Assessment of potential biopesticide options for managing fall armyworm (Spodoptera frugiperda) in Africa

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\textbf{Abstract}
The fall armyworm (FAW, Spodoptera frugiperda) originates from the tropical and subtropical regions of the Americas. Recently it was reported for the first time in Africa and has since spread rapidly across more than 30 countries in the continent. Chemical pesticides are being promoted and used for FAW management, but where application practices and/or the active ingredients are unsafe there is a need to make effective, low-risk products available. Given that biopesticides such as microbials and microbial extracts, macrobials and semiochemicals are generally considered to be lower risk options for pest management, they are a promising avenue for exploration. When used in conjunction with good crop management, they can help to keep pest levels under control, reducing the need to apply other pesticides. This study provides a basis for designing interventions to make biopesticides more widely available for FAW control in Africa. It summarizes assessments of the registered pesticides and biopesticides for 30 countries, 11 in FAW’s native range and 19 in Africa. The report identifies biopesticide active ingredients (AI) which are registered for use against FAW and provides an assessment of how appropriate these will be for use by smallholder farmers in Africa. For each biopesticide AI identified, detailed profiles were developed which covered the efficacy of the AI against FAW; the human health and environmental hazards associated with the AI; the agronomic sustainability of the AI; and whether or not the AI is practical for smallholder farmers to use. Using these data, a list of priority biopesticides for which follow-up action is recommended was compiled. Fifty biopesticide AI were identified, which have been registered in one or more of the 30 countries for FAW management. Twenty-three of these are recommended for follow-up, for example field trials or bioassays.

\textbf{Keywords}
active ingredients, bioassays, corn, efficacy, macrobials, maize, microbials, registration, risk assessment, semiochemicals, sustainability
Fall armyworm (FAW, Spodoptera frugiperda (J.E. Smith), Lepidoptera: Noctuidae), a major agricultural pest in the Americas, is newly invasive in Africa. Southern armyworm, S. eridania (Stoll) is a relatively minor agricultural pest in the Americas, which has also just been reported from Africa (Goergen, 2018), although how damaging it will be in Africa has yet to be evaluated. This study focuses on fall armyworm, but the results and conclusions will also be relevant to southern armyworm. Fall armyworm is a highly mobile species indigenous to tropical and sub-tropical regions of North, Central and South America. While FAW caterpillars can potentially feed on over 100 species of plants from a wide range of families (CABI, 2018a), in the field they mainly attack members of the Poaceae family, causing major damage to economically important cultivated grasses such as maize, rice, sorghum and sugarcane as well as other crops including cabbage, beet, peanut, soya bean, alfalfa, onion, cotton, pasture grasses, millet, tomato, potato and cotton (CABI, 2018a, Pogue, 2002). In its native range, it is often considered the most important pest of maize, for example in Brazil (Sarmento et al., 2002). In 2016 it was first reported in West Africa (Cock, Beseh, Buddie, Cafà, & Crozier, 2017; Goergen, Kumar, Sankung, Togola, & Tamò, 2016), and by the end of 2017 it had spread to over 30 countries across tropical and southern Africa as well as to Madagascar, Seychelles and Cabo Verde and has the potential to spread to parts of the Mediterranean and Asia (Day et al., 2017; FAO, 2017a; 2018a). It is projected that "tens of millions" of smallholder farmers in Africa will be affected (FAO, 2017b). Given that FAW’s Poaceae hosts include maize, sorghum, millet and teff, which are all staple crops in Africa, FAW poses a major threat to food security (Day et al., 2017).

Initial findings indicate that this concern is justified and the overall impact of FAW will be large. A recent evidence note from CABI (Abrahams et al., 2017; Day et al., 2017), commissioned by the United Kingdom’s Department for International Development (DFID), reported results of a rapid survey of farmers in Ghana and Zambia. Based on farmers’ estimates of their crop loss, it was calculated that 45% and 40% of maize production could be lost in Ghana and Zambia, respectively. Extrapolating this to 10 other maize producing countries in Africa, total annual production losses from the 12 countries, in the absence of effective control, were estimated to be 8.5 to 21 million tonnes, with a value of 250 to 630 million US dollars.

Eggs are laid as “egg masses” in batches of 100–200 eggs on leaves, and hatch in two to four days in optimum temperatures. The developing larvae eat different parts of the host plant, depending on the crop, the stage of crop development and the age of the larvae. On maize, young larvae usually feed on developing leaves in the funnel, creating a characteristic windowing effect. This and moist sawdust-like frass near the funnel and upper leaves can be an easily spotted sign of larval feeding. Early in the season, this feeding can kill the growing point, a symptom called “dead heart” in maize, which prevents any cobs forming. Young larvae hide in the funnel during the day but emerge at night to feed on the leaves. It is at this time of day that certain control options may be most effective. In young plants, the stem may be cut by larval feeding, providing evidence of damage. Older larvae stay inside the funnel, and in older plants, the larger larvae can bore into the developing reproductive structures, such as maize cobs, reducing yield quantity and quality, which protects them from traditional spray pesticide applications and natural enemies. This behaviour makes their control by direct interventions such as pesticides (including biopesticides) more difficult, especially where efficacy depends upon contact.

The preferred management option for FAW is integrated pest management (IPM) (Day et al., 2017), based on utilizing a combination of control methods that is sustainable, cost-effective and causes minimal risks to humans and the environment. However, in the face of potentially devastating losses due to FAW, many stakeholders have turned to chemical pesticides for control. Governments in Africa have purchased and distributed pesticides worth millions of dollars, often favouring the cheaper and generally higher risk products. Examples of pesticides which are reported as being used for FAW management include methomyl, methyl parathion, endosulfan and lindane, all of which are classified as highly hazardous pesticides (HHPs) (FAO, 2018a). HHPs are pesticides that are “acknowledged to present particularly high levels of acute or chronic hazards to health or environment according to internationally accepted classification systems and pesticides that cause severe or irreversible harm to health or the environment under conditions of use in a country” (FAO, 2016). Abrahams et al. (2017) reported over 60% of farmers interviewed in Ghana and Zambia had applied pesticides, while Kumela et al. (2018) found 48% of farmers used chemical sprays in Ethiopia and Kenya. Pesticide dealers and local producers of “organic” concoctions, which may be unproven and unregistered, have been quick to seize the opportunity to market their products. This has left many farmers confused as to what they should be doing. Additionally, farmers are putting themselves at risk using toxic products about which they know little and/or do not have the suitable personal protective equipment to adequately manage risks.

Given the concerns posed by pesticides, the development of low-risk management approaches using biopesticides for FAW based on biochemical, microbial or microbial pest management products is high on the list of near-term activities identified in action plans for affected countries in Africa, at both national and regional level. For example, the national FAW response plan of Ghana has four components, and Component 3, covering “Control, Management and Research,” includes the identification, testing and deployment of lower-risk options such as biopesticides. At the continental level, the Food and Agriculture Organisation of the United Nations (FAO) has developed a Framework for Partnership (FAO, 2018b). This framework emphasizes alternatives to pesticides, such as微生物s and their extracts, botanicals, semiochemicals, inorganic biochemicals, predators and parasitoids. Many of these have been evaluated in the FAW native range providing valuable information for developing these control options for Africa.

However, while there is general agreement that lower-risk biopesticides products are a highly desirable approach to control FAW and other pests, there is limited information readily and centrally.
**FIGURE 1** Flowchart to summarize the process followed in the analysis for this review (AI = active ingredient, FAW = fall armyworm, HHP = highly hazardous pesticide)
available on availability and accessibility in areas where FAW is now present in Africa. This review sets out to collate information on which biopesticides have been reported to be effective against FAW, where in Africa they are registered, and what further priority actions are needed to increase the availability of suitable biopesticides for use in IPM of FAW across Africa (Figure 1). We analysed lists of registered pesticides for 30 countries in Africa and the Americas, to identify the biopesticide active ingredients (AI) and their associated products that are registered for use against FAW and related pests. We appreciate that in doing so, there is the risk of missing AI that are not yet registered that may be effective against FAW. However, a comparison with an unpublished review by R. Gwynn (pers. comm. 2018) that included some of these, suggested that at this time unregistered AI that are potentially useful against FAW are variants or strains of AI included in our compilation.

For each biopesticide AI, we developed detailed profiles on the efficacy of the AI against FAW and the human health and environmental hazards associated with the AI; these are provided in the Supporting Information Appendix S1. Based on this information, we assessed whether their use would pose unacceptable risks to the farmers who would apply them as well as to the wider community and environment, and whether the AI is practical for smallholder farmers to use including the agronomic sustainability of the AI. Using these data, a decision matrix was developed to provide a basis to design interventions that would make suitable biopesticides more widely available for FAW control in Africa.

2 MATERIALS AND METHODS

This review article builds on the evidence note which was prepared by Abrahams et al. (2017) by updating and expanding upon the preliminary data on the biopesticides which are available for the management of FAW. The evidence note identified 54 biopesticide AI which have been registered in one or more countries for management of FAW, Spodoptera spp. or Lepidoptera in general, and one of the recommendations for next steps identified in the evidence note was that a literature review be conducted in order to prioritize biopesticide AI for follow-up. This review article is the output of that assessment. National lists of registered pesticides are regularly updated, so the information here is a snapshot of what was registered at the time the study was conducted.

2.1 Biopesticide definition

For the purposes of this study, the national regulations were followed for those countries that had already defined what a biopesticide is. However, there are many variations in the definition applied. While certain substance groups are generally accepted as being “biopesticides,” for other substance groups there is no consensus. Examples include plant-incorporated-protectants, antibiotics and microbial fermentation products. For countries that do not define what a biopesticide is, biopesticides were defined for this study as pesticide products of the following groups:

- Biochemical biopesticides:
  - Plant extracts/botanicals
  - Synthetic pheromones/semiochemicals
  - Microbial extracts/fermentation products
  - Insect growth regulators
  - Compounds synthesized by other organisms
  - Inorganic compounds

- Microbial biopesticides:
  - Bacteria
  - Fungi
  - Protozoa
  - Viruses
  - Oomycetes
  - Yeast
  - Algae

- Macrobiicals
  - Insect predators
  - Parasitoids
  - Entomopathogenic nematodes

- Plant-incorporated protectants such as genetically modified maize incorporating genes of Bacillus thuringiensis Berliner and the use of classical biological control were not considered as biopesticides and were excluded from the study.

2.2 Identification of biopesticide active substances which are registered for use against FAW in its native range

For each of the 11 selected countries in FAW’s native range that were assessed (Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Ecuador, Mexico, Panama, Peru and the USA), the most up-to-date versions (where available) of the registered pesticides and biopesticides were used to identify the full list of biopesticide AI and their corresponding products that are registered and can be used to manage FAW (Supporting Information Table S1). For these 11 countries, the extraction of data from the registered pesticides through data scraping was carried out between July and September of 2017, and represents a snapshot of what was registered at that time. CABI software capable of mining and processing large data sets was used to extract registration data from government sources such as online databases and files containing documents in pdf, Excel, Word, etc. The lists of registered pesticides for Brazil, Chile, Colombia, Costa Rica, Ecuador, Mexico, Peru and the United States include information about the pests for which the products are registered. These designations were used to identify the biopesticides that are permitted for use in FAW management in those countries. Biopesticides that are specifically registered for FAW (i.e., which listed the scientific name for FAW or one of its common names in English, Portuguese or Spanish) were identified as well as biopesticides which are more generally registered.
for other species of Spodoptera, Noctuidae, or Lepidoptera as a whole (including the common names for these higher level groups in English, Portuguese and Spanish). For the other countries that do not include information on the target pests in their lists of registered pesticides, the list of registered pesticides was cross-checked against the list of AI which are known to be registered for use against FAW, Spodoptera spp. or Lepidoptera in general in other countries.

For the national lists of registered pesticides that were not in English, the chemical names, crops, target pests and other key information was translated by matching the terms to PubChem synonyms for AI, Inter-Active Terminology for Europe database (http://iate.europa.eu/) and CABI databases. Product and company names were not translated.

2.3 | Biopesticide profiles

### 2.3.1 | Overview

For each of the AI identified in the data sets listed above, a profile was developed, including the chemical class and the relevant pest(s) for which the AI is registered (e.g., whether it was flagged specifically for FAW or more generally for Lepidoptera). The AI themselves are listed by their ISO (International Organisation for Standardization) or IUPAC (International Union of Pure and Applied Chemistry) common names, where available. For some AI, such as certain botanicals, no ISO or IUPAC common name was available. In those cases, the name used in the registration was used for the data set.

### 2.3.2 | Efficacy assessment

A literature review was conducted to assess whether any evidence is available to show that the biopesticide (AI) is effective against FAW, other Spodoptera spp. or Lepidoptera in general. Likewise, it was taken into consideration whether the evidence of efficacy is from data in Africa, FAW’s native range or the laboratory. Based on these assessments, each AI was assigned a code. The codes used to summarize the findings of the efficacy assessments are given in Table 1. According to this coding, an AI that has been found to be effective against Lepidoptera in Africa would be coded YLeAf, and an AI which has been demonstrated to be effective against FAW in its native range would be YFaNr. An AI for which no evidence of efficacy was identified would be coded simply as N.

### 2.3.3 | Hazard assessment

For each AI, any associated hazards to human health and the environment were identified. It was noted whether any of the risks posed by the biopesticide to human health or the environment were unacceptable, as follows. Each AI was assessed to determine whether it could be considered a highly hazardous pesticide (HHP). According to the FAO guidelines on HHPs (FAO, 2016), a pesticide can be classified as an HHP if it meets one or more of the following eight criteria:

- Pesticides that are extremely or highly acutely toxic (Classes 1a and 1b of the WHO Recommended Classification of Pesticides by Hazard (WHO, 2010)
- Known or presumed carcinogens (carcinogenicity Categories 1A and 1B of the Globally Harmonized System of Classification and Labelling of Chemicals (GHS) Part 3—Health hazards (UN, 2015).
- Known or regarded to induce heritable mutations (mutagenicity Categories 1A and 1B of the GHS (UN, 2015)
- Known or presumed human reproductive toxicant (reproductive toxicity Categories 1A and 1B of the GHS (UN, 2015)
- Persistent Organic Pollutants (POPs) as listed in the Stockholm Convention in its Annexes A and B (UNEP, 2017)
- Pesticide AI and formulations that are listed in the Rotterdam Convention Annex III Chemicals (Rotterdam Convention, 2018) because they have been banned or are severely restricted for health or environmental reasons. These pesticides require “prior informed consent” (PIC) when traded internationally.
- Ozone depleting substances (ODS) as listed by the 1987 Montreal Protocol (UNEP-OS, 2018).
- Pesticide AI and formulations that have shown a high incidence of severe or irreversible adverse effects on human health or the environment.

The human health hazards were deemed to be unacceptable if an AI met any of the HHP criteria (FAO, 2016).

In order to determine whether any of the identified biopesticides are HHPs, each AI was examined against the HHP criteria listed above. Identification of AI which are HHPs under criteria 5, 6 and 7 is unambiguous as these chemicals are listed in the Annexes of the indicated international agreements. Identification of AI which are HHPs under criteria 1, 2, 3, 4 is not as clear cut, as categorization of the AI depends on several available sources of information. Under criteria 8, pesticides that cause severe or irreversible harm to human health or the environment under conditions of use in a country may also be considered highly hazardous. If a review of the available hazard data indicated that an AI met one or more of the first 7 HHP criteria, the AI was considered to be an HHP. This analysis excluded HHP criteria 8 as it is context specific, depending on the situation in the country. It is presumed that the situation in the country is taken into consideration by the regulators as part of the

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**TABLE 1** Explanation of codes used to summarize the findings of the biopesticide efficacy assessments relating to fall armyworm (FAW, Spodoptera frugiperda)

| Code | Explanation of the letters in the code |
|------|----------------------------------------|
| N    | No evidence of efficacy                 |
| YFa  | Evidence of efficacy against FAW        |
| YSp  | Evidence of efficacy against other Spodoptera spp. |
| YLe  | Evidence of efficacy against Lepidoptera |
| La   | Data from the laboratory                |
| Nr   | Data from the field in FAW’s native range |
| Af   | Data from the field in Africa           |

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decision to register, restrict or ban pesticides for use in the country. The references used to identify which AI meet one or more of the first 7 HHP criteria are listed in Table 2.

For all chemicals including pesticides, the GHS (UN, 2015) describes the classification criteria and the hazard communication elements by type of hazard, covering physical hazards (e.g., flammability), human health hazards (e.g., acute toxicity, carcinogenicity) and environmental hazards (e.g., aquatic toxicity, potential for bioaccumulation). One of the main aims of the GHS is to promote the safe use of chemicals, particularly through the harmonization of labelling systems. Globally, the GHS is being implemented in many countries (e.g., Japan, New Zealand and the USA) and regions (e.g., the European Union). For many chemicals, comprehensive lists of GHS hazard statements are published in the PubChem Compound Database produced by the National Center for Biotechnology Information (NCBI, 2018) and the European Chemicals Agency Classification and Labelling Inventory (ECHA, 2017). These databases were scraped, and the full list of GHS hazard statements was compiled for each AI. These hazard statements covered the HHP criteria 1–4 as well as other hazards such as potential to induce allergies, causing damage to specific organs, corrosives, aquatic hazards, etc.

Once all GHS hazard statements associated with each biopesticide AI were collected, they were used to assign each biopesticide AI an overall hazard category using an approach adapted from the guidance set out in Annex 3 of the Guidelines on Good Labelling Practice for Pesticides (FAO, 2015). AI which fit one or more of the HHP criteria were categorized as HHPs. All other AI were grouped into categories based on the highest level of signal word found in the GHS hazard statements associated with the AI. As described in Table 3, the AI were grouped into the following five categories in order of hazard level: HHP, danger, warning, low toxicity and missing data as indicated by the absence of any known human health hazard statements. For some AI, information on key human health hazard classes was not available and a consequence it was not possible to assign these AI to an overall hazard category.

| Criteria | Description | References |
|----------|-------------|------------|
| 1        | WHO toxicity classes Ia and Ib under WHO | WHO Recommended Classification of Pesticides by Hazard (WHO, 2010). For AI not listed in the WHO Classification, the LD_{50} ranges on which the classification system is based were used to assign the AI to a toxicity class. This data came from the GHS hazard statements provided by the PubChem Compound Database (NCBI, 2018) and the European Chemicals Agency Classification and Labelling Inventory (ECHA, 2017). |
| 2        | Carcinogenicity category Ia and Ib GHS (Globally Harmonized System of Classification and Labelling of Chemicals) (UN, 2015) | World Health Organization—International Agency for Research on Cancer, Monographs on the Evaluation of Carcinogenic Risks to Humans Volume, volumes 1–118 (WHO-IARC, 2017). In addition, we referred to the GHS hazard statements provided by the PubChem Compound Database (NCBI, 2018), the European Chemicals Agency Classification and Labelling Inventory (ECHA, 2017), and the Annual Cancer Report 2016 (EPA-OPP, 2017), which is based on the list of chemicals evaluated for carcinogenic potential by the US Environmental Protection Agency—Office of Pesticide Programs. |
| 3        | Mutagenicity category Ia and Ib GHS | The GHS hazard statements provided by the PubChem Compound Database (NCBI, 2018) and the European Chemicals Agency Classification & Labelling Inventory (ECHA, 2017) were referred to. The other data sets listed under criteria 2 were also referred to as necessary. |
| 4        | Reproductive toxicity Ia and Ib GHS | The GHS hazard statements provided by the data sets listed under criterion 2. |
| 5        | Persistent organic pollutants | Paragraph 1 of annex D of the Stockholm Convention on Persistent Organic Pollutants (UNEP, 2017). |
| 6        | CPAs requiring “prior informed consent” in trade | Annex 3 of the Rotterdam Convention on the Prior Informed Consent Procedure for Certain Hazardous Chemicals and Pesticides in International Trade (Rotterdam Convention, 2018). |
| 7        | Ozone depleting substances | Text of the 1987 Montreal Protocol on Substances that Deplete the Ozone Layer (UNEP-OS, 2018). |
Finally, it was noted whether an AI was permitted for use in organic agriculture in the European Union (EU, 2013) and whether it was listed as WHO acute toxicity class U (unlikely to cause acute hazard under conditions of normal use).

### 2.3.4 Assessment of agronomic sustainability

Through a review of the literature and product labels, it was determined whether there was any evidence indicating that the biopesticide AI would compromise agronomic sustainability. In particular, this review assessed whether there was evidence for the development of resistance to the AI by FAW or other Lepidoptera. Likewise, hazard data were reviewed to assess whether the AI posed an unacceptable risk to pollinators, natural enemies or other beneficial organisms. Finally, for the biopesticides which are living organisms or may be locally produced from living organisms, it was determined whether the organisms had been classified as an invasive species in any country in Africa. If there was an indication that the AI might compromise agronomic sustainability, it was then determined whether it would be possible to put in place mitigation measures to adequately manage the risk.

The findings of this assessment were used to assign a code to indicate whether or not the available evidence indicates that the AI is agronomically sustainable (Table 4).

### 2.3.5 Practicality

Information available, primarily from product labels, was reviewed in order to assess whether or not the biopesticide would be practical for smallholder farmers to use. Information provided in the product labels was used to assess whether any special application equipment, personal protective equipment or storage conditions were required. Also, information such as the frequency and number of applications required, for example, were used to gauge whether the use of the biopesticide in a manner consistent with the product label instructions might pose prohibitively high time or labour requirements. It was noted whether or not the AI would be more appropriate for area-wide management (as opposed to use by individual smallholder farmers).

### 2.3.6 Assessment of registration status of identified biopesticides in Africa

The registration status of the identified biopesticide AI was assessed for 19 selected countries in Africa where FAW is present or is likely to spread: Benin, Burkina Faso, Cameroon, Democratic Republic of Congo, Ethiopia, Ghana, Kenya, Mali, Malawi, Mozambique, Nigeria, Rwanda, Sierra Leone, South Africa, Tanzania, Togo, Uganda, and Zambia. Tunisia was also included in the analyses as representing the...
2.3.7 | Decision matrix

A decision matrix for biopesticides that could be used to target FAW was adapted from the FAO Pesticide Registration Toolkit (FAO, 2018c) and the Plantwise plant doctor training module on how to give good recommendations (Taylor, 2015). This decision matrix, provided in Supporting Information Table S2, poses five key questions against which each AI should be evaluated, based on the five main information categories listed above, and describes criteria for how to proceed based on the answer to each question. The five key questions are as follows:

- Is the biopesticide effective against FAW, its congeners or other Lepidoptera?
- Are the risks posed by the biopesticide to human health and the environment acceptable?
- Is the biopesticide sustainable?
- Is the biopesticide practical?
- Is the biopesticide locally available?

Information from the biopesticides’ profiles was used to answer these five key questions, and this in turn served as the basis for recommendations for next steps for each AI following the decision matrix. For AI for which no evidence of efficacy against FAW was found, no follow-up action was recommended. Likewise, no follow-up action was recommended for AI which were classified as HHPs, could compromise agronomic sustainability or would be prohibitively impractical for smallholder farmers to use.

Follow-up action was recommended for AI which passed these key criteria (Figure 1). If evidence of efficacy against FAW is available from field trials in FAW’s native range, field trials were recommended to confirm the efficacy of the AI against FAW under field conditions in Africa. If evidence of efficacy was only available for other Spodoptera or Lepidopteran species or if data were only available from laboratory studies, bioassays were recommended as the next step.

3 | RESULTS

3.1 | Overview of identified biopesticide AI

The analysis of the national lists of registered pesticides and biopesticides for the 30 countries identified 50 biopesticide AI in total that are registered and allowed for use for FAW management in at least one country (listed in Supporting Information Table S1). These biopesticide AI were represented by over 1,000 products in the 30 countries.

The biopesticide products included 417 botanicals, 274 microbial products and 271 microbial extracts or fermentation products. Only one parasitoid (Trichogramma pretiosum Riley) and two entomopathogenic nematodes (Steinernema carpocapsae (Weiser) and S. feltiae (Filipjev)) were registered. Macrobiotics are expected to be under-represented as most countries do not include macro-organisms in their lists of registered pesticides, although in the present study, Brazil, Kenya and Uganda do. One unclassified biopesticide was also identified (GS-OMEGA/KAPPA-HXTX-HV1A, registered in the USA).

The biopesticide AI which were registered and potentially allowed for use for FAW management in three or more countries are shown in Figure 2. Biopesticide products containing pyrethrins, Bacillus thuringiensis, neem and spinosad were represented by the highest numbers of products.

3.2 | Efficacy

Based on the literature review, 33 of the AI have been demonstrated to be effective against FAW, other Spodoptera species or other Lepidoptera species whereas for 14 AI there was not enough evidence to confirm that the AI would be effective against any Lepidoptera. For the purposes of this analysis, all the chemical components of the synthetic FAW pheromone are grouped together as they are used in combination.

The evidence for efficacy for 21 of the AI came from trials against FAW itself. For nine of the AI, evidence of efficacy came from trials that looked at other Spodoptera species. For two of the AI, evidence of efficacy was only found from trials against other Lepidoptera, for example Lepidoptera pests of apple, cabbage and forestry.

Much of the evidence of efficacy came from field trials in FAW’s native range (16 of 33 effective AI) and laboratory trials (12 AI). Evidence of efficacy from the field in Africa was only found for five of the AI: emamectin benzoate, garlic oil, kaolin clay, oxymatrine and sex pheromones.

3.3 | Hazard profiles of identified biopesticides AI

The 50 biopesticide AI all have relatively low levels of hazard: only two of the AI met any of the HHP criteria; 10 AI were categorized as “danger”; 13 AI were categorized as “Warning”; and 15 AI were categorized as “Low hazard” (there were no known human health hazard statements associated with the AI). For 10 of the AI, there were no data available for one or more of the criteria used for identifying HHPs (Missing data). Detailed information on the hazards associated with each AI is given in Supporting Information Table S3.

None of the identified AI are currently listed in the Rotterdam database of notifications nor are any of the AI listed as candidates for listing in the Stockholm Convention as POPs. Four AI are included in the Pesticide Action Network database (PAN, 2016): borax, lufenuron, spinetoram and spinosad. Borax is listed by PAN as an HHP because it is a GHS Class 1A/1B reproductive toxin. Lufenuron is listed as an HHP by PAN because it is very bioaccumulating, very persistent in water, soil or sediment, and very toxic to aquatic organisms. Spinetoram and spinosad are listed by PAN as HHPs because they are very toxic to bees. Almost half of the Mediterranean countries which may be at risk of invasion by FAW. This analysis was conducted in January and February of 2018, using the most recent version of the national lists of registered pesticides which was available.
identified AI are permitted to be used in the EU \((N = 23)\), whilst 27 are not.

Fifteen of the identified biopesticide AI are permitted for use in organic agriculture and are listed as such in Annex II of Commission Regulation (EC) 889/2008 on rules for organic production (EU, 2013). These include azadirachtin, *Bacillus thuringiensis*, *Beauveria bassiana* (Bals.-Criv.) Vuill., rape seed oil, *Chromobacterium subsugae* Martin et al. strain PRAA4-1 cells and spent fermentation media, eugenol, *Metarhizium anisopliae* (Metchnikoff) Sorokin, orange oil, *Isaria fumosorosea* Wise apopka 97 (= *Paecilomyces fumosoroseus* fe9901), potassium salts of fatty acids, pyrethrins, spinosad and sulphur. Only three of the identified AI are classified as U (unlikely to cause acute hazard under conditions of normal use) in the WHO Recommended Classification of Pesticides by Hazard (WHO, 2010). Many of the biopesticide AI identified through this study (34 AI) are not listed in the 2009 classification. Based on the LD\(_{50}\) of the AI, seven of the biopesticides which are not listed in the 2009 WHO classification can also be considered to be class U.

### 3.4 Agronomic sustainability

Based on a review of the available literature, 33 of the AI would not compromise agronomic sustainability. Nine of the AI would require appropriate mitigation measures to be put in place. For emamectin benzoate and 2-phenylethyl propionate, the risks to agronomic sustainability were considered to be significant enough for the AI not to merit follow-up action. Five AI are highly toxic or very highly toxic to bees: 2-phenylethyl propionate, allyl isothiocyanate, pyrethrins, spinetoram, and spinosad. Six AI are highly toxic to aquatic organisms, often with long-lasting effects: allyl isothiocyanate, citric acid, cryolite, lufenuron, pyrethrins and S-methoprene. There are examples in the literature of a build-up of FAW resistance to emamectin benzoate and spinosad. Neem trees (*Azadirachta indica* A.Juss.) and *Dysphania ambrosioides* (L.) Mosyakin and Clements both have the potential to be invasive weeds in Africa, and local production should only take place after risk assessments have been conducted. Data on agronomic sustainability were not available for D-glucitol octanoate, matrine and...
oxymatrine. There was relatively little information available on the impact of most AI on natural enemies, and none on the known natural enemies of FAW in Africa, which although the subject of ongoing research in several countries have yet to be reported. However, judging by the literature on natural enemies of other Spodoptera spp. (CABI 2018a) and the closely related and ecologically similar Helicoverpa armigera (Hübner) (Cherry, Cock, den Berg, & Kfir, 2003) in Africa, it is likely that both specialist and generalist predators and parasitoids will be found to play a significant role. If that is the case, the action of AI in these natural enemies will need further consideration in bioassays and field trials, and in the design of IPM measures.

Detailed information on the agronomic sustainability of the AI is provided in the AI profiles in the supplementary data and is summarized in Supporting Information Table S5.

3.5 Practicality

The review of the literature and the product labels indicated that 33 of the AI would be practical for smallholder farmers to use, whereas seven AI would not be practical for smallholder farmers to use, at least not immediately (cinnamaldehyde, Helicoverpa zea single capsid nucleopolyhedrovirus (VPN-HZSNP), sex pheromones, soybean oil, Steinernema carpocapsae, Steinernema feltiae and Trichogramma spp.). These AI were deemed impractical for smallholders at this time for a variety of reasons, for example storage requirements, shelf life, the need for application of an area-wide management approach. For four AI (citric acid, ethyl palmitate, matrine and oxymatrine), insufficient information was available to judge whether products containing the AI would be practical to use. Although 33 AI have been identified as practical for smallholder farmers, no compatibility studies have been performed on the AI with other biopesticides and chemical pesticides which may be used for FAW control. Some AI, particularly those based on living microbials and macrobials, are likely to be directly affected by some chemical pesticides and biopesticides. Furthermore, bioassays and field trials are likely to be needed to assess whether spraying the AI in the same spray equipment used for chemical control, with and without a chemical pesticide, has any interactive effect.

Detailed information on the practicality of the AI for smallholder farmers is provided in the AI profiles in the supplementary data and is summarized in Supporting Information Table S5.

3.6 Biopesticide AI and products registered for use against FAW in its native range in the Americas

Information on the registration of biopesticide AI on a per country basis is given in Supporting Information Table S4. In FAW's native range, the country with the highest number of AI registered for use against it was the USA (35 AI, Figure 3). The USA also had a much higher number of products registered (532 products) followed by Mexico (117 products). Panama had the third highest number of candidate AI registered, but does not provide information on the crop and pest in its online database of registered pesticides so the numbers given in this case reflect the numbers of AI and their associated products which are known to be registered for use against FAW in one or more other countries.

![Figure 3](image-url) Numbers of biopesticide active ingredients (AI) (left, dark) and corresponding products (right, pale) registered in 11 countries in the native range of the fall armyworm

3.7 Registration status of identified biopesticides in Africa

The analysis of the national lists of registered pesticides and biopesticides for the 19 African countries assessed identified 29 biopesticide AI which would be allowed for use in FAW management. Of the 19 countries, only South Africa had biopesticide products which are specifically registered for use against FAW. Kenya, for example, has some pesticides registered broadly for armyworm, but no biopesticides are listed in the online database as being registered specifically for FAW. The countries with the highest number of AI and products registered which could potentially be used against FAW were Kenya (20 AI and 85 products), Tunisia (11 AI and 70 products) and South Africa (18 AI and 61 products, Figure 4). According to the Crop Life South Africa (2017) document Managing the Fall Army Worm (FAW) Outbreak in South Africa, only seven of the AI and 13 of the products registered in South Africa are permitted for use in the management of FAW. The government guidance gives different numbers. Given that registrations change, both documents may be out of date.

4 Discussion

FAW is an important and challenging pest management target in Africa, and safe, sustainable, effective interventions will be a key component of management strategies. As noted above, neonate larvae move to the funnel of maize plants and feed on the developing leaves, where they are then protected from contact pesticides. Thus, the mode of
action and timing of application of any type of pesticide is particularly important. For effective treatment, especially of larger larvae, systemic pesticides may be applied, which often require longer pre-harvest intervals. If the larval biology and behaviour is not taken into consideration together with how a potential biopesticide works (or conventional pesticide for that matter), poorly designed laboratory trials may produce unrealistic results that cannot be replicated in the field. This is a key reason, for subsequently carrying out field trials on target crops grown under local conditions to validate laboratory results.

Many of the conventional pesticides registered for FAW management in the study countries are in fact HHPs, so it is important that farmers have training, information and access to appropriate personal protective equipment which they use when handling any pesticide. In contrast, generally the biopesticide identified through this study require personal protective equipment with a relatively low level of chemical resistance.

Based on conclusions developed using the decision matrix, 23 of the AI are recommended for follow-up action (Table 5). For 10 of these AI, field trials in FAW’s native range have demonstrated the AI’s efficacy against FAW and it is recommended that field trials be carried out to confirm the AI’s efficacy against FAW in Africa. For another three AI, bioassays have demonstrated efficacy against FAW in a laboratory setting, and their efficacy against FAW should be tested in the field in Africa. Field trials are being planned to test whether FAW sex pheromones can be used to reduce populations of the AI are recommended for follow-up action (Table 5). For 10 of these AI, efficacy has been demonstrated for other Spodoptera and/or other Lepidoptera species. This evidence comes from both the laboratory and the field, in Africa and in FAW’s native range. Bioassays should be used to determine whether these AI are effective against FAW. Should these bioassays yield encouraging results, they could be followed-up with field trials, which take into consideration how the biopesticide will be used in relation to the development of the pest and the crop it is attacking, that is the degree of protection the FAW caterpillars may have from different types of biopesticide action and application.

For six of the AI where follow-up action is needed (allyl isothiocyanate, D. ambrosioides, lufenuron, pyrethrins, spinetoram and spinosad), risk factors were identified which might compromise agronomic sustainability. Before recommending that farmers use these AI, the adequacy and feasibility of mitigation measures should be assessed, for example, through participatory trials with farmers. Given that, these AI should only be pursued if no other alternatives are available. In this context, it should be noted that although mitigation measures, such as recommending use of personal protective equipment, can be suggested getting that information to the farmer in Africa and getting them to act upon it will be a challenge. Participatory trials with the farmers should help to overcome this issue.

Twenty-one AI were not recommended for follow-up action for the following reasons: a lack of evidence of efficacy (13 AI), unacceptable hazards to human health and the environment (one AI), potential impact on agronomic sustainability (one AI), prohibitively impractical for smallholder farmers (three AI) or lack of availability (three AI). However, we note that availability and practicality may change, so these last six AI may still be worth considering in the future.

The registration status of the AI identified for follow-up varies from country-to-country. Countries should prioritize FAW trials of those AI that are already registered for FAW or for other pests, particularly in Africa. Interest from a manufacturer or distributor will ultimately be important for ensuring that products are made available on the market. This could potentially be achieved through public–private partnerships. Where there is no patentable product, trials would need to be carried out by national agricultural research systems.

For many of the countries in Africa evaluated in our analysis, only a relatively small number of the identified biopesticide AI are registered for use, and very few are registered for use against FAW outside South Africa. In two countries, the Democratic Republic of Congo and Sierra Leone, there are currently no biopesticides registered that can be used against FAW, and Benin, Cameroon, Ethiopia, Nigeria and Togo all have fewer than five biopesticide AI registered which might be suitable for FAW management. Sometimes manufacturers of both chemical pesticides and biopesticides are disinclined to pursue the registration of their products in certain countries. This could be because the companies do not have a presence in the

| No. of biopesticide AI | No. of products registered |
|------------------------|---------------------------|

**FIGURE 4** Numbers of biopesticide active ingredients (AI) (left, dark) and corresponding products (right, pale) registered in 19 countries in Africa.
### TABLE 5 Overview of conclusions regarding readiness of biopesticide active ingredients (AI) for deployment in Africa. Not all AI fit comfortably in this classification, and the detailed supplementary information should also be reviewed especially the hazard profiles

| Registered for field use against FAW or other Lepidoptera in our survey | Reported effective against FAW in field trials in native range; field trials and evaluation needed in Africa | Reported effective against FAW in lab bioassays; field trials needed in Africa | Reported effective against related pests; bioassays needed for FAW, followed by field trials if justified | Not recommended for follow up on available information (at this time) |
|---|---|---|---|---|
| Not registered | Spodoptera frugiperda NPV | Dysphania ambrosioides \(^a\) | Garlic oil | Ethyl palmitate |
| Registered outside sub-Saharan Africa | Registered within sub-Saharan Africa | | | |
| Azadirachtin (neem products) Bacillus thuringiensis products Lufenuron \(^a\) Methoxyfenozide Oxymatrine Pyrethrins \(^a\) Sex pheromones \(^b\) Silicon dioxide Spinetoram \(^a\) Spinosad \(^a\) Trichogramma spp. \(^b\) | Beauveria bassiana Matrine | Capsaicin Kaolin clay Maltodextrin Metarhizium anisopliae Orange oil | Borax Canola oil (rape seed oil) Citric acid Emamectin benzoate Eugenol Steineremona spp. Sulphur | |

\(^a\)There are concerns regarding toxicity, so these AI need a more detailed risk assessment before evaluation in Africa. \(^b\)In many countries sex pheromones and macrobials do not need to be registered; hence, we include them here rather than list them as not registered or omit them from the table.

Country, because the market is perceived to be small (either because the volume used is low or the country itself is small, or the product will not be competitively priced), or there are regulatory barriers. Under these circumstances, development agencies might consider supporting the establishment of local manufacture, if a sustainable business model could be established. Harmonized subregional approaches to pesticide registration may reduce registration costs and so encourage manufacturers and distributors to pursue registration.

Countries belonging to the Comité Permanent Inter-État de Lutte contre la Sécheresse au Sahel (CILSS) apply this approach through their Comité Sahelien des Pesticides, and other sub-regions in Africa are also moving towards harmonized pesticide registration.

Currently, many different national, regional and international research organizations as well as private sector actors such as the biopesticide manufacturers themselves have made the identification of low-risk management options for FAW a high priority. Liaison with these organizations and private sector entities can also serve to provide additional information on the AI presented in this document and may also serve to identify any other AI not yet registered in any of the 30 countries covered by this study. For example, Andermatt Biocontrol (pers. comm.; Agronews, 2018) has found that a product containing Spodoptera littoralis nucleopolyhedrovirus (SpltNPV) which targets cotton leafworm (Spodoptera littoralis (Boisdruval)) is also effective against FAW. Based on the lists of registered products reviewed, the Andermatt Biocontrol product is not currently registered for use in any of the 30 countries examined, although it has been tested against FAW in Cameroon, and may be registered by the time this article is published.

For the most part, the hazard profiles do not suggest that any of the identified AI will pose an undue risk to human health or the environment. The two HHP AI which were identified (borax and citric acid) are classified as such based on the technical grade of the pure AI, and in practice, these AI are likely to be of a much lower risk. The overall toxicological profiles of the biopesticide AI as a group tend to be much less hazardous than typical conventional pesticides.

One factor that should also be considered when prioritizing potential interventions is the likely price of the product. Observations suggest that biopesticides currently on sale are often higher priced than synthetic pesticides. This may be due to higher production costs,
as well as proportionately higher registration, marketing and distribution costs if they are effective against only one or a few pests. While some farmers might be willing to pay a premium for a lower risk product, many smallholder maize farmers in Africa already have small margins, so will seek to minimize the additional cost of controlling a new pest such as FAW. This would suggest that affordability is important to consider. However, if a significant market for a lower risk product can be developed, the price may fall, so currently unaffordable products should not automatically be ruled out of further consideration.

In this study, we have collected and collated much information on the biopesticides that may be considered for use in the management of FAW in Africa. To develop the use of biopesticides as a viable alternative to more hazardous products in Africa, further activities are needed in the short to medium term, as set out below.

4.1 | Short-term (immediate) activities

For those AI considered immediately usable (i.e., reported effective and registered, with no significant toxicity concerns, column 2 in Table 5), countries will need to assess local availability and affordability, for example through surveys of biopesticides for sale at agro-input retailers and consultation with farmers and farmer groups. Where availability is limited and potential demand is not being met, private–public partnerships should be encouraged and motivated to make products based on these AI available. Further, agricultural extension materials such as pest management decision guides (CABI, 2018b) need to be reviewed and updated to reflect the availability of suitable, low toxicity biopesticide products.

For those AI considered immediately usable, but not registered in a given country, steps should be taken to fast-track their assessment for registration in that country. To facilitate this:

- Biopesticide field trial guidelines for FAW should be prepared and shared between countries. These will need to consider the implications of choice of crop, crop stage, FAW stage, application methods, and yield as a function of FAW density.
- Each country should prioritize AI for bioassays and field trials, using the information presented here combined with local insight. The list of AI to be tested through bioassays and field trials should be shared nationally through available mechanisms (such as FAW task forces) so that efforts can be maximized. Likewise, the list of priorities should be shared with other interested groups, such as the FAO FAW working groups or the FAO APG in Rome to facilitate and ensure a harmonized pest management approach.
- National organizations should conduct bioassays and field trials as needed to assess whether the priority biopesticide AI are effective under local conditions and if they could be incorporated into smallholder farmer IPM management schemes. As data become available on the role and importance of indigenous natural enemies in the control of FAW in Africa, the design of bioassays and field trials may need to evaluate the impact of AI on these groups. Consideration will also need to be given to the potential negative interaction with other control measures, particularly chemical pesticides.

- For biopesticides proven effective through laboratory and field trials, carry out risk assessments and consider registration (or the issuing of import permits for macro-organisms which are biocontrol agents).
- In parallel with the preparation for registration, steps should be taken to encourage import and/or local production and supply chains so that products will be available to farmers. Private–public partnerships will need to be developed to make these kinds of products available in countries where there is a market.
- Agricultural extension materials need to be regularly reviewed and updated to reflect the availability of suitable biopesticide products.

4.2 | Medium-term activities

Depending on each country’s regulations, some biopesticides are exempt from the requirement for registration. For example, in the USA, registration is not required for pheromones that are used exclusively as attractants in traps.

With a few exceptions, regulation of the use of macro-organisms does not fall under the mandate of the national regulatory authority for pesticides. Indeed, many countries’ regulations relating to the registration of pesticides explicitly exempt macrobials from the registration requirement. For countries in FAW’s native range, information on the registration status of macro-organisms was only available for Brazil. For most countries, the introduction and use of non-native macro-organisms is regulated by the national plant protection organization following national regulations based on the ‘Guidelines for the export, shipment, import, and release of biological control agents and other beneficial organisms’ (IPPC, 2017). Requirements and procedures for risk assessment, import permits, documentation, etc. vary by country. In addition, following the ratification of the Nagoya Protocol, regulations related to access and benefit sharing also have to be taken into consideration when using introduced biological control agents (Cock et al., 2009; Mason et al., 2018). Within their native range, most countries allow the use of indigenous macrobials as biological control agents.

To assess whether a macrobial biocontrol agent would be allowed for use in a country, the organism’s biogeography would be determined by referencing CABI’s Crop Protection Compendium (CABI, 2018a), the Plantwise Knowledge Bank (CABI, 2018b), the Fifth Edition of The Manual of Biocontrol Agents (Gwynn, 2014) and other sources as relevant. Research groups to contact could include the FAO FAW working groups and the existing International Working Group on Ostrinia and other Maize Pests of the International Organisation of Biological Control (www.iwgo.org), in order to obtain additional scientific expert advice.

In many countries, the registration of microbial biopesticides, semiochemicals and botanicals generally takes place within national regulatory systems that have been designed for the regulation of synthetic pesticides. This can slow the registration process and increase costs. In some countries, policies have been successfully put in place to promote the registration and use of biopesticides. For example, data requirements for registration may be reduced; registration fees may be lower; the registration process may be accelerated or prioritized.
there may be governmental support available for trials; certain products containing certain types of AI may not have to be registered; they may be exempted from the requirement of a maximum residue limit, etc. National regulators could consider modifying policy for the registration of biopesticides in order to fast-track the availability of low toxicity products for management of FAW and other priority pests. Governments wishing to assist their farmers by providing free or subsidized pesticides could consider subsidising biopesticides rather than synthetic pesticides, an approach Ghana is adopting in 2018 (Ayamgha, 2018). For countries where proven biopesticide AI are not locally available and other low toxicity alternatives are not available, opportunities for local production of biopesticides could be explored engaging with private sector entities.

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AUTHORS’ CONTRIBUTION

MLB, RKD and UK conceived the research; MLB, RKD, BL and SE analysed the data; MLB, RKD, BL, SE and MJWC wrote and edited the manuscript and supplementary material; UK and MLB secured funding; all authors read and approved the manuscript.

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