

INSECT FACTORY



MANAGEMENT OF AFRICAN ARMYWORM AND FALL ARMYWORM IN BOTSWANA

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Introduction

Armyworm biology and identification in Botswana

Spodoptera is a worldwide genus of moths consisting of 30 described species. Larvae (caterpillars) of *Spodoptera* species can be recognized by having a combination of morphological characters, and identification to species usually relies on morphological characters in addition to body colour, origin, and potentially host.

Spodoptera species have been recorded from the following countries:

American Samoa, Australia, Barbados, Botswana, Brazil, Cameroon, Canada, China, Colombia, Costa Rica, Dominica, Dominican Republic, Ecuador, El Salvador, France, Gambia, Germany, Ghana, Guatemala, Guyana, Haiti, Hawaii, Hong Kong, India, Iran, Israel, Jamaica, Jordan, Kenya, Malaysia, Mauritius, Mexico, Morocco, Nepal, Netherlands, New Zealand, Nicaragua, Nigeria, Norway, Palestinian Territory, Panama, Peru, Philippines, Puerto Rico, Singapore, South Africa, South Korea, Spain, St. Vincent and the Grenadines, Tahiti, Taiwan, Thailand, Tortola, Trinidad and Tobago, United Kingdom of Great Britain and N. Ireland, Vietnam, Zimbabwe.

Scientific and common names

The common name for *Spodoptera* species is 'armyworm', because of the appearance of the worm-like larvae of many species, and the behaviour of the larvae to form aggregations which move across the landscape as a marching army.

Spodoptera SPECIES FOUND IN AFRICA (Source: Rose et al. 2020)

Species	Common names	Comments
<i>S. exigua</i> (Hübner)	Lesser armyworm	Causes outbreaks; polyphagous; larvae may be confused with <i>S. exempta</i>

<i>S. littoralis</i> (Boisduval)	Cotton leafworm, Maize worm	Major pest of cotton, greenhouse vegetables and other crops
<i>S. mauritia</i> (Boisduval)	Lawn armyworm, rice swarming armyworm, paddy armyworm	Uncommon; not a pest in Africa
<i>S. cilium</i> Guenee	Lawn caterpillar	Significant pest in lawns in southern Africa
<i>S. apertura</i> (Walker)	Dark armyworm	Uncommon; no economic importance
<i>S. triturate</i> (Walker)	Large lawn caterpillar	Larvae found at the base of grasses; larvae may be confused with solitary form of <i>S. exempta</i>
<i>S. malagasy</i> Viette	Malagasy armyworm	Only recorded from Madagascar; no economic importance
<i>S. exempta</i> (Walker)	African armyworm	Significant, but episodic, pest in southern Africa
<i>S. frugiperda</i> (JE Smith)	Fall armyworm	Significant, and emerging, pest in southern Africa

IMPORTANT *Spodoptera* SPECIES NOT FOUND IN AFRICA

S. litura (Fabricius), commonly called the Indian cotton leafworm, is a serious pest of cotton and other crops in Asia, Australia and nations in the Pacific region.

IMPORTANT *Spodoptera* SPECIES FOUND IN BOTSWANA

Of the species of *Spodoptera* found across the world, only *S. exempta* (African armyworm) and *S. frugiperda* (Fall armyworm) are of economic significance in Botswana. For this reason, this Handbook focusses on these two species alone.

THE TAXONOMIC POSITION OF THE AFRICAN ARMYWORM

Class Insecta: Order Lepidoptera: Family Noctuidae: Genus *Spodoptera* (Guenée): Species *exempta* (Walker).

This species was originally described as *Agrotis exempta* (Walker 1856). It was known as *Laphygma exempta* (Walker) Hampson 1909 until 1958, when it was renamed by Zimmerman and is now known as *Spodoptera exempta* (Walker) Zimmerman 1958.

THE TAXONOMIC POSITION OF THE FALL ARMYWORM

Class Insecta: Order Lepidoptera: Family Noctuidae: Genus *Spodoptera* (Guenée): Species *frugiperda* (JE Smith).

This species was originally described in 1797 as *Phalaena frugiperda*, in 1852 it was assigned to the genus *Laphygma* (Luginbill, 1928), finally, in 1958 the genus *Laphygma* and *Spodoptera* were synonymized and since then, the valid name is *Spodoptera frugiperda*.

AAW AND FAW IDENTIFICATION

Species	AAW (<i>S. exempta</i>)	FAW (<i>S. frugiperda</i>)
Eggs	Pale yellowish colour, darkening towards hatching. Conical shape with slightly rounded apex. Laid in batches of 10-600 and covered with black scales.	Small, pale yellow, and spherical, typically laid in clusters of 100-200, or up to 500, on the underside of leaves. The masses are covered with grayish-pink or white, felt-like, or fuzzy scales.
Larvae	Gregarious larvae: Velvet-black upper surface with pale lateral lines. Head always shiny black. Solitary larvae: Cryptic colours of green-brown or pink. Appear fat and sluggish.	The young larvae are light coloured with a larger dark head. As they develop, they become browner with white lengthwise lines. The head capsule has an inverted Y shape, and there are four spots on the last abdominal segment.
Pupae	Initially light green, they darken to a reddish-brown colour as they mature. Usually 2–3 cm underground.	Shiny, reddish-brown, and measure 13–18 mm in length. They are typically found in the soil at a depth of 2–8 cm.
Adults	Stout bodied moth with abdomen covered with pale grey-brown scales except for the tip except in the female which has black hair-scales	There are slight differences between sexes with males having more patterns and a distinct white spot on each of their forewings.
Symptoms	Larvae prefer to feed on young, soft foliage. Total defoliation of the plant to ground level. Pastures, grasses and crops are attacked.	Larvae prefer to feed on young, soft foliage. Crops such as maize and sorghum are preferred.
Impact	Losses can be significant but intermittent on local, regional or national scales.	Annual losses are recurrent, and may be significant at local, regional and national scales.





The African armyworm (AAW), *Spodoptera exempta* (Lepidoptera: Noctuidae) is a native pest of pastures and cereal crops in Africa south of the Sahara, parts of Arabia, Asia, Australia and the Pacific, including Hawaii. This noctuid moth is a migrant and, in episodic plague years, many thousands of square kilometres in eastern, central and southern Africa may be infested with its larvae at densities up to and occasionally exceeding 1000/m², often in patchy outbreaks which are seldom contiguous. As a consequence, AAW has gained notoriety as a pest species second only to locusts for its sudden, short-lived outbreaks that cause severe crop losses (Kinyanjui *et al.* 2025). Economic losses caused nationally or to individual farmers may be considerable, even though available figures are imprecise. Action thresholds have been tentatively estimated to prevent a 15% crop loss (Gomez-Undiana *et al.* 2020, Rose *et al.* 2020).

In contrast, the Fall armyworm (FAW), *Spodoptera frugiperda*, is native to the Americas and has emerged as a formidable agricultural pest, posing a significant threat to a wide range of grass crops, including maize and sorghum, the staple foods for a large proportion of the world's population. First reported in Africa in 2016, FAW has rapidly spread across Asia and other regions, causing substantial economic losses and raising serious concerns regarding food security (Mendesil *et al.*, 2023). The pest's voracious feeding behaviour can lead to yield reductions of up to 50–80%, severely impacting farmers' livelihoods and destabilizing local economies (Nagoshi and Meagher, 2004). FAW was first recorded in Botswana in 2018, but since that time the insect has spread throughout the country wherever maize and sorghum crops are grown.

The urgency of addressing the combined AAW/FAW threat is underscored by the limitations of current control methods, such as the heavy reliance on chemical pesticides, which pose risks for human health and environmental sustainability. The development of resistance among AAW and FAW populations to multiple insecticides further complicates management efforts, necessitating a shift towards integrated pest management (IPM) strategies that combine biological control, cultural practices, and judicious pesticide application (Van den Berg and du Plessis 2022, Sokame *et al.* 2025). Furthermore, timely dissemination of information regarding AAW and FAW and their impacts on maize and sorghum crops in Botswana is crucial. Equipping farmers with knowledge about the armyworm life cycle, resistance mechanisms, and effective biocontrol agents is vital for implementing initiative-taking and sustainable management strategies.

The adaptability of AAW and FAW to diverse environments exacerbates the threat to maize and sorghum production, necessitating immediate and coordinated research efforts. Considering the heavy reliance on maize and sorghum as staple foods in Botswana, coupled

with the vulnerability of smallholder farmers, the potential impacts of AAW and FAW infestations on food security are profound. Addressing this challenge demands swift collaboration among policymakers, researchers, and farming communities to develop practical and effective mitigation strategies. Delayed action could jeopardise the stability of cereal production, with severe consequences for food security across the country.

Global spread of the African armyworm and Fall armyworm

The distribution of outbreaks of AAW varies both temporally and spatially, and follows the onset of the wet seasons when dry grasslands produce new growth and cereal crops are planted. Major outbreaks of African armyworm are commonly preceded by extended drought. The African armyworm is well adapted to exploit the food available in the seasonal grasslands in which it lives, and it has sophisticated ways of reacting to the environment through physiological and genetic changes. These changes are expressed through the physiology and behaviour of larvae and moths.

Outbreaks of AAW have been recorded from some part of Africa almost every year since 1919. The earliest known records are from Ethiopia in 1520, South Africa in 1878, and Sierra Leone in 1888. Prior to 1900, adult moths had been collected from Ethiopia, Gabon, Kenya, Madagascar, Mozambique, Somalia, Sudan, Uganda and Yemen. Although this distribution reflects the vagaries of collecting and recording during these early years, the records do show that African armyworm has occurred in Africa for many years and that it is certainly an indigenous species (Rose *et al.* 2020).

The population dynamics, onset and spread of AAW outbreaks are strongly influenced by weather conditions. In eastern Africa, the first outbreaks of the season appear to be caused by moths derived mainly from coastal source areas, where out-of-season rainfall enables low density populations to survive the dry 'off-season'; the moths are carried inland on the dominant easterly winds. These 'primary' outbreaks occur in association with the early rainstorms of the 'short rains' season in central or northern Tanzania or south-eastern Kenya. They are often found on the east side of high ground inland from the coast, where annual rainfall is erratic and usually low.

Outbreaks usually spread westwards and northwards from central or northern Tanzania towards Burundi, Rwanda and Kenya, and from Tanzania and Kenya to Uganda, southern Sudan, Ethiopia, Eritrea, Somalia and the Yemen. The patterns of spread are determined by the directions of the dominant winds and locations of rainstorms during the times of moth flights. Outbreak areas can be predicted from a knowledge of the wind fields and the distribution of rainstorms and moth sources.

There appears to be a simultaneous southwards spread of outbreaks from southern Tanzania, Malawi and Mozambique into Zambia, Zimbabwe, Botswana, Swaziland and South Africa, again determined by the winds. Little is currently published about these movements, and virtually nothing is known about the activity of AAW in western Africa. The three regions of eastern, central-southern and western Africa are suggested as suitable for centralized armyworm management, to correspond with the major zones of AAW movements. The

relationship between wind strength and direction and AAW appearance in each country would be a worthwhile research endeavor.

Losses in agricultural production due to the AAW affect the economies of both farmers and nations. Armyworm attack and thus cause the loss of cereal crops, pastures and rangeland. They are, therefore, also of importance to livestock production, especially for pastoralists. Farmers will sometimes replant maize when armyworm larvae have eaten the first sowing of plants down to ground level, even though the optimum planting date will have passed. Yield losses of 6% have been estimated for each day's delay after the optimum planting date in high rainfall areas. Areas with less rainfall may suffer higher yield losses of up to 92%. In contrast to FAW, little is known about genetic strains of AAW throughout its distribution and any impacts different strains have on host plant preferences.

The FAW exhibits a remarkable capacity for rapid geographical expansion. Since its initial detection in Africa in 2016, this highly invasive pest has established itself in over 80 countries across Africa, Asia, the Near East, and the Pacific. Recent reports suggest its further spread to Vanuatu and Romania in 2024 (Overton *et al.* 2021).

The rapid global spread of FAW is facilitated by a combination of biological traits and anthropogenic factors. Its strong flight capabilities, high reproductive rate, and polyphagous diet enable it to rapidly colonize new territories. Furthermore, human activities, such as international trade and transportation, have inadvertently contributed to its global dissemination. For example, the movement of infested agricultural commodities and plant materials has played a significant role in the FAW's transcontinental expansion (Matova *et al.* 2020; Agravante *et al.* 2023).

FAW invasion began in West Africa in 2016, subsequently spreading to over 44 African nations (Goergen *et al.*, 2016). This infestation has resulted in significant economic losses, with an estimated annual cost of USD 4.8 billion to African maize production alone (Sileshi *et al.*, 2019). A wide range of crops serve as hosts for FAW, including cereals such as maize, sorghum, and millets; legumes like soybean and groundnut; and other crops grown in Botswana such as ginger, tomato, cabbage, and pasture grasses (Goergen *et al.* 2016; Sileshi *et al.* 2019).

While morphologically indistinguishable, FAW exhibits two genetically distinct strains with differential host plant preferences. These preferences are not primarily driven by the diet of the individual insect, but rather by their inherent genetic makeup. However, a recent report (Nagoshi and Meagher, 2022) noted that the diet also plays a significant role in contributing to the morphological differences observed between rice (R) and maize (C) strains. Limited difference in the behaviour of R-strain and C-strain has been documented. It was reported that the two strains were found to differ in the timing of female calling and copulation, with C-strain females engaging in sexual activity early in the evening and R-strain females doing so later (Tay *et al.*, 2023).

Maize-fed FAW developed faster, with shorter egg and larval stages, compared to the rice-fed larvae, and attained larger body sizes (Navasero *et al.* 2023). This translates to higher population growth metrics for the maize strain, along with shorter average generation time

(He et al., 2021). These findings suggest that maize provides a more favourable host environment for FAW development and population growth. It is not known which strains of FAW exist in Botswana.

Key threats from armyworm species in Botswana

RAPID SPREAD AND INFESTATION

Armyworm are highly mobile pests with an exceptional reproductive capacity. These attributes facilitate their rapid spread across vast geographical areas once they have established a foothold. This rapid dispersal poses a significant challenge for farmers and agricultural authorities as it complicates control efforts and necessitates swift and coordinated response measures (Tucker *et al.* 1983, Niassy *et al.* 2021, Chisonga *et al.* 2023, Kansiime *et al.* 2023).

DIRECT CROP DAMAGE

Armyworm larvae are voracious feeders, posing a direct threat to numerous crops. They consume significant portions of leaf tissue, often resulting in extensive defoliation. In addition to leaves, AAW and FAW larvae may also damage the stems, hindering plant growth and development. While some crops exhibit a certain degree of resilience compared to maize, substantial yield losses can still occur. Unlike maize, where complete crop failure is more common, sorghum and pasture plants often survive, but with reduced productivity. This results in economic losses for farmers primarily due to increased management costs rather than total crop loss (Liu *et al.*, 2024).

PESTICIDE RESISTANCE

The evolving nature of AAW and FAW populations presents a persistent challenge to pest management. The development of insecticide resistance among AAW and the known FAW strains has reduced the efficacy of chemical control measures, necessitating the increased use of pesticides to achieve adequate control. This reliance on chemical inputs not only drives up production costs for farmers but also exacerbates environmental concerns (Gui *et al.*, 2022; Hafeez *et al.*, 2022).

SECONDARY PEST OUTBREAKS

The widespread use of broad-spectrum insecticides to manage armyworm populations (as seen in the 2025 outbreaks of both species in Botswana) can disrupt the delicate balance of the agricultural ecosystem. Beneficial insects, natural enemies of many pest species, are particularly vulnerable to these chemical interventions. The decline of natural enemies can create opportunities for secondary pests to proliferate, further complicating pest management strategies and increasing the overall impact on crop yields (Guera *et al.*, 2021).

ENVIRONMENTAL AND HUMAN HEALTH RISKS

The heavy reliance on chemical insecticides to control AAW and FAW carries significant environmental and human health consequences. Pesticide residues can contaminate soil and water bodies, harming beneficial organisms and potentially affecting human health through the food chain. Furthermore, farmers and agricultural workers are directly exposed to these

chemicals, increasing their risk of acute and chronic health problems. The long-term implications of pesticide use on human health and the environment underscore the urgent need for sustainable and integrated pest management approaches (Guera *et al.*, 2021; Gui *et al.*, 2022; Hafeez *et al.*, 2022; Tay *et al.*, 2023).

As an indigenous species, the AAW has evolved intricate ecological relationships through co-evolution with various host plants and natural enemies. These natural enemies, including parasitoids and predators, have adapted to effectively regulate AAW populations over space and time. Similar observations can be made for FAW, which exists in balance with its natural enemies in the Americas. However, the parasitoids of AAW and FAW in Botswana have not been extensively studied.

Management strategies for armyworm in Botswana

Effective management of AAW and FAW in Botswana needs a multi-pronged approach that integrates various control tactics. These key methods include:

HARNESSING PLANT RESISTANCE: A SUSTAINABLE APPROACH

Developing crop varieties with inherent resistance to AAW and FAW offers a promising and sustainable approach for preventive control. Beyond genetic resistance, agronomic practices can bolster plant defences against FAW. For example, applying silicon (Si), either by spraying it on the leaves or adding it to the soil (1% = 1.4 t Si/ha), has been shown to hinder FAW growth and promote healthier rice plants (Nascimento *et al.*, 2018). Additionally, the concept of induced resistance, where plants are primed to activate defence mechanisms, offers another potential strategy. Stout *et al.* (2009) showed the efficacy of jasmonic acid application in reducing FAW larval growth rates and enhancing the plant defence.

While genetically modified (GM) maize varieties with build-in resistance to AAW and FAW represents a promising long-term solution, their commercialization faces significant regulatory hurdles and public acceptance challenges. The success of GM cotton in controlling the cotton bollworm in China highlights the potential of this technology (Hardke *et al.*, 2011; Lü *et al.*, 2018). However, careful considerations must be given to the potential risks and benefits of GM crops before its widespread adoption.

CULTURAL CONTROL: A SUSTAINABLE APPROACH

Cultural control practices offer sustainable and environmentally friendly approaches to managing AAW and FAW populations. Staggered planting, by disrupting the pest's life cycle and limiting food availability, can effectively reduce armyworm populations. Timing planting to coincide with periods of low moth activity, often influenced by environmental factors such as temperature and rainfall, can further minimize infestation risks (Yigezu and Wakgari, 2020; Kumar *et al.*, 2022). Needless, timing planting to coincide with low moth abundance relies on knowledge of the movement of moths based on wind and weather conditions and the on-ground abundance of moths being monitored by nation-wide pheromone trapping.

Physical control measures, such as deep ploughing, can also disrupt the armyworm life cycle. The armyworm larvae bury themselves deep in the soil after they have finished feeding and pupate before emerging as adults. Deep ploughing exposes the pupae to unfavourable environmental conditions and reduces their survival rates (Yigezu and Wakgari, 2020).

Crop management practices such as planting crops in rotation with non-host crop species can deprive AAW and FAW of essential food sources, hindering population growth (Matova *et al.* 2020). Additionally, maintaining clean fields by removing crop residues, weeds, and alternative host plants reduces habitat suitability for egg-laying and larval growth, thereby limiting the species ability to establish and proliferate within and around the crop (Yigezu and Wakgari, 2020).

While trap cropping and push-pull strategies have shown promise in managing other pests, their efficacy against AAW and FAW in Botswana stays undemonstrated. Similarly, manual removal and destroying egg masses and larvae from infested plants or installing physical barriers like screens or nets, though effective on a small scale, are impractical for large-scale crop production due to labour-intensive requirements and limited impact on overall population levels.

Whilst cultural control methods form a crucial component for armyworm management, their effectiveness can be limited by factors such as the severity of infestation and the scale of production. Integrating cultural control with other management strategies, such as biological control and judicious use of insecticides, is essential for comprehensive and effective armyworm management.

BIOLOGICAL CONTROL: A NATURAL SOLUTION

Biological control offers a promising alternative to traditional chemical insecticides for enhancing AAW and FAW management in Botswana. Natural enemies, including predators and parasitoids, can significantly reduce populations of both species while promoting environmental sustainability. In addition, mixed cropping fields often harbour a greater diversity of natural enemies compared to monocultures, providing a favourable environment for biological control agents (Settle *et al.* 1996, Evans, 2005, Bianchi *et al.* 2006).

Predators of AAW include both vertebrates (mainly birds) and invertebrates (ants, beetles, thrips and spiders). Ants and thrips destroy eggs and ants kill many young larvae. Storks and crows may decimate smaller outbreaks, but have little effect on larger outbreaks. Irrespective, the role of predators in suppressing AAW outbreaks has not been quantified in Botswana.

Predatory insects such as big-eyed bugs (*Geocoris* spp.), assassin bugs (Reduviidae), and minute pirate bugs (*Orius* spp.), have demonstrated predatory behaviour towards FAW in maize elsewhere (Keerthi *et al.* 2020, Ogunfunmilayo *et al.* 2021). Their potential application in crop production systems in Botswana warrants further investigation. Even the multicoloured Asian lady beetle (*Harmonia axyridis*), known for its predatory behaviour against other pests, has shown potential against FAW in maize (Di *et al.* 2021) and, being present in Botswana, could be a valuable asset in FAW control.

Ground beetles, particularly those in the genera *Calosoma*, *Chlaenius*, *Graphipterus* and *Anthia* are demonstrated to be effective predators of armyworm larvae and pupae (Young and Hamm 1985). Spiders, including wolf spiders (*Lycosa spp.*) and other hunting spiders are important generalist predators of lepidopteran pests such as armyworm. Additionally, certain predatory insects like long-horned grasshoppers, true crickets and numerous species of earwigs (Cokola *et al.* 2023) can prey on armyworm larvae. Ants, particularly *Camponotus spp.* have also been observed as effective predators, consuming up to 23 individual armyworm larvae within the first 10 days of infestation (Dassou *et al.* 2021, 2023).

These findings underscore the potential of predatory insects as valuable allies in managing AAW and FAW populations in Botswana. Further research is essential to evaluate their efficacy under diverse cultivation systems and to develop strategies for enhancing their populations and effectiveness.

Parasitoids, such as egg parasitoids like *Telenomus remus* and *Trichogramma pretiosum*, have demonstrated high efficacy in controlling armyworm in various crops, including maize (Yigezu and Wakgari 2020, Navasero *et al.* 2023, Sampaio *et al.* 2024). These tiny wasps lay their eggs inside host eggs, resulting in the development of parasitoid offspring instead of the pest. Several species of egg-larval parasitoids belonging to the genus *Chelonus* have demonstrated high efficacy in controlling armyworm in various crops, including maize (Calcetas *et al.* 2024).

Larval parasitoids, including the braconid wasps *Campoletis sonorensis*, *Cotesia marginiventris*, and *Cotesia flavipes* are effective in parasitizing and killing armyworm larvae (Meagher Jr *et al.* 2016, Barreto-Barriga *et al.* 2021). Recent studies in the Philippines have identified a *Brachymeria spp.* (larval-pupal parasitoid) and *Copidosoma floridanum* (a larval parasitoid) as additional parasitoids (Valdez *et al.* 2024), expanding the pool of potential biological control agents. To date the parasitoid fauna of Botswana has not been studied in any detail and is a fertile area for investigation.

The diversity of parasitoid species associated with AAW and FAW underscores the potential for developing innovative and novel region-specific biocontrol programs. Investigating native natural enemies can lead to the identification of effective and sustainable control options. By harnessing the natural capabilities of these beneficial insects, integrated pest management strategies can be enhanced to effectively manage AAW and FAW populations in Botswana.

In addition to arthropods, entomopathogenic microorganisms offer a promising biological control strategy for managing AAW and FAW in Botswana. These naturally occurring pathogens offer environmentally friendly alternatives to synthetic insecticides. *Bacillus thuringiensis (Bt)*, a naturally occurring soil bacterium, is a widely used biopesticide against various lepidopteran pests, including the AAW and FAW (Hamal *et al.* 1991, Bai *et al.* 1993, Polanczyk and Alves 2005). Similarly, the entomopathogenic fungi *Metarhizium anisopliae* and *Beauveria bassiana* can effectively infect and kill armyworm larvae, making them potential biocontrol agents (Jeon and Kim 2024). For example, *Beauveria bassiana* can cause up to 93% mortality in FAW larvae under laboratory conditions (Munywoki *et al.* 2022, Jeon and Kim 2024). Similarly, *M. rileyi* caused more than 95% FAW larvae mortality under

laboratory or green house conditions (Zhou *et al.* 2020, Faria *et al.*,2022). However, quantification of the role of entomopathogenic fungi has not been undertaken in Botswana.

Entomopathogenic nematodes, such as those belonging to the genera *Steinernema* and *Heterorhabditis*, are beneficial soil-dwelling nematodes that harbour symbiotic bacteria. Upon infecting the armyworm larvae, these nematodes release the bacteria, resulting in host death (Garcia *et al.* 2008, Fallet *et al.* 2022). Baculoviruses, another group of microbial pathogens, have shown high virulence against FAW larvae, offering potential as a component of integrated pest management strategies (Cuartas-Otálora *et al.* 2019, Hussain *et al.* 2021, Gómez-Valderrama *et al.* 2022).

Integrating these biological control agents into comprehensive pest management programs can contribute to sustainable and effective armyworm control while minimizing reliance on chemical insecticides.

HABITAT MANIPULATION: CREATING A FRIENDLY ENVIRONMENT FOR NATURAL ENEMIES

Modifying crop field habitats through intercropping and agro-ecological practices can significantly enhance the diversity and abundance of natural enemies, thereby promoting biological control of AAW and FAW (Keerthi *et al.* 2023). By creating a more complex and diverse ecosystem, these strategies can support a wider range of beneficial insects, including predators and parasitoids, which play a crucial role in regulating pest populations.

CHEMICAL CONTROL: A NECESSARY TOOL BUT NOT THE ONLY SOLUTION

Insecticide application remains a critical tactic for managing AAW and FAW populations (Deshmukh *et al.* 2020, Srujana *et al.* 2021, Van den Berg and du Plessis 2022). While synthetic insecticides have been widely used, there is a growing interest in developing more environmentally friendly alternatives.

BOTANICAL INSECTICIDES: A NATURAL APPROACH

Botanical insecticides, derived from plant extracts, offer a promising approach to armyworm control and management. Neem-based and pyrethrum-based products have shown efficacy in disrupting insect development, feeding behaviour, and reproduction (Souto *et al.* 2021, Silva *et al.* 2015). These natural insecticides can provide effective control while minimizing adverse impacts on beneficial organisms and the environment.

SYNTHETIC INSECTICIDES: A CONTINUED NECESSITY

Synthetic insecticides remain a critical component of armyworm management, despite the growing emphasis on environmentally friendly alternatives. Several insecticide classes have demonstrated efficacy against armyworm larvae, including pyrethroids, anthranilic diamides, avermectins, spinosyns, and indoxacarb.

Pyrethroids, such as lambda-cyhalothrin, disrupt the larval nervous system, leading to rapid mortality upon contact (Wu *et al.* 2023). Anthranilic diamides, exemplified by chlorantraniliprole, target muscle receptors, causing paralysis and death. Avermectins, including emamectin benzoate, act on the larva's nervous system, inducing paralysis and mortality (Deshmukh *et al.* 2020, Liu *et al.* 2022).

Spinosyns, derived from natural sources, represent a class of insecticides that include spinetoram and spinosad. These compounds disrupt the insect nervous system, causing paralysis and death (Salgado 1998, Orr *et al.* 2009, Deshmukh *et al.* 2020, Srujana *et al.* 2021, Salem *et al.* 2024). Spinosad, in particular, has a unique mode of action that leads to low toxicity to mammals and beneficial insects, making it suitable for IPM strategies (Salgado 1998, Orr *et al.* 2009). Indoxacarb, another synthetic insecticide, targets the larval nervous system within the insect (Wu *et al.* 2023).

THE CHALLENGE OF INSECTICIDE RESISTANCE

While synthetic insecticides offer some control of AAW and FAW, their indiscriminate nature can lead to adverse environmental impacts, including the development of insecticide resistance. To mitigate these challenges and promote long-term sustainability, IPM strategies that combine insecticide use with other control tactics are essential. Factors such as the development of insecticide resistance, environmental conditions, and proper application techniques influence the efficacy and impact of insecticides. The implementation of decision support systems (DSSs) can help farmers manage insecticide resistance by optimizing pesticide application timing and amount. DSSs can also help farmers make more sustainable decisions about pest management including for armyworms (Che *et al.* 2013, Akaka *et al.* 2024, Tonle *et al.* 2024).

Pheromone traps: A powerful monitoring tool

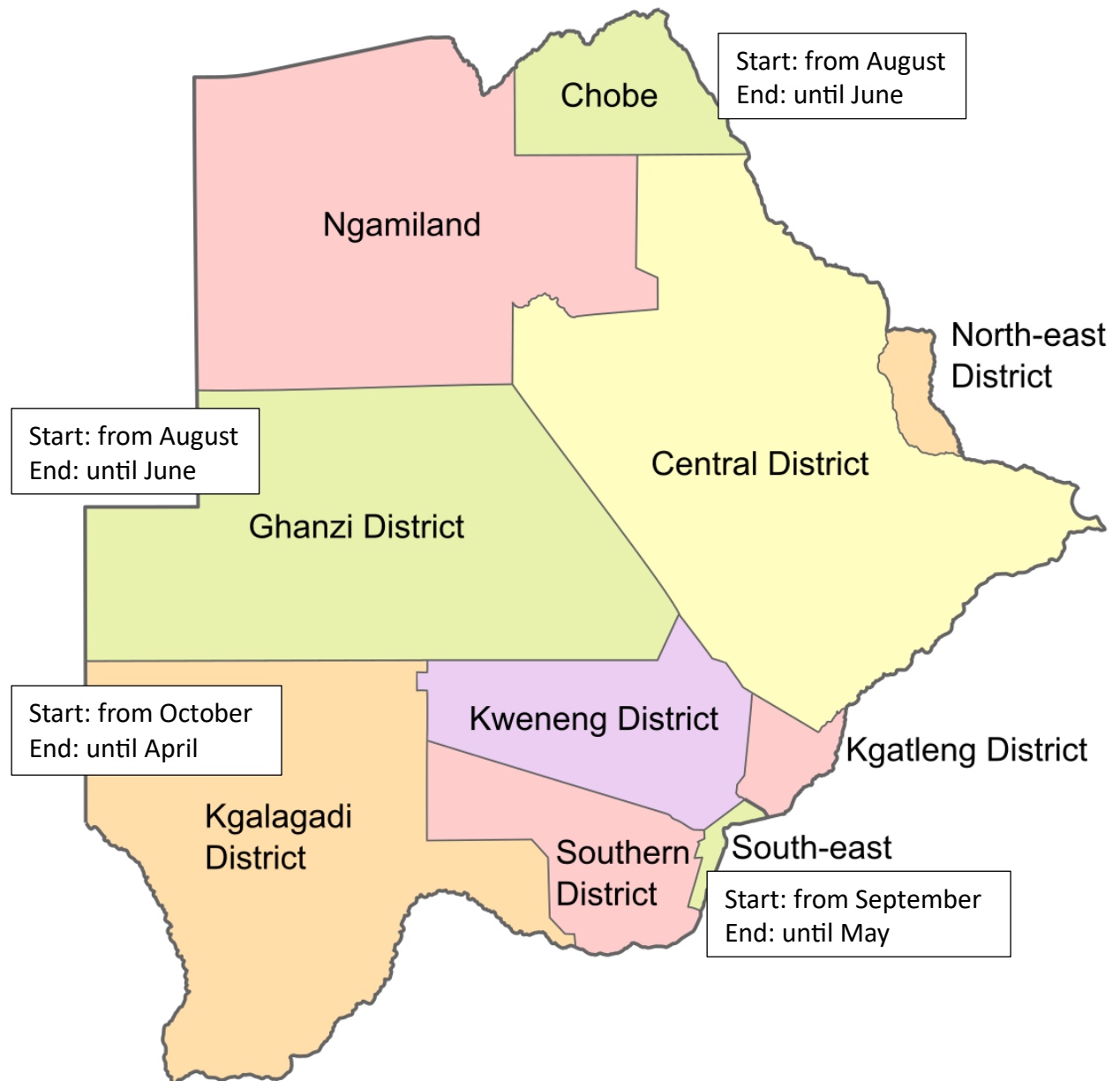
As trans-boundary pests in sub-Saharan Africa, the successful management of AAW and FAW requires strengthened regional cooperation to assist affected countries manage the impacts of outbreaks (Srinivasan *et al.* 2022). In this context, pheromone traps represent a valuable tool for managing AAW and FAW populations in Botswana. These traps effectively exploit the sex pheromones released by female moths to attract and capture male moths, thereby disrupting the mating process and consequently reducing reproduction (Jiang *et al.* 2022, Gao *et al.* 2023). The deployment of pheromone traps serves as a crucial early warning system for growers, enabling them to proactively optimize scouting efforts and precisely time the application of necessary treatments (Kumar *et al.* 2022).

Commercially available AAW and FAW pheromone lures, usually comprising a blend of compounds which mimic the sex pheromones, are widely utilized in monitoring and control programs across various countries (Sanches *et al.* 2019). By strategically placing pheromone traps across Botswana, and having a regular analysis of trap catches, growers can have an effective early-warning system and be advised to monitor armyworm population dynamics and detect infestations at their earliest stages. This initiative-taking and proactive approach facilitates timely intervention with appropriate management strategies, thereby mitigating the risk of substantial crop losses and minimizing the reliance on excessive pesticide applications (Cruz *et al.* 2012). In some other sub-Saharan African countries, the pheromone trap captures are reported to a central body which keeps farmers informed of any suspected moth outbreaks. However, such an approach is lacking in Botswana.

The challenge in a population-sparse country like Botswana is where and when to monitor for armyworm moths? In an attempt to answer this question Insect Factory has used the available meteorological data between 2019 and 2025 for various towns across the country.

By combining these data with knowledge that both armyworm species require a minimum of 11°C to undertake their development, a calculation can be derived to predict in what months armyworm moths should be monitored and which months armyworm development ceases.

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Climate change: A catalyst for armyworm expansion

Climate change is a significant driving force behind the expansion and intensification of insect pest distributions and abundances, including the armyworm species in Botswana. As global temperatures steadily rise and precipitation patterns undergo significant shifts, the

potential geographic ranges of AAW and FAW is expanding at an alarming rate, exposing new regions to its destructive potential (Yan *et al.* 2022, Zhang *et al.* 2023). Warmer temperatures facilitate an increase in the number of generations of the pests, thereby accelerating population growth and significantly expanding their geographical range (Sumila *et al.* 2024).

Furthermore, climate change indirectly influences AAW and FAW populations by altering the suitability of host plants and disrupting the intricate balance between the pest and its natural enemies. Drought stress, a frequent consequence of climate change, can significantly impact plant chemistry and structure, thereby affecting larval feeding, and development (Sumila *et al.*, 2024). Moreover, shifts in temperature and precipitation patterns can disrupt the delicate synchrony between the pests and their natural enemies, potentially leading to increased pest populations and a substantial reduction in the efficacy of biological control (Yan *et al.*, 2022).

In conclusion, climate change is a major contributing factor driving the expansion and intensification of armyworm infestations. Adapting to these rapidly changing conditions necessitates a comprehensive and integrated approach that incorporates climate-resilient agricultural practices, robust early warning systems, and carefully implemented integrated pest management strategies. By thoroughly understanding the multifaceted impacts of climate change on armyworm populations and developing effective mitigation measures, we can safeguard crop production and ensure long-term food security in the face of this escalating threat.

Future of sustainable armyworm control

Elsewhere, the relentless spread of the AAW and FAW has spurred significant research into sustainable management strategies. Addressing critical challenges such as accurate pest identification, developing resistant crop varieties, and harnessing the potential of biological control agents are paramount for mitigating the devastating impacts of AAW and FAW.

ACCURATE PEST IDENTIFICATION: A CRUCIAL FIRST STEP

Accurate identification of the AAW and FAW remains a challenge, as farmers often misidentify other armyworm or cutworm species, leading to incorrect diagnoses and inappropriate control measures. For example, Nagoshi *et al.* (2021) reported that the R-strain of FAW may be rare or even absent in Africa, at least in the west African region, but this information is unknown in southern Africa including Botswana. It should be questioned whether the apparent absence of the R-strain is due to limitations of current pest monitoring and identification methods. The implementation of improved diagnostic tools, coupled with comprehensive training programs for farmers and extension workers, is essential to enhance early detection and enable the timely implementation of targeted control measures.

DEVELOPING RESISTANT CROP VARIETIES: A GENETIC SOLUTION

Advanced breeding technologies are being employed elsewhere to develop armyworm-resistant maize varieties (Botha *et al.* 2019). Scientists are mining germplasm collections for

resistance genes and utilizing marker-assisted selection to expedite breeding programs. These new varieties aim to combine resistance mechanisms such as hindering larval development and deterring feeding or egg-laying, with desirable agronomic characteristics like high yield, broad-spectrum resistance to other pests and diseases, and superior eating quality. Significant progress has been made in developing or screening maize varieties for resistance or tolerance to FAW in particular by the International Maize and Wheat Improvement Centre (CIMMYT) for the benefit of Africa, Asia, and Latin America, and it would be prudent for Botswana to be engaged in such studies.

GENE DRIVE TECHNOLOGY: A POTENTIAL GAME-CHANGER

Gene drive technology offers a potentially transformative approach to managing AAW and FAW populations. For example, advances in genetic engineering have provided new opportunities to improve the performance of laboratory-reared male moths released into the wild through gene editing and RNAi interference (Zotti *et al.* 2018, Kumari *et al.* 2022). By introducing genes that induce sterility or mortality within the armyworm population, researchers could theoretically engineer a population decline. However, the development and release of such a technology necessitate extensive research, rigorous safety assessments, and careful consideration of the potential ecological and ethical implications. Significant progress has been made in screening for resistant and tolerant genes in maize against the corn borer, but there is an urgent need for the development and field-level implementation of additional armyworm-resistant varieties of other crops and this remains an area of ongoing research.

HARNESSING THE POWER OF THE MICROBIOME

The microbiome is a complex, dynamic community of microorganisms that inhabit specific environments, such as the animal gut, skin, and mouth, and a plant's leaves, roots and flowers. Microbiome manipulation for enhanced biocontrol is an innovative research avenue that focuses on optimizing the plant microbiome to promote beneficial bacteria and fungi capable of suppressing armyworm populations. This could involve the introduction of specific beneficial microbes or the stimulation of the growth of native microbial communities. The application of biofertilizers to enhance beneficial microbiomes within push-pull cropping systems has shown promise in pest insect management (Dzvene and Chidzuza 2024). Furthermore, research on other moth species has demonstrated that altering insect gut microbiota can be an effective strategy for managing pest populations (Castañeda-Molina *et al.* 2023). These findings underscore the significant potential of microbiome manipulation as a sustainable approach for controlling AAW and FAW populations in Botswana. Continued research is crucial to fully elucidate the intricate interactions between microbes, plants, and pests, thereby paving the way for the development of innovative and sustainable agricultural practices.

ENHANCING BIOLOGICAL CONTROL AGENTS

Enhancing biological control agents is a cornerstone of sustainable armyworm management. This involves optimising the utilisation of existing biological control agents, such as parasitoid wasps and entomopathogenic bacteria, fungi, and other microbes. Key strategies include refining rearing methods for mass production, enhancing delivery systems within crops such as the use of drones, and exploring potential genetic modifications to increase

their effectiveness against both AAW and FAW. The methods and practices of enhancing biological control agents in Botswana is a fertile, but untouched, area of research.

INTEGRATED PEST MANAGEMENT (IPM): A COMPREHENSIVE APPROACH

Integrated pest management (IPM) decision support systems (DSSs) empower farmers with data-driven insights for making informed management decisions (Akaka *et al.* 2024). These digital tools and models incorporate a range of factors, including weather patterns, adult and larval population dynamics, and crop growth stages. By providing tailored recommendations, these DSSs enable farmers to implement the most effective and sustainable pest management strategies for their specific conditions (Afam-Ezeaku and Okigbo 2025). The successful implementation of these tools will require strong collaboration among researchers, meteorologists, extension workers, and farmers, as along with effective communication channels to bridge the gap between scientific advancements and practical on-farm applications.

Research actions, responsibilities, timelines and costs

Action	Research action	Responsibility	Timeline	Cost
1	Explore the genetic diversity of AAW and FAW in Botswana	1. NARDI Field Crops and Horticulture, for genetic testing. 2. Insect Factory, for specimen collections	2 years	P500k
2	Quantification of the damage caused by AAW and FAW	NARDI Agricultural Economics and Statistics	1 year	P150K
3	Quantification of pesticide resistance	1. NARDI Field Crops and Horticulture, for laboratory studies 2. Insect Factory, for specimen collections	3 years; annual and multi-year resistance surveys; nationwide	P500k
4	Explore plant resistance via traditional methods and gene drive technology	1. NARDI Field Crops and Horticulture, for laboratory studies 2. NARDI Technology Transfer and Commercialisation, for plant variety registration	5 years; in conjunction with international collaborators	P1m

5	Impact of pupae-busting on populations of AAW and FAW	1. Insect Factory 2. Collaborating farmers	3 years to account for seasonal and annual variations	P500k
6	Development of trap cropping and push-pull technologies for better management of AAW and FAW	1. NARDI Field Crops and Horticulture, for laboratory and field studies in collaboration with 2. Insect Factory	3 years	P500k
7	Exploration of biological control agents: predators and parasitoids	1. Insect Factory 2. Collaborating institutions for invertebrate identifications	3 years to account for seasonal and annual variations in abundance and distribution	P500k
8	Exploration of biological control agents: entomopathogenic microbes	1. NARDI Field Crops and Horticulture, for laboratory and field studies in collaboration with 2. Insect Factory	3 years to account for seasonal and annual variations in abundance and distribution	P500k
9	Development of botanical insecticides	1. NARDI Field Crops and Horticulture, for laboratory and field studies in collaboration with 2. Insect Factory	2 years to account for identification and testing of botanical substances	P300k
10	Development of an armyworm early-warning system	1. NARDI Field Crops and Horticulture, for laboratory and field studies in collaboration with 2. Insect Factory 3. Meteorology Office 4. BUAN modelling group	2 years for system development, testing and deployment	P500k
11	Modelling impacts of climate change on AAW and FAW	1. BUAN Faculty of Science 2. Insect Factory	2 years for system development,	P250k

	population dynamics		testing and publication	
12	Development of an app for accurate identification of AAW and FAW	1. BUAN Faculty of Science 2. Insect Factory	2 years for system development, testing and publication	P400k
13	Exploration of the plant microbiome	1. BUAN Faculty of Science 2. NARDI Field Crops and Horticulture	3 years; discovery, isolation, and deployment	P600k
14	Development of Armyworm Handbook for Botswana	3. Insect Factory 4. Bantu Farmers Academy	1 year to collate information, draft and publish	P250k
15	Development of effective communications strategy	1. Insect Factory, in collaboration with 2. NARDI Field Crops and Horticulture 3. Bantu Farmers Academy	3 years; development and deployment; seminars/Field days/media	P400k
			Total cost	P6,850,000

Summary of Actions, Financial Allocations and Institutions (Pula)

Action	Botswana Farmers Academy	BUAN	Bureau of Meteorology	Insect Factory	NARDI	Total
1				150	350	500
2					150	150
3				150	350	500
4					1,000,000	1,000,000
5				500		500
6				250	250	500
7				500		500
8				100	400	500
9				100	200	300
10		50	50	300	100	500
11		150		100		250
12		250		150		400
13		300			300	600
14	150			100		250
15	200			100	100	400
Total	350,000	750,000	50,000	2,500,000	3,200,000	6,850,000

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