CHAPTER 01

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

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

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* Corresponding author (b.m.prasanna@cgiar.org); [1]CIMMYT, Nairobi, Kenya; [2]Huesing Agricultural and Educational Consulting LLC, USA; [3]Oakside Editorial Services, LLC, USA; [4]United States Department of Agriculture—Agricultural Research Service, Gainesville, Florida, USA; [5]Agricultural Information Institute, Chinese Academy of Agricultural Sciences (CAAS), Beijing, China; [6]Institute of Plant Protection, CAAS, Beijing, China; [7]Universitas Gadjah Mada Yogyakarta, Indonesia; [8]CSIRO, Australia; [9]GrowAsia, Singapore; [10]Center for Agriculture and Biosciences International (CABI), Nairobi, Kenya; [11]USAID Bureau of Resilience and Food Security, Washington D.C., USA.

1. Introduction

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

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

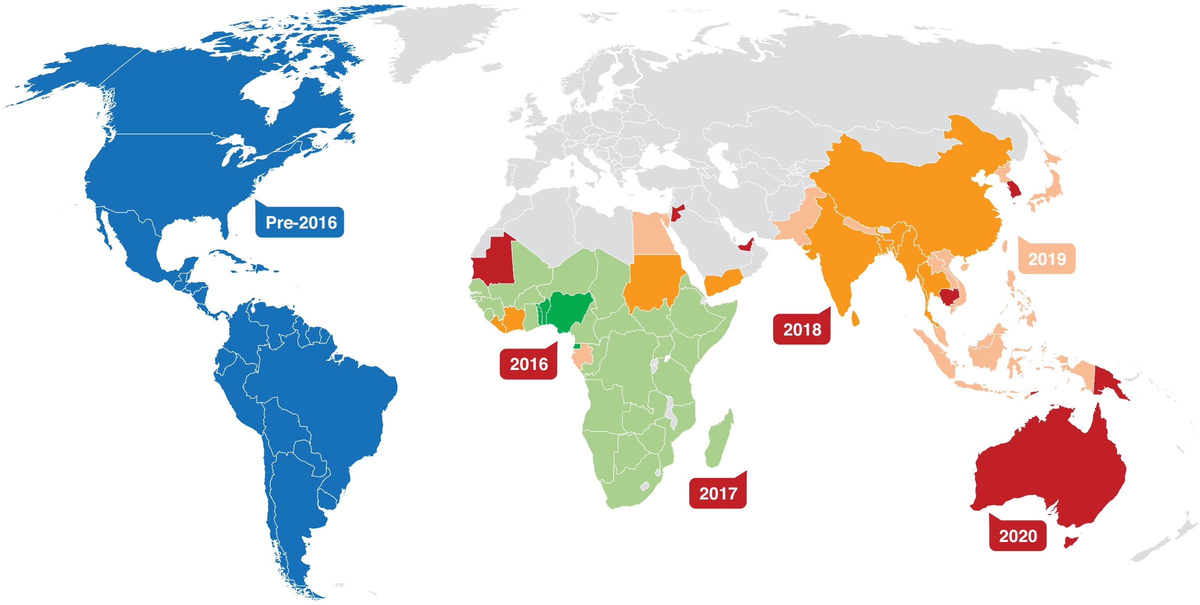

Figure 1. Global distribution of FAW, based on the published reports, and information presented in Centre for Agriculture and Biosciences International (CABI) Invasive Species Compendium (https://www.cabi.org/isc/datasheet/29810; accessed on January 2, 2021). Note that there could be some discrepancies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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

2. FAW Life Cycle

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

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

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

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

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

C. Black-headed larvae emerging out of egg mass

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

E. Distinguishing marks on medium- to large-sized larvae

F. Reddish-brow pupa

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

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

3. Molecular Comparison of FAW Populations in Africa and Asia

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

3.1. FAW Strains and Host Preference

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

3.2. Genetic Characteristics of FAW in Africa and Asia

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

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

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

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

3.3. Resistance to *Bt* and Other Insecticides

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

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

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

3.4. Need to Monitor the Evolution of FAW Strains

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

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

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

FAW is now an endemic pest across much of Africa and Asia and it is therefore essential to develop an effective GAP-IPM approach, based on farming practices, to manage this pest across Asia. Such an approach should be informed by sound scientific evidence, build on past experience combating FAW in other parts of the world, and be adaptable across a wide range of agroecological contexts (particularly for low-resource smallholders). The GAP- IPM approach provides a useful framework to achieve these goals.

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

4.1. Good Agricultural Practices (GAP)

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

4.2. Principles of IPM

The goal of IPM is to economically suppress pest populations using techniques that support a healthy crop, minimize the use of pesticides, and minimize harm to people and the environment. Because of its holistic nature and the need to integrate a variety of techniques and disciplines, IPM should not be viewed as an “off-the-shelf” solution. IPM requires that the farmer and agricultural advisor possess significant agronomic and pest management knowledge to implement an effective program based on local farming goals and conditions. The IPM process is embraced globally by international bodies such as FAO and the Organization for Economic Co-operation and Development (OECD) and is typically illustrated in the form of an IPM pyramid, based on GAP (Figure 3). An effective IPM strategy for control of FAW will employ a variety of integrated approaches including host plant resistance (native and/or transgenic), biological control, cultural control, and safer pesticides to protect the crop from economic injury while minimizing negative impacts on people, animals, and the environment. Host plant resistance will be reinforced by biocontrol options as they are developed as well as cultural control within the Asian context. As in all IPM programs, decisions on pesticide use will focus on the economic trigger elicited when these basic control options fail to limit the pest’s damage and on economically viable interventions that pose the lowest risk to human and environmental health.

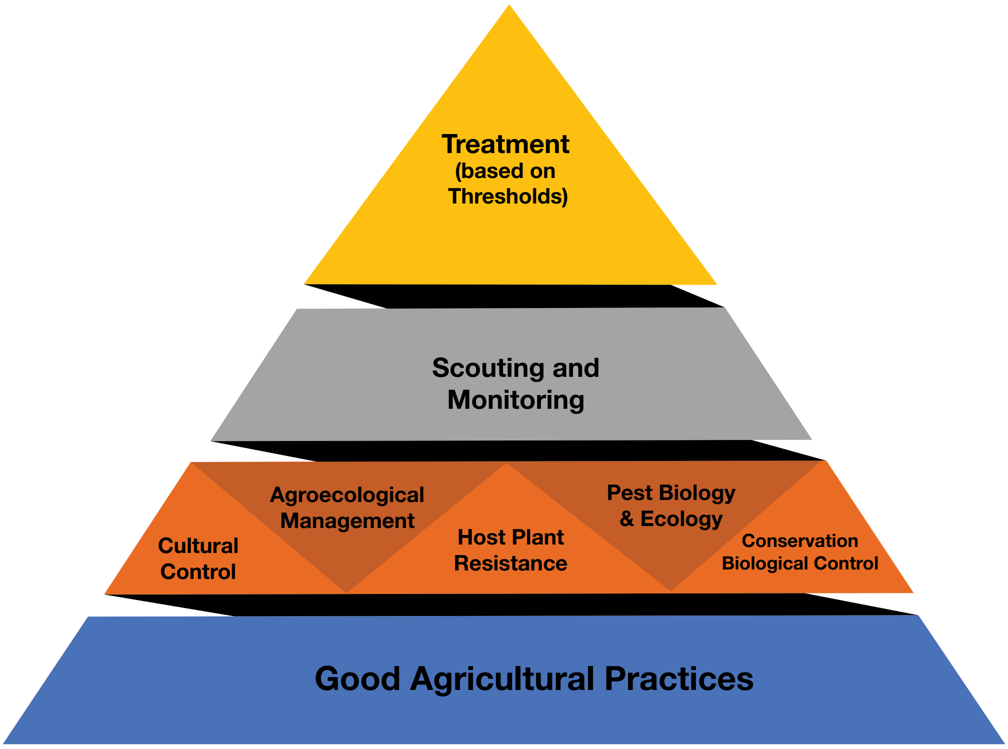

Figure 3. A conceptual illustration of IPM (modified from Naranjo 2011; Naranjo *et al.* 2020). “Treatment” may include pesticides (biopesticides and/or environmentally safer synthetic pesticides), augmentative biocontrol, mating disruption, sterile male insect release, etc. (see **Chapter 3**). These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

An IPM framework for control of FAW in maize has several key objectives:

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

4.3. Economic Threshold and Economic Injury Level

Two very important concepts in IPM are the Economic Threshold (ET) and the Economic Injury Level (EIL). A thorough explanation of the subject is provided by Stern *et al.* (1959), and Hunt *et al.* (2009). The main points are summarized here:

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

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

4.3.1. Calculation of Economic Injury Level

The EIL is the break-even point between economic loss resulting from the pest and the cost of managing the pest, *e.g.*, equipment, labor, and pesticide costs (Figure 4). Because economic conditions (*e.g.*, commodity market value, management costs) fluctuate, the EIL will fluctuate. The calculation for the EIL is:

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

where

C = Pest management costs,
V = Market value of the commodity,
DI = Yield loss per pest,
K = Proportion of the pest population controlled.

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

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

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

In principle, the EIL calculation variables (C, V, DI, K) and the EIL assessment should be an easy mathematical exercise. In practice, the ET and EIL are difficult to determine and are generally based on multiyear basic research data. For example, commodity prices and pesticide costs are fairly easy to determine but may vary significantly from place to place in a given country, which means that individual farmers may need to make adjustments in their own calculations based on the price they receive for maize and the local costs of technologies. (See Section 7.1.5 of **Chapter 3** for examples of cost-benefit calculations.) Yield loss due to a given pest also varies depending on the insect's developmental instar, the stage of development of the crop, the crop's overall health (influencing its ability to compensate for foliar damage), and the agroecosystem in which the crop is grown. Also, while data on the efficacy of some technologies are robust because the same product is used globally by thousands of farmers in many countries, efficacy data for some technologies are at best an estimation. Moreover, efficacy for some technologies may vary under different conditions, including environmental conditions and farmer's management expertise. EIL calculations also typically do not take into account the costs to human health and the environment, nor do they factor in the potential loss of natural enemies of the pest.

Likewise, the ET, which is normally the 'trigger' for a needed mitigation procedure, is very difficult to estimate because it represents a prediction of when a pest population will reach the EIL. This requires a significant understanding of the crop and agroecosystem as well as the pest's biology and population dynamics. In the case of a new invasive insect pest, estimating those dynamics is very difficult. However, in the case of FAW, which has been a pest in the America for decades, this information is readily available.

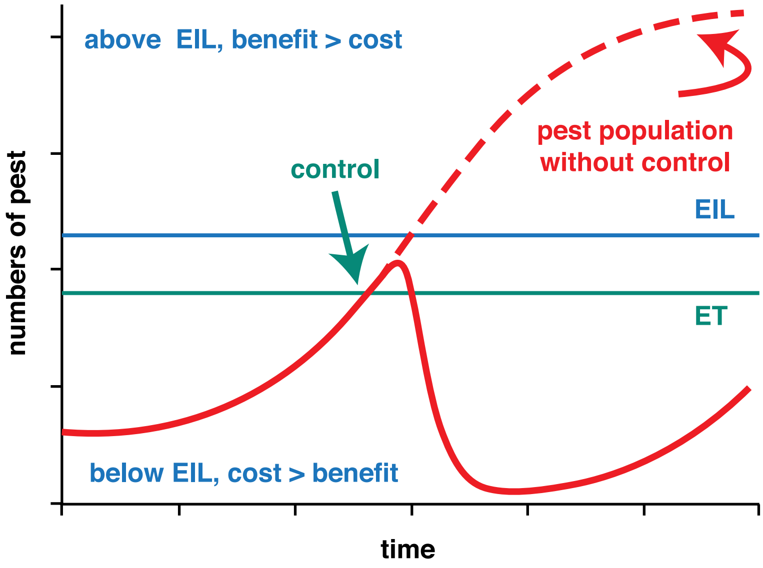

Figure 4. The relationship between pest numbers over time and calculation of the Economic Threshold (ET) and the Economic Injury Level (EIL). Figure credit: Ed Zaborski, University of Illinois; from Barbercheck and Zaborski (2015).

4.4. Action Thresholds

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

4.5. Summary of the IPM Approach

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

- GAP that promote the growth of healthy plants are important because healthy, robust plants are generally less susceptible to insect and pathogen attack and may better withstand such attacks.
- Cultural interventions at the field and farm level (*e.g.*, intercropping, conservation agriculture and its components) generally enhance the biological activity within the cropping system, providing shelter for small-range predators of the pest (*e.g.*, spiders, ants, earwigs, beetles, fungi, and bacteria) or parasitoids (*e.g., Trichogramma* spp., *Telenomus* spp., etc.). In turn, this can help control pest larvae—thereby reducing pest proliferation.
- Creating awareness among farmers on how to identify FAW damage in the field through scouting, assessing the pest population and its threat to the crop, and taking informed decisions on when and when not to apply a pesticide is critical. Reactive interventions must be used only after proper field scouting for the pest in the field.
- Pesticides should be selected judiciously and used only when necessary, as part of a holistic IPM strategy. Pesticide attributes such as environmental safety, selectivity, and environmental persistence should be considered in the decision-making process (see **Chapter 3**).

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

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

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

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

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

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

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

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

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

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

(Continued on page 16)

(Continued from page 15)

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

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

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

Footnotes:

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

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

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

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

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

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

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