Fall armyworm (*Spodoptera frugiperda*) management by smallholders

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Abstract

The fall armyworm (FAW) (*Spodoptera frugiperda*) is a crop pest species that has become global, having spread from its native American distribution to Africa and Asia since 2016. Its rapid spread, plus concerns about potential yield losses, have led to the search for sustainable management options. While most farmers affected by FAW in America have large-scale farm operations, the overwhelming majority of farmers in Africa and Asia are smallholders. This dramatically different context means that different management approaches must be sought. Large-scale producers with high-productivity, access to international market prices, risk-transfer mechanisms and the benefits of government subsidies are able to use technologies unavailable to smallholder farmers without access to those conditions. This review examines these differences and surveys the literature for accessible management options for smallholders, largely based on locally available solutions using ecological knowledge. Innovative digital solutions may also play a role in helping farmers learn about these solutions, and share them locally.

The Rapid Spread of Fall Armyworm

The fall armyworm (FAW) (*Spodoptera frugiperda*), has been a consistently important insect pest for a number of crop species, especially maize, in the Americas for centuries [1]. In the last few years, FAW has become an invasive species in Africa, the Near East and Asia. FAW was first reported in early 2016 in mainland West Africa (Nigeria, Togo, Benin) and on the island of São Tomé (São Tomé and Príncipe) [2]. It rapidly spread across sub-Saharan Africa during 2016 and 2017 and by late 2018, had been confirmed by virtually every country in sub-Saharan Africa [3]. It was confirmed in Yemen and India by July 2018 [4] and by early 2019, had been confirmed in an additional five Asian countries, including China [3].

FAW prefers maize, but it is also common on sorghum, rice and millets, and is sporadically important on a vast array of additional crops and plants, including cotton and vegetables. It is reported to infest 186 host plant species in North and Central America [5], while Montezano *et al.* [6] have reported 353 host plant species based on a literature review and additional surveys in Brazil, from 76 plant families, principally Poaceae, Asteraceae and Fabaceae.

FAW is native to tropical and subtropical regions of the Americas and migrates north and south annually, following maize plantings in temperate zones [7]. FAW is not able to enter diapause and is killed by low temperatures [1, 8]. In its native range, it is established year-round where winter temperatures rarely fall below 10 °C [8–10]. Adult females are relatively short-lived (13–19 days at 26.8 °C) but highly fecund, with around 1000 eggs being laid per female, in clusters of 100–300, usually on leaf surfaces [11]. The first and second instars scrape leaves, leaving a 'windowing' damage, while later instars leave ragged holes in young leaves emerging from the plant whorl. In a trial examining larval dispersal of *S. frugiperda,* Pannuti *et al.* [12] reported finding over 90% of recovered larvae within a 1.1 m radius

of a maize plant 14 days after being infested with an egg mass. Larvae are cannibalistic at high larval densities [13], resulting in typically one later instar larva per maize plant.

FAW Management in America

In the USA, Brazil and Argentina, FAW is routinely controlled via the use of genetically modified maize, which incorporate genes that express for the production of toxins lethal to FAW. The adoption of this technology has now surpassed 85% of the maize area planted in those three countries [14]. The use of this technology and of effective pesticides is supported by the access that the farmers have to relatively stable international markets for their maize, which is primarily used for animal feed, ethanol production, or processed to extract high fructose syrup, coupled with subsidies and risk transfer mechanisms (e.g. insurance).

Globally, the vast majority of maize farmers are smallholders, whose context is very different from that of large-scale commercial farmers. These differences include economic, ecological and cultural factors. The vast majority of smallholder maize farmers do not have access to high and stable prices for their maize, subsidies, or risk-transfer mechanisms, severely limiting their access to expensive control technologies. They also produce in much more diverse landscapes and cropping systems, and have different production goals.

FAW in Africa and Asia

FAW quickly and naturally spread across sub-Saharan Africa and Asia upon its arrival, and now routinely infests millions of hectares of maize across Africa and Asia. Although FAW is capable of feeding on many crop species, the crop most affected in Africa and Asia has been maize. However, in drier areas, such as in the Sahel, FAW has been consistently reported from crops other than maize; e.g. sorghum, millets, wheat and teff. The infestation levels vary dramatically, but the average infestation level across the continent is about 30% of plants infested with FAW [3]. Most maize farmers across the continent are now aware of the pest: 99% of maize farmers in Ethiopia were aware of FAW as were 100% of maize farmers in Kenya [15].

Maize is grown on approximately 37 million hectares annually in sub-Saharan Africa [16], the vast majority (approximately 95% of the area) in smallholdings, usually <2 ha. These small plots form a heterogeneous patchwork of often polyculture plots, mixed in a landscape of trees and shrubs across much of Africa. Most maize grown in Africa is white maize, produced for family consumption, unlike the yellow maize grown by commercial producers globally.

Asia produces about 32% of the maize globally [3]. China is the second largest maize producer in the world, growing maize on over 40 million ha. Like Africa, most maize farmers are smallholders. Unlike Africa, in Asia, most maize is yellow maize, produced as animal feed.

Smallholder Maize Producers

Smallholder maize farmers in sub-Saharan Africa typically grow their small plots of maize using almost exclusively family labour; they plant saved seed, use few purchased inputs, and their production is mostly for household consumption [17–19] If they have excess maize, they typically receive low prices from local intermediaries for their production; e.g. US$0.02/kg [FAO, in press]. Low produce price was perceived to be a risk among 100% of farmers surveyed in Ghana [18].

The low prices severely limit their ability or interest in using higher rates of purchased inputs. The concept of economic injury level and economic threshold was developed to determine the break-even point between the direct costs of pest damage and the value of the production protected or 'saved' by taking the management actions [20]. Typically, the calculation seeks a pest population level at which action should be taken to avoid economic losses. Pedigo et al. [21] defined Economic Injury level (EIL) as $EIL = C/VIDK$, where the EIL is expressed in number of injury equivalents per production unit (e.g. insects/ha), C = cost of the management activity per unit of production (e.g. US$/ha), V = market value per unit of the produce (e.g. US$/kg), I = injury units per insect per production unit [e.g. proportion defoliated (insect/ha) and D = damage per unit injury [e.g. (kg reduction/ha)/ proportion defoliated] and K = proportionate reduction of the insect population from the action.

Economic equilibrium (optimal expenditures) is reached when $C = VIDK$. For smallholder maize producers in Africa facing FAW, typical values for VIDK are: (US$0.05/kg) (1400 kg/ha) (15% yield reduction) (75% effectiveness) = US$7.88/ha. Thus, to be economically rational, a farmer should not spend more than US$7.88/ha to manage FAW under these conditions. The low prices received by the farmers and the low productivity of production result in very limited options for smallholder maize farmers to manage FAW in their maize. A recent paper by Baudron et al. [22] estimated 12% yield reduction from FAW infestation in maize in Eastern Zimbabwe.

Given this economic context, it is not surprising that most smallholder maize farmers in Africa, before the arrival of FAW, had used few purchased inputs. Most had used no pesticides. Muhammad et al. [23] conducted 350 household surveys of maize-producing families in Makueni and Machakos, Kenya and found that 0.5% had used herbicides and 2% had used insecticides. Household surveys carried out from 2010 to 2012 by the World Bank demonstrated that across six countries (Ethiopia, Malawi, Niger, Nigeria, Tanzania and Uganda) 16% of farmers used agrochemicals across all crops. This group included countries with significant agricultural input subsidy programmes. In

countries without input subsidy programmes, the use of pesticides was very low (Malawi, 3%, Niger, 8% and Uganda, 11%). The use of these inputs in maize is probably even lower, given the use of production for self-consumption and the low prices received for any market sales [24].

FAO [25] carried out household surveys in Namibia in August 2017. Interviews of 592 households in 301 villages demonstrated that only 1.7% of households used pesticides. This low proportion is in line with the 2013/2014 Namibia Census of Agriculture which found that only roughly 13 000 out of approximately 150 000 agricultural households in the communal sub-sector use pesticides of any sort, including herbicides, fungicides, insecticides and traditional products [26].

During 2016 and 2017, many governments, some with donor support, provided pesticides free of charge to farmers for FAW control or applied them with government employees. For example, in Zambia in 2017, nearly 102 000 litres of pesticides valued at 18 million Zambian Kwacha (US$1.97 million) were distributed, and a further 3 million Kwacha (US$330 000) was spent on sprayers and personal protective equipment such as gumboots and respirators [27]. In Ethiopia, the government distributed 271 779 litres of pesticides for FAW in 2017 and 167 896 litres in 2018 [28].

Not surprisingly, the use of pesticide among smallholder maize farmers increased dramatically in those countries with such policies and programmes. This was documented in a report for CABI by Rwomushana et al. [27], which said: '53% of farmers in Ghana and 43% of farmers in Zambia used pesticides (in 2018). However, when compared with 2017 data, farmers were generally using fewer synthetic chemicals (72% in 2017 for Ghana, and 62% in 2017 in Zambia)…The marked reduction in pesticide use in Zambia for the control of FAW compared to the previous year may be due to reduced purchase and distribution of pesticides by the government…The current survey (2018) also established that in Zambia, twice as many farmers were using traditional methods such as applying ash, urea or sand on larvae, while only 27% of farmers handpicked egg masses compared to 36% in 2017. The increase in farmers deploying a wider range of control methods may also be attributed in part to the lack of pesticide distribution as well as Zambian smallholder farmers' traditional non-chemical approaches to maize cultivation. A third of farmers interviewed did not apply any control measure, compared to 23% in the 2017 survey' [27]. Many donors and governments began to scale back the distribution of pesticides from 2017 to 2018, as exemplified by the 38% reduction in pesticide distribution by the Ethiopian government during that period [28].

Most smallholder maize farmers in Africa traditionally use cultural controls, including the destruction of crop residues, manipulation of planting dates, use of locally available substances and tillage methods [29]. The majority of smallholder farmers in Africa practice intercropping [30]. As free pesticide distribution diminishes, due to lack of government funds and donor fatigue, smallholders will be faced with managing FAW in their fields within the context of their production systems. This review examines the agroecological basis of sustainable integrated pest management for smallholder maize farmers and suggests a research agenda to fill knowledge gaps and validate promising practices over a wide range of ecosystems.

Since the arrival of FAW in Africa, some research has begun on management practices accessible by smallholders. Although some practices have been tried, there are still many more potential effective, accessible practices based on the agroecology of FAW in Africa and Asia that need to be explored. This review presents a survey of the agroecology of FAW that leads to management of landscapes and cropping systems to take advantage of locally available practices that are immediately accessible to smallholders, but which require further research and validation over the wide range of cropping systems and environments across Africa.

Impact of FAW Infestation on Maize Yield

The direct foliar damage from FAW feeding on maize is alarming to many farmers who have never seen this type of damage before. This alarm is often shared by politicians, leading to the urgent response of pesticide procurement and use. But the foliar damage caused by FAW in many cases does not result in dramatic yield reduction. The maize plant is quite capable, under good moisture and nutrition conditions, to compensate for a level of foliar damage that may appear alarming to farmers first seeing the damage. The response of maize plants to foliar damage at different stages of plant growth has been well studied in other parts of the world. Dozens of careful, controlled studies on the yield loss caused by FAW have been carried out in the Americas (notably, the USA, Brazil and Mexico).

In the USA, many maize farmers have subsidized crop insurance for their maize crops; specifically against hail, which can have a devastating effect on maize yields at certain moments. Crop insurance in the USA started in the 1880s when private insurance companies first sold policies to protect farmers against the effects of hail storms. In 2016, farmers spent US$981 million on crop-hail insurance to protect US$36 billion worth of crops [31]. Due to the large area covered and the importance of this insurance programme, the National Crop Insurance Service (NCIS) has reviewed and prepared 'corn loss instructions' for the private insurance companies that provide coverage to farmers.

The US Department of Agriculture published the results of NCIS research in the Corn Loss Adjustment Standards Handbook (FCIC 25080) in 2013. The results from the research show that even 70% defoliation at the 12-leaf stage is estimated to cause a 15% yield reduction. A 25% defoliation never causes more than 9% yield reduction and may cause less than a 5% yield reduction when the

damage occurs before the 18-leaf stage. These results are very significant for FAW damage, as rarely does the defoliation from FAW exceed 50%, and more typically is closer to 25%. At these levels of infestation, farmers with little experience with FAW and unaccustomed to observing significant foliar damage to their maize are likely to overestimate the impact of FAW damage on their maize yield. In some cases, however, FAW does directly infest cobs. This direct damage has a much greater impact of grain yield and grain quality than does the indirect foliar damage.

The results demonstrate the capacity of maize plants to compensate for low-level artificial defoliation across growth stages and the capacity of maize plants to compensate for higher levels of defoliation when it occurs at certain growth stages. These results were subject to further testing recently by Thomison *et al.* [32], who carried out field studies in three different locations in the midwestern United States, conducting artificial defoliations at two levels (50% and 100%) and at three stages of maize growth, then measuring the yield reduction from each treatment and comparing their results with the NCIS chart. In all cases, the field trials had lower yield losses than the NCIS chart and in most cases, significantly lower. In none of the cases did artificial defoliation at the 50% level, even when conducted up to three times, result in more than 24% yield loss.

These studies of the impact of artificial defoliation on yield clearly demonstrate maize's ability to compensate for foliar damage. While the defoliation caused by FAW looks dramatic, especially to farmers unaccustomed to seeing such foliar damage in their fields, its impact on maize yield is likely to be significantly lower than what farmers would estimate.

In addition to artificial defoliation studies, the yield loss due to FAW infestation has also been extensively studied in field trials conducted in the Americas. The maize yield response to FAW infestation in the American state of Indiana was studied by Cruz and Turpin [33]. They artificially infested maize plants with FAW larvae at 8–10 leaf stage, measured FAW feeding damage and yield in trials over 2 years. In the first year, they recorded a 15% yield reduction from 98% of plants infested versus 0% infestation. The same study showed no significant yield reduction of 31% of plants infested. In the second year, an 18% yield reduction was recorded with 100% of plants infested. Cruz *et al.* [34] examined the impact of 100% of plants infested (manually infested) with FAW at mid-whorl stage on maize yield in Brazil on three different maize varieties. Yield reductions due to FAW were measured at 58%, 29% and 21% compared to uninfected controls. The yield impact of FAW and southwestern corn borer [*Diatraea grandiosela*] was examined over 2 years by Williams and Davis [35], used artificial infestation of larvae, resulting in almost 100% of plants infested. FAW infestation resulted in 13% yield reduction, while *D. grandiosela* infestation resulted in a 57% yield reduction.

Hruska and Gladstone [36] studied the response of maize yield to different levels of plant infestation during three periods of vegetative maize growth in irrigated maize under hydric stress in Nicaragua. Chemical insecticides were applied and protected the plants from FAW and the neotropical cornstalk borer (*Diatraea lineolata*). Yields from treatments which had infestation during just one period (approximately 15 days) did not differ from complete protection. The treatment that had maximum infestation during three periods yielded 34% less than the treatment that had complete protection. Hruska and Gould [37] reported on four field trials in Nicaragua of FAW and *Diatraea lineolata* infestation and their impact on maize yield. In the four studies, the yield reduction from maximum FAW and *D. lineolata* infestations resulted in yield reductions of 25%, 17%, 25% and 43%. The differences were explained based on different infestation pressures and environmental (rainfall) conditions.

FAW Economic Thresholds and the Need for Validation in Africa and Asia

Based on the results of field trials on FAW impact on yield and the economics of maize production and protection, recommendations have been made regarding management decisions for FAW in maize in the USA. For example, Purdue University in Indiana recommends: 'The application of an insecticide is usually not economical for control of the fall armyworm. However, it may be necessary if the infestation is extremely severe and/or the plants are under stress. In such cases, if 75% of the plants exhibit whorl feeding damage and larvae are less than 1–1/4 inches (31 mm) long, and the plants are under stress, treatment may be advisable' [38].

Growing conditions of maize in Africa and Asia are quite different from conditions in the Americas. The ability of the maize plant to compensate for foliar damage depends on the genetics, nutrition and water availability of the plant. Maize varieties, plant density and other agronomic practices will also influence the relationship between FAW infestation and yield. Experimental field studies are urgently needed to validate the results from the Americas. In addition, African and Asian smallholder farmers may have different decision-making processes than American maize farmers. To date, there is only one published paper that measured maize yield loss due to FAW in Africa, reporting a 12% reduction [22].

During the first years of infestation, the only estimates of infestation levels and yield losses were available from farmers' estimates. Such estimates are fraught, due to the inexperience of farmers with FAW. Without the experience of observing damage to their maize and then harvesting the maize, farmers in Africa do not have the practical experience to guide their estimates of yield loss. In addition, farmers may sense that overestimates of damage or yield loss may result in benefits from government

programmes or foreign donations, creating an incentive to overestimate damage and yield loss.

Smallholder Maize Integrated Pest Management

Maize integrated pest management programmes in a number of countries, including the USA, Brazil and Argentina, incorporate new technologies, such as the latest generation of chemical insecticides and genetically modified hybrid varieties. The access to these technologies is made possible by the economics of producing for international markets that seek maize for use as animal feed, ethanol production and as a source of sweeteners. These same technologies are typically not accessible by smallholder maize farmers, due to the low and unstable prices and lack of access to risk transfer mechanisms. Smallholder maize farmers are very constrained in their access to integrated pest management options and must often depend on locally available, low-cost options.

Before the arrival of FAW and the free provision of pesticides to smallholder maize farmers in Africa and Asia, the overwhelming majority did not use pesticides in their maize but have instead used cultural control methods to deter or kill insect pests. The practices of intercropping maize with common beans, handpicking and killing insects, and the application of tobacco extracts, wood ash and soils to plants is common among these farmers [30]. The economic constraints on smallholder maize producers mean that their sustainable integrated pest management will be largely dependent on agroecological approaches. Those will rely heavily on knowledge and experience of FAW in the local cropping systems and the conditions that lead to the prevention of high levels of FAW damage. They will also rely on adequate manipulation of the ecosystem to maximize the effectiveness of naturally occurring enemies, coupled with the use of locally available, low-cost tactics, such as mechanical control and the use of local substances to deter or kill FAW.

Due to the typically small plot size of maize production in Africa and Asia, the direct, mechanical control (squashing egg masses and handpicking small larvae) is feasible. Good experiences have been reported with this technique in Kenya (http://www.fao.org/farmer-field-schools/news-events/detail-events/en/c/1113777/) and Ethiopia (2018), where 337 000 ha of infested FAW fields were mechanically controlled in 2017 and 402 000 ha in 2018 with satisfaction expressed.

Good management of FAW begins with preventing infestation and the impact of larval feeding. Late-planted maize is often infested with high levels of FAW as the moths seek vegetative maize. Thus, staggered planting of maize in a landscape should be avoided. The ability of maize to compensate for foliar damage is largely influenced by adequate moisture and nutrition. Many smallholders grow maize under unfavourable conditions for both and as a result, suffer greater yield loss than if the maize had adequate nutrition and moisture. Increased plant diversity, especially intercropping, has been shown to suppress herbivore populations, increase natural enemy populations and reduce crop damage [39]. Garcia Gonzalez et al. [40] found that fields intercropping pumpkin with maize had lower FAW infestations than fields of just maize. Baudron et al. [22] however, found significantly greater FAW damage in maize fields intercropped with pumpkins. Van Huis [41] showed in Nicaragua that intercropping maize with beans reduced the percentage of maize plants infested by S. frugiperda by 20% to 30%. Hailu et al. [42] demonstrated that intercropping common beans or groundnut with maize has reduced FAW oviposition by 30% in maize in Uganda.

One use of plant diversity is the 'push-pull' system that uses two types of plants: one which emits volatile chemicals that repel pest insects, such as desmodium, *Desmodium uncinatum Jacq.* (*Leguminaceae*) (push); and planting an attractive trap plant, such as Napier grass, *Pennisetum purpureum Schumach* (*Poaceae*) (pull), as a border crop around this intercropped field. Moths are repelled from the main crop by the repellent plant and are simultaneously attracted to the trap plant [43]. The use of desmodium and Napier grass in maize systems has recently been shown to be effective in reducing FAW infestations and plant damage caused by FAW [44]. Reductions are reported to be 82.7% in the average number of larvae per plant and 86.7% in plant damage per plot in climate-adapted push-pull compared to maize monocrop plots.

Role of Natural Enemies

Many studies have shown that FAW is attracted by a large array of natural enemies and their combined level of mortality can be quite high. Luginbill [1] stated in 1928: 'As has been previously mentioned, the abundance or scarcity of natural enemies to a large extent determines whether or not fall army worms become abundant enough during a season to cause destruction to a crop. Local outbreaks are often controlled by natural enemies alone'.

In Nicaragua, 15 parasitoid species, one species of a nematode parasite, three entomopathogen species and a large number of predator species have been found on S. frugiperda in maize. Important parasites are: the braconids (up to 30% parasitism of the collected larvae, mainly *Aleiodes* (= *Rogas*) *laphygmae* and *Chelonus insularis*); the tachinids (up to 60% parasitism in maize and up to 100% in weeds, mainly *Lespesia archippivora*); and mermithids (up to 30% parasitism, *Hexamermis* sp) [41]. Pair and Gross [45] found 73% FAW pupal mortality mainly due to predators. In Honduras, Wheeler et al. [46] reported that 42% of FAWs were killed by a complex of parasitoids, *Chelonus insularis* (Cresson) (Hymenoptera; Braconidae) being the most common.

Castro et al. [47] found up to 71% natural parasitism of FAW larvae by an endoparasitic nematode (Mermithidae). In Brazil, Varella et al. [48] conducted careful life table

analyses of FAW mortality, at both egg and early larval stages over 3 years. They found that total egg mortality ranged from 73% to 81% and the greatest egg mortality was due to unviability, dislodgement and predation. At the early larval stage, >95% of early larvae died from predation, drowning and dislodgment by rainfall. They note the special importance of rainfall and predation in early larval mortality. Hoballah et al. [49] studied natural mortality of FAW in Veracruz, Mexico over 2 years and found that early larvae suffered 34% and 80% natural mortality during the 2 years.

In Ethiopia, Sisay et al. [50] examined parasitism of FAW and found Cotesia icipe was the dominant larval parasitoid with parasitism ranging from 33.8% to 45.3%, while in Kenya, the tachinid fly, Palexorista zonata, was the primary parasitoid with 12.5% parasitism. Many of these parasitoids are very sensitive to chemical insecticides used in commercial maize fields, as demonstrated by Meagher et al. [51] in Florida, where they found that natural parasitism levels of FAW larvae ranged from 1% in a commercial sweet corn field to 92% in an unsprayed field on an agricultural experiment station in Palm Beach County.

Perfecto [52] found that experimental reduction in ant (Pheidole radowszkoskii and Solenopsis geminata) populations in maize fields in Nicaragua resulted in significantly greater FAW larval populations per plant and greater foliar damage to maize caused by FAW. Perfecto [53] also showed that application to the soil at planting of carbofuran resulted in significantly reduced ant foraging and increased population levels of FAW. Ants are often common in maize cropping systems in Africa. Myrmicaria natalensis is a common ant in Africa agriculture, and has been observed predating on FAW in Malawi (personal observation). This species has previously been observed attacking Heliothis armigera [54].

For smallholder farmers in Mesoamerica, the combination of the use of plant-diverse cropping systems and the levels of control by natural enemies maintains FAW populations at levels low enough levels for smallholders in Central America [55].

Although many natural control organisms of FAW appear to be already present, field surveys need to be conducted to determine their distribution across the new environments. Important gaps between the natural enemy complexes in the natural FAW distribution and the complexes present in the new range could be studied for possible classical biological control programmes.

Enhancing populations of natural enemies through landscape management

Plant diversity has also been shown to increase FAW natural enemy populations harbouring and increasing the activity of natural enemies [56, 57]. In Nicaragua, van Huis [41] demonstrated that weeds increased parasitism of FAW: 35 and 42 days after plant emergence, parasitism by the tachinid Lespesia archippivora on larvae from weeds was 10% to 20% higher than on larvae from maize; at 42 days, 54% of the maize larvae and 75% of the weed larvae were parasitized by L. archippivora. Perfecto and Sediles [58] showed that maize intercropped with beans led to a 28% decrease in FAW infestation. They attributed this to the lower populations of ants in maize monocultures.

Degri et al. [59] studied the effect of intercropping pearl millet with groundnut on stem borer infestation of millet in Nigeria and found up to 48% reduction in the per cent of plants infested with stem borer and a 58% reduction in the number of borers per plant. This reduction was attributed to the increased levels of natural enemies found in the intercropped fields. Midega et al. [57] found that in the push-pull system there is an increased abundance, diversity and activity of predatory arthropods, contributing to reducing pest populations. Cañas and O'Neil [60] tested a traditional practice in Honduras of spraying sugar water in maize fields and found that the sugar-treated maize had higher numbers of natural enemies, 35% less FAW leaf damage and 18% lower plant infestation rates than maize treated with water alone.

The observations that ants can be important predators of FAW in maize fields, coupled with the observation that these predatory ants are attracted to certain protein-based substances, has led farmers to experiment with the use of fish soup and kitchen grease to increase ant populations and decrease FAW larval populations [61].

Importance and Use of Entomopathogens

Gardner and Fuxa [62] reviewed the pathogens naturally found on FAW in the USA and noted that the S. frugiperda nucleopolyhedrovirus (SfMNPV) is commonly found naturally and frequently causes epizootics in FAW. They found up to 38% mortality in FAW attacking sorghum in the state of Georgia. Other important pathogens of FAW include fungi, bacteria and nematodes. Some of these pathogens have already been observed killing FAW larvae in Africa, sometimes at high levels (personal observation). FAW was first reported in Yemen in August 2018 and in the first reports of FAW in maize, cadavers of FAW were found infected with fungi. Similarly, fungi have been reported killing FAW soon after its arrival in India [63].

Due to their effectiveness and low mammalian toxicity, interest in using entomopathogens as bio-pesticides against FAW has increased. A number of commercial bio-pesticides are registered and available for FAW in many countries, including fungi and bacteria, and more recently SfNPV (Andermatt & AgBiTech). Some of these pathogens (Bacillus thuringiensis) have also been produced at low cost, in local production (Cuba, Brazil). Local production of Trichogramma has been successful in a number of countries (Brazil, Egypt, etc.) for FAW and other lepidopteran crop pest species.

In addition, at a very local level, some farmers have multiplied pathogens by infecting larvae with the pathogens

and then harvesting them, processing them artisanally and applying them. Some smallholders in Central America simply collect dead larvae from their fields, grind them, strain them and apply a solution of the extract into maize plants infested with FAW (personal observation).

Vega [64] reviewed 85 published papers reporting fungal entomopathogens as endophytes and their potential for biological control. Of the 38 plant species studied, maize was the most common. In a number of cases, the endophytic fungus *Beauveria bassiana* demonstrated an effect on Lepidoptera species tested. Entomopathogenic fungi are widespread in agricultural fields and help suppress crop pests. These natural enemies may be hindered by certain agronomic practices associated with conventional agriculture including the use of pesticides.

The entomopathogenic communities have been shown to be affected by the cropping systems.

A significantly higher occurrence of insect pathogenic fungi in soils from arable fields of organically managed farms versus conventionally managed farms in Norway was found by Klingen *et al.* [65]. Clifton *et al.* [66] reported similar results in Iowa, in the USA, where in 1 year of the survey, soil from organic fields and accompanying margins had significantly more entomopathogenic fungi than conventional fields and accompanying margins. Regression analysis revealed that the percentage of silt and the application of organic fertilizer were positively correlated with entomopathogenic fungi abundance; but nitrogen concentration, tillage, conventional fields and margins of conventional fields were negatively correlated with entomopathogenic fungi abundance.

Use of Locally Available Substances Toxic to FAW

Many smallholder farmers around the world use locally available substances to try to control FAW. These include local botanical extracts, soil, sand, wood ash, lime, oils and soaps.

In addition to botanical extracts, some of which have been demonstrated to be effective, other substances are reported by farmers to be useful in killing FAW larvae. With the exception of botanical extracts, the effectiveness of the other substances has been little tested and virtually no published results are in the scientific literature. These substances (wood ash, soil, sand, detergents, oils, salt, lime, urine and others) beg scientific testing, elucidation of the mechanism of action and an exploration of the robustness of results over space and time.

Among these substances, the effectiveness of botanical extracts on FAW have been studied. Neem seed powder was shown to be effective in killing FAW larvae, always causing mortality of over 70% in laboratory studies [67]. Silva *et al.* [68] confirmed this result, finding neem toxicity to FAW larvae and calculating the LC [48] values for neem seed cake and leaves at 0.13% and 0.25% respectively. Souza *et al.* [69] demonstrated that plant oils from *Corymbia*

citriodora, Eucalyptus urograndis and *Eucalyptus urograndis* had positive significant effects of protecting maize from FAW larvae. An aqueous seed extract from Carica papaya was found to produce significant mortality of FAW larvae, similar to that of the chemical insecticide malathion [70].

Salinas-Sanchez *et al.* [71] found that hexane, acetone and ethanol extracts of *Tagetes erecta* caused 48%, 60% and 72% mortality respectively of FAW larvae. Lizarazo *et al.* [72] tested three local plants in Colombia against FAW larvae and found that one of them (Polygonum hydropiperoides) produced larval mortality as high as a commercial insecticide (chlorpyrifos). Delgado Cáceres and Gaona Mena [73] achieved 82% mortality of FAW larvae with Polygonum hydropiperoides extracts at 50 g/100 ml water. Franco *et al.* [74] demonstrated 100% FAW larval mortality with water extracts of seed of Carica papaya at 10% concentration. Plant oils from turmeric, clove, palmarosa and neem were shown to have significant positive effects of protecting maize from first and second instar FAW larvae [75].

Stevenson *et al.* [76] reviewed the current status of research and use of botanically active substances in Africa and found great potential for their use in pest management in Africa. Anjarwalla *et al.* [77] collected a good deal of information on 18 pesticidal plants, much of it of use to smallholder farmers in southern and eastern Africa.

Use of Soil for FAW Control

Smallholder maize farmers around the world may place soil into infested whorls of maize plants out of desperation, but a look into soil and FAW control analysis reveals a fascinating agroecology, basis of functionality and potential for use. Soil may kill FAW larvae directly, via abrasiveness or absorption of wax from insect cuticles, causing larval desiccation.

Diatomaceous earth has long been used for insect control, especially for stored grain pests [78] and many commercial products are available. It is considered one of the safest and effective naturally occurring insecticides [79]. Diatomaceous earth adheres to the insect body and damages the protective waxy layer of the insect cuticle by absorption, and to a lesser degree by abrasion. Loss of water from insect body results in death [79]. Constanski *et al.* [80] studied the effects of several inert powders, including diatomaceous earth and bentonite on FAW. Benotite caused 93% FAW mortality, diatomaceous earth caused 47% mortality.

In addition to the direct physical properties of soil particles, soil often contains a rich ecosystem of microorganisms, some of which may kill FAW larvae. A number of studies have looked at these entomopathogenic communities. Valicente and Barreto [81] found that 75% of 1448 soil samples in ten Brazilian states, 75% contained *Bacillus thuringiensis*. Ramirez-Rodriguez and Sánchez-Peña [82] isolated the fungal entomopathogen *Beauveria bassiana*

from the soil in Mexico and found that it caused 98% mortality of FAW larvae. Williams *et al.* [83] sampled soil from maize fields in southern Mexico, Guatemala and Belize and found that 29% of the samples contained SfMNPV occlusion bodies/polyhedra in high levels. Williams *et al.* [83] sampled soil from maize fields in southern Mexico, Guatemala and Belize and found that 29% of the samples contained SfMNPV occlusion bodies/polyhedra in levels high enough to produce mortality in early instar FAW larvae.

Knowledge Gaps

Research on host plant resistance, including genetically modified plants, and chemical control is advancing in the private sector and international research institutes. Most of these new technologies are not accessible by smallholder farmers. Large knowledge gaps exist for the use of biological control, plant chemical ecology and the use of locally available substances to deter or kill FAW. Very little research is being carried out on the use of these methods by smallholders.

The research and experiences from the Americas demonstrate that FAW has a complex agroecology that can be used to sustainably manage FAW. Smallholders in Central America and Mexico have been sustainably managing FAW for thousands of years. Many smallholders still use the traditional mixed cropping systems (milpa), where maize, common beans and a cucurbit are grown together in polycultures. The experiences and the research from this context are especially informative for smallholders in Africa and Asia. Experiences and research from large-scale commercial maize farms in the Americas are probably less useful for smallholders.

Experienced farmers do not panic if FAW infests their maize. They understand that the population levels are not great and that they do not cause much damage or yield loss. They also go to the fields often to observe and mechanically control FAW. They have a basic understanding that many of the FAW eggs and larvae are naturally killed in the fields by rain, due to desiccation, or the direct action of natural enemies. Farmers sometimes try to attract natural enemies (e.g. by spraying sugar water) and when they need to, they use locally available substances that have shown to be effective in the past (use of local botanical extracts, soil, ash, lime, salt, oils, soaps and urine).

These elements of smallholder maize integrated pest management need to be carefully studied across the ecosystems of Africa and Asia, to better understand under what conditions they work best, understand their mechanisms and to begin to develop recommendations that can be up-scaled. Many farmers are already trying some of these innovations in their fields. For example, the use of fish soup to attract ants to fields has been reported from Malawi. Researchers should work with farmer innovators in their fields to test and measure the results of these practices under different conditions. Special attention should be paid to the costs, both economic and labour time of different approaches, to ensure that the tactics are accessible by smallholders. This type of co-creation is part of Farmer Field Schools, which are a natural crucible for doing farmer-led and researcher-aided research.

In addition to co-creation with farmers, researchers should pay special attention to conducting controlled yield-loss studies as a response to different levels of FAW infestation at different periods of maize growth. These data should be gathered from a number of ecosystems across the continent so that better decisions can be made by farmers and resource allocators. Farmer Field Schools have been shown to be an excellent medium for smallholder farmer innovation and co-creation [84].

Digital Technologies

A promising innovation that is being developed by FAO and partners is the use of digital technologies that have the potential of delivering FAW advice, based on local conditions and creating communities of farmers to share experiences locally. FAO has developed the Fall Armyworm Monitoring and Early Warning System [3]. These tools are able to help farmers correctly identify and monitor populations of FAW while providing them with off-line, free advice based on local conditions delivered from satellite data. This scalable technology shows huge potential in delivering up-to-date information and advice to farmers in their pockets.

Conclusion

FAW continues to spread into new territory, moving further east and north in Asia, as well as north from sub-Saharan Africa. The vast majority of farmers in the new territories are smallholders. These farmers have limitations and special contexts which define their options for management of FAW. Fortunately, there is a vast literature and knowledge about the ecology of FAW systems, including chemical ecology and natural biological control, which can be harnessed and tested in the new environments and landscapes of FAW in Africa and Asia. This review has examined this extensive literature and reviews the FAW management options for smallholders, largely based on locally available solutions using agroecological knowledge.

Acknowledgements

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