CHAPTER 06

Agroecological Management of Fall Armyworm in Asia

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1. Introduction

Following its discovery in Africa in 2016 and the significant impact that it had across Africa (Day *et al.* 2017), the 2018 arrival of fall armyworm (FAW; *Spodoptera frugiperda* J.E. Smith) in Southern India raised alarm of the risk for crop losses across Asia (Sun *et al.* 2021; ASEAN 2020). Farming systems and cropping patterns are, however, considerably different in Asia than in Africa. These differences are likely to have implications for the ways in which FAW interacts with the crops grown by farmers and the intensity and extent of pest damage that results. Some of the largest generalizable differences between the two continents include the predominance of rice (*Oryza sativa*) as a staple crop that is usually grown at least once a year in Asia as a result of the region's monomodal monsoon rain pattern. Maize, which is the introduced FAW biotype's preferred host crop (see **Chapter 1**), can be grown throughout the year in different parts of Asia, and is often (but not always) rotated with rice. Maize is predominantly grown during the monsoon season in South Asia. In the farming systems of the Indo-Gangetic Plains (IGP) that span India, Nepal, Pakistan, and Bangladesh, maize is also increasingly grown using irrigation in the winter season following the summer rice crop (Timsina *et al.* 2011), although in parts of the IGP where monsoon-season rainfall is not excessive and soils are well drained, maize can also be grown in the summer. Across the Himalayan foothills and in the more mountainous environments of South East Asia, maize is grown as a primary crop during the monsoon season after the onset of sufficient rainfall (Gerpachio and Pingali 2007). Much of the maize produced in the Himalayas is open-pollinated, subsistence oriented, and low-input, while the hybrid maize cultivated in South Asia tends to be grown with more inputs as a cash crop sold to the animal feed industry (Timsina *et al.* 2011). In South East Asia's mountainous areas, maize is also commonly included in slash-and-burn farming systems that replace primary forests (Mertz *et al.* 2009). Irrigated or flood-retreat maize is also grown as a cash crop in Asia's riverine deltas.

The ways in which FAW interacts with maize and the rich diversity of cultivated and uncultivated species in Asia's agroecosystems is the subject of this chapter. Agroecology is a scientific discipline and approach to farm and cropping systems design that encourages the purposeful use of biological diversity and ecological interactions among species and their environment (Nicholls and Altieri 2016; Pretty 2003). Manipulation of the factors influencing biodiversity and ecological processes are prioritized to support productive, resource-conserving, and resilient farm management practices that minimize negative environmental and socioeconomic impacts (Altieri 1999). With a focus on providing practical and actionable advice for extension services, and following a review of invasive species biology as it pertains to FAW, this chapter focuses on the applicability of agroecological methods to manage FAW in Asia's diverse farming systems.

2. FAW Source-Sink Relationships and Life History

FAW is a highly mobile species and can migrate from one region to another depending on the intensity and direction of the wind for dispersal (Day *et al.* 2017). This positively affects the species' ability to find host plant resources and quality habitat (which ecologists refer to as 'sinks') throughout the calendar year. In Asia, sinks can take the form of maize crops, which are grown throughout the calendar year, though sinks can also be alternative host species that allow FAW to mature following egg hatch and to disperse following pupation. These locations, therefore, become FAW population 'sources' that can, following migration, colonize new areas with patches of maize (Figure 1).

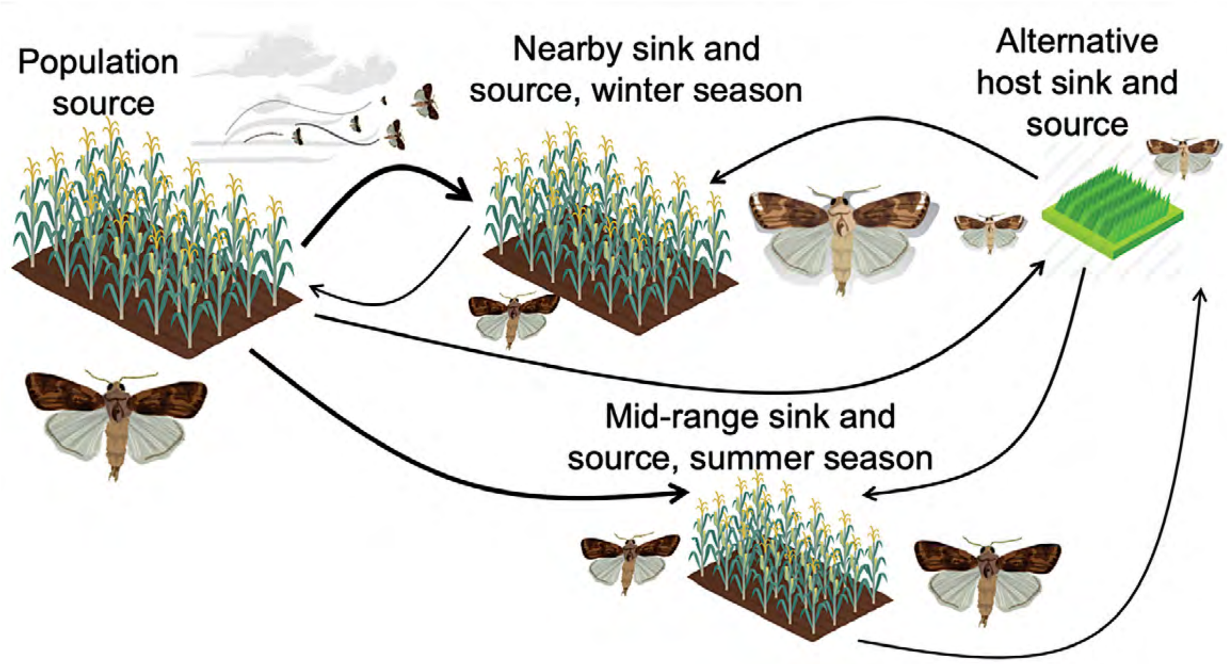

Figure 1. Source–sink relationships between FAW and its habitat that permit year-round population maintenance and growth in Asia.

Combined with the traits of FAW that make it highly adaptable to multiple environments (Table 1), FAW is a particularly challenging pest from an agroecological point of view.

Table 1. Characteristics associated with FAW that affect its status as an invasive pest species.

Trait	What does this mean?	Why is this a concern for management of FAW?
Polyphagous	FAW can eat over 80 species of plants, but prefers maize as its host (Capinera 2002)	FAW can survive and reproduce on a large number of alternative host plant species even if maize is not present in the environment.
High fecundity	FAW reproduces and grows very rapidly. Adult female months can lay 1,500-2,000 eggs within their lifetime (Capinera 2002)	FAW populations can increase very rapidly; multiple generations can occur in a single maize crop.
High dispersal range	When aided by the wind, adult moths can migrate several hundred kilometers in a single night (Early *et al.* 2018)	FAW can spread over large areas in a very short time. In Asia, FAW can easily migrate between areas in which maize is grown in the monsoon and winter seasons, sustaining the FAW metapopulations.
Wide adaptability	FAW is adapted to many environments (sinks) in which it can flourish (Day *et al.*, 2017)	Because FAW is polyphagous and can disperse over large areas, it can survive and reproduce, with population sinks becoming sources within a short time.

Longer-term management requires an understanding of the numerous ways in which lepidopteran pests such as FAW interact with their environments at each stage of their lifecycle (Figure 2) to aid in the design of ecologically based approaches to enhance pest mortality through a variety of mechanisms at the crop, field, field margin, and landscape levels. These management interventions can be targeted at the specific stages of the FAW lifecycle when the potential for reducing crop damage to specific fields is the greatest.

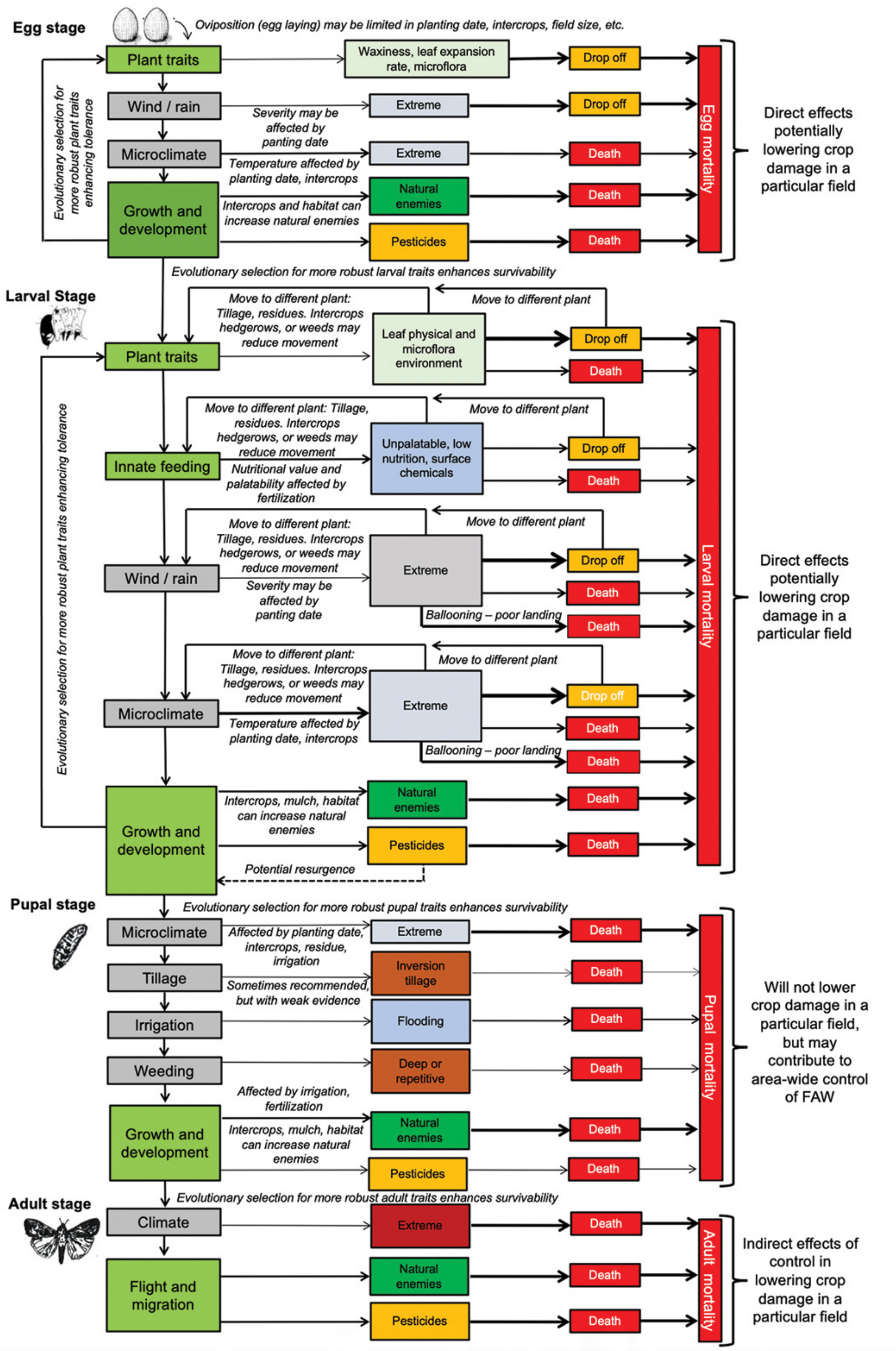

Figure 2. Biotic and abiotic interactions affecting FAW development and mortality during each major stage of its lifecycle. Thicker arrows indicate potentially stronger effects. "Natural enemies" refers to a range of predators, parasitoids, and pathogens that may limit FAW populations. Adapted and expanded following Zalucki *et al.* (2002).

As a lepidopteran pest, FAW undergoes progressive maturation after egg hatches to the neonate and subsequent larval instars. Management of FAW at these stages of the lifecycle is more likely to reduce damage to a particular crop field in which FAW is observed, as management interventions will limit the species' ability to hatch and/or feed on the crop. Once the larvae drop from the host plant and bury into the soil to pupate, management options affecting crop damage in specific fields become more limited. This is because after emergence from the soil as an adult, FAW takes flight to find mates and migrate to other fields that can be even hundreds of kilometers away (Early *et al.* 2018). Some of the management techniques that are sometimes advised by extension services are to reduce pupal density within fields (for example tillage, weeding, or irrigation) and are therefore less likely to reduce damage by inducing FAW mortality. This is not to imply that these actions are not useful; rather, they may indirectly improve crop growth and affect yield, while also potentially contributing to area-wide FAW control by limiting the ways in which particular maize fields become sources of FAW spread to new areas. Once FAW reaches the adult stage, farmers' options for FAW control are generally limited to efforts aimed at reducing egg laying in their fields (Harrison *et al.* 2019).

3. Principles of Agroecology and Pest Management

Achieving the long-term regulation of FAW populations and limiting damage to crops requires knowledge of the FAW life cycle in the context of a multi-pronged approach that utilizes ecological complexity to achieve pest suppression by maximizing beneficial biological interactions between FAW and other plant, insect, fungal, and vertebrate species (Harrison *et al.* 2019). Agroecosystems include the interactions and ecological processes between all non-living and living components of ecosystems that support agricultural production. Agroecological approaches also entail an understanding of the evolution of pests and their natural enemies, as well as applying their population dynamics to pest management (Karlsson Green *et al.* 2020). They aim at enhancing the diversity of species that play functional roles in increasing productivity, stability, and resilience through enhanced biological interactions that generate ecosystem services including pest regulation (Bottrell and Schoenly 2018). Agroecological methods also aim to enhance nutrient flows and recycling (*e.g.*, through the use of manures, recycling of crop residue, etc.) to improve crop and soil health, while also minimizing losses of nutrients to the environment in ways that can cause pollution (Figure 3).

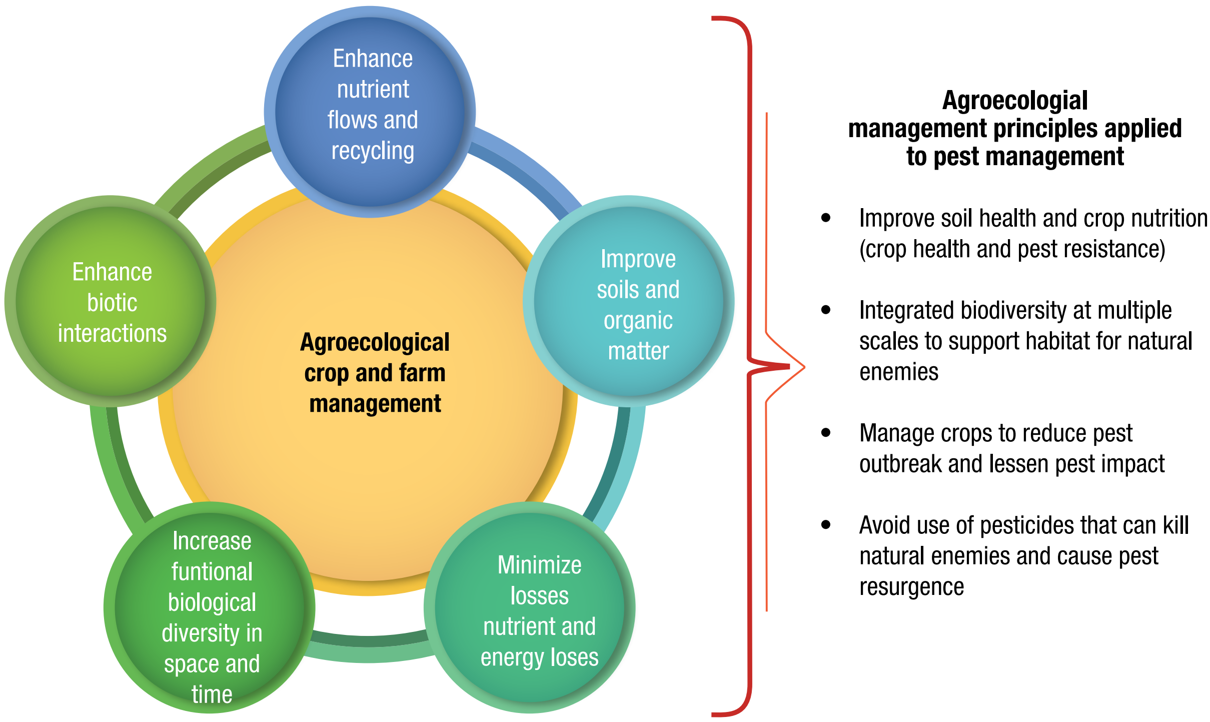

Figure 3. Principles of agroecological crop and farm management and their application in pest management.

Applied to the management of pests—including invasive species—agroecological approaches prioritize efforts to:

- increase soil organic matter, provide habitat to ground-dwelling predators, and provide balanced nutrition to crops (Alteri and Nicholls 2003);
- purposefully integrate biodiversity into the farming system, with emphasis on provision of habitat for natural enemies (Nicholls and Altieri 2004; Altieri and Letourneau 1982; Letourneau 1987; Landis *et al*. 2000); and
- manage crops and agricultural landscapes in ways that reduce the risk of pest outbreak, such as by increasing plant health, using tolerant or resistant cultivars, planting at times of the year when pest pressures are likely to be lower, or by reducing pest populations during critical and susceptible stages of the crop growth cycle (Pretty and Bharucha 2015).

Agroecological approaches within the IPM framework seek to minimize the use of pesticides, and, where possible, use the least-toxic product possible to encourage conservation biocontrol and avoid damaging human and environmental health (see also **Chapter 3**). This point is particularly relevant because pesticides—especially those that are broad-spectrum and kill both pests and natural enemies—can adversely cause the resurgence of pests when naturally occurring populations of predators and parasitoids are killed (Tscharntke *et al.* 2016; Meagher *et al.* 2016; van Huis 1981). These functional groups—which are beneficial to farmers—are often more affected by pesticide sprays than the target pest itself (Karlsson Green *et al.* 2020).

4. Biological Interactions, Agroecology, and Pest Management at Differing Scales

Farmers require multiple methods—'baskets' of options—to respond to the threat that FAW poses in Asia. The following sections describe agroecological considerations and opportunities to manage FAW as an invasive species at the plant and crop scale, the field scale, within and around crop field margins, and at the landscape level.

4.1. Plant and Crop Scale

Plants have multiple methods of defense against pests. In the case of FAW, host plant resistance mechanisms affect the egg and larval life stage, though they can also be deployed to limit oviposition, especially through mating disruption technologies. The architecture of plants (and also their configuration in crop fields) can modify the microclimate in ways that may be less favorable for the egg, neonate, and later-instar larval survival (Harrison *et al.* 2019). Pests survive by consuming and deriving their nutrition from the crops they attack. Crop varieties with native genetic resistance can be bred that have more 'hairy' leaves (called trichomes) that can limit palatability (Wiseman and Davis 1979). In addition to their toughness, leaves can also have surface waxes and can emit chemicals that can reduce pest attack. The former quality can also cause eggs to poorly attach after oviposition and drop off the plant, causing mortality (Zalucki *et al.* 2002) (Figure 2). Digestibility can also be lowered through breeding for the accumulation of phytochemicals or metabolites that can reduce pest development and survival (Constabel and Kurz 1999). Pests may also be controlled by the leaf macrofloral environment, for example if fungal species that limit egg or larval development are present or can be manipulated in ways that affect survivability (He *et al.* 2021).

CIMMYT has been undertaking systematic studies on native genetic resistance to FAW in Africa, including identification of sources of resistance to the pest. These FAW-tolerant inbred lines are now being used in breeding programs by public and private sector institutions in Asia (*e.g.*, in India), although Asia-adapted FAW-tolerant improved maize varieties are yet to be deployed. *Bt* maize varieties (expressing one or more FAW resistance proteins from *Bacillus thuringiensis*) are being commercialized in the Philippines and Vietnam (host plant resistance is discussed in detail in **Chapter 4**). The development of resistance to *Bt* toxins is also a concern as observed in other countries where both crop species and varietal monocultures are common (Midega *et al.* 2006; Huang *et al.* 2014). Studies examining other non-target ecological effects of *Bt* transgenes in agroecosystems producing maize (cf. Lang and Otto 2010; Wolfenbarger *et al.* 2008) have been implemented so far only in the Philippines and Vietnam in Asia; multi-year and multi-location studies across on insect resistance management would be useful.

4.2. Crop Field Scale

4.2.1. Land Preparation and Crop Establishment

FAW may come into contact with the soil during its early neonate and larval stage if it drops off of the plant as a result of the leaf physical or chemical environment, or during extreme weather events (Figure 2). First-instar FAW larvae also disperse from plant to plant by ballooning in a process called 'phototaxis' (Rojas *et al.* 2018), in which larvae emit silk from their bodies that is caught by the wind. This facilitates ballooning and dispersal from plant to plant. Larvae that fail to intercept other plants, or that are knocked off maize leaves due to extreme weather events will fall to the soil. Once on the soil, they will attempt to access other plants, though they may be predated or die from exposure on the soil surface before finding a new host plant. Studies of soils in Brazil also demonstrated that soils may contain bacteria such as *Bt* that can cause larval mortality (Ramierez-Rodriguez and Sanchez-Peña 2016). Soil is also abrasive to young larvae, which lack well-developed exoskeletons, and may cause injury and death (Harrison *et al.* 2019).

FAW also pupates in the soil at 2- to 8-cm depth (Capinera 2002). For these reasons, some FAW pest management guidelines suggest inversion tillage to expose pupae to natural enemies and higher temperatures at the soil surface (ASEAN 2020; GoN 2019), but the effectiveness of this technique is questionable. Tillage may indeed mechanically kill pupating FAW or expose them to natural enemies, though after emergence as an adult, FAW will fly up and migrate to other areas, often over considerable distances (Early *et al.* 2018; Sparks 1979). This means that destruction of pupae by tillage may limit a particular field's strength as a source of FAW, though tillage itself will have no direct effect on the subsequently planted maize crop. In addition, parasitoids can also lay eggs in pupae by ovipositing through the tunnel larvae dig into the soil (Capinera 2002); such soil structures may be destroyed by tillage events, inadvertently limiting this ecosystem service.

Oviposition by FAW may, however, actually be lower in the early stages of maize growth in no-till systems where crop residues are retained as mulch (All 1998), as shown in Figure 4. In Zimbabwe, Baudron *et al.* (2019) observed that zero-tilled maize fields in which residues were maintained lowered FAW attack. Evidence from North and Central America showed similar results (Clark *et al.* 1993; Rivers *et al.* 2016). In addition to limiting FAW oviposition, this effect is likely the consequence of the ways in which an undisturbed soil environment with mulch—which modifies the soil microclimate and enhances habitat for a diversity of insects—can facilitate increased densities of predatory spiders, ants, and beetles. Residue mulch may also impede the movement of larvae from plant to plant during ballooning, and/or if larva drop off the plant and attempt to transit to a new host (Harrison *et al.* 2019). Mulching also increases soil biological activity, which over time can increase soil carbon status that positively affects the retention and supply of nutrients and crop health; from a practical standpoint, however, mulches can also transfer plant diseases and hence should be used carefully (Rodríguez-del-Bosque and Salinas-García 2008). Conversely, zero-tilled and mulched fields have also been associated with higher soil moisture conditions in arid environments that create improved maize vegetative growth that can also increase oviposition (Kumar and Mihm 2002). Despite these concerns, evidence from South Asia indicates that zero-tillage with mulch can maintain yields (Gathala *et al.* 2015), though it may take several years for yield increases to be observable. Farmers should therefore be carefully apprised of the potential trade-offs associated with zero-tillage and mulching as a mechanism of pest control, so that they may make appropriately informed pest management decisions.

Figure 4. Large zero-tilled maize field in eastern China. Note the vegetational strips permitted to grow after each 10th maize row, and the field's proximity to hedgerows and tree cover. These structures may assist in reducing FAW oviposition and movement between plants when the crop is young, in addition to facilitating control by natural enemies. Photo: Tim J. Krupnik (CIMMYT).

4.2.2. Early Planting

Early or timely planting is often advised as a low-cost, relatively easy to implement, and agroecologically sound method of reducing the risk of FAW attack in maize (Harrison *et al.* 2019). Farmers may escape from FAW damage if they plant early and the crop develops to maturity before pest pressure builds up during the season. FAW development and the number of generations that may attack maize is at least partly controlled by temperature (Early *et al.* 2018). Winter maize in Asia, particularly in subtropical and tropical areas, can be established as an irrigated crop and can enable farmers to avoid rapid pest development and attack as maize matures during cool winters. Similarly, FAW attack is likely to be higher during the warmer monsoon season. Systematic research on these topics is not yet done in Asia; therefore, some caution should be exercised when advising farmers to go for early planting. This is because of the implications of FAW's large dispersal and migration range. Moreover, most maize in Asia is grown during the monsoon season, while there are pockets of winter-grown maize (particularly in Bangladesh and the region's deltas) that could, at least in principle, serve as sources of FAW dispersal in the monsoon season. As such, further research is needed to assure this advice is indeed sound, although timely planting does tend to be a fundamental tenant of good agronomy.

Early establishment of maize in the winter season is, however, complicated by the time necessary to harvest the preceding rice crop and for fields to dry out enough to become trafficable for land preparation and planting. Farmers in high-monsoon rainfall areas may have fields that stay wet too long to facilitate early planting; conversely, for those that have well-drained fields, high-yielding and short-duration rice varieties are increasingly available and can be used to accelerate maturation and harvest, thereby increasing opportunities for planting early-maturing maize, effectively altering the cropping sequence. Reduced tillage and mechanized seeding can also help accelerate maize establishment (Krupnik *et al.* 2018). In the summer season, farmers with access to irrigation who grow maize may wish to consider a starter irrigation, if possible, to establish the crop rather than waiting for monsoon rains to commence. For those without irrigation, sub-seasonal (~1 month in advance) and seasonal (3+ months in advance) rainfall forecasts can also assist farmers in being fully prepared so they may plant immediately after the first rainfall.

4.2.3. Nutrient and Organic Matter Management

Poor and unbalanced application of fertilizers without sufficient attention to soil organic matter management can lead to increased pest damage (Harrison *et al.* 2019). For extension agencies advising farmers on FAW management, this means that efforts should be focused on assuring that farmers are equipped with both the resources and the knowledge to provide adequate and balanced plant nutrition for healthy crop development, which can in turn improve resistance to pest attack. Considering FAW management, fertilization will affect two of the three categories of plant resistance described by Painter (1951), including pest preference and tolerance of plant damage without significantly affecting growth. Indirectly, 'healthy' and well-fertilized crops may also affect antibiosis, as the production of some of the plant secondary metabolites are linked to nitrogen availability.

Maize is considered as a "heavy feeder", meaning that it requires high levels of nutrients. Poorly fertilized crops tend to experience higher levels of FAW attack (Harrison *et al.* 2019). Conversely, because nitrogen from overly large doses of urea application can cause a surge in excess nutrient availability in the crop, pests may find crops nutritionally attractive, thereby increasing attack. As such, rational rates of nutrients should be applied that are neither poor nor excessive. The release of nutrients from organic materials is slower (Alteri and Nicholls 2003) and can be coupled with fertilizers to sustain plant growth over time. Soils higher in organic matter also tend to be associated with higher populations of ground-dwelling predators. Similarly, the application of compost and organic matter can also create habitat for detritivores (organisms that decompose plant residues) that can serve as alternative prey for predators, hence helping to maintain their population when FAW or other pests are not available as a food source (Landis *et al.* 2000; Thomson and Hoffmann 2007; Nicholls and Altieri 2004).

It is also important to note that many of the soils in subtropical and tropical Asia–especially in upland environments–are acidic (von Uexküll and Bosshart, 1989; Hossain *et al.* 2021; von Uexküll and Mutert, 1995). In sorghum, Gardner and Duncan (1982) found increased FAW foliar damage on acidic soils. This effect was due to the retarded rate of sorghum growth in more acidic soils with pH below 5.4, in which plants remained in the vegetative and whorl development stage longer than on neutral soils. This extended duration during the critical stages is conducive for FAW attack, affecting crop performance. Comprehensive studies on the implications of soil pH on FAW damage in maize are still lacking. Corrective actions to overcome soil acidity in Asia are likely to assist in crop growth more generally in addition to potentially mitigating FAW attack.

4.2.4. Water Management

Land area devoted to irrigated winter maize in the eastern IGP of South Asia is growing (Timsina *et al.* 2011). Because FAW pupates in the soil, flood irrigation could potentially aid in drowning and reducing populations before they emerge as adults. Similarly, in lowland environments of Asia where winter maize is rotated with summer rice, seasonal flooding at the landscape scale may reduce overall FAW populations. Research is needed to confirm whether these hypotheses do indeed result in FAW pupal suppression, although it should be noted that such strategies are unlikely to reduce the incidence of FAW in the particular fields to which irrigation is applied. This is because following pupation, FAW adults migrate in order to reproduce and then oviposit in other fields (Early *et al.* 2018; Sparks 1979).

4.2.5. Intercropping and Relay Cropping

Intercropping, in which two or more crops are grown in the same field at the same time, is common in Asia (Yadav *et al.* 2020). Intercropping is also a widely studied agroecological pest management tool (Trenbath 1993). Diversification of species within the crop field creates environments that encourage higher populations of natural enemies, which in turn can reduce the pest incidence (Nicholls and Altieri 2004; Andow 1991), including FAW (Altieri 1980). Four major mechanisms can be identified that improve pest control in intercrops. First, they can (1) reduce the ability of adult females to identify and lay eggs in the crop (Ampong-Nyarko *et al.* 1994). This may be achieved by the emission of plant volatiles that repel egg-laying females so they cannot locate the host crop (Khan *et al.* 2010; Pichersky and Gershenzon 2002). Intercrops can also (2) reduce the movement of larvae between host plants within the crop (by disrupting ballooning in a similar way as described for mulch) (Päts and Ekbom 1994). They can also (3) improve crop growth through the modification of the microclimate, and by (4) attracting and creating habitat for natural enemies (Midega *et al.* 2006; Landis *et al.* 2000; Yadav *et al.* 2020). In particular, maize intercropped with pulses (legumes) has been shown to reduce pest damage (Rwomushana *et al.* 2018). The specific intercrop species that are 'best-bet' for reducing FAW attack in Asia have yet to be formally determined, as research in a range of countries is ongoing. However, early candidate intercrops that appear to have some benefits include cowpea (*Vigna unguiculata),* pigeon pea (*Cajanus cajan*), and soybean (*Glycine max*), although horticultural and spice crops are also gaining popularity, as discussed below.

Intercropping can also result in trade-offs that can increase pest damage, if not carefully managed. For example, Baudron *et al.* (2019) observed that pumpkin-maize intercrops that maintained a closed canopy across the field may act as 'bridges', allowing FAW larvae to disperse between maize plants to avoid the environmental and predation risks they may otherwise encounter if moving along the soil surface. This is especially an issue with GM maize when the crop is planted as part of a refuge-in-a-bag (RIB) approach.

These points are important, as maize is intercropped with a wide range of species in Asia that are understudied from the perspective of pest management and FAW in particular. In South Asia, farmers commonly incorporate horticultural crops such as red amaranth (*Amaranthus cruentus*) or even spices such as coriander (*Coriandrum sativum*) in maize fields, growing them as an understory with increased levels of fertilization applied to boost growth (Figure 5). In comparison to pulses, which may be picked multiple times during the season as an intercrop, these alterative intercrops are harvested early, well before maize reaches advanced vegetative stages. Coordinated research is urgently needed to examine the efficacy of different intercrop configurations on FAW control in Asia.

Figure 5. (A) A farmer in Bangladesh, harvesting red amaranth as a leafy vegetable from an intercrop with maize. Photo: D.B. Pandit (CIMMYT). (B) A maize–cowpea intercrop growing under experimental conditions to evaluate crop performance and rates of FAW damage in Dinajpur, Bangladesh. Photo: Tim J. Krupnik (CIMMYT).

4.2.6. Push-Pull Systems

The push-pull system is a type of intercropping developed and popularized in East Africa to control lepidopteran pests, including stem borers and FAW (Hailu *et al.* 2018; Midega *et al.* 2018). In these systems, maize is intercropped with a 'push' crop such as *Desmodium* spp. that repels FAW oviposition through its production of plant volatiles, while fields are surrounded with a 'pull' species such as napier grass (*Pennisetum purpureum* Schumach.), which is commonly grown in South Asia as a fodder for livestock, or brachiaria (*Brachiaria* spp.), among other species. These border-planted species are meant to attract and trap lepidopteran pests (Harrison *et al.* 2019). Further information can be found at http://www.push-pull.net.

A recent study (Midega *et al.* 2018) indicated that FAW damage can be significantly reduced, and maize yields increased, in East Africa if farmers carefully implement push-pull in their fields. Research to evaluate the performance and applicability of push-pull systems has commenced in

India, Nepal, and other Asian countries. Push-pull systems require initial investments by farmers and a significant change in crop management practices, *i.e.*, planting and maintaining borders of attractant 'pull' species, that should be considered in any and all experimental comparisons with other pest control methods (Harrison *et al.* 2019). The lack of evidence on the effectiveness of push-pull systems in Asia therefore indicates that it should be cautiously advised to farmers, with clarification of the potential costs they may incur in management of the system. As with all technologies, their use should be evaluated using the CESAS model of cost, efficacy, safety, accessibility and scalability as outlined in **Chapter 1**.

4.2.7. Refugia to Limit Resistance and Encourage Biological Control

Refugia are parts of fields or agricultural landscapes in which crops are not sprayed with pesticides and are planted adjacent to transgenic crops (Cerda and Wright 2004). Refugia may also be natural areas within or adjacent to agricultural fields in which non-crop habitat is maintained. In the former case, refugia are intended to provide microhabitats in which pests such as FAW can develop and disperse without selecting for resistance to pesticides or *Bt* crops. This is because individuals dispersing from refugia subsequently mate with members of their species that may have escaped from the effects of pesticide application or transgenic control due to their higher level of resistance. By doing so, the selection of resistant populations of pests can be slowed, as the frequency of alleles conferring resistance will be diluted by alleles conferring susceptibility from populations dispersing from refuges (Karlsson Green *et al.* 2020).

Similarly, refugia can also provide habitat to natural enemies. Following spray events, both arthropod and vertebrate natural enemies can disperse into fields and control surviving pests. Gras *et al.* (2016), for example, showed how birds can affect lepidopteran larval and adult pest control as they disperse from trees and forests and patrol adjacent agricultural areas. Large-range aerial predators such as bats also play a role in predating adult FAW moths while in flight (Gras *et al.* 2016; Maine and Boyles 2015). Farmers in Bangladesh commonly erect bird perches by pushing small tree branches into the soil in rice fields to encourage pest suppression; similar approaches could be applied to maize, although FAW's nocturnal feeding habit and ability to hide within maize whorls may limit the ability of many birds to retrieve worms. Further research on this potential mechanism of pest suppression is needed.

Structured refugia may not be necessary in highly diverse agricultural landscapes where farm sizes are small and farmers cultivate a wide diversity of crops, for example in Bangladesh, or in parts of Nepal and Eastern India, and in Indonesia. However, in landscapes dominated by monocultures of maize and in which pesticides are widely used, for example, in parts of China, or in the western IGP, refugia can be used within agroecosystems to slow resistance and conserve natural enemies. Research on the role of refugia in the maintenance of these ecosystem services is currently very limited in Asia.

4.2.8. Weeds and Weeding

Although weeds are themselves considered as a type of "pest" by most farmers, they can also support natural enemy populations (Bàrberi *et al.* 2010). So long as weeds do not seriously compete with the crop, Penagos *et al.* (2003) suggested that their presence within fields may provide habitat to natural enemies that assist in maize pest control. Yet because FAW can consume a variety of plant species beyond maize—with a preference for grasses —pest managers often advise farmers to clean their fields and field margins of grassy weeds, as they could also support FAW (Moraes *et al.* 2020). During the cropping season, and within cropped fields, Baudron *et al.* (2019) also confirmed that frequent weeding reduced FAW in agroecosystems where gramineous weed flora dominated. In addition to reducing habitat for FAW, frequent manual or mechanical weeding (including earthing-up prior to in-season irrigation) may also have some effect on reducing the survival of pupae in the soil, while also reducing crop–weed competition and improving yield. This hypothesis needs to be further tested, especially in the Asian context.

Sedges or broadleaved weeds between maize rows may reduce the ability of first-instar FAW larvae to balloon and move between plants, while also supporting populations of natural enemies (van Huis 1981). Non-grassy weeds may assist in controlling FAW, although extension services advising farmers to use these tactics must be very clear to avoid significant levels of weed growth that may compete with the crop. Despite these questions, no studies considering interactions between FAW and weeds have yet been conducted in Asia. Combined with the wider availability of chemical herbicides in Asia relative to Africa's more input constrained farming systems, information on the potential effects of weeds as ecological components of maize systems subjected to FAW pressure are currently inferred from studies outside the continent. Systematic research is, therefore, needed to address this gap and provide integrated weed and arthropod pest management advice that conserves natural enemies while also reducing FAW survivability.

4.3. Field Edges and Farm Margins

Farm sizes in Asia tend to be relatively small (less than 2 hectares). Fields are often separated by walking paths or bunds that separate fields. The integration of trees into farming systems and homesteads is also relatively common. Agroecological management systems work to leverage these structures and their function in agroecosystems to benefit of farmers.

For example, bunds and field margins can be planted to species that provide habitat and food sources for natural enemies that can enter fields and control pests, potentially including FAW (Harrison *et al.* 2019). Parasitoids that rely on nectar for survival can be encouraged by cultivating flowering plants in these areas. Where farmers cannot afford to plant new species, they may manage field margins and bunds through the selective removal of species that compete with nectar-producing plants, thereby encouraging their growth (Bàrberi *et al.* 2010). Live fences, windbreaks, and hedgerows between fields can also provide habitat to beneficial insects that can disperse into fields and control pests (Aluja *et al.* 2014), in addition to potentially limiting the ability of ballooning FAW larvae to transit between fields (Harrison *et al.* 2019).

Theoretically, these agroforestry structures can also provide connectivity within farm landscapes, allowing populations of natural enemies to build and disperse across these habitats and then move into farmers' fields. Agroforestry structures can also encourage birds and bats that can predate pests in cultivated fields (Maas *et al.* 2016), though Tscharntke *et al.* (2016) pointed out that birds and bats also consume and do not discriminate between pests and natural enemies. Bats are, however, well-known to provide ecological services in the form of adult FAW moth control during flight (Maine and Boyles 2015; Boyles *et al.* 2011); as such, bats play an important role in overall population regulation of FAW and may be encouraged as a line of defense against invasion. Most studies have focused on how agroforestry can increase populations of natural enemies, although studies linking agroforestry, natural enemy populations, FAW, and crop yields are lacking in Africa (Harrison *et al.* 2019), and also in Asia.

4.4. Agroecological Management at the Landscape Level

Beyond fields and field margins, agroecological approaches also consider management at the landscape level. Theoretically, more complex and diverse agricultural landscapes offer more habitat for arthropod and vertebrate natural enemies that can move within and between fields to facilitate pest control, while also maintaining natural enemy populations over time (Harrison *et al.* 2019). Forest patches may be similarly important in maintaining populations and pest control services (Maas *et al.* 2016; Boyles *et al.* 2011). Young forests located in proximity to maize fields with a diversity of successional plant species that provide habitat to natural enemies have been linked to moderate FAW control (Wyckhuys and O'Neil 2009). On the other hand, Harrison *et al.* (2019) noted that evidence for the effects of landscape diversity on FAW control in the Americas is inconsistent, and that no research on this topic has been conducted in Africa. Similarly, studies on the interactions of FAW with landscape diversity and complexity in Asia are lacking, though the complexity of landscapes in Asia and Africa make this a compelling area of study (Figure 6).

Figure 6. Satellite images of 2.25-km^2 areas demonstrating the diversity in agricultural landscapes in (A) United States, (B) rural Zimbabwe, and (C) Nepal. Note the increasing complexity in Zimbabwe and Nepal relative to the United States, and the corridors and patches of forest visible in the Nepal landscape.

From a practical standpoint, there is some likelihood that farmers in Asia—at least in more complex landscapes with smaller fields and patches of forest and agroforestry systems—are benefitting in some way from the ecological service of pest control, in addition to the other products and services produced by diverse vegetation in the landscape. Maize in South East Asia's mountainous areas is often grown in fields cleared during slash-and-burn agriculture (Mertz *et al.* 2009), though the maintenance of forest patches near cleared fields can increase the prevalence of natural enemies in ways that benefit farmers (Boyles *et al.* 2011). Communities and policymakers should therefore be apprised of the potential benefits of landscape diversity and the maintenance of forests and may be encouraged to maintain them, though the practicality of such advice from the standpoint of agricultural extension services may be limited. These changes require higher-level policy action, and the time and resources to affect change at the political as well as at the community level.

5. Conclusions: What We Know and What We Still Need to Know for Effective Extension

Agroecological management of pests, including FAW, aims at enhancing the diversity of species in agricultural systems that interact and function to enhance productivity, resilience, and stability through the flow of ecosystem services. In other words, agroecological management of pests like FAW should focus on building and maintaining habitat for natural enemies like arthropod predators, parasitoids, and even vertebrate predators. Many of the agroecological management practices described in this chapter are easily compatible with agronomic best practices that can aid in pest management. From the standpoint of managing FAW as a newly invasive species in the context of Asia's farming systems, it is useful to reflect on and conclude which practices may or may not be most applicable for farmers in Asia. The points below summarize the key agroecological principles and highlight their applicability as a part of a 'basket' of options for sustainable FAW management.

- **Encourage ecological awareness and understanding:** Agroecology is knowledge intensive and requires efforts to raise awareness and understanding of the principles described in Section 3 of this chapter. Extension agents and farmers should be encouraged to learn about agroecology and the interactions between species in agricultural systems in the context of hands-on learning within the field. Learning should also focus on a solid understanding of FAW and the numerous abiotic and biotic interactions that this pest species has with its environment at each phase of the life cycle. This will help equip farmers and pest managers with more sophisticated information to make increasingly comprehensive and relevant intervention decisions.
- **Crop-pest interactions:** Although crops can be bred in ways that improve their capacity to tolerate/resist insect-pests like FAW, studies supporting the use of particular maize varieties as being more tolerant to FAW have not yet been conducted in Asia. As such, advising farmers to use particular varieties against FAW in Asia is premature at this time. Moreover, efforts on host plant resistance need to be intensified in Asia, similar to what is being done in Africa by organizations like CIMMYT (see **Chapter 4**).

- **Land preparation and crop establishment:** Available scientific evidence points to positive FAW suppression when farmers practice zero-tillage and maintain mulches on the soil surface. The reasons for these outcomes are complex, but are likely related to the provision of habitat for natural enemies that aid in reducing the impact of FAW. While some countries and organizations are advising tillage to control pupal build-up in the soil, this approach is likely to be only effective in the context of area-wide efforts to manage FAW because FAW migrates to new areas after emergence. The recycling or addition of organic matter to the soil also improves soil quality, though it may take time for farmers to experience significant yield benefits when transitioning into zero-tillage systems. Where residues are not widely used as fuel or feed, they can be relatively easily left in fields to aid in maintaining natural enemies and ground-dwelling predators.
- **Timely planting:** Although there is no documented evidence at this time that early planting in Asia can assist in reducing FAW attack, the principle of timely planting makes sound ecological sense and is likely to be advantageous to farmers. This approach suggests that when farmers establish their maize crops in a timely manner, they can potentially escape from the risk of pest attack as temperatures and pest populations build up in both the monsoon and winter seasons. In rainfed areas, farmers can benefit from sub-seasonal and seasonal rainfall forecasting to help them prepare for planting immediately after the first sufficient rain event. In areas where farmers can access ground or surface water, they may consider using a starter irrigation, if possible, to advance establishment of the crop. In cropping systems where monsoon-season rice is rotated with winter maize and soils can be drained, farmers can consider using higher-yielding but short-duration rice varieties as well as mechanized maize establishment to advance cropping.
- **Soil and nutrient management:** Poor soil fertility and unbalanced application of fertilizers, including both under- and over-application of nitrogen without sufficient attention to soil organic matter management can lead to increased pest damage. There is considerable scientific evidence for the benefits of balanced fertilization on pest and FAW control. Extension services should focus on the resources and knowledge to provide adequate and balanced plant nutrition for healthy crop development, which in turn can aid in pest management. In addition, farmers can and should be generally advised to retain residues as mulch and/or to apply organic matter to the soil. This can enhance habitat for natural enemies that can aid in FAW control.
- **Intercropping:** Maize is commonly grown in association with other crops in Asia. Evidence from Africa and the Americas indicates that intercropping with cowpea, pigeon pea, and soybean can reduce oviposition of FAW on maize, while also increasing habitat for natural enemies. Intercropping can also reduce FAW ballooning dispersal from plant to plant, though intercrops should be carefully designed to avoid contiguous canopy cover that might enable larvae that have fallen off maize plants to move to another maize plant without landing on the soil and thus risking mortality..
- **Encourage refugia:** In relatively non-complex agricultural landscapes in which maize is grown, for example in the Mekong or Ayeyarwady Deltas, or in the western IGP, refugia can assist in maintenance of natural enemies. In Asian countries where *Bt* maize is now being grown to control FAW, such as in the Philippines and Vietnam, the use of refugia has to be rigorously practiced to delay the evolution of FAW and other lepidopteran pest populations developing resistance to *Bt*. Refugia can also be useful in landscapes where *Bt* crops are not used, but where insecticide pressure is high, to slow resistance and help manage pest resurgence.
- **Increase biological diversity at field edges and farm margins:** Bunds and field margins can be planted to species that provide habitat and food sources for natural enemies that can enter fields and control pests, potentially including FAW. Agroforestry structures such as live fences, windbreaks, and hedgerows between fields can also provide connectivity and habitat natural enemies that can disperse into fields and control pests.
- **Encourage biologically diverse and habitat-rich landscapes:** Theoretically, more complex and diverse agricultural landscapes can offer more habitat for arthropod and vertebrate natural enemies. These organisms can move within and between fields to facilitate pest control, while also maintaining natural enemy populations over time. Similarly, agricultural fields located near forests may potentially benefit from the ecosystem service of pest control by predators or parasitoids that disperse from within forests and search for prey or egg-laying sites. Agricultural communities and policymakers should therefore be apprised of the potential benefits of landscape diversity and the maintenance of forests and may be encouraged to maintain them.

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