rows. 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).

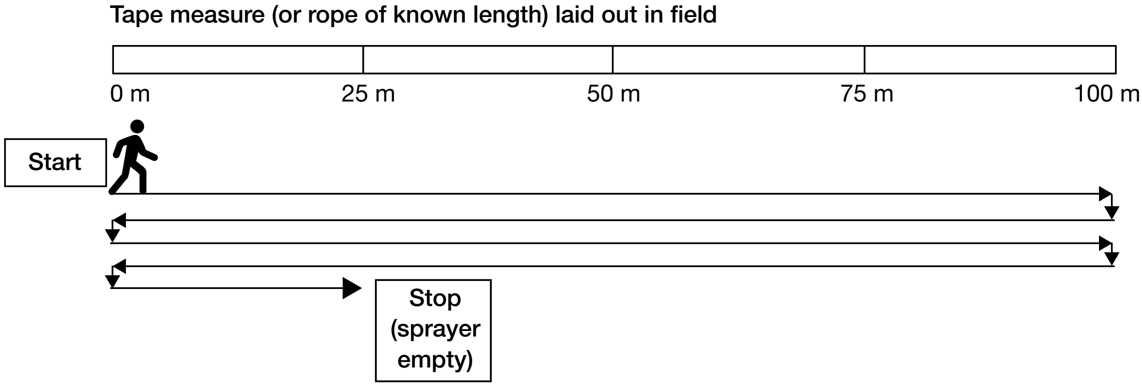

Figure S8. Use of tape measure for sprayer calibration. The applicator fills the sprayer tank with a measured amount of water and sprays the ground while walking up and down the length of the tape measure until the sprayer is empty. The applicator must count the number of passes up and down the field, 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 m².

________ m		________ m		________		________ m²
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				________ ha
Area covered by sprayer (in square meters)	÷	**10,000 m^2/ha**	=	**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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