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Review

# Agro-ecological options for fall armyworm (*Spodoptera frugiperda* JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest

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ABSTRACT

Fall armyworm (FAW), a voracious agricultural pest native to North and South America, was first detected on the African continent in 2016 and has subsequently spread throughout the continent and across Asia. It has been predicted that FAW could cause up to $US13 billion per annum in crop losses throughout sub-Saharan Africa, thereby threatening the livelihoods of millions of poor farmers. In their haste to respond to FAW governments may promote indiscriminate use of chemical pesticides which, aside from human health and environmental risks, could undermine smallholder pest management strategies that depend to a large degree on natural enemies. Agro-ecological approaches offer culturally appropriate low-cost pest control strategies that can be readily integrated into existing efforts to improve smallholder incomes and resilience through sustainable intensification. Such approaches should therefore be promoted as a core component of integrated pest management (IPM) programmes for FAW in combination with crop breeding for pest resistance, classical biological control and selective use of safe pesticides. Nonetheless, the suitability of agro-ecological measures for reducing FAW densities and impact need to be carefully assessed across varied environmental and socio-economic conditions before they can be proposed for wide-scale implementation. To support this process, we review evidence for the efficacy of potential agro-ecological measures for controlling FAW and other pests, consider the associated risks, and draw attention to critical knowledge gaps. The evidence indicates that several measures can be adopted immediately. These include (i) sustainable soil fertility management, especially measures that maintain or restore soil organic carbon; (ii) intercropping with appropriately selected companion plants; and (iii) diversifying the farm environment through management of (semi)natural habitats at multiple spatial scales. Nevertheless, we recommend embedding trials into upscaling programmes so that the costs and benefits of these interventions may be determined across the diverse biophysical and socio-economic contexts that are found in the invaded range.

## 1. Introduction

In 2016, the fall armyworm (FAW; *Spodoptera frugiperda* J E Smith, Lepidoptera: Noctuidae), a voracious agricultural pest native to North and South America, was first detected on the African continent (Goergen et al., 2016). It spread quickly from West Africa across the continent, causing extensive damage to crops (Abrahams et al., 2017) and has subsequently spread across Asia (Kalleshwaraswamy et al., 2018). In its native range, FAW is known to feed on over 350 plant species (Montezano et al., 2018) but considering just maize, rice,

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sorghum and sugarcane it has been calculated that FAW could cause up to $US13 billion per annum in crop losses across sub-Saharan Africa (SSA) (Abrahams et al., 2017). Moreover, due to the high consumption of these cereal crops, particularly maize, in smallholder diets, FAW could have a substantial negative impact on food security. In short, FAW threatens to undermine progress on sustainable development goals for millions of poor farmers.

In the Americas, FAW is a sporadic and long-distance migratory pest, with the adult moths capable of flying over 100 km in a single night (Johnson, 1987). It does not have a diapause phase and hence is only capable of overwintering in warmer climates. The female deposits egg masses of a few hundred eggs, usually on the underside of the leaves, and first instar larvae show phototaxis, moving towards the top of the plant, and disperse by ballooning on silk threads (van Huis, 1981). Later instars do not move between host plants and are cannibalistic (Chapman, 1999). In maize, FAW larvae feed on young leaf whorls, ears and tassels, although late instar larvae can cut through the base of maize seedlings killing the whole plant. FAW has two genetic strains, both of which have been detected in Africa (Goergen et al., 2016); the “rice strain” which prefers rice and other grasses and the “maize strain”, which feeds predominantly on maize and to a lesser extent on sorghum (Sparks, 1979). In the invaded range, FAW is projected to constitute a lasting threat to several important crops, as the region provides diverse host plant sources and favourable climatic conditions for constant reproduction in many areas (Goergen et al., 2016; Midega et al., 2018; Montezano et al., 2018).

Management of FAW will require a multi-pronged approach that augments existing smallholder pest management strategies. Fortunately, there are many potential low-cost control options that build on local knowledge and ecological principles. Importantly, these are often more relevant to smallholders who lack financial resources to purchase chemical pesticides or expensive seed (Abate et al., 2000; Altieri and Trujillo, 1987; Grzywacz et al., 2014; Orr and Ritchie, 2004; van Huis and Meerman, 1997; Wyckhuys and O'Neil, 2010). Agro-ecological approaches are compatible with plant breeding and biological control options, and may also be compatible with judicious use of safe chemical pesticides. However, most of the chemical pesticides commonly used are broad spectrum and thus kill natural enemies. Hence their use is likely to undermine agro-ecological approaches (Meagher et al., 2016; Perfecto, 1990; van Huis, 1981; Witmer et al., 2003). In fact, natural enemies are often more severely impacted than the pest (Halley et al., 1996) and indiscriminate spraying can lead to perverse effects, if reductions in natural enemy populations allow the pest to escape its natural control agents (Hardin et al., 1995; Lewis et al., 1997; Ruberson et al., 1994; Tscharntke et al., 2016). In addition, the largely uncontrolled and improper use of chemical pesticides in Africa and elsewhere, including many products and formulations that are banned in the developed world, is a serious concern for human health and the environment (Lewis et al., 2016).

Deployment of FAW control options requires an understanding of current smallholder pest management strategies and the way these are constrained by farm management and livelihood factors (Altieri and Trujillo, 1987; Kebede, 2014; van Huis and Meerman, 1997; Wyckhuys and O'Neil, 2010). Smallholder farmers in Africa and Asia already contend with a variety of crop pests, including several native armyworm species (Kfir et al., 2002; Rose et al., 2000). Prior to the arrival of FAW, it was estimated that insect pests, attacking crops at various stages pre- and post-harvest, reduced yields by approximately 30% across Africa, although particular outbreaks not infrequently result in complete crop failure (Grzywacz et al., 2014). Hence, FAW control strategies will need to be integrated into a broader pest management perspective, with a focus on interventions that can generate pest control benefits across a wide array of pests and that are suited to a diversity of crops and cropping systems. Knowledge of current smallholder pest management strategies can also inform the design of interventions to improve adoption (Abate et al., 2000; Altieri and Trujillo, 1987; Wyckhuys and O'Neil, 2007).

Here, we review current knowledge of the effects of agro-ecological approaches on population densities of FAW and its natural enemies, as well as on the impact of FAW on crop yield. Based on the findings, we identify agro-ecological management options for FAW that are effective and suited to smallholder farming systems. These measures can be immediately piloted and upscaled. Nonetheless, because of the diverse biophysical and socio-economic contexts occurring in the invaded range, we strongly recommend embedding trials in upscaling programmes to gain an understanding of how the performance of different options varies geographically. Furthermore, we suggest that such trials adopt a farm systems approach so that potential trade-offs may be explicitly examined. We also identify promising novel interventions and make recommendations for research to refine and develop these. We believe this information should be useful to both researchers and national and international agencies concerned with FAW management and enable them to consider how they might pilot approaches through their existing rural development programmes. Details of our methods including search terms are provided in the online Supplementary Materials (Appendix S1).

## 2. Overview of agro-ecological approaches to pest management

Since the dawn of agriculture, farmers have exploited the pest-control services of organisms living in and around their fields (Fig. 1; Huang and Yang, 1987). Agro-ecological approaches to pest management are based on three complementary strategies (Fig. 1): (i) sustainable soil fertility management, which improves crop health and pest resistance (Fig. 1(1–3); Altieri and Nicholls, 2003); (ii) promoting biodiversity at a range of spatial scales from the field up to the landscape and thereby providing living space for natural enemies (Fig. 1(3–6), 1 (8–12); Altieri and Letourneau, 1982; Bàrberi et al., 2010; Landis et al., 2000; Murrell, 2017; Nicholls and Altieri, 2004); and (iii) specific management activities designed to prevent outbreaks or reduce their impact. Many interventions are already aligned with other concepts of sustainable land management, such as climate smart agriculture. For example, measures can include crop rotations, intercropping and mulching of crop residues at the field scale; allowing diverse crop margins and in-field diversity to develop (Tschumi et al., 2016), planting shrubs and trees, and allowing some areas to regenerate naturally (Pumariño et al., 2015) at the farm scale; and increasing the amount and diversity of forest cover and the area under different agricultural crops at the landscape scale (Gurr et al., 2003; Landis et al., 2000; Murrell, 2017; Veres et al., 2013). Diversity is an essential element, because different natural enemies may be more effective at controlling different pests, or pests at different developmental stages or in different seasons. Research has demonstrated that the importance of diversity in the delivery of ecosystem services, including pest control, increases as environmental heterogeneity through space and time increases (Tylianakis et al., 2008), and strongly seasonal climates with high inter-annual rainfall variation create highly heterogeneous conditions for farmers over much of the range invaded by FAW.

Nevertheless, management of biodiversity across scales can also be tailored to enhance the pest control function (Fig. 1). Within the field, specific inter-crops can be used to reduce pest infestation (i) by reducing the movement of larvae between crop plants (Päts et al., 1997), (ii) by reducing oviposition on crop plants (Ampong-Nyarko et al., 1994), mainly through the emission of volatiles that directly repel egg-laying females or provide olfactory camouflage (Khan et al., 2010; Pichersky and Gershenzon, 2002), and (iii) by harbouring natural enemies and increasing their activity (Landis et al., 2000; Midega et al., 2006). Many natural enemies respond to plant volatiles that are released when the plant is damaged by a herbivore (Hoballah et al., 2002; Hoballah and Turlings, 2001), but these signals are often much reduced in strength in modern crop varieties (de Lange et al., 2016; Hoballah et al., 2002). However, some natural enemies may respond to semiochemicals

**Fig. 1. Agro-ecological approaches to pest management:** (1) ***Minimum soil disturbance*** enhances biological properties of soil, thereby improving soil fertility management and plant nutrition; (2) ***Mulching of crop residues*** protects the soil surface and adds carbon to improve soil fertility management, and in addition provides habitat for insect predators especially spiders, earwigs, beetles and ants; (3) ***Planting leguminous inter-crops*** or cover crops improves soil fertility management through nitrogen fixation, diversifies the field environment for beneficial insects, including insect predators and parasitoids, and through the production of olfactory cues can deter pests from laying eggs (also in the case of FAW, intercrops may trap the ballooning first instar larvae thereby increasing mortality); (4) ***Shrubs/trees*** with flowers or extra flora nectaries support populations of ants and small wasps; (5) ***Boundary trees*** (e.g. fodder trees, fuelwood trees, shelter trees) provide perches and roosts for birds and bats and increase the structural diversity of the farm habitat through shade and shelter; (6) ***Crop rotation*** – improves soil fertility management and diversifies the farm environment; (7) ***Regular scouting*** by the farmer to identify pests and assess damage enables informed pest management decisions; (8) ***Weeds*** allowed to grow between the maize rows and along field margin can provide habitat for insect predators and encourage parasitoids and predatory wasps through provision of nectar (however, weeds can also compete with the crop and sometimes provide alternative hosts for pests, hence detailed understanding of their effects is required); (9) ***Diverse field margins*** provide habitat for generalist predators, such as spiders, beetles, earwigs and ants; (10) ***Insectivorous birds and bats*** provide an important role in reducing pest abundance in diverse agro-ecological systems; (11) ***Nest site provision*** for predatory wasps or ants could be used to enhance the local abundance of insect predators; (12) ***Predatory wasp*** – these wasps hunt pest caterpillars to provision their larvae. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

released by strategically selected companion plants (Khan et al., 2008). Where their growth does not impede the crop, weeds can provide a pest control function through providing habitat for natural enemies (Penagos et al., 2003). Selective removal of some plants and planting of others can improve the benefits rendered by field margins (Bàrberi et al., 2010; Norris and Kogan, 2005). For example, plants with simple open flowers, such as many Apiaceae, can provide nectar for parasitoids and social wasps. Trees can provide alternative prey and nest sites for generalist natural enemies, such as ants (Aluja et al., 2014). Ants may be an underappreciated pest control agent in tropical agricultural systems, as they are important insect predators in natural ecosystems, but their role in pest control has not been well investigated (Fuller et al., 1997; Morris et al., 2015; Offenberg, 2015; Philpott and Armbrecht, 2006; Way and Khoo, 1992). Social wasps are also important predators of lepidopteran larvae and their service to agriculture has probably been underestimated (Held et al., 2008; Symondson et al., 2002). Diversity can also be managed at larger scales to enhance the pest control function (Gurr et al., 2003; Landis et al., 2000; Murrell, 2017; Veres et al., 2013). Judiciously placed linear features, such as live fences or wind breaks, can increase connectivity for beneficial species and create barriers to the movement of crop pests. However, landscape features can also affect the outcome of interactions among natural enemies (Tscharntke et al., 2016). For example, insectivorous birds feed on both crop pests and their insect natural enemies and the direction of the effect on pest control can depend on the amount of tree cover (Gras et al., 2016; Martin et al., 2013). Management for pest control can even be extended to the provision of nest sites (e.g. insect hotels) for natural enemies (Fig. 1(11); Huang and Yang, 1987).

An agro-ecological approach to pest control involves the integration of complementary interventions, across a range of spatial scales, into the farming system. Most measures are multi-functional, such as those contributing to improved soil health or diversification of farm produce. Hence, the approach exploits natural synergies within smallholder farming systems. Moreover, specific measures usually provide pest control benefits for a variety of pest species. Redundancies in the approach also provide farmers with choices, so they can opt to incorporate measures according to the specific constraints they face. Providing farmers with baskets of options will be essential for upscaling agro-ecological approaches for pest management in SSA (Coe et al., 2014). However, it will also be important to identify potential negative effects of interventions, such as increases in the burden of labour on women and young children. Last, it is critical to consider the role of agro-dealers, who could have an important role in supplying inputs, such as seeds or seedlings for inter-crops and field margin plants, but who through the existing market chains may be more inclined to promote indiscriminate use of often dangerous, broad-spectrum chemical pesticides.

## 3. Agro-ecological control of FAW

### 3.1. Background

Reports from FAW's native range support general agro-ecological principles of pest management through enhancing the role of natural enemies (Altieri, 1980; Altieri et al., 1978; Ashley, 1979; Clark, 1993; Fuller et al., 1997; Hay-Roe et al., 2016; Hoballah et al., 2004; Lewis and Nordlund, 1980; Meagher et al., 2016; Perfecto, 1991, 1990; Perfecto and Sediles, 1991; van Huis, 1981; Wheeler et al., 1989; Wyckhuys and O'Neil, 2010, 2006). A noteworthy observation is that farmers in Honduras and Guatemala, who were managing diverse smallholdings within complex landscapes including forest patches, did not regard FAW as a serious pest (Morales et al., 2001; Wyckhuys and O'Neil, 2010). FAW caused minimal damage in these fields and never sufficient to warrant the use of pesticides (Wyckhuys and O'Neil, 2007). Whereas in bio-climatically similar areas where farmers cultivate maize in large-scale monocultures, FAW is a serious pest (Blanco et al., 2014). van Huis (1981) also noted that where maize in Nicaragua was grown alongside cotton that was heavily sprayed with pesticides, FAW was a much more prominent pest than in other areas that were typically not sprayed.

FAW is prey to a diversity of natural enemies. It is attacked by over 150 parasitoid and parasite species from 14 families, including families within the Hymenoptera, Diptera and Nematoda (Ashley, 1979; Molina-Ochoa et al., 2003) and by diverse taxa of insect predators (Braman et al., 2002; Fuller et al., 1997; Perfecto, 1991; van Huis, 1981; Wyckhuys and O'Neil, 2006). Evidence also suggests that parasitoids do not show any preference for the rice or maize FAW strains (Hay-Roe et al., 2016). Hence, there is reasonable hope that effective control can be achieved with native natural enemies in the invaded range. Already, five parasitoids belonging to two orders and three families (including four larval parasitoids and one egg parasitoid), have been recovered from FAW in East Africa (Sisay et al., 2018). Combined rates of parasitism ranged from 50% in Jimma, Ethiopia to 4% at Pwani, Tanzania. Moreover, generalist predators, including ants and social wasps, which play important roles in lowering populations of lepidopteran pests of cereal crops in Africa (Midega et al., 2006), have been observed attacking FAW larvae SSAunpublished observations).– > .

### 3.2. Field management

#### 3.2.1. Fertiliser application

Healthy plants and vigorous plant growth are important plant physiological attributes for withstanding pests and diseases. However, inappropriate use of inorganic fertilisers can result in increased pest damage (Altieri and Nicholls, 2003). For example, Kaqchikel farmers in Guatemala complained that since the introduction of inorganic fertilisers herbivorous pests, including FAW, had become a problem in their traditionally managed maize fields (Morales et al., 2001). Meanwhile, experiments in Guatemala showed that crops fertilized with inorganic fertilizers had a higher abundance of aphids than organically fertilized crops (Morales et al., 2001). Fertilisation with inorganic fertilisers can result in a spike in nitrogen uptake and the production of foliar nitrogen, which is attractive to insect herbivores (Altieri and Nicholls, 2003; Morales et al., 2001). In their review of the topic, Altieri and Nicholls (2003) found that crops in soils with high organic matter and active soil biology exhibit lower abundance of insect herbivores than those in degraded soils with low organic carbon content. Nonetheless, application of inorganic fertilisers can result in improved yields, despite higher pest pressure, as a consequence of improved plant growth. A substantial yield gap exists across the vast majority of smallholder farms, as a consequence of inadequate plant nutrition (Vanlauwe et al., 2014). Hence, we recommend sustainable soil fertility management approaches, which aim to improved soil nutrient status and increase soil organic carbon. Measures include the use of nitrogen fixing cover crops, crop rotation, inter-cropping – including the use of fertiliser trees – and addition of composted livestock manure, alongside the application of inorganic fertilisers.

Sustainable soil fertility management is also compatible with efforts to increase the role of agricultural soils in climate change mitigation, which is a significant component of most nationally determined contributions (NDCs) under the Paris Agreement. There have been numerous reviews of development programmes aimed at improving smallholder soil fertility management (e.g. Thierfelder et al., 2015). Overall, these studies find that, despite the obvious benefits, uptake among farmers is low, which can be attributed in part to the time it takes for soils to accumulate carbon and for the benefits to be realised (Vanlauwe et al., 2014). Higher risks, especially in the first year or two, for example, from increased weed pressure and increased management complexity, also serve as barriers to adoption. However, linking pest control benefits to sustainable soil fertility management may help overcome impediments to adoption.

#### 3.2.2. Effects of minimum soil disturbance and crop residue retention (Fig. 1-1-2)

In the Dominican Republic, Del Rosario (1981; reported in Kumar and Mihm, 2002) found that FAW infestations were reduced by 30–60% in no-till maize as compared to conventional controls, and similar results are reported from Costa Rica (reviewed in Andrews, 1988). In Florida, Clark (1993) found that carabid beetles, rove beetles, spiders and ants were important predators of FAW in reduced-tillage maize fields. Moreover, he showed that fields with the highest level of mulch coverage and lowest tillage intensity had the highest densities of predators. All (1988) found there was no difference in pest damage between plough-based and no-tillage-based systems, except when residues were present. And, Roberts and All (1993) found that FAW infestation in maize was reduced at the seedling stage in no-till systems with residue retention, but the difference declined as the maize continued to grow. In a wheat-maize rotation conservation agriculture system in central Mexico, Rivers et al. (2016) found significantly higher spider activity in no-till maize and with residue retention in wheat. Higher levels of soil cover increased predation of FAW before and after planting in maize and before planting in wheat. FAW damage was also significantly reduced in no-till maize (Rivers et al., 2016; FAW damage was not investigated in wheat). In a series of experiments focusing on the performance of different maize hybrids in Mexico, Kumar (2002) and Kumar and Mihm (2002) found that zero-tillage consistently resulted in lower FAW damage and increased yields by around 10%, as compared to plough-based tillage systems. Addition of mulch in the no-till systems resulted in variable results for FAW damage and had no significant effect on yield (Kumar and Mihm, 2002). Initial results from Zimbabwe suggest that minimum tillage systems also lower FAW infestation rates in SSA (Baudron et al., 2019).

FAW is a highly fecund, migratory pest with overlapping generations that does not have an extended life-cycle phase in the soil (it does not diapause and pupation is just a few days). Therefore, tillage, which is usually a once-off intervention practised at the onset of the season, is unlikely to effectively control this pest. Tillage has not been found to be an effective control measure for FAW in the Americas. In contrast, the evidence presented in the previous paragraph that minimum tillage systems, especially when associated with surface mulch, reduce FAW damage and increase yields.

Physical structures on top of the soil create a favourable microclimate, reducing temperatures and increasing humidity, and provide shelter and hunting space for arthropod predators. Spiders, in particular, appear to respond positively to increased ground cover (Reichert and Bishop, 1990; Rivers et al., 2016). Mulch may also act as a barrier to FAW larvae when burrowing into the soil to pupate and increase predation during this stage. Perfecto (1990, 1991) reported that ants killed 92% of FAW pupae in smallholders fields in Nicaragua. However, mulch can sometimes promote pests or diseases, although this can usually be avoided if non-crop biomass is used (Boosalis and Doupnik, 1976). For example, in a small study in NE Mexico, Rodríguez-del-Bosque and Salinas-García (2008) found no tillage with maize residue retention increased incidence of fungi (*Fusarium* spp. and *Aspergillus flavus*) that cause mycotoxin contamination in maize. Mulch can also increase maize stem rot in more humid sites, while in drier sites it may increase termite attack. Hence, residue mulching interventions should be tailored to local conditions and where possible use non-crop biomass in rotation systems to avoid pest and disease carry-over.

As a pest control measure, minimum soil disturbance and mulching of residues can be easily integrated with existing efforts to promote sustainable intensification and climate change adaptation through conservation agriculture (Thierfelder et al., 2016, 2015). However, in many smallholder farming systems crop residues are fed to livestock, which can be an impediment to adoption of mulching (Baudron et al., 2014; Valbuena et al., 2012). Use of fodder trees or other alternative livestock feeds, combined with composting of animal manure, can be integrated with low tillage and mulching as a holistic suite of measures for soil fertility management with anticipated benefits for FAW control.

#### 3.2.3. Effects of inter-cropping (Figs. 1–3)

Inter-crops can reduce pest damage by (i) improving soil health and

promoting vigorous plant growth, especially in the case of N-fixing intercrops or those that serve to ameliorate the field microclimate (Sida et al., 2018b), (ii) inhibiting movement of larvae among plants (van Huis, 1981), (iii) preventing female moths from laying eggs, through visual or chemical disruption (Khan et al., 2010), and (iv) providing habitat for natural enemies (Midega et al., 2006). In experiments conducted by Altieri et al. (1978) in Columbia, FAW infestation rates as cutworm were 14% lower and as a whorl feeder 23% lower in maize-bean inter-crops as compared to monoculture maize. Altieri (1980) also found that early planting of beans, up to one month before maize, substantially reduced FAW infestation. In Nicaragua, inter-cropping with beans reduced FAW infestations by 20–30% and significantly reduced damage to whorls (van Huis, 1981). This was due to reduced larval dispersal, because the inter-crop trapped the ballooning 1st instar larvae. This mechanism may also explain why early planting of the inter-crop increased its effect in the study by Altieri (1980). In addition, van Huis (1981) found that maize polycultures supported higher densities of natural enemies, including earwigs and spiders, that fed on early larval instars. Meanwhile, inter-cropping reduced parasitism of FAW by braconids but increased parasitism by tachinids (van Huis, 1981). Also in Nicaragua, ants were found to be more common in maize-bean inter-crop fields than in maize monocrops (Perfecto and Sediles, 1991).

A system developed for controlling stemborer and *Striga hermonthica* (Del.) Benth. (a parasitic weed), known as climate adapted push-pull, was also found to be effective against FAW on maize in East Africa (Midega et al., 2018). In push-pull systems, farmers inter-crop cereals with plants that exude pest repellent volatiles, such as *Desmodium* spp., ("push") and plant pest attractive grass species, such as *Pennisetum purpureum* Schumach, as a border around the field ("pull"). Pest survival on the pull plant may be low (Khan et al., 2007; Midega et al., 2011) or it can be used for focused pesticide application. On average the climate adapted push-pull system, which uses the drought tolerant companion plant, *Desmodium intortum* (Mill.), as the push and *Brachiaria* cv Mulato II as the pull, reduced FAW infestation by 86% and increased maize grain yields 2.7-fold in drought prone areas of East Africa (Midega et al., 2018). FAW belongs to the same family as *Busseola fusca* Fuller, one of the lepidopteran stemborer species effectively controlled by the push-pull system (Midega et al., 2014). Therefore, although the causal factors behind the pest control effect and increased yields were not investigated, it is likely to include the activity of semiochemicals emitted by the companion plants, improved soil health (*Desmodium* spp. being some of the most efficient nitrogen fixing legumes (Whitney, 1966)), and activities of natural enemies. The companion plants provide valuable fodder thus facilitating crop-livestock integration. The effectiveness of this system against FAW implies an urgent need to optimize it for broader application. Early results from Uganda suggest that other leguminous intercrops are effective in reducing FAW infestations, but exhibit lower control over *Striga* than *Desmodium* (Hailu et al., 2018). There is also a need to fully elucidate the mechanisms of FAW control for sustainability and for extension to other pests and cropping systems in the region. Needless to say, push-pull systems can be integrated with other measures to control pests, including soil fertility management and habitat diversification at field and farm scales (Kebede, 2014; Midega et al., 2018).

Whether as cover crops, green manures, multi-cropping systems, part of a push-pull system or fertiliser trees, inter-crops can play an important role in controlling pests, including FAW.

#### 3.2.4. Effects of weeds and weed management (Figs. 1–8)

Altieri (1980) found that when weeds were also permitted to grow in his maize-bean intercrop plots in Columbia, there was an eight-fold reduction in FAW infestation relative to the maize monoculture. Similarly, in Florida, FAW infestation was approximately 50% lower in plots with weeds, as compared to those without (Altieri, 1980). In Honduras, Portillo et al. (1991) found that FAW infestation was higher in fields treated with herbicide than in weedy fields under normal smallholder management. In a comparison between clean and weedy maize plots in Chiapas, Mexico, Penagos et al. (2003) found that FAW infestation was over 2.5 times higher in the clean plots at 20 days post-planting. However, the numbers of FAW larvae declined markedly thereafter and were not significantly different among treatments. Arthropods (mostly predatory Carabid beetles) were over twice as abundant in weedy plots, as compared to clean plots, but the numbers of parasitoids were similar (Penagos et al., 2003). van Huis (1981) investigated the effect of weeds on FAW infestation in maize in Nicaragua. He found that weeds increased oviposition by FAW and that when weeds were abundant throughout the plot FAW larvae were common on both maize and weed plants. However, van Huis (1981) also found that when weeds were cleared in a strip either side of the maize row there were almost no FAW larvae on the maize. As FAW oviposited almost exclusively on the maize, van Huis (1981) suggested the main effect of weeds was to trap the ballooning 1st instar larvae. van Huis (1981) also recorded significantly higher densities of insect predators and parasitoids in weedy plots. Hence, van Huis (1981) suggested weed management could be an important tool for FAW management in smallholder fields.

In conclusion, several reports indicate that the presence of weeds increases the abundance of natural enemies in maize plots and often reduces FAW infestation. However, if weeds become overly abundant they will compete with the crop and reduce yields. Thus, we suggest that farmers need to manage weeds, but that they could consider leaving some weeds in a strip between the maize rows for pest control benefits. The topic would benefit from further research to better understand which types of weed more effectively reduce FAW infestation and how best to manage them.

### 3.3. Habitat diversification at farm scale (Figs. 1-4,1-5,1-6,1-9)

#### 3.3.1. Diversity of habitats

Countless studies have shown that habitat diversification at farm scales results in an increased abundance of natural enemies and their improved effectiveness in controlling insect pests (Andow, 1991; Wyckhuys and O'Neil, 2006). In two smallholder managed agro-ecosystems in Honduras, Wheeler et al. (1989) recorded high levels of parasitism (43%) of FAW. Also in Honduras, Wyckhuys and O'Neil (2010) reported that higher abundance of natural enemies was associated with early successional environments with high floral diversity surrounding fields. Fields supported diverse assemblages of parasitoids and predators and FAW infestation rates remained below economic threshold levels (Wyckhuys and O'Neil, 2006). In a survey across four states in Molina-Ochoa et al. (2004, 2001) found that parasitoid diversity and FAW parasitism rates were highest in areas with the highest diversity of habitats near maize fields. Using sentinel larvae placed in maize fields in Florida, Hay-Roe et al. (2016) found that different parasitoid species preferred the field edge and the centre, but overall FAW parasitism rates were similar in both habitats. They also found parasitoid species abundances varied seasonally. Recoveries of sentinel larvae from pastures were very low, which the authors attributed to the large numbers of predators, especially ants, social wasps and spiders (Hay-Roe et al., 2016). In sweet corn fields in Florida FAW parasitism rates varied from 1% to 92% (Meagher et al., 2016). Mean FAW parasitism rates were far higher in areas without pesticide spraying (44 ± 9.6%) than in sprayed areas (15 ± 2.5%), and the highest rate was recorded from an unsprayed site with the highest plant diversity around the field while, conversely, the lowest rate was recorded from a sprayed site with very low plant diversity in habitats abutting the sample site (Meagher et al., 2016). In summary, evidence from the Americas supports the ecological principle that increased habitat diversity around the field increases efficacy of natural enemies in controlling FAW.

#### 3.3.2. Field margins (Figs. 1–4,1-9)

Leaving strips of weeds alongside fields can provide habitat and alternative food to a variety of natural enemies (Figs. 1–4) (Holzschuh et al., 2009). Wyckhuys and O'Neil (2007) recorded significantly lower FAW infestation levels in fields bordered by habitats of high floral richness and cover, and a marginally significant negative association was found with grass cover at short distances (< 100 m) from the field border. Experimental plantings of two wild flower mixes bordering bermudagrass increased populations of beneficial arthropods, especially foliar spiders and carabids, and predation rates on artificially placed FAW eggs and larvae were very high (Braman et al., 2002). In Peru, in an assessment of the quality of refuge plants around a maize field, Quispe et al. (2017) found that plants with bracteal extra-floral nectaries attracted the highest abundance and diversity of both predators and parasitoids, including species that attack FAW. They also found that plants with high foliage density attracted more alternative hosts and higher parasitoid and predator densities (Quispe et al., 2017).

#### 3.3.3. Agroforestry (Fig. 1-5)

Through diversifying the farm environment, especially the increased structural diversity that trees and shrubs provide, agroforestry is an important component of the agro-ecological pest management toolkit (Aluja et al., 2014; Philpott and Armbrecht, 2006; Pumariño et al., 2015). However, we could not find any studies that specifically examined the role of agroforestry in FAW management. Trees are likely to enhance the abundance of birds and bats (Figs. 1–10) and increase their role as natural enemies of FAW (Maas et al., 2016, 2013). Bats in particular may be important control agents of the adult moths (Boyles et al., 2011; Lee and McCracken, 2005; Maine and Boyles, 2015). For example, in Texas it has been estimated that 100 million Brazilian free-tailed bats (*Tadarida brasiliensis*) consume up to 4 billion noctuid moths each night, and consumption patterns correlated with the seasonal migrations of pests, including FAW (Lee and McCracken, 2005). Birds also consume large numbers of crop pests (Jones et al., 2005b; Kirk et al., 1996) and are more diverse and abundant in maize fields with diverse field margin habitats (Jones et al., 2005b). Moreover, in laboratory trials red-winged black birds (*Agelaius phoeniceus* L) preferentially selected larger, non-parasitized FAW larvae, which would enhance their pest control effect (Jones et al., 2005a). However, only a few bird species may be able to extract FAW larvae from the whorls and husks (Kirk et al., 1996).

In SSA, a number of development agencies have been promoting the use of fertiliser trees, such as *Gliricidia sepium* (Jacq.) Kunth ex Walp, *Tephrosia volgelii* Hook. f., and *Faidherbia albida* (Delile) A. Chev, to improve soil health and provide other benefits, such as on farm woodfuel and livestock fodder production. Incidental reports suggest that these inter-crops may also reduce infestations of FAW and other pests. Parts of all three tree species are known to have insecticidal properties, and leaf extracts of *Tephrosia* are widely used as a traditional insecticide (Stevenson and Belmain, 2017). Hence, it is possible that these species deter ovipositing female pests when used as an inter-crop, but further research is required to substantiate their effectiveness.

A significant advantage of agroforestry is the multi-functionality of trees (Sida et al., 2018b), for example, improving soil health, providing shade for livestock, protecting crops against temperature stress and reducing transpiration, and supplying woodfuel, timber, and fodder, as well as providing a pest control benefit. However, use of trees within cropping systems needs to consider potential trade-offs in tree-crop interactions, especially with respect to competition for light and water (Ndoli et al., 2018; Sida et al., 2018a). Nonetheless, agroforestry is being widely promoted within the concept of climate smart agriculture and hence there is ample opportunity to establish trials and determine the efficacy of trees in the management of FAW and other pests.

#### 3.3.4. Provision of nest sites for natural enemies (Figs. 1–11)

The provision of ant nest boxes to control pests in *Citrus* orchards in ancient China is perhaps the first documented use of an agro-ecological approach to pest management (Huang and Yang, 1987). However, the use of artificial nest sites to augment populations of natural enemies is not widely practised and is even more poorly documented (Staab et al., 2018). Nevertheless, nest sites are often limiting, especially in agricultural environments, so it stands to reason that nest site provisioning could enhance the local abundance of beneficial insects. In New Zealand the wasp *Ancistrocerus gazella* Panzer, a common predator of leaf-rollers in orchards, nested in holes drilled in blocks of wood and when moved to a new site provisioned fresh nest holes with leaf-rollers (Harris, 1994). Management of weaver ants (*Oecophylla* spp.) in forestry plantations (Offenberg et al., 2004) and on fruit trees (van Mele, 2008) suggests the provisioning of ant nest boxes might be an effective pest management tool for arable crops. Social wasps (Figs. 1–12) are important predators of lepidopteran larvae and efficient predators of FAW (Held et al., 2008), even burrowing down into the maize whorl to extract larvae. In a study in Brazil, which used boxes (or Vesparies) containing *Polistes* nests, wasps on average collected 1.54 larvae per colony per hour and predated 77% of FAW present in maize plots (1 colony per 25 $m^2$), providing effective control (Prezoto and Machado, 1999).

Nest site provision can be seen as a low-cost approach to traditional biological control involving *in situ* augmentation of native natural enemies rather than the typically expensive programmes focusing on laboratory rearing and releasing. The risk is low, but the cost-benefit relationship of this approach of FAW management needs to be investigated.

### 3.4. Landscape scale options

#### 3.4.1. Landscape management

While in practice the role of the landscape in regulating populations of natural enemies and crop pests is rarely considered in pest management, experimental studies provide evidence that natural enemies have a strong and consistent positive response to landscape complexity (Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Gurr et al., 2017; Landis et al., 2000; Murrell, 2017). Nevertheless, the landscape can also promote disservices, such as alternative food plants for pests or sources of seed for noxious weeds (Tscharntke et al., 2016; Zhang et al., 2007). Hence, management strategies need to consider the characteristics of the natural enemies they aim to promote and those of the unwanted organisms they aim to avoid (Chaplin-Kramer et al., 2011; Tscharntke et al., 2016; Zhang et al., 2007). Nonetheless, there is growing evidence that preserving and restoring semi-natural habitats not only increases densities of natural enemies but also enhances pest control services (Gurr et al., 2017; Midega et al., 2014), although results are not always consistent (Karp et al., 2018). For example, in a test of the role of landscape complexity on FAW parasitism rates, Menalled et al. (1999) found that complexity correlated with increased parasitism in only one out of three sites. However, in a study on infestations of the closely related cotton bollworm, *Helicoverpa armigera* Hüber, in cotton fields in China, Liu et al. (2016) found that egg parasitism by *Trichogramma chilonis* Ishii was best predicted by landscape composition within 2 km of a field, with lower parasitism rates in landscapes dominated by crop fields. Also, in a recent meta-analysis of aphid biological control in several cropping systems, Rusch et al. (2016) found that on average pest control via natural enemies was 46% less effective in homogeneous landscapes dominated by cultivated land, as compared with more complex landscapes. These findings indicate that studies assessing the role of landscape features on in-field FAW infestation and parasitism in the invaded range are warranted.

Landscape management requires the cooperation of large numbers of stakeholders who often have very different interests. Hence, sustainable landscape approaches are usually government led and externally financed to a substantial degree, although communities should have a large say in determining objectives and monitoring progress to

ensure sustainability (Prasanna et al., 2018).

#### 3.4.2. Restoration of forest

Maintaining remnants of forest in agricultural landscapes can be effective for conservation of arthropod biodiversity and contribute to biological control in adjacent crop fields (Landis et al., 2000; Veres et al., 2013). Forest patches near crop plantations have been shown to increase the local abundance and diversity of natural enemies, such as predatory solitary wasps and insectivorous birds and bats (Boyles et al., 2011; Jones et al., 2005b; Maas et al., 2013, 2016; Sousa et al., 2011). Sousa et al. (2011) evaluated the influence of forest distance on predatory solitary wasp abundance and richness and its relation to the natural biological control of FAW in maize fields in Brazil. They found that wasp abundance decreased, whilst FAW abundance increased, with the distance from the forest. Meanwhile, Wyckhuys and O'Neil (2007) found that spiders and ground beetles reached high abundance in maize fields within coffee agroforest landscapes.

Given the scale of the global land restoration agenda (Bonn Challenge: 350 Mha by 2030), embedding trials of the effects of restoration treatments, including planting and natural regeneration, on pest control and other ecosystem services is essential (Gellie et al., 2018).

### 3.5. Crop management and cultural control options

#### 3.5.1. Early planting

Early planting after the first effective rains usually provides better growing conditions for maize, making use of more heat units at the beginning of the cropping season. Control of pests in early planted crops derives from low pest pressure at this time of the season. However, early planting is also associated with increased risk of crop failure, as the initial rains may be erratic. Smallholder farmers may therefore be hesitant to plant their crops early and resort to either staggered planting or delaying the planting by using shorter season varieties (Thierfelder et al., 2016). Current advice to farmers is to wait for the first effective planting rains of 30–50 mm that fall in 2–3 consecutive days. This normally assures adequate soil moisture for crop establishment, especially if this is not the first rainfall event, and reduces the risk of crop failure. Staggered planting also helps farmers disaggregate labour peaks and hence potentially benefits women and children who are usually responsible for planting and caring of the young crops.

#### 3.5.2. Spraying with sugar solution or fish soup

Spraying with sugar solution or fish soup may be a low-cost option for encouraging natural enemies into the crop. Sugar on leaves attracts ants, solitary wasps, parasitoids and other natural enemies, while fish soup is specifically for attracting ants. The effectiveness of such a measure will depend on the availability of natural enemies around the field. In Honduras, sugar-solution treated maize had significantly higher densities of natural enemies, 18% lower FAW infestation and 35% lower leaf area damage than water-only treatments (Canas and O'Neil, 1998). In a comparison of spraying (i) water only, (ii) water plus sugar (10%) and (iii) water plus molasses in Parana state (Brazil), Bortolotto (2014) found that there was no difference among treatments in predator densities, but the rate of FAW parasitism was much higher in the sugar and molasses treatments (~11.5%), as compared to the water only treatment (~6.5%). We could not find any research on the application of fish soups, but farmers traditionally use this on their crops in parts of Africa. Clearly, more research is required to understand under what circumstances these interventions may be effective in controlling FAW and other pests. However, these are certainly worth investigating as a potential low-cost responses to outbreaks that are an environmentally benign alternative to chemical pesticides.

#### 3.5.3. Sand and ash

Pouring a mixture of sand and ash into the leaf whorl has been found to be effective in killing FAW larvae, and is being promoted as a low-cost cultural pest control option by FAO (FAO, 2018). However, the high labour demands of such an approach make it only feasible for small plots and, moreover, there is a risk that promotion of this approach may result in a substantial increase in the burden of work on women and children, who are often assigned crop tending tasks. Nevertheless, using sand and ash may provide an immediate solution to a FAW outbreak for families who cannot afford chemical pesticides. In the longer term promoting other agro-ecological approaches is likely more effective.

#### 3.5.4. Crushing egg masses and hand-picking larvae

Crushing egg masses and hand-picking larvae are very labour intensive options that are, nevertheless, available to farmers in the event of an outbreak. Due to the high labour demands it will not be effective for large plots and may increase the burden of labour on women and children. A healthy crop will out grow low densities of FAW with little or no impact on yields (Hruska and Gould, 1997). Hence, egg crushing and caterpillar picking should only be promoted as a last option in the event of an outbreak. As above, longer term solutions through promoting other agro-ecological approaches are likely more effective.

### 3.6. Integrated pest management – when to spray?

The rapid spread of FAW has in some cases resulted in indiscriminate spraying of pesticides, often without regard to whether chemical control is necessary or even effective within the local context (McGrath et al., 2018). Indiscriminate spraying not only wastes money and has potential negative impacts on human health and the environment (particularly where knowledge concerning the safe use of these toxic chemicals is limited; Lewis et al., 1997; Meagher et al., 2016; Pretty and Bharucha, 2015; Tscharntke et al., 2016), but also undermines agro-ecological approaches by reducing populations of natural enemies. Evidence from the Americas indicates that where chemical pesticides are applied, populations of natural enemies are reduced and their impact on FAW populations greatly diminished (Meagher et al., 2016; Perfecto, 1991; van Huis, 1981). In Nicaragua, van Huis (1981) found that 15 days after spraying with pesticides FAW populations were actually higher, as compared to clean controls. Therefore, effective use of agro-ecological approaches requires that only safe chemical pesticides are used and only as a last resort.

However, the practice of donating or subsidizing pesticides by national programs that are socially or politically motivated to provide these free of charge to farmers (de Groot, 1995; Hruska and Gladstone, 1988), encourages unnecessary use of chemical pesticides (Hruska and Gladstone, 1988) and neglect of traditional pest management practices (van Huis and Meerman, 1997). It may also lead to emergence of resistance, as has been reported in FAW for a broad spectrum of chemical agents in the Americas (Carvalho et al., 2013; Okuma et al., 2018; Yu, 1991; Yu and McCord, 2007) and to Bt maize in the US and Brazil (Huang et al., 2014; Omoto et al., 2016; Storer et al., 2012). We suggest that nationally supported crop insurance schemes might be more appropriate than promotion of discounted pesticides.

Knowledge concerning the relationships between pest numbers, host responses to injury and resultant economic losses, forms the basis of decision making in an IPM system (Pedigo et al., 1986; Supplementary Materials Table S1). However, previous studies for FAW in maize, show large variation in the injury levels resulting from a given level of FAW infestation, large variation in plant response to injury and, in many cases limited yield loss despite significant incidences of damaged plants in fields (Supplementary Materials Table S1). This variation is likely driven by differences in plant age, plant nutrition, climate, and the abundance and efficacy of natural enemies. The only published guidelines on action thresholds for FAW control in Africa are those suggested by McGrath et al. (2018). However, not only are the original data highly variable, but the trials were conducted under very

**Table 1**
Summary of evidence for agro-ecological approaches for FAW control.

| Method | Description | Effectiveness | Strength of scientific evidence |
|---|---|---|---|
| 1. Field management interventions | | | |
| **1.1 Fertilisation** to provide adequate and balanced plant nutrition using legume crops and fertiliser trees, organic manure, as well as inorganic fertilisers | Unbalanced plant nutrition through use of inorganic fertilisers on poor soils can lead to increased pest damage. The aim of this intervention is to increase levels of soil organic carbon and soil biological activities to provide adequate plant nutrition supports healthy plant growth and increase pest resistance. | High: Farmers may need to purchase inputs, but increased yields more than compensate. ***Could be scaled up immediately.*** | Strong evidence for effects of good plant nutrition on pest control in general, but no specific studies on FAW. However, there are a number of *ad hoc* observations of sickly plants being more heavily attacked than healthy plants by FAW. Altieri and Nicholls (2003); Morales et al. (2001); Vanlauwe et al. (2014) |
| **1.2 Minimum tillage:** In place of ploughing or hoeing and ridging, minimum tillage reduces soil disturbance through the use of rip-lines, digging small planting holes with a hoe or dibble sticks. | Minimum tillage, especially in combination with residue retention, improves soil health and increases soil organic carbon, and thus supports both improved plant growth and increased abundance of natural enemies in and above the soil. | Medium to high: Benefits can take 2–5 yrs to be fully realised and weeds are often a problem in the first 1–2 yrs. Increased management complexity can be an impediment to adoption. ***Could be scaled up immediately.*** | High for pest control in general, but few studies specifically on FAW. Increase abundance of natural enemies in no-till fields: Piñango et al. (2001); Witmer et al. (2003). Reduction in FAW infestation: Del Rosario (1981; in Kumar and Mihm, 2002); Andrews (1988); Baudron et al., *in submission*). Yield increase: Kumar (2002); Kumar and Mihm (2002). |
| **1.3 Mulching:** Spreading of plant biomass, usually crop residues, on soil surface | Mulching enhances soil biological activity and increase soil organic carbon, and thus supports improved plant growth. Mulch also ameliorates the soil microclimate and provides habitat for natural enemies. However, crop residues sometimes harbour pests and disease (Rodríguez-del-Bosque and Salinas-García, 2008), and hence use of non-crop biomass in a rotation system is preferred. Application rates and mulch management should be tailored to local conditions. | Medium to high when combined with minimum tillage. Crop residues are often feed to livestock, requiring alternative animal feed or source of biomass. However, livestock manure on the field benefits the system. ***Could be scaled up immediately.*** | Strong evidence of increased natural enemy abundance but few studies on impact on FAW damage or yield. Most studies do not separate minimum tillage from mulching. Increased abundance of insect predators in maize: All (1988); Clark (1993); Reichert and Bishop (1990); Rivers et al. (2016). Reduced FAW damage: Rivers et al. (2016); Roberts and All (1993), but Kumar and Mihm (2002) had variable results. Kumar (2002) and Kumar and Mihm (2002) did not find any increase in yield over minimum tillage. |
| **1.4 Intercropping:** Planting of additional crops in rows or strips (alleys) between the main crop. Intercrops can include legumes (e.g., pigeon pea, cow pea, velvet beans, lab, beans) and other crops (e.g. cassava, sweet potatoes, pumpkins), or plants providing a ecosystem service, such as fertiliser trees (e.g. *Tephrosia*, *Gliricidia* or *Faidherbia albida*) or green manures. | Pest control with intercrops functions by (i) disrupting pest host location and hence reducing the number of eggs laid on the crop; (ii) enhancing soil biology and crop microclimate, thereby promoting health plants and vigorous growth; (iii) inhibiting movement of pest larvae among plants; (iv) increasing the abundance of natural enemies. Under push-pull systems the intercrop is combined with a pest attracting plant which is planted in the field margin. | Medium to high: The extent of the benefits depends on the selection of an appropriate companion crop. The climate-adapted push-pull system resulted in an 86% reduction in pest damage and a 2.7× increase in maize yield in East Africa. ***Could be scaled up immediately.*** | High for the general effect of intercropping, but more evidence required for the specific effects of particular intercrops and assessing cost benefits across contexts. Increased abundance of natural enemies: Perfecto and Sediles (1991); van Huis (1981). Reduced FAW damage: Altieri et al. (1978); Hailu et al. (2018); Midega et al. (2018); Perfecto and Sediles (1991); van Huis (1981). Increased yield: Midega et al. (2018); van Huis (1981). |
| **1.5 Reduced weed management:** Some weeds are allowed to grow in a strip between the crop rows | Weeds trap ballooning 1st instar larvae and provide habitat and alternative food resources for natural enemies. | Unknown: Likely to be attractive to smallholders as it reduces labour for weed management. ***Requires further investigation.*** | Weak: Reduced infestation: Altieri (1980); Penagos et al. (2003); Portillo et al. (1991); van Huis (1981). Baudron et al. (in submission) also found FAW infestation increase when weeds were not controlled in Zimbabwe. |
| **2. Managing diversity at farm to landscape scales** | | | |
| **2.1 Field margins:** Allowing diverse field margins to develop, especially including plants with nectar sources and dense foliage | Field margins provide habitat and alternative food sources for natural enemies, which can come into the crop when pests appear. Diversity increases pest control function through complementarity. | High: The relative benefits depend on the opportunity costs, which varies with the degree of land availability. However, even relative small field margins can provide a valuable pest control function. It may be necessary to control weed species in margins. ***Should be trialed and research conducted to investigate benefits of different field margin plants.*** | High. Many observational studies show increases in natural enemy abundance and reductions in FAW infestation. However, there are no studies examining the effects on yield. Increased abundance of natural enemies: Andow (1991); Quispe et al. (2017); Meagher et al. (2016); Molina-Ochoa et al. (2004, 2001). Increased levels of parasitism or predation: Andow (1991); Meagher et al. (2016); Molina-Ochoa et al. (2004, 2001). |

(*continued on next page*)

**Table 1** (*continued*)

| Method | Description | Effectiveness | Strength of scientific evidence |
|---|---|---|---|
| **2.2 Diversify the farm environment** through crop rotation and agroforestry | Greater diversity, especially of semi-natural habitats, promotes living space for natural enemies. Pest build up is reduced through lowering the available habitat to each particular pest. | High: The relative benefits depend on the opportunity costs, which varies with the degree of land availability. However, economic benefits are derived from diversifying farm portfolios and increasing resilience. ***Could be scaled up immediately.*** | High. Many observational studies show increases in natural enemy abundance and reductions in FAW infestation. However, there are no studies examining the effects on yield and experimental studies are lacking. Increased abundance of natural enemies: Andow (1991); Hay-Roe et al. (2016); Meagher et al. (2016); Molina-Ochoa et al. (2004, 2001); Wheeler et al. (1989); Wyckhuys and O'Neil (2007). Increased levels of parasitism or predation: Andow (1991); Hay-Roe et al. (2016); Meagher et al. (2016); Molina-Ochoa et al. (2004, 2001); Wheeler et al. (1989). |
| **Providing nest sites for natural enemies:** Provision of nest boxes/insect hotels to enhance populations of natural enemies, including bats, ants, earwigs, social wasps and solitary wasps. | Species populations are often limited by nest site availability, especially in agricultural environments. Nest provision may be a low cost method of augmenting abundance of natural enemies. | Evidence is limited but all attempts appear to indicate it is effective. Using vesparies,Prezolo and Machado (1999) reduced FAW populations by 77%. ***Requires further investigation.*** | Weak: Few studies overall and only one in FAW. Reduced FAW infestation: Prezoto and Machado (1999) |
| **3.1 Diversifying habitats to increase landscape complexity:** Restoration of forests and management of semi-natural habitats at larger scales. | Natural and semi-natural habitats provide living space for varied natural enemies, including birds and bats. Diversity increase pest control function through complementarity. | Weak to medium: Although overall diversity provides complementarity, some interactions may negative, if for example habitats are a source of weeds or pests. Benefit will also depend on opportunity costs. Usually landscape interventions require external support to the community. ***Requires further investigation.*** | Strong evidence for increased abundance of natural enemies and pest control effect at smaller scales, but results at landscape scales are equivocal. Increased abundance of natural enemies: Sousa et al. (2011). Reduced FAW infestation: Sousa et al. (2011). Menalled et al. (1999) at one site and no effect at 2 sites. |
| **4. Cultural control** | | | |
| **4.1 Optimal timing of planting:** Planting with the first effective rains | The crop established while pest population remains low, hence escaping important phase of FAW impact. | Unknown, probably low in African context, because of the availability of alternative host plants and suitable climate for FAW to breed year round. Farmers often wish to stagger planting to spread out labour demand and as an insurance against rainfall variability. ***Requires further investigation.*** | Evidence from highly seasonal environments in N. America indicates it is a successful strategy. However, there is no information available from Africa and outcomes are likely to be very different. |
| **4.2 Spraying with sugar solution or fish soup:** As an alternative to using chemical pesticides a 10–20% sugar spray or protein rich fish soup is sprayed on the crop. | The bait attracts natural enemies into the field, especially ants and parasitoids. | Sugar solution had a modest effect in Americas (18% reduction infestation and 35% reduced leaf damage in one study). Effect of fish soup unknown. However, ants are known to be very effective predators of FAW. ***Should be trialed as an alternative to chemical pesticides.*** | Limited, just two studies on sugar spray: Bortolotto (2014); Canas and O'Neil (1998). |
| **4.3 Pouring sand or ash in the leaf whorl:** An alternative response to pest out-breaks to use of chemical pesticides. | Sand and ash irritate the soft skinned larvae forcing them out of the whorl or directly killing them. | Unknown: Labour requirements are substantial. ***Requires further investigation.*** | None |
| **4.4 Crushing egg masses and picking larvae:** An alternative response to pest out-breaks to use of chemical pesticides. | Direct mortality of pests. | Unknown: Labour requirements are substantial. ***Requires further investigation.*** | None |

different ecological conditions to those found in smallholder fields. Furthermore, preliminary results from Zimbabwe suggest that yield loss cannot be predicted from assessments of infestation and leaf damage alone (Baudron et al., 2019). In addition, approaches to calculating economic thresholds (e.g McGrath et al., 2018) typically ignore many costs, including damage to the pest control services provided by natural enemies and risk to human health and the environment. Given the high degree of uncertainty surrounding the relationship between infestation levels, plant damage and yield loss, and poor knowledge concerning the effectiveness of chemical pesticides, especially when applied by smallholder farmers without proper equipment or training, we would advise much more conservative thresholds until better data are available. Cultural responses, such as sugar spray or fish soup, may be tried as a low-cost initial response, while pesticides should only be applied as a last resort and only formulas that are less toxic to natural enemies.

## 4. Conclusions

Several of the agro-ecological approaches described in this article are known to be effective against FAW. In Table 1, we provide a summary of the reviewed information. A number of interventions are ready to be piloted at scale, including (i) minimum tillage, (ii) biomass mulching, (iii) intercropping, including use of cover crops and alley cropping, (iv) diversifying the farm environment through crop rotation, agroforestry and management of field margins and (semi)natural habitats. However, interventions need to be tailored to local contexts and hence field trials should be embedded into up scaling programmes, so that interventions can be fine-tuned. This would have the additional benefit of delivering a comprehensive understanding of the cost/benefit ratios of these interventions across a broad spectrum of biophysical and socio-economic contexts. Indeed, we would advocate embedded such trials in all ongoing sustainable intensification programmes, as a quick way to gain an understanding of the effects of such interventions on FAW and other pests. Furthermore, for the development of meaningful

IPM strategies, it is essential that we improve our understanding of the relationship between FAW infestation, leaf damage and yield loss by conducting trials and collecting data on important co-variates, in particular the abundance of natural enemies.

Other interventions show considerable promise but require a more thorough testing before they can be recommended for up scaling. These include the possibility of managing weeds to provide living space for natural enemies, providing nest sites to augment populations of important natural enemies, such as ants and social wasps, and cultural interventions, such as spraying sugar or fish soup in response to an outbreak.

In addition, we recommend that ecologists team up with researchers from other disciplines to explore potential synergies. For example, agro-ecological approaches may benefit (or potentially inhibit) traditional biological control involving the release of laboratory reared parasitoids. Similarly, working with crop breeders to enhance the production of plant SOS chemicals by the crop when attacked by herbivores could greatly enhance the benefit of agro-ecological approaches. It will also be important to determine which of the FAW strains are present in an area and which ones pose a threat to particular crops. The food preferences of the two different strains may determine their ability to survive on alternative hosts during the non-cropping season, which especially at larger scales may determine the effectiveness of control options. Even at the plot scale, the effectiveness of, for example, a push-pull system might depend on which strain of FAW is attacking a field.

Last, it is important that research is conducted on smallholders current pest management strategies, how to communicate evidence-based pest control advice most effectively, and how to establish the market chains needed to support agro-ecological options.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.05.011.

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