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Area-wide pest management and prospects for fall armyworm control on smallholder farms in Africa: A review

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ABSTRACT

Currently, the management of many highly mobile and very destructive insect pests such as fall armyworm is still carried out for the most part, on a field-by-field basis. Chemical pesticides remain the most predominant pest control option, despite their direct effects on human health, the environment, and biodiversity. Integrated Pest Management which involves the use of a combination of techniques has been promoted for the long-term prevention of pests, but they too, are usually applied by producers independently of others. Uncoordinated and reactive field-by-field pest management addresses only a small fraction of a local pest population, allowing for fast re-invasion of managed farms. Area-wide pest management, where coordinated pest management tactics are used over a broad landscape, has been suggested as a key strategy for the sustainable management of invasive and mobile pests. Using narrative review methodology, we give a description and synthesis of available literature on area-wide pest management on smallholder farms around the world. We specifically examine the successes, facilitators, and barriers to effective implementation of the approach. We discuss these cases considering changing institutional and socio-economic factors and assess prospects for sustainable area-wide management of fall armyworm in Africa.

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1. Introduction

1.1. Background and justification

Global plant health is increasingly being threatened by plant pests (Giovani et al., 2020). Many of the economically most damaging pests are invasive species that have escaped the biotic constraints, which keep their populations in check in their regions of origin. This has been fostered by climate change, rapid globalization of trade in agricultural products, and increasing tourism which have increased the introduction and spread of invasive harmful organisms (Bebber et al., 2014). Invasive species can have a devastating impact on important staple crops such as maize, and other high-value cash crops including tomatoes, peas, and green beans (Pratt et al., 2017), constituting a threat to the incomes of rural families and food security worldwide (Savary et al., 2019). Eschen et al. (2021) estimate the annual cost of invasive species to African agriculture at USD 65.58 billion, with crop yield losses constituting 55% of this cost. The global significance of invasive species is recognized by target 15.8 of the Sustainable Development Goals (Osborn et al., 2015).

Currently, the management of many highly mobile and very destructive invasive pests is still carried out, for the most part, by individual producers who rely on the use of chemical pesticides (Tambo, Kansiime et al., 2020; Vreysen et al., 2007). Chemical pesticides are however, often used indiscriminately and inappropriately by farmers, using unsafe storage facilities, and not adhering to safety instructions (Agmas et al., 2020). This is an unsustainable long-term solution due to potential resistance development, environmental pollution, biodiversity losses, and human health risks. Other pest control options, relying on the use of integrated pest management (IPM) have been developed and promoted as cost-effective and environment-friendly control measures for agricultural pests (Akeme et al., 2021; Harrison et al., 2019; Hulme, 2006), but they too, are often applied by producers independently and on a field-by-field basis. This field-by-field approach to pest management has been attributed to several factors such as heterogeneity of farm conditions (Abate et al., 2000), differences in farmer socio-economic conditions and farming objectives or interests (Garcia-Figuera et al., 2021), and lack of policy and institutional support for coordinated actions at landscape level (Kruger, 2016).

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The uncoordinated and reactive field-by-field approach of pest management only addresses a small fraction of a local pest population at a given time, allowing for fast reinvasion of controlled farms by the pest presence in the vicinity, either from untreated farms, alternative hosts, or wild hosts. Area-wide pest management (AWPM) therefore is one of the strategies that can be used for sustainable management of insect invaders (Vreysen et al., 2007). Contrasted to conventional pest management approaches, AWPM is the long-term planning of pest management over a broad geographical area using coordinated and synchronized actions between farmers aimed at maintaining the pest below economic levels. AWPM programs integrate various pest management practices at landscape level aimed at ensuring pest suppression and reduced use of insecticide sprays. Consequently, the reduction in the use of synthetic pesticides improves on- and off-farm sustainability, reduces costs for farmers, and delivers social benefits to the entire community (Pretty & Bharucha, 2015).

However, AWPM programs are not always successful due to collective action problems. These problems arise when individuals cannot be excluded from the benefits of others' efforts, such as in the provision of public goods (Sandler, 2015). This is the case with AWPM where by preserving crops from pests has public good attributes because one farmer's benefits from pest control do not reduce benefits to others in the affected landscape (Lansink, 2011). This problem has traditionally been addressed by government intervention in a *top-down* approach by assuming regulatory command of plant health services, establishing rules to stop disease spread, funding initial management efforts, and sometimes mandatory control of pests on private lands (Epanchin-Niell, 2017). However, *top-down* approaches are often insufficient and unsustainable on their own to prevent the spread of emerging plant pests due to high transaction costs (Colella et al., 2019), requiring approaches that integrate community-based initiatives and local knowledge with the government expertise and resources (Epanchin-Niell, 2017). This therefore requires paying attention not only to the ecological, environmental, and economic elements but also to social and institutional dimensions for sustainable pest management (Kruger, 2016; Ostrom, 2010).

1.2. Fall armyworm impacts on africa's maize farming systems

Maize is the most widely grown cereal crop in sub-Saharan Africa (SSA) (FAO, 2021), and more than 300 million people out of approximately 1 billion people depend on it as the main staple food crop (http://dtma.cimmyt.org/index.php/background). Maize accounts for 30 – 50% of low-income household expenditures and over 30% of the caloric intake of people in sub-Saharan Africa (Macauley, 2015). Maize is continuously and severely affected by insect pests resulting in important yield losses. For instance, significant maize yield losses have been caused by lepidopteran stem borers, *Busseola fusca* (Fuller) (Noctuidae), and *Chilo partellus* Swinhoe (Crambidae). Production losses of up to USD $450 million to farmers in eastern Africa by *C. partellus* alone have been reported (Pratt et al., 2017).

Despite its recent invasion of the African continent in 2016 (Goergen et al., 2016), fall armyworm (*Spodoptera frugiperda* J E Smith, Lepidoptera: Noctuidae) is arguably the most damaging pest on maize. Studies in Africa have estimated maize yield losses due to fall armyworm ranging between 8.3 and 20.6 million tons per year if left uncontrolled (Abrahams et al., 2017; Day et al., 2017), accounting for between 11% to 58% of production (Bariw et al., 2020; Chimweta et al., 2020; De Groote et al., 2020, 2020; Kassie et al., 2020). The economic loss to fall armyworm in Africa has been estimated at US $9.4 billion annually (Eschen et al., 2021).

When the fall armyworm was first detected, many governments in Africa quickly acted to support farmers through the distribution of synthetic pesticides. Farmers have also tried a mix of other practices based on indigenous knowledge and experience with endemic pests such as handpicking of larvae and egg masses, adding soil/sand/ash to plant whorls, household soaps, and drenching tobacco extracts (Tambo et al., 2020a; Yigezu & Mulatu, 2020). Use of agroecology-based practices such as maize rotation with non-host crops, intercropping, 'push-pull', sowing multiple maize varieties, and in-field diversity to promote natural pest regulation have also been reported in some farming systems (Akeme et al., 2021; Murray et al., 2019; Scheidegger et al., 2021; Yigezu & Mulatu, 2020). The use of synthetic insecticides however, remains the most commonly used method for the management of the fall armyworm across Africa's farming systems (Kansiime et al., 2019, 2020; Njuguna et al., 2021; Tambo et al., 2020b).

Environmental suitability modeling using temperature and precipitation data shows that large areas of Africa are highly suitable for fall armyworm (Early et al., 2018), and a possibility of year-round breeding and infestation in Africa given the variations in rainfall patterns, cropping seasons, and planting dates between countries and regions (Timilsena et al., 2022). Coupled with its reported resistance to pesticides, makes fall armyworm an agriculturally important insect pest in the region (Zhou et al., 2020). In addition, given the limited local knowledge of effective management practices, its notable ability to invade new habitats, and lack of coordinated actions on a landscape level, fall armyworm management has become challenging, requiring integrated approaches. This was the motivation for this review to understand how area-wide pest management has been applied in various contexts and prospects for this approach for the sustainable fall armyworm management in Africa.

1.3. Objectives and methods

The main objective is to review evidence on area-wide management of plant pests on smallholder farms, identifying success and practice for effective pest management. We draw case studies from across the world focusing on different pests, crops, and management techniques, and discuss these data given changes in institutional and socio-economic factors, that may hinder effective uptake of the approach, and based on lessons learned, propose integrated actions for sustainable area-wide management of fall armyworm in Africa.

The study employed a narrative review methodology (Paré et al., 2015). This method enables the description and synthesis of available literature on a topic, providing a conclusion from the evidence, without necessarily seeking generalization or cumulative knowledge from what is reviewed (Dixon-Woods et al., 2005). We are cognizant of the weaknesses of this approach as it lacks explicit and reproducible methods, but given our intention to gather qualitative lessons, this approach serves the study's purposes. Narrative reviews are also considered helpful in presenting a broad perspective on a subject, often including a description of the history or development of a problem or its management (Slavin, 1995), as is the case with this review.

The review included peer-reviewed articles published in the following databases: CAB Abstracts, Science Direct, and PubAg (Keyword search terms used: area-wide pest management+facilitators+barriers, collective action, sustainable pest management, invasive pests management, integrated pest management, non-chemical pest control, fall armyworm management). Using snow-bowling methods, we used the references from the articles obtained by this method to check for additional relevant material. We reviewed over 100 documents, covering up to 10 pests. We included seven pest (or pest orders) cases where the available literature covered the extent of the problem, management approaches used and effectiveness of the approach in managing the pest on a wide scale.

2. Results

2.1. Cases of successful area-wide pest management programs

2.1.1. Area-wide classical biological control of cassava mealybug in africa and asia

Cassava mealybug *Phenacoccus manihoti* Mat. Ferr. (Homoptera: Pseudococcidae) was first detected in Africa, in Zaire and Congo in the early 1970s, and spread the following 10 years over the entire cassava belt of Africa, causing root yield losses of up to 84% (Nwanze, 1982). Aerial releases of a parasitoid wasp *Apoanagyrus (Epidinocarsis) lopezi* (Hymenoptera: Encyrtidae) were initiated in 1981 and by 1991 the biological control agent had spread to 26 African countries, bringing the pest under control in 95% of all the cassava fields. Zeddies et al. (2000) showed that the biological control strategy had a benefit-cost ratio of 200 when cassava was listed at world market prices and of about 370–740 when inter-African prices were considered.

In late 2008, cassava mealybug was detected in Thailand and by 2011 the pest rapidly spread and infested many provinces of Thailand, and its neighboring countries and Indonesia (Muniappan et al., 2009). In Thailand, the cassava mealybug reduced cassava yield from 30 million tons per year to 22 tons per year (Aekthong & Rattanakul, 2019), estimated at US$ 30 million, within two years of first detection (Bellotti et al., 2012). Guided by the biological control successes against this pest in Africa, *A. lopezi* was introduced to Thailand in 2009 from the IITA station in Benin, and rearing labs were established in different parts of the country. Subsequent introductions of *A. lopezi* were made in neighboring countries, and an integrated campaign was launched to scale up the biological control of the mealybug.

Three years of exerted (sub)continent-wide efforts to combat the cassava mealybug by adopting area-wide pest management showed a reduction in pest infestation and restored yields in Thailand's cassava crop. Wyckhuys et al. (2018) shows that *A. lopezi*, released throughout Thailand in 2010 effectively established in 97% of mealybug-affected fields in mainland Southeast Asia by 2014, and colonized 27% of sites across insular Indonesia by late 2017. Experimental assays using popular cassava varieties showed that biological control secured yield gain of between 5.3 and 10.0 tons per ha and provided biological control services worth several hundred dollars per ha (at local farm-gate prices) in Asia (Thancharoen et al., 2018).

Some of the factors that underpinned the success of the biological control campaign of *P. manihoti* in Africa and Asia include; (i) globe-spanning collaboration between the Food and Agriculture Organization of the United Nations (FAO), centres of the Consultative Group on International Agricultural Research (CGIAR) and CABI, and a swift mobilization of national government institutions and decisive action; (ii) easy access to the parasitoid, quick establishment of facilities to rear and distribute adapted natural enemies from South America; and (iii) heightened extension campaigns that boosted preparedness and prevented certain detrimental practices such as unguided use of insecticides (Neuenschwander, 2001; Wyckhuys et al., 2021).

2.1.2. Area-wide IPM strategy to reduce insecticide resistance in helicoverpa armigera in the cotton-grain systems in australia

The cotton bollworm *Helicoverpa armigera* (Hubner), a key insect pest of cotton is one of the most studied insect pests worldwide. Besides having a wide host range (>180 plant hosts from > 45 families), including some of the essential global food crops, *H. armigera* has repeatedly developed resistance to insecticides (Dilbar Hussain et al., 2015; Yang et al., 2013) now reported at 55 active ingredients (www.pesticideresistance.org). This pest causes damage to crops estimated at more than USD 2 billion per year worldwide, excluding the socio-economic and environmental costs associated with its control (Tay et al., 2013).

In northwest Australia, cotton production was abandoned ten years after it began as it soon became unfeasible and costly. Farmers applied more than 30, of which many were nonselective, pesticide applications per season (Wilson et al., 2018). This approach led to insecticide resistance. To curb this situation, the Australian cotton industry progressively adopted IPM combined with an area-wide management strategies such as trap cropping, cultural practices, conservation of beneficial organisms, optimal planting date, and use of plant growth regulators. There was also improved coordination of general management of the pest. Indeed Zalucki et al. (2009) envisaged that for migratory, polyphagous and outbreak pest species, such as *Helicoverpa* spp. individual field-based IPM continues to fail requiring the implementation of area-wide pest management.

This approach was facilitated by an industry-wide extension campaign around IPM philosophy. The campaigns targeted all farmers in the region, regardless of what they were growing. This enabled a mindset shift by farmers from a field-by-field reactive approach to compliance with an area-wide IPM strategy for the management of insecticide resistance. Regular group meetings and commitment to implementing the tactics that made up the strategy were vital, as was the research support that demonstrated and communicated the efficacy of these tactics to the participants (Wilson et al., 2018). Wilson et al. (2018) show that IPM is now embedded in the industry, and the strategies and collective efforts of all stakeholders resulted in a dramatic decrease in insecticide active ingredients applied per hectare.

2.1.3. Management of false codling moth using an area-wide IPM and sterile insect technique in south africa

The false codling moth (FCM), *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae), is a key pest of citrus, stone fruit, and other crops in many countries throughout Africa, including South Africa. While FCM has been reported to cause yield losses of up to 90% in various countries, the main reason for its high pest status is its quarantine status, which restricts international trade of its host crops such as citrus, macadamia, capsicum and several *Solanaceae* crops, leading to huge economic losses (Adom et al., 2021). In South Africa, although FCM was suppressed to some extent by the use of an integrated program that combined the use of insecticides, field sanitation, microbial, and augmentative biological control, it was considered less effective in managing the pest (Bloem et al., 2007). The sterile insect technique (SIT) was therefore developed as an additional method for FCM suppression, and an approach that could be easily integrated into an area-wide IPM strategy to lower its introduction into countries currently free of this pest.

Assessment of the effectiveness of the SIT showed that crop losses due to FCM infestation were reduced by 95% in the SIT-treated area compared to the control orchard, leading to the commercialization of the technique (Hofmeyr et al., 2016). In the 2007–2008 season, commercial sterile insect releases were done over 1,500 ha of citrus orchards in the Citrusdal region, Western Cape Province, gradually expanding to about 19,000 ha in three different regions by 2017–2018 (Boersma, 2021). Over the years, the status of *T. leucotreta* as a pest threat systematically reduced in areas where sterile insects were released, compared to non-release areas.

The SIT program was a joint effort of international and national public and private organizations. After a successful pilot phase, this program component of the project was transferred to the private sector, currently owned by the Citrus Growers Association (CGA), and a large moth mass rearing facility was constructed and skills built for technical staff as a result of technology transfer. Working through the CGA played a significant role in the success of the program as it was an industry-driven project aimed at securing sustainable citrus exports for the farmers (Boersma, 2021). Other factors contributing to the success of the program were: the area-wide integration of the FCM suppression method that included monitoring, sanitation practices, and treatment of hotspots in conjunction with other integrated pest control practices; well-trained and capable management that ensured sustainable production of sterile insects; and support of farmers and industry (Boersma, 2021).

2.1.4. Integrated pest management strategy for the suppression of mango fruit flies in east africa

Mango is an important food and cash crop enterprise in Sub-Saharan Africa (SSA). Its production and trade have been limited among other factors, by insect pests infestation particularly, tephritid fruit flies (e.g. *Bactrocera dorsalis* (Hendel), *Ceratitis cosyra* (Walker), etc.), and diseases such as anthracnose and powdery mildew (Ekesi et al., 2011). Annual losses of horticultural produce associated with fruit fly infestation in Africa are estimated at US$2 Billion, either directly through loss of yield or indirectly through loss of market opportunities (Lux et al., 2003). Many farmers rely on chemical pesticides for the control of fruit flies, which has resulted in the development of resistance in the pest to certain pesticides (Vontas et al., 2011).

In the effort to contain the fruit fly, an area-wide IPM program was developed and promoted by ICIPE in the horticultural sub-sector in East Africa and other SSA countries. The strategy consists of; spot application of food bait, male annihilation technique (MAT), use of biopesticide, releases of parasitoids (*Fopius arisanus* (Sonan) and *Diachasmimorpha longicaudata* (Ashmead) (both Hymenoptera: Braconidae), and use of orchard sanitation (Muriithi et al., 2016). Evaluation of this program in Kenya showed a 48% average increase in mango net income by adopters compared to the previous season irrespective of the IPM combination component used (Muriithi et al., 2016). Kibira et al. (2015) show that, on average, mango IPM participants had approximately 54.5% reduction in the magnitude of mango rejection, and spent 46.3% less on insecticide per acre than the non-participants.

The strategy included a combination of affordable and easy-to-apply IPM strategies which encouraged farmer participation. Partnership with private companies to produce the products to make them commercially available for farmers. However, adoption rates of the technology varied amongst farmers depending on farmers' socio-economic characteristics and knowledge levels (Muriithi et al., 2020).

2.1.5. Synchronized crop rotations and conservation of natural enemies for control of rice pests in indonesia

The green revolution in Asia in the late 1960s saw a great boost in rice production as a result of the introduction of short-duration and high-yielding varieties, the product of collaborative research between the International Rice Research Institute (IRRI) and national research programs in several Asian countries. As a result of the green revolution, Indonesia achieved self-sufficiency in rice production in 1984. Excessive pesticide use to control rice pests, however, resulted in the development of resistance. Local pests that were once considered minor such as the brown planthopper *Nilaparvata lugens* (Stal) became major problems. In 1977 Indonesia lost 106 Mg of rice to the rice brown planthopper, an estimate of more than US$ 109 worth of rice (Wardhani, 1992). Other environmental problems such as the death of non-target species and beneficial species, increased pesticide residues in soil, water and food, and acute poisoning to people were also reported as a result of massive pesticide use.

Given these challenges, the Government gradually altered its policy of pest control from a unilateral method (depending only on pesticides) to area-wide Integrated Pest Management, which was officially adopted in 1989 (Thorburn, 2015; Vreysen et al., 2007). The strategy emphasized the use of cultural controls (synchronized planting, crop rotation, field sanitation, the use of plant resistance), pest monitoring and the the judicious use of pesticides.

Studies show that the program helped farmers reduce the use of pesticides by approximately 56% and increased rice yields by approximately 10% (Resosudarmo, 2016). The success of the Indonesian National IPM Program was based on the combination of two key factors: (i) national policy decisions that supported and reinforced the shift from a unilateral method to area-wide IPM in rice, and (ii) massive farmer education and participation which empowered those implementing the techniques of IPM (McClelland, 2002).

2.1.6. Insect-resistant Bacillus thuringiensis (Bt) crops

Bacillus thuringiensis (*Bt*) crops are plants genetically engineered (modified) to contain toxins of the bacterium, *Bt* to be resistant to certain insect pests. As a highly selective form of host plant resistance, *Bt* crops effectively control several key lepidopteran pests and have become a cornerstone in overall integrated pest management (IPM). Dively et al. (2018) show that area-wide *Bt* adoption suppresses pests, with declines expanding beyond the planted *Bt* crops into other non-*Bt* crop fields, and a subsequent reduction in pesticide application. For instance, transgenic cotton that produced one or more insecticidal proteins of *Bt* planted on over 15 million ha in 11 countries in 2009 contributed to a reduction of over 140 million kg of insecticide active ingredient between 1996 and 2008 (Naranjo, 2011). In India, widespread adoption of *Bt* led to area-wide suppression of bollworm populations, so conventional cotton farmers also substantially reduced their pesticide applications (Kathage & Qaim, 2012). In China, extensive historical data on the adoption of *Bt* cotton have shown a linear decline in populations of *H. armigera* on cotton in six provinces in northern China, which has also been mirrored in many of the other crops affected by *H. armigera* in the country (Wu et al., 2008). In Africa, *Bt* maize was adopted in South Africa and reported to be effective against maize stalk borers in addition to reducing the chemical sprays and increasing yield and income (Keetch et al., 2005).

The wide-scale adoption and use of *Bt* cotton represents a very successful implementation of a synchronous control approach that results in large reductions in total pest populations (Naranjo, 2011). Most of the *Bt* crops have been used in the USA, Brazil, Argentina, Canada, China, India and South Africa, and some of the facilitating factors include; a high standard of crop management and good agricultural practices, the presence of adequate seed multiplication and distribution systems, implementation of strategies to delay or prevent the development of resistance to *Bt* toxins in the target insect populations, and the ability of authorities to enact and implement biosafety regulations (Hillocks, 2005).

2.1.7. Biological control of lepidopteran pests in rice in the greater mekong subregion

While rice production in the Greater Mekong Subregion (China, Myanmar, Thailand, Cambodia, Vietnam, and Laos) remains an important economic activity, it is not a profitable venture, mainly due to several production constraints, especially the lepidopteran pests (Horgan & Crisol, 2013; Litsinger et al., 2006). Cheng et al. (2010) estimated yield loss of about 20% in rice-producing countries as a result of stem borers alone. An IPM strategy using *Trichogramma* was introduced in the region to reduce farmers' pesticide inputs and increase yields (Babendreier et al., 2020).

Through EU funding, *Trichogramma* Rearing Facilities (TRFs) were established in each country targeting rice stem borers. This was followed by capacity building of production personnel and training of trainers to provide a constant supply of egg cards for farmers' fields in each local vicinity and technical skills training respectively. In addition, the IPM initiative was implemented using a village approach where farmers within a larger community joined forces and harmonized pest management systems (Babendreier et al., 2020). In addition to *Trichogramma* production other cultural practices e.g. growing nectar plants in rice bunds, alternate wetting and drying (AWD) were included in the IPM package. Implementation of the IPM strategy in GMS resulted in higher rice yields (2–10%), an increase in the abundance of natural enemies, and a reduction in insecticide applications by farmers (Babendreier et al., 2020). Initial results of the impact of this area-wide IPM program using *Trichogramma* in the MGS region pointed to compounded positive cost-benefit ratios.

2.2. Facilitators for area-wide pest management

Area-wide pest management facilitators are elements or circumstances that support and encourage the effective use of comprehensive pest management solutions over a wider geographic area. These enablers can play a critical role in ensuring effective pest control and minimizing pests' detrimental effects on agriculture and the environment. Some of the essential enablers based on the reviewed case studies include:

2.2.1. Technology availability and cost-effectiveness

Farmers' access to a combination of advanced, affordable and easy-to-apply IPM strategies technologies encourages their participation in area-wide pest management (eg Muriithi et al., 2020). The area-wide integration of the FCM suppression method that included monitoring, sanitation practices, SIT, and treatment of hotspots in conjunction with other integrated pest control practices ensured sustainable pest management (Boersma, 2021). Mankad et al. (2017) report cost of technology as the dominant barrier cited concerning the uptake of SIT for fruit flies in southeastern Australia. Farmers tend to use cost-effective approaches that minimize their financial risks. Therefore, if farmers consider the relative costs of AWPM to be prohibitive, it becomes a barrier to their widespread involvement.

2.2.2. Collaboration and partnerships

Collaboration among various stakeholders, including government agencies, agricultural organizations, research institutions, industry actors and local communities, proved essential for coordinating and sustaining efforts and resources to implement area-wide pest management (Aitken et al., 1995). For example, the engagement of the private sector played a significant role in the success of the continued production of the SIT technique for continued management of false codling moth in South Africa. Similarly, globe-spanning collaboration between various institutions and private sector engagement enabled the quick mobilization of parasitoids for the control of cassava mealybug from the point of origin, allowing a quick response. The success of rice IPM programs in Indonesia and Vietnam was characterized by high levels of farmer/community participation in the experimental phase, which increased the adoption rates of the developed technologies in the final phase of implementation.

2.2.3. Awareness and knowledge about area-wide pest management

Key AWPM components, such as coordinating pest management activities across defined areas (e.g. ensuring all growers align management strategies to pest biology promptly, or providing a platform to share information) require an understanding of the true meaning of AWPM and its techniques. The reviewed AWPM programs focused on implanting the necessary managerial and technical knowledge for smallholder farmers and the general public, and continually providing extension advice to increase their ability to manage target pests. Heightened extension campaigns boosted preparedness and prevented certain detrimental practices such as the unguided use of insecticides (Neuenschwander, 2001; Wyckhuys et al., 2021), and are also considered important to avoid farmer backsliding to former practices (Zalucki et al., 2009).

2.2.4. Collective action and cooperation among farmers

The benefits of controlling invasive species naturally constitute a collective good (Garcia-Figuera et al., 2021; Yung et al., 2015), and therefore require a significant amount of cooperation across diverse individuals, institutions and communities (Kruger, 2016). Collective action works best when those involved already have established mutual trust (reciprocity), a good reputation in following agreed rules, perceive a shared commitment to change and have similar goals to ensure that pest management behaviors are implemented correctly and coordinated across multiple individuals (Marshall et al., 2016). Building mutual trust helps address the challenge of social loafing and conditional participation that may limit the widespread adoption of AWPM (Mankad et al., 2017; Marshall et al., 2016; Ostrom, 2010). In addition, community-based management guarantees that the defined guidelines for area-wide pest management are in line with the predominant social norms, culture, and agroecological circumstances in a community. Norms can be either established by external agencies or internally created that define acceptable and appropriate actions within a given group or community, thus guiding human behavior (Ostrom, 2010). Social norms are held in place by social sanctions (‘punishments’) for non-adherence to the norm or social benefits (‘rewards’) for adherence. There is a need for self-organization at the community level, and recognition of organization, to allow farmers to devise, monitor and enforce a set of rules, among resource users (Martin et al., 2016; Travers et al., 2011).

2.2.5. Institutional arrangements

The management of plant pests has public good characteristics, thus successful implementation of AWPM has been possible when particular institutional arrangements are in place to guide pest management approaches (Ostrom, 2010). Institutional arrangements such as enactment of laws and regulations, government spearheading response mechanisms for emerging pests, and developing contracts, guidelines, procedures and standards for farmers or communities to follow are key for the implementation of AWPM. For example, the ability of authorities to enact and implement biosafety regulations enabled wide-scale adoption of Bt-based AWPM (Hillocks, 2005). Equality, national policy decisions that supported and reinforced the shift from a unilateral method of pesticide use to area-wide IPM in rice in Asia.

2.3. Why is AWPM not working effectively today?

While successful examples of area-wide pest management have been discussed, achieving effective area-wide pest management in Africa still faces several challenges. These challenges have become more important today compared to before due to various institutional and socio-economic factors. Some of these barriers are:

2.3.1. Policy changes

In Africa, agricultural policies typically place a higher emphasis on productivity and production than on environmental sustainability (Day et al., 2022). As such, the use of synthetic pesticides to manage pest populations is encouraged, which has led to an increase in pesticide use across Africa’s farming systems. Besides, the pricy registration processes and sparse regional harmonization of input regulatory systems, unintentionally hamper access to alternative and low-risk pest control products such as biopesticides (Day et al., 2022). The pesticide situation is also partly due to the emergency response strategy to pest invasions by most governments that includes the procurement and free distribution of pesticides in efforts to curb the menace, for example for fall armyworm control (Koffi et al., 2020; Rwomushana et al., 2019). Chemical pesticides are, however, often used indiscriminately and inappropriately by farmers, using unsafe storage facilities, and not adhering to safety instructions (Agmas et al., 2020). Policy support for environmentally friendly IPM practices is rare, while counter-interventions from pesticide industry are common (Pretty & Bharucha, 2015), further contributing to the global increase in pesticide use.

2.3.2. Training and extension deficiencies

According to Jørs et al. (2017) and Parsa et al. (2014), weak farmer management skills and insufficient outreach and training shortcomings have contributed to the low adoption and departure from AWPM. This lack of knowledge and awareness is due to well-known problems with agricultural extension in many developing countries, where funding has been cut and commodities programs compete for limited resources (Larochelle et al., 2019). Farmers experiment gradually, and exposure to technology is a major factor in its overall acceptance.

2.3.3. Inadequate government support

The implementation of area-wide pest management programs has historically been hampered by inadequate government support for agricultural research and development (R&D). However, in recent years, the rate of growth in agricultural R&D investment has been declining globally, while a large number of developing countries have experienced negative growth rates over the past decade. Despite the commitment by member countries of the African Union to spend 1% of their GDP on R&D, by 2019, the continent's funding was only 0.42%, a sharp contrast to the global average of 1.7% (Wachira, 2021). This lack of funding significantly affects the ability of many African nations to conduct extensive pest management programs. Research funding for area-wide IPM is scarce, and extension programs struggle to offer the kind of farmer assistance that AWPM adoption frequently requires.

2.3.4. Farmers' behavioral and socio-economic factors

Farmers' behaviors regarding profit maximization have changed over time in response to a variety of developments, such as market forces, environmental awareness, technical breakthroughs, and shifting societal norms (Garcia-Figuera et al., 2021). Additionally, differentials in financial resources, farmer perceptions, type of enterprises, and access to subsidized farm inputs (Caniço et al., 2021; Tambo; Kansiime et al., 2020) have increasingly motivated farmers to apply field-by-field as opposed to area-wide pest management. For example, AWPM requires synchronizing farming activities with other farmers which can be an obstacle to farmers who opt for early planting or off-season planting to meet market demands. Similarly, as farmers embrace crop diversification to mitigate risks associated with monoculture, field-by-field pest management becomes apparent as different crops within a single field may have distinct pest profiles and management needs. The increasing adoption of technologies for precision agriculture, such as GPS-guided equipment, remote sensing, and variable rate applications, has also enabled farmers to customize their pest management strategies for particular fields. With such a level of accuracy, pesticides can be applied selectively, lowering the overall use of chemicals and limiting any negative effects on the environment. Conversely, Norton et al. (2019) opine that farmers' failure to use AWPM may be attributed to present bias. This means a decision-maker prefers immediate results. This bias explains farmer preference for pesticides because their action leads to immediate insect deaths.

2.3.5. Climate change

Pest distribution and behavior have changed as a result of climate change. Growing pest problems are exacerbated by changing precipitation patterns and rising temperatures. Pests that were once restricted to certain locations can now flourish in new areas. Climate change has also changed the ecological conditions which makes it difficult to find a one-size-fits-all area-wide IPM package. Certain components of AWPM packages may only be appropriate under specific conditions. Similarly, pest pressure is not uniform, pests may emerge at different phases of the crop cycle, and evolve over time and rarely do complete AWMP 'packages' exist for an entire crop or ecosystem (Alwang et al., 2019).

3. Prospects for area-wide management of fall armyworm

Significant progress has been made in the development of techniques for the management of fall armyworm. Borrowing on the review of cases on successful pest management using area-wide approaches, we recommend the implementation of institutional, policy and community arrangements that enable regional deployment of control programs for wide-scale management of fall armyworm.

3.1. Enhanced regional and national collaboration

The current institutional arrangements for fall armyworm control in Africa include the FAO-led Global Action for Fall Armyworm Control. The three-year global initiative takes radical, direct and coordinated measures to strengthen prevention and sustainable pest control capacities at a global level. Some countries have established fall armyworm national task forces involving multi-institutions and multidisciplinary teams. In Ghana for example, fall armyworm control was coordinated through state committees, and ensured the supply of pesticides (bio-rationales), mass awareness campaigns and workshops for technical teams to raise awareness and promote participation (Kansiime et al., 2020). There are also other institutions such as international organizations and NGOs supporting specific components of the response such as farmer awareness, research and early warning systems at the regional and country levels. There is a need to strengthen regional and national collaboration for research, monitoring and early warning, development of coordinated actions, and policy instruments to enable sustainable management of fall armyworm. Collaboration leverages available resources to avert challenges associated with limited government funding for agriculture R&D.

3.2. Public-private partnerships to enhance access to low-cost farmer-friendly practices

Many fall armyworm control options have been evaluated in different contexts in Africa that are based on area-wide applications such as biological control options using entomopathogenic microbes and parasitic wasps (Niassy et al., 2021). Similarly, efforts to develop fall armyworm-*Bt*- resistant varieties have been trialed in different parts of the world including Africa (Bilbo et al., 2020; Brewer et al., 2014; Michelotto et al., 2017; Overton et al., 2021). There are also many potential low-cost smallholder-friendly solutions building on agroecology practice and farmer-local knowledge that have been tested with relative levels of efficacy (Harrison et al., 2019). These options need to be made available to farmers as part of the fall armyworm area-wide integrated pest management (IPM) strategy. Fostering public-private partnerships will ensure the developed technologies are continuously made available to farmers through available input distribution channels. For example, pest-resistant seeds, biopesticides and other biological control agents have a high potential for the private sector to produce and market them. Private sector involvement and promotion can help solve the generic problem that farmers are unaware of AWPM-compatible solutions (Norton et al., 2019).

3.3. Farmer awareness and knowledge

Area-wide pest management represents a departure from typical farm management practices, and as such, multiple methods are needed to promote its diffusion among farming communities (Harris et al., 2013). These include integrated mass media campaigns, open-access information materials, extension visits, field days, and farmer field schools to enable experiential learning. Many information sources are currently available on fall armyworm and need to be sufficiently updated with new techniques and promoted for wide-scale use by extension and farmers. Other available resources that help with field diagnosis include; USDA-APHIS PestLens (https://pestlens.info/), PestNet Listserv (www.pestnet.org), Plantwise knowledge bank (www.plantwise.org/knowledgebank), and CIMMYT MaizeDoctor (http://maizedoctor.org/). CABI has also developed the 'Fall armyworm information portal' through CABI's open-access Invasive Species Compendium (www.cabi.org/isc/fallarmyworm) to further facilitate access to all of the available information in one place. At the country level, training of technical personnel and fall armyworm awareness campaigns have also been done in partnership with the government, NGOs, and private sector. The campaigns provide information on the identification of fall armyworm, scouting and timely action, and possible management practices, and these need to be heightened to ensure reach.

3.4. Community-led AWPM

As described in this review, the field-by-field approach to managing a highly mobile pest such as fall armyworm is inefficient due to its dispersal mechanisms creating interdependency between farmers. Yet, smallholders still apply field-by-field management practices, that also vary across countries, regions, and places. This is observed by the fact that most farmers have to manage their limited resources individually and that the option of collectively managing a pest is unknown to most smallholder farmers. As more research is done on technologies that are based on area-wide management, farmer organization around local community structures such as farmer cooperatives can play a big role in enhancing AWPM of fall armyworm as it provides opportunities for accessing knowledge, inputs and other resources, addressing some of the participation barriers. Development of community-AWPM plans with key actions and responsibilities can enlist the trust and support of smallholders to participate in AWPM activities. Community involvement is critical in the assessment of the feasibility and testing of the effectiveness of available technical options, their social acceptability, and cultural suitability before starting an AWPM. Adequate local support remains largely a key component to achieving proper control of highly mobile pests in Africa.

4. Conclusion

A review of the literature shows several examples in many parts of the world where AWPM projects have operated successfully to protect major field crops menaced by insect pests. The success of AWPM programs was dependent on the continuous and positive interactions between farmers, agricultural advisory services providers, researchers, and government personnel. The AWPM programs were based on multi-year planning and availability of an organization (or collaborative effort) dedicated exclusively to its implementation, and the incorporation of environmental- and farmer-friendly pest management techniques. Further, AWMP programs worked well when they were able to leverage the existing social and economic connections between farmers, usually at a landscape level. However, achieving effective area-wide pest management in Africa still faces several challenges. These challenges have become more important today compared to before due to various institutional, policy, market and socio-economic factors. As such, farmers continue to apply control measures on a never-ending field-by-field basis. For fall armyworm, control options that are based on area-wide applications have been trialed but remain at the field testing level with limited release or commercialization. There have been multi-stakeholder continental and national efforts to ensure monitoring and management of the fall armyworm in African countries, but local-level efforts where the impact is felt most remain largely fragmented. The prospects for the sustainable management of fall armyworm and other highly mobile pests should be the engagement of stakeholders, farmers and the general public in awareness of area-wide management efforts, as well as the establishment of local structures and institutional arrangements to support the long-term viability of AWPM programs. Regional and national collaboration for research, monitoring and early warning should be promoted to leverage resources and avert challenges associated with limited funding. Finally, fostering public-private partnerships will create an outlook for developed fall armyworm control products enabling wide utilization.

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Data availability statement

Data sharing does not apply to this article as no new data were created or analyzed in this study.

Public interest statement

Invasive pests, like the fall armyworm, pose a significant threat to our environment, food security, and economy. They destroy crops, disrupt ecosystems, and make it necessary to use more dangerous pesticides. Area-wide integrated pest management is a sustainable and eco-friendly solution that benefits us all. By using natural predators, resistant crops, cultural practices, and precise monitoring, we reduce the need for chemical pesticides and protect our environment. In addition to preserving our food supply, this strategy promotes the well-being of pollinators and other useful insects. Farmers, stakeholders, and the general public play vital roles in area-wide pest management by ensuring coordinated and synchronized actions aimed at maintaining the pest below economic levels.

References

Abate, T., van Huis, A., & Ampofo, J. (2000). Pest management strategies in traditional agriculture: An African perspective. *Annual Review of Entomology*, *45*(1), 631–659. https://doi.org/10.1146/annurev.ento.45.1.631

Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., Colmenarez, Y., Corniani, N., Day, R., Regan Early, R., Julien Godwin, J., Gomez, J., Gonzalez-Moreno, P., Murphy, S. T., Oppong-Mensah, B., Phiri, N., Pratt, C., Richards, G., Silvestri, S., & Witt, A. (2017). *Fall armyworm: Impacts and implications for Africa. Evidence Note.* https://www.invasive-species.org/fawevidencenote

Adom, M., Fening, K. O., Billah, M. K., Wilson, D. D., Hevi, W., Clottey, V. A., Ansah-Amprofi, F., & Bruce, A. Y. (2021). Pest status, bio-ecology and management of the false codling moth, *Thaumatotibia leucotreta* (Meyrick) (Lepidoptera: Tortricidae) and its implication for international trade. *Bulletin of Entomological Research*, *111*(1), 17–30. Cambridge Core. https://doi.org/10.1017/S0007485320000358

Aekthong, S., & Rattanakul, C. (2019). Investigating the use of wasps anagyrus lopezi as a biological control agent for cassava mealybugs: Modeling and simulation. *Advances in Difference Equations*, *2019*(1), 237. https://doi.org/10.1186/s13662-019-2176-3

Agmas, B., Adugna, M., & Staddon, P. L. (2020). Attitudes and practices of farmers with regard to pesticide use in NorthWest Ethiopia. *Cogent Environmental Science*, *6*(1), 1791462. https://doi.org/10.1080/23311843.2020.1791462

Aitken, L., Brough, E., Norton, G., & Foster, J. (1995). *Industry and community participation in agricultural extension: An integrated pest management case study*. Cooperative Research Centre for Tropical Pest Management.

Akeme, C. N., Ngosong, C., Sumbele, S. A., Aslan, A., Tening, A. S., Krah, C. Y., Kamanga, B. M., Denih, A., & Nambangia, O. J. (2021). Different controlling methods of fall armyworm (Spodoptera frugiperda) in maize farms of small-scale producers in Cameroon. *IOP Conference Series: Earth and Environmental Science*, *911*(1), 012053. https://doi.org/10.1088/1755-1315/911/1/012053

Alwang, J., Norton, G., & Larochelle, C. (2019). Obstacles to widespread diffusion of IPM in developing countries: Lessons from the field. *Journal of Integrated Pest Management*, *10*(1), 10. https://doi.org/10.1093/jipm/pmz008

Babendreier, D., Hou, M., Tang, R., Zhang, F., Vongsabouth, T., Win, K. K., Kang, M., Peng, H., Song, K., Annamalai, S., Horgan, F. G., & Adamczyk, J. (2020). Biological control of lepidopteran pests in rice: A multi-nation case study from Asia. *Journal of Integrated Pest Management*, *11*(1), 5. https://doi.org/10.1093/jipm/pmaa002

Bariw, S. A., Kudadze, S., Adzawla, W., & Yildiz, F. (2020). Prevalence, effects and management of fall army worm in the Nkoranza South Municipality, Bono East region of Ghana. *Cogent Food & Agriculture*, *6*(1), Article 1. 1800239. https://doi.org/10.1080/23311932.2020.1800239

Bebber, D. P., Holmes, T., & Gurr, S. J. (2014). The global spread of crop pests and pathogens. *Global Ecology and Biogeography*, *23*(12), 1398–1407. https://doi.org/10.1111/geb.12214

Bellotti, A., Herrera Campo, B. V., & Hyman, G. (2012). Cassava production and pest management: Present and potential threats in a changing environment. *Tropical Plant Biology*, *5*(1), 39–72. https://doi.org/10.1007/s12042-011-9091-4

Bilbo, T. R., Reay-Jones, F. P. F., Greene, J. K., & Musser, F. (2020). Evaluation of insecticide thresholds in late-planted bt and non-bt corn for management of Fall armyworm (Lepidoptera: Noctuidae). *Journal of Economic Entomology*, *113*(2), 814–823. https://doi.org/10.1093/jee/toz364

Bloem, S., Carpenter, J., & Hofmeyr, H. (2007). Area-wide control tactics for the false codling moth thaumatotibia leucotreta in South Africa: A potential invasive species. In M. J. B. Vreysen, A. S. Robinson, & J. Hendrichs (Eds.), *Area-wide control of insect pests* (pp. 351–359). Springer Netherlands.

Boersma, N. (2021). The suppression of the false codling moth in South Africa using an AW-IPM approach with a sit component. In *Area-wide integrated pest management* (pp. 93–109). CRC Press. https://doi.org/10.1201/9781003169239-6.

Brewer, M. J., Odvody, G. N., Anderson, D. J., & Remmers, J. C. (2014). A comparison of Bt Transgene, hybrid background, water stress, and insect stress effects on corn leaf and ear injury and subsequent yield. *Environmental Entomology*, *43*(3), 828–839. https://doi.org/10.1603/EN13309

Caniço, A., Mexia, A., & Santos, L. (2021). Farmers' knowledge, perception and management practices of fall armyworm (Spodoptera frugiperda Smith) in Manica province, Mozambique. *NeoBiota*, *68*, 127–143. https://doi.org/10.3897/neobiota.68.62844

Cheng, X., Chang, C., & Dai, S. M. (2010). Responses of striped stem borer, Chilo suppressalis (Lepidoptera: Pyralidae), from Taiwan to a range of insecticides. *Pest Management Science*, *66*(7), 762–766. https://doi.org/10.1002/ps.1939

Chimweta, M., Nyakudya, I. W., Jimu, L., & Bray Mashingaidze, A. (2020). Fall armyworm [Spodoptera frugiperda (J.E. Smith)] damage in maize: Management options for flood-recession cropping smallholder farmers. *International Journal of Pest Management*, *66*(2), Article 2. 142–154. https://doi.org/10.1080/09670874.2019.1577514

Colella, C., Carradore, R., & Cerroni, A. (2019). Problem setting and problem solving in the case of olive quick decline syndrome in Apulia, Italy: A sociological approach. *Phytopathology*, *109*(2), 187–199. https://doi.org/10.1094/PHYTO-07-18-0247-FI

Day, R., Abrahams, P., Bateman, M., Beale, T., Clottey, V., Cock, M., Colmenarez, Y., Corniani, N., Early, R., Godwin, J., Gomez, J., Moreno, P. G., Murphy, S. T., Oppong-Mensah, B., Phiri, N., Pratt, C., Richards, G., Silvestri, S., & Witt, A. (2017). Fall armyworm: Impacts and implications for Africa. *Outlooks of Pest Management*, *28*(5), 196–201. https://doi.org/10.1564/v28

Day, R., Haggblade, S., Moephuli, S., Mwang'ombe, A., & Nouala, S. (2022). Institutional and policy bottlenecks to IPM. *Current Opinion in Insect Science*, *52*, 100946. https://doi.org/10.1016/j.cois.2022.100946

De Groote, H., Kimenju, S. C., Munyua, B., Palmas, S., Kassie, M., & Bruce, A. (2020). Spread and impact of fall armyworm (Spodoptera frugiperda J.E. Smith) in maize production areas of Kenya. *Agriculture, Ecosystems and Environment*, *292*, 106804. https://doi.org/10.1016/j.agee.2019.106804

Dively, G. P., Venugopal, P. D., Bean, D., Whalen, J., Holmstrom, K., Kuhar, T. P., Doughty, H. B., Patton, T., Cissel, W., & Hutchison, W. D. (2018). Regional pest suppression associated with widespread Bt maize adoption benefits vegetable growers. *Proceedings of the National Academy of Sciences*, *115*(13), 3320–3325. https://doi.org/10.1073/pnas.1720692115

Dixon-Woods, M., Agarwal, S., Jones, D., Young, B., & Sutton, A. (2005). Synthesising qualitative and quantitative evidence: A review of possible methods. *Journal of Health Services Research & Policy*, *10*(1), 45–53. https://doi.org/10.1177/135581960501000110

Early, R., González-Moreno, P., Murphy, S. T., & Day, R. (2018). Forecasting the global extent of invasion of the cereal pest Spodoptera frugiperda, the fall armyworm. *NeoBiota*, *40*, 25–50. https://doi.org/10.3897/neobiota.40.28165

Ekesi, S., Chabi-Olaye, A., Subramanian, S., & Borgemeister, C. (2011). Horticultural pest management and the African Economy: Success, challenges and opportunities in a global environment. *ISHS Acta Horticulturae*, *911*(911), 165–183. https://doi.org/10.17660/ActaHortic.2011.911.17

Epanchin-Niell, R. S. (2017). Economics of invasive species policy and management. *Biological Invasions*, *19*(11), 3333–3354. https://doi.org/10.1007/s10530-017-1406-4

Eschen, R., Beale, T., Bonnin, J. M., Constantine, K. L., Duah, S., Finch, E. A., Makale, F., Nunda, W., Ogunmodede, A., Pratt, C. F., Thompson, E., Williams, F., Witt, A., & Taylor, B. (2021). Towards estimating the economic cost of invasive alien species to African crop and livestock production. *CABI Agriculture and Bioscience*, *2*(1), 18. https://doi.org/10.1186/s43170-021-00038-7

FAO. (2021). *FAOSTAT database. Food and Agriculture Organization (FAO) of the United Nations*. http://www.fao.org/faostat/en/#home

Garcia-Figuera, S., Grafton-Cardwell, E. E., Babcock, B. A., Lubell, M. N., & McRoberts, N. (2021). Institutional approaches for plant health provision as a collective action problem. *Food Security*, *13*(2), 273–290. https://doi.org/10.1007/s12571-020-01133-9

Giovani, B., Blümel, S., Lopian, R., Teulon, D., Bloem, S., Galeano Martínez, C., Beltrán Montoya, C., Urias Morales, C. R., Dharmapuri, S., Timote, V., Horn, N., Chouibani, M., Mezui M'Ella, J. G., Herrera, V., Castinel, A., Goletsos, C., Moeller, C., Naumann, I. … Rossi, J. P. (2020). Science diplomacy for plant health. *Nature Plants*, *6*(8), 902–905. https://doi.org/10.1038/s41477-020-0744-x

Goergen, G., Kumar, P. L., Sankung, S. B., Togola, A., Tamò, M., & Luthe, D. S. (2016). First report of outbreaks of the Fall armyworm Spodoptera frugiperda (J E Smith) (Lepidoptera, Noctuidae), a new alien invasive pest in west and Central Africa. *Public Library of Science ONE*, *11*(10), e0165632. https://doi.org/10.1371/journal.pone.0165632

Harris, L. M., Norton, G. W., Karim, A. N. M. R., Alwang, J., & Taylor, D. B. (2013). Bridging the information gap with cost-effective dissemination strategies: The case of integrated pest management in Bangladesh. *Journal of Agricultural and Applied Economics*, *45*(4), 639–654. https://doi.org/10.1017/S1074070800005174

Harrison, R. D., Thierfelder, C., Baudron, F., Chinwada, P., Midega, C., Schaffner, U., & van den Berg, J. (2019). Agroecological options for fall armyworm (Spodoptera frugiperda JE Smith) management: Providing low-cost, smallholder friendly solutions to an invasive pest. *Journal of Environmental Management*, *243*, 318–330. https://doi.org/10.1016/j.jenvman.2019.05.011

Hillocks, R. J. (2005). Is there a role for bt cotton in IPM for smallholders in Africa? *International Journal of Pest Management*, *51*(2), 131–141. https://doi.org/10.1080/09670870500117292

Hofmeyr, J. H., Hofmeyr, M., Carpenter, J. E., Bloem, S., & Slabbert, J. P. (2016). Sterile insect releases for control of thaumatotibia leucotreta (Lepidoptera: Tortricidae): An assessment on semi-commercial scale. *African Entomology*, *24*(1), 80–89. https://doi.org/10.4001/003.024.0080

Horgan, F. G., & Crisol, E. (2013). Hybrid rice and insect herbivores in Asia. *Entomologia Experimentalis Et Applicata*, *148*(1), 1–19. https://doi.org/10.1111/eea.12080

Hulme, P. E. (2006). Beyond control: Wider implications for the management of biological invasions. *Journal of Applied Ecology*, *43*(5), 835–847. https://doi.org/10.1111/j.1365-2664.2006.01227.x

Hussain, D., Saleem, M., Ghouse, G., & Abbas, M. (2015). Insecticide resistance in field populations of helicoverpa armigera (hübner) (Lepidoptera: Noctuidae). *Journal of Entomological Science*, *50*(2), 119–128. https://doi.org/10.18474/JES14-24.1

Jørs, E., Aramayo, A., Huici, O., Konradsen, F., & Gulis, G. (2017). Obstacles and opportunities for diffusion of integrated pest management strategies reported by Bolivian small-scale farmers and agronomists. *Environmental Health Insights*, *11*, 1178630217703390. https://doi.org/10.1177/1178630217703390

Kansiime, M. K., Beseh, P., Hevi, W., Lamontagne-Godwin, J., Clottey, V. A., Rwomushana, I., Day, R. K., Rware, H., Aboagye, E., & Williams, F. (2020). *Implementation of fall armyworm management plan in Ghana: Outcomes and lessons for invasives species management*. CABI Study Brief 32: Learning. https://doi.org/10.1079/CABICOMM-62-8138

Kansiime, M. K., Mugambi, I., Rwomushana, I., Nunda, W., Lamontagne-Godwin, J., Rware, H., Phiri, N. A., Chipabika, G., Ndlovu, M., & Day, R. (2019). Farmer perception of fall armyworm (Spodoptera frugiderda J.E. Smith) and farm-level management practices in Zambia. *Pest Management Science*, *75*(10), 2840–2850. https://doi.org/10.1002/ps.5504

Kassie, M., Wossen, T., De Groote, H., Tefera, T., Sevgan, S., & Balew, S. (2020). Economic impacts of fall armyworm and its management strategies: Evidence from southern Ethiopia. *European Review of Agricultural Economics*, *47*(4), Article 4. 1473–1501. https://doi.org/10.1093/erae/jbz048

Kathage, J., & Qaim, M. (2012). Economic impacts and impact dynamics of bt (Bacillus thuringiensis) cotton in India. *Proceedings of the National Academy of Sciences*, *109*(29), 11652–11656. https://doi.org/10.1073/pnas.1203647109

Keetch, D. P., Webster, J. W., Ngqaka, A., Akanbi, R., & Mahlanga. (2005). Bt maize for small scale farmers: A case study. *African Journal of Biotechnology*, *4*(13). 1505–1509. https://doi.org/10.4314/ajfand.v4i13.71805

Kibira, M., Affognon, H., Njehia, B., Muriithi, B., Mohamed, S., & Ekesi, S. (2015). Economic evaluation of integrated management of fruit fly in mango production in Embu County, Kenya. *African Journal of Agricultural and Resource Economics*, *10*(4), 343–353. https://doi.org/10.22004/ag.econ.229815

Koffi, D., Agboka, K., Adenka, D. K., Osae, M., Tounou, A. K., Anani Adjevi, M. K., Fening, K. O., Meagher, R. L., Jr., & Schmidt-Jeffris, R. (2020). Maize infestation of Fall armyworm (Lepidoptera: Noctuidae) within agro-ecological zones of Togo and Ghana in West Africa 3 yr after its invasion. *Environmental Entomology*, *49*(3), 645–650. https://doi.org/10.1093/ee/nvaa048

Kruger, H. (2016). Designing local institutions for cooperative pest management to underpin market access: The case of industry-driven fruit fly area-wide management. *International Journal of the Commons*, *10*(1), 176–199. https://doi.org/10.18352/ijc.603

Lansink, A. O. (2011). Public and private roles in plant health management. *Food Policy*, *36*(2), 166–170. https://doi.org/10.1016/j.foodpol.2010.10.006

Larochelle, C., Alwang, J., Travis, E., Barrera, V. H., & Dominguez Andrade, J. M. (2019). Did you really get the message? Using text reminders to stimulate adoption of agricultural technologies. *The Journal of Development Studies*, *55*(4), 548–564. https://doi.org/10.1080/00220388.2017.1393522

Litsinger, J. A., Alviola, A. L., Cruz, C. G. D., Canapi, B. L., Batay-An, E. H., & Barrion, A. T. (2006). Rice white stemborer scirpophaga innotata (walker) in southern Mindanao, Philippines. II. Synchrony of planting and natural enemies. *International Journal of Pest Management*, *52*(1), 23–37. https://doi.org/10.1080/09670870600552463

Lux, S. A., Ekesi, S., Dimbi, S., Mohamed, S., & Billah, M. (2003). Mango Infesting Fruit Flies in Africa. Perspectives and Limitations of Biological Approaches to Their Management. In P. Neuenschwander, C. Borgemeister, & J. Langewald(Eds.), *Biological Control in Integrated Pest Management Systems in Africa* (pp. 277–293). CABI. https://doi.org/10.1079/9780851996394.0277

Macauley, H. (2015). *Cereal crops: Rice, maize, Millet, sorghum, wheat*. Background paper, Feeding Africa Conference. 21-23 October, 2015. https://www.afdb.org/fileadmin/uploads/afdb/Documents/Events/DakAgri2015/Cereal_Crops-_Rice__Maize__Millet__Sorghum__Wheat.pdf

Mankad, A., Loechel, B., & Measham, P. F. (2017). Psychosocial barriers and facilitators for area-wide management of fruit fly in southeastern Australia. *Agronomy for Sustainable Development*, *37*(6), 67. https://doi.org/10.1007/s13593-017-0477-z

Marshall, G. R., Coleman, M. J., Sindel, B. M., Reeve, I. J., & Berney, P. J. (2016). Collective action in invasive species control, and prospects for community-based governance: The case of serrated tussock (nassella trichotoma) in New South Wales, Australia. *Land Use Policy*, *56*, 100–111. https://doi.org/10.1016/j.landusepol.2016.04.028

Martin, P., Le Gal, E., & Choy, D. L. (2016). Effect of social and institutional fragmentation on collective action in Peri-Urban settings. In B. Maheshwari, B. Thoradeniya, & V. P. Singh (Eds.), *Balanced urban development: Options and strategies for liveable cities* (pp. 465–480). Springer International Publishing. https://doi.org/10.1007/978-3-319-28112-4_28.

McClelland, S. (2002). Indonesia's integrated pest management in rice: Successful integration of policy and education. *Environmental Practice*, *4*(4), 191–195. Cambridge Core. https://doi.org/10.1017/S1466046602990095

Michelotto, M. D., Neto, J. C., Pirotta, M. Z., Duarte, A. P., de Feitas, R. S., & Finoto, E. L. (2017). Efficacy of transgenic mayze insecticide treatment to control fall armyworm in late-season maize in São Paulo state, Brazil. *Ciência e Agrotecnologia*, *41*(12), 128–138. https://doi.org/10.1590/1413-70542017412020816

Muniappan, R., Shepard, B., Watson, G., Carner, G., Rauf, A., Sartiami, D., Hidayat, P., Afun, J., Goergen, G., & Rahman, A. Z. (2009). New records of invasive insects (Hemiptera: Sternorrhyncha) in Southeast Asia and West Africa. *Journal of Agricultural and Urban Entomology*, *26*(4), 167–174. https://doi.org/10.3954/1523-5475-26.4.167

Muriithi, B. W., Affognon, H. D., Diiro, G. M., Kingori, S. W., Tanga, C. M., Nderitu, P. W., Mohamed, S. A., & Ekesi, S. (2016). Impact assessment of Integrated Pest Management (IPM) strategy for suppression of mango-infesting fruit flies in Kenya. *Crop Protection*, *81*, 20–29. https://doi.org/10.1016/j.cropro.2015.11.014

Muriithi, B. W., Gathogo, N. G., Diiro, G. M., Mohamed, S. A., & Ekesi, S. (2020). Potential adoption of integrated pest management strategy for suppression of mango fruit flies in East Africa: An ex ante and ex post analysis in Ethiopia and Kenya. *Agriculture*, *10*(7), 278. https://doi.org/10.3390/agriculture10070278

Murray, K., Jepson, P., & Chaola, M. (2019). *Fall armyworm management by maize smallholders in Malawi: An integrated pest management strategic plan*, Mexico, CDMX, CIMMYT. https://hdl.handle.net/10883/20170

Naranjo, S. E. (2011). Impacts of Bt transgenic cotton on integrated pest management. *Journal of Agricultural and Food Chemistry*, *59*(11), 5842–5851. Article 11. https://doi.org/10.1021/jf102939c

Neuenschwander, P. (2001). Biological control of the cassava mealybug in Africa: A review. *Biological Control*, *21*(3), 214–229. https://doi.org/10.1006/bcon.2001.0937

Niassy, S., Agbodzavu, M. K., Kimathi, E., Mutune, B., Abdel-Rahman, E. F. M., Salifu, D., Hailu, G., Belayneh, Y. T., Felege, E., Tonnang, H. E. Z., Ekesi, S., & Subramanian, S. (2021). Bioecology of fall armyworm Spodoptera frugiperda (J. E. Smith), its management and potential patterns of seasonal spread in Africa. *Public Library of Science ONE*, *16*(6), e0249042. https://doi.org/10.1371/journal.pone.0249042

Njuguna, E., Nethononda, P. D., Maredia, K., Mbabazi, R., Kachapulula, P. W., Rowe, A., & Ndolo, D. (2021). Experiences and Perspectives on Spodoptera frugiperda (Lepidoptera: Noctuidae) Management in Sub-Saharan Africa. *Journal of Integrated Pest Management*, *12*(1, 7), 1–9. https://doi.org/10.1093/jipm/pmab002

Norton, G. W., Alwang, J., Kassie, M., & Muniappan, R. (2019). *Economic impacts of IPM practices in developing countries* (pp. 140–154). CABI Publishing. https://doi.org/10.1079/9781786393678.0140

Nwanze, K. F. (1982). Relationships between cassava root yields and crop infestations by the mealybug, phenacoccus manihoti. *Tropical Pest Management*, *28*(1), 27–32. https://doi.org/10.1080/09670878209370669

Osborn, D., Cutter, A., & Ullah, F. (2015). *Universal sustainable development goals: Understanding the transformational challenge for developed countries. Report of a study by stakeholder forum, May 2015*. https://sustainabledevelopment.un.org/content/documents/1684SF_-_SDG_Universality_Report_-_May_2015.pdf

Ostrom, E. (2010). Polycentric systems for coping with collective action and global environmental change. *20th Anniversary Special Issue*, *20*(4), 550–557. https://doi.org/10.1016/j.gloenvcha.2010.07.004

Overton, K., Maino, J. L., Day, R., Umina, P. A., Bett, B., Carnovale, D., Ekesi, S., Meagher, R., & Reynolds, O. L. (2021). Global crop impacts, yield losses and action thresholds for fall armyworm (Spodoptera frugiperda): A review. *Crop Protection*, *145*, 105641. https://doi.org/10.1016/j.cropro.2021.105641

Paré, G., Trudel, M.-C., Jaana, M., & Kitsiou, S. (2015). Synthesizing information systems knowledge: A typology of literature reviews. *Information & Management*, *52*(2), 183–199. https://doi.org/10.1016/j.im.2014.08.008

Parsa, S., Morse, S., Bonifacio, A., Chancellor, T. C. B., Condori, B., Crespo-Pérez, V., Hobbs, S. L. A., Kroschel, J., Ba, M. N., Rebaudo, F., Sherwood, S. G., Vanek, S. J., Faye, E., Herrera, M. A., & Dangles, O. (2014). Obstacles to integrated pest management adoption in developing countries. *Proceedings of the National Academy of Sciences*, *111*(10), 3889–3894. https://doi.org/10.1073/pnas.1312693111

Pratt, C. F., Constantine, K. L., & Murphy, S. T. (2017). Economic impacts of invasive alien species on African smallholder livelihoods. *Food Security Governance in Latin America*, *14*, 31–37. https://doi.org/10.1016/j.gfs.2017.01.011

Pretty, J., & Bharucha, Z. P. (2015). Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects*, *6*(1), 152–182. https://doi.org/10.3390/insects6010152

Resosudarmo, B. P. (2016). *Impact of the integrated pest management program on the Indonesian economy. EEPSEA research report Rr2016059. Economy and Environment Program for Southeast Asia (EEPSEA)*. https://ideas.repec.org/p/eep/report/rr2016059.html

Rwomushana, I., Bateman, M., Beale, T., Beseh, P. K., Cameron, K., Chiluba, M., Clottey, V., Davis, T., Day, R. K., Early, R., Godwin, J., Gonzalez-Moreno, P., Kansiime, M. K., Kenis, M., Makale, F., Mugambi, I., Murphy, S. T., Nunda, W., Phiri, N. A., Pratt, C., & Tambo, J. A. (2019). *Fall armyworm: Impacts and implication for Africa*. CAB International. https://www.invasive-species.org/wp-content/uploads/sites/2/2019/02/FAW-Evidence-Note-October-2018.pdf

Sandler, T. (2015). Collective action: Fifty years later. *Public Choice*, *164*(3), 195–216. https://doi.org/10.1007/s11127-015-0252-0

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, *3*(3), 430–439. https://doi.org/10.1038/s41559-018-0793-y

Scheidegger, L., Niassy, S., Midega, C., Chiriboga, X., Delabays, N., Lefort, F., Zürcher, R., Hailu, G., Khan, Z., & Subramanian, S. (2021). The role of desmodium intortum, Brachiaria sp. and Phaseolus vulgaris in the management of fall armyworm Spodoptera frugiperda (J. E. Smith) in maize cropping systems in Africa. *Pest Management Science*, *77*(5), 2350–2357. https://doi.org/10.1002/ps.6261

Slavin, R. E. (1995). Best evidence synthesis: An intelligent alternative to meta-analysis. *Journal of Clinical Epidemiology*, *48*(1), 9–18. https://doi.org/10.1016/0895-4356(94)00097-a

Tambo, J. A., Day, R. K., Lamontagne-Godwin, J., Silvestri, S., Beseh, P. K., Oppong-Mensah, B., Phiri, N. A., & Matimelo, M. (2020a). Tackling fall armyworm (Spodoptera frugiperda) outbreak in Africa: An analysis of farmers' control actions. *International Journal of Pest Management*, *66*(4), 298–310. https://doi.org/10.1080/09670874.2019.1646942

Tambo, J. A., Kansiime, M. K., Mugambi, I., Rwomushana, I., Kenis, M., Day, R. K., & Lamontagne-Godwin, J. (2020b). Understanding smallholders' responses to fall armyworm (Spodoptera frugiperda) invasion: Evidence from five African countries. *Science of the Total Environment*, *740*, 140015. https://doi.org/10.1016/j.scitotenv.2020.140015

Tay, W. T., Soria, M. F., Walsh, T., Thomazoni, D., Silvie, P., Behere, G. T., Anderson, C., Downes, S., & Knapp, M. (2013). A brave new world for an old world pest: Helicoverpa armigera (Lepidoptera: Noctuidae) in Brazil. *Public Library of Science ONE*, *8*(11), e80134. https://doi.org/10.1371/journal.pone.0080134

Thancharoen, A., Lankaew, S., Moonjuntha, P., Wongphanuwat, T., Sangtongpraow, B., Ngoenklan, R., Kittipadakul, P., & Wyckhuys, K. A. G. (2018). Effective biological control of an invasive mealybug pest enhances root yield in cassava. *Journal of Pest Science*, *91*(4), 1199–1211. https://doi.org/10.1007/s10340-018-1012-y

Thorburn, C. (2015). The rise and demise of integrated pest management in rice in Indonesia. *Insects*, *6*(2), 381–408. https://doi.org/10.3390/insects6020381

Timilsena, P. B., Niassy, S., Kimathi, E., Abdel-Rahman, E. M., Seidl-Adams, I., Wamalwa, M., Tonnang, H. E. Z., Ekesi, S., Hughes, D. P., Rajotte, E. G., & Subramanian, S. (2022). Potential distribution of fall armyworm in Africa and beyond, considering climate change and irrigation patterns. *Scientific Reports*, *12*(1), 539. https://doi.org/10.1038/s41598-021-04369-3

Travers, H., Clements, T., Keane, A., & Milner-Gulland, E. J. (2011). Incentives for cooperation: The effects of institutional controls on common pool resource extraction in Cambodia. *Ecological Economics*, *71*(C), 151–161. https://doi.org/10.1016/j.ecolecon.2011.08.020

Vontas, J., Hernández-Crespo, P., Margaritopoulos, J. T., Ortego, F., Feng, H.-T., Mathiopoulos, K. D., & Hsu, J.-C. (2011). Insecticide resistance in Tephritid flies. *Pesticide Biochemistry and Physiology*, *100*(3), 199–205. https://doi.org/10.1016/j.pestbp.2011.04.004

Vreysen, M. J. B., Robinson, A. S., & Hendrichs, J. (Eds.). (2007). *Area-wide control of insect pests: From research to field implementation*. Springer. https://doi.org/10.1007/978-1-4020-6059-5

Wachira, K. (2021). Countries spend less than 1% of GDP on research 17 June 2021. *University World News*.https://www.universityworldnews.com/post.php?story=20210616151534847

Wardhani, M. A. (1992). Developments in IPM: the Indonesian case. In Oli (Ed.), *Integrated Pest Management in the Asia-Pacific Region CAB International, Kuala Lumpur* (pp. 27–35).

Wilson, L. J., Whitehouse, M. E. A., & Herron, G. A. (2018). The management of insect pests in Australian cotton: An evolving story. *Annual Review of Entomology*, *63*(1), 215–237. https://doi.org/10.1146/annurev-ento-020117-043432

Wu, K.-M., Lu, Y.-H., Feng, H.-Q., Jiang, Y.-Y., & Zhao, J.-Z. (2008). Suppression of cotton bollworm in multiple crops in China in areas with bt toxin–containing cotton. *Science*, *321*(5896), 1676–1678. https://doi.org/10.1126/science.1160550

Wyckhuys, K. A. G., Orankanok, W., Ketelaar, J. W., Rauf, A., Goergen, G., & Neuenschwander, P. (2021). Biological control: Cornerstone of area-wide-integrated pest management for the cassava mealybug in tropical Asia. *Area-Wide Integrated Pest Management*, 17–32. https://doi.org/10.1201/9781003169239-3

Wyckhuys, K. A. G., Wongtiem, P., Rauf, A., Thancharoen, A., Heimpel, G. E., Le, N. T. T., Fanani, M. Z., Gurr, G. M., Lundgren, J. G., Burra, D. D., Palao, L. K., Hyman, G., Graziosi, I., Le, V. X., Cock, M. J. W., Tscharntke, T., Wratten, S. D., Nguyen, L. V., You, M. … Neuenschwander, P. (2018). Continental-scale suppression of an invasive pest by a host-specific parasitoid underlines both environmental and economic benefits of arthropod biological control. *PeerJ*, *6*, e5796. https://doi.org/10.7717/peerj.5796

Yang, Y., Li, Y., & Wu, Y. (2013). Current status of insecticide resistance in helicoverpa armigera after 15 years of bt cotton planting in China. *Journal of Economic Entomology*, *106*(1), 375–381. https://doi.org/10.1603/EC12286

Yigezu, G., & Mulatu, W. (2020). Local and indigenous knowledge of farmers management practice against fall armyworm (Spodoptera frugiperda) (J. E. Smith) (Lepidoptera: Noctuidae): A review. *Journal of Entomology and Zoology Studies*, *8*(1), 765–770.

Yung, L., Chandler, J., & Haverhals, M. (2015). Effective weed management, collective action, and landownership change in western Montana. *Invasive Plant Science & Management*, *8*(2), 193–202.

Zalucki, M. P., Adamson, D., & Furlong, M. J. (2009). The future of IPM: Whither or wither? *Australian Journal of Entomology*, *48*(2), 85–96. https://doi.org/10.1111/j.1440-6055.2009.00690.x

Zeddies, J., Schaaba, R. P., Neuenschwanderb, P., & Herrenb, H. R. (2000). Economics of biological control of cassava mealybug in Africa. *Agricultural Economics*, *24*(2), 209–219. https://doi.org/10.1016/s0169-5150(00)00064-5

Zhou, C., Wang, L., Price, M., Li, J., Meng, Y., & Yue, B.-S. (2020). Genomic features of the fall armyworm (Spodoptera frugiperda) (J.E. Smith) yield insights into its defense system and flight capability. *Entomological Research*, *50*(2), 100–112. https://doi.org/10.1111/1748-5967.12413