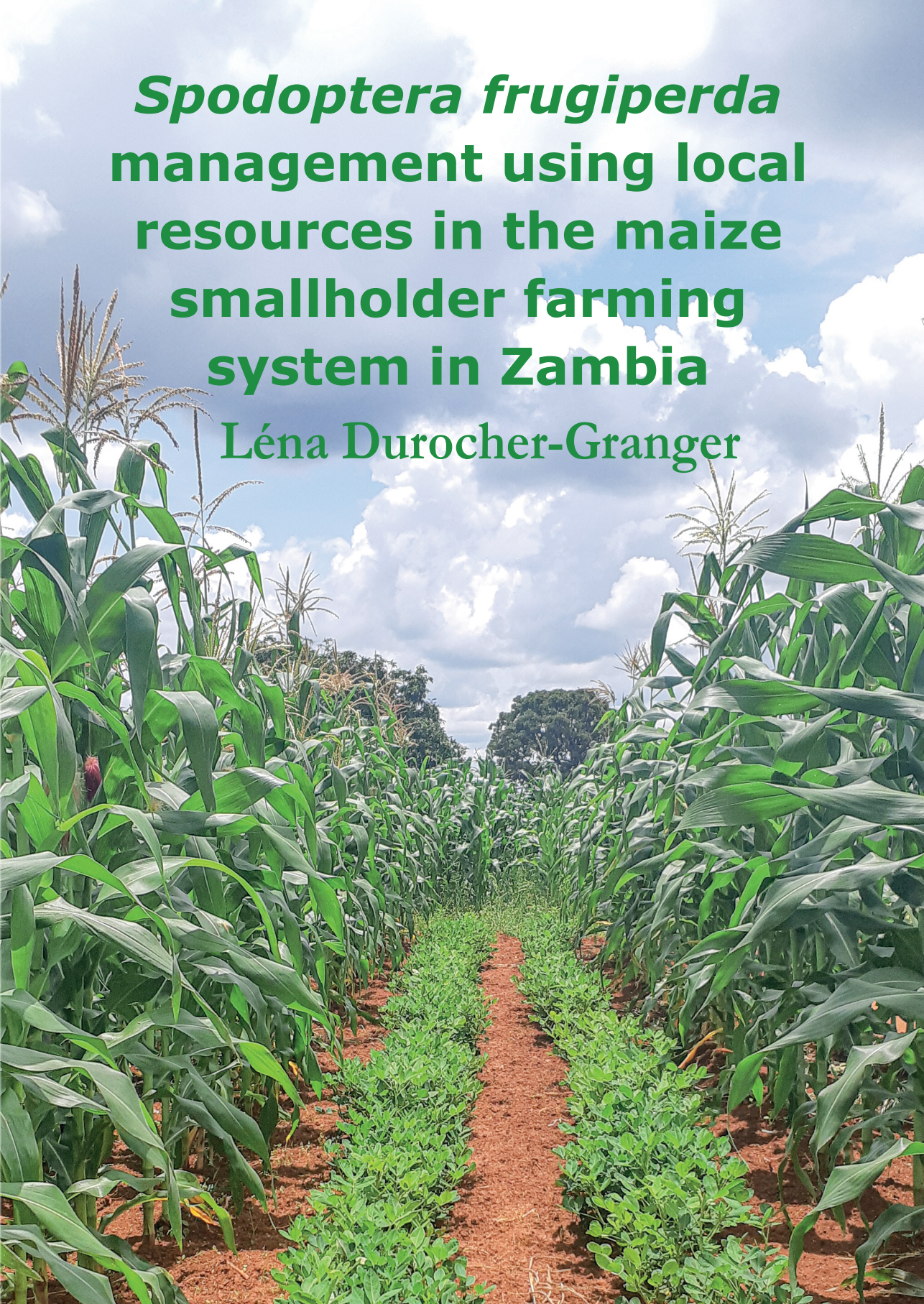
Spodoptera frugiperda management using local resources in the maize smallholder farming system in Zambia

Léna Durocher-Granger



Propositions

1. Individual practices relying on chemical pesticides hinder proper management of highly mobile insect pests.
   (this thesis)

2. Traditional leadership is essential for supporting the uptake of biocontrol practices in farming communities.
   (this thesis)

3. Transformative changes at institutional level are hindered by externally funded, short-term projects.

4. The quality of a PhD research is determined more by the application of the soft skills acquired than by formal training.

5. Existing extension curricula are ineffective in addressing collective action challenges in agriculture.

6. High costs of childcare remain detrimental for the professional career and growth of women.

Propositions belonging to the thesis, entitled

Spodoptera frugiperda management using local resources in the maize smallholder farming system in Zambia

Léna Durocher-Granger
Wageningen, 4th June 2026

Spodoptera frugiperda management using local resources in the maize smallholder farming system in Zambia

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Spodoptera frugiperda management using local resources in the maize smallholder farming system in Zambia

Léna Durocher-Granger

Thesis

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1 General introduction and thesis outline

Highly mobile invasive alien species (IAS) such as insect pests are particularly challenging to control once established and can pose serious threats to food security, especially in low- and middle-income countries (LMIC), where measures to prevent and eradicate new invasions are limited (Early et al., 2016). The rate of new bioinvasions have drastically increased since the last few decades and is predicted to keep increasing worldwide with globalization and international trade. Furthermore, combatting invasive species cannot be done in isolation. Therefore, global, national and regional collaborations are critical to develop programmes and implement interventions by integrating farming communities in the process who are often the most impacted by IAS (Garcia-Figuera et al., 2021). This interdisciplinary thesis integrates entomological and social science research to uncover the institutional and social factors needed at community level to sustainably manage IAS using local natural resources.

Invasive alien species impacts and challenges

IAS are plants or animal species that have been introduced outside their natural range, accidentally or deliberately through human activities negatively impacting native biodiversity, ecosystem services and human well-being and economy (Convention on Biological Diversity, 2025; International Union for Conservation of Nature, 2025). Characteristics that make IAS successful include rapid establishment, fast development and high reproductive rates, phenotypic plasticity, effective exploitation of resources, survival on a wide range of food types and in various environmental conditions, lack of natural enemies from their region of origin, high dispersal capacities and being fierce competitors for resources (Convention on Biological Diversity, 2025; Holzmueller & Jose, 2009; Stohlgren & Schnase, 2006). Although not all non-native species have negative effects, invasive crop pests and pathogens can have major disrupting ecological, economic and social impacts on food security and ecosystem resilience (Bebber et al., 2014; Early et al. 2016; Paini et al. 2016; Pratt et al. 2017). Sileshi et al. (2019) estimated the total annual losses across Africa from sixteen IAS affecting all categories of food crops to a very conservative USD 1 billion but more recently, this amount was recalculated at USD 65.58 billion for seven IAS on five agricultural crops (Eschen et al., 2021a). LMIC are particularly at risk of biological invasions due to limited national and regional phytosanitary capacities, absence of regulatory frameworks and policies, low investment in biosecurity, lack of coordination, poor public awareness and knowledge on IAS invasions (Early et al., 2016; Sileshi et al., 2019).

Spodoptera frugiperda

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), an IAS native to the Americas has become one of the most damaging insect pests worldwide after its accidental introduction and establishment in Africa and Asia since 2016 (Goergen et al., 2016; Kenis et al., 2023). Its impressive ability to colonize and establish in new environments is driven by its high mobility, high reproductive rate, lack of diapause and broad host range (CABI, 2019; Day et al., 2017; Hruska, 2019;

Sileshi et al., 2019). Indeed, FAW can fly up to 100 km per night, disperse about 500 km before oviposition and lay up to 1,000 eggs per female and feed on over 200 plant species. In its native range, FAW does not have a diapause phase in the lifecycle and is killed by frost (Hruska, 2019; Luginbill, 1928; Sileshi et al., 2019) which is a characteristic alongside the absence of its natural enemies from its native range that allowed it to thrive and spread rapidly across Africa. FAW usually has six larval stages but is known to have highly variable larval development, which can range from five to ten instars depending on host-plant suitability and climate (Montezano et al., 2019) and the final larval stage is the one causing the most damage to crops.

In its native range, a complex of parasitoid, predator, parasitic nematode and entomopathogen species kill *S. frugiperda* eggs, larvae, pupae and adults. Egg parasitoids such as *Trichogramma pretiosum* Riley are regularly found attacking FAW eggs at a parasitism rate of less than 5%. *Telenomus remus* (Nixon), which has been introduced from Asia, is found on rare occasions in the Americas on FAW eggs. *Chelonus insularis* Cresson, a braconid egg-larval parasitoid, is one of the most commonly found parasitoids across the Americas attacking FAW. Other common larval parasitoids found in the Americas are the Ichneumonidae *Campoletis sonorensis* (Cameron), *C. flavicincta* (Ashmead), *Pristomerus spinator* (F.), *Eiphosoma laphygmae*, the Eulophidae *Euplectrus plathypenae* Howard, Braconidae *Cotesia marginiventris* (Cresson), *Aleiodes laphygmae* (Viereck), *Meteorus laphygmae* Viereck, *Archytas incertus* (Macq.) and *A. marmoratus* Townsend, and the Tachinidae *Lespesia archippivora* Riley (Hruska, 2019; Kenis et al., 2023; Molina-Ochoa et al. 2003; van Huis, 1981). Predatory ants (e.g. *Solenopsis* spp.), solitary and social wasps (e.g. *Polistes* spp.), earwigs (e.g. *Doru* spp.), ground beetles, assassin bugs (Reduviidae), and minute pirate bugs (e.g. *Orius* spp.) are important mortality factors of FAW eggs and larvae in the native range, however less studied than parasitoids (Hruska, 2019; Kenis et al., 2023; Wyckhuys & O'Neil 2006). Parasitic nematodes *Hexamermis* (Mermithidae) have been regularly cited in literature attacking FAW larvae and one species (*Noctuidonema guyanense* Remillet and Silvain) has also been reported killing FAW adults (Molina-Ochoa et al., 2003). Pathogens such as the entomopathogenic fungus *Metarhizium rileyi* and *S. frugiperda* multiple nucleopolyhedrovirus (SfMNPV) are commonly found killing FAW larvae naturally in the environment (Hruska, 2019). Studies have also highlighted the importance of other factors such as natural mortality, dislodgement and drowning by rainfall and predation of egg masses and early larval stages (Hruska, 2019; Kenis et al., 2023).

In Africa and Asia, FAW has caused extensive crop damage and losses threatening food security mainly in regions with low rainfall and high temperatures allowing more generations per year (Day et al., 2017). In Southern Africa, it feeds not only on maize as its main host but also on sugarcane, rice and wheat and indigenous crops such as sorghum, pearl millet and finger millet (CABI, 2019; Sileshi et al., 2019). On maize, FAW prefers to attack tender and young vegetative leaves, but it can also attack silk, closed tassels and early cob stages decreasing the quantity and quality of the grains (Mohamed et al., 2023; Pannuti et al., 2016). When FAW was first detected in African countries, it

created a sense of panic due to the ravaged appearance of maize leaves. Having no specific knowledge on FAW management, farmers were initially relying on their experiences with other maize pests to attempt to reduce damage and losses using cultural and mechanical practices. In reaction to the outbreaks, governments quickly made available synthetic pesticides to farmers following devastating crop losses, in some instance between 100,000 to 300,000 litres (Hruska, 2019).

Zambia agricultural context and maize production

Zambia is a landlocked country located in Southern Africa, with a population of more than 20 million people, of which 53% live in rural areas (FAO, 2025). Three main agroecological zones divide the country based on rainfall patterns, soil types and other climatic characteristics: region I (< 800 mm/year), region II (800-1000 mm/year) and region III (1000-1500 mm/year) (Figure 1). The agricultural sector contributes about 20% to the Gross Domestic Product (GDP) and employs nearly 70% of the labour force in the country. Zambia counts 1.6 million smallholder farmers (20% women-

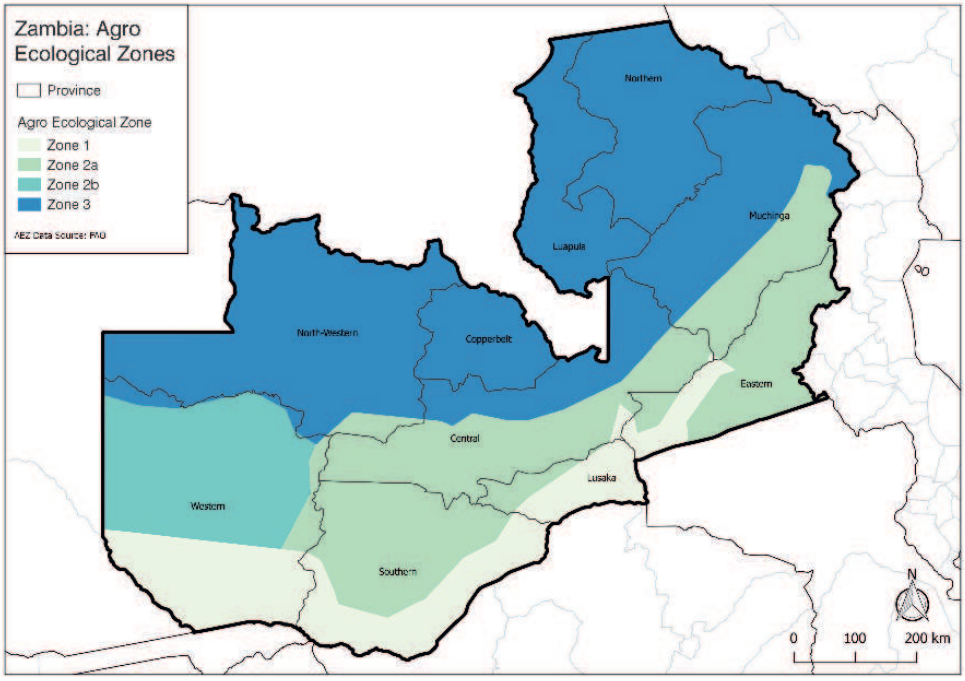


Figure 1: Agroecological zones of Zambia (Map provided by Tim Beale, CABI; data source: GAEZ Data Portal, FAO, 2024).

headed households) contributing to the agricultural sector, of which 73% farm on an area of less than 2 ha (Bwalya et al., 2015). Smallholder farmers are proudly recognized across the country as the backbone of agriculture contributing 80% to the food needs. Agriculture in Zambia is characterized as low-input, low-yield and rain-dependent. One rainy season occurs in Zambia, generally between November and March; however, rain patterns have become highly unpredictable due to climate change. Despite a substantial investment from the Zambian government in agriculture over the past decades, poverty and

malnutrition are still high, with a score of 30.7 (serious) on a 100-point scale in 2024 on the Global Hunger Index (Global Hunger Index, 2025; Zulu et al., 2015). About 80.5% of the rural population lives in extreme or moderate poverty (Bwalya et al., 2015). Nonetheless, looking at the trend over the past two decades, the situation has improved, passing from 53.1 (extremely alarming) in 2000 to 32.6 (serious) in 2016 (Global Hunger Index, 2025). Many challenges restrain smallholder farmers in increasing productivity to reduce rural poverty including inconsistency in climatic conditions (droughts, unpredictable rainfall and floods), timely access to subsidized and quality inputs, degraded soils due to overuse of lands, poor access to extension services, markets and credit, lack of proper storage facilities, maize prices fluctuation, and pests and diseases pressure (Kuteya & Kabwe, 2015; Malesu et al., 2024).

In Zambia, maize is a critical commodity and subsistence food for 20 million people providing nearly 50% of the population daily calorie intake (FAO, 2013). It is a source of carbohydrates, protein, calcium, iron, potassium, and vitamins such as C, E, K, B_1, B_2, B_3, B_5 and B_6 (Rouf Shah et al., 2016). Between 2013 and 2023, an average of 1.17 million ha of maize was cultivated in Zambia yielding 2.95 million tonnes (2.5t/ha) (FAO, 2025). Under optimal conditions and practices, Zambia has the potential to produce an average of 6.3 to 8.8 t/ha, which is indicative of the vast yield gap that highlights the challenges mentioned above on crop productivity (Gatti et al., 2023; Namonje-Kapembwa et al., 2015). FAW was first detected at the start of the rainy season, in late 2016. Household surveys across all the agroecological zones reported an estimated average maize yield loss of 40% in 2017 (Day et al., 2017) and 35% in 2018 (Rwomushana et al., 2018). This reduction in yield losses between the years may be explained by a few reasons; local natural enemies increasingly attacking and killing FAW, overestimation of yield losses by inexperienced farmers in the first year and increased knowledge on the FAW lifecycle and management (Hruska, 2019). During the first rainy season experiencing FAW outbreaks (2016-2017), 60% of farmers were using chemical pesticides, which was subsidized by the government, followed by hand-picking of egg masses and caterpillars (36%), depositing ash on larvae, frequent weeding and uprooting and burning infested plants (Day et al., 2017). The control measures used were very labour intensive, mainly executed by women and youth who usually conduct pest scouting and hand-picking of pests. Furthermore, in the following rainy season of 2017-2018, 9% of farmers reported using monocrotophos, a highly hazardous pesticide listed in the Rotterdam Convention (Rwomushana et al., 2018). Since its detection in 2016, FAW has caused reductions in yield and incomes in Zambia, especially for smallholder farmers who are more vulnerable to pest outbreaks. As the majority of them never needed to use synthetic pesticides for maize production before the arrival of FAW, adopting the use of synthetic pesticides has potential to greatly impact the environment and human health negatively. Thus, sustainable and safer options are needed to support smallholder farmers in Zambia to boost crop productivity, reduce dependency on chemical pesticides, and alleviate poverty.

Integrated pest management

Integrated pest management (IPM) is defined as a sustainable approach focusing on long-term prevention of multiple pests through a combination of techniques such as biological, cultural, physical and chemical tools, which minimizes economic, health and environmental risks. The justification for using chemicals is done when regular monitoring of pest numbers and their natural enemies and antagonists, alongside damage indicates that economic thresholds have been reached and that there are no other tools available anymore. The chemical intervention is aiming at removing only the target organism. IPM encompasses a wide range of tools from preventive, monitoring, surveillance, cultural controls and biological control before resorting to the use of synthetic pesticides (Ehler, 2006; University of California, 2025). However, this system must be effective economically, be socially accepted and be supported by governments.

Biological control

Biological control is one component of the IPM approach. Eilenberg et al. (2001) defined biological control (also known as biocontrol) as: "The use of living organisms to suppress the population density or impact of a specific pest organism, making it less abundant or less damaging than it would otherwise be". These living organisms can be categorised as macro-organisms such as parasitoids, predators or nematodes or micro-organisms such as fungi, viruses or bacteria. Biocontrol is classified in three main types: augmentative, classical and conservation. Augmentative biocontrol techniques release a large amount of biocontrol agents for seasonal control such as *Trichogramma* spp. against the European corn borer (*Ostrinia nubilalis*) in Canada (Gagnon & Baute, 2024). Classical biocontrol refers to the intentional introduction and permanent establishment of exotic natural enemies in a new region, targeting an exotic pest where both the pest and the natural enemy come from the same origin. Many classical biocontrol programmes have shown great success saving entire crop industries and, sometimes people from starvation. In Africa, two major IAS of cassava causing severe threat to food security, namely the cassava green mite (*Mononychellus tanajoa*) and the cassava mealybug (*Phenacoccus manihoti*), were successfully reduced and maintained under the economic threshold through the introduction of natural enemies from their region of origin in South America (Eilenberg, 2006; Neuenschwander, 2001). These successes emerged from many years of international collaboration and efforts. Conservation biocontrol is defined as the modification or management of the environment or existing practices to protect and enhance natural enemies that are already present in the system, aiming at reducing the effect of pests. Various conservation practices can be used to conserve and increase natural enemies' populations by providing food (pollen, nectar and honeydew) and shelter such as mulching, cover crops, intercropping or incorporating strips consisting of non-crop plants. These practices often rely on natural pest control and ecosystem service principles aiming at reducing a number of pests in the agroecosystem rather than targeting one specific pest species. However, it is important to stress the fact that conservation biocontrol is a process that needs time to see the results.

The first few years may not yield the expected results as the practices need to be consistent over time to reach the desired outcome (Eilenberg, 2006).

Intercropping

Many agroecosystems have become highly unfavourable environments for natural enemies due to high disturbance, simplified landscapes (monocrops) and high reliance on pesticides. Many studies have shown that monocrops have more frequent and higher pest populations with higher damage than diverse cropping systems (Chabi-Olaye et al., 2005; Huss et al., 2022; Letourneau et al. 2011; Tamburini et al., 2020). Intercropping, the practice of growing two crops or more in alternate rows in the same area (Ruthenberg, 1971), has been practiced globally by farmers for thousands of years using local crops (Hruska, 2019). If used with the right combination of companion crops, intercropping can provide important agronomic, socio-economic and nutritional benefits, mainly in smallholder farming systems (Li et al., 2023; van Huis, 1981). Agronomic benefits include but are not limited to deterring pest oviposition by interfering with visual and olfactive clues, conserving moisture, improving soil content and reducing erosion, reducing need for fertilizer, suppressing weeds, greater combined yield/ha (land equivalent-ratios), and attracting and feeding natural enemies (Huss et al., 2022). Supplementary food provided to natural enemies from crops or non-plant crops has been proven to increase survival, fecundity and longevity (Landis et al., 2000).

Push-pull technology, a system based on chemical ecology, has been developed in Kenya by icipe for controlling stem borers, *Busseola fusca* and *Chilo partellus*, and *Striga* weed in maize in cereal-livestock smallholder farming systems. The "push" element, *Desmodium uncinatum* Jacq., is intercropped with maize to repel moths of laying eggs on the maize, while the "pull" element, Napier grass *Pennisetum purpureum* (Schumach), serves as an attractant for moths to lay eggs away from the maize and later be fed to cattle. It was found that *Desmodium* root exudates can stimulate germination of *Striga* seeds, but also simultaneously inhibit their attachment to host roots through an allelopathic mechanism, thereby reducing the seed bank in the soil (Khan et al., 2016). Additionally, the push-pull approach has been found benefiting larval and pupal parasitoids where parasitism rates were significantly higher compared to maize monocrops (Midega et al., 2009). These combined effects of repelling and trapping the pests and recruiting natural enemies resulted in significant reduction in plant damage from stemborer larval feeding and increased yield in push-pull system compared to monocrop maize (Midega et al., 2005).

Increasing plant diversity combined with local natural enemies in Latin America usually keep FAW populations under control for smallholder farmers (Hruska, 2019). Early studies of intercropping legumes with maize in Latin America to reduce FAW have demonstrated good control. For example, in Honduras, Castro et al. (1994) found that intercropping maize or sorghum with cowpeas reduced FAW infestation but increased the abundance of the predator *Doru taeniata* (Dohrn) (Forficulidae). Altieri (1980) and van Huis (1981) found similar results for intercropping maize with beans in Colombia

and Nicaragua respectively. More recent laboratory studies investigated multiple-choice assays with fall armyworm moths where fewer eggs were deposited on maize and sorghum when combined with cowpea and cabbage compared to maize or sorghum alone (Sisay et al., 2023). The authors also found that in multiple- and dual-choice assays, FAW females laid more eggs and egg masses on maize than on sorghum. However, in no-choice assays, no difference was found on the number of egg masses between maize and sorghum, but the total number of eggs was higher on maize. Early field studies observed the same pattern, and it was suggested that maize could be used as a trap crop in regions where sorghum is the dominant staple food (Castro et al., 1988). While a growing number of laboratory and field studies are investigating the deterrent or repellent effects of intercropping on FAW using local crops in Africa, there is also a need to study indigenous weed and non-crop species in relation to the attraction and promotion of natural enemies.

Challenges in adopting IPM and biocontrol

Despite worldwide investments in projects and programmes focusing on integrating IPM training and knowledge transfer, adoption of IPM by farmers remains very limited, especially in LMIC (Alwang et al., 2019; Morse & Buhler, 1997; Parsa et al., 2014; World Bank, 2005). IPM adoption faces numerous challenges including but not limited to educational, technical, institutional, political, social and economic constraints. A study conducted in 96 countries revealed that the main challenges and obstacles for IPM adoption in developing countries include lack of training on IPM implementation and technical support to farmers, lack of favourable government policies and support, and limited level of education, literacy and financial resources by farmers for implementation (Parsa et al., 2014). Interestingly, the authors highlighted that the top obstacle to IPM adoption in LMIC was the lack of collective action within a farming community that is required for IPM to be effective and sustainable. Alwang et al. (2019) concurred with these findings and add that obstacles to adoption of IPM are not limited to the lack of information but also encompass limitations such as on complexity of IPM recommendations, locally adapted recommendations not being scalable to different agroecological conditions, lack of market and economic incentives, low profitability, and risks and uncertainties. Specifically looking at intercropping practices, when applied as an IPM tool aiming at reducing pest infestations, farmers can be discouraged due to the time and resources required to develop a locally adapted system using the optimal combinations of plant species. Moreover, it does not guarantee a successful harvest neither increased productivity (Huss et al., 2022). Indeed, competition among crops in some combinations can lead to yield losses. The intercrops used can also benefit pests as supplementary food sources. Finally, intercropping can increase complexity in management and labour costs mainly for farmers that have adopted mechanisation because tools may not be adapted to more than one type of crop and the intercrops may need to be planted and managed manually (Huss et al., 2022).

Biocontrol being a key component of IPM also faces specific obstacles and challenges influencing the adoption, non-adoption and discontinuation of biocontrol practices. Many studies and reviews unveiled that social and institutional factors affected its adoption (Barratt et al., 2018; Brodeur et al., 2018; Messing and Brodeur, 2018; van Lenteren, 2012). For example, in Iran, education level and participation in extension activities (Niyaki et al., 2010) were strongly correlated to biocontrol adoption while overall safeguarding of on-farm health, economic benefits, social acceptance and environmental protection were motivations for the adoption of biocontrol amongst Iranian rice farmers (Abdollahzadeh et al., 2016). However, it was suggested that the perceived ease of use of biocontrol was not a factor affecting the adoption (Sharifzadeh et al., 2017). Furthermore, for effective implementation, biocontrol requires first public education, then acceptance and support from the general public, especially for classical biocontrol (Messing & Brodeur, 2018; Niyaki et al., 2010). High reliance on chemical pesticides and lack of coordination amongst the farming community are also challenges that can impede the success of programmes such as augmentative biocontrol despite a careful implementation with farmers (Babendreier et al., 2019). In addition, extension officers supporting farmers often work for pesticide companies heavily promoting their usage which offer a quick fix targeting the symptoms without addressing the root causes of the pest problems neither offering long-term integrated solutions (Ehler, 2006). Overall, when biocontrol is used adequately, farmers can significantly reduce pesticides usage and increase yield (Niyaki, 2010). The various studies on challenges of IPM and biocontrol adoption conclude that providing effective incentives to farmers for adoption is critical alongside technical support and training on the usefulness of the technology and compatibility with other practices (Abdollahzadeh et al., 2017; Sharifzadeh et al., 2017; Babendreier et al., 2019). Lastly, a recent study has highlighted the need to not only look into socio-economic variables as drivers for adoption for agricultural innovations but also at the complexities of innovation and decision-making processes raising from experiences, response to changing contexts and circumstances, and navigating social and group dynamics (Adesina et al., 2025).

Collective pest management

Common-pool resources are resources that are made available to all for example fisheries, forests, grazing lands and water resources, therefore making it difficult to exclude anyone in using them while the use by one person may reduce its availability for others. As these common natural resources are limited (finite), challenges can raise if the resources are not managed properly such as in the case of overuse and degradation. Consequently, self-interest of individuals to overexploit a resource for short-term gain can lead to collective harm or public bad known as “Tragedy of the Commons”. Applying the same concepts, Ostrom has also extended these principles to public goods which look at common efforts contributing to the collective benefit, such as pests and diseases prevention. Through years of extensive research, Ostrom (1990) developed eight Design Principles for the successful and sustainable management by communities of common resources and public goods through collective action. The

Theory of Collective Action highlights social dilemmas such as free-riders and ways of managing them through agreed rules, monitoring and sanctions. Despite that the eight Design Principles for the successful management of natural common resources were not developed for the management of highly mobile pests, the operationalization of the principles for their management are very relevant and applicable, however, underexplored. Many successful examples exist in literature demonstrating the effective and finite control of highly destructive pests through collective and coordinate manner while reducing the need for chemical pesticides application such as the famous case of the cassava mealybug in Africa mentioned above (Klassen, 2008; Kruger, 2016).

Although area-wide pest management (AWPM) approaches borrow some principles from collective action theory, they still tend to focus on the technical aspects while underestimating the social and institutional key components for it to be effective (Kruger, 2016). AWPM emerged from failure of individual producers to manage certain highly mobile and very destructive pests (Klassen, 2008). The core idea of AWPM is that several serious economic pests can be effectively managed through uniform, organized, coordinated and consistent suppressive measures on their entire populations over large areas, including refuges and foci, rather than using a conventional approach by managing localized pest populations by single household or producers, e.g. by using a field-by-field approach (Faust, 2008; Klassen, 2008). The majority of these mobile and destructive pests, such as FAW, are being controlled by individual farmers heavily relying on synthetic pesticides. These isolated management tactics are counterproductive as one single refuge not adequately managed can result in the build-up and establishment of damaging pest populations on previously well-managed farms. Consequently, these farms normally under control are then forced to apply broad-spectrum fast-acting chemical pesticides in an attempt to save the crops, defeating the principles of the IPM approach (Klassen, 2008).

However, as AWPM is usually a top-down approach initiated by governments, its implementation can encounter challenges mainly in remote farming communities. Indeed, AWPM needs a dedicated organization and comprehensive multiyear plan requiring massive financial investment and technical expertise using advanced technology such as GIS software and satellite imagery aiming at developing pest forecasting models and locating alternative hosts areas. LMIC generally don’t have access to these expertise or expensive technologies unless short- or medium-term foreign projects provide support following a specific devastating outbreaks such as the Desert Locust. Therefore, other forms of collective pest management are required for farming communities to prevent new IAS to establish and to eradicate those that have established and spread. Bottom-up approaches, self-organized or community-based collective action (Ostrom, 2009) supported by governments can also become very effective in managing IAS (Galarza-Villamar et al., 2024). So far, this approach has been underexplored but is gaining momentum (Graham et al., 2019) mainly due to the increase in global trade, tourism and changing climatic conditions driving a steep increase in new annual bioinvasions.

Disciplinary, multidisciplinary, interdisciplinary and transdisciplinary approaches

With today's complex societal issues such as climate change and food insecurity, research teams often consist of two or more disciplines to address such challenges. With a disciplinary approach, experts examine deeply a topic from a specific field of study following its established methods, theories, and principles (Stock & Burton, 2011). Research teams using multidisciplinary approaches work independently within their field of study on different aspects of a problem or project where different disciplines contribute to separate components without necessarily integrating them deeply. Interdisciplinary approaches bridge and synthesize methods and perspectives from two or more disciplines where experts from different disciplines collaborate to jointly frame and solve a problem such as integrating natural and social scientists. Experts bring their unique viewpoints to cross boundaries to create new knowledge through a more comprehensive understanding (Shanableh et al., 2022; Stock & Burton, 2011). Transdisciplinary approaches co-create a new conceptual, methodological or theoretical framework by blending and transcending disciplinary boundaries, aiming for a holistic and integrated understanding. Experts work together to create a shared framework that incorporates insights from multiple disciplines. The goal is to develop a unified approach to address complex issues. Transdisciplinary research is also considered when transcending the boundaries between science and other forms of knowledge and expertise with non-academic experts (e.g., general public, user groups, farmers, land owners), implying that research is consistently carried out in a participatory manner (Stock & Burton, 2011).

Research approach

With this research thesis, I aim at contributing to the research gaps highlighted above regarding challenges in managing highly mobile invasive alien species by using a collective approach. This thesis presents interdisciplinary research integrating biological and social sciences to co-design methods using local natural resources to reduce crop damage at farming community level. However, the thesis leans towards a transdisciplinary approach due to the investigation of a potential new framework using the collective action theory to co-design and implement the use of biocontrol in managing highly mobile pests with farmers. As this thesis encompasses research on local natural enemies of FAW and collective actions within farming communities in Zambia, various quantitative and qualitative methodologies to collect and analyse data were used across the empirical chapters such as parasitoids surveys and interviews with farmers. Four farming communities growing maize and facing FAW infestations in two distinct agro-ecological zones of Zambia was the system selected for this research thesis due to the recent invasion of this invasive insect pest in Africa and the importance of maize for the country.

Objectives and research questions

The objectives of this thesis were to 1) identify local natural enemies attacking fall armyworm in Zambia and evaluate the factors contributing to enhancing their populations, 2) understand the factors

influencing collective action within farming communities in order to develop collective pest management applying biocontrol practices and to evaluate their efficacy as guidelines to control highly mobile invasive alien species. The research questions guiding this thesis were:

1. Which local parasitoid species are successfully attacking fall armyworm in Zambia and what factors are affecting their occurrence?
2. Which social conditions affect the effectiveness, maintenance and sustainability of a collective action at community level for implementation of biocontrol?
3. How planting dates can be an effective IPM tool to reduce FAW incidence and maximize conservation of natural enemies?
4. Which local companion crops best promote natural enemies' populations and reduce fall armyworm populations?
5. What factors shape the willingness of communities to collaborate for pest management and what are the prospects for a collective action?

Thesis outline

This section outlines the chapters and presents features of the different research methodology used for both entomology and social sciences. More details on methodology can be found in the separate chapters. A graphical presentation of the connections between the chapters is shown in Figure 2.

In **Chapter 2**, local parasitoid species attacking fall armyworm larvae and eggs on maize crops are surveyed and the factors influencing the occurrence of the parasitoid species are evaluated. Fall armyworm larvae and egg masses were collected weekly from four maize fields established specifically for the purpose of this survey. FAW egg masses and larvae were reared in the laboratory allowing them to feed and develop on an artificial diet. Thereafter, the parasitoid species emerging from FAW were identified using morphological and molecular tools. Parasitoid species abundance and diversity are compared with other regions in Africa and the Americas and assessed against factors influencing their occurrence. Implications for conservation biocontrol programmes and fall armyworm management are discussed in the context of smallholder farmers in Africa.

Chapter 3 looks into the social and institutional conditions needed to create an efficient and sustainable collective action promoting biocontrol of fall armyworm among smallholder farmers in rural Zambia. The conceptual framework takes into consideration Ostrom's eight Design Principles for a community-based management of common-pool resources and criteria of an agricultural innovation that meet the community's requirements. Focus group discussions and in-depth interviews were conducted with smallholder farmers in two districts of Zambia. Conditions already in place are discussed in relation to the traditional structure of the communities, and how these would support a collective action using biocontrol to manage fall armyworm. Implications of the findings are discussed in relation to reduction of chemical pesticide applications and increase food safety and security in farming communities.

In Chapter 4, we tested the commonly recommended cultural practice of planting early to avoid peak infestation of FAW. Densities of FAW, parasitoids abundance and diversity, and probabilities of parasitism were assessed between early, intermediate and late planting of maize. Plots of maize were planted at 3-week intervals where FAW larvae and eggs were sampled weekly. Maize growth stage effect was also studied together with planting date effects on FAW and its associated parasitoids. Possible explanations for the difference observed between the three planting dates and the different maize growth stages are discussed providing important insights which can contribute to the development of locally adapted IPM strategies for FAW management.

In **Chapter 5**, local companion crops found to be grown by smallholder farmers in rural communities were evaluated for their potential to attract parasitoids and to deter oviposition by fall armyworm female moths. On-station trials over two rainy seasons evaluated fall armyworm density and parasitism by parasitoids as well as parasitoids abundance and diversity on maize intercropped separately with cowpeas, groundnuts, beans, sorghum and sunflower. Results are discussed in relation to increasing efforts for conservation biocontrol through habitat management, specifically intercropping practices, on smallholder farming systems to reduce the impact of fall armyworm damage on maize crops.

In **Chapter 6,** I address the intervention created by the project on conservation biocontrol of fall armyworm using a collective pest management approach in the farming communities selected. A survey was conducted with project participants and non-participants to assess the ecological knowledge acquired from the project, and knowledge on collective action for pest management. Willingness to use conservation biocontrol practices and to collaborate in managing fall armyworm was also evaluated alongside planning and limitations for long-term pest management. This chapter consolidates the previous chapters on conservation biocontrol and collective action research and offers prospects and recommendations on implementation of collective pest management using biocontrol in rural farming communities.

Chapter 7 summarises the outcomes of the five empirical chapters and discusses the implications and applicability of these findings. In this chapter, I also reflect on the research approach and its limitations and recommend further research to co-create sustainable collective pest management strategies with farming communities and how to integrate them in national agricultural programmes and policies.

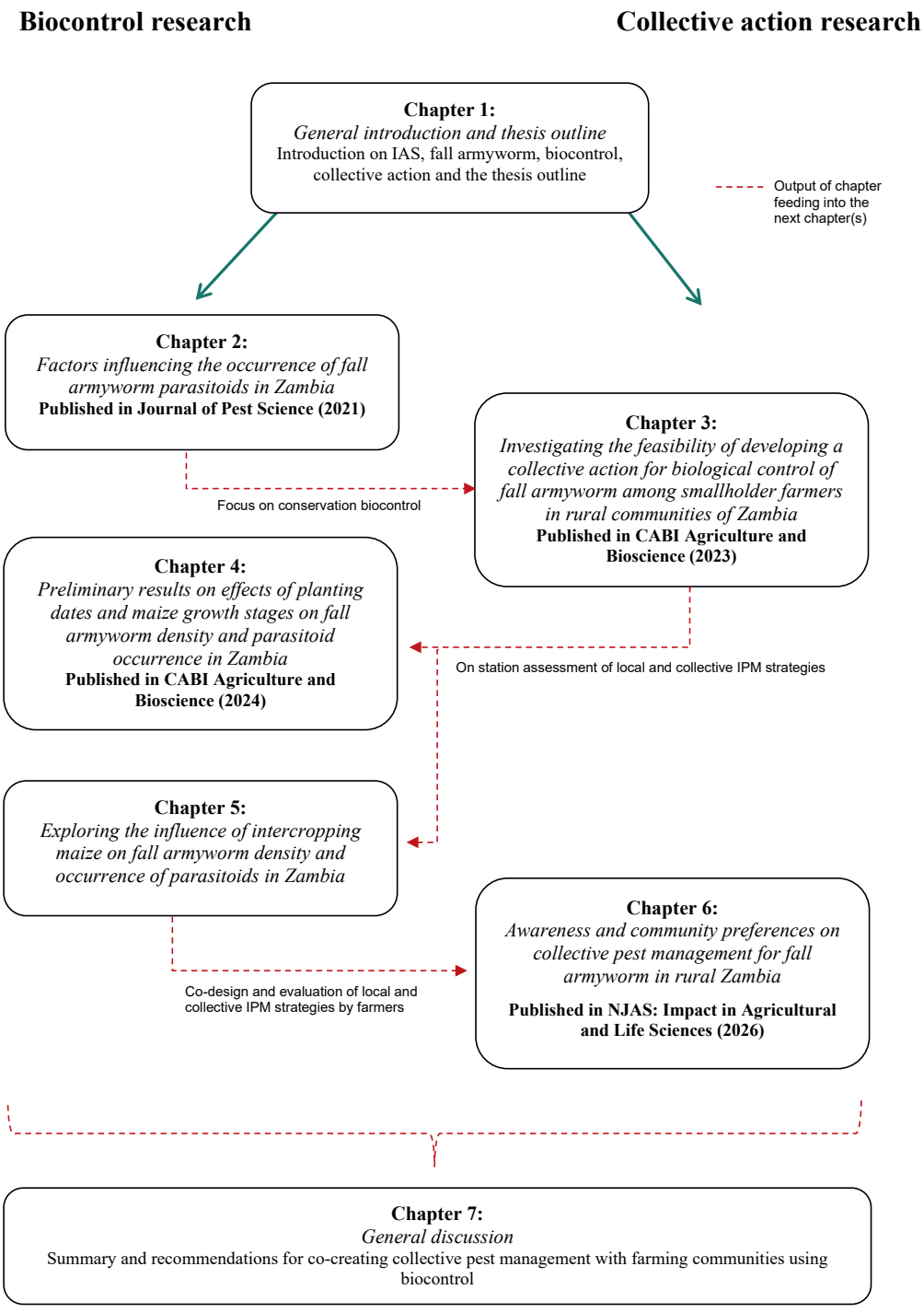


Figure 2. Graphical presentation of connections between biocontrol and collective action chapters.

2 Factors influencing the occurrence of fall armyworm parasitoids in Zambia

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ABSTRACT

Invasive alien species have environmental, economic and social impacts, disproportionally threatening livelihood and food security of smallholder farmers in low- and medium-income countries. Fall armyworm (FAW) (*Spodoptera frugiperda*), an invasive insect pest from the Americas, causes considerable losses on maize to smallholder farmers in Africa since 2016. The increased use of pesticides to control FAW in Africa raises concerns for health and environmental risks resulting in a growing interest in research on biological control options for smallholder farmers. In order to evaluate the occurrence of local natural enemies attacking FAW, we collected on a weekly basis FAW eggs and larvae during a maize crop cycle in the rainy season of 2018-2019 at four locations in the Lusaka and Central provinces in Zambia. A total of 4373 larvae and 162 egg masses were collected. For each location and date of collection, crop stage, the number of plants checked and amount of damage were recorded to analyse which factors best explain the occurrence of the natural enemy species on maize. Overall parasitism rates from local natural enemies at each location varied between 8.45% and 33.11%. We identified 12 different egg-larval, larval and larval-pupal parasitoid species. Location, maize growth stage and larval stage significantly affected parasitoid species occurrence. Our findings indicate that there is potential for increasing local populations of natural enemies of FAW through conservation biological control programmes and develop safe and practical control methods for smallholder farmers.

INTRODUCTION

Invasive alien species (IAS) have environmental, economic and social impacts, disproportionally threatening livelihood and food security of smallholder farmers in low- and medium-income countries (LMIC) (Early et al., 2016; Paini et al., 2016; Pratt et al., 2017). Following a biological invasion, smallholder farmers in LMIC face important crop losses due to a lack of knowledge about management practices at early stages of the invasion (Machekano et al., 2017). Additionally, local natural enemies might not be efficient or adapted in keeping the new IAS under control in the newly invaded ecosystem. A range of methods for control and management of IAS relying on prevention, monitoring and rehabilitation of impacted systems is available through various techniques such as chemical, biological and physical control methods (DiTomaso et al., 2017).

Despite the number of biological control agents commercially available, the efficacy and safety of the products, and the many success stories using various biological control techniques, there is still a lack of uptake in biological control (Barratt et al., 2018; Brodeur et al., 2018; Messing & Brodeur, 2018; van Lenteren, 2012). In particular, classical biological control through the introduction of exotic natural enemies has managed to save important staple and cash crops from IAS where chemicals have failed including the citrus industry and cassava production (Menzler-Hokkanen, 2006). However, investigations on classical biocontrol agents can be long-lasting and, when no suitable agent is available or when time is running out to save crops, augmentative and conservation biological control can play an important role in mitigating damage caused by established IAS. Although augmentative and conservation biological control strategies use local natural enemies to target a pest, their implementation differs regarding the type of biological control agents and techniques used (Lazarovits et al., 2007).

Parasitoids are among the most widely used natural enemies in biological control. Various biotic and abiotic factors such as temperature, rainfall, altitude, landscape characteristics (connectivity, complexity and composition), food and shelter sources, sink habitats, host density, volatile emissions and seasonality can influence the diversity, abundance and parasitism rates in the field (Bernasconi Ockroy et al., 2001; D'Alessandro et al., 2009; Mailafiya et al., 2010; Tscharntke & Brandl, 2004). These factors are important to evaluate and understand when searching for potential biological control agents as they will influence the spatial and temporal activities of the natural enemy populations. Hence, evaluating the factors influencing the occurrence and abundance of parasitoids alongside the natural enemy species present is a crucial first step in order to plan successful and practical biological control programmes for smallholder farmers.

The fall armyworm (FAW), *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), a highly transboundary migratory moth native to the Americas, was first detected in Central and Western Africa in early 2016 (Goergen et al., 2016) and since then it has spread across the African and Asian continents (Rwomushana et al., 2018) causing significant damage to maize, its principal food source. In Zambia, FAW infestation was first detected on maize in late 2016 and was reported to affect 22% of the maize grown for the 2017 crop season (International Plant Protection Convention, 2017). In 2018,

98% of farmers reported maize to be affected in Zambia with an average maize loss of 35% (Rwomushana et al., 2018). As maize is the major staple food in Africa, FAW has been identified as a serious threat to food and nutrition security for smallholder farmers if not controlled. When FAW was first detected, the immediate reaction was to use chemical control to contain the spread and to minimize damage (Tambo et al., 2020a). However, the excessive use of pesticides has raised concerns not only for health and environmental risks but also for sustainability efforts, undermining integrated pest management strategies for smallholder farmers (Harrison et al., 2019; Sisay et al., 2019).

This study is the first step toward a biological control programme to control fall armyworm for smallholder farmers in Zambia. The aim of this study was to assess which local parasitoid species successfully develop in FAW in Zambia and the factors influencing the occurrence of these local species over a maize crop season.

MATERIALS & METHODS

Fields location

Fieldwork was carried out during the rainy season of December-March 2018-2019. Four sampling sites were planted with maize at the onset of the rain during the 3rd week of December (Figure 1). The four sites were located in the Lusaka and Central provinces; the Zambia Agriculture Research Institute (ZARI) - Mt Makulu, Chilanga (-15,549023; 28,250960, altitude: 1229m), Kasisi Agricultural Training Centre (Kasisi) (-15,258464; 28,477081, altitude: 1113m), Golden Valley Agricultural Research Trust, Chisamba (-14,967373; 28,097464, altitude: 1147m) and Chalimbana (-15,359412; 28,488572, altitude: 1130m). Additionally, between September and December 2018 (dry season), larvae were irregularly collected at ZARI and Chisamba on irrigated maize. Standard agronomic practices for maize fields were adopted as recommended by the Ministry of Agriculture to smallholder farmers in Zambia.

Egg mass and larva collections

After maize emergence, each site was visited weekly for collecting FAW eggs and larvae until tasselling and silking stages. The numbers of plants checked were counted using a hand tally counter, and plants were selected randomly in a zigzag (W) pattern until the field was covered. Each plant was assessed thoroughly for egg masses and larvae in a non-destructive manner to allow continuous collection over the crop cycle. Hidden larvae in whorls or between the leaves were collected using a paintbrush to avoid damaging the maize plants. For each collection, date, maize crop stages (Table 1), number of plants showing fresh damage and maize damage level using the Davis scale were recorded (Davis & Williams, 1992). The number of plants with fresh damage and the maize damage level were recorded using two zigzag patterns in the field consisting of 5 stations (locations in the field where the assessment starts) of 10 consecutive plants each for a total of 100 plants assessed per site and date combination.

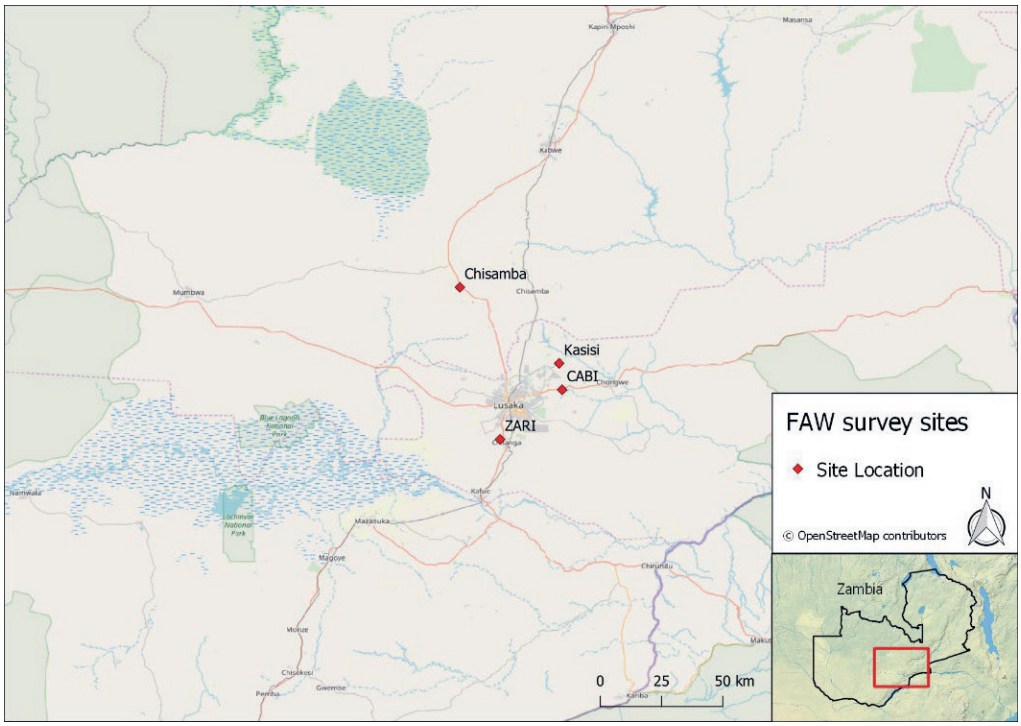


Figure 1. Location of the 4 experimental fields surveyed for fall armyworm natural enemies from January to March 2019.

Table 1. Maize development stages.

Vegetative	Reproductive
VE: emergence	R1: silking
V1: first leaf collar	R2: blister
V2: second leaf collar	R3: milk
V3: third leaf collar	R4: dough
V(n): n^{th} leaf collar	R5: dent
VT: tasseling	R6: maturity

Rearing of samples

On the same day of the field collection, egg masses and larvae collected from the maize fields were placed individually in Petri dishes (90mm diameter) and were given a sample ID number. Larval stage was estimated for each larva collected based on head capsule width. *Spodoptera frugiperda* is known to have highly variable larval development, ranging from five to ten instars depending on host plant suitability and climate (Montezano et al., 2019). We did not assess the exact number of instars and their head capsule width at our sites but assumed that they passed through six instars, as this is often the case in favourable host plant and climatic conditions, and used the head capsule widths usually observed in such situations (e.g. Capinera, 2008; Montezano et al., 2019).

Larvae were reared on artificial diet (Frontier Scientific Services (Newark, DE, USA), general diet for Lepidoptera F9772, with antibiotics 14% active chlortetracycline) in the laboratory at ZARI (27 ± 2 ºC and 50 ± 5% RH) until emergence of the parasitoids or adult moths. Egg masses and larvae were observed every day and the development of parasitoids or FAW moths was recorded. Dead larvae and pupae were dissected to record absence or presence of parasitoid larvae.

Identification of parasitoids

All adult parasitoids obtained during this study were morphologically identified by one of the authors (MK) using various identification keys and collections of insects gathered during previous studies on *S. frugiperda* parasitoids (Agboyi et al., 2019; Agboyi et al., 2020). Some representative specimens were brought to the Natural History Museum in London for comparison with the collection holdings and identified with the assistance of specialists (see Acknowledgements). In addition, adults of some species and sub-samples of parasitoid larvae emerging from FAW larvae but unable to pupate in the Petri dishes were subjected to molecular analyses using the mtDNA barcode gene (mtDNA) cytochrome c oxidase subunit 1 (COI) in order to compare them with existing barcode datasets. To obtain barcodes (around 600 bp of the mitochondrial gene from the samples, we followed the protocols described by Kenis et al. (2019). Sequences obtained in the present study were compared with authenticated sequences available from the Barcoding of Life Data system (BOLD; http://www.boldsystems.org/) (Ratnasingham & Hebert, 2013) and additional sequences from the GenBank® data base (http://www.ncbi.nlm.nih.gov/genbank/) (Benson et al., 2016).

Statistical analysis

Parasitism rate

Parasitism rates (±SE) for each location were calculated using the overall number of parasitized larvae (determined through parasitoid emergence and dissection of dead larvae) divided by the total number of FAW larvae collected, expressed as a percentage.

Parasitoid occurrence

Statistical analysis was performed using R version 3.5.2 (R Core Team, 2014), using packages multcomp (Hothorn et al., 2008), nnet (Venables & Ripley, 2002), ggplot2 (Wickham, 2016), car (Fox & Weisberg, 2019) and emmeans (Lenth, 2020). A multinomial logistic regression model was used to analyse the occurrence of parasitoid species attacking FAW in Zambia. The parasitoid species found within each FAW was set as the categorical dependent variable, whilst location, larval stage, maize crop stage and FAW density level were used as independent variables. FAW density was calculated based on the total numbers of larvae collected divided by the total number of plants checked for each collection, expressed as FAW larvae/plant. FAW density level was included instead of the damage score (Davis scale) or the infestation rate (% of plant showing fresh damage) because FAW density level was determined to be a more accurate measure of FAW population in the field. An analysis of deviance was

then conducted to assess the overall effect of each independent variable followed by a Holm–Bonferroni adjusted pairwise comparison test on all significant results.

Parasitism rate and FAW density

A binomial regression was used to analyse the effect of FAW larval density on parasitism rate. Parasitism rate and FAW densities were calculated for each collection (4 sites and 9 sampling dates, n=36). Parasitism rate was set as the dependent variable and represents the number of parasitized larvae (determined through parasitoid emergence and dissection of dead larvae) divided by the number of FAW larvae collected, expressed as a percentage. FAW larval density was set as the independent variable and represents the number of FAW larvae divided by the total number of plants checked per collection. To account for the overdispersion identified in the model a quasibinomial distribution was used.

FAW density and maize growth stage

A one-way analysis of variance test was conducted to assess whether there was a statistically significant difference in fall armyworm density across maize development stages. Fall armyworm density is defined as the number of fall armyworm specimens per number of plants checked.

RESULTS

Egg and larvae collection and parasitoid identification

Overall, 4373 larvae and 162 egg masses were collected over the season from the four sites. No egg parasitoid was obtained. From the rainy season, eleven species of larval parasitoids have been recovered from four families (Table 2). From the dry season, one additional parasitoid species recovered from one FAW pupa which was absent during the rainy season has been identified as *Metopius discolor* Tosquinet. Parasitism rates from local natural enemies at each location were 8.45% ± 0.77 (Chisamba, n= 1313), 12.86% ± 0.99 (Chalimbana, n= 1143), 33.11% ± 1.37 (Kasisi, n=1172) and 13.15% ± 1.24 (ZARI, n=745).

A large number of parasitoid larvae did not develop to the adult stage either because they died after emergence from their host larva in the Petri dish without making a cocoon or because the host larva died too early (35.5% of FAW larvae). Sub-samples of the hymenopteran parasitoid larvae that died in the Petri dishes were sent for molecular identification, which revealed that they belonged to the species *Chelonus bifoveolatus* Szépligeti and *Coccygidium luteum* Brullé and further morphological examinations suggest that both species were abundant. However, it is possible that some larvae that were not sequenced belonged to *Chelonus curvimaculatus* Cameron, whose larvae are probably similar to those of *Ch. bifoveolatus*. Because not all larvae could be assigned to *Chelonus* spp. or *C. luteum*, dead Hymenoptera larvae were considered as a single parasitoid species in the analyses. Nematodes from the Mermithidae family were also recovered from two FAW but further identification was not

possible. Despite that nematodes can be considered as parasitoids, we did not include them in the statistical analysis because insect parasitoids were the focus of the study.

Parasitoid occurrence

Location

The analysis of deviance indicated that location had a significant effect on parasitoid occurrence (d.f.=36, X^2=371.57, P<0.001). The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex at each location where significantly different (P<0.01). Chisamba had the highest diversity of all sites with nine species of parasitoid found overall including *M. discolor* from the dry season, whilst ZARI had the lowest diversity with four species. Kasisi had eight parasitoid species present whilst Chalimbana had seven species. Of the species found at all sites, Kasisi had significantly larger numbers of Hymenoptera mortality whilst Chisamba had the greatest proportion of the tachinid *Drino quadrizonula* (Thomson) (Figure 2).

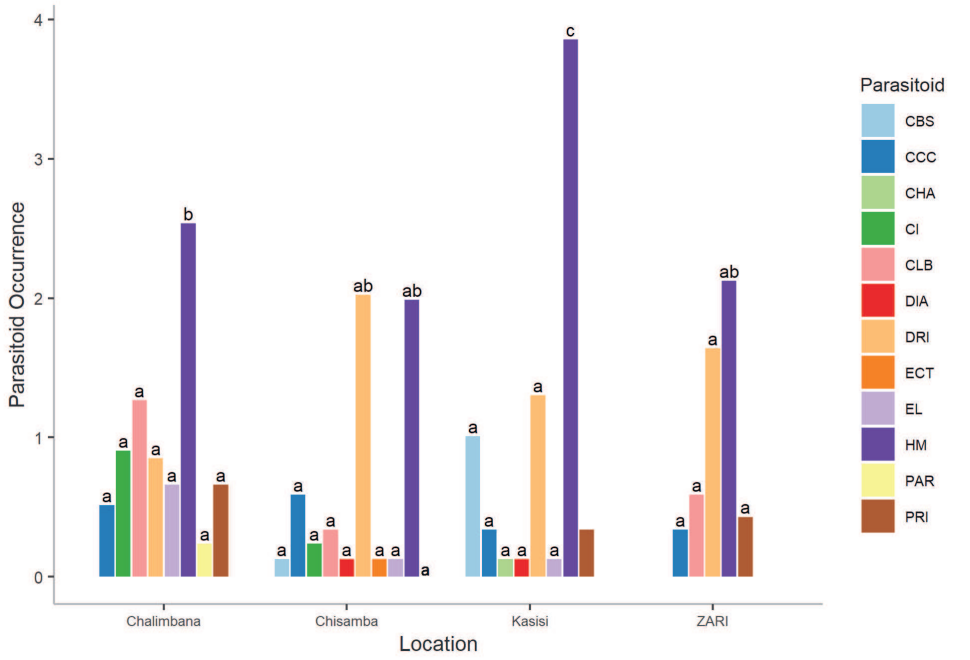


Figure 2. Parasitoid species recovered from FAW collected on experimental sites for each location, Zambia. The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex at each location where significantly different (P<0.01). To account for high mortality in Hymenoptera, occurrence of parasitoid species is visualized as log ((number of parasitoid species/total number of parasitoids)+1)*100). CBS = *Chelonus bifoveolatus*, CCC = *Chelonus curvimaculatus*, CHA = *Charops* sp., CI = *Cotesia icipe*, CLB = *Coccygidium luteum*, DIA = *Diadegma* sp., DRI = *Drino quadrizonula*, ECT = *Enicospilus capensis*, EL = *Euplectrus laphygmae*, HM = Hymenoptera mortality, PAR = *Parapanteles* sp., PRI = *Pristomerus* sp.

Table 2. Parasitoid species recovered from *Spodoptera frugiperda* in Zambia from four experimental sites, 2018-2019.

					Experimental sites			
					Chisamba	Chalimbana	Kasisi	ZARI
Order	**Family**	**Sub-family**	**Species**	**Parasitoid type**				
Hymenoptera	Braconidae	Agathidinae	*Coccygidium luteum* Brullé	Larval	+	+	+	+
		Cheloninae	*Chelonus bifoveolatus* Szépligeti	Egg-larval	+	-	+	-
			Chelonus curvimaculatus Cameron	Egg-larval	+	+	+	+
		Microgastrinae	*Cotesia icipe* Fernández-Triana & Fiaboe	Larval	+	+	-	-
			Parapanteles sp	Larval	-	+	-	-
	Ichneumonidae	Campopleginae	*Charops* sp.	Larval	-	-	+	-
			Diadegma sp.	Larval	+	-	+	-
		Cremastinae	*Pristomerus* sp.	Larval	-	+	+	+
		Ophioninae	*Enicospilus capensis* Thunberg	Larval	+	-	-	-
		Metopiinae	*Metopius discolor* Tosquinet*	Larval-pupal	+	-	-	-
	Eulophidae	Eulophinae	*Euplectrus laphygmae* (Ferrière)	Larval	+	+	+	-
Diptera	Tachinidae	Exoristinae	*Drino quadrizonula* (Thomson)	Larval	+	+	+	+

Maize stage

Occurrence of parasitoid species was significantly impacted by maize crop stage (d.f.=48, X^2=162.86, P<0.001). The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex where significantly different at all maize stages (P<0.01). The largest number of parasitoid species was found at stages V5-7 with 11 species whilst the highest abundance of parasitoids was found during the V8-10 stages. At stages V11-12 and VT-R1, we found a significant decrease in both occurrence and abundance of parasitoids where the remaining species are *D. quadrizonula, C. luteum*, *C. bifoveolatus* and dead hymenopteran larvae (Figure 3).

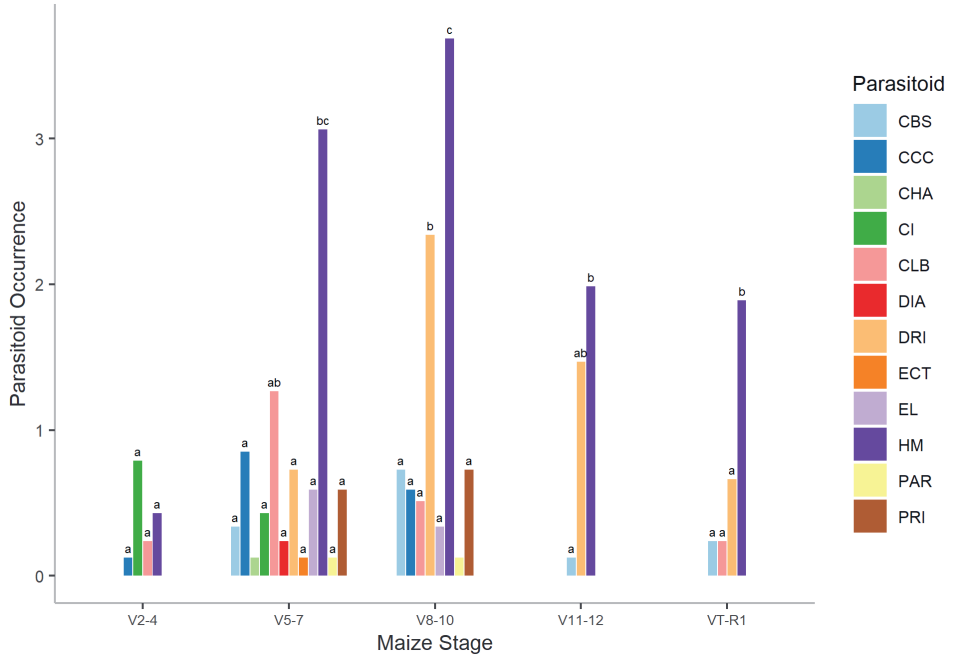


Figure 3. Parasitoid species recovered from FAW larvae collected on experimental sites for each maize growth stage, Zambia. The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex where significantly different at all maize stages (P<0.01). To account for high mortality in Hymenoptera, occurrence of parasitoid species is visualized as log((number of parasitoid species/total number of parasitoids)+1)*100).

Larval stage

Larval stage had a significant effect on parasitoid occurrence (analysis of deviance test, d.f.=48, X^2=404.58, P<0.001). The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex where significantly different at all larval stages (P<0.01), except L1-L2 and L3 (P=0.125). Further analysis showed that this difference was largely due to high mortality due to Hymenoptera and *D. quadrizonula*, with considerable mortality due to Hymenoptera being found for the early larval stages and larger numbers of *D. quadrizonula* being found in L5 and L6 larvae (Figure

4). Ten species emerged from the early instar larvae L1 to L4 compared to three species emerging from L5 and L6. The last larval instar was parasitized nearly exclusively by the tachinid fly *D. quadrizonula,* whereas from L5 larvae we obtained only the tachinid and Hymenoptera larvae belonging to *Chelonus* spp. and/or *Coccygidium luteum*.

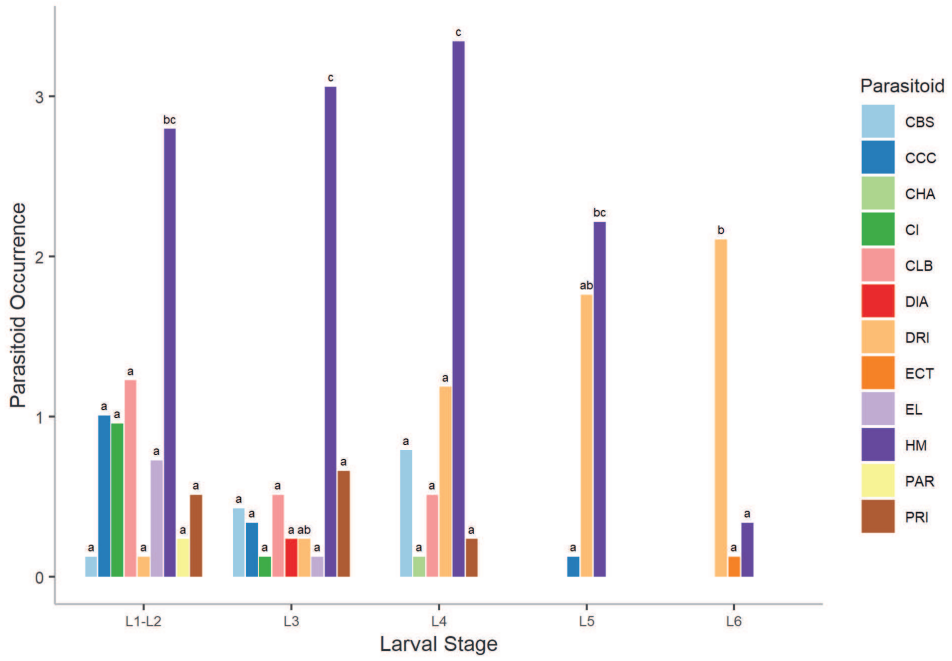


Figure 4. Parasitoid species recovered from FAW collected on for each larval stage, Zambia. The Holm–Bonferroni adjusted pairwise comparison tests indicated that the parasitoid complex where significantly different at all larval stages (P<0.01), except L1-2 and L3 (P=0.125). To account for high mortality in Hymenoptera, occurrence of parasitoid species is visualized as log((number of parasitoid species/total number of parasitoids)+1)*100).

FAW density

The analysis of deviance indicated that FAW density had a significant effect on parasitoid occurrence (d.f.=12, X^2=35.82, P<0.001). This effect was largely the result of mortality due to Hymenoptera and *D. quadrizonula*.

Parasitism rate and FAW density

FAW density had a significant effect on parasitism rate (analysis of deviance, d.f.=1, X^2=3762.2, P<0.001). There was a general positive relationship between FAW density and parasitism rate. Most FAW collections over the maize lifecycle resulted in parasitism rates ranging between 0 and 30% when FAW density was between 0.2 and 0.6 larvae per plant. Between 0 and 0.2 larvae per plant,

parasitism rates ranged from 0 to 20%. Between 0.6 and 1, parasitism rates ranged from 0 to 45% (Figure 5).

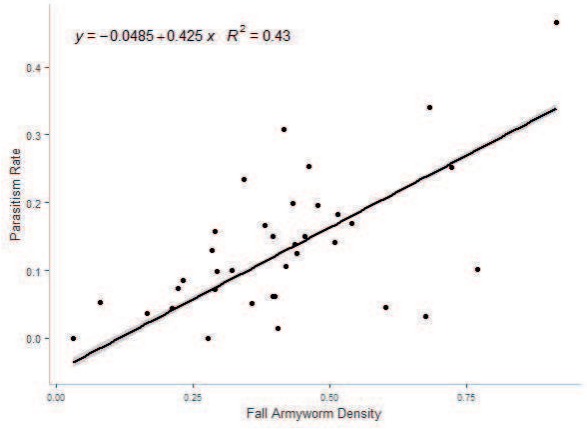


Figure 5. Parasitism rate (proportion of parasitized FAW larvae divided by the total abundance of FAW larvae collected) in relation to FAW larval density (proportion of FAW larvae collected on plants checked), n=36. The black line represents the linear model y=-0.0485+0.425x where the R^2=0.43.

FAW density and maize growth stage

There was no significant different in fall armyworm density across maize stages (d.f. = 4, F = 0.513, p = 0.738) (Figure 6). Early larval stage was the most common stage present across maize development, with the exception of V11-V12 where FAW in late larval stage were more frequently found.

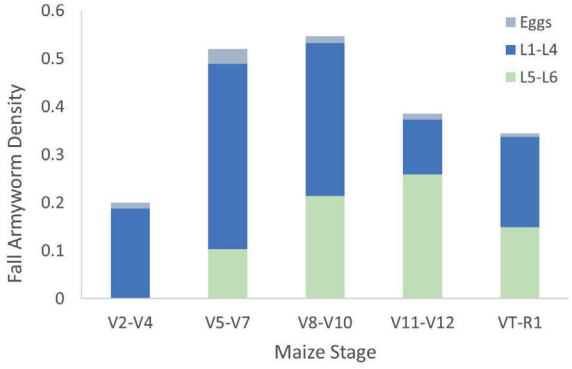


Figure 6. FAW density for eggs, early and late larval stage in relation to growth stages. FAW density is the total number of FAW present per number of plants checked at each stage of maize development.

DISCUSSION

Eleven species of parasitoids from four families were found attacking eggs (egg-larval parasitoids) and larvae of *S. frugiperda* during the rainy season 2018-2019 and one additional hymenopteran parasitoid species during the dry season. Our findings are consistent with previous studies on the parasitoid complex of *S. frugiperda* across Africa. Two of the three most abundant species

on our sites, *Ch. bifoveolatus* and *C. luteum*, were also the species most frequently collected in Ghana, Benin, Senegal and Tanzania (Agboyi et al., 2020; Koffi et al., 2020; Ngangambe & Mwatawala, 2020; Tendeng et al., 2019). *Drino quadrizonula*, the third abundant species in this study, was found in low numbers on *S. frugiperda* in Ghana and Benin (Agboyi et al., 2020). Other species found both in Zambia and West Africa, albeit in low numbers, include *Cotesia icipe* Fernández-Triana & Fiaboe, *M. discolor*, and *Charops* sp. The two species *C. luteum* and *C. icipe* have also been recorded on *S. frugiperda* in Kenya, Tanzania and Ethiopia and *Ch. curvimaculatus* in Kenya (Sisay et al., 2018; Sisay et al., 2019). However, our study also found five new associations of parasitoids with fall armyworm in Zambia: *Euplectrus laphygmae* (Ferrière), *Parapanteles* sp., *Diadegma* sp., *Pristomerus* sp. and *Enicospilus capensis* Thunberg. The large number of parasitoid species having adopted *S. frugiperda* as host in Africa may be due to the presence of several other *Spodoptera* species, such as *S. exempta*, *S. exigua* and *S. littoralis* (e.g. Agboyi et al., 2020, Fiaboe et al., 2017; Merrett, 1986; Yu et al., 2005), and of *Helicoverpa armigera* (van den Berg et al., 1988) which are known hosts of several parasitoids reared during this study.

Overall, larval parasitism rates were rather similar or slightly lower than studies in other parts of Africa. In Ghana, Agboyi et al. (2020) observed average parasitism rates varying from 5.1% to 38.8%, with up to 75% at some sites. In Kenya, Ethiopia and Tanzania, average larval parasitism rates up to 50% were observed (Sisay et al., 2019). Published parasitism rates often vary with sampling methods and calculations (van Driesche, 1983). However, larval parasitism and parasitoid richness of *S. frugiperda* in Africa are rather high for a species that recently invaded the continent (Cornell & Hawkins, 1993). In contrast, while egg parasitism by *Telenomus remus* was very frequent in Ghana, Benin, Kenya and Tanzania (Agboyi et al., 2020; Sisay et al., 2019), we did not find a single parasitized egg mass in our sites in Zambia. The absence of egg parasitism may be due to a relatively short rainy season compared to other investigated countries, such as Ghana, Benin, Kenya and Tanzania, where bimodal rainfall patterns occur and where *S. frugiperda*, other insect hosts and their host plants can be found throughout the year (Mailafiya et al., 2010; van den Berg et al., 1988). In Kenya, a similar study investigated the factors affecting parasitoid diversity, abundance and parasitism of stem borers on maize (Mailafiya et al., 2010). They found the lowest parasitoid richness in the driest locations and highest richness in bimodal rainfall distribution compared to a single rainfall distribution. This suggests that the high parasitoid diversity is maintained through the seasons due to a spatial and temporal continuity of plant and insect hosts. This study is in accordance with our suggestion that the long dry season in Zambia may contribute to the relatively low parasitism rates observed during the short rainy season. However, further studies in other years and at other sites and regions in Zambia are needed before drawing firm conclusions regarding the influence of climate on parasitism. In addition, parasitism rates, based on the total number of larvae collected, may be underestimated because host larval mortality was not negligible, and some parasitoid eggs or larvae may have been missed when dead host larvae were

dissected. More generally, the laboratory rearing of parasitized larvae should be improved to minimise parasitoid mortality at the larval stage, before pupating.

Our results indicate an effect of location on parasitoid occurrence despite the relatively short distance between each site. Various factors can influence this finding such as variation in rainfall, temperature, landscape, farming and grazing activities. Knowing that habitat fragmentation, intensive tillage, grazing activity, destruction of non-crop habitats and pesticide use can negatively affect parasitoid activities and parasitism rates, these factors need further consideration in the development of biocontrol programmes of FAW. Kasisi, where the highest parasitism rates were observed, is a training centre where conservation and organic agriculture are practiced through the year, while the other sites are located in areas where pesticides are commonly used. Mailafiya et al. (2010) also investigated farming activities in relation to parasitoid diversity and abundance and found that low parasitoid diversity was found where maize is cultivated on a commercial scale and intense grazing activities across seasons. The authors concluded that natural habitat is an important refuge to maintain parasitoid diversity. Refuges may also play an important role in the conservation of natural enemies of FAW (Harrison et al., 2019).

An interesting and unexpected finding among our results was the variation in parasitoid occurrence through the maize growth cycle. The parasitoid species attacking eggs and early larval stages such as *Ch. curvimaculatus*, *C. icipe*, *E. laphygmae*, *Parapanteles* sp., *Diadegma* sp. and *Pristomerus* sp. were observed only during the vegetative maize growth stages (V2-V4 to V8-V10) despite that all FAW stages (eggs, early and late larval stages) were present until VT-R1 and that no difference in FAW density was found across maize growth stages. These parasitoid species were absent beyond the V8-V10 stage. During the last two maize stages both occurrence and abundance of parasitoids recorded from the FAW larvae decrease and mainly the tachinid fly *D. quadrinozula* remains associated with FAW larvae. A few or a combination of possible factors may influence this effect such as plant structural complexity, composition of vegetation, host quality, host density, volatile organic compounds and seasonality. Plant structural complexity is known to affect host-finding success and foraging behaviour where more hosts are parasitized on simple plants compared to complex plants (Andow & Prokrym, 1990; Gingras & Boivin, 2002; Gingras et al. 2002; Gingras et al. 2003; Lukianchuk & Smith 1997). So far, these studies have mostly involved generalist egg parasitoids of the genus *Trichogramma*. When maize reaches the reproductive stage, the plant displays a more complex structure than during the vegetative stage with one to twelve leaves. Therefore, as the parasitoids found in Zambia are generalists, or specialized on *Spodoptera* spp. feeding on various plants (Yu et al., 2005), they might not be adapted to forage and parasitize hosts hidden in maize reproductive structures such as cobs, tassels and silks. However, conclusions cannot be drawn without further studies.

Herbivore-induced plant volatiles (HIPVs) emitted by maize plants that attract natural enemies may also play a role in the temporal distribution of parasitoid species in our study. Maize plants of 10

to 21 days old (3 to 9 leaf stages) emit induced volatiles when *Spodoptera exigua* or *S. littoralis* feed on the young leaves and consequently attract more natural enemies compared to undamaged plants (D'Alessandro et al., 2009; Turlings et al., 1991; Fritzsche-Hoballah & Turlings, 2001). While most studies on HIPVs and natural enemies have been conducted under controlled laboratory conditions, some have demonstrated their effects under field environments (Aartsma et al., 2019; Aartsma et al., 2020; Bernasconi Ockroy et al., 2001; De Lange et al., 2018; Drukker et al., 1995; Poelman et al., 2009; Shimoda et al., 1997). Furthermore, a recent study using 3-leaves stage (9-12 days old) maize plants confirmed that *S. frugiperda* has lower HIPVs induction on maize than other *Spodoptera* species (De Lange et al., 2020). More field and laboratory-based studies are needed to understand this tri-trophic interaction between maize, *S. frugiperda* and its natural enemies.

FAW density also has a significant effect on parasitoid occurrence. A larger number of parasitoids and species were recovered when FAW density peaks at V5-V7 and V8-V10. *S. frugiperda* is known to prefer feeding on vegetative stages of maize when the whorl is still present (Capinera, 2008) and results from our study show that FAW larvae population builds up until V8-V10 and then starts decreasing from V11-V12. A recent study conducted under field, field cages and greenhouse conditions aimed at understanding FAW larval choice during maize reproductive stages demonstrated that feeding sites are chosen by first-instar larvae (Pannuti et al., 2016). In addition, leaves from reproductive stages and opened tassels were not suitable for development and survival of early larval stages compared to silk, closed tassels and kernels tissues. Our findings are consistent with this study as we observed FAW larval density declining from V11-V12 when leaves start drying up and tassels are developing. During field collection, we have also observed FAW larvae feeding on closed tassels and silk during maize stages VT-R1 but not on opened tassels. According to these observations, maize growth stages and structures available influence FAW larval density which thus affects parasitoid occurrence. As shown in the results, this difference in parasitoid occurrence is mainly due to the tachinid fly *D. quadrizonula* which is associated with late larval stages which become more abundant later in the crop cycle, from V8-V10. As demonstrated above, a tri-trophic approach is needed in future studies to fully understand interactions between maize growth stages, *S. frugiperda* and its natural enemies.

The relationship found between FAW larval stages and parasitoid species is consistent with literature on similar species attacking FAW in the Americas or from the same species attacking other Noctuidae pests in Africa. Ten of the twelve species found in Zambia have been recovered from larvae collected in the first to fourth larval stages. This finding is encouraging for biological control programmes as early larval stages are the stages that need to be controlled before too much damage is done to the crop. In the Americas, the egg-larval parasitoid *Ch. insularis* is the most common parasitoid of fall armyworm (González-Maldonado et al., 2014; Jaraleño-Teniente et al., 2020; Meagher Jr et al., 2016; Molina-Ochoa et al., 2003; Ordóñez-García et al., 2015; Ruíz-Nájera et al., 2007). While other countries in Africa have recorded one species of *Chelonus* (*Ch. curvimaculatus* in Kenya (Sisay et al.,

2018; Sisay et al., 2019) and *Ch. bifoveolatus* in Ghana, Benin, Senegal and Tanzania (Agboyi et al., 2020; Koffi et al., 2020; Ngangambe & Mwatawala, 2020; Tendeng et al., 2019), in Zambia we have recorded two species. This could have some implication for interspecific competition, therefore, further studies are needed to understand the interaction and ecological niches of both species, mainly if classical biological control is considered in the future with *Ch. insularis*. *Cotesia marginiventris*, a species related to *C. icipe*, attacks the first to second instar larvae of noctuid moths. In our study, all except one (L3) *C. icipe* parasitoids were recovered from larvae collected as L1 and L2. This parasitoid was present at low parasitism rates during the early maize crop stages only. Similarly, *E. laphygmae* was also present at the early stage of the fall armyworm infestation, attacking L1-L2 instar larvae at very low incidence. However, literature reported that *E. laphygmae* attacks L2 to L4 instar larvae of native African Noctuidae pests (Gerling & Limon, 1976; Gudeta, 1998). The same behaviour was observed from this species in Malawi during an outbreak of *S. exempta*, where *E. laphygmae* appeared early in cereal crops followed by *Apanteles* (=*Cotesia*) species (Smee, 1946). Very limited information is available on the biology of *Parapanteles* species, but from our results and a study in Africa (Valerio et al., 2005), the genus seems to prefer L1-L2 for oviposition.

Coccygidium luteum, one of the most common parasitoids on FAW in Africa, was recovered from larvae collected as L1 to L4 in the field. A study by Agboyi et al. (2019) showed that *C. luteum* females attack the L1 stage of FAW, but that the parasitoid larvae emerge from the host between 8 to 10 days after oviposition in L1, which correspond to the development time of unparasitized FAW larvae up to L4 (Montezano et al., 2019). The only tachinid fly recovered from fall armyworm larvae was *Drino quadrinozula*. Tachinid flies are known to attack mostly late instar larvae (van den Berg et al., 1988). Over the crop cycle, they started to appear only when the population of late instar larvae had peaked at V8-V10 maize stage. This category of parasitoids can be of importance in the control of FAW mainly by reducing subsequent dispersal of adult moths to other fields. While the rearing of tachinid flies can be difficult in the laboratory, further research on conservation biocontrol to improve parasitism and population would benefit the fight against FAW.

Pristomerus spinator is found in the Americas to attack FAW larval stage L3-L4 (Cave, 1995) and on the African continent, *Pristomerus* spp. have been recorded attacking L2-L4 of *Helicoverpa armigera* (van den Berg et al., 1988) which is in accordance with our results. van den Berg et al. (1988) have reviewed in detail the natural enemies of *H. armigera* in Africa of which many species or genera overlap with the species found in this study. As *H. armigera* has similar larval development stages as *S. frugiperda* (L1-L6), we can assume that the following parasitoids attack similar host stages: *Charops* sp. (L1), *Diadegma* sp. (L3), *Enicospilus sp.* (L3-L4) *and Metopius discolor* (L5-L6), which again is consistent with our findings. Only one or two specimens of these latter parasitoids were recorded during the 2018-2019 season, and the same species are also observed to be rare on *H. armigera* except for

Charops sp. However, the FAW larval stages associated with the parasitoid species in our study are the stages at the day of field collection, therefore, we cannot be sure of the host stage attacked.

Numerous studies looked into the relation between parasitism and host density (May et al., 1981; Stirling, 1987; Walde & Murdoch, 1988). This relation can be categorised as direct, inverse or independent (Godfray, 1994). Although our results show a general direct relationship between FAW density and parasitism rate, this result needs to be considered with caution because we did not discriminate between spatial (within-generation) and temporal (between-generation) density dependence, which are very different concepts (Dempster & Pollard, 1986). In our study, we neither sampled enough sites nor did we study enough generations to draw firm conclusions on density dependence. In addition, host-parasitoid density should better be assessed per parasitoid species, which was not possible here because most parasitoids died as undetermined Hymenoptera, and some species only had one or two specimens over the whole season.

In our study, twelve species were found to attack and develop on FAW egg, larval and pupal stages. Nevertheless, none of the species seems to show high efficacy in the field to keep FAW under control. The biological features of highly mobile pests and their shifts in crops and habitats make them very successful in invading a new environment. However, their natural enemies may encounter difficulties adapting to new habitats in order to follow the seasonal movement of the pest which eventually impacts their effectiveness as biological control agents (Hirose, 1998). In conservation biological control, effective natural enemies of mobile pests should be characterized by good colonization ability, dispersal of a portion of the new generation from the fields when hosts are present, high mobility and have a shorter generation time than the host. In the light of these recommendations, many more studies will be critical for evaluating the biology and ecology of local African parasitoids which are still unknown and poorly studied for many. Furthermore, surveys of natural enemies occurring sporadically at various stages of the crop cycle may lead to an underestimation of the parasitoid complex and various parasitoid species might be overlooked in surveys. As conservation biological control focuses, among other strategies, on enhancing food and shelter resources to local natural enemies, a thorough inventory of the natural enemies and their roles during the crop cycle is critical to assess timely and effective conservation practices.

CONCLUSION

In conclusion, our study found associations of local parasitoid species with the invasive alien species *S. frugiperda* in Zambia. We also demonstrated that location, maize growth stage and larval stage are factors strongly influencing parasitoid species occurrence. This research showed the importance of understanding the spaciotemporal activities of local natural enemies and tri-trophic interactions when elaborating a biological control programme. This is specifically relevant for conservation biological control in order to develop timely management practices against a specific pest

stage in order to enhance parasitoid populations and mobility across crop and non-crop habitats. Further studies are needed to determine the exact species of parasitoids through both molecular and morphological identification, the effect of maize growth stage on parasitoid attractiveness, abiotic factors influencing diversity and abundance, the population dynamics of the main parasitoids and the role of HIPVs on parasitism of fall armyworm in order to develop safe and practical control methods for smallholder farmers.

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3 Investigating the feasibility of developing a collective action for biological control of fall armyworm among smallholder farmers in rural communities of Zambia

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ABSTRACT

Fall armyworm, *Spodoptera frugiperda*, an alien invasive pest from the Americas, was detected in Zambia late 2016 and since has caused significant losses on maize threatening livelihood and food security. Individually, farmers continue to rely on synthetic pesticides, a reactive measure to manage new invasive insect pests, posing risks to human health, the environment and biodiversity. Biological control has been proven to be an efficient, cost effective and safe method for pest and disease management, and when adopted collectively, its effectiveness can increase. In addition, collective action has been acknowledged to be a critical component for invasive species management but is still poorly studied in low- and middle-income countries (LMIC) where the national plant health system, in-place to prevent and manage biological invasions, is limited. To study the feasibility of creating a collective action to promote biological control for fall armyworm among smallholder farmers in rural Zambia and the social and institutional conditions needed for it to be successful and sustainable, we conducted focus group discussions and in-depth interviews in two districts with maize smallholder farmers. Our model to assess the results applies both Ostrom's eight Design Principles for a community-based management of common-pool resources and criteria of an agricultural innovation that meet the community's requirements, and also pays attention to the exchange and brokering processes needed to match the two. Our results showed that some conditions are already in place to support a collective action to manage fall armyworm such as matching rules to local conditions, collective-choice arrangement, conflict-resolution mechanism and minimal recognition of rights to organize which are supported by traditional leadership of the communities. However other conditions would need to be strengthened for the collective pest management to be sustainable. The most important criteria for a pest management innovation selected by participants from both districts, in no specific order, were price, efficacy, recommended by agrodealer/extension officer and immediate action. This study fills a gap in understanding social and institutional conditions in LMIC needed to sustain a collective action that aim at controlling a highly mobile and invasive pest. Our study emphasizes the need to redefine technologies and dissemination in terms of supporting the processes of co-designing innovation based on social and ecological conditions.

INTRODUCTION

Globalization, international trade and environmental changes significantly facilitate biological invasions, processes by which an organism is introduced and established beyond its native range, resulting in major economic, environmental and social impacts (Early et al., 2016, Paini et al., 2016, Pratt et al., 2017). Invasive alien species (non-native species, weeds, plant diseases and plant pests, causing economic or environmental harm) have disproportionate impacts on smallholder farmers in low- and middle-income countries (LMIC), especially in Sub-Saharan Africa, where national capacity to prevent and manage biological invasions is limited (Early et al., 2016). The total annual cost of alien invasive species to agriculture in Africa was estimated in a recent study at USD 65.58 billion (revised from 3.66 trillion since the publication of this chapter) (Eschen et al., 2021a). Fall armyworm (FAW), *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), a highly mobile and migratory insect first detected in 2016 in West and Central Africa (Goergen et al., 2016), is estimated to cause US$9.4 billion loss in Africa (Eschen et al., 2021b) and US$159 million on maize crop in Zambia specifically (Rwomushana et al., 2018). This insect pest is a successful invasive species due to its high reproduction rate, ability to feed and survive on more than 300 host plants, and its migration patterns (Day et al., 2017). Indeed, females can lay up to 1,000 eggs and disperse about 500km before oviposition. Moreover, as climatic conditions are favorable throughout the year across the African continent, there is constant food source availability and no observed diapause behavior making FAW even more difficult to control (Du Plessis et al., 2020). So far, extension and advisory services to control FAW have been directed at individuals and field level management (FAO & CABI, 2019a).

Invasive species can raise public-bad (a bad that is non-excludable and non-depletable, negatively affecting everyone equally) dilemmas due to their rapid spreading abilities which allow them to cross property boundaries creating interdependency among land owners (Graham et al., 2019). Consequently, if a land owner does not participate in controlling the invasive species, his/her land can become a propagule or breeding source that reinvade neighbouring fields increasing costs and effort for others (Epanchin-Niell et al., 2010; Kruger, 2016). FAW dispersal mechanisms create interdependency between farmers during outbreaks. Sustainable, long-term management in a fragmented or mosaic landscape is not possible by individuals acting alone. Indeed, management of FAW is currently accomplished by individual farmers who heavily rely on the use of synthetic pesticides despite the health and environmental risks (Day et al., 2017). FAW was detected late 2016 in Zambia and in a household's survey in 2017, 60% of farmers mentioned using synthetic pesticides to control FAW as their main control method (Day et al., 2017). It was also found that a highly hazardous pesticide listed in the Rotterdam Convention was used by about 9% of famers in 2018 (Rwomushana et al., 2018). Farmers in various countries also tried controlling the pest using different cultural, mechanical, botanical and biocontrol methods with diverse outcomes (Abro et al., 2021; Kansiime et al., 2019;

Tambo et al., 2020b), however, the use of synthetic pesticides was always found the most common control method.

Over the last decade, collective action, defined as a process where a group of people voluntarily commit to achieve a common goal (Meinzen-Dick et al., 2004), has been identified as a key component, however not the only one, for the successful control of invasive alien species (Epanchin-Niell et al., 2010; Graham et al., 2019; Garcia-Figuera et al., 2021; Marshall et al., 2016; Stallman & James, 2015). The lack of effective collective action among farmers is often a greater obstacle in controlling invasive species than lack of information (Marshall et al., 2016; Parsa et al., 2014). Many successful examples of collective pest management exist in the literature. The cotton bollworm, *Helicoverpa armigera* (Hubner), is a good example as its rapid pesticide resistance development now to 55 active ingredients (Hussain et al., 2015; Yang et al., 2013) has stimulated a landscape approach combining both technical and organization aspects (Wilson et al., 2018). A collective strategy to manage *H. armigera*'s pesticide resistance and outbreaks with cotton and non-cotton growers in Australia was essential. Many actors were involved in this strategy, however the cooperation among farmers was crucial to successfully halt the outbreaks and the pesticide resistance development which needed a shift from a field-to-field approach to a collective and coordinated management (Wilson et al., 2018). In Colombia, transboundary leaf-cutting ants management was investigated using participatory landscape-level research with the community (Ravnborg et al., 2000). This research focused on testing with farmers and finding the best technical and organizational solutions to a collective problem. Significant progress on ant control happened once mechanisms to encourage the majority of farmers in the area to participate in the simultaneous control of the nests. Initiatives for FAW collective action include the FAO-led Global Action for Fall Armyworm Control that has been instrumental in coordinating collaboration at regional and national levels in Africa. The actions taken involving multi-institutions and multidisciplinary teams are focusing on mass awareness campaigns, workshops for technical teams and supply of safe pesticides. Furthermore, international organizations and NGOs have provided support for specific components such as farmers awareness, research and early warning systems on a regional and national scale.

Conditions for effective collective management of invasive species have been reviewed by Graham et al. (2019) in relation to Ostrom's eight Design Principles (1990) for a community-based management of common-pool resources and 10 factors affecting self-organized collective action (Ostrom, 2009). Well-defined boundaries, monitoring and graduated sanctions alongside number of users, norms (social capital) and knowledge of the socioecological system were the most commonly mentioned design principles and factors respectively found in literature by Graham et al. (2019). Top-down approaches from governments, NGOs and scientists, are insufficient to ensure monitoring and management efforts across all actors due to the high transaction costs (e.g., time, labor, financial resources) (Garcia-Figuera et al., 2021). A community-based collective action building on existing

institutional arrangements could therefore offer an alternative (Marshall et al., 2016). Additionally, further empirical data are needed to understand under which conditions farmers are willing to collectively manage invasive species in LMIC and which pest management options are practical and acceptable under local socioeconomic and cultural contexts.

Biological control (either classical, augmentative or by conservation), later referred as biocontrol, is the use of living organisms to suppress or impact a specific pest population (Eilenberg et al., 2001). Biocontrol can improve and protect public goods such as food security, human health, biodiversity, and ecosystem services (Burra et al., 2021; Delaquis et al., 2018). Biocontrol has been proven an effective, safe and economic solution to pest management where chemicals have failed to control pests (Menzler-Hokkanen, 2006). As reviewed by Desneux et al. (2007), pesticides not only have lethal effect on pollinators and natural enemies, but also sublethal effects including development rates, malformations, perturbations of the foraging patterns and feeding behaviors. Over 30 species of indigenous parasitoids in 17 African countries have been found attacking FAW, promising potential for the biocontrol of FAW with native natural enemies (reviewed in Kenis et al., 2023). If communities decide to adopt biocontrol as an innovation to manage an invasive species, further collective action dilemmas may arise. For instance, the lack of sanctions, leadership, or monitoring system in a farming community may compromise the long-term benefits and sustainability of such initiatives if farmers fear that some won't follow the rules collectively agreed upon. Ideally, when implementing biocontrol schemes at landscape level, for example augmentative releases, all farmers would be required to decrease use of toxic products and numbers of applications in order to increase the effectiveness of the biocontrol agents (Babendreier et al., 2019). In the case of conservation biocontrol, the impact may only be seen years after consistent effort to modify and restore habitats of local natural enemies (Eilenberg, 2006). This time-lag may discourage end-users, despite the fact that natural pest control can provide long-lasting economic and environmental benefits.

The objective of this study is to determine the feasibility of a collective action using biocontrol to manage FAW among smallholder farmers in rural Zambia, and the social and institutional conditions needed to successfully sustain the collective action. The authors did not intend to study current control methods used by smallholder farmers to control FAW. The following research questions were addressed: How is the farming community in rural Zambia structured in terms of social capital, leadership, information sharing, internal and external communication and trust relationships, and how does it shape a potential collective pest management? What are farmers' attitudes towards a biocontrol management option of FAW based on collective action, and what criteria of an innovation is required for adoption? Our assumption is that communities with a strong social capital, leadership and internal and external communication will be able to develop and sustain a collective action for pest management. This study is part of a transdisciplinary research project aiming at understanding how best to collectively

develop and implement biocontrol programmes with smallholder farmers to control transboundary insect pests (Durocher-Granger et al., 2021).

Conceptual framework

Ostrom (1990) proposed eight Design Principles (DPs) for a community-based management of common-pool resources. These design principles are meant to provide guidance on important components or conditions that help to successfully sustain common-pool resource management by a group of users over time and generations but are not exhaustive. Although Ostrom' eight Design Principles were not designed for collective pest management, it has been found that they are well suited for addressing collective efforts and social dilemmas in agricultural ecosystems (Damtew et al., 2021; Galarza-Villamar et al., 2021; Kruger, 2016; Stallman, 2011; Tafesse et al., 2020). As suggested by Ostrom in 1990, further theoretical and empirical work is still needed, mainly in LMIC. Our model applies Ostrom eight Design Principles to the context of managing FAW, a highly mobile pest which characterizes the public bad and the sustainable and long-term management using biocontrol represents the common good to achieve by means of collective and coordinated actions. Landscape and management are highly fragmented in Zambia with around 95% of the 1.6 million small scale farmers owning less than 5ha of land (CIAT; World Bank, 2017). The successful invasive behavior of FAW allows it to quickly spread over large areas of maize fields, generating a collective action dilemma that is at the core of this study. Because biocontrol is an external innovation that needs to be introduced to

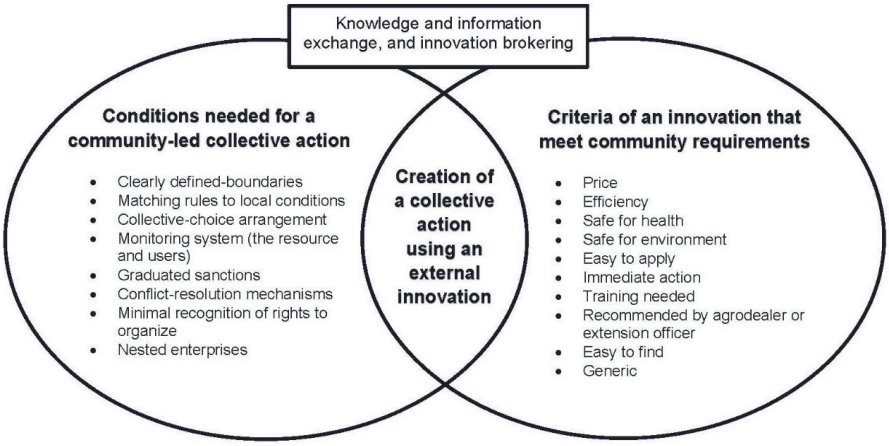


Figure 1: Framework to study the conditions needed for the feasibility of a community-led collective action. Legend: The framework applies Ostrom's eight Design Principles (1990) for a community-based management of common-pool resources supplemented with the criteria required by communities for an agricultural innovation to be adopted. A component related to innovation brokering and knowledge and information exchange was added to ensure a good match between externally introduced innovation and conducive conditions for collective action (Klerkx et al., 2009).

the communities, we supplemented the model with the criteria required by communities for an agricultural innovation to be adopted. We have also included a component related to innovation brokering and knowledge and information exchange to indicate that there is a need for processes that ensure a good match between externally introduced innovation and conducive conditions for collective action (Klerkx et al., 2009) (Figure 1).

METHODS

Study area

The study was conducted in Zambia between December 2019 and February 2020. Four farming communities from two districts were selected: Chintembe and Chimoto (Mumbwa district, Central province, 15° 02' S, 27° 06' E) and Hambale and Musika (Siavonga district, Southern province, 16° 23' S, 28° 42' E). Mumbwa district has an annual average precipitation between 800 to 1000 mm and annual mean temperatures are about 22.1℃ (agro-ecological zone IIa) (Makondo et al., 2014). Chintembe and Chimoto are located along the M20 road 11km South from Mumbwa town. Hambale and Musika are located about 25km North from Siavonga and 180km South from Lusaka. Siavonga district has an annual average precipitation of <800 mm and annual average temperature of about 26.7℃ (agroecological zone I) (Makondo et al., 2014). Maize occupies about 84% and 72% of the total area cultivated in Southern and Central provinces, respectively (Jain, 2007).

Study design

To understand collective action dilemmas and local institutions, we organized focus group discussions (FDGs) (Appendix 1) in each village engaging farmers with activities on past, current and potential collective community activities and trust. With this methodology, we are seeking the explicit use of group interaction and negotiations of different perspectives to generate data allowing a better understanding of the community structure and activities (Acocella, 2012; Hennink, 2013). Furthermore, focus groups were used as an exploratory tool to gain insights on sensitive subjects such as trust and power dynamics among the participants and with outsiders. Relying on a collective dimension and the interactions among the participants, the role of the researcher is limited to moderator, therefore decreasing the risk of collecting biased data. Additionally, this method is useful in capturing a comprehensive range of opinions and experiences about a given topic (Hennink, 2013). We hosted three FGDs for each village dividing the men, women and youth (less than 35 years old). Homogeneity among participants helped create a safe and comfortable environment to discuss openly and prevent inhibition. Whereas in heterogeneous groups, marginalized people such as women and youth may not express their views or answer questions in the presence of participants of different hierarchical positions such as men or elderly people (Acocella, 2012; Sieber et al., 2014). Thus, to allow effective participation and interaction amongst all participants and to collect unbiased data from all groups, we hosted the separate FGDs.

The in-depth interviews (Appendix 2) with the community members were developed in order to collect complementary information from individual farmers, to validate focus group discussion data, and to understand further the socioeconomic context which contains sensitive information that cannot be shared during FGDs. The questionnaire was designed as semi-structured focusing on basic information about the interviewee, farmer sources of information, FAW ecological knowledge and lifecycle. Each interviewee was asked to rate from 1 (not important) to 5 (very important) the importance of each criterion of an innovation/product when choosing between pest management options; price, efficiency (ability of achieve an end goal with the limited amount of resources), safe for health, safe for environment, easy to apply, immediate action, training needed, recommended by agrodealer or extension officer, easy to find and generic. The criteria are operationalisation of the variables presented by Meijer et al. (2015) from characteristics of agricultural innovation (benefit and costs) and communication and extension to provide attributes to an innovation in term of pest management (Parsa et al., 2014).

In total, 96 farmers were involved in the FGDs, and an additional 24 participants took part in the in-depth interviews as shown in Table 1. The participants were selected with the help of the camp officers and the headmen from each village and are representative of the two villages and two districts. The participants were selected based on 1) growing maize each rainy season, 2) being an active member of the farming community and 3) belonging to one of the three groups (men, women and youth). Both the FGDs and interviews were tested with farmers from Chilanga district, Mapepe village, located close to the Zambia Agriculture and Research Institute (ZARI) and refined to improve the tools. Interviewers sought informed consent from the participants prior to collecting and recording their information and the data was handled in accordance with the General Data Protection Regulation (GDPR).

Table 1. Descriptive statistics of the participants involved in the focus group discussions and in-depth interviews.

Region			**Participants**		
Focus group discussions					
Province	District	Village	Men	Women	Youth
Central	Mumbwa	Chintembe	8	8	8
		Chimoto	8	8	8
Southern	Siavonga	Hambale	8	8	8
		Musika	8	8	8
In-depth interviews					
Central	Mumbwa	Chintembe	2	2	2
		Chimoto	2	2	2
Southern	Siavonga	Hambale	2	2	2
		Musika	2	2	2

Data analysis

The software Atlas.ti (Version 9.1.7.0) was used to analyze the qualitative data collected through FGDs and individual interviews with a content analysis. The answers participants gave were coded and analyzed to retrieve common themes and patterns in relation to Ostrom' eight DPs (1990). Following coding, data were split up into meaningful and relevant segments, categorized and compared and, finally, reassembled again (Boeije, 2010). An inductive approach was applied: the codes were retrieved from the data, using a bottom-up approach and in vivo coding. A thematic analysis was applied to identify patterns in raw data as described by Braun and Clarke (2006). Data sharing codes or implying a common meaning were grouped and compared. This analysis was approached with a contextualist method in order to describe the experiences and meanings expressed by the participants (realist method) and to fit and contextualize them in the context of rural Zambia with the support of theories on collective action (constructive method).

From the in-depth interviews, mean (±SD) calculated from rating of each criterion of a product for selection, amount spent on pesticide and amount willing to spend on biocontrol products were analyzed using a two-sample t-test assuming equal variances between Mumbwa and Siavonga districts. Stata software 17.0 (StataCorp, 2021) was used for the tests and levels of significance were tested at 1%, 5% and 10% as the basis for rejecting the null hypothesis.

RESULTS

This section provides details on the situation at the time of the study (rainy season 2019-2020) on FAW knowledge, pesticide expenses and biocontrol followed by results from the FGDs on past, current and potential collective activities, local institutions, and trust, reciprocity and reputation within the communities in relation to Ostrom's eight DPs. This section is also supported and complemented by qualitative and quantitative data from the in-depth interviews with farmers on criteria of an innovation for adoption and knowledge and information exchange, and innovation brokering.

FAW knowledge, pesticides expenses and biocontrol

During individual interviews, farmers were asked to identify images of FAW lifecycle stages compared to common pests of maize in Zambia namely *Busseola fusca* (Fuller) (maize stalk borer), *Spodoptera exempta* (Walker) (African armyworm) and *Helicoverpa armigera* (Hübner) (cotton bollworm). Identification of the right images is captured in Table 2 per district and lifecycle category. Very few farmers identified correctly the FAW stages when compared to other common pests affecting maize in Zambia. When asked to organize the FAW lifecycle, in general, the pupa stage was not recognized or was misplaced in the cycle compared to the correct order (moth-egg-caterpillar-pupa). Follow up questions prompted the participants to explain further the FAW cycle. Eight farmers in Mumbwa mentioned that FAW comes from a butterfly that lays eggs on maize. In Siavonga, four farmers mentioned that eggs were deposited on the maize by an insect, but only one mentioned the insect was a butterfly. In Mumbwa, nine farmers explained that the larva was going into the soil or

turning into a butterfly after damaging the crop. In Siavonga, four farmers explained that they either change to another stage or fly away while the other farmers could not explain where the larva went after damaging their maize.

Table 2. Numbers of farmers.

Life cycle	**Egg**		**Larva**		**Adults**		**FAW cycle**	
Districts	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect	Correct	Incorrect
Mumbwa	2	10	2	10	2	10	2	10
Siavonga	1	11	3	9	1	11	1	11

Farmers in Mumbwa spend on average 1,162 Zambian Kwachas (K) (±K2,534) annually (range K150 to K10,000) on pesticide depending on the size of their field and type of crops while in Siavonga, farmers spend on average K172 (± K202) annually (range K0 to K550) and half of the participants don't buy pesticides. No significant difference was found between districts on the mean amount spent on pesticides (*t*-test=1.3503, *p*-value=0.1907). All the 24 farmers mentioned that they would be willing to try biocontrol options and in Mumbwa would spend on average K233 (±K180) and in Siavonga K329 (±K123) for biocontrol products. No significant difference was found between both districts on the amount they were willing to pay for biocontrol products (*t*-test= -1.5211, *p*-value=0.1424).

When asked if they had heard of biocontrol, all 12 farmers in Mumbwa said they had never heard of it while only two in Siavonga recalled an introductory meeting at the beginning of the project where biocontrol was mentioned as an option to control FAW. The two farmers described biocontrol as a practice that targets the pest without harming other beneficial insects and is friendly to human health and the environment. All 24 farmers were aware that once one of them see FAW in his/her field, everyone else has it, demonstrating knowledge on interdependency amongst farmers.

Applying Ostrom's eight Design Principles

DP1- Clearly defined boundaries. In this case study, the boundaries described during the study by participants were not geographical but institutional and traditional. Each village is under the authority of a headman, and each headman is part of a committee led by a chief. The villages involved in the current study consisted of around 130 households in Mumbwa district and 30 to 35 in Siavonga district. However, in Siavonga, households are located farther apart. Each farmer or newcomer is allocated a portion of land by the headman within the village to cultivate usually next to their fellow farmers but fields from different villages may border each other. Under their traditional community structure, the headman of each village engages and coordinates members for communal work. Participants involved in the FGDs and interviews explained that any collective work or activity is mostly organized within the village structural boundaries coordinated by the headmen but that they can showcase to other villages their experiences and success. If several villages benefit from the same resources, such as the

school, clinic or the road, then the committee of headmen will coordinate the villages' members to participate in the tasks required to benefit everyone. Every community participant of the study reported to be involved in some kind of collective work, from cleaning the streets during the rainy season to molding bricks for building the school, one person per household would be called to participate in the activity.

DP2- Matching rules to local conditions. Farmers explained having the option to join a cooperative for agricultural activities however the description demonstrated dissonance between external rules and the local conditions. Cooperatives were described by farmers as a top-down initiative, where communities don't have the authority to initiate their creation. Cooperatives were initiated outside the village either by the government or a local NGO where guidelines on the structure and coordination of the system were provided, but it was never a local initiative from the farmers in accordance with the traditional community structure. Moreover, each cooperative establishes a maximum capacity for the number of members able to join, on average between 20 and 30 members. To become members, farmers have to pay a membership, fees and shares. The amounts for each vary depending on the cooperative and location but mainly range between K50 to K200. In Mumbwa, farmers from different villages often join the same cooperative based on shared aptitudes or income generation activities such as dairy farms or growing vegetables. To benefit from the Farmer Input Support Programme (FISP), a government programme that subsidizes farmers with inputs to boost maize production across the country, cooperatives need to be registered with the local government. The cooperative structure was established before the Zambian government started the FISP in 2002. Since its implementation, the government work with the established cooperatives to register farmers and distribute the subsidized inputs (Burke et al., 2012; Chiboola M., ZARI social scientist, personal communication). The incentive to become a member is now mainly to benefit from the discounted inputs and less exchanges happen between members [FDG-Men Musika: *Fertiliser is cheap when you are in a cooperative*; FGD-Men Chimoto: *FISP would never look at you as an individual*]. Few participants mentioned learning and sharing new skills and knowledge on farming practices as a reason to join the cooperative. At the time of data collection in 2019, in Mumbwa, 79% of the participants were involved in cooperatives, while in Siavonga only 2% were involved since most of the farmers had to cancel their membership due to lack of financial resources. Other reasons mentioned for not joining or leaving the cooperatives included lack of interest or time, poor leadership, no tangible benefits, poor communication, and distrust from previous experience.

DP 3- Collective-choice arrangement. Despite that no collective pest management project has occurred in the past, the participants had a strong opinion about the decision-making process to reach consensus in the village. For example, if some community members need to be selected to take part in an initial training, the headman would call a meeting and collectively they would discuss and agree on who would be the best learners able to transmit the knowledge to the rest of the community. This

selection process is based on trust, reciprocity and reputation of individuals from previous experiences. Even if farmers already have experience on electing executive committee under the cooperative organizational system, any decision affecting the whole community is discussed, negotiated and agreed. Additionally, the headman was identified consistently as the key figure in the development of any project within the community and would need to be involved and updated regularly.

DP 4- Monitoring system. Farmers agreed that participation and activities need to be reinforced by the headman. The headman can even create rules and laws for the benefit of all and apply compulsory participation. Farmers insisted that they will encourage and demonstrate the benefits to reluctant and non-participating farmers to motivate them and can even work on their behalf. As fields from farmers belonging to the same village are next to each other, they meet often in the field where they discuss and exchange information. These informal meetings based on trust and reciprocity can provide a space for monitoring the pest occurrence and members' adherence to rules. It was also mentioned that the whole village should be well informed on the progress and benefits of a project even if only a few selected farmers will take part in a training initially or be involved during a pilot phase. Local and national plant health authorities do not establish or reinforce rules with incentives or sanctions neither monitor farmers to ensure proper pest management. Indeed, poor and unpredictable telecommunication networks and road infrastructure in remote rural areas make it challenging for the national plant health authorities to regularly monitor farmers' field and enforce rules.

DP 5 - Graduated sanctions. The headman was again identified as the authority to call meetings, to ensure farmers' participation in projects, and to be involved in cases where a fellow farmer does not comply with the rules established by the group. Discussing with the farmers to explain the benefits and encouraging participation were the most common solutions proposed, however no sanctions such as fines or payments where mentioned. Two groups decided that farmers who do not participate would be removed from the working group. No sanction or incentives is implemented by plant health authorities for pest management as mentioned above.

DP 6- Conflict-resolution mechanisms. Traditional leaders such as the headman were identified by participants to organize meetings and play a mediator role when needed to resolve conflicts [FGD-Men Chimoto: *We can ask the headman to ensure participation through a meeting on condition that the headman should have been informed of the training*, FGD-Men Chintembe: *The headman has the authority to ensure inclusiveness into the collective effort*]. If conflicts can't be resolved, it will then be passed on to the senior headman before escalating to the chief. Extension officers and local governments do not play a role in conflict-resolution of farming communities (Sheleni H., extension officer, Ministry of Agriculture, personal communication).

DP 7 - Minimal recognition of rights to organize. At local and national levels, plant health authorities in Zambia provide recommendations on how best to manage FAW field-by-field but collective pest management is not known from any community member. Plant health authorities rely mainly on local

extension officers to provide advisory services to farmers and distribute insecticides for the control of FAW. Despite the fact local and national governments encourage the establishment of cooperatives and provide pest management advice, traditional leaders are more trusted and respected for the establishment and enforcement of rules within the communities for a wide range of activities. Government officers can't overrule chief or headman authorities who are considered of higher hierarchy.

DP 8 - Nested enterprises. Villages are already divided in sections in a decentralized manner. Participants mentioned that each section would elect one representative who can be involved in a project or be trained on everyone's behalf. They would therefore ensure to reach out to all farmers of the village [FGD-Men Chimoto: *We can have decentralized group trained to prepare* [*the product*] *for distribution to the village around the divided groups*].

Rating of criteria of an innovation

During the in-depth interviews, when asked to rate from 1 (not important) to 5 (very important) for selecting pest management options, on average farmers in Mumbwa rated price as the most important criterion of a product, followed by efficacy and recommended by agrodealer/extension officer. In Siavonga, farmers rated efficacy as the most important criterion, followed by price and immediate action. Easy to find and easy to apply were rated low in both communities as less important for selection. Significant differences were found between both districts in rating price, safe for health, immediate action, training needed and easy to find (Table 3).

Knowledge and information exchange, and innovation brokering

Within the community

In Mumbwa, gardens were all located in the same area close to the stream, therefore farmers interact daily and learn how to grow vegetables from each other. In Siavonga, where the farmers are farther apart, these exchanges still happen frequently, mostly involving women who meet at least once a week at the borehole to collect water. When facing a problem, farmers will consult their neighbours to know if they are facing the same issue. The lead farmer was another trusted figure within the community for agricultural knowledge as they are selected by fellow farmers to attend training, establish demonstration plots and to transfer knowledge to others.

Employed by the government, extension officers assist farmers in improving farming practices to increase crop productivity and income (Swanson & Claar, 1984). The relationship that extension officers have with farmers is personal and they have a good command of farmers' agricultural situation. Being the only regular contact reaching the community, farmers are mainly dependent on the extension officer for new agricultural knowledge and updates. Furthermore, the community places itself under the authority of the extension officer. As for the headman, farmers want the extension officer to be aware of any project they are involved in, recognizing in the presence of the extension officer a warranty of

trustworthiness. The role of the extension officer focuses mainly on technology and information transfer. Whenever lead farmers are not able to advise on agricultural issues, farmers can reach the extension officer by phone and meet in the communities to provide a solution. For outsiders, the extension officer is the main technical contact point with the community concerning agriculture, who will contact the headman to agree on potential projects in the village.

Table 3. Results of two sample *t*-test (means ±SD) rating of criteria of an innovation or a product for acceptance by participants from Mumbwa and Siavonga. The variables analysed were the rating between 1 and 5 between both district (1= not important and 5=very important).

Characteristics	District	N	Mean	SD	*t*-value	*p*-value
Price	Mumbwa	12	5.000	0	5.2035	<0.00001***
	Siavonga	12	3.667	0.888		
Efficiency	Mumbwa	12	4.583	0.900	0.4098	0.6859
	Siavonga	12	4.417	1.083		
Safe for health	Mumbwa	12	4.000	0.739	2.7663	0.0113**
	Siavonga	12	2.667	1.497		
Safe for environment	Mumbwa	12	3.250	1.215	0.4771	0.6380
	Siavonga	12	3.000	1.348		
Easy to apply	Mumbwa	12	1.917	1.564	-0.4302	0.6713
	Siavonga	12	2.167	1.267		
Immediate action	Mumbwa	12	2.250	1.138	-2.4010	0.0252**
	Siavonga	12	3.417	1.240		
Training needed	Mumbwa	12	1.917	1.505	-1.8269	0.0813*
	Siavonga	12	3.083	1.621		
Recommended by agrodealer or extension officer	Mumbwa	12	4.167	1.267	1.7064	0.1020
	Siavonga	12	3.167	1.586		
Easy to find	Mumbwa	12	1.667	0.888	-2.1828	0.0400**
	Siavonga	12	2.417	0.793		
Generic	Mumbwa	12	2.583	1.165	-0.4302	0.6713
	Siavonga	12	2.833	1.642		

*<0.01, ** <0.05, ***<0.001

Outside the community

The agrodealer is a recurrent contact outside the farming community. While in Mumbwa the participants could mention several ones, in Siavonga farmers trust only one agrodealer, which they called by name, underlying a constrained relationship. Compared to the extension officers, agrodealers don't assist farmers in the communities but have their shop in town which farmers must physically visit for advice or to buy inputs. However, this exchange of information is unilateral: when consulted, the agrodealer provides solutions in terms of which inputs to use. Generally, the farmers consult the agrodealers for chemicals advice only.

Exchanges with outsiders are less frequent than with the extension officers or agrodealers in the communities and every contact is strongly mediated [FGD-Youth Chimoto: [*An outsider*] *cannot come directly to us. He has to go to the extension officer first and he/she would go to the headman and*

then maybe. FGD-Men Hambale: *You must come through the extension officer,* FGD-Women-Hambale: *If someone comes to me, I will send him to the headman and he will ask for contact details*]. Nevertheless, being introduced by the extension officer and headman would not be enough for an outsider to gain the trust of the community. Strongly relying on reputation and peer-to-peer control, farmers want to know everything about the person and will ask around about the reputation of this person before accepting to work with the outsider. Farmers want to be able to track and get in contact with someone for accountability in order to be able to trust the person [FGD-Women Musika: *We would need to know where your shop is,* FGD- Men Chintembe: *I would trust someone when I know with who he had worked in the past*].

DISCUSSION

Our case study brings to light the critical role of local traditional institutions in rural Zambia and their potential to uplift a collective action for the sustainable management of FAW and other invasive species. In relation to Ostrom's eight Design Principles, our results indicate that matching rules to local conditions (DP2), collective-choice arrangement (DP3), conflict-resolution mechanism (DP6) and minimal recognition of rights to organize (DP7) are conditions clearly in place and conducive for the successful establishment of a collective action for the communities involved in this case study. However, other conditions such as the monitoring system (DP4) and graduated sanctions (DP5) were found weaker and will need further effort to strengthen them as they are always critical in the success of a collective action. These findings are consistent with similar studies (Garcia-Figuera et al., 2021; Graham et al., 2019; Kruger, 2016) suggesting that not all design principles are as important compared to common-pool resources management and that relevance of each design principle may vary according to the cultural context of farming communities. We therefore suggest that invasive species management programmes in LMIC should recognize and build on local institutions to develop collective interventions.

A well-coordinated pest management project at community level can bring significant collective benefits in the long-term such as increased livelihood through reduced pesticide expenses and yield losses, and improved environment, human health and water quality from reduced pesticide usage (Kruger, 2016). However, highly mobile pests such as FAW can bring considerable social dilemmas within a farming community where the main resource is grown in a mosaic pattern over a large area or when the geographical or institutional boundaries do not match with the boundaries of the pest. In Zambia, maize is the main staple crop cultivated over an area of 1.3m ha (FAO, 2022) by approximately 1.6m smallholder farmers where 71.5% own less than 2ha and 23.8% between 2-5ha of farmland (CIAT; World Bank, 2017). At the onset of the rain, farmers start planting maize in small, fragmented plots neighbouring each other, making FAW's main food widely available. For government officers, field boundaries may be unclear and coordinating actions or monitoring farmers can be challenging due to the high number of farmers spread across a vast territory. The data collected in our

case study clearly showed that farmers abide by their local community structure which is consistent with traditional leadership in sub-Saharan Africa and rural Zambia (Tiwari et al., 2017). The boundaries defined by participants were consistently related to the village social structure led by the headman rather than the geographical boundaries delimiting villages or farms (DP1). While this demonstrates the strong social capital (shared knowledge, understanding, norms and rules), a collective action to manage a highly mobile pest affecting a large area such as FAW will require consistent effort to overcome mismatches between institutional boundaries and agroecological/geographical boundaries. Nevertheless, the well-defined leadership through the headmen committee and the chiefdom territory can provide a foundation to establish the geographical limits of the collective action. While spraying pesticides can be done in an uncoordinated manner, at farm level, according to habitat fragmentation and land boundaries, the implementation of biocontrol practices is more effective on a regional or landscape level under coordinated actions (Babendreier et al., 2019; Cumming and Spiesman, 2006; Stallman and James, 2015).

Conservation biocontrol through habitat management may not be immediately effective opposed to the preference indicated by farmers: the restauration of natural enemies' populations may be seen only after a few years. In this case, some farmers may decide to opt-out of the collective action if the outcomes are not readily observable, putting pressure on the commitment of other farmers or even creating a counterproductive situation. Indeed, developing a biocontrol scheme requires an efficient governing system. Farmers must jointly adopt field management and agronomic practices, such as decreasing pesticide applications, using chemicals that are non-toxic to natural enemies, keeping natural habitats and creating refuges and corridors for natural enemies (Gurr et al., 2000; White, 2019). In the case of FAW, even if the majority of farmers cooperate and follow rules, only one field not adequately managed can be enough to serve as a breeding spot to reinvade neighbouring fields.

As discussed by Ostrom (2009), if the initial rules established are not congruent with local conditions (DP2), the sustainability of a collective action might not be achieved. Our study clearly demonstrates that a collective action would be best initiated by communities due to the traditional community structure where rules comply with local conditions and stakeholders' interests and attributes (Garcia-Figuera et al., 2021) and that national and local governments can't interfere with traditional leadership (DP7). While cooperatives have contributed benefits to many isolated farmers in Zambia to reduce poverty (Pinto, 2009; Öjermark & Chabala, 1994), their institutional structure doesn't acknowledge the rich social capital existing in the communities, as observed by Akwabi-Ameyaw (1997) in Zimbabwe. Cooperatives are defined as "associations of persons who have voluntarily joined together to achieve a common end" (ICA, 1995). It represents a legacy of the economic progress expectations following the end of the colonial regimes (Bowman, 2011). Indeed, farmers joined cooperatives according to the money available for membership and with the main interest of accessing the subsidized inputs from the FISP. As an example, merging farmers from different villages, the peer-

to-peer control, monitoring of the resource and users, and knowledge exchange based on trust, reciprocity and reputation are missing. Exchange, cooperation and consensus happen within the village traditional institutions rather than between members of the same cooperative. Furthermore, not only are cooperatives external initiatives but they also have a maximum number of participants which doesn't promote equality, especially towards youth who are often unable to afford the membership fees. In the case of biocontrol and pest management in Zambia, a community-based initiative developed and implemented in accordance with local social conditions would be more effective than relying on cooperatives to implement rules and a monitoring system.

The traditional power inherited by the headman would play a central role in the development or modification and enforcement of the rules agreed by the members (DP3). Although the headman is not recognized as a source of agricultural information, any rules created and enforced by him will be respected. In the establishment of a collective action, working rules must be agreed upon by the community in order to set up a system based on mutual trust promoting the required actions. Setting up such a system increases transactional costs in terms of resources and time (Oliver & Marwell, 1988). Our study demonstrated that the involvement of local leaders, such as the headman, can offset these costs (Ostrom & Ahn, 2009). The collective-choice arrangements, reflecting the strong social capital of the communities in rural Zambia, is a paramount condition required to be in place for effective collaboration. Another important condition to sustain trust and reciprocity needed for a collective action is the prerequisite of a monitoring system implemented by the resource users rather than external authorities (DP4). While farmers trust each other in equally participating in a project, the peer-to-peer control is maintained through traditional authority represented by the headman. If farmers do not abide to rules commonly agreed, the headman can intervene as a mediator who also secures the conflict-resolution mechanism in the community (DP6). Furthermore, farmers value the promotion of incentives rather than sanctions to motivate other farmers to join or remain in a project using demonstrations or even working on their behalf (DP5). Besides, farmers constantly insisted on the need to receive progress updates or mentioned they always receive. Monitoring systems, graduated sanctions and conflict-resolution mechanisms are strongly intertwined and deeply rooted within the traditional leadership of the villages. These principles are of paramount importance for the effective collective management of FAW due to its high mobility and reproductive rate, characteristics which can escalate quickly into outbreaks if no control method is applied. As farmers from the same village own fields next to each other, it becomes easier to jointly monitor the resource as well as exchanging knowledge and lessons learned.

When FAW was first detected in Zambia late 2016, the government quickly acted to support farmers mainly in distributing free chemical pesticides to spray (Kansiime et al., 2019). However, due to the lack of knowledge on how best to manage this new invasive species, its impressive ability to invade, rapid establishment and lack of diapause in Africa, its management quickly became challenging.

Therefore, the role of the extension officer became crucial in communicating new knowledge on the pest. Extension officers have regular contact with the communities and are seen as an important source of information in agriculture. The communities already trust the extension officers; they have a good reputation for responding to requests, and their involvement in any new project is mandatory. Indeed, the trust and reputation that extension officers have gained in the communities can considerably reduce the transaction costs needed for a collective action implemented as a top-down approach. Being in charge of various villages, extension officers can connect and coordinate different communities who don't normally have regular interaction consequently increasing the outreach and impact of the coordinated actions. Additionally, their endorsement for a product or an innovation is highly valued by farmers for acceptance. Agrodealers were also identified as a local source of knowledge and information when farmers face problems with their crops, however their role could not support a collective action within the community due to their remote location and sporadic interventions. Nevertheless, they can contribute to increasing collective knowledge and valorizing collective pest management by providing nature-based advice or alternatives to chemical pesticides that meet communities' requirements. These results highlight the need to upscale training and capacity building of extension officers and agrodealers on ecosystem services, natural pest control and biocontrol products as they are the main source of information in agriculture (Constantine et al., 2020). Within the community, the continuous exchanges between farmers are an important channel for the creation and development of local knowledge (i.e. know-how, practices, skills developed by people sharing history and experiences (Beckford & Barker, 2007)) supporting a collective action, as well as trust, reciprocity and reputation.

Most farmers had never heard of biocontrol as a pest management option and heavily rely on chemical pesticides as their main control method for FAW. Farmers showed willingness to pay for biocontrol products with limited knowledge on the innovation indicating openness to try new pest management practices. The limited knowledge on FAW lifecycle and differentiation with other common pests could be a constraint for a collective action as a good command of the pest cycle and behavior is crucial for its management in relation to interdependency between farmers (Tafesse et al., 2018). A previous study in Zambia (Kansiime et al., 2019) showed that 91% of farmers could recognize FAW caterpillar and damage however the images were not compared with other pest species. The current national extension system focuses on a specific topic when a new problem arises rather than looking at the whole agroecological system. Providing further training on biocontrol and the various pests found in agroecological systems would increase collective knowledge on the different management options focusing on the system rather than a single pest where farmers could collectively decide which option suits them most.

The linear model of innovation assumes that knowledge is generated by innovators, transferred by communication workers and applied by farmers (Leeuwis, 2004). However, many studies have shown that characteristics of an innovation, perceptions and attitudes of farmers, and local

socioecological conditions can influence its adoption or dis-adoption (Leeuwis, 2004). As Mumbwa and Siavonga are located in different agroecological zones, the social and ecological conditions are therefore different. Siavonga region receives much less rain than Mumbwa and farmers have to rely on drought-tolerant crops such as sorghum, millet and cowpeas whereas Mumbwa farmers enjoy a longer rainy season and can even grow vegetables during the dry season due to streams around gardens. Consequently, both communities expressed different preferences in the criteria of an innovation or product for its selection. In Mumbwa, when deciding to buy a product, farmers consider the price as their priority compared to efficacy in Siavonga. Furthermore, Mumbwa participants gave more importance than Siavonga participants to "safe for health" and "price". However, Siavonga rated higher than Mumbwa the criteria "immediate action", "training needed" and "easy to find". The distance from the communities to the agrodealer in Siavonga (at least 25 km) and the costs in transportation may partially explain the preference for a product that is easy to find and rapidly effective. In Mumbwa, various NGOs have worked in the region promoting alternatives to pesticides and conservation agriculture where safe products for health and environment have been scored high in importance. Finally, both communities rated recommended by extension officer or agrodealer an important determinant for acceptance supporting the trust and reputation that farmers have towards them. These findings support the theory that extension needs to move away from the "one-size-fit-all" dissemination methodology and should be redefined in terms of supporting the processes of co-designing innovation based on social and ecological conditions (Leeuwis, 2004; Kruger, 2016).

CONCLUSION

This study fills a gap in understanding social and institutional conditions in LMIC needed to sustain a collective action that aim at controlling a highly mobile and invasive pest. Under the traditional leadership of sub-Saharan Africa, we found that matching rules to local conditions, collective-choice arrangement, conflict-resolution mechanism and minimal recognition of rights to organize are conducive conditions already in place for the successful development of a collective action for the management of a highly mobile and invasive pest. Our study highlighted the need to understand and build on the local institutional structures in collective pest management, especially for biocontrol schemes where the long-term benefits are more effective on a landscape level and can take time to be appreciated. If properly coordinated, biocontrol schemes implemented at the landscape level have the potential to significantly reduce the need for applying pesticides, and in this case, increase food safety and security and the livelihoods of vulnerable marginalized farmers. However, further empirical research and implementation trials are needed. Indeed, this next step can be challenging for research purposes due to the large area and extended period needed to test the innovation. To successfully achieve collective management of highly mobile and invasive pests, we therefore recommend developing a long-term plan with farmers to progressively phase out pesticides and transition towards natural pest control provided by ecosystem services where chemicals are the last resort.

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4 Preliminary results on effects of planting dates and maize growth stages on fall armyworm density and parasitoid occurrence in Zambia

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ABSTRACT

Fall armyworm (FAW), *Spodoptera frugiperda*, has become one of the main invasive species on earth since it was first found outside its native range in Africa in 2016. Integrated pest management (IPM) is a comprehensive tool that can help farmers managing pests while reducing the need of synthetic pesticides. Within an IPM strategy, proper time of planting is a critical management decision for farmers as planting too early or too late can lead to complete loss of the crop. Commonly, planting early to avoid peak infestation of FAW is recommended to farmers, however, no empirical data in Africa is available to sustain the advice. We studied the effects of planting date of maize as well of maize growth stages on FAW density and on its local parasitoids in a field study. Three plots were setup (early, intermediate and late planting) and data was collected weekly in each plot. Plots were 20m x 20m to avoid small-plot effects, but the relatively large size of the plots was resource intensive and prevented replication. As such, this paper presents preliminary results due to the lack of true replicates across locations and years. Generalized Linear Models were used to model FAW density and parasitoids abundance and diversity. Our results showed an increase of egg masses over time from early to late planting. Additionally, parasitism probabilities were lower in the early planting treatment than for the intermediate and late plantings and decreased with increased maize maturity. Results on biodiversity of parasitoids show a less even trend for early and late whorl stages which are dominated by one or two species while maize reproductive stages show a more even distribution of species. Our preliminary research is the first to provide empirical evidence that planting early helps to avoid the peak activities of FAW moths. These findings provide important information for the sustainable management of FAW in Zambia with the aim to reduce chemical inputs and increase farmers' incomes and livelihood.

INTRODUCTION

Biotic and abiotic factors such as rainfall, temperature, altitude, vegetation, natural enemies and agronomic management practices, play pivotal roles in influencing the occurrence, infestation rate and damage caused by pests (Conte et al., 2007; Marchioro & Foerster, 2016; Savopoulou-Soultani et al., 2012; Thakur & Rawat, 2014; Wolda, 1978). For smallholder farmers with limited resources, the timing of planting, as part of an integrated pest management (IPM) approach, is one of the most important tools for pest control as planting too early or too late can result in complete crop loss. Time of planting can impact pest density, and therefore, damage incurred to crops. For instance, research on the maize stalk borer *Busseola fusca* (Fuller) (Lepidoptera: Noctuidae) has shown that late planting is associated with higher infestation rates, higher damage, and subsequently increased yield losses (Ebenebe et al., 1999; Gebre-Amlak et al., 1989). Understanding the population dynamics of insect pests and the community composition of local natural enemies can help develop a comprehensive pest management strategy centred on ecosystem services and cultural practices.

Indeed, a good understanding of the pest dynamics and tri-trophic interactions (plant – pest – natural enemies) over the crop season can help avoid high infestation rates and yield losses by pests, and unnecessary pesticide applications. Furthermore, natural enemy populations can be conserved and enhanced at specific crop growth stages if diversity and abundance are known over time (Durocher-Granger et al., 2021). Just like insect pests, parasitoids are also affected by biotic and abiotic factors. Temperature, rainfall, landscape characteristics, seasonality, host density, host stages and herbivore-induced plant volatiles are known to influence diversity, abundance, and parasitism rates in the field (Bernasconi Ockroy et al. 2001; D'Alessandro et al. 2009; Mailafiya et al. 2010; Tscharntke & Brandl 2004). As being dependent on their hosts for development, parasitoids would obviously benefit to synchronize their emergence as adults with the presence of susceptible host stages (Godfray, 1994). This is especially important in tropical regions where a long dry season is observed and depending on whether the insect hosts have one or a few generations a year. Therefore, good knowledge of the parasitoid complex and dynamics under these climatic conditions is even more essential for developing a targeted IPM approach.

Globally, the adoption of IPM remains alarmingly low, particularly in low- and middle-income countries (Alwang et al., 2019; van Huis, 1981; Parsa et al., 2014). IPM, especially the biocontrol component, is often implemented and adopted only as a last resort to exit a crisis. A pesticide treadmill is observed around the world which is characterized by overuse of synthetic insecticides (frequent applications, high dosages and limited range of active ingredients and/or mode of actions) leading to the development of pesticide resistance, pest resurgence, emergence of secondary pests and the depletion of beneficial insect populations (Bakker et al., 2020). This cycle, therefore, aggravates dependencies on pesticides for pest management. Fall armyworm [FAW, *Spodoptera frugiperda* (J.E. Smith)] (Lepidoptera: Noctuidae) management does not escape these major problems and collective efforts to develop sustainable and low-impact practices have already created extensive knowledge to

develop best management practices for smallholder farmers in Africa and Asia (reviewed by Kenis et al., 2023). Smallholder farming systems need to become more resilient for the upcoming decades as pest invasions are likely to increase with change in climatic patterns and increasing trade routes (Early et al., 2016).

FAW has become a major maize pest worldwide after its invasion and establishment on the African and Asian continents since 2016 (Kenis et al., 2023). In Africa alone, the yield loss is estimated to be USD 9.4 billion (Eschen et al., 2021b). In Zambia, farmers have reported maize yield losses ranging between 21% and 77% in 2017 (national average of 40%) (Day et al., 2017), and 10% and 58% (national average of 35%) in 2018 (Rwomushana et al., 2018), showing a wide variation between agroecological regions. FAW has not been observed yet in Africa undergoing diapause, but studies suggest its potential regional migration (Nagoshi et al., 2018; Nagoshi et al., 2022). As maize monocropping is found across Africa at different periods of the year, regional migrations alongside resident local populations persisting on wild hosts and irrigated maize are likely to colonize maize fields at the onset of the rain.

Early planting is commonly recommended to smallholder farmers to avoid the peak infestation of FAW (Ayala et al., 2013; Deshmukh et al., 2021; Harrison et al., 2019). However, empirical data are missing to support this advice. This study aimed at identifying optimal planting time for maize by evaluating FAW density, parasitism probabilities and parasitoid abundance and diversity for early, intermediate and late planting. We also investigated maize growth stages effect on FAW density, parasitism probabilities and parasitoid abundance and diversity.

MATERIALS AND METHODS

Experimental design

Field studies were carried out during the rainy season from December 2021 to April 2022. An irrigation system was used once the rains stopped after mid-March 2022 to maintain the late planting plot until cob maturity. The site was located in Zambia's Lusaka province; Chalimbana (15°21'33.9"S, 28°29'18.9"E; altitude: 1,130m). Three fields of maize (variety MRI624; Syngenta Seeds Zambia), measuring 20 m x 20 m, were planted at three-week intervals from the start of the rains (planting-date schedule shown in Table 1). A 75 cm gap between maize rows was maintained, and 30 cm between maize plants. Standard agronomic practices for maize fields were adopted as recommended by the Ministry of Agriculture to smallholder farmers in Zambia. Neighbouring fields were planted with maize crops like every rainy season as maize is mainly rainfed in Zambia. Pseudoreplicates were used in order to avoid an effect of small plots on FAW density by increasing the size of each plot at 20m x 20m. The large size of the plots was resource intensive and prevented replication. Data were also collected during the rainy season 2019-2020, however, due to covid lockdown in March 2020, the data collection was ended prematurely, and the late planting treatment was not completed. Therefore, this study presents preliminary results due to lack of replications across sites, years and treatments.

Table 1. Schedule of the three planting date treatments.

Treatment	Date planted	First sampling date	Last sampling dates	Number of samplings
Early planting	20th December 2021	31st December 2021	11th April 2022	15
Intermediate planting	10th January 2022	21st January 2022	11th April 2022	12
Late planting	1st February 2022	11th February 2022	11th April 2022	9

Data collection

From maize germination (90%), 100 random plants were sampled weekly from each field using a random sampling method. Plants were assessed thoroughly for egg masses and larvae in a non-destructive manner to allow continuous collection over the crop cycle. During each assessment, the number of egg masses and larvae were recorded for each maize plant. A paintbrush was used to extract the hidden larvae in whorls or between the leaves to minimise damage to the maize plants. Date and growth stage of the maize plant were recorded for each sampling date in each of the planting date treatments.

Rearing and identification of the samples

Egg masses and larvae collected from the maize fields were placed individually in Petri dishes and given a unique sample ID number. Larval stage was determined for each larva collected based on head capsule width as described in Durocher-Granger et al. (2021). Larvae were reared on beet armyworm F9219B artificial diet (Frontier Scientific Services, Newark, DE, USA), with antibiotics (aureomycin) in the laboratory, and kept at 27 ± 2 ºC and 50 ± 5% RH. Egg masses and larvae were observed every day until emergence of the parasitoids or adult moths and the development of parasitoids or FAW moths was recorded. Dead FAW larvae and pupae were dissected to record absence or presence of parasitoid larvae. If parasitoid larvae were found, their presence was recorded as "Hymenoptera-related mortality".

All emerged adult parasitoids were morphologically identified by two of the authors (LDG and MK) using various identification keys and collections of insects gathered during previous studies on *S. frugiperda* parasitoids (Agboyi et al., 2020; Durocher-Granger et al., 2021). Seven parasitoid larvae which emerged from FAW larvae but were unable to pupate in the Petri dishes were identified with molecular analyses using the mtDNA barcode gene (mtDNA) cytochrome c oxidase subunit 1 (COI), following the method described in Durocher-Granger et al. (2021) to compare them with verified sequences from the Barcoding of Life Data System (BOLD; http://www.boldsystems.org/) (Ratnasingham & Hebert, 2013) and supplementary sequences from the GenBank® database (http://www.ncbi.nlm.nih.gov/genbank/) (Benson et al., 2018).

Data analysis

Fall armyworm density

To estimate the effects of planting date (early, intermediate and late planting) and maize stage groups (VE-V7, V8-V14, VT-R6; Table 2) on the number of FAW (larvae and eggs separately), we

modelled FAW density using Generalized Linear Models (GLM). We used a negative binomial distribution to model the count data and account for overdispersion. We used a Bayesian approach to fit the model because there are conditions with zero FAW, for which confidence intervals cannot be estimated using classical frequentist approaches. In addition, the Bayesian approach is robust because it uses Markov chain Monte Carlo resampling (MCMC), a non-parametric method (Gelman et al., 2013). We ran eight chains of 10,000 iterations (50% for warm up) for a total of 40,000 iterations with the default adaptive priors. The model was validated by inspecting convergence diagnostics (presence of divergence(s), chain mixing, effective number of iterations). We used the posterior distributions to estimate the magnitude of the differences among treatments, as well as to approximate the degree of certainty for the direction of the differences.

Table 2. Maize stage categories.

Maize stage groups	Maize growth stages
VE-V7	Emergence to seventh leaf collar
V8-V14	Eighth to fourteenth leaf collar
VT-R6	Tasseling to maturity

Parasitism probabilities

GLMs were used to analyse parasitism probabilities as a function of maize stage groups (VE-V7, V8-V14, VT-R6) and planting date (early, intermediate and late planting). We specified a binomial distribution to model the proportion of FAW parasitized while taking into account the number of FAW sampled on each date. We fitted the model using a Bayesian approach for the reasons mentioned above. Parasitism probabilities were tested for larval parasitoids and egg parasitoids separately and then together. Parasitoid species were categorized into functional groups of host stages attacked (egg or larva) as shown in Table 3. We use the R package brms (Bürkner, 2017), which provides an R style wrapper for the Stan Hamiltonian Monte Carlo sampler (Stan Development Team, 2023).

Parasitoid biodiversity

GLMs were used to model the relative abundance (proportion) versus species rank relationship for planting date (early, intermediate and late planting), and for different maize stage groups (VE-V7, V8-V14, VT-R6). The slope is a proxy for species evenness, where a steeper slope corresponds to a less even distribution of species (Whittaker, 1965). We fitted the relationships on the log-log scales to allow a linear relationship and compare the fitted slopes among planting dates and maize stage groups.

All analyses and graphical representations were conducted in R (R Core Team, 2022) using the aforementioned R packages.

Table 3. Functional groups of parasitoids by stage of FAW attacked.

Functional groups by stage attacked	Order	Family	Sub-family	Species
Egg parasitoids	Hymenoptera	Scelionidae		*Telenomus remus* (Nixon)
		Braconidae	Cheloninae	*Chelonus bifoveolatus* Szépligeti
				Chelonus curvimaculatus Cameron
Larval parasitoids		Braconidae	Agathidinae	*Coccygidium luteum* Brullé
			Microgastrinae	*Cotesia icipe* Fernández-Triana & Fiaboe
				Parapanteles sp
		Ichneumonidae	Campopleginae	*Diadegma* sp.
			Cremastinae	*Pristomerus* sp.
	Diptera	Tachinidae	Exoristinae	*Drino quadrizonula* (Thomson)

RESULTS

Fall armyworm density

FAW larvae

The expected density of FAW larvae ranges from 0.10 to 0.69 per plant across treatments. Fewer larvae were found in the early planting date treatment than in the other treatments, but the difference was not clear (certainty < 75%). However, we found a clear effect of maize stage groups (Figure 1): VE-V7 < V8-V14 (odds ratio = 17.9:1, certainty = 95%), VE-V7 > VT-R6 (odds ratio = 5.8:1 certainty of 85%), V8-V14 > VT-R6 (odds ratio = 222:1, certainty > 99.9%).

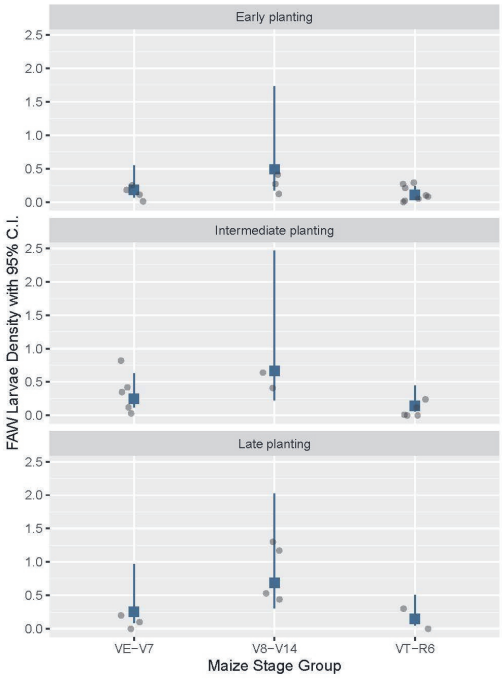


Figure 1: Estimated fall armyworm larval density (number of larvae/number of plants sampled) by planting date and maize stage groups. The squares show the estimated density and the whiskers, the 95% confidence intervals (C.I.) for each maize stage group and treatment combination.

FAW egg masses

The expected density of FAW egg masses ranges from 0.0002 to 0.17 per plant across treatments (Figure 2). We found relatively clear differences among planting dates: Early < Intermediate (odds ratio = 12.8:1, certainty = 93%), Early < Late (odds ratio = 1211:1, certainty > 99.9%), Intermediate < Late (odds ratio = 34:1, certainty > 97%). Among maize stage groups, only one difference was clear: VE-V7 < V8-V14 (odds ratio = 69:1, certainty = 98.5%), the other differences having degrees of certainty below 80%.

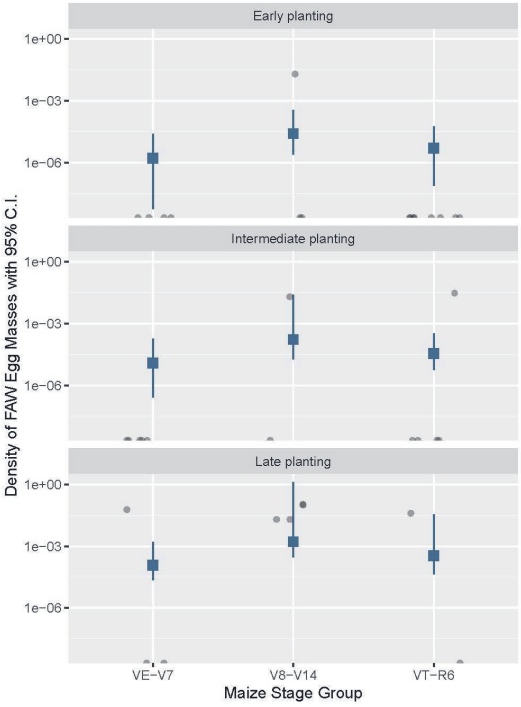


Figure 2. Estimated fall armyworm egg masses density (number of egg masses/number of plants sampled) by planting date and maize stage groups. The densities are plotted on the $\log_{10}$ scale with zeros placed at the lower edge of the graph. The squares show the estimated density and the whiskers, the 95% C.I. for each maize stage group and treatment combination.

Parasitism probabilities

All parasitoids

The expected parasitism probabilities for all species varied between 2% and 39% depending on the planting date and maize stage group (Figure 3). The early planting treatment had lower parasitism probabilities than both the intermediate planting (odds ratio = 291:1, certainty = 99.7%) and the late planting (odds ratio = 2665:1, certainty > 99.9%). There was no clear difference in the parasitism probabilities between the intermediate and late planting treatments (certainty of only 74%). Parasitism probabilities decreased with increasing maize growth stages. VE-V7 stages had higher probabilities of parasitism than V8-V14 (odds ratio > 40000:1, certainty > 99.9%) and VT-R6 (odds ratio > 40000:1, certainty > 99.9%), and V8-V14 had a slightly higher probabilities than VT-R6 (odds ratio > 410:1, certainty 99.8%).

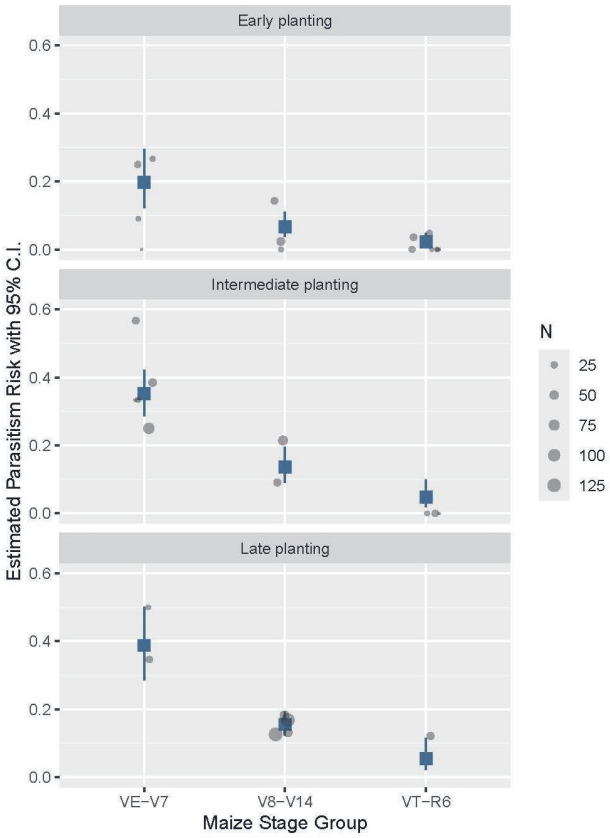


Figure 3. Parasitism probabilities across the different planting date treatments and maize stage groups for all parasitoids. The squares show the estimated density and the whiskers, the 95% C.I. for each maize stage group and treatment combination. The size of the points is proportional to the number of FAW larvae sampled (N).

Larval parasitoids

The expected parasitism probabilities for larval parasitoids varied between 1 and 26% depending on the planting date and maize growth stage (Figure 4). Parasitism probabilities tended to be lower for the early planting date than for the intermediate (odds ratio = 11.4:1, certainty = 92%) and late planting dates (odds ratio = 7.7:1, certainty = 89%), but the difference between intermediate and late planting dates was not clear at all (odds ratio = 1.08:1, certainty = 52%). Maize growth stages had a clear effect: VE-V7 stages had higher probabilities of parasitism than V8-V14 (odds ratio > 40000:1, certainty > 99.9%) and VT-R6 (odds ratio > 40000:1, certainty > 99.9%), and V8-V14 had a very slightly higher probabilities than VT-R6 (odds ratio = 89:1, certainty = 98.9%).

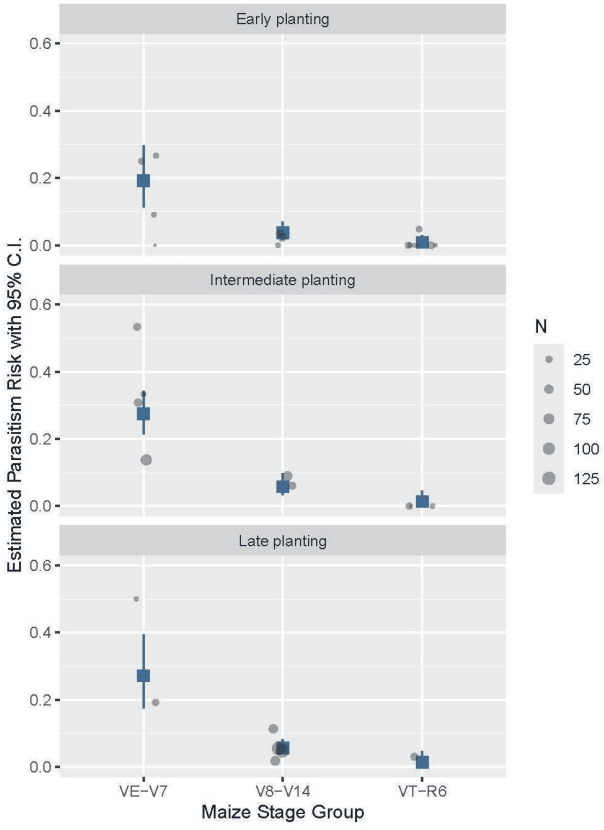


Figure 4. Parasitism probabilities across the different planting date treatments and maize stage groups for larval parasitoids. The squares show the estimated density and the whiskers, the 95% C.I. for each maize stage group and treatment combination. The size of the points is proportional to the number of FAW larvae sampled (N).

Egg parasitoids

The expected mean parasitism probabilities by egg parasitoids were very low across planting dates and maize stage groups and varied only from 0.6% to 5% (Figure 5). Parasitism probabilities tended to increase with later planting dates: lower in the early planting date than in the intermediate (odds ratio = 10.7:1, certainty = 91.5%) or late (odds ratio = 36.8:1, certainty = 97.4%) dates, but there was no clear difference between intermediate and late planting dates (odds ratio = 2.6:1, certainty = 73%). Parasitism probabilities tended to decrease with later maize stage groups: lower for VT-R6 than for V8-V14 (odds ratio = 9.5:1, certainty = 90.5%) or VE-V7 (odds ratio = 12.2:1, certainty = 92.4%), but the difference between VE-V7 and V8-V14 was rather small and uncertain (odds ratio = 1.6:1, certainty = 61%).

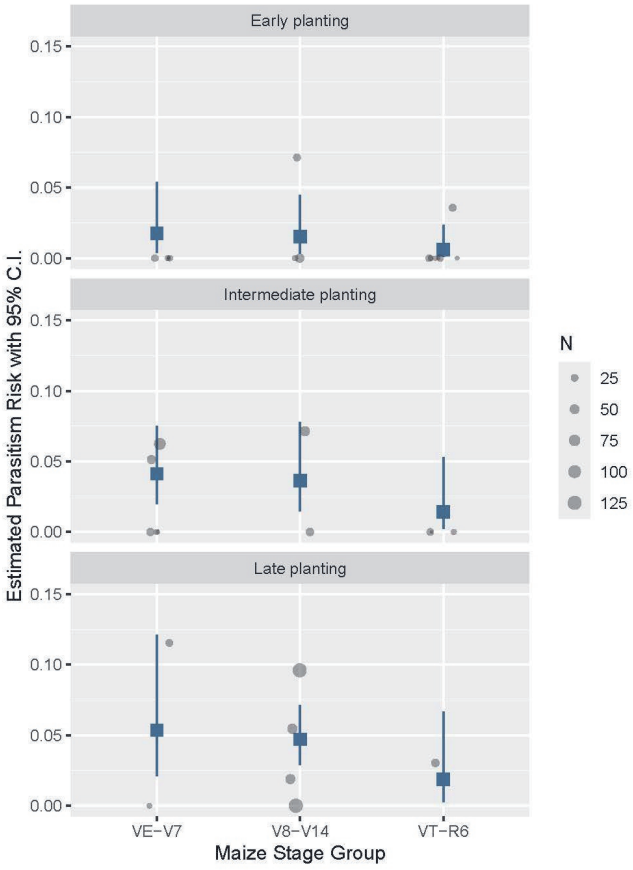


Figure 5. Parasitism probabilities across the different planting date treatments and maize stage groups for egg parasitoids. The squares show the estimated density and the whiskers, the 95% C.I. for each maize stage group and treatment combination. The size of the points is proportional to the number of FAW larvae sampled (N).

Parasitoid biodiversity

Analysis of evenness by planting date treatments

Parasitoid abundance showed that *C. luteum* was the most abundant species followed by *Ch. curvimaculatus* for early planting (66% and 17%), intermediate planting (55% and 17%) and late planting (47% and 18%) (Figure 6). The slopes, and therefore species evenness, were very similar for all three planting dates. Species evenness tended to increase slightly with planting dates but there was a lot of uncertainty. Species abundances tended to be more even for the late planting date than for the intermediate planting date (odds ratio = 8.2:1, certainty = 89%) and early (odds ratio = 11.7:1, certainty = 92%) planting dates. The difference between early and intermediate dates was less clear (odds ratio = 2.5:1, certainty = 71%).

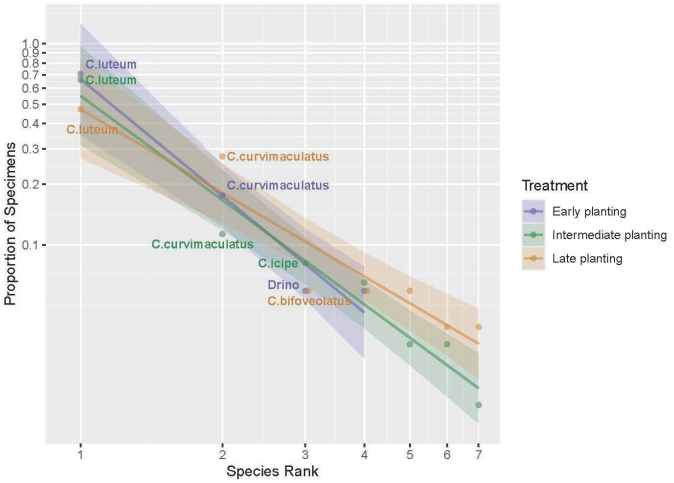


Figure 6. Relative abundance of parasitoid species (evenness of species abundances) by planting dates.

Analysis of evenness by maize stage groups

The rank-abundance plot shows that species evenness was higher for the latest maize stage group (VT-R6) than the other two maize stage groups (VE-V7 and V8-V14), as shown by the differences in slopes (Figure 7). The odds that this difference was real is over 160:1, or over 99% certainty. Results showed that VE-V7 and V8-V14 maize stages were dominated by one or two species while reproductive stages (VT-R6) showed a more even distribution of species with *Ch. bifoveolatus* (25%), *Ch. curvimaculatus* (25%), *C. luteum* (25%) and *D. quadrizonula* (25%). At VE-V7 stages, *C. luteum* was the most abundant species (40%), followed by *C. icipe* (14%) whilst at V8-V14 stages, *C. luteum* was dominating (54%) followed by *Ch. curvimaculatus* (18%).

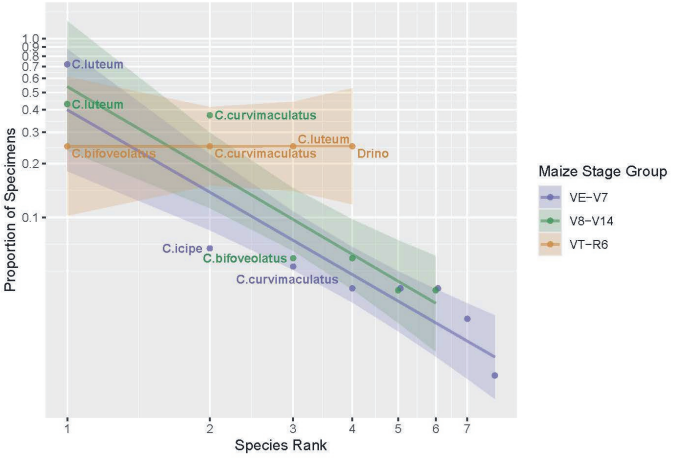


Figure 7. Relative abundance of parasitoid species (evenness of species abundances) by maize stage groups.

DISCUSSION

Our study showed an effect of planting dates on FAW density with an increase of FAW egg masses from early to late planting. However, no clear effect of planting dates was detected on FAW larvae density. Nevertheless, the increase in the number of egg masses reflects the buildup of FAW adult populations and therefore, supports the recommendation that early planting helps to avoid the peak of moth flight activity (Harrison et al., 2019; Deshmukh et al., 2021). It is important to interpret these results with caution and compare them with similar agroecological zones where a short rainy season is followed by a long dry season. However, due to the lack of true replication, we are unable to extend the interpretation of the results to other regions or to extrapolate to further years. In Zambia, maize is largely rainfed and a sole rainy season occurs from November to March. A similar study in Chad by Mbaidiro et al. (2023) found opposite results where early planted maize had three times more larvae per plant than the late planting. As pointed out by the authors, their results can be explained by biotic and abiotic factors such as increases in rainfall and buildup of natural enemy populations as the rainy season progresses. However, the high infestation found in early maize in Chad could also be influenced by regional migration patterns of FAW adults coming from neighbouring countries (Nagoshi et al., 2018; Nagoshi et al., 2022) or by the nearby occurrence of irrigated maize or other host plants at the end of the dry season. In Zambia, our results suggest that local populations of FAW persisting on irrigated crops surrounding the research field during the dry season seem to be the main source of infestation at the onset of the rain leading to a buildup of the population over the rainy season. This is also consistent with FAW larval development models developed from the same research field and other research sites in Zambia from previous years showing that eggs and young larvae were present in the fields soon after maize emergence (Lowry et al., 2022). Farmers using irrigation systems establish new maize crops once the rainfed maize is harvested. Therefore, the buildup of FAW population at the end of the rainy season is likely to migrate on irrigated maize and to persist during the dry season. These persisting local FAW populations are then ready to reinvade maize crops at the beginning of the rainy season. In addition, smallholder farmers prefer to use staggered planting techniques for maize crops due to lack of mechanisation, to reduce risk of erratic early rains or to spread labour peaks (planting, weeding, applying inputs, etc.) (Harrison et al., 2019), which result in an increase of pest incidence as the rainy season progresses.

Furthermore, FAW eggs and larvae were found during maize reproductive stages (VT-R6) but at lower rates than during early and late whorl stages. As the cropping season progresses, the availability of the preferred maize stage (i.e., young vegetative maize leaves) becomes limited. However, reproductive structures such as silk, closed tassels and early cob stages are still suitable food for FAW larval development (Mohamed et al., 2023; Pannuti et al., 2016). Studies have found that maize silk produces a toxin chemical compound called favone glycoside (silk maysin) which can also provide protection against the Lepidoptera attack (Anjorin et al., 2022) which could explain the lower abundance of FAW larvae during silk stage. Nevertheless, this outcome has implications for farmers'

incomes as damage to silk, tassels or cobs can lead to kernel abortion, reduction in grain formation, fungal infection, aflatoxin contamination and loss of grain quality (Anjorin et al., 2022; FAO and CABI, 2019b). Farmers generally use chemicals to control FAW in the early to late whorl stages, however research on safe cultural practices to reduce damage to reproductive structures should also be explored to avoid losing income due to a poor-quality harvest.

Our study also shows higher probabilities of parasitism for FAW eggs and larvae on intermediate and late planting compared to early planting for both larval and egg parasitoids. The lower parasitism probabilities on early planting maize are likely due to the generally lower availability of parasitoids early in the season. Parasitoids attacking FAW from our research study probably undergo a diapause or quiescence period even if diapause has not been observed for FAW, which, in Africa, is present all year-round on various rainfed and irrigated crops. Synchronization of adult parasitoid emergence with the presence of specific host stages is particularly important for species parasitizing hosts with one or few generations per year (Godfray, 1994). As studied by Seymour and Jones (2000), diapause in tropical parasitoid species is induced by humidity due to the limited annual variations in daylength, the main cue inducing insect diapause in temperate regions. In their study on *Microplitis demolitor* (Wilkinson), a solitary braconid parasitoid of *Helicoverpa armigera* (Hübner) and *Helicoverpa punctigera* Wallengren (Noctuidae: Lepidoptera), the adult parasitoids emerged roughly 38 days after diapause was terminated. While its hosts use temperature as an environmental cue to terminate diapause, *M. demolitor* uses increased humidity. In Lusaka, annual variation in daylength ranges between 11 hours and 15 minutes, and 13 hours and 4 minutes (WorldData.info, 2015), which is a small variation compared to temperate climates. Furthermore, Lusaka province, where the research experiment was conducted, the daily temperature ranges from 25 °C to 32 °C and exhibits a long dry season from usually early to mid-March until November to December, with a variation in relative humidity between 40% and 80%. Therefore, humidity variation in our research study is likely to play a role in the abundance of local parasitoids at the onset of the rains and throughout the rainy season.

We also found an effect of maize growth stages on parasitism probabilities. These results suggest that the probabilities of an event of parasitism are higher during early whorl stages than late whorl or reproductive stages, and that late whorl stages are also more likely to have parasitized FAW larvae than during reproductive stages. These results are important considering recommendations to farmers to spray chemical insecticides during the early and late whorl stages against FAW. As part of an integrated pest management approach, spraying chemical insecticides early can be counter-productive alongside the simultaneous recommendation to farmers to conserve natural enemies. As higher parasitism probabilities occur in the early whorl stages, broad-spectrum chemical insecticides have the potential to reduce the populations of natural enemies attacking FAW in the field, which can lead to a resurgence of the pest. Instead, the focus should be on conserving and enhancing local natural enemies found during the VE-V7 stages as these are the stages where parasitism is more likely to occur and there is an opportunity to build up their populations for the next maize stages. In addition, herbivore-

induced plant volatiles are also likely to play a role in attracting more parasitoids during the early vegetative stages of the crop, younger leaves being more attractive upon infestation than older leaves to natural enemies (Takabayashi et al., 1994).

As found in the rainy season 2018-2019 (Durocher-Granger et al., 2021), maize growth stages affect the parasitoid abundance and diversity; early and late whorl stages have higher diversity but are dominated by one or two species. According to our results, *C. luteum* is the dominating species during early and late whorl stages. As found across African countries, this parasitoid species is one of the most common and abundant FAW parasitoids (Kenis et al., 2023). As parasitoids are highly host-stage specific, the peak of their adult populations should be observed following the peak of their preferred host stage. *C. luteum* attacks first instar larvae of FAW under laboratory conditions (Agboyi et al., 2019), therefore the high abundance of that species during early whorl stages reflects the high abundance of first instar larvae FAW during these maize stages. Its high abundance during late whorl stages also reflects the overlapping generations of FAW during the same crop cycle. So far, little is known about the biology and ecology of this parasitoid, and further studies would be required to facilitate an augmentative biocontrol programme. *C. icipe* was the second most abundant parasitoid during early whorl stages. This parasitoid prefers first and second instar larvae of FAW (Mohamed et al., 2021), therefore its high abundance in early whorl stages is expected. *Ch. curvimaculatus*, being an egg-larval parasitoid, requires eggs to be available for oviposition. However, it kills its host larva when the parasitoid larva emerges to build a cocoon. Therefore, the peak of adult emergence may be seen only during the late whorl stages as its cycle spreads over two host stages. The trend of parasitoids diversity and abundance on the reproductive stages of the maize is interesting as no species is dominant in these stages but there is rather an equal distribution of four species. This is consistent with our previous study where diversity and abundance of parasitoids decreased as the maize matured (Durocher-Granger et al., 2021). *Ch. curvimaculatus* seems to be one of the parasitoids colonizing the fields in the early season alongside *C. luteum*, *C. icipe* and *Parapanteles* sp. Results on *D. quadrizonula*, a tachinid fly, are also consistent with our previous study where this species was recorded from late whorl stages, when late FAW instar larvae had increased in abundance. Indeed, tachinid flies tend to attack late instar larvae of lepidopteran pests (van den Berg et al., 1988). It is important to note that the trend observed from that study is year- and location-specific and cannot be extrapolated to other years or regions in Zambia considering the difference in agroecological zones and variability in climatic conditions, especially regarding the rainfall patterns. However, according to our results on biodiversity of parasitoids and maize growth stages, the location of the current research is likely to observe the same dominating species during the early and late whorl stages, but the reproductive stages can vary greatly among years due to the uniformity of species found at these stages.

As compared to our previous surveys on FAW parasitism in 2018-2019 (Durocher-Granger et al., 2021) one additional species of egg parasitoid, *T. remus*, was found. Interestingly, egg mass parasitism was low (0.6% to 5%) and did not contribute significantly to FAW mortality across maize

stages and over the rainy season. Egg parasitoids, having a much shorter life cycle than larval parasitoids and being more exposed to drought in host eggs on plants than larval parasitoids in their cocoons, may suffer even more from long dry seasons as those experienced in Central Zambia.

CONCLUSION

In conclusion, the results from this study provide preliminary field evidence that early planting helps avoiding high peak activities of moths. However, we cannot extend this recommendation to other locations and years until the research is replicated in more regions and years. Furthermore, important insights on parasitoids seasonal activity, diversity and abundance can also supports the development of a comprehensive IPM strategy around cultural and biological control management.

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5 Exploring the influence of intercropping maize on fall armyworm density and occurrence of parasitoids in Zambia

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ABSTRACT

Natural pest control in agriculture can provide major economic benefits, which can be enhanced through practices such as habitat manipulation and intercropping. Following the identification of fall armyworm (FAW), *Spodoptera frugiperda*, in Zambia, extensive damage was reported on maize crops across the country. However, many local parasitoid species were found attacking and developing successfully in FAW. This research focused on exploring the natural resources available for smallholder farmers to maximize pest control by intercropping maize with commonly grown crops, as a first step to narrow down suitable companion crops for FAW management. Fieldwork was carried out during the two rainy seasons of December to March 2019-2020 and 2020-2021 at two sites in the Lusaka province. The five companion crops tested alongside maize control were cowpeas, groundnuts, beans, sorghum and sunflower. Data collection occurred weekly until the reproductive stages of maize and included FAW egg masses and larvae, maize stages and date. Egg masses and larvae were incubated at the laboratory until adult moths or parasitoids emerged. The influence of intercropping varied across sites and years. We found a higher FAW larval density on intercropped maize but lower on sorghum plants, and parasitism rates were on sorghum plants. Additionally, we found a less even abundance of parasitoid species in maize control treatment, and an association of the parasitoid *Chelonus curvimaculatus* with sorghum plants, and of *Pristomerus* sp. with sunflower and maize control treatments. This first assessment of intercropping maize with companion crops points toward important findings which need to be studied further to improve our understanding of tri-trophic interactions between native crops, FAW and parasitoid species.

INTRODUCTION

The provision of natural pest control in agriculture by arthropods, as a subset of ecosystem services (the direct and indirect goods and services provided by ecosystems to humans), has been estimated to be USD 4.5 billion annually in the US only (Losey & Vaughan, 2006), and USD 400 billion globally (Costanza et al., 1997; van Lenteren, 2006). However, agricultural intensification through reduced diversity of vegetation, larger field sizes and increased use of agrochemicals is threatening natural enemies' diversity and, consequently, natural pest control. Furthermore, agroecosystems in the tropics can be highly unfavourable environments for natural enemies due to over-use and misuse of broad-spectrum pesticides and lack of non-crop habitats as sources of shelter and food (Landis et al., 2000), which decreases ecosystem resilience in responding to pest outbreaks. Biological control programmes can tackle some of these constraints by increasing natural enemy populations through mass rearing and periodic releases (augmentative biocontrol) or by improving the availability and quality of the resources needed by local natural enemies over time and space (conservation biocontrol) (Lazarovits et al., 2007). Habitat management, an element of conservation biological control, focuses on practices altering the habitat to improve the availability and quality of the resources needed by natural enemies (e.g. food, shelter or alternative prey or hosts) to reach their optimal performance in agroecosystems (Jervis et al., 2023a; Landis et al., 2000). Some examples of habitat management are mulching, intercropping, presence of flowering non-crop plants within or around the field and cover crops (Gurr et al., 2004).

Two hypotheses support the potential causes of lower pest population densities in diverse agroecosystems (Pimentel, 1961; Root, 1973). The resource concentration hypothesis suggests that a diverse flora has direct negative impacts on the ability of insect pests to find and utilise the host plant and to remain in the crop habitat, affecting their visual and olfactory cues (Root, 1973). The enemies hypothesis proposes that better conditions in more diverse systems, such as food sources, enhance natural enemy abundance and, therefore, reduce pest populations (Pimentel, 1961). In the past two decades, an increased number of studies have reported positive effects of floral and extrafloral nectar, pollen and honeydew resources on physiological (longevity, fecundity and flight capacity) and behavioural (attraction) responses of hymenopteran parasitoids (Araj & Wratten, 2015; Bianchi & Wäckers, 2008; Irvin & Hoddle, 2015; Russell, 2015; Shearer & Atanassov, 2004; Tena et al., 2015; Wäckers et al., 2008; Wanner et al., 2006; Zhu et al., 2015). Other agronomic practices such as mulching, intercropping and the use of flowering ground-cover plants have also proven to increase predator and parasitoid populations in agroecosystems (Gurr et al., 2004; Schmidt et al., 2004; Thomson & Hoffmann, 2007).

Fall armyworm (FAW), *Spodoptera frugiperda* (JE Smith) (Noctuidae: Lepidoptera), an invasive insect pest from the Americas, has caused extensive damage to maize crops in Africa and Asia since 2016 (Goergen et al., 2016; Kenis et al., 2023). Since the identification of FAW in 2016,

researchers in Zambia have conducted surveys across the country and identified so far 17 species of local parasitoids attacking and developing successfully on FAW (Chipabika et al., 2023; Durocher-Granger et al., 2021; Sun et al., 2021). Therefore, leveraging the richness of local parasitoids has great potential in Zambia to maintain the pest under the economic threshold by increasing the abundance and efficacy of these natural enemies through habitat management (Landis et al., 2000). Various studies have already looked into the effects of intercropping maize with legumes to reduce FAW infestations and increased parasitoid abundance with positive results (Hailu et al., 2018; Tanyi et al., 2020; Udayakumar et al., 2021). In parallel, laboratory studies have investigated the olfactory responses, attractiveness and oviposition preference of different crops and volatile organic compounds (VOCs) on FAW. Sisay et al. (2023) found that FAW female moths oviposited significantly more eggs on maize alone compared to maize in combination with other plants.

Conservation biological control is believed to be the field of biocontrol with the greatest potential in low- and medium-income countries due to the high plant (crops and non-crops) diversity and due to the fact that complex agroecosystems are low risk in case of crop failure (Nicholls & Altieri, 2004; Wyckhuys et al., 2013). However, understanding which food source is used by which natural enemies and selecting the right companion plants is crucial for developing effective conservation biocontrol programmes. Indeed, enhancing populations and, therefore, the efficacy of natural enemies in the field should not favour the pest by acting as refuges (Huss et al., 2022; Landis et al., 2000). Furthermore, natural enemies exploit different food sources based on their accessibility and nutritional values (Jervis et al., 2023a). Designing sustainable and pest-resilient agroecosystems in various agroecological zones of the world that suit specific needs of farming communities and that are practical is a complex challenge (Nicholls & Altieri, 2004). Indeed, restoring agricultural diversity is site-specific, mainly crop/plant combinations, and co-designing the new agroecosystems need to be done closely with farming communities (Nicholls & Altieri, 2004).

This research aimed at exploring and providing a first assessment of the influence of intercropping maize on fall armyworm density and parasitoid abundance and diversity in order to narrow down the potential companion crops to be integrated in a FAW management strategy. While conservation biocontrol involves the study of various natural enemies including parasitoids, predators and entomopathogens, this exploratory study looked only at parasitoids. This paper is part of transdisciplinary research, which co-creates and evaluates with farmers the potential of using local resources to control a highly mobile invasive pest. The companion crops selected in this research were the most common crops grown by smallholder farmers, either as intercrop or monocrop besides maize, based on inception meetings hosted with two communities in both Mumbwa and Siavonga districts of Zambia in August 2019.

MATERIALS AND METHODS

Experimental design

Fieldwork was carried out during the rainy seasons of December-March 2019-2020 and December-March 2020-2021. The two sites were located in the Lusaka province; the Zambia Agriculture Research Institute (ZARI) - Mt Makulu, Chilanga (-15,549023; 28,250960, altitude: 1229 m) and the CABI site in Chalimbana (-15,359412; 28,488572, altitude: 1130 m). We faced the following constraints in site and space availability to conduct the research. First, finding a field where pesticides were not applied excessively was challenging, limiting our options for sites. Secondly, other on-station trials at the same time constrained the availability of space, limiting plot size and distance between plots in some instances. Considering these limitations, a balance was needed to assess all crops identified by farmers.

During the rainy season 2019-2020, five replicates of three treatments (maize monocrop, maize-groundnuts (*Arachis hypogaea;* variety MGV4), maize-cowpeas (*Vigna unguiculata*; variety Lutembwe) were established at the CABI site. Space availability allowed for plots measuring 5x5m (5m of bare soil between plots). A 75 cm gap between maize rows was maintained, and 30 cm between maize plants. In the following year, at the CABI site, four treatments (maize monocrop, maize-cowpeas, maize-beans (*Phaseolus vulgaris*; variety Mbereshi) and maize-groundnuts) and five replicates were established at the onset of the rains during the last week of December 2020. Additional space allowed for increased plot size measuring 15x15m (5m of bare soil between plots). A 75 cm gap between maize rows was maintained, and 30 cm between maize plants. ZARI station at Mount Makulu, being the Head office for the national agricultural research institute, has limited space available during the rainy season due to many projects conducting field trials. Therefore, space allowed only for three treatments (maize monocrop, maize-sunflower (*Helianthus annuus*; variety Milika), maize-red sorghum (*Sorghum bicolor*; variety FSV-23-1)) and four replicates to be established. The plots were planted at the onset of the rains during the last week of December 2020. The plots measured 10x10m (2m of bare soil between plots). A 75 cm gap between maize rows was maintained, and 30 cm between maize plants. In the intercropped plots, the intercrops were planted every other row. For all sites and years, treatments were completely randomized, and the maize variety used was MRI624 (medium maturity). Standard agronomic practices for all maize fields and sites were adopted as recommended by the Ministry of Agriculture to smallholder farmers in Zambia.

Data collection

From maize emergence, data were collected weekly at all sites and years. Maize plants were sampled randomly for FAW eggs and larvae until tasselling to blister stages of the maize (CABI 2019-2020: maize control = 22 plants, maize intercropped = 11 plants; CABI 2020-2021: maize control and intercropped = 50 plants, ZARI: maize control and intercropped = 85 plants). For the sorghum intercrop treatment, sorghum plants were also sampled for FAW larvae and egg masses. Each plant was assessed

thoroughly for egg masses and larvae in a non-destructive manner to allow continuous collection over the crop cycle. Hidden larvae in whorls or between the leaves were collected using a paintbrush to avoid damaging the maize plants. For each sampling collection, date and maize stage category (Table 1) were recorded. On the same day of the field collection, egg masses and larvae collected from the maize fields were placed individually in Petri dishes (90 mm diameter) and they were given a unique sample ID number. Larvae were reared on beet armyworm F9219B artificial diet (Frontier Scientific Services, Newark, DE, USA), with antibiotics (aureomycin) in the laboratory, and kept at 27 ± 2 ºC and 50 ± 5% RH. Larval stage was determined for each larva collected based on head capsule width as described in Durocher-Granger et al. (2021). Egg masses and larvae were observed every day until emergence of the parasitoids, larvae from egg masses or adult moths and the development of parasitoids or FAW moths was recorded. Dead FAW larvae and pupae were dissected to record absence or presence of parasitoid larvae. If hymenopteran parasitoid larvae were found, their presence was recorded as "Hymenoptera-related mortality".

Table 1: Maize stage categories.

Maize stage category	Maize growth stages
V0-V7	Emergence to seventh leaf collar
V8-V11	Eighth to eleventh leaf collar
V12-V14	Twelfth to fourteenth leaf collar
VT-R2	Tasseling to blister

All emerged adult parasitoids were morphologically identified by two of the authors (LDG and MK) using various identification keys and collections of insects gathered during previous studies on *S. frugiperda* parasitoids in Africa (e.g., Agboyi et al., 2020; Durocher-Granger et al., 2021). If parasitoid larvae emerging from FAW failed to pupate in the Petri dishes, these were collected and preserved in 70% ethanol for molecular identification. Overall, forty-three parasitoid larvae were identified with molecular analyses using the mtDNA barcode gene cytochrome c oxidase subunit 1 (COI), following the method described in Durocher-Granger et al. (2021) to compare them with verified sequences from the Barcoding of Life Data System (BOLD; http://www.boldsystems.org/) (Ratnasingham & Hebert, 2013) and supplementary sequences from the GenBank® database (http://www.ncbi.nlm.nih.gov/genbank/) (Benson et al., 2018).

Data analysis

Factors affecting fall armyworm density

To explore factors affecting the density of fall armyworm egg masses and larvae, we used a Generalized Linear Mixed Model (GLMM) with a negative binomial distribution to model the number of FAW with an offset to consider the number of plants sampled. For the analysis of FAW egg masses in the CABI 2019-2020 experiment, a binomial distribution was used as all the counts were zeros or

ones. We included intercrop type and maize stage category as fixed effects and the replicate as a random effect, but no interaction terms because the sample size was too low to do so reliably. These analyses were run individually for each of the three experiments. We fit the model using a Bayesian approach to deal with conditions that have all abundances of 0, for which frequentist approaches cannot estimate confidence intervals. In addition, the Bayesian approach is non-parametric (with MCMC) and therefore more robust to outliers or deviations from the specified distribution.

We ran eight chains with 5,000 iterations each (excluding the first 2,500 for warm up), for a total of 20,000 iterations post warm up. This is an order of magnitude higher than required to ensure that the effective sample size is sufficient even with autocorrelation in the chains. Statistical models were validated using convergence diagnostics and effective sample size (Gabry et al., 2019). The importance of the predictor variables was evaluated using the widely applicable information criterion (WAIC) (Vehtari et al., 2017), where models with lower WAIC have stronger support. When the WAIC of the model with a treatment effect was lower than the WAIC of models without it (difference of at least two), we considered the effect of the treatment to be supported. When the effect of the treatment was supported, pairwise comparisons were performed using the posterior distributions.

Factors affecting parasitism probabilities

Analyses were conducted to model the effect of intercropping treatments on the parasitism probabilities of FAW larvae. Parasitism of FAW eggs was not analysed because there was insufficient data - one single instance of *Telenomus remus* (Nixon) (Appendix 3 Table S1 to S3). Parasitoid species in Table 2 were included in the analysis. We used a GLMM (see above) with a binomial distribution to model the proportion of FAW larvae that were parasitised while accounting for the number of FAW sampled. Analyses were done separately for each experiment (CABI 2019-2020, CABI 2020-2021, ZARI 2020-2021) because each one had different treatments.

Table 2: Parasitoid species included in parasitism probabilities analysis.

Order	Family	Sub-family	Species
Hymenoptera	Braconidae	Cheloninae	*Chelonus bifoveolatus* Szépligeti
			Chelonus curvimaculatus Cameron
		Agathidinae	*Coccygidium luteum* Brullé
		Microgastrinae	*Cotesia icipe* Fernández-Triana & Fiaboe
			Parapanteles sp
	Ichneumonidae	Campopleginae	*Diadegma* sp.
		Cremastinae	*Pristomerus* sp.
Diptera	Tachinidae	Exoristinae	*Drino quadrizonula* (Thomson)

Parasitoid species evenness

We compared the evenness of parasitoid species abundances among intercrop types using an abundance-rank relationship (Whittaker, 1965). By plotting the relative abundances of each species against its abundance rank, we obtained an index of evenness, where a shallow slope characterises

diverse communities and a steep slope characterises communities dominated by a few species. In order to compare the evenness of the intercrop type, we used a Generalized Linear Model (GLM). The proportion of abundance was the response variable modelled using a binomial distribution and the abundance rank, intercrop type, and their interaction were included as fixed effects, the interaction being indicative of differences amongst slopes. The model was fitted using a Bayesian approach (as above), for each of the three experiments.

Community composition of parasitoids

We explored the effect of intercrop type on the community composition of parasitoids using a transformation-based redundancy analysis (tb-RDA). We pooled parasitoid data for each site and calculated the proportional incidences for each species. These data were Hellinger-transformed and then a Redundancy Analysis (RDA) was used to estimate the proportion of variance in the composition associated with intercrop type. The significance of the effect was estimated by comparing the observed variance explained with values obtained using 10,000 random permutations.

All analyses and graphical representations were conducted in R using the following packages: car (Fox & Weisberg, 2019), tidyverse (Wickham et al., 2019), brms (Bürkner, 2017), bayesplot (Gabry et al., 2019), tidybayes (Kay, 2024), MuMIn (Bartoń, 2023), vegan (Oksanen et al., 2015), BiodiversityR (Kindt & Coe, 2005), ggbeeswarm (Clarke et al., 2023) and parallel (R Core Team, 2024).

RESULTS

Density of fall armyworm egg masses

The number of egg masses collected was very small, making any statistical inference challenging. For both CABI experiments, no effect of maize stage category or intercrop type was supported (the null models had the lowest WAICs) (Figure 1a and 1b). For ZARI 2020-2021, an effect of intercrop type (but not maize stage category) was weakly supported (ΔWAIC ~3; Figure 1c). There is, however, a high level of uncertainty and the clearest difference (between maize plants and sorghum plants in the sorghum treatment, where maize plants have a slightly higher FAW egg mass density) only had a certainty of 89% (odds ratio slightly less than 8:1).

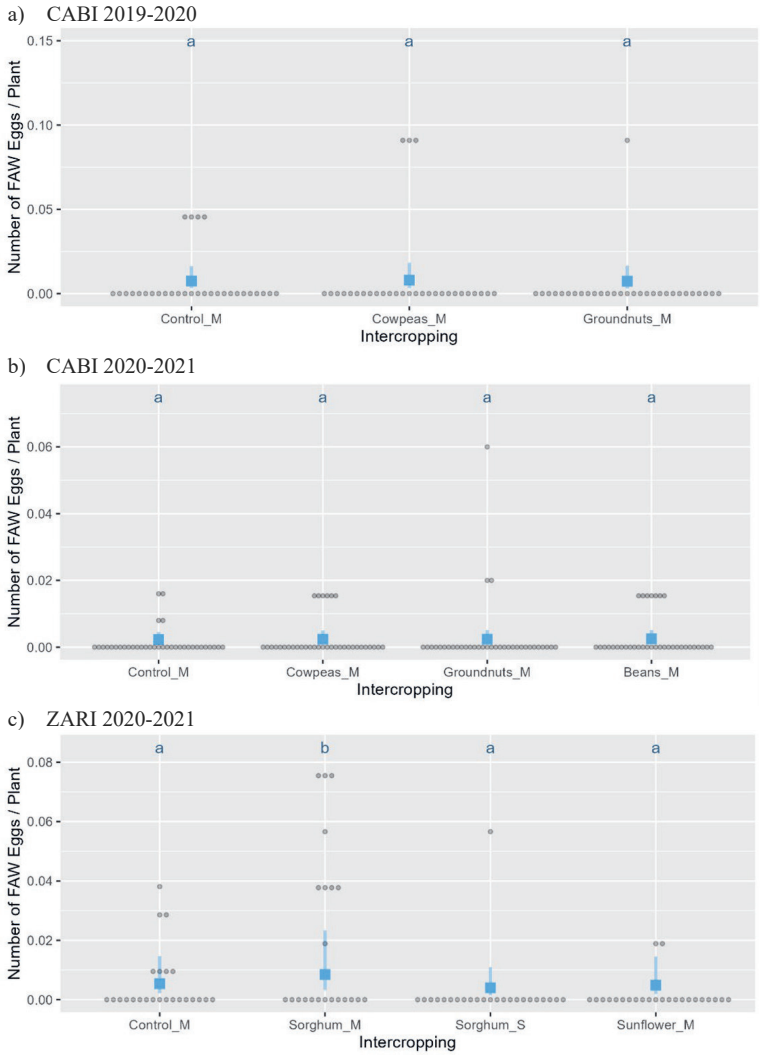


Figure 1. Mean density of fall armyworm egg masses for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Error bars indicate the 95% C.I. The dots show observations. Intercropping treatments are indicated by Treatment_M when maize plants were sampled and by Treatment_S when sorghum plants were sampled for assessing egg mass densities.

Density of fall armyworm larvae

In the CABI 2019-2020 experiment, maize stage category had a small effect on the density of FAW larvae (ΔWAIC ~ 3) (Appendix 3 Figure S1a), but it is not clear whether intercrop type did (ΔWAIC < 2). Maize intercropped with cowpea had slightly higher FAW density than maize control (certainty of 95% or odds ratio of 19:1) and maize intercropped with groundnuts (certainty of 97.5% or odds ratio of 40:1) (Figure 2a). There were clear effects of both intercrop type and maize stage category in CABI 2020-2021 (ΔWAIC > 10) and ZARI 2020-2021 (ΔWAIC > 11) (Appendix 3 Figure S1b and S1c). In the CABI 2020-2021 experiment, the density of FAW larvae was lower in the maize control

than in maize intercropped with cowpea (approximate certainty of 99.9% or odds ratio of 1700:1), groundnuts (certainty of 99.9% or odds ratio of 6600:1) or beans (certainty of 2500:1 or odds ratio of 99.9%) (Figure 2b). In ZARI 2020-2021, maize plants in the sorghum (certainty of 98.9% or odds ratio of 90:1) and sunflower (certainty of 99.6% or odds ratio of 250:1) treatments had a higher FAW density than the control, and sorghum plants had a lower FAW density than maize plants in the sorghum treatment (certainty of > 99.99% or odds ratio greater than 20,000:1) (Figure 2c).

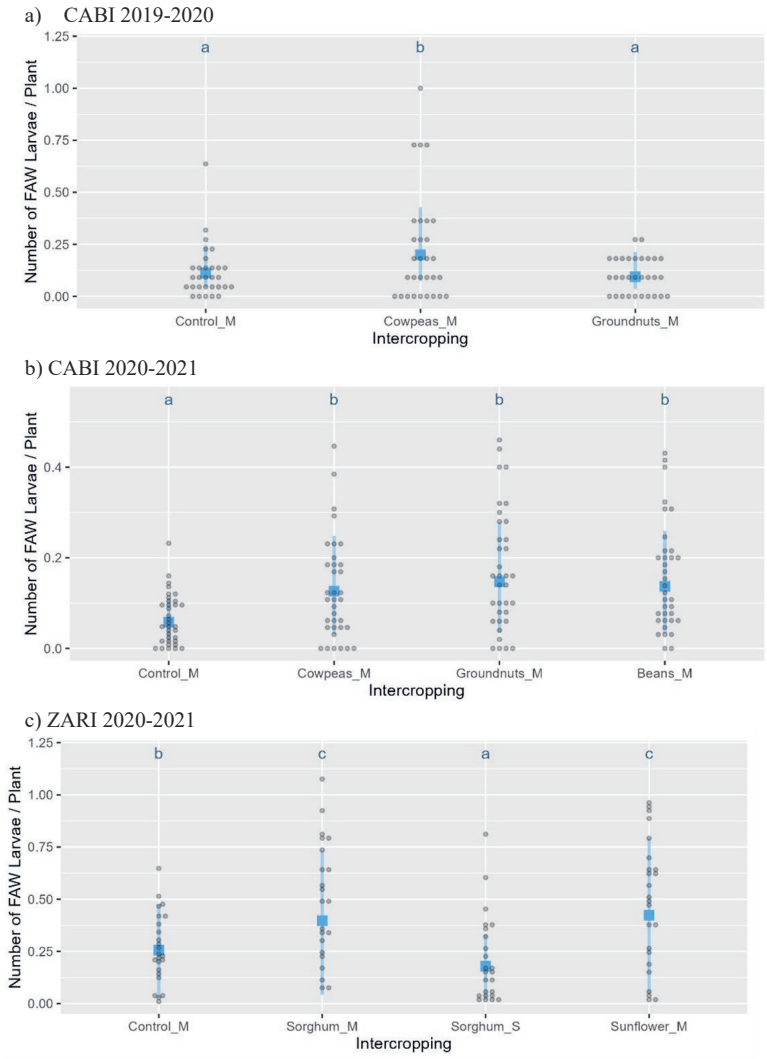
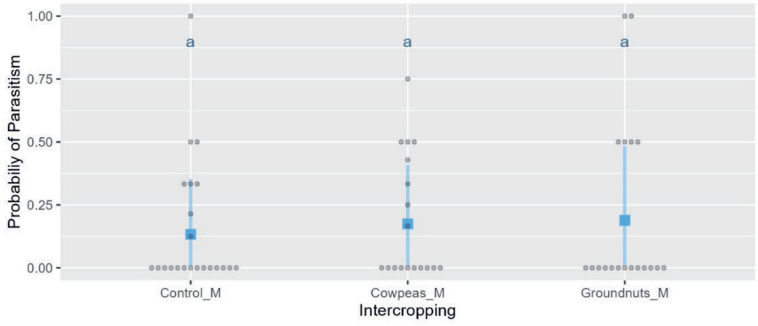


Figure 2. Mean density of fall armyworm larvae for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Vertical bars indicate the 95% C.I., and the letters indicate differences among groups with a certainty level of 95% or more (odds ratio of 20:1). The dots show observations. Intercropping treatments are indicated by Treatment_M when maize plants were sampled and by Treatment_S when sorghum plants were sampled.

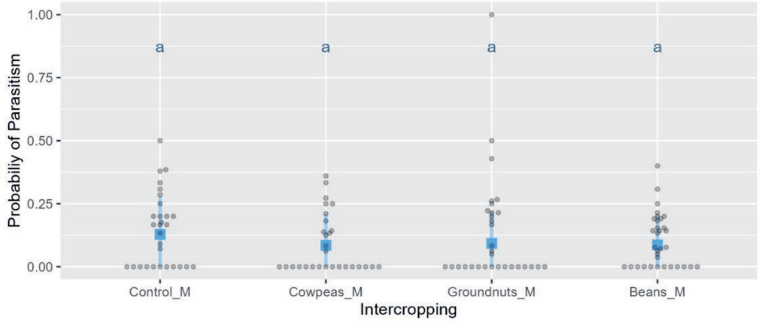
Probabilities of larval parasitism

For CABI 2019-2020, no effect of the intercropping treatment or maize stage was supported as all models had WAIC values higher than or practically equal to that of the null model (Figure 3a and Appendix 3 Figure S2a). For CABI 2020-2021 and ZARI 2020-2021 however, both intercropping and maize stage effects were supported ($\Delta WAIC_{CABI\ 2020\text{-}2021} > 24$, $\Delta WAIC_{ZARI\ 2020\text{-}2021} > 67$) (Appendix 3 Figure S2b and S2c). We focus on the comparisons among intercropping treatments. For CABI 2020-2021, differences among treatments were not very clear despite the support for an effect; the clearest differences were between control vs cowpeas and control vs beans (higher in the control by about 4% with a certainty of 90%; Figure 3b). For ZARI 2020-2021, differences were clearer: parasitism was lower on sorghum plants in the sorghum treatment than on maize plants in the control (4% difference with a certainty of 96%) or sunflower (5% difference with a certainty of 97%) treatments (Figure 3c).

a) CABI 2019-2020



b) CABI 2020-2021



c) ZARI 2020-2021

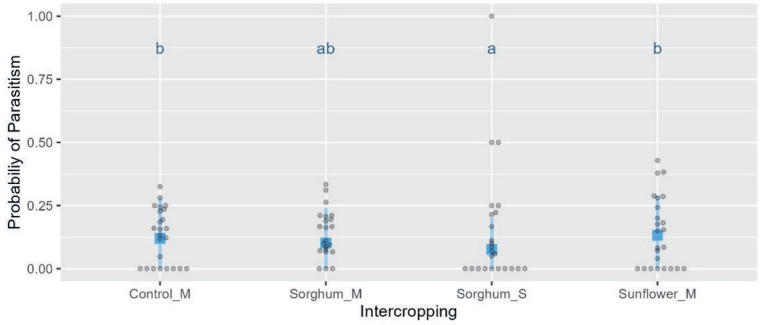
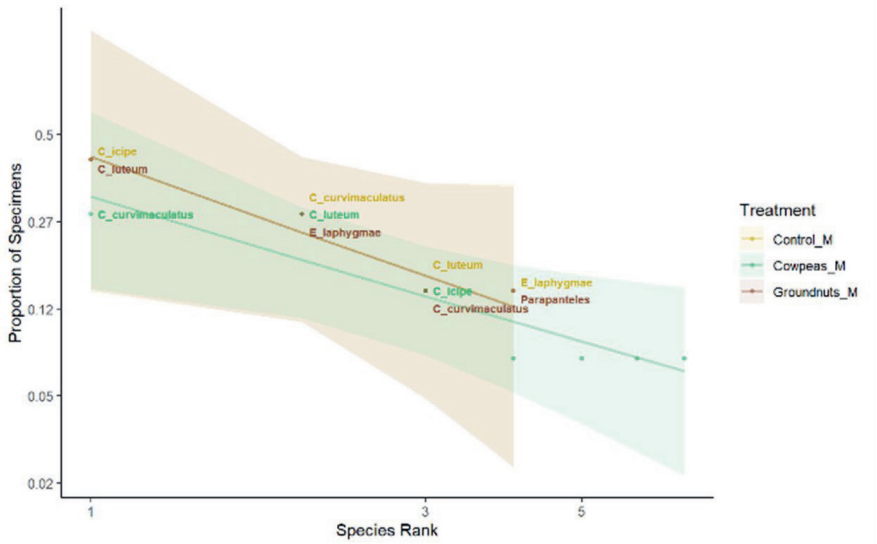


Figure 3. Mean parasitism probabilities by larval parasitoids for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Vertical bars indicate the 95% C.I. The dots show observations. Intercropping treatments are indicated by Treatment_M when maize plants were sampled and by Treatment_S when sorghum plants were sampled.

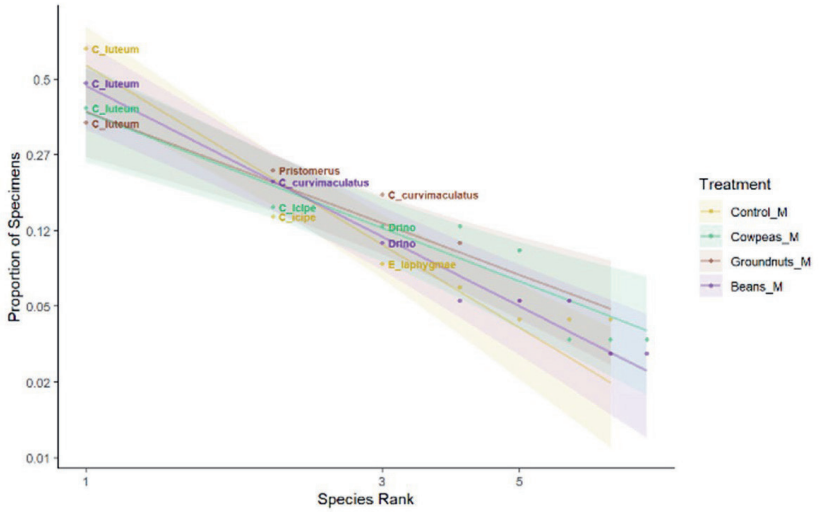
Parasitoid species evenness

Intercrop type did not have a significant effect on the evenness of species abundances in the CABI 2019-2020 experiment (Figure 4a) but did so in the other two. In CABI 2020-2021, species abundances were slightly less even in the control treatment than in the cowpeas (97% certainty or 30:1) or groundnuts (98% certainty or 50:1) intercrop types (Figure 4b). In the experiment ZARI 2020-2021, abundances were slightly less even in the control treatment than maize plants (99% certainty or 95:1) or sorghum plants (97% certainty or 40:1) in the sorghum intercrop type. Similarly, abundances were slightly less even in the sunflower treatment than maize plants (> 99.9% certainty or 3000:1) or sorghum plants (99.4% certainty or 160:1) in the sorghum intercrop type (Figure 4c).

a) CABI 2019-2020



b) CABI 2020-2021



c) ZARI 2020-2021

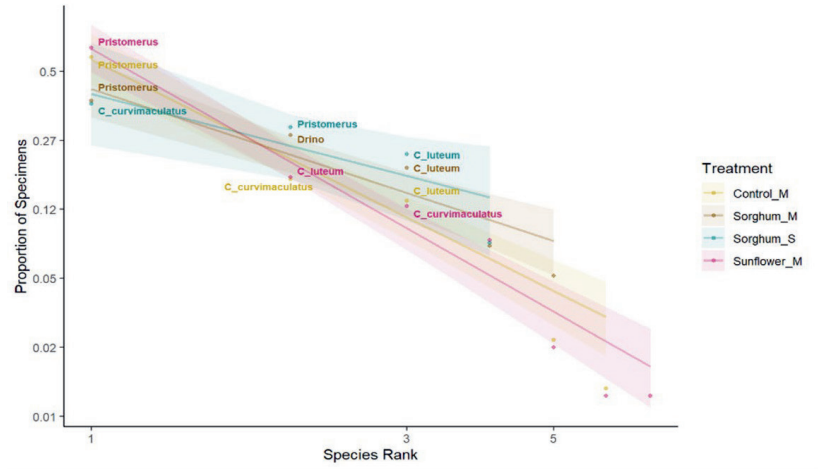


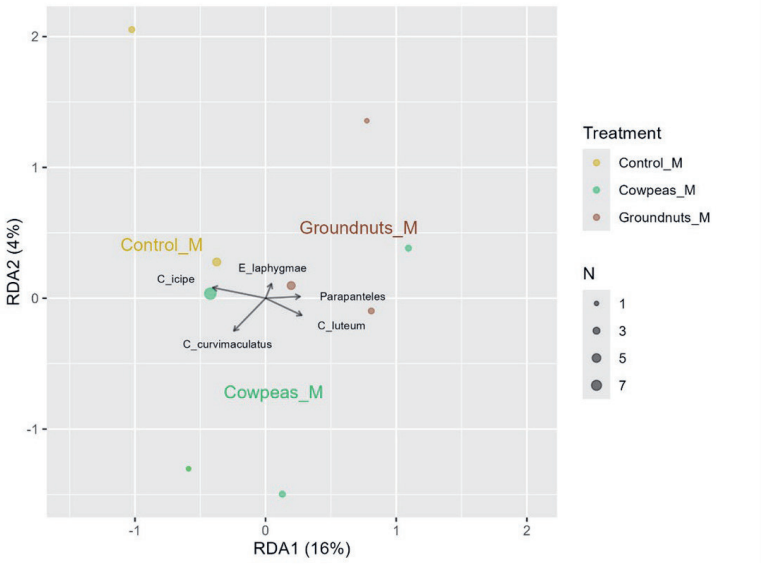
Figure 4. Rank-abundance curves for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021, where steeper slopes indicate less even species abundances. Relative abundance (logit scale) is plotted against the abundance rank of each species (log scale) by treatment. The lines show the fitted slope by treatment with 95% C.I. and the dots show the observations. Intercropping treatments are indicated by Treatment_M when maize plants were sampled and by Treatment_S when sorghum plants were sampled.

Community composition of parasitoids

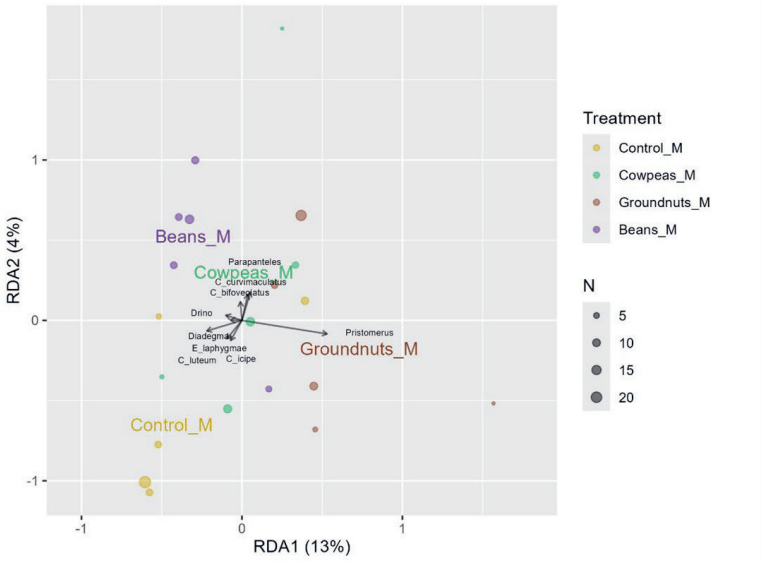
There was no significant effect of intercrop type on the composition of parasitoid communities in the CABI 2019-2020 (PERMANOVA: $F_{2,7}$ = 0.8614, p = 0.5755) or CABI 2020-2021 (PERMANOVA: $F_{3,16}$ = 1.1441, p = 0.2923) experiments (Figure 5a and 5b). There was a significant effect, however, in the ZARI 2020-2021 experiment (PERMANOVA: $F_{3,12}$ = 2.3228, p = 0.0119), where

intercrop type explained a small proportion of the variance in community composition (adjusted R^2 = 0.21). The control and sunflower treatments tended to be associated with more *Pristomerus* sp., contrary to the sorghum treatment. In the sorghum treatment, sorghum plants were associated with more *C. curvimaculatus* and slightly fewer *Drino* sp., *C. icipe* and *C. luteum* (Figure 5c).

a) CABI 2019-2020



b) CABI 2020-2021



c) ZARI 2020-2021

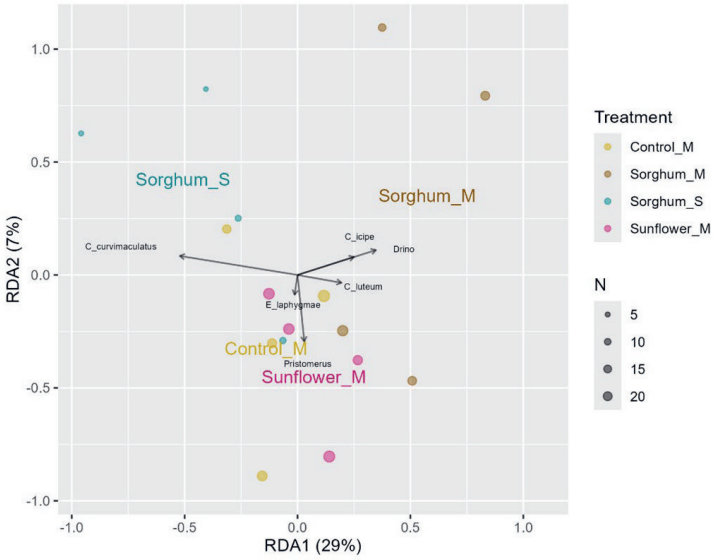


Figure 5. Ordination plots (triplot) of the Redundancy Analysis of the parasitoid community matrix for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Scaling type 2 was used to emphasise the association between species and the intercrop type. Black lines show the correlation among species relative abundances and their association with the first two constrained components (RDA1 and RDA2). Each dot shows the species compositions of one replicate by treatment (colour coded) with the size of the dot being proportional to the number of larvae (N) in the sample. The approximate centroid of each treatment is shown by the location of the treatment label. Intercropping treatments are indicated by Treatment_M when maize plants were sampled and by Treatment_S when sorghum plants were sampled.

DISCUSSION

Our study found variable outcomes of intercropping on FAW larvae and egg density, parasitism probabilities, parasitoid species evenness and community composition of parasitoids across the years and sites. The main influence found were a higher FAW larval density on intercropped maize but lower on sorghum plants, lower parasitism rates on sorghum plants, less even abundance of parasitoid species in maize control treatment, and an association of the parasitoid *Chelonus curvimaculatus* with sorghum plants, and of *Pristomerus* sp. with sunflower and maize control treatments. Intercropping practices contributing to conservation biocontrol can take years of consistent effort before seeing a reduction in pest populations and stability in parasitism rates in space and time (Eilenberg, 2006; Macfadyen et al., 2011). Indeed, the sites selected for the current study were not managed under conservation biocontrol programmes prior to the intercropping experiments, and conservation biocontrol had not been practiced in the adjacent fields. A substantial amount of literature on habitat management and intercropping reports a decrease of pest infestation and crop damage compared to a monocrop (reviewed in Andow, 1991; Kenis et al., 2023 for FAW; Landis et al., 2000). However, this could be due to neutral or negative outcomes of such studies being under-reported.

Our study found a slight influence of intercropping on probabilities of parasitism by larval parasitoids during the 2020-2021 rainy season. While at the CABI site the differences could not be determined, at ZARI the difference observed was on the sorghum plants, which show lower probabilities of parasitism than maize plants in the control and sunflower-maize treatments. Concurrently, FAW larval density was lower on sorghum plants compared to maize plants in all the other treatments at ZARI. The sorghum used in the experiment at ZARI is a native and drought-tolerant variety that tassels early when plants are still short, meaning that the window available for FAW to feed on the plants is shorter than for maize plants. Therefore, the lower parasitism probabilities could be due to lower overall FAW density over time. Interestingly, despite the low parasitism probabilities, the community composition of parasitoid species shows an association between sorghum and *C. curvimaculatus*. *Chelonus* species, being egg-larval parasitoids, need the presence of egg masses in the field to oviposit but kill the FAW larvae. This association found in our study is unclear, as we observed higher FAW egg density on maize plants than on sorghum plants from the maize-sorghum combination. Further research is needed to understand the tri-trophic interactions between sorghum, FAW as a new invasive species in Africa and native parasitoids.

A field study in Cameroon found that egg parasitism of stem borers was significantly higher in intercropped maize compared to maize monocrop; however, larval parasitism was not affected by intercropping (Chabi-Olaye et al., 2005). Instead, their study showed that larval parasitism was related to days after planting. As the parasitoid complex at our study sites is mainly composed of larval parasitoids, which can fly much longer distances than egg parasitoids, this may explain that larval parasitoids were found in all plots with no significant difference in probabilities of parasitism. Sites and space available for our experimental research were limited, therefore, the plots may have been too close to each other for larval parasitoids. Additional trials should consider bigger plots (e.g. 20x20 m), far from each other, different sites and a minimum of three years' research to track progress on conservation biocontrol. Field trials are affected by various abiotic and biotic factors, such as weather conditions, soil composition and the presence of predators, which can influence the outcomes of the treatments. Furthermore, increasing crop diversity may also better promote generalist predators, such as spiders or ground beetles and immature stages of other predators such as hoverflies and lacewings, which are less mobile than parasitoids (Cai et al., 2010; Munyuli et al., 2007; Puliga et al., 2023).

Parasitoid abundance analysis showed that sunflower-maize and control treatments were generally dominated by a few species compared to maize plants in the maize-cowpea, maize-groundnut, and maize and sorghum plants from the maize-sorghum intercrops where parasitoids abundance show a more even distribution. Parasitoids benefit from feeding on extrafloral nectar by increasing survivorship, fecundity, and field retention, leading to higher rates of parasitism and pest suppression (Cavallini et al., 2023; Mizell & Mizell, 2008). Maize monocropping is food-limited for parasitoids as it does produce only pollen, not nectar, and synovigenic parasitoid species that require eggs to mature

after emergence may be food-limited in such an environment (Jervis et al., 2023a). Therefore, only a few parasitoid species may be able to survive under such conditions if they don't require sugar food after females emerge. However, this will require further investigation. Companion plants may not only provide pollen, floral and extrafloral nectar but also honeydew provided by phloem feeders (Tena et al., 2016).

Cowpeas and sunflowers are known to have extrafloral nectaries on stipules and inflorescences, and flower bracts and phyllaries, respectively (Mizell & Mizell, 2008). Recent lab and field studies have shown the potential for cowpea and sunflower to be used in conservation biocontrol. As an example, *Bracon* spp. parasitoids were being attracted to their VOCs (Cavallini et al., 2023), parasitism rates were higher when maize was intercropped with cowpeas and sunflower. Furthermore, these crops have the potential to deter pest oviposition when combined with maize (Chabi-Olaye et al., 2005; Fathi, 2018; Sisay et al., 2023). However, this effect may be specific to *Bracon* species and may not be applicable to other parasitoid species, indicating the need to study specific crop-parasitoid species combinations. Considering the diversity of parasitoid species attacking FAW and of companion crops across the African continent, it would be critical that further studies investigate in open fields and in laboratory experiments the direct benefits of pollen, floral and extrafloral nectar of common companion crops on parasitoid species' fecundity and longevity alongside parasitism rates. For example, sunflower treatment in our experiment at ZARI was associated with more *Pristomerus* sp. parasitoids, an association that has not been reported previously to our knowledge. It is currently not possible to determine whether the resource concentration or the enemies hypothesis is being supported by our research. However, many studies concluded that both hypotheses are likely complementary (Russell, 1989).

Additionally, our results show that FAW density was higher on intercropped maize compared to maize control. This effect may be seen because the intercrop plots had half the number of maize rows compared to maize control, putting more pressure on the fewer maize plants. However, insect pests can also benefit from this supplemental and rich food source provided by extrafloral nectaries (Huss et al., 2022). FAW female moths may have benefited from pollen and extrafloral nectaries to increase fecundity provided by companion crops. It would therefore be critical to not only assess the effect of extrafloral nectaries on the fecundity and longevity of parasitoids but also of their hosts. Moreover, consistently across years and sites, maize stage has an effect on FAW density where V5 to V11 stages had generally higher numbers of FAW larvae per plant as shown by our previous studies (Durocher-Granger et al., 2021; Durocher-Granger et al., 2024). Parasitism probabilities by larval parasitoids were also higher at maize stages VE-V7 and V8-V11 than stages V12-V14 and reproductive stages (VT-R2) during the rainy season 2020-2021.

CONCLUSION

Despite the limitations with experimental design, our study points towards an indication of the influence of intercropping mainly on attractiveness of parasitoids to some intercrops. These findings provide interesting starting points to develop multi-year and multi-country research programmes on conservation biocontrol in Africa. International collaborations would be critical for conducting laboratory experiments, such as testing the responses of *Ch. curvimaculatus* to sorghum (healthy vs damaged by insect pests) or looking at the effects of intercropping on physiological changes (e.g. secondary metabolites) in maize plants. In addition, we suggest testing nectar component analysis and parasitoid feeding preference to confirm the association between parasitoid species and intercrops found in our study and to assess how feeding affects their behaviour (Sobhy et al., 2025; Varennes et al., 2016). Alongside research on parasitoids, we suggest including predators and entomopathogens in conservation biocontrol studies. However, despite the successful research outcomes of the past decades, conservation biocontrol is still generally under-funded with isolated short-term projects of about two or three years. Indeed, the timeline and spatial scale needed for conservation biocontrol to yield profitable results through a balanced agroecosystem does not offer a “quick fix” solution to alien invasive species.

ACKNOWLEDGEMENTS

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6

Awareness and community preferences on collective pest management for fall armyworm in rural Zambia

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ABSTRACT

Collective pest management can provide benefits over individual field-by-field management, especially for highly mobile pests when consistent and coordinated actions are implemented. Since its invasion in Africa, fall armyworm (FAW) has quickly established due to widely available maize fields managed by millions of smallholder farmers. As a highly mobile pest, FAW's management is complicated and indicates the need for collective action. Conservation biocontrol such as intercropping can offer simple, low-cost and adaptable solutions to smallholder farmers as pest management alternatives to chemical insecticides that reduce pest pressure and chemical usage. Between 2019 and 2022, a project on conservation biocontrol using local companion crops to manage FAW in smallholder farming systems was implemented in two districts of Zambia. The study presented here aimed to assess the intervention considering farmers ecological knowledge, and willingness and preferences to operationalize collective action principles, long-term pest management and consider the limiting factors. The results show that the intervention increased farmers' knowledge of the concept of biocontrol and natural enemies. Farmers in both communities demonstrated a positive attitude towards a collective action to manage FAW and showed willingness to implement it at the community level. Boundaries, local conditions and leadership were found to be critical to support a collective action. The main factors limiting the implementation of a collective action for FAW management was lack of knowledge, coordination and support. This study recognizes the knowledge needed and limitations to promoting collective pest management and fills a gap in approaches to the management of FAW in Africa.

INTRODUCTION

In sub-Saharan Africa, maize (*Zea mays*) is one of the main staple crops grown over 40 million hectares (FAO, 2024) predominantly under rainfed conditions. Maize production in the region has many constraints including low soil fertility, climate change, irregular rainfalls, weeds, pests and diseases, and post-harvest losses (Reynolds et al., 2015). The arrival of fall armyworm [FAW, *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)], a highly mobile and invasive species, has put maize production under more pressure. Indeed, FAW has become one of the most damaging insect pests on earth after its accidental introduction to Africa compelling farmers to significantly increase their use of chemical insecticides (Kenis et al., 2023). If used indiscriminately, chemical insecticides can lead to pest resistance and loss of natural enemies resulting in pest resurgence and/or secondary pest outbreaks. Chemical insecticides can also result in contamination of water bodies and the environment. Integrated pest management (IPM) offers a range of preventive and curative practices where the use of chemical insecticides should be the last resort. However, IPM has very low adoption rates in low- and medium-income countries (Alwang et al., 2019; Parsa et al., 2014; Tambo & Liverpool-Tasie, 2024). Agroecological strategies such as crop diversification should be attractive to smallholder farmers since they are safe, implemented at no to low cost and can be locally adapted, whilst, contributing to food diversity and security, and reducing pest infestations (Wyckhuys et al., 2013). Some benefits of crop diversification include increase soil fertility, soil moisture conservation and support of natural enemy populations through the provision of food, shelters and corridors to move between fragmented habitats (Samways, 2020). Habitat management, a subset of conservation biocontrol, can offer efficient tools to smallholder farmers to manage pests when co-designed and adapted to local conditions (Nicholls & Altieri, 2004). However, these conservation strategies have greater impact for management of highly mobile pests when implemented on a landscape level (Babendreier et al., 2019; Cumming & Spiesman, 2006; Stallman & James, 2015).

Smallholder farmers own or manage small plots of land, usually less than two hectares, representing around 80% of all farms in sub-Saharan Africa. In some countries, smallholder farmers provide up to 90% of food production which contributes to food security and biodiversity conservation (Mugambiwa, 2023). Consequently, due to the highly fragmented landscape, coordinated actions amongst farmers on a large scale remain challenging. Additionally, many social and biophysical interactions trigger a wide range of challenges in rural Africa. These interactions increase the complexity of challenges that smallholder farmers face and hinder effective collective action and stakeholder coordination (Galarza-Villamar et al., 2024). This is particularly true for the sustainable and long-term management of highly mobile and invasive species such as FAW. Eradication and management of invasive alien species (public-bad) face societal and institutional challenges where individual interests may prevent the creation of a public good, in this case collective pest management. Most smallholder farmers take action to manage pests only when the pest has incurred heavy or irreversible damage to their crop. This reactive field-by-field approach coupled with uncoordinated

actions amongst farmers favours the pest by allowing the easy reinvasion of neighbouring fields. Indeed, only one field not adequately managed can become a breeding source for an invasive species (Kansiime et al., 2024; Kruger, 2016; Marshall et al., 2016). Therefore, there is an urgent need to develop long-term, sustainable and collective pest management strategies at local, regional and global levels.

Collective action does not always emerge by itself and, in this case, may require interventions to support understanding of invasive pests' biology and how it translates into interdependency. Technical support can also help to gain insights on how communities would operationalize the key principles of collective action to foster effective pest management (Damtew et al., 2021; Durocher-Granger et al., 2023; Stallman & James, 2015; Tafesse et al., 2020). Knowledge and preferences may depend on a range of factors such as available resources, past experiences and established social structures. Ostrom (1990) identified eight principles for the management of common-pool resources which can also be adapted to the management of public-bads such as invasive alien species as shown by the growing amount of literature and field studies in the past decade (Damtew et al., 2021; Durocher-Granger et al., 2023; Galarza-Villamar et al., 2021; Galarza-Villamar et al., 2024; Kruger, 2016; Tafesse et al., 2020; Stallman, 2011). The eight Design Principles are clearly defined boundaries (DP1), matching rules to local conditions (DP2), collective-choice arrangements (DP3), monitoring system (the resource and users) (DP4), graduated sanctions (DP5), conflict-resolution mechanisms (DP6), minimal recognition of rights to organize (DP7) and nested enterprises (DP8) (Ostrom, 1990).

This research paper examines an intervention that focused on farmer awareness and training on FAW biology and its local associated natural enemies, and use of demonstration plots where maize was intercropped with local companion crops for FAW management. The intervention also incorporated awareness meetings and discussions on how to collectively implement conservation biocontrol through crop diversification (based on Ostrom's eight Design Principles), and feedback loop meetings between farming communities and scientists. This study assessed the knowledge (ecological and collective action concepts) acquired by participating communities, preferences for collective action operationalization and factors limiting implementation in relation to collective pest management, crop diversification and long-term pest management. The research questions guiding the study included:

I. What factors influence knowledge on FAW ecology and biology and its associated natural enemies?
II. What is the willingness of communities to cooperate for pest management and what are the prospects for a collective action?
III. What socio-economic factors affect planning of long-term pest management at community level?
IV. How do communities envisage operationalizing principles for collective pest management in line with Ostrom's eight Design Principles?

MATERIALS & METHODS

Study areas

The study was conducted with communities in Central and Southern provinces of Zambia where a project on FAW conservation biocontrol took place over three rainy seasons between August 2019 and March 2022 (Durocher-Granger et al., 2023). Study sites were selected with the assistance of the extension officers from each district and included the following villages; Chintembe and Chimoto (Mumbwa district in Central province; 15°02'S, 27°06'E; agro-ecological zone IIa) and Hambale and Musika (Siavonga district in Southern province; 16° 23' S, 28° 42' E; agroecological zone I). These districts and communities were selected for the project due to the importance of maize, grown for subsistence every rainy season, and high infestation levels of FAW since its detection in Zambia in December 2016. Mumbwa district has an annual average precipitation between 800 to 1000 mm and annual mean temperatures of 22.1℃ whilst Siavonga district, located in a dryer region in the South of the country, has an annual average precipitation of <800 mm and annual mean temperature of 26.7℃ (Makondo et al., 2014).

Interventions

In August 2019, inception meetings were held with the selected farming communities to understand the socio-economic conditions, local crops grown and associated pests in each district. These initial meetings aimed at co-creating field designs of maize intercropping with local companion crops to test their efficacy in deterring FAW oviposition and to attract natural enemies. Over the rainy seasons 2019-2020, 2020-2021 and 2021-2022 (November to March), lead farmers, selected by the group of participants, hosted demonstration plots using cowpeas, groundnuts and sunflowers. The first year, farmers were free to test their own intercrop design. During the second year, 15x15m demo plots were established and planted with maize-cowpeas, maize-sunflower, maize-groundnuts combinations and maize monocrop; these were also used to collect data on the presence of FAW and its natural enemies. In the third year, meetings were hosted prior to the rainy season to discuss farmers' experiences during the first two years and to develop a common design based on best results and experiences. Farmers discussed amongst themselves and shared experiences leading to a collective agreement for the forthcoming season to plant maize rows with two rows of sunflowers around the field as edge rows and after the first weeding (once the maize has reached knee-high), to plant cowpea between rows.

During each rainy season, FAW larvae were collected and reared in the lab at CABI in Lusaka to evaluate parasitoid species and parasitism rate (number of parasitoids/total number of FAW larvae expressed as percentage) from the intercropped and monocropped maize plots. At the end of each crop cycle, feedback loop meetings were organized with farmers and scientists. During these meetings, farmers shared their experiences with the different intercropping combinations, and entomologists presented the parasitoids species specimens and the parasitism rates for each field sampled (intercrops

vs maize monocrop). The parasitism rates were also compared to previous years to show the progress as more farmers were gradually joining the intervention by implementing maize intercrop every rainy season. These meetings offered a space for both the farmers and scientists to share experiences and to co-design the next steps for FAW management at community level. During these meetings, the beneficial effects of companion crops were also discussed with farmers. For example, some companion crops deter FAW oviposition and/or can provide extra-floral nectar for natural enemies enhancing their populations. Ostrom's eight Design Principles (1990) were also discussed in a way that aligned with the existing traditional community structure (Durocher-Granger et al., 2023). Discussions were also held on how farmers could best coordinate and increase crop diversity (through maize intercropping) to achieve a greater impact on FAW management compared to a field-by-field approach. Key topics included defining physical boundaries, identifying stakeholders, establishing rules and agreements, designing a monitoring system, implementing sanctions, and providing incentives. Researchers ensured that these feedback and reflection sessions were sufficient and regular according to farmers' availabilities. The intervention complemented the current agricultural extension services system on FAW management where one extension officer is assigned to a camp (group of neighbouring villages). These camps form a block, and blocks are under the jurisdiction of a district. Depending on the population size, a variable number of districts are grouped under a province. Camp officers deliver extension services based on individual requests or pest reports from several farmers. These services are provided either through direct individual interventions or as training sessions for small groups of farmers from the same village or lead farmers from neighbouring villages.

Data collection

Surveys were conducted over two weeks from the 21st of May to the 4th of June 2022 in Siavonga and Mumbwa districts. A semi-structured questionnaire (Appendix 5) with closed and opened-ended questions was used to allow deeper understanding of the ecological knowledge acquired from participating communities, their preferences for collective action operationalization and the limiting factors for implementation in the communities involved in the project since 2019. Therefore, a purposive sampling method was used where about half of the interviewees had been actively participating in the activities. A significantly higher number of women participated in the interviews, reflecting the active participation of women in agriculture due to men seeking off-farm income opportunities. The descriptive statistics of the interviewees by district are presented in Table 1. The questionnaire was pre-tested in a different district from the study (Chongwe) and revised prior to use in the study areas. All surveys were conducted by trained enumerators in a 1-to-1 interview format and took an average of 45 minutes per interviewee. Prior to interviews the objectives of the study were explained to participants and informed consent obtained. The data was handled in accordance with the General Data Protection Regulation (GDPR).

Analytical approach

The objective I of this paper evaluated the factors influencing knowledge on FAW ecology and biology and its associated natural enemies. Five outcome variables were therefore analysed separately to understand better the knowledge of interviewees on ecological concepts, which were explained at various occasions during the project intervention. We chose to use a probit regression model for each of the five outcome variables because the answers were binary (Table 2A of Appendix 4). The motivation behind this approach is because each life stage of FAW has different characteristics and is found in different locations of the maize plant, and that a good understanding of the FAW life cycle is important for its management (Day et al., 2017). Outcome variables were coded 1 when the ecological knowledge responses matched scientific knowledge and 0 if it didn't match or no answer was provided. Each of the five outcome variables were assessed as follow:

A. **Biocontrol concept**: desirable answer includes one or more of the three following options (1) living organisms that feed on or reproduce inside FAW and kill it, (2) non-chemical methods to kill pests, (3) promoting natural enemies with food and shelter such as flowering crops/plants.
B. **How natural enemies kill FAW**: desirable answer includes one or more of the three following options (1) insects/organisms laying eggs in the FAW, (2) insects/organisms hatching/emerging from FAW, (3) insects/organisms eating or taking away the FAW.
C. **Type of natural enemies**: parasitoids (wasps or flies), nematodes and/or predators such as wasps, ants, ladybird beetles, birds, etc, and/or their descriptions.
D. **FAW lifecycle**: egg – larva – pupa – moth organized in a cycle.
E. **FAW larvae identification**: Correct identification of fall armyworm, *Spodoptera frugiperda* (JE Smith), presented next to *Busseola fusca* (Fuller) (maize stalk borer), *Spodoptera exempta* (Walker) (African armyworm) and *Helicoverpa armigera* (Hübner) (cotton bollworm).

The objective III sought to understand which socio-economic factors affect planning of long-term pest management at community level. Therefore, such as for objective I, we used a probit regression model because the outcome variable was binary (0 = do not plan, 1= plan).

The socio-economic factors considered as potential explanatory variables in shaping knowledge on FAW ecology and planning of long-term pest management (research questions I and III) included several standard demographic variables (such as age, education level, and gender) that are used in most studies that seek to understand the use or uptake of agricultural practices. We also included land-tenure (farming on owned or rented land), participation in the project interventions, pesticide usage, wealth (operationalised through an asset index) and the estimated level of food security as potentially relevant variables. These explanatory variables have been shown in several studies to affect interest and investment in agronomic improvement as well as ecological knowledge either traditional or through training (Adjei-Nsiah et al., 2007; Duffy et al., 2021; Tetteh et al., 2025; Wyckhuys & O'Neil, 2007). We also validated the choice of these explanatory variables with the extension officers from the two districts based on the cultural and socio-economic context of the communities.

To assess wealth, respondents were asked to indicate their ownership of 20 durable assets selected based on a representation of wealth in the surveyed villages. The assets index was then calculated using a principal component analysis (PCA) following Filmer and Pritchett (2001) to assign weight to each asset. Food security was estimated with the help of an index, the household dietary diversity score (HDDS), assessing the number of different food categories consumed in the past 24h from a list of 12 categories (Swindale & Bilinsky, 2006) (see Table 2A of Appendix 4). The HDDS was then calculated by adding each category. HDDS with higher scores indicates better access to diverse foods which score generally increases when income increases. The average HDDS in the richest 33 percent of households, using the assets index as a proxy for wealth, was used as a guide for setting the target level of HDDS for the purpose of performance monitoring (Swindale & Bilinsky, 2006). This was calculated for each district separately (Table 1).

Table 1. Characteristics of interviewees.

Variables	Description	District	Mean	SD
Gender	Gender (1=male)	Siavonga	0.20	0.41
		Mumbwa	0.33	0.47
Age	Age (years)	Siavonga	46.51	14.89
		Mumbwa	47.40	15.35
Education	Interviewee has completed secondary education (1= completed)	Siavonga	0.90	0.30
		Mumbwa	0.91	0.28
Land title	Own land title (1= owned)	Siavonga	1.00	0.00
		Mumbwa	0.96	0.20
Land size cultivated	Land size cultivated (hectares)	Siavonga	2.03	1.19
		Mumbwa	0.96	0.20
Participation in project	Participated in the project (1=participation)	Siavonga	0.44	0.50
		Mumbwa	0.41	0.49
Pesticide usage	Pesticide applied in the last rainy season (1= applied)	Siavonga	0.44	0.50
		Mumbwa	0.27	0.45
HDDS	Score based on 12 food categories (1 category = 1 point)	Siavonga (1st tercile)	2.84	1.16
		Siavonga (2nd tercile)	3.70	1.36
		Siavonga (3rd tercile)	4.79	2.10
		Mumbwa (1st tercile)	5.50	1.57
		Mumbwa (2nd tercile)	6.36	1.50
		Mumbwa (3rd tercile)	6.79	1.73
Assets index	Household assets index	Siavonga (1st tercile)	-2.33	0.60
		Siavonga (2nd tercile)	-1.00	0.40
		Siavonga (3rd tercile)	1.44	1.47
		Mumbwa (1st tercile)	-1.06	0.76
		Mumbwa (2nd tercile)	0.74	0.50
		Mumbwa (3rd tercile)	3.43	1.22

A summary of the outcomes and explanatory variables and their descriptions for objectives I and III can be found in Table 2A of Appendix 4. From the repository, data were exported in an Excel spreadsheet and analysed using Stata 17.0 (StataCorp, 2021). The levels of significance for all models were set at 0.01, 0.05 and 0.10.

Objectives II and IV aimed at understanding, through opened-ended questions, participants' willingness and limitations in implementing intercropping and participating in a collective action to manage FAW, participants' preferences/views on a potential structure for the collective action, and their planning and limitations regarding pest management were also recorded. For qualitative answers on willingness, limitations and operationalization of the collective action, content was coded in relation to Ostrom's eight Design Principles where refined categories were developed inductively and analysed to retrieve similar answers and categorized by district to detect any differences.

RESULTS

Knowledge on FAW and natural enemies

The probit regression A showed that knowledge on the biocontrol concept was affected significantly by gender, age, level of education and participation in the project. Women, older respondents with basic education either primary or secondary, and those who had participated in the project were better informed on the biocontrol concept. Level of education and participation in the project positively affected ecological knowledge on type of natural enemies and how they kill FAW (B and C). Age showed a significant effect on knowledge of the FAW cycle (D) where older respondents were better informed. District and HDDS also significantly affected knowledge on the lifecycle of FAW where farmers from Siavonga district and those with lower HDDS scored better. The probit regression E showed that gender, age, district and total size of cultivated land (ha) were significantly related to the ability to differentiate the FAW caterpillar amongst other species attacking maize in Zambia.

Table 2. Summary of statistical significance of explanatory variables on ecological knowledge.

Variables	Biocontrol concept	Sig	Type of natural enemies	Sig	Explain how natural enemies kill FAW	Sig	FAW cycle	Sig	FAW larvae identification	Sig
Gender	0.098	*	0.371	ns	0.212	ns	0.552	ns	0.009	***
Age	0.024	**	0.115	ns	0.107	ns	0.037	**	0.03	**
Education level	0.008	***	0.02	**	0.056	*	0.193	ns	0.746	ns
District	0.96	ns	0.571	ns	0.494	ns	0.002	***	0.057	*
Land title	0.455	ns	0.555	ns	0.283	ns	0.45	ns	0.57	ns
Total land size cultivated (ha)	0.529	ns	0.923	ns	0.625	ns	0.122	ns	0.039	**
Participation in project	0	***	0	***	0	***	0.137	ns	0.218	ns
HDDS	0.862	ns	0.174	ns	0.648	ns	0.004	***	0.548	ns
Assets index	0.674	ns	0.534	ns	0.387	ns	0.85	ns	0.273	ns

** p<0.1, **p<0.05, ***p<0.01, ns = not significant*

Women and older respondents from Mumbwa with larger portions of cultivated land scored better (summary of all probit regressions A to E in Table 2 and full details in Appendix 4 Table 2B to 2F). Fifty-four percent of women, regardless of involvement in the project, correctly identified the FAW caterpillar. Most of the respondents who had matching responses with scientific knowledge on ecological concepts were participants in the project (Table 3). Additionally, respondents who reported matching responses for biocontrol concept (86%), naming natural enemies (88%) and explaining how they kill FAW (87%) either had a primary or secondary school education. However, this result is representative of the education level of all respondents interviewed in the study. About 90% either had a primary or secondary education (Table 1).

Table 3: Number of interviewees who provided matching answers with scientific knowledge on biocontrol according to participation in the project.

Participation in project	Biocontrol concept	Name natural enemies	Explain how natural enemies kill FAW
Participated	58	56	53
Did not participated	16	14	12
Total	74	70	65

Willingness to participate in collective FAW management

In Mumbwa, all the respondents said they would be willing to participate in the collective implementation of intercropping with neighbouring farmers for FAW management, and in Siavonga 97% were willing to participate. Most respondents would also be willing to coordinate the implementation of flower strips and crop diversification with neighbours. Almost all respondents were willing to reduce chemical insecticide application jointly with neighbours, although slightly less would be willing compared to implementing intercropping, flower strips or crop diversification (Table 4).

Table 4. Proportion of respondents by district willing to implement collective cultural practices.

Questions	Siavonga	Mumbwa
Implement the intercropping with your neighbours	97%	100%
Implement flower strips between fields with your neighbours	97%	99%
Decreasing insecticides usage with your neighbours	94%	97%
Implement crop diversification with your neighbours	96%	99%

Limiting factors for collective FAW management using intercropping

The participants from Mumbwa and Siavonga identified several limiting factors to implementing or upscaling intercropping. These include a lack of knowledge on suitable crop combinations, optimal planting times, and general intercropping practices. Additionally, limited access to inputs and financial resources, the high labour demands compared to mechanized farming, incompatibility with existing farm management practices, and overall labour intensity were cited as major constraints (Figure 1). In Mumbwa, 25 participants explained that intercropping is not compatible with their existing farming practices such as ploughing with oxen, that herbicide applications for maize

could burn the legumes or that legumes climb on the maize. In Siavonga, lack of knowledge, access to seeds other than maize and requiring manual labour were their main limiting factors. However, peer-to-peer influence seems to limit willingness of farmers to try the practice as 12 of the participants had negative perceptions of intercropping based on others' opinions.

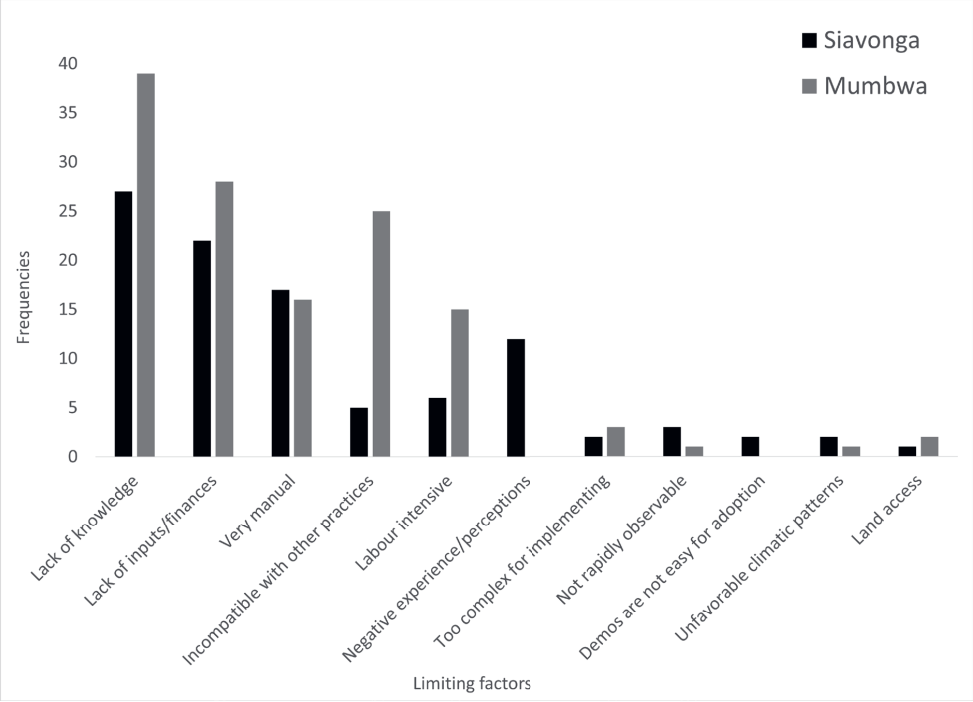


Figure 1. Frequencies of the limiting factors for implementing or upscaling intercropping by district.

Operationalization of the collective action

Respondents in Siavonga (45) and Mumbwa (49) most frequently suggested defining the physical boundaries of the collective action (DP1) by grouping neighbouring farmers with adjacent fields rather than houses. Headman's boundaries were also frequently cited, though more so in Siavonga (45) than in Mumbwa (15), while camp officers were mentioned more often in Mumbwa (25) than Siavonga (14). Groups led by lead farmers were less frequently mentioned, by only 5 respondents in Siavonga compared to 22 in Mumbwa. Village limits were considered only in Mumbwa, where 8 respondents mentioned them, while no respondents in Siavonga referred to this approach. Consistently, when asked who (social boundaries) would take part in a collective action to manage FAW (DP1), 44 respondents in Siavonga and 54 in Mumbwa indicated, with the highest frequencies, individuals with adjacent fields, the second most frequent answer was by village in both Siavonga (7) and Mumbwa (15). Fewer respondents expressed the preference for a gender or age-related group with 3 in Siavonga

and 9 in Mumbwa. Clubs/cooperatives and the entire camp were mentioned each 3 times in Mumbwa only.

Preference for coordinating the group and to lead on the agreed rules (DP2) was given to the headman (Siavonga: 45, Mumbwa: 34), followed by elected leaders (Siavonga: 26, Mumbwa: 31), lead farmers (Siavonga: 15, Mumbwa: 31), and camp officers (Siavonga: 23, Mumbwa: 22). In Mumbwa, these four categories were mentioned in similar frequencies alongside the secretary of the village (24), who was not mentioned in Siavonga. Group members were the least preferred option in both districts (Siavonga: 8, Mumbwa: 3). Community meetings were the preferred mechanism to be used to agree on the rules of the collective action (DP3) (mentioned 66 times in Siavonga and 69 in Mumbwa). The headman was the second preferred option to decide on the collective action rules and was equally cited in Siavonga (26) and Mumbwa (28). In Mumbwa group leaders or an elected executive community were of similar importance in deciding on rules to the headman (28) but less important in Siavonga (9). Support from camp officers was mentioned in lower frequencies for both districts (Siavonga: 7, Mumbwa: 8), while the village secretary was mentioned by only 7 Mumbwa respondents.

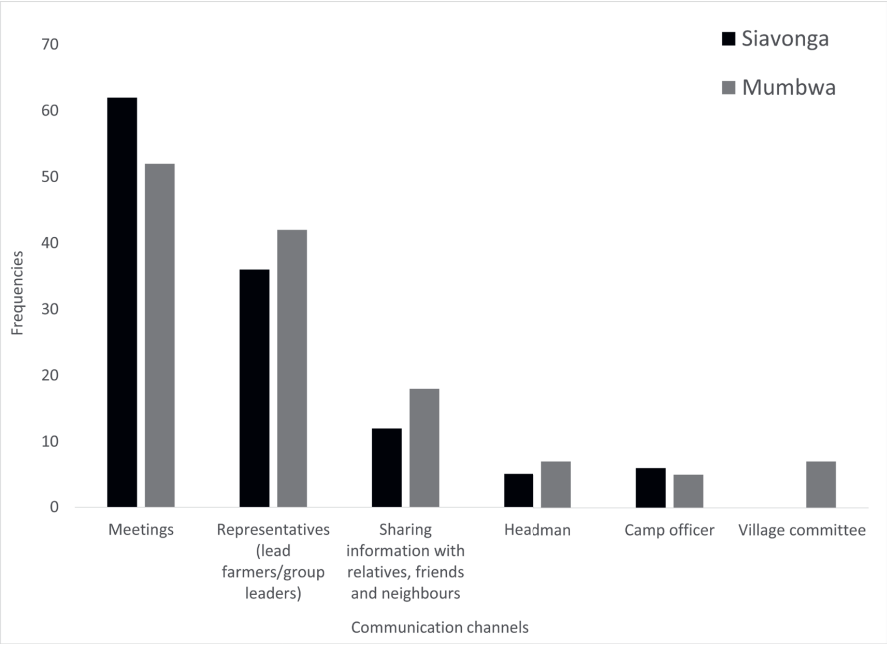


Figure 2. Frequencies on preferences for top-down communication channels to members on the collective action to manage FAW by district.

There was a preference for information and decisions regarding the collective action (DP2) to be escalated from the leader to the farmers through meetings or by announcement by representatives (lead farmers or group leaders) (Figure 2). Farmer exchanges such as field days, organized field visits, and community meetings were the main communication channels mentioned to communicate with members

and outsiders on the collective action (knowledge and information exchange) (Figure 3). Respondents agreed that monitoring of the resources and the users (DP4) needs to be done, from highest to lowest frequencies, by the group members moving together, a monitoring committee, lead farmers, the headman, through meetings, the extension officer, the village secretary or the chief (Figure 4). In both communities, 70% of the participants believe that incentives (inputs such as intercrop seeds and farming tools) and sanctions (being reported to the headman for enforcement, penalty fees and removing a non-compliant from the group) are needed (DP5). In Siavonga, 81% of the respondents trust that the community will follow the agreed rules while in Mumbwa, a higher proportion of respondents (96%) trust the community will follow the agreed rules.

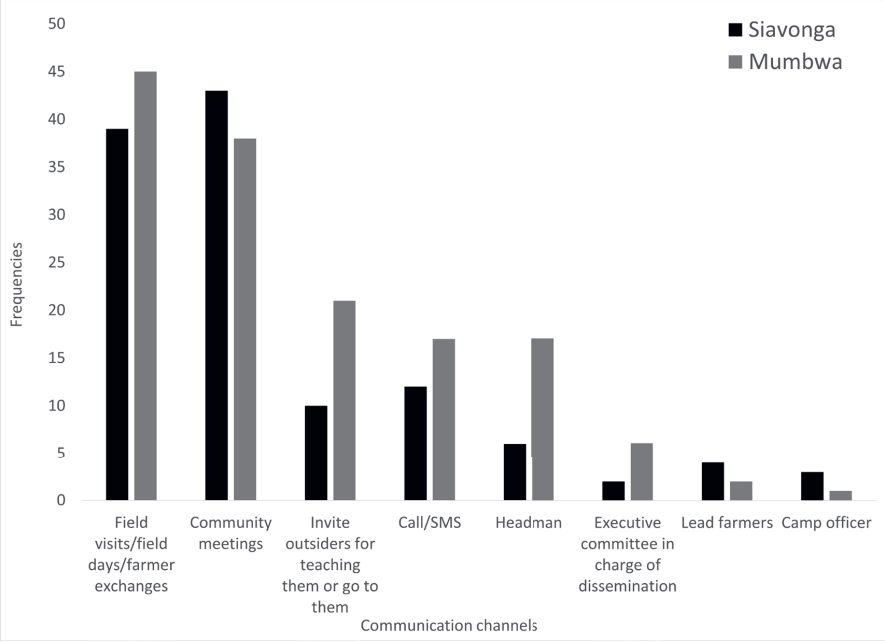


Figure 3. Frequencies on preferences for communication channels with its members and outsiders on the collective action to manage FAW by district.

Limiting factors for operationalizing the collective action

According to respondents, the main factors limiting the community in coordinating actions for FAW management were: lack of knowledge on how to coordinate such management (non-participants were not aware that it was an option compared to field-by-field management), lack of finances, poor coordination among farmers, lack of coordination from authorities, and inconsistent climatic patterns. Additional reasons included lack of seeds (other than maize), discouragement from fellow farmers, lack of trust among farmers, lack of willingness, and resistance to change (Figure 5).

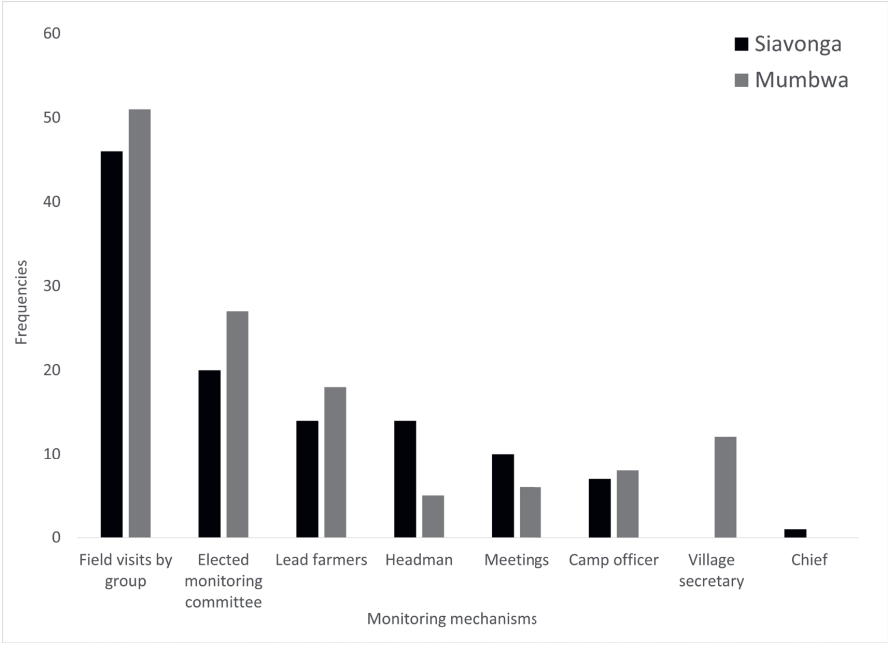


Figure 4. Frequencies on preferences for mechanisms to monitor the resources and users of the collective action managing FAW by district.

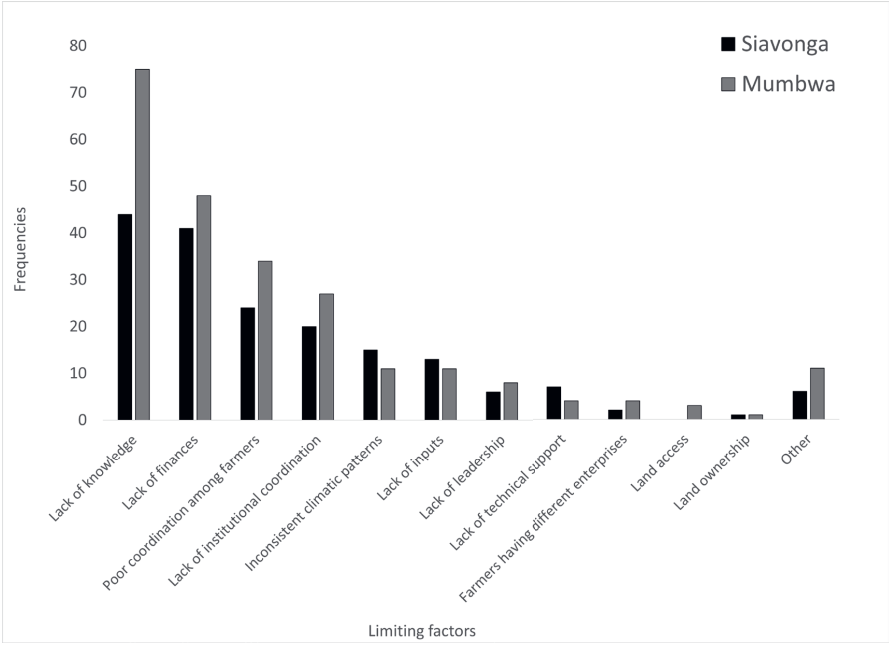


Figure 5. Frequencies of factors limiting the community to coordinate actions for FAW management by district.

Long-term pest management

The probit regression showed that assets index, HDDS and chemical insecticide usage significantly affect the long-term planning of pest management (Table 5). Respondents that are food secure, wealthier and use chemical insecticides plan ahead to manage pests. When asked if they plan for pest management, 35% of farmers from both districts answered that they do plan ahead compared to being reactive (Table 6). Approximately 25% of respondents from both districts said that they plan ahead 1 to 3 months for pest management.

Table 5. Probit regression on factors affecting long-term planning for pest management.

Explanatory variables	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
Gender	0.103	0.231	0.45	0.654	-0.349	0.556	ns
Age	0.002	0.006	0.37	0.709	-0.01	0.015	ns
Level of education	0.018	0.152	0.12	0.905	-0.281	0.317	ns
District	0.351	0.247	1.42	0.156	-0.134	0.836	ns
Land title	0.341	0.657	0.52	0.603	-0.946	1.629	ns
Total land size cultivated (ha)	-0.05	0.034	-1.47	0.142	-0.116	0.017	ns
HDDS	0.128	0.061	2.10	0.035	0.009	0.248	**
Pesticides usage	0.487	0.21	2.32	0.02	0.076	0.898	**
Assets index	0.153	0.058	2.63	0.009	0.039	0.266	***
Constant	-1.608	0.815	-1.97	0.049	-3.205	-0.01	**
Mean dependent var		0.418	SD dependent var			0.494	
Pseudo r-squared		0.115	Number of obs			213	
Chi-square		33.268	Prob > chi2			0.000	
Akaike crit. (AIC)		276.235	Bayesian crit. (BIC)			309.848	

** p<0.1, ** p<0.05, *** p<0.01, ns=not significant*

Table 6. Proportion of respondents planning ahead for pest management.

Pest management	**Siavonga**	**Mumbwa**
Proportion of respondents planning for pest management compared to being reactive	38% (37/98)	43% (49/115)
Proportion of respondents planning ahead	35% (34/98)	35% (40/115)
How far ahead?		
1- End of rainy season/harvest	5% (5/98)	10 % (12/115)
2- 1-3 months before rains	25% (25/98)	23% (27/115)
3- At the onset of the rainy season	4% (4/98)	0.9% (1/115)

Limiting factors for long-term pest management

In both Mumbwa and Siavonga, insufficient income was the first limiting factor to planning for long-term pest management. Farmers explained was that if a pest doesn't appear that year, then they save money on chemical insecticides and the funds available can be reallocated to other priorities. As farmers don't know which pest will attack the crop after planting, they prefer to wait to buy the right chemical insecticide. The other main constraints to planning pest management included lack of knowledge, inconsistent climatic patterns and being reactive (believing it is not necessary to plan) (Figure 6).

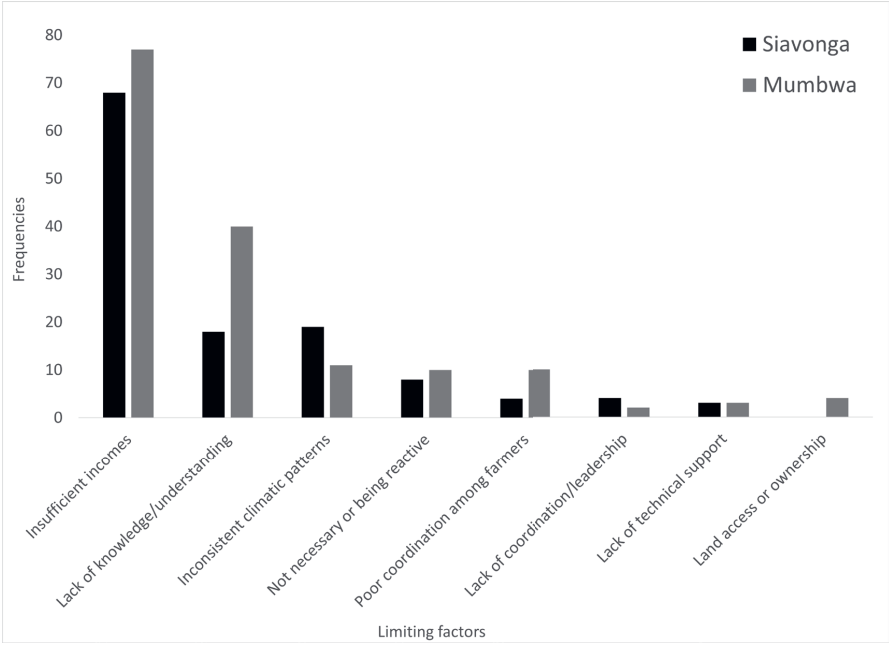


Figure 6. Frequencies of factors limiting long-term planning for pest management.

DISCUSSION

Collective pest management promises great potential for farming communities to tackle serious plant health threats including insect pests, diseases and weeds (Epanchin-Niell et al., 2010; Garcia-Figuera et al., 2021; Graham et al., 2019; Marshall et al., 2016; Stallman & James, 2015). However, while farmers can have good knowledge on the pest biology and ecology, lack of awareness, understanding and support on how to coordinate efforts amongst farmers can impede efficient and effective collective action. Our study showed that communities already have local knowledge on pests and that the project improved knowledge on concepts such as biocontrol and natural enemies. Furthermore, we found high levels of willingness to collectively implement cultural practices such as intercropping for FAW management. However, several factors are limiting the implementation of intercropping such as lack of knowledge on conservation biocontrol, lack of inputs and financial resources. Farming communities had a common vision of how they would like to operationalize collective action principles with only small differences between districts. The main limiting factors for implementing a collective action on FAW management were lack of knowledge, lack of financial resources and lack of coordination. Understanding of planning for pest management was limited to the purchase of chemical insecticides, and the lack of knowledge of other types of pest management are major hindrances to long-term and sustainable pest management.

Ecological knowledge and social differentiation

Although the intervention was conducted over a short period of time between 2019 and 2022, project participants clearly had better understanding of biocontrol and natural enemy concepts compared to non-participants. Indeed, description of the biocontrol concept, type of natural enemies of FAW and explanation of how these natural enemies kill FAW from project participants better matched scientific knowledge compared to non-participants. Some explanations of biocontrol from project participants include: "Management where insects eat fellow insects and reduce them in number" and "This is when the natural enemies like ants and flies and other insects attack the FAW". Many project participants mentioned wasps and flies referring to hymenopteran and dipteran parasitoids attacking FAW (Durocher-Granger et al., 2021), which was consistent with the feedback loop meetings when scientists presented the various parasitoids species to the communities. Project participants explained in their own words how parasitoids kill FAW showing a good understanding of the concept: "They lay eggs in armyworms then hatch other insects" or "They impregnant the FAW and produce other insects". Some non-participants of the project also had previous knowledge of these concepts which was primarily associated with training from local NGOs and cotton companies on conservation farming and judicious use of chemical insecticides. These farmers explained predatory behaviours of the ladybug beetles on aphids in cotton fields as a basic concept of biocontrol, or predatory wasps and ants taking away the FAW from the maize whorls. The difference in knowledge between participants and non-participants is notable as non-participant's knowledge was mainly limited to observations in their fields of abundant and noticeable natural enemies such as wasps, ants and ladybug beetles. While project participants explained parasitoids life cycle which is a more cryptic process not easily observable. This was also observed by Wyckhuys and O'Neil (2007) with Honduran smallholder farmers on IPM training.

However, the knowledge of FAW caterpillar and life cycle was not influenced by the intervention. Farmers already had basic knowledge on FAW biology due to awareness training and mass campaign by the Ministry of Agriculture since FAWs detection in Zambia in 2016. Additionally, FAW caterpillar was correctly identified against other lepidopterous pests by 54% of the women respondents regardless of participation in the project. This ecological knowledge was mainly based on their own experience and existing local knowledge in the community. In the communities involved in the project, we observed a feminization of agriculture where women are now leading the majority of farming activities, apart from land preparation and chemical spraying. This is because men need to seek off-farm incomes due to low farm productivity. Most farmers actively participating in the project after the inception meetings in August 2019 were women. Therefore, developing collective pest management programmes would need to be tailored to women's needs and time considering their growing contribution and responsibilities in agricultural production. For example, trainings would need to happen at convenient times and locations for women with consideration of their domestic chores and childcare responsibilities. Also, considering women's low access to extension services, inputs and

markets, biocontrol programmes would require initial incentives by providing seeds and linkage to markets for intercrops as well as regular technical support. Additionally, older farmers had better knowledge on the biocontrol concept, FAW lifecycle and caterpillar identification. Again, these outcomes are reflecting the socio-economic context of the communities as youths rarely have land allocated to them for farming and consequently are less involved in agricultural training and meetings.

An interesting finding was that food insecure farmers scored better in sorting the FAW life cycle from eggs to moth. From a smallholder farmer's perspective, if subsistence agriculture is the only means for food security, understanding the pest biology and its management is critical. In general, communities in Siavonga are more food insecure as crops fail regularly due to poor rainfall and high infestation of pests. Land preparation and planting are predominantly manual with little to no chemical inputs reflecting the low crop productivity and incomes generated by agriculture in the region. Therefore, farmers in Siavonga scoring better with the FAW lifecycle reflects the fact that smallholder farmers in the region are highly affected by FAW infestations and depend on the survival of their crops as subsistence food. These findings suggest not only that our project intervention improved ecological knowledge, but also that social differences related to gender, access to land, age and levels of food insecurity play a role in shaping such knowledge and understanding. Farmers, being active and heterogeneous receivers of technology, have different experiences, knowledge and needs which should be considered in training and extension programmes (Leeuwis, 2004).

The need to re-think training and extension activities

High levels of willingness to collaborate on pest management, collaborative attitude and trust were found amongst farming communities. This willingness was also found in a study in Missouri (USA) where 91% of farmers were willing to cooperate if simple and local efforts were coordinated (Stallman & James, 2015). However, the main limiting factor for implementation by the communities in Zambia was the lack of knowledge on crop diversification, such as intercropping, and collective pest management. Additionally, the various limiting factors (labour intensive, incompatibility with current practices, complexity and negative perceptions) mentioned by farmers raise some concerns regarding the willingness to implement cultural practices collectively. Farmers may have given socially desirable answers to questions about their willingness in the expectation that they could benefit from input provision at a later stage, or in order to call for institutional support. Our study highlights that knowledge on collective pest management is lacking from farmers compared to ecological knowledge. Although we did not interview key informants, our understanding of Zambia's current agricultural extension system suggests that most extension officers are unfamiliar with concepts like area-wide pest management and collective pest management. The extension system in Africa is predominantly responding to individual (or household) demands or to a specific problem affecting all farmers equally in an area such as FAW (Leeuwis, 2004; Msuya et al., 2017). Collective pest management is still far from being promoted by extension officers and implemented by farmers compared to conventional

practices and a reform at institutional level of the extension system would be needed to shift perceptions and behaviours to sustainably manage invasive species (Cieslik et al., 2021; Dormon et al., 2007; Msuya et al., 2017).

Boundaries, local conditions and leadership

Not all Design Principles apply to every pest management situation, and our research highlights that clearly defined boundaries (DP1) and congruence between rules and local conditions (DP2) would be critical principles in the design and implementation of biocontrol programmes for farming communities in rural Zambia. Farmers showed understanding of the technical concept of interdependency and the problem with field-by-field management leading to reinvasion of mobile pests. Indeed, the majority said that the social and physical boundaries must be farms adjacent to each other for more efficient and effective control of FAW, rather than by houses as farms are often located a few kilometres away from the houses. Furthermore, both rural farming communities expressed strong preferences for their traditional leaders to be coordinators of the group and safekeepers of the agreed rules. However, responsibilities in Mumbwa were often given to the lead farmers, elected executive committee or the village secretary. This difference is observed due to the high number of organized farmers' groups such as cooperatives and clubs in Mumbwa compared to Siavonga. Collective action relies strongly on social capital meaning trust, reciprocity and social cohesion (Barnaud & Muradian, 2024). A collective action for FAW management would therefore need to consider the local conditions, existing relationships and established social institutions to ensure social cohesion and trust amongst groups. Furthermore, as rural communities may be formed of thousands of farmers owning less than two hectares of land, strong leadership and communication from either traditional or elected leaders would be critical in achieving control of the pest. Indeed, externally led and funded collective action to control invasive species rarely persist once programmes end (Graham et al., 2019).

Trust building mechanisms

Mechanisms to build trust such as community meetings, monitoring, and sanctions are essential in a system that aims at reducing the impact of public-bads on communities. Community meetings were the preferred mechanism to agree on collective rules, and offer a platform to strengthen trust, relationships and communication amongst the participants as rules can be decided and voted through a transparent process. Furthermore, through regular face-to-face meetings, the community members can share local knowledge based on their observations from the field. These regular feedback meetings can consequently support the modification of the rules as needs be (collective-choice arrangements). As members decided to monitor the resource and users (efficacy/performance of the new practices, adherence to the rules and the FAW infestation) as a group through field visits or by an elected monitoring committee, this will increase trust and cohesion amongst members. Once again, collective action is crucial in pest management, as a lack of crop monitoring by farmers can result in complete

yield loss in areas with severe FAW infestations. Graduated sanctions are critical in a collective action to build trust amongst the members showing that rules will be enforced. Communities mentioned warnings such as enforcement by the headman, penalty fees and stricter consequences such as removal from the group. Removal from the group would not contribute to better FAW management as the individual would not comply anymore with the agreed rules and his/her field may become a breeding source for reinvasion. Therefore, the collective action should emphasize on enforcement and penalty fees as other participants would witness effects of breaching the rules resulting in increasing the trust in the system (Kruger, 2016; Tafesse et al., 2020). There is already a high degree of trust within the communities that fellow farmers will adhere to the rules and the implementation of a collective action to control FAW. Indeed, a sustainable system for collective action relies on relationships, trust and communications (Cieslik et al., 2021; Galarza-Villamar et al., 2024), and these attributes are critical in the case of pest management and biological control as mobile insect pests and natural enemies are not restricted to individual fields.

The need for institutional change

While the preferences from both districts on operationalization of the collective action principles provide an essential foundation, it is also important to understand the limitations and obstacles that could hinder an efficient FAW management system based on coordinated and collaborative efforts. Both districts consistently mentioned the same limitations regarding coordinating FAW management with the predominant factor being the lack of knowledge on how to coordinate such actions. The lack of financial resources was mainly related to the purchase of seeds for intercropping such as legumes which is specific to the intervention on conservation biocontrol practices. To implement a well-managed pest management system, substantial changes need to happen at various scales from institutional to regional and local levels (Allen & Horn, 2009). A complete reform is needed regarding how agricultural extension is delivered in order to eradicate in good time or to manage highly mobile and invasive species. Institutions such as governmental agencies need to develop strategies and policies to be coordinated at regional levels (e.g. district offices) for actions to be implemented at local levels involving extension officers and farming communities or cooperatives. Furthermore, university curriculums for extensionists would need to be adapted to shift mindset on collective pest management systems (Msuya et al., 2017).

Fostering a preventive planning culture

The intervention implemented in the wider research on conservation biocontrol was based on the extension services system that is currently organized and delivered. As a result of the curative and individual farm household extension system, our study highlighted that pest management in the studied communities strongly revolves around chemical insecticides. Planning is currently focused on chemical insecticides for farmers and possibly also for extension officers. If farmers plan ahead, it is mainly to

buy chemical inputs in advance pointing to the high dependency on chemical control as the sole management option. Pest management is more reactive and curative than preventive, which was also a behaviour observed in smallholder farmers communities in Honduras two decades ago (Wyckhuys & O'Neil, 2007). For resource-poor farmers, planning and buying ahead can be risky and inputs bought can be wasted in case they are not needed, or if the wrong product is bought. Furthermore, our findings clearly demonstrate that poverty and food insecurity impede the planning of pest management. This finding highlights the importance of selecting carefully where and how biocontrol programmes should be implemented first as pest management will not be a priority if communities are food insecure. Collective action needs very different kinds of planning and relationships relying on long-term planning amongst strategic stakeholders (Allen & Horn, 2009) which is particularly important for invasive species management.

CONCLUSION

Collective pest management such as through conservation biocontrol practices promises great potential to smallholder farmers in low- and medium-income countries. However, some persisting challenges impede its implementation such as economic pressure and lack of knowledge and support on how to coordinate actions amongst farmers and how to sustain a monitoring system. Pest management interacts within a complex social, technical and ecological system; therefore, it is essential to build an adaptable systems approach based on farmers' experiences and local conditions as pest management is complex and constantly evolving (Allen & Horn, 2009). Close collaboration with local traditional leaders such as influential elders would be critical to ensure that communities self-organize and sustain a collective action (Ostrom, 2009). While project interventions can increase ecological knowledge of a subset of a population, such training needs to be embedded in the national agenda to scale up its outreach to most of the farming population. This is an important step so that all farmers can understand their interdependency linked to the biology of the invasive species. To be able to achieve this goal, more needs to be done to develop strategies and policies at national levels including a shift in curriculums for extensionists. As farming communities are willing to cooperate for collective pest management, there is a momentum to strengthen and leverage the existing social structures. Indeed, community-based efforts can be linked through multi-level coordination with regional pest management programmes and national agricultural policies.

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7 General discussion

Prelude

My research project was implemented as part of larger global programmes led by CABI on invasive species management and biocontrol research. The two programmes, being Action on Invasives (2018-2020) and PlantwisePlus (since 2021), have focused on pest prevention, preparedness and pesticide risk reduction. Zambia was chosen as a focus country to implement activities and support the government to strengthen national capacity in preventing and managing invasive species. In line with these global programmes, the two leading objectives of my thesis were to 1) identify local natural enemies attacking fall armyworm in Zambia and evaluate the factors contributing to enhancing their populations, and 2) understand the factors influencing collective action within farming communities to collectively develop pest management methods through biocontrol practices. My main research questions were: 1) Which local parasitoid species are successfully attacking fall armyworm in Zambia and what factors affect their occurrence? 2) Which social conditions affect the effectiveness, maintenance and sustainability of a collective action at community level for implementation of biocontrol? 3) How can planting dates be an effective IPM tool to reduce FAW incidence and maximize conservation of natural enemies? 4) Which local companion crops best promote natural enemy populations and reduce fall armyworm populations? and 5) What factors shape the willingness of communities to collaborate for pest management and what are the prospects for collective action? In this last chapter, I will address the research questions, summarize my research and provide wider perspectives on the findings. I also suggest how the research can contribute to supporting national policies and future research which could continue contributing to the knowledge gaps on collective management of invasive species.

The five empirical chapters presented in this study, bringing entomology and social sciences together, propose a new approach by leveraging community-based and collective efforts rather than individual field-by-field reactive pest management using chemical inputs to achieve the common goal of fighting invasives species. While fall armyworm (FAW), *Spodoptera frugiperda* (JE Smith) (Lepidoptera: Noctuidae), was the species targeted in my research, my thesis focused on a community-based approach in managing a highly mobile invasive pest. FAW, being a devastating insect pest of maize and other staple crops in Africa and Asia, because FAW will not be the last threat from an invasive pest that farmers face. While fundamental research by scientists is critical to fully understand new invasive species biology, ecology and management methods in the newly invaded area, rural communities cannot wait for researchers to find solutions. For example, classical biological control which identifies, imports and releases exotic natural enemies from the country of origin of the pest is a very effective tool in managing invasive species but is also a lengthy multi-year process of extensive research, testing and regulatory review due to international and national regulations before a biocontrol agent is approved for release (Sheppard et al., 2019). Hence, farming communities need to become more resilient when new plant health problems arise by experimenting and developing their own solutions using local resources while classical biocontrol is studied. This type of resilience can be

supported by research, such as the research describes in this thesis. Considering the gaps and challenges in managing invasive species, my main goal was to identify which farming practices farmers can easily implement collectively to enhance local natural enemies aiming at reducing the pest pressure and need for synthetic pesticides. Therefore, my thesis contributes to further understand how the provision of natural pest control services can be enhanced locally and collectively for a common benefit.

The first step of my research required a good understanding of the local species of natural enemies attacking FAW which then directed the development of biocontrol strategies to test with farmers. The high diversity of larval parasitoid species found from the initial survey, presented in Chapter 2 (12 species of egg-larval, larval and pupal parasitoids), laid the foundation for the prospect of enhancing their populations through conservation biocontrol. Once I had knowledge of the potential to increase natural enemies' efficiency in the field, I addressed the social and institutional conditions needed to create an efficient and sustainable collective action promoting biocontrol of FAW among smallholder farmers (Chapter 3). After identifying the opportunities and existing conditions on the basis of the Collective Action Theory that can be transferred and applied to pest management, I also identified the gaps and areas that need to be strengthened for effective management of invasive species. Through field observations, results from Chapter 2 on FAW density and lack of empirical data in Africa on the commonly recommended cultural method of planting early to avoid peak infestation of FAW, I decided to conduct field trials to validate the recommendation (Chapter 4). The testing of early, intermediate and late planting of maize confirmed a build-up of FAW population through the rainy season but also revealed a slow start of the activity of parasitoids in the fields most likely caused by a diapause triggered by a decrease in humidity during the dry season. Following inception meetings and discussions with farmers on the main crops grown for either subsistence or the market, a selection of crops was jointly selected with farmers for testing their potential in repelling FAW and attracting parasitoids, as well as testing their compatibility with other farming techniques in maize fields. While the effects of these companion crops tested on-station in reducing FAW density are not clear, some associations were found between companion crops and parasitoid activity (Chapter 5). Simultaneously, farmers involved in the project tested and validated the preferred crop combinations and design for their agricultural context, experimenting and providing feedback to the farming communities and the team of researchers. Therefore, to be able to assess the potential for conservation biocontrol to be adopted and scaled up across a farming community, I evaluated the intervention co-designed with farming villages (Chapter 6) and provided insights into how pest management can be collectively implemented as a community-based approach. In this last chapter, I summarize and synthesize key findings from the five empirical chapters and discuss the implications of the research on pest management for smallholder farmers and policies at local, regional and national levels. I also align the theory of collective action to pest management and suggest how this can be implemented with farming communities. Then, I reflect on the limitations of my research and conclude on the study's main lessons.

Building on local biodiversity and ecological context

Diversity of native parasitoid species

FAW being an invasive alien species (IAS), there was little expectation to find suitable parasitoid species attacking and developing successfully on FAW in Zambia. However, as other native Noctuidae species and specifically *Spodoptera* species, such as *S. exempta*, *S. littoralis* and *S. exigua,* are found in Zambia (Fiaboe et al., 2017; Merrett, 1986; Yu et al., 2005), 14 parasitoid species were recovered from FAW eggs, larvae and pupae only through this research (Chapters 2, 4 and 5). These local species include two egg parasitoids, two egg-larval parasitoids, nine larval species and one larval-pupal species. Simultaneous research across all the agroecological zones found at least two additional parasitoid species (*Tiphia* sp. and *Micromeriella* sp.) (Chipabika et al., 2023). These two egg parasitoids, which are *Telenomus remus* and *Trichogramma mwanzai*, were confirmed through morphological and molecular identifications as parasitoids developing successfully in FAW eggs. These occurrences being minimal and not consistent between the rainy seasons make it difficult to elaborate a programme on conservation biocontrol targeting FAW egg masses. However, egg-larval and larval parasitoids showing high abundance such as *Chelonus curvimaculatus*, *Chelonus bifoveolatus*, *Coccygidium luteum* and *Pristomerus* sp. have potential to be promoted and enhanced through conservation biocontrol mainly in areas managed with no or low chemical pesticide inputs. It also became apparent that no information was available on the biology of these native parasitoids before the invasion of FAW.

Temporal complementarity and functional diversity

This research helped filling a knowledge gap on the biotic and abiotic factors influencing abundance and diversity of native parasitoid species in Zambia (Chapters 2 and 5). Parasitoids continuously explore their environment using visual, olfactory and gustatory cues to maximize their fitness and the fitness of their progeny, known as foraging behaviour (Fellowes et al., 2023). While the presence of FAW larval stages was an obvious factor influencing their occurrence as each parasitoid species is specifically adapted to one (e.g. eggs) or a few pest stages (e.g. first and second larval instars) (Godfray 1994), this research elucidates which parasitoid species first colonized the maize field, and which ones target the first larval instars providing crucial information for selecting species as biocontrol agents. *Cotesia icipe*, *Euplectrus laphygmae* and *Parapanteles* sp. are the first species to colonize the field targeting L1 instars during the first three weeks after sowing maize seeds. However, their abundances are low and decrease following these first three weeks limiting their ability to control FAW through the maize crop cycle (Chapters 2 and 5). Parasitoids attacking early larval instars would be more effective in controlling FAW to limit maize damage before the larvae reach the late instars, which inflict the most damage to maize. Following these three weeks, *C. luteum* and *Pristomerus* sp. increase in abundance until *Drino quadrizonula* become the dominant species attacking late larval instars at late vegetative stages of the maize (Chapters 2 and 5). *Chelonus curvimaculatus* is the predominant egg-

larval parasitoid during early vegetative stages while *Ch. bifoveolatus*' abundance gradually increases from late vegetative stages to reproductive stages of maize (Chapter 5). These patterns in abundance and diversity were observed consistently every rainy season showing temporal complementarity between species, meaning that parasitoid species use host resources at different stages or generations (Macfadyen et al., 2011; Jervis et al., 2023b).

However, this large number of parasitoid species found attacking FAW does not necessarily mean better pest control as the majority of species are larval parasitoids attacking L1-L4 stages (same functional group) and most likely complement each other across time. Nevertheless, higher parasitoid species richness has been associated with more stable and less variable parasitism rate over time in case of environmental change (Macfadyen et al., 2011). Interspecific competition would need to be investigated in both laboratory and field settings to further understand the type of interactions (null, additive, antagonistic or synergistic) among species of a natural enemy community (Jervis et al., 2023b). For example, *Charops* sp., *Diadegma* sp., *Metopius discolor* and *Enicospilus capensis* were found only once or twice during this research; however, *Charops* is one of the most common genera in Kenya, Tanzania and Ghana attacking FAW larvae (Sisay et al., 2019; Abang et al., 2021) pointing to different functional diversity and interspecific interactions across various agroecological systems. Functional diversity in relation to temporal complementarity would be an important topic to further investigate considering the large numbers of generalist parasitoids attacking FAW in Zambia and to understand how this helps maintaining the provision of natural pest control services, especially in the case of climatic shocks. This information is also critical for the reconstruction of the community of natural enemies following the release of exotic natural enemies under classical biocontrol programmes (Jervis et al., 2023b).

Early planting as an effective IPM tool

Highly polyphagous pests like FAW can maintain local populations on wild grasses and other crops until the main food source is available again (Day et al., 2017). These alternative hosts can serve as a refuge during the long dry season in Zambia. At the onset of the rains, these local populations most likely move on to the widely available maize across the country. While a lot is still presumed in Africa about FAW migrations and overwintering patterns, my thesis research confirmed that planting early helps avoiding a high peak of adult moths' activity later in the season (Chapter 4). Farmers who plant late take the risk of higher FAW infestation. However, early planting resulted in very low parasitism rates compared to intermediate and late planting, suggesting a probable humidity-induced diapause triggered by a drastic decrease in humidity. Natural enemies appear to build up their populations slowly at the onset of the rains delaying the natural pest control of FAW infestations. This finding of my research is critical mainly for conservation biocontrol programmes aiming at boosting the populations and therefore the efficacy of the natural enemies to control the pest. For example, conservation biological control programmes could investigate maintaining some parasitoid species which do not

enter diapause during the off-season either on FAW or native hosts during the dry season. These conservation efforts could help enhancing their populations and therefore parasitism of FAW as soon as the rainy season starts where FAW is the most active. Nonetheless, early planting should be emphasized with farmers as an effective and free IPM tool. The research on planting dates also revealed that no information is available about regional migrations in the Southern Africa region and on behaviours of resident populations of FAW during the dry season. To develop comprehensive area-wide strategies to control FAW at regional levels, studies on the migration patterns and resident populations are still needed to fill this knowledge gap (Nagoshi et al., 2018; Nagoshi et al., 2022).

Intercropping research requires further investigation

Despite that our study was not conclusive on which local companion crops best promote natural enemies while reducing FAW populations, my research still provides valuable insights into tri-trophic interactions looking into the dynamics between the infested crop (maize and sorghum), FAW and the native parasitoid species (Chapter 5). It also points towards which crops and parasitoid species combinations need more investigation and could potentially be used in conservation biocontrol of FAW in Zambia. Although sunflower-maize intercropping did not show a decrease in FAW density or overall higher parasitism rate, the intercropping combination showed strong association with *Pristomerus* sp. parasitoids. The same was observed with sorghum plants and *Ch. curvimaculatus*. Therefore, future studies could investigate how *Ch. curvimaculatus,* being an egg-parasitoid and showing colonization of maize fields during the early vegetative stages (Chapters 2 and 5), could be enhanced early at the onset of the rains in sorghum crops with tailored companion plants. Better understanding of the associations between indigenous crops and native parasitoids could help support programmes on conservation biocontrol by targeting specific parasitoid species at the right time in the crop cycle (Landis et al., 2000; Midega et al., 2005; Midega et al., 2009).

While the current research did not look directly at the effects of herbivore-induced plant volatiles (HIPVs) on FAW infestation or parasitoid attraction, the results suggest that HIPVs may play a role in pest suppression (Chapters 2 and 4). HIPVs are well known for their critical role in alerting parasitoids when a plant is under herbivore attack (Turlings & Erb, 2018). In Chapters 2 and 4, we demonstrated that maize growth stages strongly influence the occurrence of parasitoids with higher abundance and diversity during vegetative stages than reproductive stages. It has been shown in some tri-trophic systems that younger leaves are more attractive than older leaves to natural enemies once infested by pests (Takabayashi et al., 1994; Kennedy, 2003). Alongside maize, further research would be critical in understanding the response of local parasitoids to HIPVs of indigenous crops such as sorghum and millet and if HIPVs play a role in these systems. And if so, do local parasitoids show a stronger response to HIPVs emitted by local native crops compared to commercial crops?

During the feedback loop meetings hosted between the researchers and the farmers, the latter expressed the preference of planting sunflowers as a border row around the maize, and cowpeas as

intercrop between rows after the first weeding (about one month after planting maize seeds). This preference was confirmed after three rainy seasons of trial-and-error for many practical reasons from the farmers. First, lower infestation was observed when intercropping with sunflowers and cowpeas. Secondly, this method was fitting better with their traditional technique of planting and weeding maize using oxen and hoes. Lastly, in drought-prone areas with degraded soils of Zambia cowpea is already used as an intercrop in maize system for moisture retention and nitrogen fixation. Furthermore, cowpea is consumed as a legume but also as a green leafy vegetable, while sunflower is processed for oil. This preference of farmers emerging from my interdisciplinary research supports the opinions that scientific knowledge needs to be co-designed and validated by farming communities in terms of adaptability and feasibility (Leeuwis, 2004; Kruger, 2016). When adapted locally and co-designed with farmers, innovation has greater potential for adoption and to solve local problems (Nicholls and Altieri, 2004).

Pest management as a collective action problem

With increased rates of new bioinvasions driven by the intensification of global trade and climate change (Early et al., 2016, Paini et al., 2016, Pratt et al., 2017), it is becoming clear that pest management needs to be rethought into a collective perspective. Invasive species pose collective action problems with their transcending nature of crossing farm boundaries affecting farming communities and entire regions (Graham et al., 2019) such as in the case of FAW invasion. Aligning the Collective Action Theory (Ostrom, 1990) to pest management involves understanding how farmers, communities, stakeholders, and local, regional and national governments can cooperate to solve a shared problem - in this case, pest management - especially when the benefits are non-excludable (everyone gains from a low pest population) and non-rivalrous (one person's gain doesn't reduce another's).

As confirmed in Chapter 3, it is critical to examine how individuals already coordinate actions and collaborate to achieve a common goal, particularly when individual incentives may not align with group benefits. This first phase should investigate collective actions beyond pest management which will inform on the existing social structures and institutions that can be leveraged for control of the invasive species (Chapters 3). In pest management, one farmer’s inaction can lead to pest resurgence in others' fields or the overuse of (subsidized) pesticides by large number of farmers can lead to resistance or harm to beneficial insects in farms managed under biological control programmes (Babendreier et al., 2019; Hendrichs et al., 2007; Epanchin-Niell et al., 2010; Kruger, 2016). Furthermore, social dilemmas can arise and need to be managed by the group (Ostrom, 1990) such as free-riders problem where individuals benefit from the collective action without contributing, or when tension results from short-term individual benefits (e.g. subsidized or free farming inputs) rather than long-term collective benefits emerging from the invasive species prevention and control. To reduce the risks of these social dilemmas, social norms and trust help sustain cooperation while institutions and rules guide and enforce participation in the collective action, alongside incentives and sanctions (economic, social or regulatory) which support the adherence to the agreed rules (Chapters 3 and 6).

Building on existing social capital

As presented in Chapters 3 and 6, farming communities already have conducive social structures and institutions in place, following Ostrom's eight Design Principles, to leverage an effective collective action for pest management. Although, my research concurring with similar studies found that not all Design Principles can be applicable to the management of invasive species (Kruger, 2016; Graham et al., 2019; Garcia-Figuera et al. 2021). The relevance of each Design Principle may vary depending on the pest biology and ecology, and cultural context of farming communities. Nevertheless, while the Collective Action Theory was not designed for pest management, it is still very relevant and adaptable. In Chapter 3, when investigating the feasibility of a collective action to manage FAW, matching rules to local conditions (DP2), collective-choice arrangement (DP3), conflict-resolution mechanism (DP6) and minimal recognition of rights to organize (DP7) were conditions in place and conducive for the creation of a collective action. Whereas the monitoring system (the resource and users) (DP4) and graduated sanctions (DP5) were found weaker. Interestingly, when assessing the intervention of the project in Chapter 6 with the same communities, clearly defined boundaries (DP1), monitoring system (DP4) and graduated sanctions (DP5) gained importance as leading principles. This observed change could be a result of continued exchanges through feedback loop meetings and analyses between the farming communities and the research team jointly refining the concepts and principles for the implementation of collective efforts in managing FAW and consequently learning which Design Principles are of higher importance for this precise situation.

In Chapter 6, I also highlighted the necessity to carefully select where, when and how such interventions are best implemented. Indeed, my research demonstrated that resource-poor and food-insecure farmers do not prioritize planning for pest management and are predominantly inclined to reactive interventions using chemical insecticides. Therefore, I suggest that programmes either beforehand or in parallel address social issues around poverty and food insecurity for farming communities to be in a good position to prevent and manage pests, especially when new invasive alien species are first detected. This can prevent situations such as the one observed in one of the communities that we worked with, which had consumed the cowpea seeds provided by the project that were meant as a resource for the on-farm maize intercropping experiment in order to address their food insecurity.

Local leadership

A critical factor to manage a collective action is strong leadership, regardless of whether the collective action is being coordinated from a top-down or a bottom-up approach. In rural communities such as in Zambia, traditional leadership from the chief and headman/headwomen is highly respected, even from local, regional and national governments (Chapter 3). Traditional leadership can be overlooked nowadays as pest management often focuses on "modern" organizations to reach out to farmers such as cooperatives. However, traditional leaders can have significant impact on pest monitoring and management by mobilizing their communities to scout regularly for plant health

problems, and to pursue community members to adhere to rules and agreements for pest management. This finding came out strongly in both Chapters 3 and 6 as a conducive social/traditional institution that can strongly influence positively a collective action for management of invasive species. While most communities follow traditional leadership which is central for the coordination of any collective decision affecting the whole community, other farming communities are inclined to rely on self-organized committees with elected leaders such as cooperatives or farmers' organizations for pest management (Chapter 3). Therefore, a collective action would need to be tailored to the farming community, especially in a culturally diverse country such as Zambia. This observation from my thesis highlights the fact that a good understanding of the social capital of the communities is a crucial first step as this would be the foundation of how best to approach the collective pest management strategy. Furthermore, local leaders, either traditional or elected, have the authority for setting and maintaining rules agreed between community members and can reinforce them as needed, as well as offering a space for conflict resolution (Chapter 3). While this research and other recent studies on invasive species focused on Ostrom's eight Design Principles (Epanchin-Niell et al., 2010; Stallman and James, 2015; Marshall et al., 2016; Graham et al., 2019; Garcia-Figuera et al., 2021), further studies should also explore the ten factors that affect self-organized collective action (Ostrom, 2009; Graham et al., 2019) which consider social capital requirements in more detail such as leadership.

Prospect for collective pest management

As explained above, the existing social capital lays a strong foundation to develop a sustainable collective action for pest management. The first step in co-creating that collective action would be to align individual interests to a shared goal – e.g. maize farmers wanting to reduce FAW damage in their crop. These established groups or networks offer a space for collective decision making such as deciding on sharing scouting activities in fields and on the type of treatment methods and timing of application/implementation (e.g. early planting, intercropping, rotation strategies, spraying regime of biopesticides, etc.). Additionally, information-sharing networks can establish mechanisms for reinforcing trust and communication such as the creation of physical or digital platforms to report pest outbreaks and monitor the crop and progress on pest control, as well as (non-)compliance to rules from members (Chapter 6).

Just like invasive species, natural enemies also cross physical boundaries freely. Therefore, a joint investment in buying biocontrol agents or inputs to enhance local natural enemies' populations would benefit the whole community in reducing management costs but also discourage counter-productive practices such as reactive applications of chemical insecticides. While governments and NGOs can support and facilitate the early coordination of a collective pest management and supply of biocontrol agents or inputs, farming communities should be at the forefront of implementation. Incentives such as providing cowpea seeds before the cropping season (Chapter 6) or rewards/premium prices for participating in the programme can be provided at the early stages to encourage farmers to

test and validate the management methods for large scale adoption. Besides incentives, regulatory framework can mandate certain practices and impose penalties for non-compliance to deter free-riding behaviours (Chapter 6). In Table 1, I summarize the application of the Collective Action Theory principles to pest management in rural farming communities of LMIC as general guidelines which can be adapted.

Table 1. Application of Collective Action Theory principles to pest management.

Principles	Application in pest management
Shared goals	Reducing the pest population below the economic threshold.
Mutual benefit	Lesser damage resulting in lower expenditure for pest management.
Community-based groups	Building on existing traditional leadership/ cooperatives/clubs and promoting local coordination.
Trust	Use of local champions and/or respected and influential leaders to encourage participation and for monitoring.
Communication	Information sharing networks such as a local groups or digital platform to monitor and report pest outbreaks.
Rules and agreements	Create and agree on local guidelines (e.g. intercropping schemes, crop rotation, release of parasitoids, spraying of biopesticides, trap crops, etc).
Monitoring of the resources and accountability	Monitoring of the crop health and pest levels for adjustments of the rules/agreements, and monitoring of members for compliance to rules.

Implications for national policies

Current situation in Zambia with FAW

Following the initial outbreak of FAW in Zambia in 2016, the Government of the Republic of Zambia adopted emergency measures and spent over 3 million US$ in one year only in the procurement of pesticides, personal protective suits and equipment, early maturing maize varieties and distribution of requisites to various districts of Zambia (Disaster Management and Mitigation Unit, 2017; FAO, 2020). Nine years later during the rainy season of 2024-2025, many medium-scale and commercial farmers as well as seed companies in Zambia reported spraying chemical pesticides 8 to 12 times during the maize growth season to manage FAW (personal communication), well above the maximum of the two recommended applications per crop cycle by the manufacturer. Unfortunately, despite the excessive use of chemical pesticides, this did not result in effective control of the pest and in some instances, total loss of the crop. Additionally, during meetings with smallholder farmers in hotspot regions for FAW, they admitted that they even spray synthetic insecticides on the cobs attacked by FAW raising grave concerns regarding food safety. These examples demonstrate the gravity of the reliance on synthetic pesticides which could lead to a rapid increase in pesticide resistance (Bakker et al., 2020). Nine rainy seasons after the detection of FAW, the situation in Zambia seems to have aggravated rather than being under control, mainly in hotspot regions hit by climate change characterized by low and erratic rainfalls, and high temperatures.

Contribution to national extension manual

Guided by national and international research since 2016 on FAW such as the outcomes from my thesis research, a FAW taskforce was formed with national experts to develop a technical national extension manual entitled "Integrated fall armyworm management in Zambia" (Republic of Zambia - Ministry of Agriculture, 2025). This manual was developed based on scientifically proven, sustainable and available technologies following IPM principles, where recommendations from my research were integrated including early planting and conservation of native parasitoid species. Following the publication and release of the national manual, the government released funds in 2024 to train over 300 extension officers who are expected to train a targeted 1 million maize farmers across the country using the extension manual. Despite the various challenges in managing FAW, the Ministry of Agriculture decided in 2025 to slowly decrease the total amount of synthetic pesticides subsidized to smallholder farmers for FAW control due to concerns raised by farmers, consumers and the government itself on the risk of pesticides to human health and the environment (Republic of Zambia - Ministry of Agriculture, 2025). This decision aligns with the simultaneous training and deployment of the extension manual and priority of the government to promote safer pest control methods. This new strategy from the government highlights the practicality and importance of my interdisciplinary research which has directly contributed to the national extension manual and influenced agricultural policies.

Need to re-orient agricultural extension approaches, policies and curricula

In addition to providing food security, agriculture has been shown in many countries to be a powerful tool to improve the economy and alleviate poverty (De Janvry & Sadoulet, 2010). However, despite the high investment in the agricultural sector in Zambia since independence, maize production remains significantly below its full potential, and rural poverty has aggravated (Zulu et al., 2015). This situation over decades points toward the need to re-orient agricultural investments, extension approaches and policies using (climate-resilient) system approaches. Indeed, the maize-centred agricultural policies, rainfed-dependent agriculture and high reliance on chemical inputs have left farmers vulnerable to climatic shocks and pest outbreaks (Mulenga et al., 2015). In the rainy season of 2023-2024, Zambia has suffered a severe drought and lost half of the maize crops anticipated for harvest, putting the country in an emergency state (reliefweb, 2024). As climate change is increasingly impacting agriculture mainly through reduced rainfall, research on conservation biocontrol integrating drought-tolerant staple crops (i.e., sorghum and millet) can help both reducing dependency on synthetic pesticides and securing harvest in case of erratic rainfall. Indeed, in case of drought crop diversification through intercropping not only can support natural pest control services but also mitigate crop losses by retaining moisture for cereals and provide alternative subsistence food in case of crop failure (Huss et al., 2022).

However, sorghum has being largely abandoned by smallholder farmers both as a subsistence and cash crop due to lack of incentives following years of maize-centred policies (Zulu et al., 2015).

Such initiatives should be supported through subsidized programmes such as the Farmer Input Support Programme (FISP) by enabling an environment which promotes climate-resilient agriculture, safer and sustainable pest management, agricultural growth and poverty reduction. In recent years, the government has gradually increased support to shift policies towards production of legumes to diversify the national crop production such as including soyabeans in FISP which is however not a crop consumed at household level. Additionally, these policies also need to be supported by intentional awareness, training and financial resources to extension officers and farmers for adoption of innovations. Smallholder farmers and the general population of Zambia would benefit if the government reviewed its maize-centred agricultural policies considering the new climatic conditions to better support national food security and strengthen resilience from climatic shocks.

Furthermore, the Government of Zambia could also consider investing in agricultural research and development such as rearing facilities for parasitoids and mass production of entomopathogens for key insect pests. Zambia, having a central location in Southern Africa with eight neighbouring countries, has the potential to create local jobs by investing in infrastructure to produce and distribute biocontrol agents in the Southern African region. Youths who are often unemployed after university graduation due to job scarcity would benefit from employment and contribute to supporting local and national economy. Likewise, academic curricula at universities and colleges currently mainly teach conventional pest management strategies with synthetic pesticides. University graduates employed as agricultural extension officers by the government have rarely heard of biocontrol, and even less of area-wide pest management. The current extension model is based on a one-to-one consultation with individual farmers reporting a problem and following a diagnosis, the farmer is recommended chemical applications for the plant health problem. Thus, there is an urgent need to re-orient the extension approach to be more inclusive and collective if we truly want to reduce dependency on chemical pesticides. More commitment is needed from all stakeholders mainly to intentionally include biocontrol into national policies and the academic curricula.

Limitations of the research

Besides the important insights generated through this research, the study also has certain limitations which are discussed below.

Constraints in human and financial resources for large-scale research

Considering the vast surface area of Zambia and the restrictions in human and financial resources available for the project, my research was conducted near Lusaka. Nevertheless, this constraint allowed me to collect FAW larvae and eggs and field data at a frequent rate (sometimes twice a week in the same fields), allowing more consistent and better data collection over time. Consequently, it is difficult to extrapolate the results to other agroecological regions across Zambia that have different climatic conditions and crops grown. This limitation emphasizes the unrealistic expectation of a one-size-fits-all approach. However, the proximity of the research sites has resulted in the development of

a FAW larval model contributing to programmes and spin-off projects across Africa on FAW early warning systems (Lowry et al., 2022), which is not included in this thesis.

Limitation in sites selection

While Zambia has plenty of natural resources and land available, it was challenging to find suitable fields where pesticides were not applied excessively. Therefore, the sites selected for intercropping did not have any irrigation system and I was relying solely on the rains. Most of the rainy season during the period of my research experienced dry spells or droughts, making it challenging to maintain maize plants and some field trials and data were consequently lost (Chapter 4). Due to the limitation in field selection, the location and sizes of the fields were therefore restrained compelling me to balance between the number of replicates and size of the plots. In some instances, the plot size was limited to five meters with two meters space between plots. These differences were considered in the statistical models, although it also brought complications from a statistical point of view when combining years and sites and to compare and extrapolate results (Chapter 5).

Limited contribution of farming communities in defining the problem

As this research thesis was part of a wider global programme, which had been predetermined with donors on the impact pathways, the farmers had limited inputs in defining the problem (FAW outbreaks on maize). However, the research has been planned in a way that farmers were involved early in the process in co-designing the intervention and were consulted regularly on how to design and implement the intercropping. This participatory approach allowed the farmers to test their own designs and to disseminate their experiences with fellow farmers. Indeed, when visiting the communities during the project, other farmers in proximity of the lead farmers hosting demonstration plots had adapted some of the intercropping designs on their own farms. For example, one farmer had decided to mix maize and sunflower seeds before sowing her fields allowing the sunflowers to grow randomly within the field thus decreasing manual labour to sow sunflowers as border rows.

CONCLUSION

The invasion of FAW into Africa has proven that the management of highly mobile invasive alien species requires actions and collaborations beyond the current conventional extension system which focuses on vertical knowledge transfer from extension officers to individual farmers. This interdisciplinary research has demonstrated that pest management is not just a technical or individual problem - it is a collective action problem. Because pests move across farm boundaries and responses by one actor affect others, managing them effectively requires cooperation. Without coordination, individual actions may be undermined, leading to recurring outbreaks, resistance development, and economic losses. Framing pest management as a collective action problem allows us to design more effective, community-driven, and sustainable strategies.

Furthermore, as research on control practices can take years to be developed and refined for newly IAS, local and available solutions can be implemented in the meantime by farmers to mitigate damage and crop losses. Future research should focus on evaluating simple, small and locally co-designed innovations, such as intercropping with local companion plants or early planting, which can be monitored and evaluated consistently by farming communities for rapid uptake. Fundamental research can also learn from local initiatives and outcomes such as the interactions between the crop, pest and natural enemies as solutions are tested in farming communities. These local initiatives can allow continuous feedback and adjustment between researchers and farming communities having bigger chances of success than working with a one-size-fits-all approach. Consequently, it would be paramount to implement these participatory approaches with communities from a try-and-learn perspective and work with farmers who are willing to test innovations and provide feedback over a few years.

All in all, my thesis research has presented many important findings on the potential of enhancing natural pest control services using local natural enemies to lower IAS populations and what factors influence their abundance and diversity. The findings also filled a gap by creating knowledge and awareness on new ways of managing IAS, specifically promoting biocontrol options to reduce synthetic pesticide usage. One of the main lessons learned is that research also needs to be re-oriented to be more inclusive from the beginning promoting interdisciplinary and transdisciplinary approaches. Collective strategies to pest management, especially using biocontrol, has great potential in reducing global usage of chemical pesticides with the aim of improving environmental and human health, food safety and security, and livelihood.

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Summary

Fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), an insect pest originating from the Americas, has become one of the main invasive alien species (IAS) worldwide since it was first detected in 2016 in Africa, where it causes considerable losses on cereals such as maize, sorghum, rice and sugarcane. IAS disproportionately affect livelihood and food security of smallholder farmers in low- and medium-income countries (LMIC), causing severe negative environmental, economic and social impacts. Following the invasion of FAW, the majority of African governments reacted to the outbreaks by purchasing and providing, for free, massive amounts of synthetic pesticides to smallholder farmers in the hope to mitigate crop losses, raising great concerns for health and environmental risks. These reactive measures resulted in a growing interest in research on biological control options for smallholder farmers. Additionally, when applied individually on a field-by-field basis, synthetic pesticides have little impact on highly mobile insect pests such as FAW, which can travel hundreds of kilometres to find a suitable maize field to oviposit. Integrated pest management (IPM), a comprehensive tool that can help farmers manage pests while reducing the need for synthetic pesticides, is still poorly adopted, especially in LMIC. Proper time of planting, which is part of an IPM approach, is a critical management decision for farmers, as planting too early or too late can lead to complete loss of the crop. Commonly, planting early to avoid peak infestation of FAW is recommended to farmers, however, no empirical data in Africa was available to sustain this advice.

Biological control, a component of IPM, most often used as the last solution to turn to when all other options have failed, has been proven to be an efficient, cost effective and safe method for pest and disease management. Classical biocontrol, a very impactful tool in the management of IAS, can be a lengthy multi-year process when it comes to searching for exotic natural enemies to release in the newly invaded area. Augmentative and conservation biocontrol can be used to mitigate crop damage when local solutions are available, and, when adopted collectively, their effectiveness can increase. Over the past few decades, experts on invasive species and social scientists investigated the role of collective action for invasive species management and found that the principles can be applied and adapted to reduce the damage caused by IAS across a landscape. However, its application is still poorly studied in low- and middle-income countries (LMIC) where national plant health systems in place to prevent and manage biological invasions, are limited. “Collective pest management” can provide benefits over individual field-by-field management, especially for highly mobile pests when consistent and coordinated actions are implemented. Since its invasion in Africa, FAW has quickly established due to widely available small maize fields (< 2ha) individually managed by millions of smallholder farmers. As a highly mobile pest, FAW’s management is complicated and indicates the need for collective action. Conservation biocontrol such as intercropping can offer simple, low-cost and adaptable solutions to smallholder farmers as pest management alternatives to chemical insecticides, which can reduce pest pressure and chemical usage. The research presented in this thesis aimed at identifying which farming practices farmers can easily implement collectively to enhance local natural enemies, with the main goal of reducing pest pressure and need for synthetic pesticides. The geographic focus of my thesis was

located in the maize belt of Central and Lusaka provinces of Zambia where FAW is a major pest problem.

In **chapter 2**, I surveyed the local native parasitoid species successfully attacking FAW and evaluated the factors affecting the occurrence of local natural enemies. During the rainy season of 2018-2019, I collected on a weekly basis FAW eggs and larvae throughout the maize crop cycle at four locations in the Lusaka and Central provinces in Zambia. To evaluate which factors affected parasitoids occurrence, I recorded on a weekly basis the maize growth stage, number of plants checked and level of damage. Egg masses and larvae were brought back to the laboratory and kept with artificial diet until parasitoids or FAW moths emerged. Overall, I identified 12 different egg-larval, larval and larval-pupal parasitoid species with parasitism rates varying between 8% and 33%. Factors influencing parasitoid species occurrence were location, maize growth stage and FAW larval stage. I conclude this first empirical chapter by indicating that there is potential for enhancing local populations of parasitoids that have adopted FAW as a host through conservation biological control programmes in order to develop safe and practical control methods for smallholder farmers.

Chapter 3 studies the feasibility of creating a collective action to promote biological control of FAW among maize smallholder farmers in rural Zambia, and the social and institutional conditions needed for it to be successful and sustainable. I therefore developed a model combining both Ostrom's eight Design Principles for a community-based management of common-pool resources and criteria of an agricultural innovation that meet the community's requirements. The tools developed included questionnaires for focus group discussions and in-depth interviews with smallholder farmers of two maize growing districts. I found that some conditions are already in place to support a collective action to manage FAW, such as matching rules to local conditions, collective-choice arrangement, conflict-resolution mechanism and minimal recognition of rights to organize, which are conditions supported by traditional leadership of the communities. I conclude that while some conditions would still need to be strengthened for a collective pest management to be sustainable, my study is a first step towards co-designing agricultural innovations based on social and ecological conditions.

Chapter 4 reports preliminary effects of planting date and maize growth stages on FAW density and on its local parasitoids from a field study. Early, intermediate and late planting treatments were organized in a complete randomized block design and data on maize growth stage, number of egg masses and larvae were collected weekly in each replicate. Egg masses and larvae were brought back to the laboratory and were fed with artificial diet until parasitoids or FAW moths emerged. The common recommendation of early planting to avoid peak infestation was confirmed as results showed an increase in the number of egg masses over time from early to late planting. Parasitism probabilities were lower in the early planting treatment than for the intermediate and late planting treatments and decreased with increased maize maturity. Parasitoid biodiversity showed dominance by one or two species for early and late whorl stages while maize reproductive stages showed a more even distribution of four species. This preliminary research provided the first empirical evidence that planting early helps to avoid the

peak activities of FAW moths. Additionally, these findings provided important information on parasitoid activities in a country with unimodal rainfalls, contributing to developing conservation strategies for the sustainable management of FAW in Zambia.

Chapter 5 explores the influence of intercropping on natural pest control in agriculture. In this chapter, I focused on investigating the natural resources available for smallholder farmers to maximize pest control by intercropping maize with commonly grown crops. Fieldwork was carried out during the two consecutive rainy seasons of December to March 2019-2020 and 2020-2021, at two sites in the Lusaka province. The five companion crops tested alongside maize control were cowpeas, groundnuts, beans, sorghum and sunflower. To assess the influence of intercropping on FAW density and parasitoids' attractiveness, I collected data in the field, on a weekly basis, on FAW egg masses and larvae numbers, and maize stages. Egg masses and larvae collected from the field were incubated in the laboratory until emergence of adult moths or parasitoids. Despite the lack of a clear trend in the data due to variability in the experimental field design across sites and years, I found associations of the parasitoid *Chelonus curvimaculatus* with sorghum plants, and of *Pristomerus* sp. with sunflower and maize control treatments. I conclude by suggesting that global collaboration is needed to further understand the various components underlying the tri-trophic interactions between maize, native crops, FAW and local native parasitoid species.

Chapter 6 consolidates the entomology and social sciences by assessing the experiences of smallholder farmers with intercropping maize with local companion crops. Specifically, I assessed their experiences in terms of ecological knowledge, willingness and preferences to operationalize collective action principles, long-term pest management and evaluated their limiting factors. Farmers' knowledge of the concept of biocontrol and natural enemies increased following the project intervention. Farmers showed a positive attitude towards a collective action to manage FAW and showed willingness to implement it at the community level. Boundaries, local conditions and leadership were found to be critical to support a collective action. The main factors limiting the implementation of a collective action for FAW management were a lack of knowledge, coordination and support. This study highlighted the knowledge needed and the limitations of the current extension system in promoting collective pest management and suggests a way forward in improving management approaches of highly mobile pests.

Considering all the findings from the five empirical chapters, I consolidated and synthesized in **Chapter 7** the new insights and perspectives created during this interdisciplinary research, integrating the viewpoints of farmers who participated in the co-design, implementation and testing of intercropping practices. I further discussed the implications and influence of my research on national policies and challenge the current agricultural extension system, which focuses on reactive and individual pest management approaches. I also discussed the limitations of my research and concluded by emphasizing the need for new collective pest management approaches to uplift biocontrol programmes.

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Despite the many challenges faced, this learning journey has been rewarding and allowed me to meet so many amazing people sharing the same passions of sustainable crop production and co-

designing solutions with farmers. With some mixed feelings, I can now close this chapter proudly but also a bit nostalgic that it is ending. If one could be a PhD candidate forever, it would definitely be at Wageningen University.

S

Supplementary materials

Belonging to Chapter 3

Appendix 1: Focus Group Discussion questions for farmers

Consent approval after reading the consent statement.
Does you consent to take part in the survey Yes ( ), NO ( )

Selected farmer groups

Date of interview (dd/mm/yy)	
Facilitators	
Province	
District	
Village	
No. of participants	
Group (women, men or youth)	

Trust:

N.B. Try not to mention the world trust to the farmers!

Open questions

1. **Where do you buy agricultural supplies (e.g. seeds, pesticides…)?** *To know if the relationship with agrodealers they have is based on the need (therefore one is good as the other) or on trust.*
    a. **Do you always go to the same agrodealer, or you buy from any? Why?**
2. **To whom do you go if the place where you usually buy your inputs run out? Or who do you ask for advices?** *To understand if there is a (trust) relationship among farmers and agrodealers.*
3. **If a farmer buys the seeds and the pesticides and then ends up with a very low harvest, who do you think he should ask account for that (e.g. agrodealer) if any?** *To understand if they work alone or if they rely on third party.*
4. **If your farm is facing a problem, who do you ask for help?** *To see who do they trust/value as knowledgeable.*

Activity

To understand which features they value as trustable

Instruction for the facilitators:
After telling the story to the participants, first, **brainstorm** with them about the **characteristics** they would look for in deciding if they accept the deal or not.
Look for a word that sum up the examples/characteristics given.
Retrieved these words in the list given below. If some words are not mentioned ask the participants about.

Introduction:
Someone comes to you and promise you to buy your harvest if you now buy his seeds.
We have on this post-it some adjective to describe this person/company. We would like to know which of this characteristic you would value the most in accepting such a deal.

Rules:
Place no more than **4** post-it in each of the 3 circles (circles are position inside each other from bigger to smaller). Circles are based in order of relevance where the inner one is the most relevant.
Participants are allowed to negotiate the meaning of the post-it/add new ones.

NB: they can also rank more than one item in the same position

Words:

1. HONESTY – In proposing the deal, a detailed and clear explanation is given; the quantity of seeds promised matching the reality.
2. COMMITMENT – the development of the work will be checked up; issues will be openly addressed
3. DELIVERY – results are delivered; deadlines are met; they bring a product
4. ACCOUNTABILITY – the person/company take responsibility for his/its actions; brings data assuring a market for the product they sell
5. CAPABILITY – the person/company has tools and financial resources; it is a big company
6. RELIABILITY – good knowledge about farming
7. EXPERIENCE – the person/company has been working in this business for sometimes already
8. MUTUALITY – the person/company has a vision/objective that are similar to yours
9. LOCAL – the person/company come from your same region/country
10. TRANSPARENCY – the person/company's final goal is clear; the person/company speaks openly about the business
11. REPUTATION – the person/company has a good reputation
12. VISIBILITY – the person/company shown official logos/uniforms

Collective action:

N.B. **Try not to mention the words collective action to the farmers!**

Information on the organization among farmers:

1. Are you part of a cooperative/group?
2. How is the cooperative/group organised in terms of
    a. Meetings
    b. Fees
    c. voting system
    d. etc
3. Was it an initiative of the community? How is the cooperative/group related to the government (e.g. subsides/projects...)?
4. The members of your cooperative/group are coming from other villages as well? How many different villages are involved?
5. Approximately, how many people from your village are involved in such a project (cooperative/club)? NB participants can provide a number, a percentage or any indicators useful to give us an idea if the majority of farmers is involved or not in those projects.

   a. Why in your opinion the other community members choose not to join any cooperative/club? NB. If the answer is lack of interest specify what does it means.
6. Do you ever have exchanges with other cooperatives/groups close by?
7. Why did you decided to join/not join the cooperative/group?
8. Is there a maximum number of membership for the cooperative/group? Min-max?

Willingness to cooperate as a group

1. If you are taught to make a product from local resources, would you invest time in doing so?
2. Would you buy the equipment individually or through a farmers' group to share the costs?
3. How would you organise the training? Training of trainers (women, youth, men?) and then they pass on the knowledge to other members of the group?
4. How would you share the product then? Any farmer would prepare his own products, or some farmers would be designated to do so for the whole community/cooperative/group?
5. How would you check with/on others? E.g make sure that the effort is not coming only from you but that most of the community is actually involved? For instance: organising meetings, giving the leadership to someone, etc...
6. How long would you give it a try before having results?
7. Do you think your village is already engaged in similar activities (e.g .activities that requires the participants to invest in a project that will benefit everyone)? In which occasion do you, as a community/village, come together to share so?

Belonging to Chapter 3

Appendix 2: In-depth interview with farmers

Questionnaire						

1. Consent approval after reading the consent statement.

Do you consent to take part in the survey YES ( ), NO ( )

Data handlers

Date of interview (dd/mm/yyyy)	
Interviewer Name	
Province	
District	
Village	
GPS coordinates (UTM)	N: _____GPS_N S: _____GPS_S E: _____GPS_E W: _____GPS_W

2. General household information

Provide details about the primary respondent

1.1 Name of respondent	1.2 Gender: (1) Male (0) Female	1.3 Year of birth	1.4 Primary activity: (1) farming (2) salaried employment (3) business, (4) off-farm work (5) other specify	1.5 Education level (1) None (2) Primary (3) Secondary (4) Tertiary	1.6 Ethnic group

2.1. Is the respondent the head of household? [_] Yes [_] No

If NO, what is the relationship of main respondent to the head of household? (select one answer)

[_] Spouse (1)
[_] Parent (2)
[ ] Child (3)
[_] Other family member (4): _____
[_] Unrelated (5)

2.2. Who takes the farming decisions in the household e.g. what crops/varieties to grow, pest management?

[_] Household head (1)
[_] Joint decision making (husband & wife) (2)
[_] Wife (where not household head) (3)
[_] Other family member (4)

2.3. What is your average income (year/month as the interviewed preferred)?

_____

2.4. What is the amount from farming?

2.5. Which activity is the main source of income from farming?

2.6. Do you have livestock? _____

2.7. How many people are in your household, including yourself and household head?
_____ people

2.8. How are these household members distributed across age?

Age Categories	**Male**	**Female**	**Number working on the farm at least once a week**
Age: 0-5 years			
Age: 6-17 years			
Age: 18-25 years			
Age: 26-35 years			
Age: 36-55 years			
Age: >55 years			

2.9 Are all household members ages 6 to 17 currently in school?

[_] YES (1)
[_] NO (0)

3. Sources of agricultural information

3.1. From which sources do you get information on agriculture for you and your household members who are involved in agriculture?

Category	**a) Receive info from this source?**	**c) If yes, for which crop(s)***	**b) Practices****	**c) Frequency of receiving information from this source last season**
Neighbours, friends and family	N – Y			
Lead farmer	N – Y			
Agricultural programs on radio/TV	N – Y			
Government extension officers	N – Y			
Plant doctor/Plant clinic	N – Y			
Magazine/newspaper	N – Y			
Agro-dealers/input suppliers	N – Y			
Demonstration plots/field days/Farmer field school	N – Y			
Farmer cooperative	N – Y			
Mobile sms/voice services	N – Y			
Headman	N – Y			
Agricultural days	N – Y			
Other, Specify_____	N – Y			

***Crop**		****Practices**	
1=Maize	7= Sunflower	1= Crop rotation	7= Intercropping
2=Tomato	8 = Sesame	2= Time of planting	8= Use of pesticides for pest and
3=Cassava	9 = Sugarcane	3= Manure use (include compost)	disease control
4=Sweet potato	10 = Rice	4= Inorganic fertilizer use	9= Soil and water conservation
5=Sorghum	11= Groundnut	5= New varieties of crops use	10= Irrigation
6= Pearl Millet	12= Bean	6= Quality seeds (either certified or QDS)	11= Marketing of products
	13 = Other, specify		12= Conservation farming

3.2 Identify your top three sources of information, the most used

1. _____
2. _____
3. _____

3.3 Which information source do you believe being more reliable? _____

3.4 Do you verify the information you get among other information sources? Can you share an example?

3.5 Did you share any of the agricultural information received with other farmers?
[_] YES (1)
[_] NO (0)

3.6 **If yes**, with whom did you share information?
[_] Other household members
[_] Other relatives living outside this community
[_] Community members/neighbours
[_] Group members/peers
[_] Other: _____

3.7 **If yes**, which topics did you discuss with the people you share information with?

[_] Crop rotation
[_] Time of planting
[_] Manure use (include compost)
[_] Inorganic fertilizer use
[_] New varieties of crops used
[_] Quality seeds (either certified or QDS)
[_] Intercropping
[_] Use of pesticides for pest and disease control
[_] Soil and water conservation
[_] Irrigation
[_] Marketing of the products
[_] Knowledge of pests and diseases

3.8 On average, with how many (number) people did you share information with? _____ people

3.9 Are you part of the same cooperative?
[_] YES (1)
[_] NO (0)

3.10 Are you part of the same village?
[_] YES (1)
[_] NO (0)

3.11 What blockers do you face in sharing information?
[_] Lack of leadership and organization in the community
[_] No interest in sharing information
[_] The other farmers are not interested
[_] I assume other farmers already know
[_] I don't feel able to advise other farmers
[_] It is safer not to share
[_] Not aware of common interest (e.g. the information is only relevant for my situation)
[_] I grow different crops then my relatives/neighbours
[_] Far away
[_] Other: _____

4. Costs/Benefits evaluation

4.1. What do you consider when you decide which type of pest management to apply?

_____
_____

4.2. When you choose which farming management practices to apply, what are the three most important benefits and the three most limiting factors you consider?

BENEFITS:

1._____
2._____
3._____

LIMITATIONS:

1._____
2._____
3._____

4.3. Below are some possible qualities of a product for pest management. Rate each option according to its importance for you in choosing a pest management practice over another - ranging between 1 (not important) to 5 (very important).

Benefit	**Rate**	**Notes**
Price		
Efficiency		
Safety for health		
Safe for environment		
Easy to apply		
Immediate action		
Training needed		
It is recommended by agrodealer/agricultural extensions		
The product is easy to find		
The product is generic: it is effective against different type of pests		
Other:		

5. Knowledge on fall armyworm

5.1 Can you recognize eggs of the fall armyworm?
Picture chosen: _____

5.2 Can you recognize the caterpillars of fall armyworm?
Picture chosen: _____

5.3 Can you recognize the adult of fall armyworm?
Picture chosen: _____

5.4 Put the cycle of FAW in order - egg, caterpillars, pupa and adult.
Order: _____-_____-_____-_____

5.5 How did FAW arrive in your field?

5.6 After damaging your crop, where does it go?

5.7 Is the farmer next to you having fall armyworm in his/her field?
[_] YES (1) [_] NO (0)

6. Knowledge on pest control - biocontrol

6.1. How do you control FAW (or other pests if FAW not recognised)? If chemical, name active ingredient or trade name? How did you get to know about this type of control?

Product/practice:	Where did you hear/learn it from?

6.2. Are there other methods you heard about, but you are not adopting?
6.3. Why did you choose to adopt this method in the first place?
6.4. Have you ever heard about biocontrol (if not previously mentioned)?
[_] YES (1)
[_] NO (0)
6.5. **If yes**, who did you hear it from?
6.6. **If yes**, can you explain how it works in your words?

If not explain:
The idea of biocontrol is the use of living organisms (natural enemies) to control a pest. Natural enemies are organisms that feed or reproduce on the pest. For instance, in a cotton crop, a natural enemy of aphids (pest) are ladybird beetles (natural enemies). Biocontrol is a method that become more effective over the years when use consistently and once the population of the natural enemies is enhanced, the control of the pest is easier. However, the natural enemies are also affected by pesticides therefore in order to apply this method, the application of pesticides must be reduced using less toxic chemicals.

6.7. How much do you spend on pesticide/year? _____
6.8. Would you be willing to use biocontrol products? [_] YES (1)[_] NO (0)
6.9. Would you be willing to produce it yourself? [_] YES (1)[_] NO (0)
6.10. How much would you be willing to pay for biocontrol products?
1. [_] 0 kwas - 50 kwas
2. [_] 50 kwas -100 kwas
3. [_] 100 kwas - 150 kwas
4. [_] 150 kwas - 200 kwas
5. [_] 200 kwas - 250 kwas
6. [_] 250 kwas - 300 kwas
7. [_] 300 kwas - 350 kwas
8. [_] 350 kwas - 400 kwas
9. [_] 500 kwas - more specify: _____

6.11 If your village decide to produce the biocontrol product for everyone, which group of people would you think would be more suitable to do that and why?

6.12 Is there, in your village, a group of people designated to do/produce something benefitting the entire community (e.g mill)? How have they been identified?

Belonging to Chapter 5

Appendix 3: Tables of parasitism rates of FAW parasitoids for rainy seasons 2019-2020 and 2020-2021

Table S1. Parasitism rates of FAW for each parasitoid species for the different intercropping and control plots on the CABI site, rainy season 2019-2020.

	Egg parasitoids	**Egg-larval parasitoids**	**Larval parasitoids**						**Unparasitized FAW larvae**
Treatments	***Telenomus remus***	***Chelonus curvimaculatus***	***Cotesia icipe***	***Coccygidium luteum***	***Drino quadrizonula***	***Euplectrus laphygmae***	***Parapanteles* sp.**	**Undetermined Hymenoptera-related mortality**	**FAW**
Cowpeas	33%	7.0%	3.5%	7.0%	1.8%	1.8%	1.8%	1.8%	75.4%
Groundnuts	0.0%	3.4%	0.0%	10.3%	0.0%	6.9%	3.4%	0.0%	75.9%
Maize control	0.0%	3.0%	4.5%	1.5%	0.0%	1.5%	0.0%	6.0%	83.6%

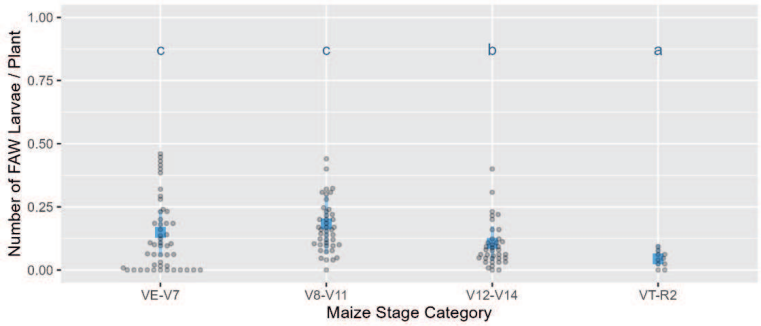
Table S2. Parasitism rates of FAW for each parasitoid species for the different intercropping and control plots on the CABI site, rainy season 2020-2021.

	Egg-larval parasitoids		**Larval parasitoids**								**Unparasitized FAW larvae**
Treatments	***C. bifoveolatus***	***C. curvimaculatus***	***C. icipe***	***C. luteum***	***Diadegma* sp.**	***D. quadrizonula***	***E. laphygmae***	***Parapanteles* sp.**	***Pristomerus* sp.**	**Undetermined Hymenoptera-related mortality**	**FAW**
Beans	0.8%	3.3%	0.8%	7.8%	0.4%	1.6%	0.0%	0.8%	0.4%	2.0%	82.0%
Cowpeas	0.5%	1.9%	2.3%	6.1%	0.0%	1.9%	0.5%	0.5%	1.4%	1.9%	83.1%
Groundnuts	0.5%	3.3%	1.9%	6.7%	0.0%	1.0%	0.0%	1.0%	4.3%	1.9%	79.4%
Maize control	0.0%	1.0%	3.7%	15.7%	1.0%	1.6%	2.1%	0.0%	1.0%	1.6%	72.3%

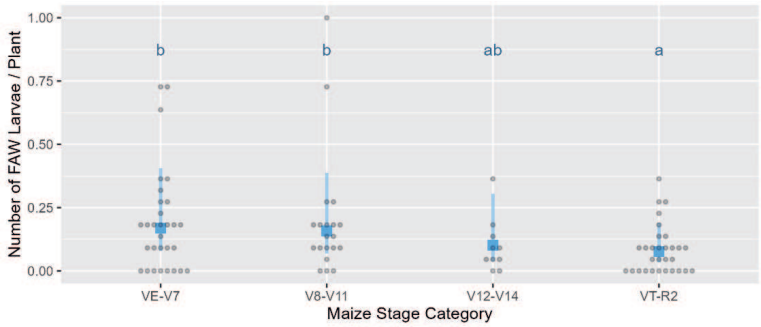
Table S3: Parasitism rates of FAW for each parasitoid species for the different intercropping and control plots on the ZARI site, rainy season 2020-2021.

	Egg-larval parasitoids	**Larval parasitoids**							**Unparasitized FAW**
Treatments	***C. curvimaculatus***	***C. icipe***	***C. luteum***	***Campoletis* sp.**	***D. quadrizonula***	***E. laphygmae***	***Pristomerus sp.***	**Hymenoptera-related mortality**	**FAW**
Sorghum (maize)	1.0%	1.6%	4.2%	0.0%	6.0%	0.0%	8.3%	2.9%	76.1%
Sorghum (sorghum)	7.6%	0.0%	4.6%	0.0%	1.5%	0.0%	6.1%	3.1%	77.1%
Sunflower	3.5%	0.5%	5.0%	0.3%	2.3%	0.3%	16.5%	2.5%	69.3%
Maize control	3.6%	0.0%	2.8%	0.0%	2.3%	0.4%	11.4%	3.4%	76.1%

a) CABI 2019-2020



b) CABI 2020-2021



c) ZARI 2020-2021

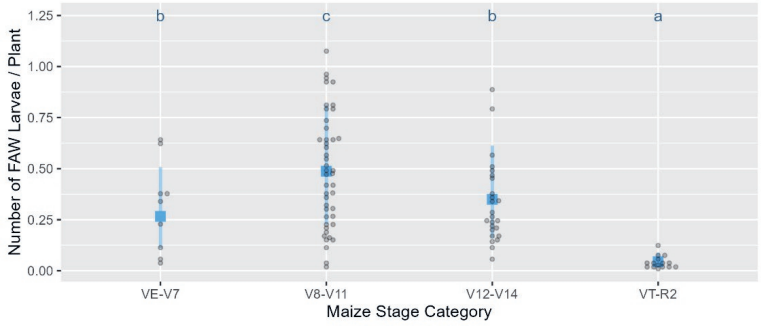
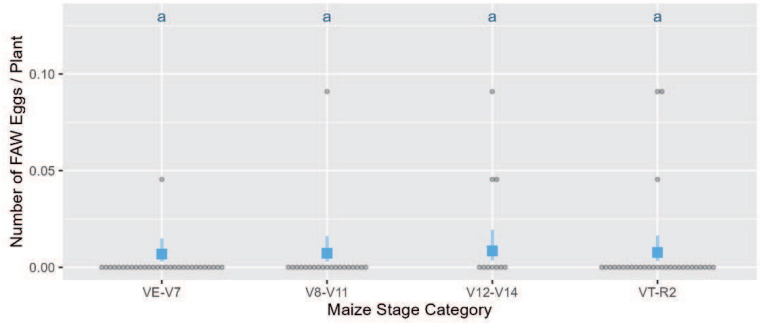
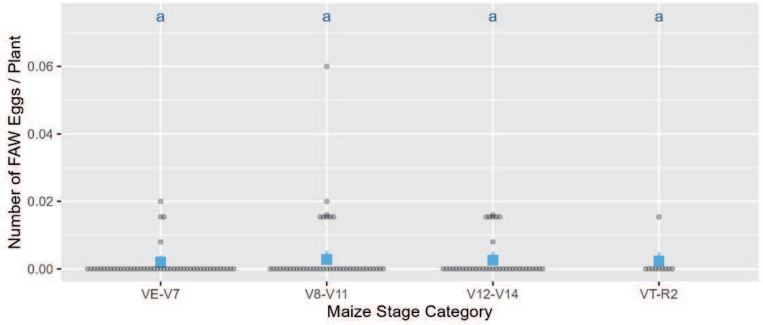


Figure S1. Mean density of fall armyworm larvae in relation to maize stage category for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Vertical bars indicate the 95% C.I., and the letters indicate differences among groups with a certainty level of 95% or more (odds ratio of 20:1). Each dot is an observation.

a) CABI 2019-2020



b) CABI 2020-2021



c) ZARI 2020-2021

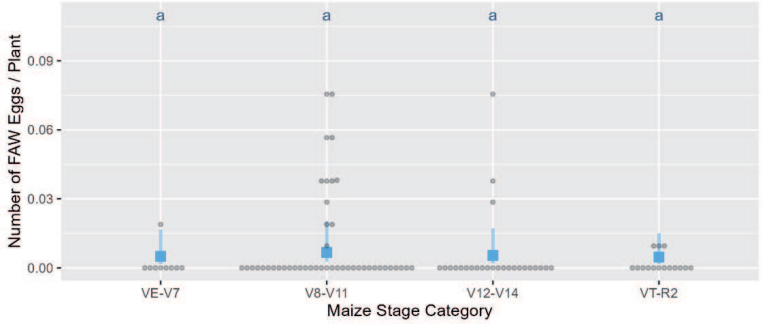


Figure S2. Mean parasitism probabilities by larval parasitoids in relation to maize stage category for a) CABI 2019-2020, b) CABI 2020-2021, and c) ZARI 2020-2021. Vertical bars indicate the 95% C.I., and the letters indicate differences among groups with a certainty level of 95% or more (odds ratio of 20:1). Each dot is an observation.

Belonging to Chapter 6

Appendix 4: Descriptions of variables and results of probit models for ecological knowledge and pest management

Table 1A: Description of outcome and explanatory variables used for probit models

Outcome variables					
Biocontrol concept	0 = Doesn't match	1 = Matches			
Type of FAW natural enemies	0 = Doesn't match	1 = Matches			
Explanation of how natural enemies kill FAW	0 = Doesn't match	1 = Matches			
Correct order of the FAW cycle	0 = Incorrect	1 = Correct			
Correct identification of FAW larvae	0 = Incorrect	1 = Correct			
Plan ahead	0 = No	1= Yes			
Explanatory variables					
Gender	Female = 0	Male=1			
Age	Number				
Education	0 = None	1 = Primary	2 = Secondary	3 = Tertiary (certificate/diploma)	4= Degree (B.Sc. and over)
District	0 = Mumbwa	1 = Siavonga			
Land title	0 = Lease	1 = Own			
Farming land size cultivated	Number (hectares)				
Participation in the project	0= Did not participated	1= Participated			
HDDS	Food categories : (1) cereals, (2) white tubers and roots, (3) vitamin A rich vegetables and tubers, dark green leafy vegetables, other vegetables, (4) vitamin A rich fruits, other fruits, (5) organ meat, flesh meat, (6) eggs, (7) fish, (8) legumes nuts and seeds, (9) milk and milk products, (10) oils and fats, (11) sweet and (12) spices, condiments and beverages.				
Assets index	Assets: house ownership, floor material, wall material, roofing material, bed, house pump, refrigerator, radio, TV, DVD, mobile, sofa, car, motorbike, bike, cart, hoes, plough, harrow, sprayer				
Pesticide usage	0= No	1= Yes			

Table 2A: Probit regression on factors affecting knowledge on biocontrol concept.

Biocontrol_concept	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
respondent_gender	**-.432**	**.261**	**-1.65**	**.098**	**-.944**	**.08**	*
respondent_age	**.016**	**.007**	**2.26**	**.024**	**.002**	**.031**	**
respondent_education	**.45**	**.171**	**2.64**	**.008**	**.116**	**.785**	***
respondent_district	.013	.254	0.05	.96	-.485	.51	
respondent_land_ti~e	-.557	.745	-0.75	.455	-2.018	.904	
farming_~_cultivated	-.031	.049	-0.63	.529	-.127	.066	
respondent_partici~n	**1.571**	**.212**	**7.41**	**0**	**1.155**	**1.987**	***
HDDs	.011	.065	0.17	.862	-.116	.139	
Asset_Index	.027	.064	0.42	.674	-.099	.153	
Constant	-1.845	.92	-2.01	.045	-3.648	-.042	**

Mean dependent var	0.352	SD dependent var	0.479
Pseudo r-squared	0.279	Number of obs	213
Chi-square	77.036	Prob > chi2	0.000
Akaike crit. (AIC)	219.330	Bayesian crit. (BIC)	252.943

*** *p<.01, ** p<.05, * p<.1*

Table 2B: Probit regression on factors affecting knowledge on natural enemies.

Name_natural	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
respondent_gender	-.233	.261	-0.90	.371	-.745	.278	
respondent_age	.012	.007	1.58	.115	-.003	.026	
respondent_education	**.409**	**.175**	**2.33**	**.02**	**.066**	**.753**	**
respondent_district	.148	.261	0.57	.571	-.364	.659	
respondent_land_ti~e	-.437	.74	-0.59	.555	-1.887	1.014	
farming_~_cultivated	.004	.043	0.10	.923	-.08	.089	
respondent_partici~n	**1.625**	**.218**	**7.45**	**0**	**1.198**	**2.053**	***
HDDs	.089	.066	1.36	.174	-.039	.218	
Asset_Index	-.041	.065	-0.62	.534	-.168	.087	
Constant	-2.368	.93	-2.54	.011	-4.191	-.544	**

Mean dependent var	0.333	SD dependent var	0.473
Pseudo r-squared	0.280	Number of obs	213
Chi-square	76.012	Prob > chi2	0.000
Akaike crit. (AIC)	215.143	Bayesian crit. (BIC)	248.756

*** *p<.01, ** p<.05, * p<.1*

Table 2C: Probit regression on factors affecting knowledge on how natural enemies kill FAW.

Explain_natural	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
respondent_gender	-.327	.262	-1.25	.212	-.841	.187	
respondent_age	.012	.007	1.61	.107	-.003	.026	
respondent_educatio n	**.332**	**.174**	**1.91**	**.056**	**-.009**	**.673**	*
respondent_district	.176	.258	0.68	.494	-.329	.681	
respondent_land_ti~e	-.795	.741	-1.07	.283	-2.247	.657	
farming_~_cultivated	-.025	.051	-0.49	.625	-.125	.075	
respondent_partici~n	**1.557**	**.217**	**7.16**	**0**	**1.131**	**1.983**	***
HDDs	-.03	.066	-0.46	.648	-.16	.1	
Asset_Index	.057	.065	0.86	.387	-.072	.185	
Constant	-1.31	.905	-1.45	.148	-3.084	.465	

Mean dependent var	0.310	SD dependent var	0.464
Pseudo r-squared	0.268	Number of obs	213
Chi-square	70.762	Prob > chi2	0.000
Akaike crit. (AIC)	212.927	Bayesian crit. (BIC)	246.540

*** *p<.01, ** p<.05, * p<.1*

Table 2D: Probit regression on factors affecting knowledge FAW life cycle.

Cycle	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
respondent_gender	.136	.229	0.60	.552	-.313	.585	
respondent_age	**.013**	**.006**	**2.09**	**.037**	**.001**	**.025**	**
respondent_education	-.205	.157	-1.30	.193	-.513	.103	
respondent_district	**-.727**	**.239**	**-3.04**	**.002**	**-1.196**	**-.258**	***
respondent_land_ti~e	-.483	.64	-0.75	.45	-1.738	.772	
farming_~_cultivated	.062	.04	1.54	.122	-.017	.14	
respondent_partici~n	.284	.191	1.49	.137	-.09	.658	
HDDs	**-.176**	**.06**	**-2.91**	**.004**	**-.295**	**-.058**	***
Asset_Index	-.011	.058	-0.19	.85	-.125	.103	
Constant	.705	.792	0.89	.374	-.848	2.258	

Mean dependent var	0.385	SD dependent var	0.488
Pseudo r-squared	0.106	Number of obs	213
Chi-square	30.106	Prob > chi2	0.000
Akaike crit. (AIC)	273.801	Bayesian crit. (BIC)	307.414

*** *p<.01, ** p<.05, * p<.1*

Table 2E: Probit regression on factors affecting knowledge on FAW caterpillar.

Caterpillar	Coef.	St.Err.	t-value	p-value	[95% Conf	Interval]	Sig
respondent_gender	**-.596**	**.228**	**-2.61**	**.009**	**-1.043**	**-.149**	***
respondent_age	**.014**	**.007**	**2.18**	**.03**	**.001**	**.027**	**
respondent_education	.053	.163	0.32	.746	-.267	.373	
respondent_district	**.442**	**.232**	**1.90**	**.057**	**-.013**	**.896**	*
respondent_land_ti~e	.336	.59	0.57	.57	-.821	1.492	
farming_~_cultivated	**.114**	**.056**	**2.06**	**.039**	**.006**	**.223**	**
respondent_partici~n	.245	.199	1.23	.218	-.144	.634	
HDDs	-.036	.06	-0.60	.548	-.153	.081	
Asset_Index	-.065	.06	-1.10	.273	-.183	.052	
Constant	-.765	.758	-1.01	.313	-2.25	.721	

Mean dependent var	0.690	SD dependent var	0.464
Pseudo r-squared	0.107	Number of obs	213
Chi-square	28.219	Prob > chi2	0.001
Akaike crit. (AIC)	255.470	Bayesian crit. (BIC)	289.083

*** *p<.01, ** p<.05, * p<.1*

Belonging to Chapter 6

Appendix 5: Questionnaire used for farmers interviews

1. **Consent approval after reading the consent statement.**
   Do you consent to take part in the survey Yes ( ), NO ( )

   Data handlers:
   1.1. Date of interview: (dd/mm/yyyy)
   1.2. Interviewer name:

2. **General household information and participation in project**
   Ideal respondent: household head and/or spouse. Most of these questions can be completed without having to question the respondent directly (e.g. gender).

   Provide details about the primary respondent:
   a. Name of respondent
   b. Head of household: Yes _____ No ____
      If NO, what is the relationship of main respondent to household head? (select one answer)
      Spouse (1)
      Parent (2)
      Child (3)
      Other family member (4) specify;_____
      Unrelated (5)
   c. Gender: 1= male, 0=female
   d. Year born:_____
   e. Primary activity: 1=Crop Farming 2=livestock keeping 3=Waged employment 4=Other_____
   f. Education level: 1=none, 2= primary, 3= Secondary, 4= tertiary (certificate or diploma), 5= Degree (B.Sc. and over)
   g. Region of origin - Province
   h. Current location - Province
   i. District: _____
   j. Camp: _____
   k. Village: _____
   l. Own land: Yes _____ No ____
   m. Farming land size: _____ (ha)
   n. Participation in the project: Yes ____ No ____

3. Ecological knowledge

3.1. FAW

Can you recognize eggs of the fall armyworm?

Picture chosen: A/B/C/D

Can you recognize the caterpillars of fall armyworm?

Picture chosen: A/B/C/D

Can you recognize the adult of fall armyworm?

Picture chosen: A/B/C/D

Put the cycle of FAW in order - egg, caterpillars, pupa and adult.

Order: _____-_____-_____-_____

3.2. Natural enemies

- Have you heard of biocontrol as pest management option? Yes ____ No _____
- If yes, can you explain in your own word?
- Can you name some of the natural enemies attacking FAW in your field?
- Can you explain how they control the FAW?

4. Limitations

4.1. **Conservation biocontrol – intercropping**

What limit you to implement intercropping? Or to upscale?

- Labour intensive (need to employ more staff)
- Very manual (need to week more often)
- Too complex for implementing
- Trials/demos are not easy for adoption
- Results are not rapidly observable
- Not compatible with other aspects of farm management (herbicide for maize kills other crops).
- Other:

5. Collective action – *to evaluate perception and willingness to participate in future community management of FAW***.** *As the project ends, what will you continue doing and why?*

5.1. Are you willing to coordinate *intercropping* with your neighbours for FAW management?

5.2. Are you willing to coordinate *flower strips between fields* with your neighbours for FAW management?

5.3. Are you willing to coordinate *decreasing insecticides usage* with your neighbours for FAW management?

5.4. Are you willing to coordinate *diversity of crops* with your neighbours for FAW management?

5.5. Who would be part of the group and how this will be decided?

5.6. How the physical boundaries of the management will be decided?

5.7. Who would be coordinating and leading the agreed rules for management?

5.8. How would the community agree on common rules to follow for FAW management?

5.9. Would you trust the community to follow agreed rules?

5.10. How the community would be organised to escalate information from the leader to the farmers?

5.11. How would the community monitor that other farmers follow the agreed rules?

5.12. Would you need to monitor the FAW infestation level in the neighbouring fields?
5.13. Would the community need incentives or sanctions to ensure that members of the group follow the agreed rules?
5.14. How would the community communicate with its members and with outsiders the collective/community action in place?
5.15. If a member is unable to follow the plan agreed due to illness or other commitment, how this will be handled?

5.16. What are the main factors limiting the community to coordinate actions for FAW management?

- Insufficient incomes
- Lack of knowledge/understanding
- Lack of coordination
- Lack of leadership
- Poor coordination among farmers
- Lack of technical support
- Farmers having different enterprises.
- Land access
- Land ownership
- Climatic patterns
- Other, specify _____

6. Long-term pest management

6.1. Do you plan for pest management? Yes _____ No _____
6.2. Do you plan ahead? Yes _____ No _____
6.3. How far ahead do you plan pest management? _____
6.4. What factors are limiting you to plan long-term pest management? Open questions but tick any mentioned.

- Insufficient incomes
- Lack of knowledge/understanding
- Lack of coordination
- Lack of leadership
- Poor coordination among farmers
- Lack of technical support
- Land access
- Land ownership
- Inconsistent climatic patterns
- Other, specify _____

7. Pesticide information.

7.1. Have you used pesticides the last 2 rainy season? Yes ____ No _____
7.2. Are you willing to reduce pesticide applications to implement other natural pest control through as intercropping or flower strips? Yes____ No ____
7.3. Why: _____

8. Assets index. *To understand if poverty is a variable that explain willingness in cooperating, and if it affects long-term pest management planning.*

Name of Asset	**Own = 1, Doesn't own = 0**
House/Domestic	
Ownership (Owned = 1, other = 0)	
Floor material	
Wall material	
Roofing material	
Bed	
House pump	
Refrigerator	
Radio	
Television	
DVD Player	
Mobile phone	
Sofa set	
Transport	
Car/Truck	
Motorcycle	
Bicycle	
Cart (animal drawn)	
Farm	
Hoes	
Plough	
Harrow	
Sprayer	

9. Household Dietary Diversity Score.

I would like to ask you about the foods and drinks YOU OR ANYONE ELSE IN THE HOUSEHOLD ate or drank **yesterday during the day and at night** (i.e. **PAST 24 HOURS**) IN THE HOME. [**note for enumerator: consider foods eaten by any member of the household, and exclude foods purchased and eaten outside of the home**]

No.	Food group	Examples	*1=Yes; 0=No*
1	CEREALS	Bread, noodles, biscuits, cookies or any other foods made from millet, sorghum, maize, rice, wheat + *nshima, samp*	
2	WHITE TUBERS AND ROOTS	White potatoes, white yams, cassava, or foods made from roots e.g.	
3	VITAMIN A RICH VEGETABLES AND TUBERS, DARK GREEN LEAFY VEGETABLES, OTHER VEGETABLES	Pumpkin, carrots, squash, or sweet potatoes that are orange inside + *other locally available vitamin-A rich vegetables (e.g. sweet pepper).* Dark green/leafy vegetables, including wild ones + *rape, bondwe, pumpkin leaves, cassava leaves etc.* Other vegetables (e.g. tomato, onion, eggplant), including wild vegetables	
4	VITAMIN A RICH FRUITS, OTHER FRUITS	Ripe mangoes, cantaloupe, dried apricots, dried peaches + *other locally available vitamin A-rich fruits*	
5	ORGAN MEAT (IRON RICH), FLESH MEAT	Liver, kidney, heart or other organ meats or blood-based foods beef, pork, lamb, goat, rabbit, wild game, chicken, duck, or other birds	
6	EGGS	Eggs	
7	FISH	Fresh or dried fish or shellfish	
8	LEGUMES, NUTS AND SEEDS	Beans, peas, lentils, groundnuts, seeds or foods made from these	
9	MILK AND MILK PRODUCTS	Milk, cheese, yogurt or other milk products	
10	OILS AND FATS	Oil, fats or butter added to food or used for cooking	
11	SWEETS	Sugar, honey, sweetened soda or sugary foods such as chocolates, sweets or candies	
12	SPICES, CONDIMENTS, BEVERAGES	Spices (black pepper, salt), condiments (soy sauce, hot sauce), coffee, tea, alcoholic beverages OR *local examples*	

About the author



Léna Durocher-Granger was born on October 21st, 1985, in Greenfield Park, Canada and was raised in Sherrington, a small agricultural village of the Québec province. As a child, she was always interested in insects and nature but wasn't aware that it could be a profession. After high school, she undertook a technical degree in biology and ecology at the Cégep de St-Laurent, where she discovered her passion for entomology. She then continued her BSc studies in bioecology at the Université du Québec à Trois-Rivières. During that time, she enrolled in a three-month volunteering programme in Mali to develop her understanding and experience in international development. Once back, she started an MSc in Entomology at McGill University and Agriculture and Agri-Food Canada in St-Jean-sur-Richelieu. During her lab-based MSc thesis, Léna was developing knowledge and skills working with parasitoids but also wondering how her newly acquired competencies could be beneficial for farmers around the world. When an opportunity arose to work in Nicaragua and Honduras as a biocontrol advisor for two years, she embarked on a new journey in international development where she worked with local institutions to support smallholder farmers in developing countries to reduce chemical pesticides used in their fields. This combination of education and work experience led her to work for CABI in developing extension materials for smallholder farmers around the world. With the diversity of projects she worked on while based in the UK, her interest in returning to scientific research was revived, and she conceptualized a PhD project between biocontrol of invasive species and community engagement with smallholder farmers. In early 2018, she moved to the Netherlands to start her PhD research as an external PhD candidate at Wageningen University in collaboration with the Entomology and Knowledge, Technology and Innovation groups.

List of publications

Durocher-Granger L., Martel, V & G. Boivin. (2011). Gamete number and size correlate with adult size in the egg parasitoid *Trichogramma euproctidis*. *Entomologia Experimentalis et Applicata*, 140, 262-268. https://doi.org/10.1111/j.1570-7458.2011.01158.x

Durocher-Granger L., Mfune T., Musesha M., Lowry A., Reynolds K., Buddie A., Cafa G., Offord L., Chipabika G., Dicke M & Kenis M. (2021). Factors influencing the occurrence of fall armyworm parasitoids in Zambia. *Journal of Pest Science* 94(4), 1133-1146. https://doi.org/10.1007/s10340-020-01320-9 (**Chapter 2 of this thesis**)

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Education statement

PE&RC Training and Education Statement
With the training and education activities listed below the PhD candidate has complied with the requirements set by the Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 30 ECTS (= 22 weeks of activities)

Review/project proposal
- Review: Chapter 1 of the thesis – General introduction
- Proposal: Spodoptera frugiperda management using local resources in the maize smallholder farming system in Zambia | 6 ECTS

In-depth / Topical / On-site Postgraduate Courses
- Farming Systems and Rural Livelihoods | PE&RC | 2018 | 3 ECTS
- Bugs at your services | PE&RC | 2019 | 1.5 ECTS

Methodological / Statistical Postgraduate Courses
- Basic Statistics | PE&RC | 2019 | 1.5 ECTS
- Design of experiments | PE&RC | 2019 | 3 ECTS
- Generalized Linear Models | PE&RC | 2022 | 0.9 ECTS

Deficiency, refresh, brush-up courses
- Introduction to Technology, Agro-ecology and Development | WASS | 2019 | 1.8 ECTS

Invited review of journal manuscripts
- Archives of Phytopathology and Plant Protection | Biocontrol based packages of fall armyworms (*Spodoptera frugiperda*) attacking maize in eastern central, Tanzania | 2020 | 1 ECTS
- International Journal of Tropical Insect Science | Activity of natural enemies of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) in different cropping seasons of maize in South India | 2022 | 1 ECTS
- International Journal of Tropical Insect Science | Host-instar selection and inter-specific competition of the braconid parasitoids, *Cotesia marginiventris* and *Microplitis rufiventris* | 2022 | 1 ECTS
- International Journal of Tropical Insect Science | Crop mixtures influence fall armyworm infestation and natural enemy abundance in maize-based intercropping systems | 2024 | 1 ECTS
- BioControl | Haunted by cane toads - An exploratory survey of public attitudes and knowledge about classical biological control | 2025 | 1 ECTS
- Crop Protection | Farmers' knowledge of fall armyworm, *Spodoptera frugiperda* (J.E. Smith) damage and factors affecting control method choices in Benin, West Africa | 2025 | 1 ECTS

Competence, skills and career-oriented activities
- Competence Assessment | Nora Lubsen | 2018 | 0.3 ECTS
- The Essentials of Scientific Writing and Presenting | Irene Houkes-Jansen | 2020 | 1.2 ECTS
- Making an Impact! How to increase the societal relevance of your PhD research | P.J. Vermeulen | 2023 | 1 ECTS
- Brain Training | Y.H.M Smolders | 2020 | 0.3 ECTS
- KTI skill sessions | Auke Pols | 2020-2022 | 0.6 ECTS

Scientific Integrity/Ethics in science activities
- Ethics in Plant and Environmental Sciences | P.J. Vermeulen | 2022 | 0.3 ECTS

PE&RC Retreat, PE&RC Day, and other PE&RC events
- PE&RC Day 2018, 2022 | 0.6 ECTS
- PE&RC First years weekend | 2018 | 0.9 ECTS
- PE&RC Midterm weekend | 2021 | 0.6 ECTS
- PE&RC Last year weekend | 2022 | 0.6 ECTS

National/local scientific meetings, seminars, and discussion groups
- Collaboration with UKCEH scientists on ozone pollution research in tropical agriculture (field research, development of datasheet on ozone pollution in agriculture development of datasheet on ozone pollution in agriculture organized and facilitated 3 webinars 2021-2022 | 2.3 ECTS
- SDG conference – 'Towards Zero Hunger: Partnerships for Impact' Wageningen University & Research | 2018 | 0.6 ECTS
- Biodiversity in Agroecosystems | 2022 | 0.2 ECTS
- EPPO workshop - Use of DNA barcoding, from theory to practice | 2018 | 1.3 ECTS
- Wageningen Gender Studies Symposium: What does it mean to "do gender" in the CGIAR? | 2018 | 0.1 ECTS

International symposia, workshops and conferences

- IWGO-IOBC conference | Engelberg, Switzerland | 2019 | 2.2 ECTS
- W@SABI - International conference on invasive species | Online | 2021 | 1.6 ECTS
- FAW IWGO workshop | Online | 2021 | 1.3 ECTS
- IWGO - IOBC Conference | Nairobi, Kenya | 2023 | 1.9 ECTS
- IOBC 3rd ICBC | San José, Costa Rica | 2024 | 2.2 ECTS

Societally relevant exposure

- Blog: https://blog.plantwise.org/2021/09/02/webinar-ozone-pollutions-threat-to-tropical-agriculture/ 2021 | 0.1 ECTS
- News article: https://www.cabi.org/news-article/new-research-reveals-factors-influencing-the-parasitoids-that-help-to-control-invasive-fall-armyworm/ 2021 | 0.1 ECTS
- Interview for press article. Scientists look to solve ozone threat to Africa's food security | Reuters https://icpvegetation.ceh.ac.uk/webinar-highlights-ozone-pollution%E2%80%99s-current-future-threat-agriculture 2022 | 0.2 ECTS
- Blog: https://blog.invasive-species.org/2022/03/15/can-intercropping-make-fall-armyworms-natural-enemies-more-effective/ | 2022 | 0.1 ECTS
- Blog https://blog.plantwise.org/2023/05/22/conserving-biodiversity-biocontrol-for-sustainable-agriculture/ 2023 | 0.1 ECTS
- Blog: https://blog.invasive-species.org/2023/05/30/study-examines-potential-for-collective-action-to-fight-fall-armyworm-with-biological-controls-in-rural-zambia/ 2023 | 0.1 ECTS

BSc/MSc thesis supervision

- Research topic 1: Traditional community structure and collective action to control FAW in rural Zambia | 3 ECTS

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