Fall Armyworm: Impacts and Implications for Africa

Evidence Note (2), September 2017

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Executive Summary

This report, commissioned by the Department for International Development, indicates that the arrival of fall armyworm (FAW) in Africa has the potential to cause maize yield losses in a range from 8.3 to 20.6 million tonnes per annum, in the absence of any control methods, in just 12 maize-producing countries. This represents a range of 21%-53% of the annual averaged production of maize over a three year period in these countries. The value of these losses is estimated between $2,481m - $6,187m.

Evidence indicates that FAW's spread to the limits of its viable African habitat within the next few cropping seasons should be expected. This may include northern Africa and Madagascar. It is suggested that national authorities undertake the steps set out below as far as possible:

- Promote awareness of FAW, its identification, damage and control, in particular IPM, to farmers, extension agents, plant health inspectors and other stakeholders
- In consultation with extension agents and agronomists, promote awareness of potentially benefical agronomic practices
- In consultation with agro-input suppliers, prepare and communicate a list of available recommended and regulated pesticides and biopesticides
- Provide emergency/temporary registration for the recommended pesticides and microbial biopesticides
- Arrange for laboratory efficacy tests of recommended pesticides to be conducted by authorised national laboratories
- Regularly review recommendations and publicise changes promptly and widely, simultaneously monitoring FAW populations for resistance
- Assess preferred crop varieties for resistance or tolerance to FAW
- Consider short-term subsidies for small-scale farmers – for example to reduce prices for lower-risk products

Conclusions within the report have been derived from a randomised survey of FAW impacts on maize and other crops undertaken in Ghana and Zambia. It was found that environmental conditions where FAW is found in Ghana and Zambia closely match those of its native range in the Americas. Environmental suitability maps have been produced to determine regions in Africa at consequent risk of FAW invasions, and these have been overlaid with maize cropping zones. Full details of the methodologies used and analysis carried out are presented in the full report and its annexes.

Behaviour, biology and ecology of the fall armyworm

The fall armyworm, scientific name *Spodoptera frugiperda*, is a moth – a polyphagous (ie able to feed on many types of food) pest that is indigenous throughout the Americas. It has not previously been established outside the Americas but its two strains have now appeared in Africa and are rapidly spreading throughout the tropical and subtropical regions of the continent. It is widely agreed to be one of the most damaging crop pests in the Americas, feeding on over 80 different crops. Its impact on maize yields in Africa has been – and is likely to continue to be – significant. Research to date suggests that both strains entered Africa as stowaways on commercial aircraft, either in cargo containers or airplane holds, before subsequent widespread dispersal by the wind.

Current spread in Africa

At the time of publication of this document in September 2017, 54 countries in Africa were surveyed and researched. CABI examined the present situation in all countries through internet mining, academic and grey literature reviews, and discussions with contacts in country.

Of the countries surveyed, 28 have confirmed the pest on their territory (compared to 12 in April 2017). A further nine countries have conducted or are presently conducting surveys, and either strongly suspect its presence or are awaiting official confirmation. Two countries have stated that FAW is absent. No information on FAW presence or absence could be gathered from the remaining 15 countries.

Due to their suitable climate, reports of FAW presence and impact are to be expected in further West African countries, such as Sierra Leone, Mali, Senegal, Liberia, and Cote D'Ivoire, which so far have not officially reported FAW, plus the Central African Republic and Sudan. Angola and Nigeria appear at risk of suffering increased pest outbreaks given their environmental suitability for FAW, or the relative proportion of maize grown in suitable areas. Madagascar, which has not as yet reported FAW, is also at risk. Of particular note is the high environmental suitability on the Mediterranean coast in Morocco, Algeria, Tunisia and Libya, increasing the possible spread of this insect to Europe, and the high suitability areas in Ethiopia that could enable the pest to progress towards the Middle East and Asia.

The impact of FAW on maize yield and economics: national, continental, household and trade perspectives

National level

Impacts of FAW for were estimated for 10 additional major maize-producing countries by extrapolating estimates of proportion of yield loss from data from Ghana and Zambia and combining this with published data on national maize production and other information. The 10 additional countries included are major producers of maize in Africa (in terms of metric tonnes/year): Benin, Cameroon, Democratic Republic of Congo, Ethiopia, Malawi, Mozambique, Nigeria, Uganda, Tanzania, and Zimbabwe.

The estimates indicate that for these countries taken together, and in the absence of any appropriate control measures, the potential impact of FAW on continental wide maize yield lies between 8.3 and 20.6 million tonnes per year of total expected production of 39m tonnes per year and with losses lying between US$2,481m and US$6,187m per year of total expected value of US$11,590.5m per year.

Household level

FAW is likely to directly affect capital costs, through increased labour needed and the type of knowledge required to deal with the pest; through yield losses and the ability of agricultural lands to respond to shocks; and financially, through increasing the cost of production due to costs of control (defined as the cost of technology and its application) and its effect on income. It will also indirectly affect households' social and physical capital (the household's assets).

Impacts on trade

International trade carries the risk of introducing pests to countries where they are not yet present. Thus, the arrival of FAW in Africa creates a new risk for countries importing from affected African countries if FAW is absent from the importing country. This includes countries in North Africa, Asia and Europe, although the report focuses on Europe as a major importer of agri-food products from Africa and for which good data is available.

If consignments arriving in Europe are found to contain FAW, treatment may be required, import may be refused, or the consignment could even be destroyed, so there is a cost when contaminated consignments are intercepted by importing countries. To reduce the likelihood of this happening, additional measures may be required in the exporting country. This will also incur a cost to the producers and the national plant protection organisation.

Control

While there is a large volume of literature on FAW control in the Americas, the agricultural systems there are often very different from those in Africa.

The full report examines the cost and use of conventional pesticides to control FAW. Within individual households action threshold decisions on whether and what to spray will depend upon the cost of treatments, the size of farm, and multiple other factors. Further study in this area is warranted. An Integrated Pest Management (IPM) approach is strongly recommended. Reliance on single control methods may, in the long run, either be unsustainable or ineffective and, in the worst cases, increase the likelihood of FAW resistance.

Monitoring

Monitoring the health of a crop is important when decisions are required regarding whether to intervene. Three approaches to monitoring are used in Latin America: scouting, pheromone traps, and light traps.

Control

Various control mechanisms are assessed

- *Chemical control*, or the application of poisons to the pests or crops
- *Microbial organisms* that attack FAW in its native range, for example *Beauvaria bassiana* and *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV)
- Inundative releases of *macrobials*, including predatory insects and parasitic wasps (parasitoids)
- The use of genetically modified crops that are resistant to FAW, containing Bt genes
- *Mass trapping* of male moths using pheromones, preventing them from mating
- *Integrated pest management (IPM)*, a combination of methods minimising pesticide use

The evidence from Latin America indicates that an IPM approach is necessary, in which pesticide use is minimised, natural enemies are encouraged in various ways, crops are monitored, and one or more interventions are made only when necessary. Uptake of IPM should be encouraged through financial incentives and subsidies, providing agricultural advisory services, and creating a better policy and regulatory environment.

In conclusion, the main objectives of the study, funded by UKaid from the Department for International Development were to:

- Estimate the impact of FAW on maize yield and revenue loss at a national level through a rapid assessment of the situation in Ghana and Zambia
- Estimate these impacts at a broader Africa continental level by extrapolating data on yield loss estimated for Ghana and Zambia
- Estimate some aspects of impact at a household level in Ghana and Zambia where sufficient data was available from the studies in these two countries
- Understand the pest's potential impact on trade across the continent

CABI's work on FAW is part of a wider programme on the management of Invasive Species (www.invasive-species.org/). Work carried out under this programme has identified that management of biological invasions across sectors, would have a greater chance of improving rural livelihoods. This will require a number of coordinated procedural interventions:

- Making information and data available
- Facilitating cross-sectoral partnerships so that a collaborative group of concerned stakeholders can react quickly to mounting crises caused by biological invasions
- Building capacity at national and regional level to publicise, to train and to deliver best practice solutions – particularly IPM approaches
- Facilitating the adoption of best practices at scale, so that participatory large-scale implementation plans are developed and validated to increase local production of a tested best practice

Section 1: Behaviour, biology and ecology of the fall armyworm

Here we provide a short overview of the fall armyworm (FAW), including an overview of its life cycle and behaviour. These factors in turn impact on the crops it can damage, and how far and how fast its geographic distribution can change. There are two strains of FAW: we speculate on how these strains invaded Africa and from which original, native location. Subsequent sections of this report describe how the strains may be controlled. We identify here a number of outstanding research questions, answers to some of which may reduce the risk of future invasion by FAW of new countries in Africa – and beyond, in Europe and Asia.

The FAW, scientific name *Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae), is a moth – a polyphagous pest that is indigenous throughout the Americas (Todd and Poole 1980, Commonwealth Institute of Entomology 1985). It is regularly intercepted in intercontinental trade (CABI 2017a, EUROPHYT 2017) but has not previously become established outside the Americas. It has now appeared in Africa (Goergen *et al.* 2016, Cock *et al*. 2017) and is rapidly spreading throughout tropical and subtropical regions of the continent (section 2).

Host range

The FAW caterpillars feed on the leaves, stems and reproductive parts of more than 100 plant species (Pogue 2002, CABI 2017a), causing major damage to economically important cultivated grasses, such as maize, rice, sorghum and sugarcane, as well as other crops, including cabbage, beet, peanut, soybean, alfalfa, onion, cotton, pasture grasses, millet, tomato, potato and cotton. FAW is widely agreed to be one of the most damaging crop pests in the Americas, as discussed in section 3. Its impact upon maize yields in Africa has been – and is likely to continue to be – significant. This impact is discussed in detail later in this report.

Life cycle and biology[1]

Following emergence, the adult moths feed at suitable flowers from dark for up to two hours, before females start calling, by emitting pheromones to attract males to mate. Adults fly by night, and are attracted to lights, especially those with a strong ultra-violet component. The use of pheromone traps, which have been used to monitor populations in Integrated Pest Management (IPM) programmes (eg Starratt and McLeod 1982, Cruz *et al.* 2010), is considered in section 4. Oviposition starts later on in the same night that mating took place. Eggs are laid as 'egg masses' in batches of 100–200 eggs and hatch in two to four days in optimum temperatures. Oviposition is usually on the underside of leaves, but as the density

[1] The text in this section is based heavily on Sparks (1979), Johnson (1987), CABI (2017a), and other sources mentioned within the narrative.

of moths increases, oviposition becomes increasingly indiscriminate, on other parts of the food plant, other non-host plants and inanimate objects. Adult moths mostly live for two to three weeks. Females will mate multiple times during this period and lay multiple egg masses, with a potential fecundity of up to 1,000 eggs per female.

There are six larval instars: it is the final instar which consumes the most plant material (77%) and causes the most damage. 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 leaves, 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, see section 4. In young plants, the stem may be cut, providing evidence of damage. Older larvae stay inside the funnel and so are protected from traditional spray pesticide applications and natural enemies. In older plants, the larger larvae can bore into the developing reproductive structures, such as maize cobs, reducing yield quantity and quality.

In the native range, the rate at which larvae develop is affected by diet and temperature (an acceptable range of between 11°C and 30°C). Recent FAW outbreaks in Ghana and Zambia have occurred in temperatures well above this range but it should be noted that these distributions (see Section 2, figure 6) are generally within the environmental conditions found in FAW’s native range.

In southern Florida, where FAW breeds continuously, the life cycle takes about one month in summer, two months in spring and autumn, and three months in the winter. In cooler climates development slows down to one or a few generations per year. FAW has no diapause mechanism and frost kills the insect, so in the USA damage in the cooler more northerly states is caused by moths migrating from populations in Central America to southern Texas and Florida. Much still needs to be understood about the pest’s behaviour in the hotter climates of sub-Saharan Africa. Frost is not a big issue in most of the continent, and this needs to be taken into account when surveying and understanding the pest's habits over time.

Identification of larvae in the field is not straightforward, especially for inexperienced observers, as they are easily confused with similar species such as the African armyworm (*S. exempta*) and the cotton leafworm (*S. littoralis*), as well as species of other noctuid genera, such as African maize stalk borer (*Busseola fusca*) or even stem borers of other families, such as the spotted stem borer (*Chilo partellus*; Crambidae). CABI has prepared guides to assist with diagnosis (CABI 2017b, 2017c), which are being disseminated through national programmes via the Plantwise knowledge bank. Fully developed larvae burrow 2–10 cm into the soil to pupate; pupation may take from one to five weeks, depending on the soil temperature.

Larvae, especially larger larvae, are cannibalistic, feeding on other *S. frugiperda* larvae, especially smaller ones, when they co-occur. Cannibalism was found to account for approximately 40% mortality when maize plants were infested with two or four fourth-instar larvae over a three-day period (Chapman *et al.* 2000). This behaviour, which is different to that of African armyworm, is accentuated when food is limited and larvae are crowded (Chapman *et al*. 2000). The role of this density-dependent mortality in the overall population dynamics is not clear (Chapman *et al*. 1999) but could be an important point, as density-dependant mortality may reduce the intensity of some outbreaks, although clearly the experience in Africa shows that it does not prevent outbreaks. Dispersal of the newly hatched larvae should minimise cannibalism when population levels are low. What this also means is that assumptions based on the biology and ecology of African armyworm may not be directly transferable to FAW.

Mobility and dispersal

FAW moths generally disperse about 500 km (300 miles) before oviposition, which is sufficient to move from seasonally dry habitats to wet habitats in Central America (Johnson 1987). Moths fly downwind, above the boundary layer (the lowest part of the atmosphere, above which the wind direction and strength may be different), so the direction of movement depends largely on prevailing winds. When the wind pattern is right, moths can move much larger distances: for example, 1,600 km from Mississippi to southern Canada in 30 hours has been recorded (Rose *et al.* 1975). Clearly, FAW has the potential to spread rapidly across Africa: at least 500 km per generation, with a suitable wind.

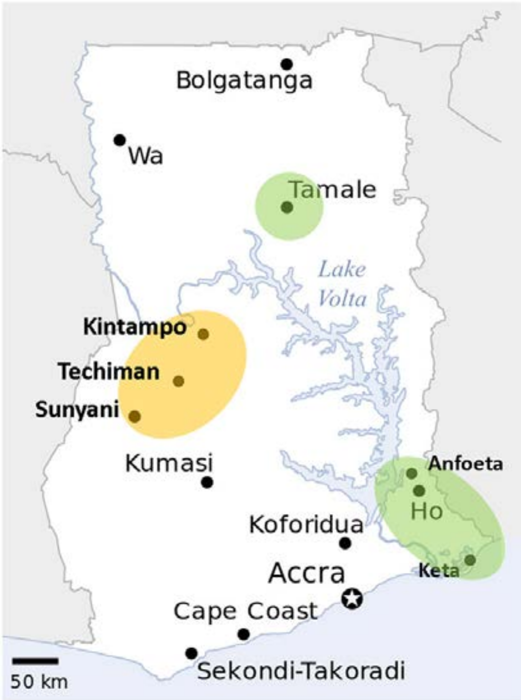
As yet, the literature review undertaken by CABI has found little evidence regarding what triggers adult dispersal, or indeed whether it is a feature of every generation. Similarly, we have found no studies on whether part of each generation remains *in situ*, or whether the entire generation disperses. It seems likely that dispersal is triggered by the level of crowding experienced by the larvae, but this has not been tested. This makes it difficult to make robust forecasts of the likely pest problem in the next cropping cycle. Anecdotal observations from South America indicate that there is poor correlation in FAW populations from one crop season to the next (Y. Colmanarez, pers comms.). There may also be geographical or strain differences in this behaviour.

It has been assumed that FAW disperse on wind-assisted flights until they are sexually mature and ready to mate (Rose *et al.* 1975), but we have not found any definitive studies on this aspect. However, this seems likely and would explain why males disperse alongside females.

Taxonomic and genetic issues

For more than 30 years, it has been known that in the Americas *S. frugiperda* occurs in two races: a 'rice strain' (R strain) and a 'corn strain' (C strain) (Pashley *et al.* 1985); the former is thought to preferentially feed on rice and various pasture grasses and the latter on maize (corn), cotton and sorghum, although this may be geographically variable – for example, this is not consistent in Argentina (Juárez *et al.* 2012). It should be noted that both strains will eat maize. The strains are morphologically identical, but can be distinguished using DNA barcodes. For a fuller discussion of the genetic questions relating to the two strains, please refer to Cock *et al*. (2017). The practical implications for management of each race have not as yet been evaluated.

In October 2016, as part of a process of examining the origin of FAW introduction and its implications, samples of caterpillars on maize were collected from the Brong Ahafo, Volta and Northern regions of Ghana. Results of the molecular identification showed that *S. frugiperda* in Ghana were indeed divided into the two strains – corn and maize, matching those reported in the Americas. No hybrid forms were found. A map of the results can be found in Figure 1.



Map of Ghana showing three survey locations (highlighted), including major towns and towns closest to collection sites. Both strains of *Spodoptera frugiperda* were found in samples from Keta and Anfoeta (Volta), and Tamale (Northern), shaded green, but only rice strain from collections around Techiman and five nearby communities (Brong Ahafo), shaded brown. Map from Cock *et al.* (2017) based on an OCHA/ReliefWeb created by the UN Office for the Coordination of Humanitarian Affairs (OCHA), downloaded from Wikipedia (https://commons.wikimedia.org/wiki/File:Ghana_-_Location_Map_(2013)_-_GHA_-_UNOCHA.svg) under a CC BY 3.0 licence, and edited using Microsoft Publisher TM and Adobe Photoshop Elements TM.

Figure 1. Location of FAW sampling regions in Ghana.

In addition to these results, CABI managed to gather an additional 53 samples from various locations in Ghana during the household survey in July 2017, to pinpoint the origin and possible entry points into Africa.

The different techniques used to analyse Ghanaian samples has implications for future pest diagnosis and identification, particularly for invading or new pests in developing countries. Currently, extension and research staff in most developing countries rely on limited in-country capacity for identification of pest problems (eg as documented by Mugambi *et al.* (2016) in Kenya), occasionally with external support through programmes such as Plantwise or from international agricultural research centres (Goergen *et al*. 2016). In the case of FAW, once present in Africa the pest was able to establish itself while remaining relatively undetected. Additionally, a coherent and coordinated notification and alerting system for extension staff within and between countries would be a key step in knowledge management and early response to invasive threats. This is discussed further in section 4.4.

Spodoptera frugiperda was first reported in mainland West Africa (Nigeria, Togo, Bénin) and in the island of São Tomé (São Tomé and Príncipe) (Goergen *et al*. 2016). Four specimens barcoded from Nigeria matched the corn strain and two from São Tomé matched the rice strain. Both strains were subsequently reported from Ghana (Cock *et al.* 2017) and Togo (Nagoshi *et al*. 2017b), and both are in Zambia (CABI data). It seems more likely that both strains have been present in mainland Africa since the first introduction, rather than that the rice strain has spread from an initial establishment in São Tomé to the mainland.

Nagoshi *et al.* (2017b) analysed the Togo populations for the CO1 haplotypes used to characterise the Texas and Florida strains, and found that all Togo material of the corn strain was h4, the haplotype that is most common in the Florida strain and almost absent in the Texas strain (Nagoshi *et al.* 2017a). This lack of diversity supports the view that the original introduction involved a very small number of individuals, representing just a portion of the American diversity. Furthermore, although it does not prove the area of origin, the probability is high (>90%) that the introduction was from the characterised Florida strain, which is restricted to the eastern seaboard of the USA, and the Caribbean islands (apart from the continental island of Trinidad, where the Texas strain is found). The fact that, so far, only one haplotype of the corn strain has been found in Africa needs to be tested at more than one locality. If this is confirmed, then there may be implications regarding FAW biology and ecology given that this may vary between the haplotypes. There is no equivalent genetic population in the Americas, ie restricted to the rice strain and haplotype 4 of the corn strain, so it is possible that the African population will differ in biology and ecology.

At the moment, the two strains seem to be spreading more or less together in Africa. It is likely that the introduced population has gone through a genetic bottleneck during the introduction and establishment phase, and it is possible that this may have led to changes in the dynamics of hybridisation, so that no assumptions should be made about the relationship of the two strains, and their ability to hybridise in Africa. In planning management options, it should be anticipated that all behaviours, including dispersal strategies and food plants observed in the Americas will occur in Africa until observations of the two strains spreading in Africa indicates otherwise. Further sampling and genetic analysis will throw light on these aspects.

Pathways of entry and spread

Cock *et al.* (2017) include an analysis of the likely pathways of introduction in the context of the framework put forward by Hulme *et al.* (2008). Understanding how FAW reached Africa will have implications for the probability of it spreading beyond Africa, eg into tropical Asia, and may suggest options to reduce that risk. Of the six possible types of pathway of entry that Hulme et al. recognise (intentional introduction of a commodity, escape of an intentionally introduced commodity, contaminant of a intentionally introduced commodity, stowaway on a vector, dispersal along a human-created corridor, unaided dispersal), only three might have been applicable in this case: contaminant of a commodity, stowaway on a vector and unaided dispersal.

As Goergen *et al.* (2016) have stated, the original introduction or introductions must have involved at least one female of each *S. frugiperda* strain. Because intercontinental introductions like this are rare events, and this is the first recorded occurrence of *S. frugiperda* in Africa, we think it more likely that the two *S. frugiperda* strains were introduced together than that there were separate introduction events for each *S. frugiperda* strain at more or less the same time. Introduction may have been as eggs, caterpillars, pupae or adults, or any combination of these.

Adults fly actively and, as noted, regularly move over long distances with air currents before oviposition; however, the prevailing trade winds are from Africa to the Americas, not the other way around, making unaided dispersal by adult flight a very unlikely pathway of entry in this case. Furthermore, if this were a possibility, it seems unlikely that it would not have happened before, perhaps long ago.

Transfer as a contaminant of a commodity, eg fresh produce, is a possibility. In an analysis of quarantine interceptions on entry into the USA, 1984–2000, McCollough *et al*. (2006) found that insects in cargo were most frequently intercepted on cut flowers, plant parts and fruit (in rank), whereas insects in baggage were most frequent on fruit, plant parts, seeds and cut flowers (in rank). Given their feeding habits, larvae of *S. frugiperda* are most likely to be transferred from the Americas within plant parts, eg a maize cob with the sheath in place. Pupation normally takes place in the soil, but could occur amongst plant material if confined, eg a bag of fresh, infested produce. Both of these scenarios are possible in the context of modern air transport and travel. Analysis of the interceptions on plant produce coming into the European Union and Switzerland, 2012–2016 (EUROPHYT 2017), revealed an average of 7.2 interceptions of *S. frugiperda* per year, of which 17 were on capsicum peppers, 11 on other *Solanum* spp. and eight on parts of other plants. Suriname was the most common source country (26 interceptions), but *S. frugiperda* was also intercepted from Dominican Republic, Ecuador, Guatemala, Mexico and Peru – but not from the USA. However, compared with trade to Europe, the cargo importation of fresh produce known to harbour early stages of *S. frugiperda* from the Americas into Africa is extremely limited, estimated at less than 10 tonnes per year (FAO 2017). The combination of phytosanitary precautions and minimal trade in fresh produce between Africa and the Americas indicates that the chances of transferring viable numbers of both *S. frugiperda* strains together as contaminants are extremely small. No consolidated data is available on how much and what type of produce is carried in passenger baggage, nor on interceptions of insect pests at African ports.

On balance, we consider the possibility of a successful transfer as a stowaway on a direct flight to be significantly more likely. Eggs are laid in tightly packed groups: they have been recorded being laid on inorganic substrates (Sparks 1979, Thomson and All 1984) and egg masses can be laid in, or on, parts of aircraft, including wheel bays. In one 1950 study (Porter and Hughes 1950), more than 9,000 aircraft coming from South America and the Caribbean were examined at Miami airport: Lepidoptera eggs were found on 98 of these (0.86%), and the predominant species was *S. frugiperda*. The number of egg masses on each plane varied from one to about 1,000. Survival rates of insects on intercontinental flights may be high (Russell 1987) and would be excellent on cargo containers transferred within a pressurised hold. For eggs to be the means of transfer, it would be necessary after arrival for the aircraft — or whatever part of its equipment had eggs on it — to be placed close to, and upwind from, suitable food plants, thereby enabling newly hatching caterpillars to be carried to them, ballooning on silk threads on the wind. Alternatively, pre-oviposition female moths could settle in parts of an aircraft, such as the cargo holds or wheel bays, and this also seems a possible mechanism for transfer.

As an illustration only, in December 2016 there were direct commercial flights between Atlanta (Georgia, USA) and Lagos (Nigeria), and between São Paulo (Brazil) and Lomé (Togo). Such routes might provide an opportunity for the transfer of adults and eggs via an air route. Alternatively, if the same plane was used on sequential flights from America to Europe, and then from Europe to Africa, this also could provide a viable possibility for introduction. We have not attempted to assess how often this happens and on what routes.

Nagoshi *et al*.'s (2017b) analysis of the haplotypes present in maize infestations in Togo showed that all specimens of the corn strain were of haplotype 4, typical of the Florida strain, and absent or almost absent (<10% in South America) in different parts of the range of the Texas strain. Of the two possible source airports just mentioned, Atlanta (lying between the Florida and Texas strains yet to be characterised) is the more likely to be the source of haplotype 4. It seems a reasonable hypothesis that this introduction into Africa comprises just one corn strain haplotype and originated in the range of the Florida strain, quite likely from the eastern seaboard of the USA. A more definitive answer would require genomic (mitochondrial) comparison between examples of both species in order to see if the differences seen in the CO1 barcode region are reflected in differences in other functional genes.

Onward spread within Africa is already happening and there are widespread reports of this in the press and online in many countries in central, eastern and southern Africa, as summarised in section 2. We have no evidence regarding the methods of spread within Africa, but it seems likely that unaided dispersal by wind-assisted flight, as contaminants of nationally and internationally traded commodities, and as eggs on or as stowaways in, aircraft and vehicle vectors could all play a role. However, wind-assisted flight alone should be sufficient to enable FAW to spread throughout suitable habitats in sub-Saharan Africa, and medium-term planning should be based on this expectation.

Recently reported outbreaks in southern Africa raise the question as to how long *S. frugiperda* has been present in this region. Given that the climate is more seasonal and there are marked dry seasons in southern Africa, *S. frugiperda* is unlikely to be breeding continuously, unlike in much of West Africa, and so it may have taken several years to build up to outbreaks. Hence, it is not impossible that the original reports in West Africa do not represent the first introductions into the continent.

In order to assess the risks of future spread to Asia, it would be appropriate to assess the potential pathways in light of this analysis.

1. **Unaided dispersal**. Is agriculture sufficiently continuous that FAW can spread to the Mediterranean or Asia in jumps of 500 km with the wind?
2. **Contaminant of a commodity.** Is there trade in commodities fed on by FAW between areas of Africa that are infested, or are expected to be infested, and Asia? If so, phytosanitary measures will be needed.
3. **Stowaway on a vector.** Are there direct flights between areas of Africa that are infested, or are expected to be infested, and Asia? If so, some research on survival of FAW eggs

on aircraft surfaces during flights would be useful, and phytosanitary measures should be considered.

Section 2: Current spread into Africa

Spread into Africa

What is the extent of the spread of *S. frugiperda* in mainland Africa? Given what we know about its extent and rate of spread in the Americas, and that the conspicuous new damage to maize cobs in the field was easily detected and recognised as new by extension staff, CABI thinks *S. frugiperda* can be expected to spread to the limits of suitable African habitats within a few years (Cock *et al.* 2017), including northern Africa and Madagascar.

Previously reported distribution

In the first evidence note (*Fall Armyworm Status: Impacts and Control Options in Africa, Preliminary Evidence Note*), produced by CABI in April 2017, CABI carried out a literature review to understand the current distribution of FAW across Africa.

By 28 April 2017, 17 countries had a confirmed FAW presence through official (red fill) and unofficial (dark orange fill) sources. Nine more (light orange fill) were suspected of having the pest. It was clear that the evidence note report indicated just the current distribution, and the situation was constantly worsening.

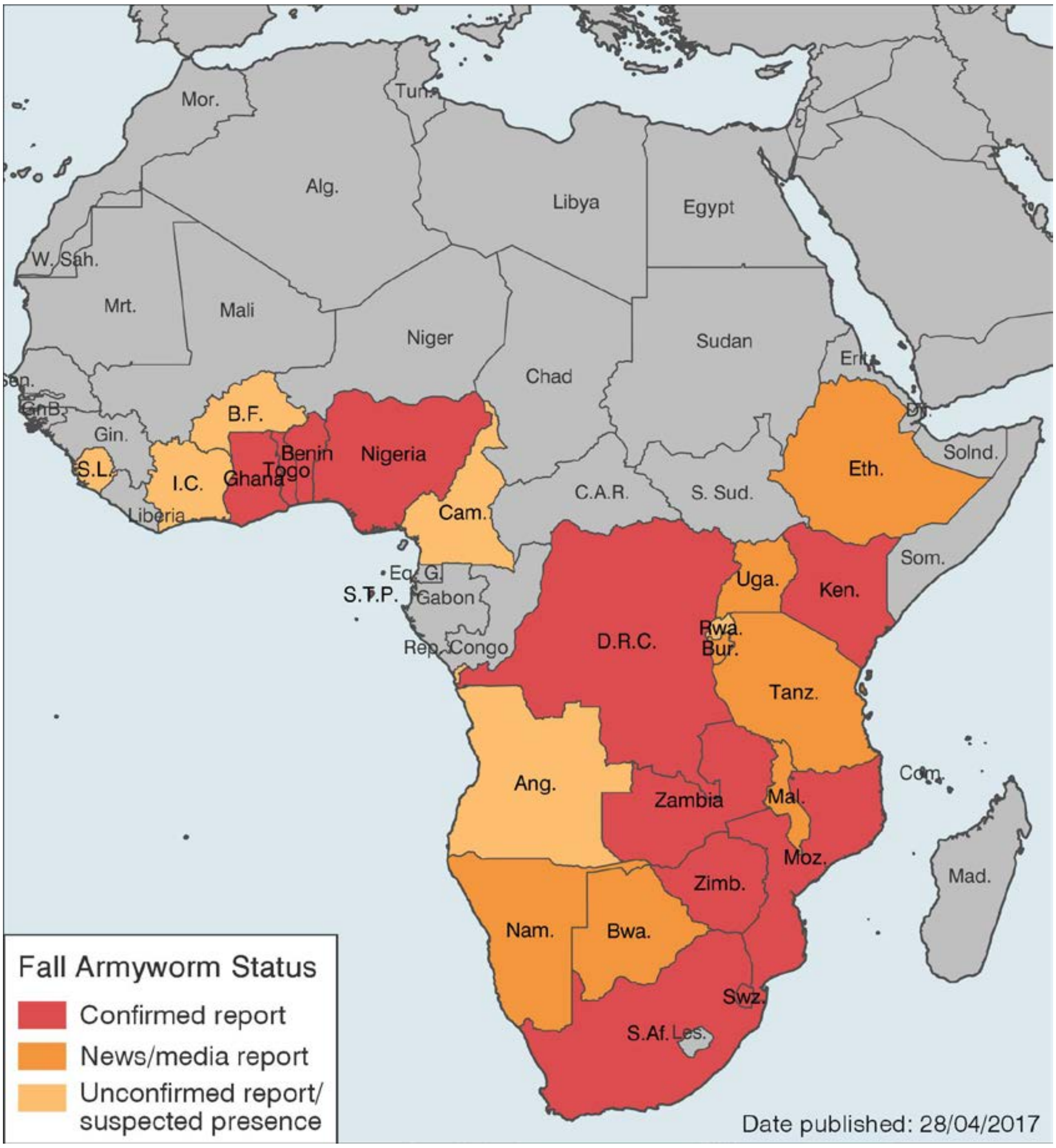


Figure 2. Previously reported distribution of FAW in Africa.

Methods for current distribution review

At the time of publication of this document in September 2017, 54 countries in Africa were surveyed and researched. CABI researched the present situation in all countries through internet mining, academic and grey literature reviews, and discussions with contacts in country. Internet mining took place through the Google and Bing Search engines and review a minimum of 10 pages of results for each of the 54 countries. News channels, official organisation webpages as well as reports were reviewed and the main information was taken from each. Although these are non-official sources, the internet review was linked with our discussions with key contacts in many countries. Finally, a review of the academic literature, presentations in many official workshops that took place over the last six months, and a collection of grey literature from official sources were reviewed.

Current distribution

Currently, 28 countries have officially reported the pest on their territory, compared to 12 in April 2017. Countries confirm the pest's presence through a variety of sources, including IPPC (eight reports), ministerial declarations, peer reviewed journals, and UN affiliated organisation reports. A further nine countries have conducted or are presently conducting surveys, and either strongly suspect its presence or are awaiting official confirmation, at the time of publication. Two countries have stated that FAW is absent from the country. It was not possible to gather any information on FAW presence or absence in the remaining 15 countries.

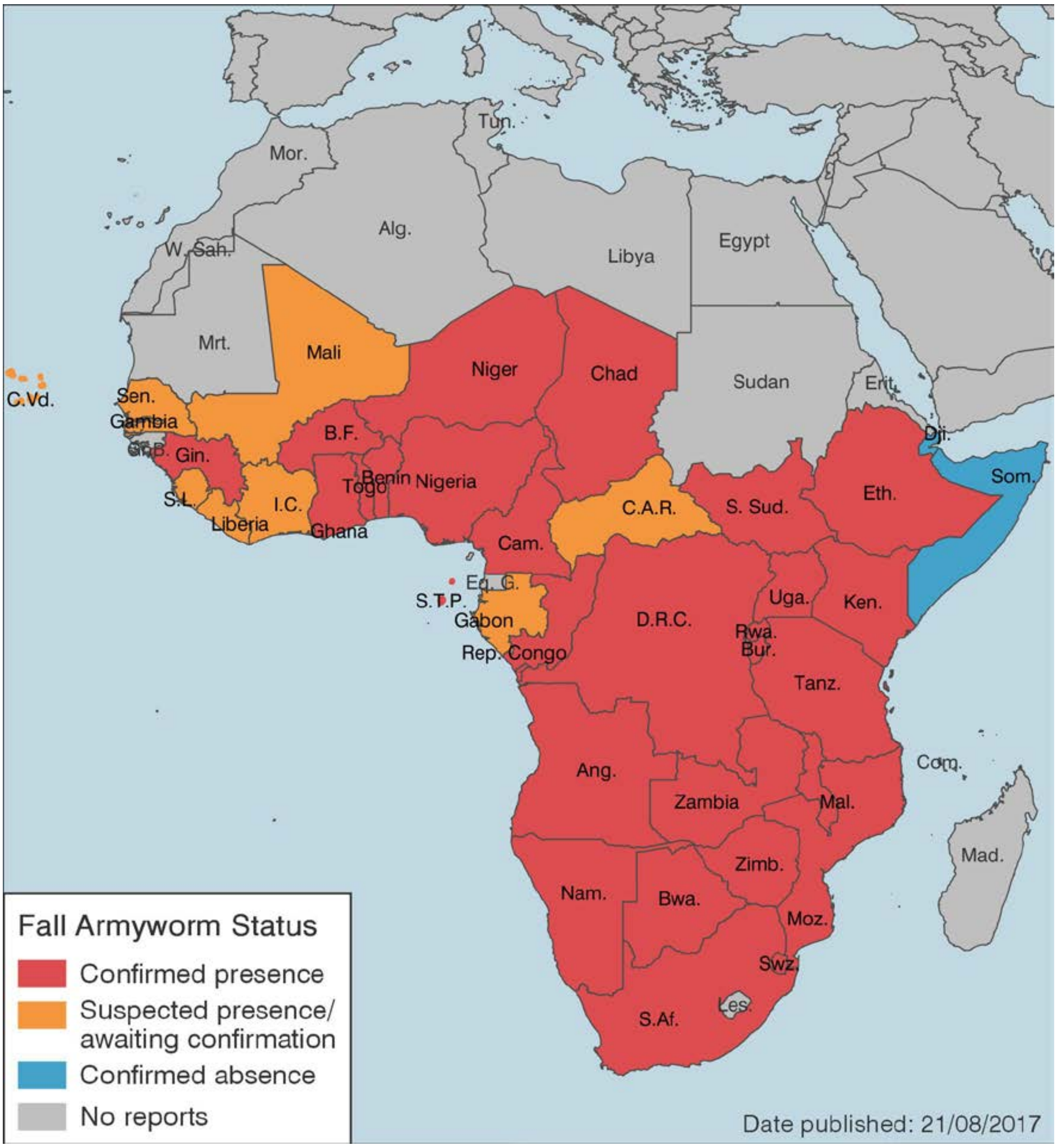


Figure 3. Current distribution of FAW in Africa.

Map of known impacts in Africa

Through various lines of enquiry, including internet mining, white and grey literature searches and personal communications with officials and scientists working in various countries, we have compiled a map of known impacts by administrative regions in the 37 countries with official/suspected presence. The continental overview is illustrated below (figure 4). Clearly, this figure is not a comprehensive map of FAW presence in Africa, but only what has been found through literature research and disucssions with key individuals. A breakdown of subnational presence, with some key impact reports, is featured in the subsequent tables (1 and 1a). Countries with weak reporting infrastructure inevitably will be under-represented in terms of our impact analysis.

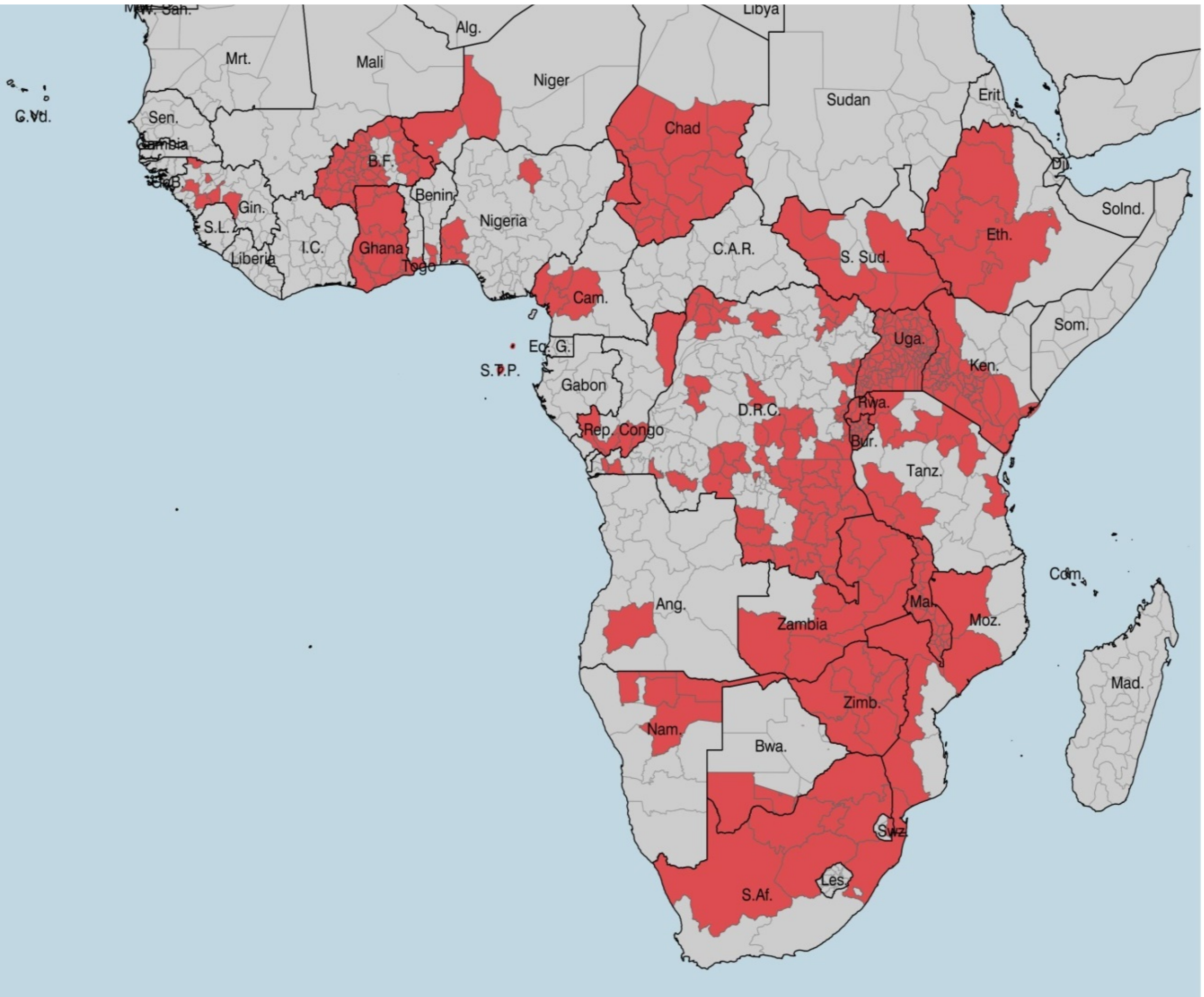


Figure 4. Map of known impacts from literature research, personal communications and internet mining.

Table 1 Individual country information based on literature, internet mining and personal communications

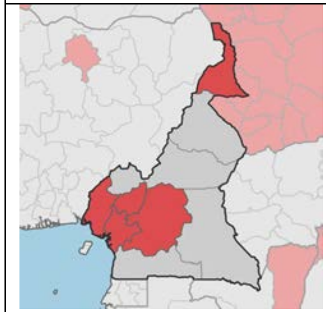
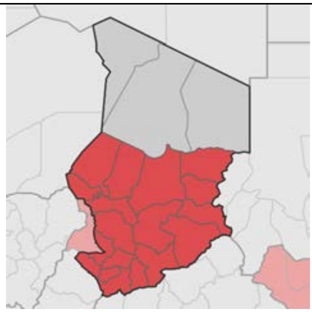
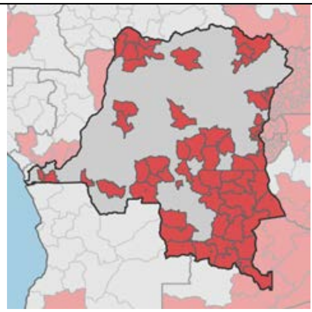
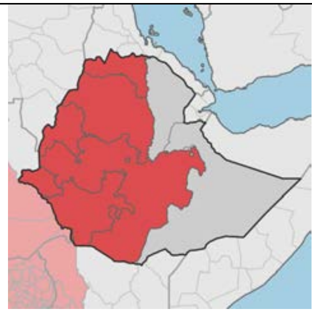
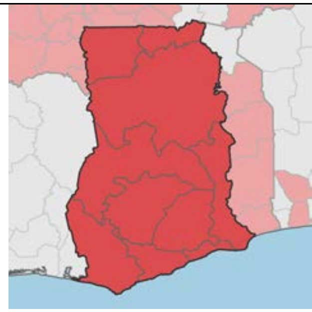
Cameroon (August 17)	Chad (July 2017)	Democratic Republic of Congo (August 2017)	Ethiopia (April 2017)	Ghana (June 2017)
				
Damages of between 25 and 75% spotted in fields	Losses recorded of up to 100% in some areas	58% of the country affected: losses estimated at $270 million; affects 250 million meals leading to food insecurity; $2 million spent on maize replanting	Pest covers 500,000 hectares out of 2 million 1 million households involved; Government has allocated nearly USD 2.3 million to tackle the problem, buying 150 000 litres of pesticides,	125,000 hectares affected in 2017 so far; $4 million allocated to fight the outbreak, to purchase chemicals and education; estimated economic losses of about $164 million;

Table 1 (cont.)

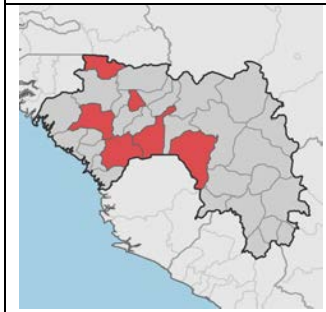
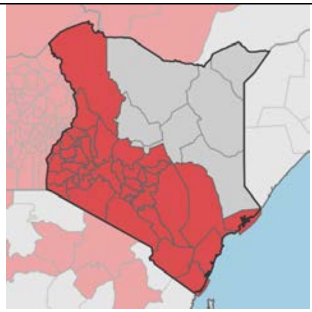
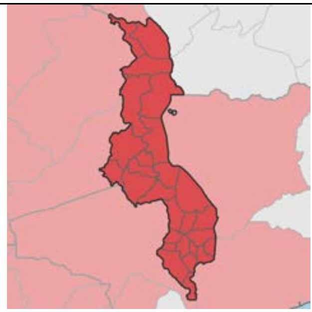
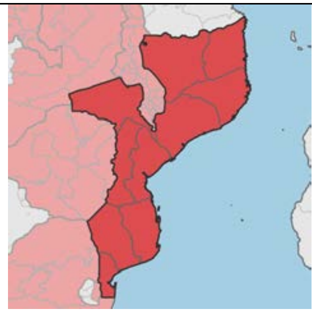
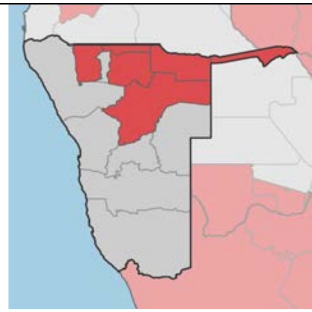
Guinea (June 2017)	Kenya (May 2017)	Malawi (June 2017)	Mozambique (2017)	Namibia (March 2017)
				
500-600 hectares affected across the country Crop protection department not worried however as they feel problem is contained	27 of the 47 counties affected; 250,000 hectares of maize affected; 158 million dollars lost. expected 25% decrease of maize production; $10 million expected to be spent by Government	Ministry of Agriculture reported that about 138,344 hectares out of the total 1,547,339 hectares of planted cereals was infested by the FAW	No further information	50,000 hectares of maize and millet crop destroyed 21,000 households affected 50 to 60% of harvest will be lost due to outbreaks in one district

Table 1 (cont.)

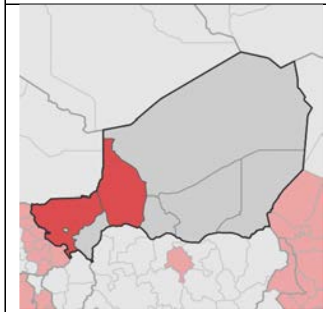
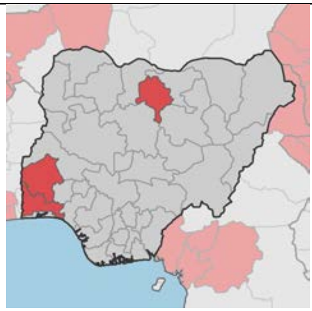
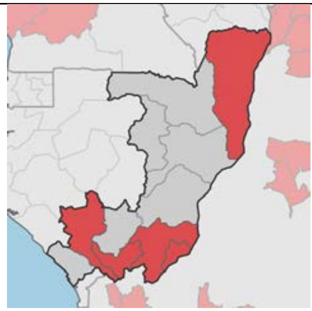
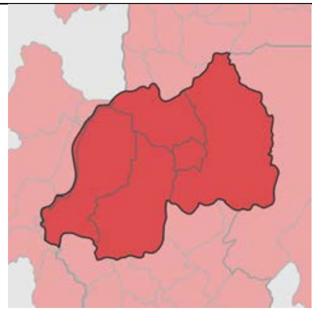
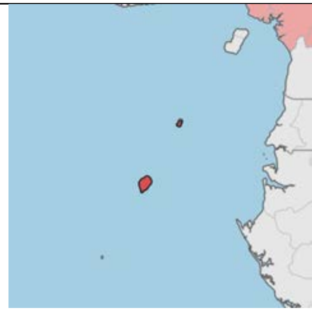
Niger (March 2017)	Nigeria (June 2016)	Republic of Congo (August 2017)	Rwanda (June 2017)	Sao Tome et Principe (June 2016)
				
No further information	FAW reported in 22 states of the country	Present in five areas in the north and south	17% of maize crop affected; military had joined the fight to halt their spread; 21,000 hectares of maize and sorghum crops affected	No further information

Table 1 (cont.)

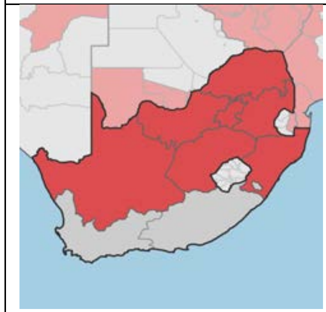
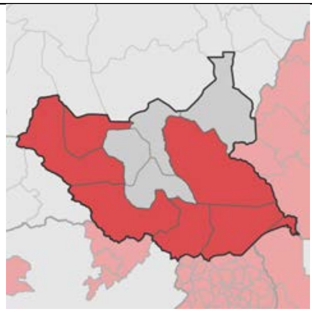
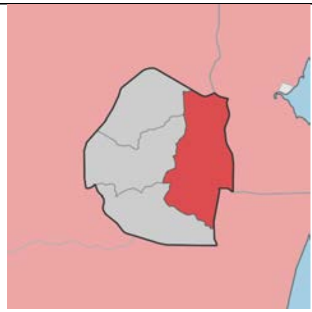
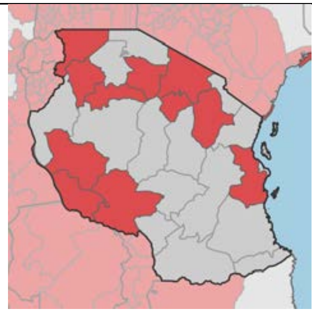
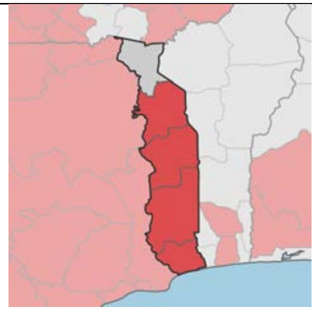
South Africa (July 2017)	South Sudan (July 2017)	Swaziland (March 2017)	Tanzania (May 2017)	Togo (June 2016)
				
No further information	500 hectares completely destroyed, with potential losses on 166,000 hectares of South Sudan's 664,000 hectares of arable land; government initially provided 588,000 US dollars to purchase pesticides	Statement by Principal Secretary of the Ministry of Agriculture: 'Effects will be felt by farmers in crop production'. Over 32 hectares destroyed in Big Bend district	2,000 litres of Cypermethrin were issued by the government to the affected regions, at a cost of $100,000. 3,000 hectares damaged in one ward alone	No further information

Table 1 (cont.)

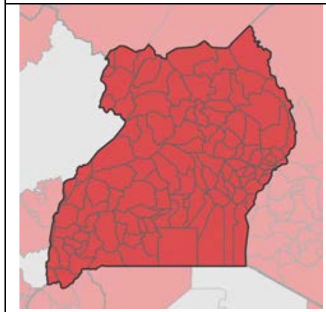
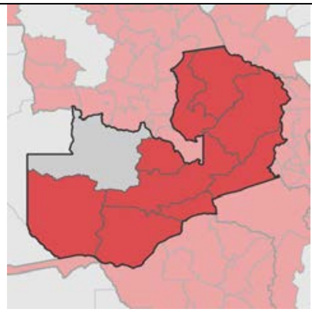
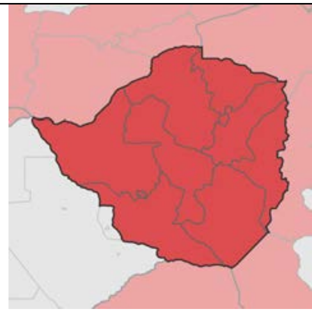
Uganda (July 2017)		Zambia (March 2017)		Zimbabwe (May 2017)
				
Possible losses of $193 million on medium predictions; up to 11% of losses in the maize sector; 980,000 of 1.3 million hectares affected; 20,000 hectares destroyed – up to 40% of maize has been lost in 20 western and central Ugandan districts; close to $7 million has been allocated by government to help purchase pesticides		223,000 hectares of maize (20% of total maize plants affected); 87,000 short maturing varieties needed to be replanted; 200,000 tonnes of maize destroyed by FAW; government has spent $3 million to control pest; 10% of Zambian farms (2434,000 farmers covering 191,000 hectares) have been affected; 102,000 litres of pesticides, valued at Zambian kwacha (ZMW) 18 million, distributed; ZMW 3 million for purchase of work suits, gum boots, sprayers, respirators		About 10% (130,000 hectares) of Zimbabwe's nearly 1.3 million hectares of land under tillage affected by the pest outbreak

Table 1a

Mali	July 2017	Detected and reported – awaiting official confirmation	Emergency transboundary Outbreak Pest situation update 7 - July 2017 (OFDA-AELGA); NPPO personal communication
Cape Verde	July 2017	Detected and reported – awaiting official confirmation	Emergency transboundary Outbreak Pest situation update 7 - July 2017 (OFDA-AELGA); NPPO personal communication
Sierra Leone	July 2017	Suspected but not confirmed – awaiting confirmation	Emergency transboundary Outbreak Pest situation update 7 - July 2017 (OFDA-AELGA)
The Gambia	July 2017	Suspected but not confirmed – awaiting confirmation	Emergency transboundary Outbreak Pest situation update 7 - July 2017 (OFDA-AELGA)
Senegal	July 2017	Suspected but not confirmed – awaiting confirmation	Emergency transboundary Outbreak Pest situation update 7 - July 2017 (OFDA-AELGA)
Central African Republic	August 2017	Identification of samples in progress	NPPO personal communication
Liberia	August 2017	Identification of samples in progress	NPPO personal communication
Ivory Coast	August 2017	Identification of samples in progress	NPPO personal communication
Gabon	August 2017	Identification of samples by IITA in progress	NPPO personal communication
Somalia	August 2017	No FAW reported	FAO-SFE Training of Trainer (ToT) workshop on FAW action meeting – 2017
Djibouti	August 2017	No FAW reported	FAO-SFE ToT workshop on FAW action meeting – 2017
Lesotho	August 2017	No information available	
Equatorial Guinea	August 2017	No information available	
Guinea-Bissau	August 2017	No information available	
Madagascar	August 2017	No information available	
Eritrea	August 2017	No information available	
Mauritania	August 2017	No information available	

Morocco	August 2017	No information available
Tunisia	August 2017	No information available
Algeria	August 2017	No information available
Libya	August 2017	No information available
Egypt	August 2017	No information available
Sudan	August 2017	No information available
Comoros	August 2017	No information available
Mauritius	August 2017	No information available
Seychelles	August 2017	No information available

Forecasted distribution based on climatic suitability

Using data collected in the field in Ghana and Zambia and more detailed information on current FAW locations, improvements have been made to FAW distribution forecasts. Work by Regan Early (Exeter University) combined seven different species distribution modelling techniques to generate 560 models which assessed and simulated the relationships between climatic conditions and the pest's biological and ecological properties. It was found that precipitation in the wettest quarter and the coldest annual temperatures were important variables. The results were combined to produce an environmental suitability index across the continent. The map (Figure 5) shows possible hotspots, as well as areas where climatic conditions are not considered favourable. In this map a suitability of 0.5 means a 50% probability that an area is suitable for FAW. Dark blue shading represents a low probability of FAW environmental suitability. Yellow shading represents a moderate suitability index. Orange and red signifies the environmental variables are suitable or very suitable for the FAW to establish itself.

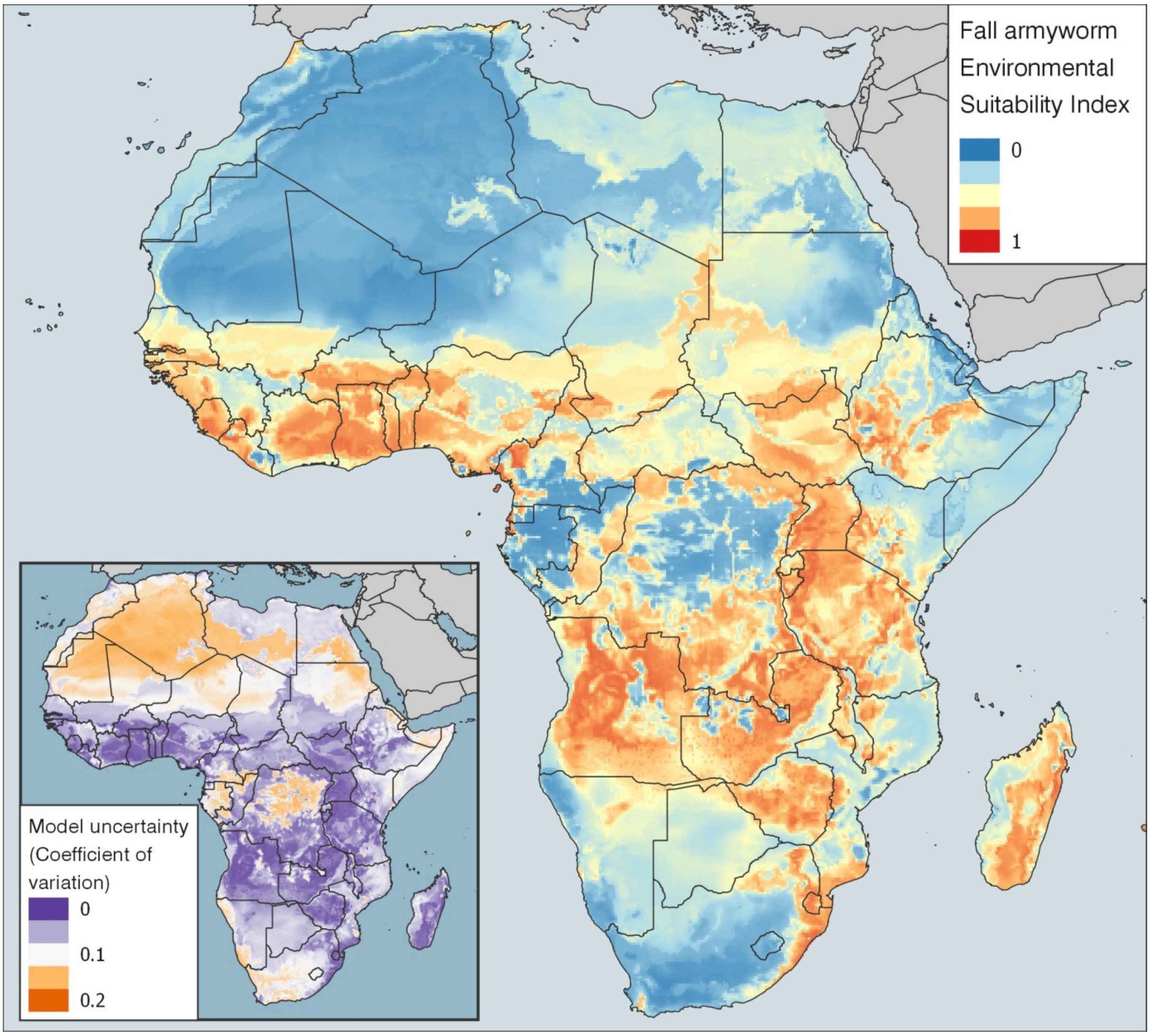


Figure 5. Environmental suitability for FAW in Africa.

A significant amount of ground observation data from Ghana and Zambia has been collected and incorporated into the model. Along with data from the native range in the Americas this has helped to refine the model across Africa. As stated in the methodology section, the model aggregates results from seven different techniques (Annex 2). The final figure above takes into account discrepancies between the various models (inset in figure 5 above) and the amount of disagreement between models, relative to the mean suitability (coefficient of variation). The orange areas in the inset figure are where the models disagree most about suitability. As we can see, the disagreement between models is higher (orange) in areas where the final model predicts there to be a low chance of FAW distribution, and disagreement between models is low (purple) in locations predicted to be at high risk of FAW distribution. This can largely be explained by the climatic variables that are taken into account within the native range of FAW: for example, in the Sahara, whilst the final model predicts a low environmental suitability, the inset figure shows there to be a higher disagreement between the models. This is due to some models favouring high temperatures as key to the development of the pest, whilst not taking into account the extremely dry conditions that will not favour the pests' feeding requirements, particularly on maize. Whilst it is important to acknowledge the disagreement between models, the final suitability model presented in figure 5 is a reliable model that takes into account the major variables that dictate FAW distribution according to climate.

Ecological niche occupation in the Americas and Africa

A forecasting exercise was also conducted to calculate the possible shift in ecological niche occupation of FAW in relation to its native range in the Americas. Overall, all but 3% of the Ghana and Zambia distribution of FAW is in environmental conditions that match the native range. Hence, it seems that FAW has largely stayed within the same climatic conditions as its native range. This implies minimal evolution of the pest towards other climates, and is helpful for any pest management activities.

This analysis needs to be carried out using other country data in order to understand the pest's evolution according to climate. This will help us to monitor the insect's possible shift to other climatic ranges, and to prevent and control the pest from the outset. If the pest does move to new climates, not only would it cause substantially bigger economic damage, but it would also make it very difficult to forecast the species distribution using **any** modelling technique (physiological, SDM, CLIMEX), as we would not be able to predict how the species' behaviour will evolve.

The blue line in Figure 6 is the overall climate in the Americas, and the blue shaded area represents the species' niche in its native range in the Americas. The orange line represents Ghana and Zambia's climatic conditions. The pale and dark patch included within the orange line represents the conditions within which the species has been found in Ghana and Zambia. The orange shaded area (to the left of the light/dark patch) shows the part of the African range that is found in environmental conditions that differ from the native range. As we can see, this orange patch is very small (3%) compared to the entire blue shaded area.

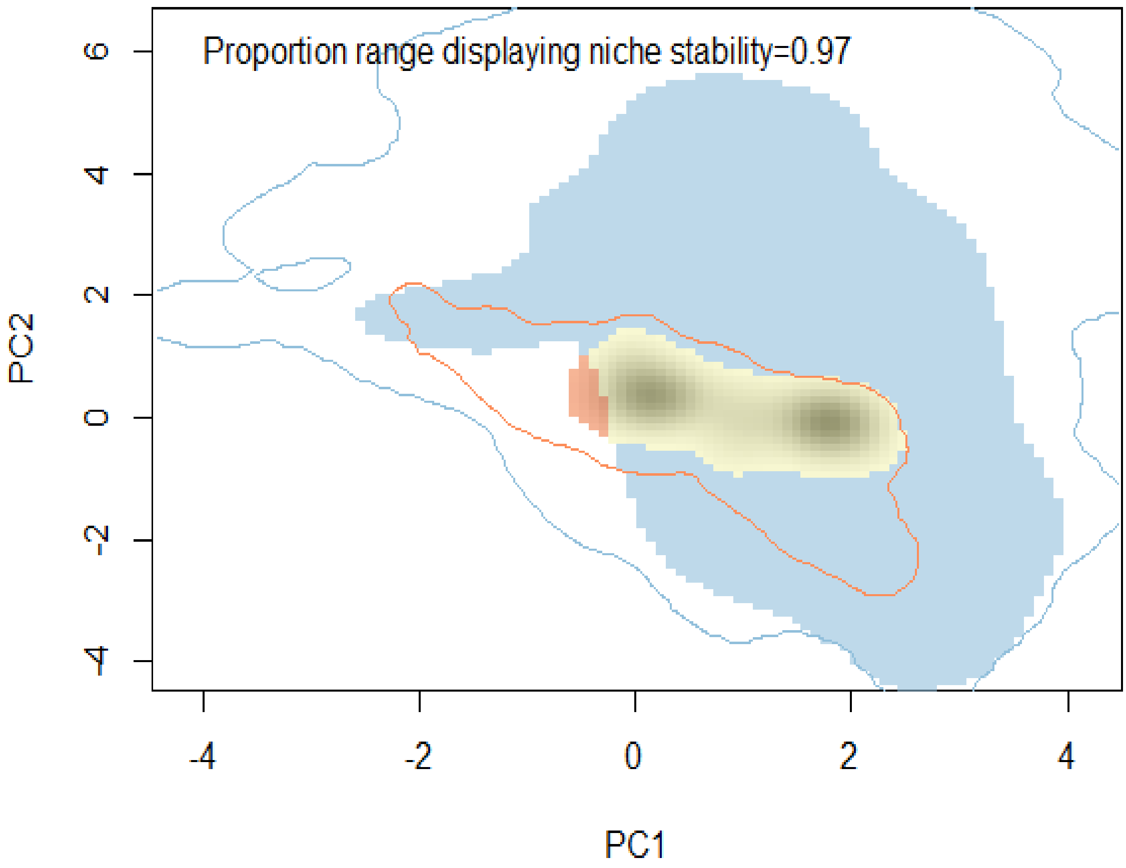


Figure 6. Overlap in the environmental niches occupied in the Americas and Ghana and Zambia. Both the X and Y axis are coefficients.

Correlation between known impacts and current predictions

This section focuses on correlating information from different databases to understand the current and potential spread at the continental level. Figure 7 below overlays information gathered from the literature search and communications on the known presence of FAW at the national and subnational levels with maize growing regions of Africa (Harvest Choice 2015). Many of the areas in southern Africa which grow maize are already affected by FAW, apart from Angola, the southern part of the Democratic Republic of Congo and the entire Island of Madagascar. Further north, Nigeria grows vast quantities of maize, but FAW is only reported in two zones, in the west and north of the country. West Africa also grows maize, yet many countries have not reported FAW. If we relate these results to the next map, it is possible to make some predictions regarding the future.

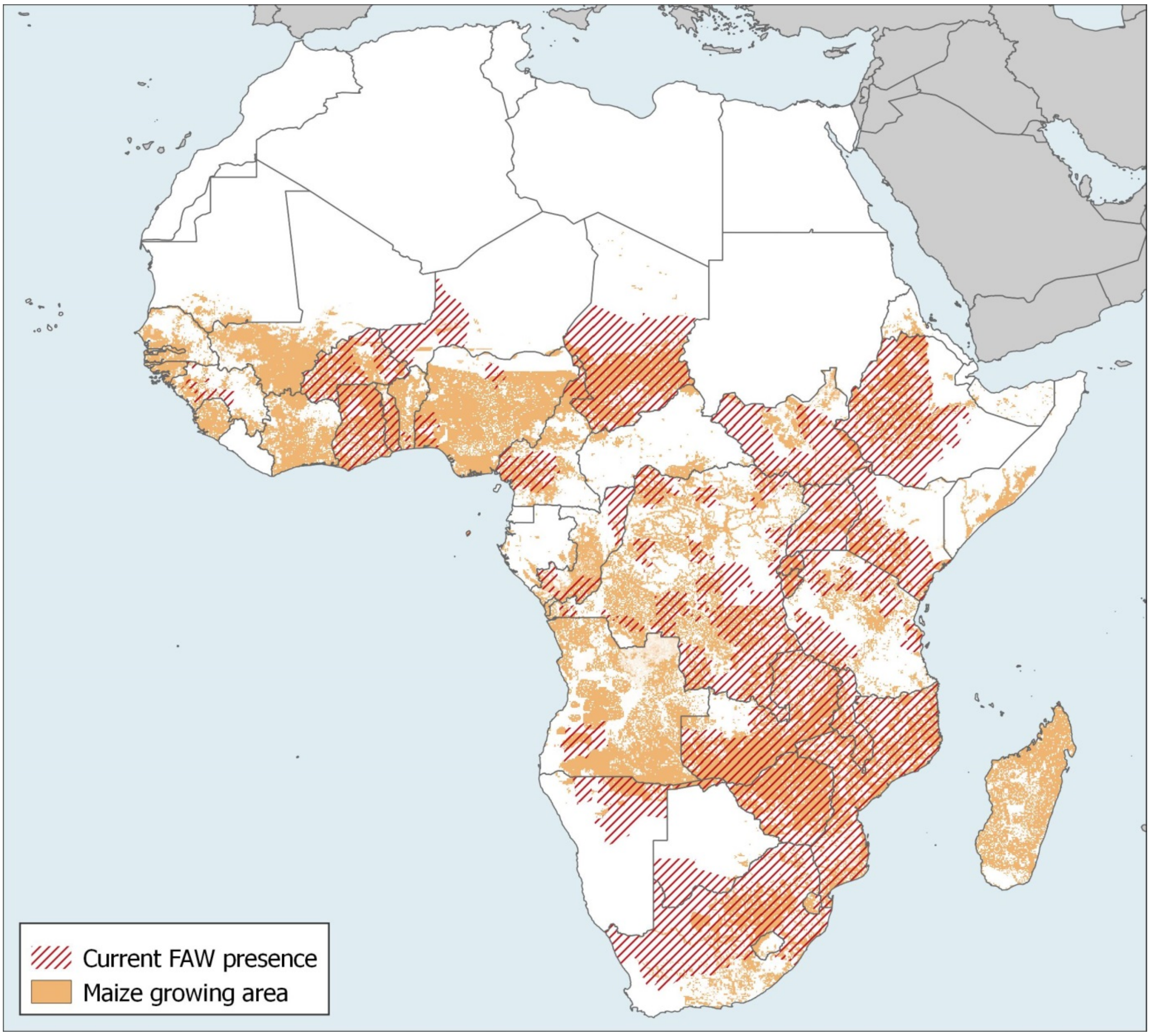


Figure 7. Map overlaying information of known FAW presence and maize growing regions of Africa.

Figure 8 below overlays information about environmental suitability with the known presence of FAW at national and subnational levels. Again, many of the areas that are predicted to be suitable have already identified FAW affecting their crops. However, as stated above, some areas which seem extremely suitable, such as Nigeria, southern Sudan, Cote d'Ivoire, Mali and the multiple countries along the west coast of the continent, from Liberia to Senegal, have not reported the pest as of yet.

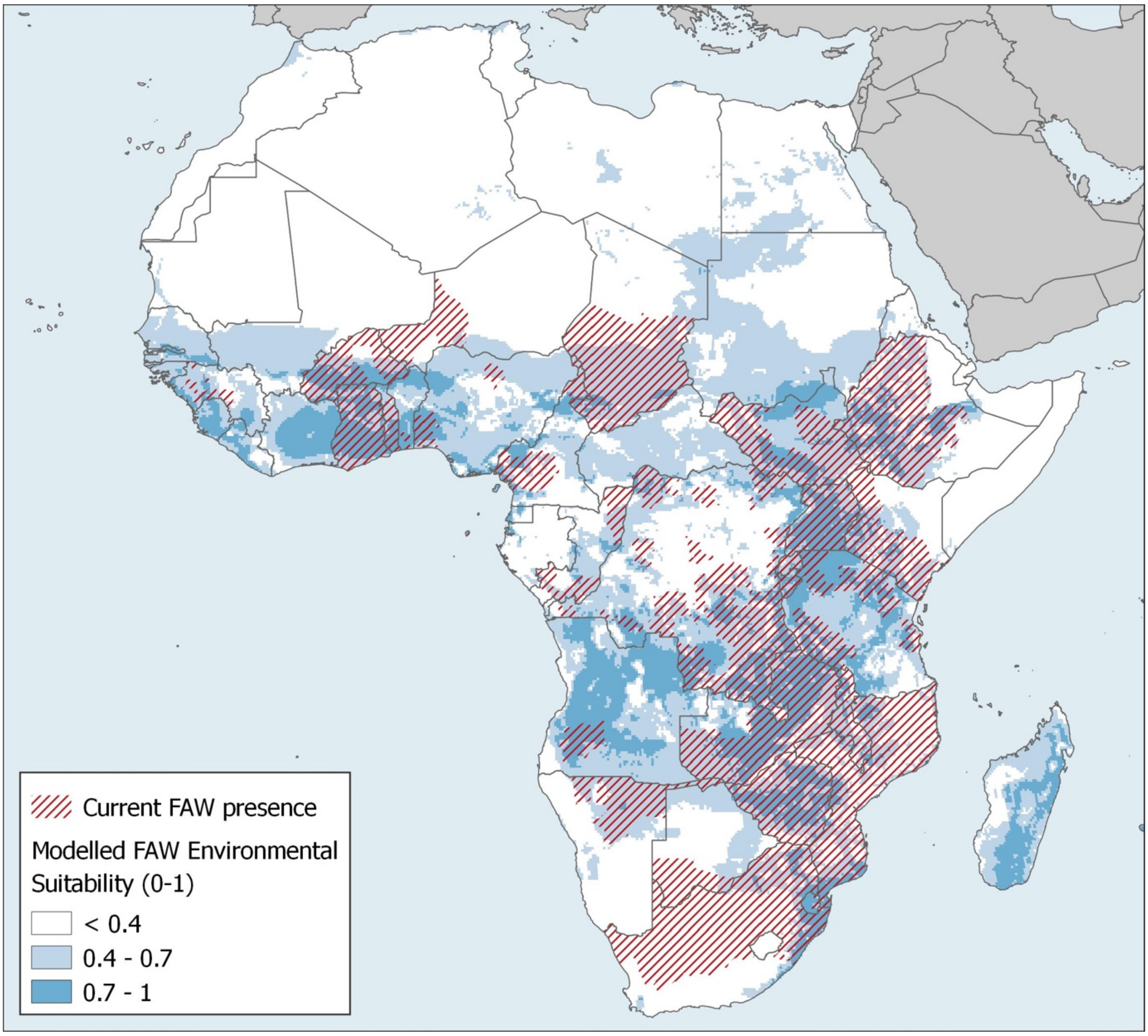


Figure 8. Map overlaying information about current and predicted distribution (by environmental suitability indices) of FAW.

Therefore, the mapping analyses points towards some predictions regarding future impacts. We can expect more reports of FAW in west Africa, particularly in Senegal, Sierra Leone, Liberia, Cote D'Ivoire and Mali, as well as the Central African Republic and Sudan. We also predict many more reports of pests in Angola and Nigeria, considering these countries' favourable environmental climates and the intensity of their maize growing activities.

Southern Sudan and Botswana could be interesting case studies to understand how the pest evolves in a country with minimal maize production. The environmental suitability model seems to contradict current known impacts in South Africa. However, we can attribute this to the oversimplification of the known distribution, which shows an entire province as affected if

FAW is reported there, irrespective of the intensity or impacts of the pest. Whilst there may be some FAW reports in the North and North-West provinces, the likelihood is that, based on the environmental suitability map, the impacts will be very small. However, in the East, the situation could be extremely serious, bearing in mind the suitability indices and the amount of maize grown.

FAW has currently not been recorded in Madagascar, although the climatic conditions and maize growing activities are extremely conducive to FAW expansion. Indeed, 80% of the country's maize production is grown in agro-climatic conditions that are similar to those in Zambia and Ghana, where FAW has been found. Given Madagascar's reliance on agriculture for its gross domestic product (24%, World Bank data), this is an important area of concern. We would strongly recommend that rigorous prevention and monitoring activities be initiated in this country as soon as possible.

Apart from the majority of the African conditions between the Tropics of Cancer and Capricorn, of particular note is the high environmental suitability on the Mediterranean coast, in Morocco, Algeria, Tunisia and Libya, increasing the possible spread of this insect to Europe. Also important are the high suitability areas in Ethiopia that could enable the pest to progress towards the Middle East and Asia. In western Africa, whilst many countries, such as Sierra Leone, the Gambia, Senegal, Liberia, Guinea-Bissau and Cote D'Ivoire, have not officially reported FAW, it would not be surprising to hear of its confirmed presence soon due to the suitable climate there.

Somalia has no record of FAW, and the country's climate seems to be not particularly suitable. However, with the constant threat of famine and political unrest in the country, even limited FAW impacts could lead to economic and social strife around the southern part of the country.

Section 3: The impact of FAW on maize yield and economics: national, continental, household and trade perspectives

The main objectives of the study were to:

1. Estimate the impact of FAW on maize yield and revenue loss at a national level through a detailed study of the situation in Ghana and Zambia
2. Estimate these impacts at a broader Africa continental level by extrapolating data on yield loss estimated for Ghana and Zambia
3. Estimate some aspects of impact at a household level in Ghana and Zambia where sufficient data was available from the detailed studies in these two countries
4. Understand the pest's impact on trade across the continent

Methods and extra analyses can be found in Annexes.

Studies in Ghana and Zambia: last completed maize growing season

Maize is the most important staple cereal crop grown by smallholders in sub-Saharan Africa (Macauley 2015) and is also one of the dominant cereals grown in most other African countries. In sub-Saharan Africa, maize is grown across diverse agro-ecological zones (AEZs) where over 208 million people depend on the crop for food security. Maize accounts for almost half of the calories and protein consumed in eastern and southern Africa, and one-fifth in West Africa (Macauley 2015).

Maize production in relation to sectors in Ghana and Zambia

In Ghana, maize accounts for more than 50% of total cereal production and is grown in all six AEZs (see Annex 3). The country grows 1.8 million metric tonnes of maize (FAO stats 2017). However, more than 70% is produced from three of the AEZs: guinea savanna, forest savanna, and transitional and semi-deciduous rainforest (Amanor-Boadu 2012). The main growing season is the long rainy season between April and July, although some maize is also grown during the short rains, which usually occur between September and November.

Most production is by smallholder farmers (>70%) using traditional tillage and rain-fed conditions (Amanor-Boadu 2012). Despite the importance of maize, the average maize yield is one of the lowest in the world (Ragasa *et al.* 2014) at 1.2–1.8 tonnes/hectare, with a potential of 4–6 tonnes/hectare. Maize is a main subsistence crop but is also grown for poultry feed (approximately 10%) and, to a lesser extent, livestock feed (Voto 2017). Domestic trade in maize for these industries largely relies on a network of traders linked by personal and ethnic ties: local traders either buy directly from farmers or from 'aggregators' (Voto 2017).

Likewise, in Zambia, maize forms over 50% of cereal production and is grown in all four AEZs (see Annex 3). The country also grows 2.9 million metric tonnes of maize (FAO stats

2017). There is only one growing season in Zambia, coinciding with the rainy period: November to April.

The main ‘maize basket’ lies in Eastern Province which itself lies in the AEZ IIa (Aregheore 2017). Production has increased in recent years because of the use of Green Revolution technologies and an input subsidy scheme (Global Yield Atlas 2017). Maize is mostly produced by smallholders – they form 97% of all households that grow maize and contribute to over 60% production (JAICAF 2008). Maize is the most important subsistence crop for smallholders, but approximately 20% of rural households also sell maize. However, those who sell tend to have larger holding sizes (5–20 hectares) (Global Yield Atlas 2017). On the other hand, 35% of rural households need to purchase maize to cover their production deficit.

Results and discussion

The following section is based on the results from a household socio-economic survey conducted in Ghana and Zambia over the period of July 2017. The questions were directed towards farmers’ perception of losses specifically due to FAW over the last full growing season.

Estimates of national yield and revenue losses due to FAW

According to the analysis of the proportion of maize yield loss from FAW, there are some significant differences between AEZs in Ghana, particularly when Sudan savanna is compared with the semi-deciduous forest and the transitional zones (Figure 9). There is no relation between yield loss (all data combined) and when FAW was first seen by the farmers.

For Zambia, differences in proportion of maize yield loss are also found between AEZs, particularly zone IIb and zone III (Figure 9). There is insufficient data on the proportion of yield loss and the season when first seen by the farmers to allow a similar analysis to the one done for Ghana.

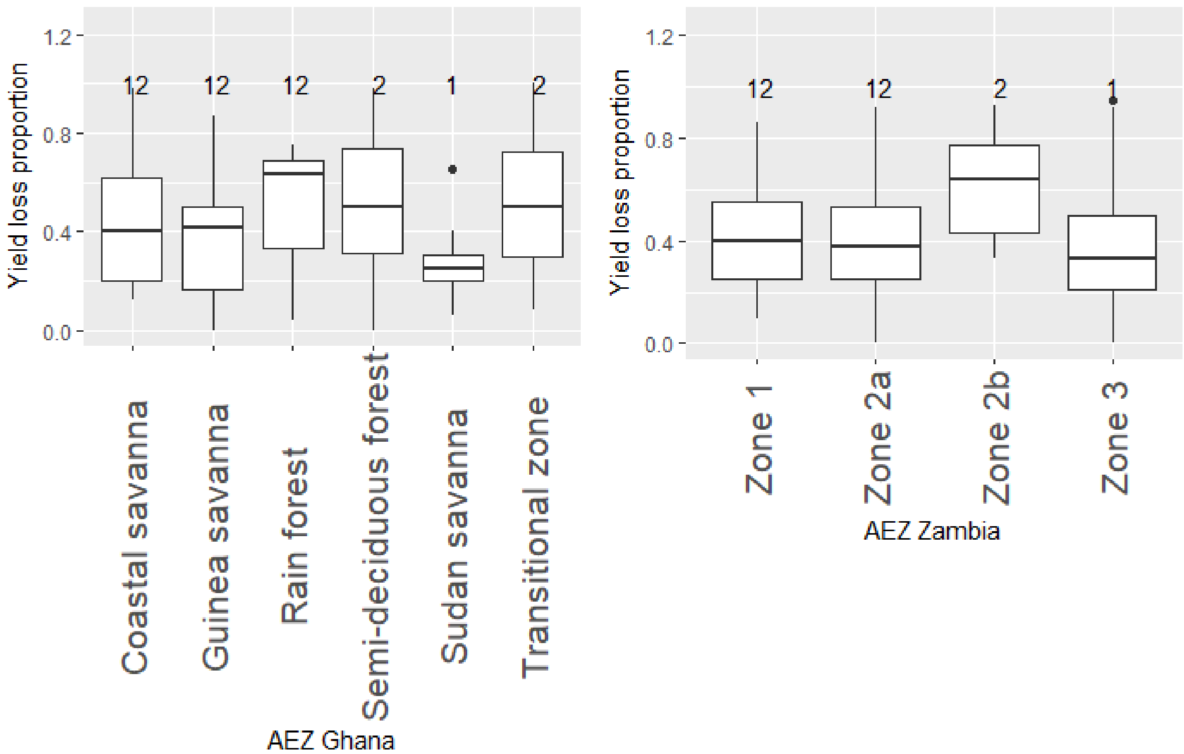


Figure 9. Box plot showing variation in proportion of yield loss in relation to AEZs in Ghana (left) and Zambia (right). Horizontal line in the box indicates the median, while top and bottom edges of the box indicate upper and lower quartile respectively. Ends of vertical lines represent the maximum and minimum values excluding outliers (black dots). Numbers at top of the graphs denote grouping of AEZ based on significant differences in a linear model (ie AEZ with same numbers at top have similar yield loss values).

The estimated percentage yield losses (lower, upper and median for each AEZ and nationally for Ghana and Zambia for the last completed growing season are shown in Table 2: the lower and upper values represent the lower and upper quartile of significance in yield loss values for each AEZ and nationally. The range of values nationally is greater for Ghana than for Zambia. A number of factors may be contributing to this. The greater number of AEZs in Ghana compared with Zambia, and the fact that maize is not grown extensively in all of these AEZs, and that not all may be equally suitable for FAW, are likely to be some of the factors involved, as indeed may be the time of arrival of FAW in the two countries.

Table 2. Ghana and Zambia: the estimated percentage yield loss (lower, upper and median) for AEZ and nationally

Country and AEZ	% yield loss (lower)	% yield loss (upper)	% yield loss (median)
Ghana			
Coastal savanna	0.20[1]	0.63[1]	0.42[1]
Guinea savanna			
Rain forest			
Semi-deciduous forest	0.30	0.73	0.52
Sudan savanna	0.20	0.31	0.27
Transitional zone	0.30	0.73	0.52
National (all zones)	0.22	0.67	0.45
[1] Coastal savanna, guinea savanna and rain forest were pooled together to calculate the mean values of yield loss for AEZs that we proved were not significantly different: this is why in the table the values are the same. However, they are not merged in the table below because of the different production values			
Zambia			
1	0.25	0.53	0.41
2a			
2b	0.44	0.77	0.62
3	0.21	0.50	0.38
National (all zones)	0.25	0.50	0.40

In both countries we can see high variabilities of proportional yield losses across the different AEZ and within the same AEZ. However this variability seems to be more prominent in Ghana than in Zambia. Whilst it is difficult to interpret the variability, the sample sizes and climatic variability and maize growth across the different AEZs in both countries (see annex 3 and the spread of the household surveys all have an impact. This will need to be considered in more detail as FAW impacts are better understood over time.

In Zambia lower impact is found across AEZ that display the lowest (<800mm) and the highest (>1,000mm) rainfall levels. However, rainfall variability is within a limited range, which might lead to reduced variability in terms of losses across the different AEZ.

For Ghana, the estimated expected maize production (last complete growing season) and estimated lower and upper yield and economic losses are given in Table 3; the equivalent data for Zambia is given in Table 4.

Table 3. Ghana: the estimated expected maize production (last complete growing season) and estimated lower and upper yield economic losses

AEZ and national	Maize production (three-year mean) (thousand tonnes)	Value of Maize with no FAW (three-year average FAO stats) (US$ million)	Yield loss (lower) (thousand tonnes)	Yield loss (upper) (thousand tonnes)	Mean yield loss (thousand tonnes)	Yield loss (lower) (US$ million)	Yield loss (upper) (US$ million)	Mean yield loss (US$ million)
Coastal savanna	124.1	42.8	24.7	77.7	52.4	8.5	26.8	18.1
Guinea savanna	230.0	79.4	46.1	145.4	97.1	15.9	50.2	33.5
Rain forest	71.2	24.7	14.3	45.2	30.1	5.0	15.6	10.4
Semi-deciduous forest	732.0	252.7	221.6	534.8	380.1	76.5	184.5	131.1
Sudan savanna	146.0	50.2	29.1	44.8	40.0	10.1	15.5	13.8
Transitional	522.2	180.1	157.7	380.6	271.1	54.5	131.3	93.5
National (all zones)	**1,825.5**	**629.8**	**401.6**	**1,213.9**	**824.3**	**138.5**	**418.8**	**284.4**

Table 4. Zambia: the estimated expected maize production (last complete growing season) and estimated lower and upper yield economic losses

AEZ and national	Maize production (three- year mean) (thousand tonnes)	Value of Maize with no FAW (three-year average FAO stats) US$ million	Yield loss (lower) (thousand tonnes)	Yield loss (upper) (thousand tonnes)	Mean yield loss (thousand tonnes)	Yield loss (lower) (US$ million)	Yield loss (upper) (US$ million)	Mean yield loss (US$ million)
1	550	94.5	137.3	291.1	225.7	23.5	50.1	38.8
2a	1,651	284.0	412.9	875.2	677.1	71	150.6	116.5
2b	116.5	19.8	50.2	88.6	72.2	8.5	15.3	12.4
3	597.0	102.6	123.7	298.2	223.9	21.2	51.4	38.5
National (all zones)	**2,913.0**	**500.9**	**728.1**	**1,456.1**	**1,154.0**	**125.2**	**250.4**	**198.4**

In Ghana, the expected maize production in the last completed growing season was highest in three main maize growing AEZs: semi-deciduous, transitional and guinea savanna (see Table 3). The estimated highest proportions of yield loss (Table 2) from FAW occurred in the first two of these. In Zambia, the highest maize production in the last completed growing season was in the main maize growing zone, 2a (Table 4), but this did not suffer from the highest proportionate yield loss, which occurred in zone 2b. The latter was significantly different from the estimated proportion losses in the other AEZs.

In summary, although the mean proportional loss is lower in Zambia than in Ghana, the total national mean loss is higher in Zambia because of the higher annual output of maize in that country. The percentage loss (using the mean loss figure) of total expected national production is 45% in Ghana and 40% in Zambia.

The estimated lower and upper economic losses for Ghana and Zambia expressed as percentages of agricultural GDP (averaged over the last three years) are given in Table 5; agricultural GDP is also expressed as a percentage of national GDP. The estimates suggest that, currently, the FAW is affecting agricultural performance more severely in Zambia than in Ghana. However, this needs to be kept in context: Zambia's mean three-year agricultural GDP is much lower than that of Ghana (US$2.3 billion versus US$9.9 billion), and thus the percentage impact of the FAW on agricultural GDP is higher in the former.

Table 5. Estimated lower and upper economic losses for Ghana and Zambia expressed as percentages of agricultural GDP (from FAO stats 2017

Country	% agricultural GDP loss (lower)	% agricultural GDP loss (upper)	Agricultural GDP as % of national GDP
Ghana	1.40	4.24	23
Zambia	5.41	10.82	8

An estimate was also made of the per capita economic loss to a maize farmer in each country. Data was obtained on the number of households growing maize in each AEZ in each country, and also on the average family size. Older data was adjusted in relation to current population size in the agricultural sectors of the countries (FAO stats 2017). The resulting lower and upper estimates are given in Table 6. The livelihoods of smallholder farmers who are only able to produce enough maize for subsistence without excess for sale will be significantly affected by FAW, especially in areas where the upper estimates of yield loss are manifested.

Finally, national development programmes in Zambia and Ghana need to be taken into account, to provide some sort of context in relation to the FAW impact. In Ghana, for example, the main 2017 harvest is projected to be an extremely productive one, with talks of a yield increase of over 30% due to an extremely large seed and fertiliser subsidy programme (the Planting for Jobs programme) initiated at the end of April 2017). For the majority of the data collected for this exercise, however, the Planting for Jobs programme began too late. Out of 156 interviews in Ghana, only 25 respondents answered questions about a planting season that incorporated April 2017.

Table 6. The estimated lower and upper per capita loss for a maize farmer over the last complete maize growing season in Ghana and for Zambia

Country	Per capita loss (US$) (lower)	Per capita loss (US$) (upper)
Ghana	14.69	35.42
Zambia	13.51	27.03

Three quarters of the sampled farmers in Ghana rely on farming activities for over 60% of their household income. Of these, half rely on farming activities for more than 90% of their household income. The large majority of farmers in the survey (94%) ranked maize as the most important crop that contributes to their household income. Moreover, in terms of food security contribution, maize was ranked as the most consumed crop by over three quarters of the farmers surveyed.

In Zambia, over three quarters (85%) of the sampled farmers rely on farming activities for more than 60% of their household income. Of these, just over half (55%) rely on farming activities for more than 90% of their household income. Over three quarters of farmers ranked maize as the most important contributing crop to household income. Cassava, sweet potatoes, soybean and cotton also ranked highly. In terms of household consumption, overall 96% of farmers ranked maize as the most consumed crop by the household, these include almost all farmers that rely mainly on agricultural activities.

There are differences between the countries as seen by the household survey: in Ghana maize is ranked as the main contributor to income. In Zambia, maize is perceived as the main contributor to household consumption. However, both countries show how important maize is, and consequently the impact of FAW on maize, to subsistence farmers in both countries.

Area affected by FAW per household

The categories of area affected in each AEZ in each country are shown in Figure 10. In Ghana, severe area infestations (>90%) occurred in semi-deciduous forest (one of the main production areas of maize) and coastal savanna. In Zambia, the severe infestations occurred in zones 2a, the major production area, and zone 3.

An analysis of the combined data from Ghana and Zambia on area affected per household in relation to yield loss per household (last completed growing season) did not show any significant relationship.

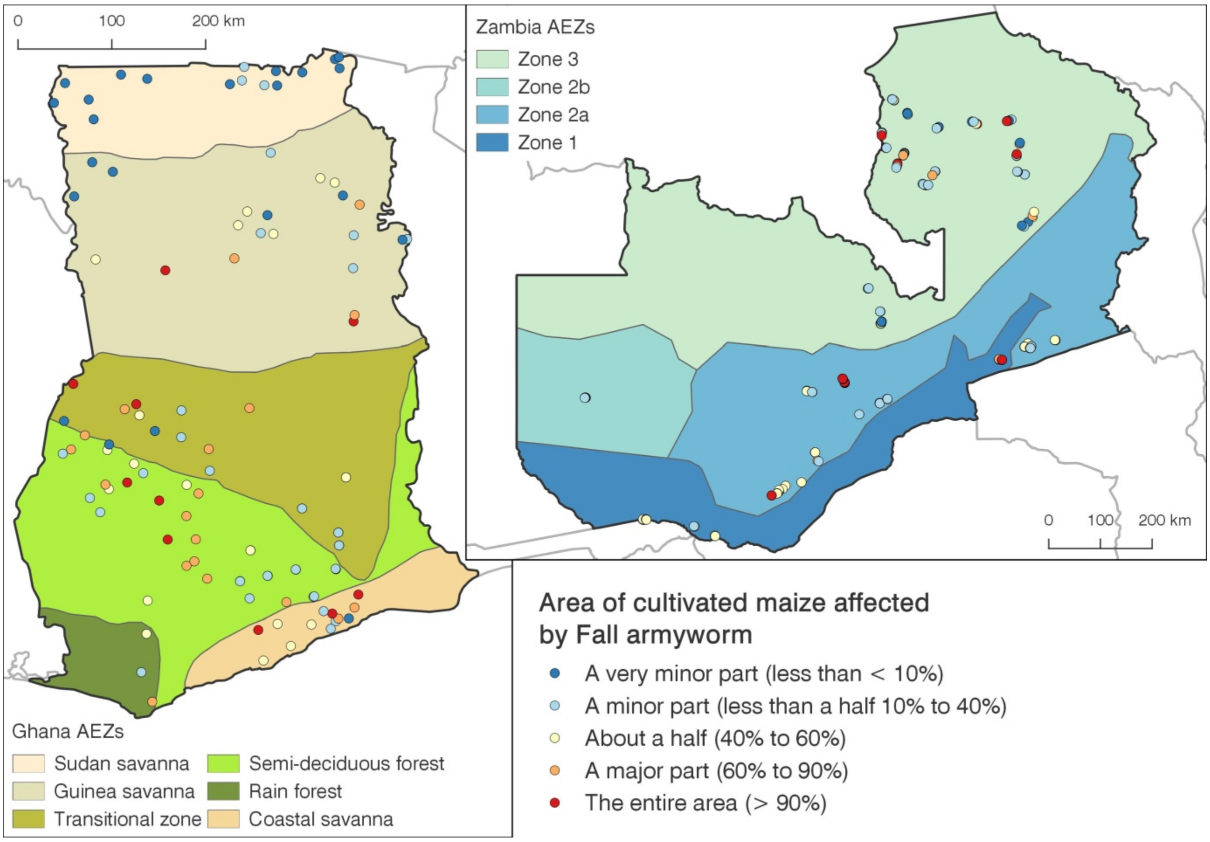


Figure 10. The distribution of survey farm records of area of maize crop affected by FAW across the AEZs of Ghana and Zambia.

Estimates of continental yield loss due to FAW

Context

The FAW is now well distributed across the African continent and national reports on the status in many countries have been published. However, the content of information in the reports is very variable, which makes it difficult to provide wider estimates of FAW impacts on maize yield and revenue loss at a national level based on these sources. Several of the reports do indicate areas of maize affected in the last complete growing season, and in some cases these areas cover a large portion of countries' maize regions. However, an analysis of the pooled data from Ghana and Zambia indicates that the proportion of yield loss is not strongly related to area affected (see below). Thus, the aim here was to estimate the *potential impacts* on national yield and revenue on the other major maize-producing countries that are *likely to occur in the maize-producing seasons up to mid-2019*, assuming that the FAW will spread throughout all areas where it is predicted to survive (see the earlier environmental suitability modelling section). This is a likely scenario of spread given the current status of FAW across the African continent. However, keeping the context in mind, in the previous section it was shown that for Ghana and Zambia the estimated national percentage loss of expected production in the last completed growing season was 45% and 40%, respectively. These are, however, means within a range and it is difficult to predict actual impacts in the future in these two countries as FAW may be affected by a number of ecological variables, such as natural enemies or competition from other pests. Thus, the estimated future impacts in other major producing countries are also calculated within a range.

The general approach was to estimate impacts of FAW for 10 other major maize-producing countries (by extrapolating estimates of proportion of yield loss from data from Ghana and Zambia (see methodology) and combining this with published data on national maize production and other information for the countries. The same general method and formulae for estimating impacts on maize yield and economics at a national level were used as for the national-level impacts in Ghana and Zambia. The 10 countries included are the major top producers of maize in Africa (in terms of metric tonnes/year) (Table 7). Kenya and South Africa are not included as there was insufficient data for these countries for the models.

Table 7. Other major maize-producing countries included in the continent-wide study of FAW impact

Benin
Cameroon
Democratic Republic of Congo
Ethiopia
Malawi
Mozambique
Nigeria
Uganda
Tanzania
Zimbabwe

Results and discussion

The total estimated national yield and revenue losses for each of the 10 countries, plus Ghana and Zambia, are summarised in Table 8. Losses are related to total expected maize production and value in each country. Note that the same lower and upper proportional loss limits (derived from the same Ghana and Zambia methodology) have been used for each of the other countries. Thus, to provide perspective on these losses, the revenue losses have also been expressed as lower and upper percentage loss to agricultural GDP, averaged over the last three years (Table 9).

Table 8. Expected maize production and estimated lower and upper yield and economic losses in the top maize-producing countries included in the study

Country	Maize production (three-year mean) (thousand tonnes)	Value of maize with no FAW (three-year average FAO stats) US$ million	Yield loss (lower) (thousand tonnes)	Yield loss (upper) (thousand tonnes)	Mean yield loss (thousand tonnes)	Economic loss (lower) (US$ million)	Economic loss (upper) (US$ million)
Benin	1,285.3	376.5	295.6	735.8	530.4	86.6	215.6
Cameroon	1,665.7	697.8	319.2	794.4	687.4	133.7	332.8
Democratic Republic of Congo	1,173.4	343.7	254.5	633.4	484.2	74.5	185.5
Ethiopia	6,628.3	1,580.2	1,227.2	3,054.7	2,735.2	292.6	728.3
Ghana	1,825.5	629.8	401.6	1,213.9	824.3	138.5	418.8
Malawi	3,344.9	979.7	769.3	1,915.0	1,380,3	225.3	561.0
Mozambique	1,247.2	365.3	99.7	239.2	514.7	35.0	84.1
Nigeria	9,302.7	3,271.8	2,129.1	5,299.7	3,838.9	748.7	1,863.6
Uganda	2,748.3	805.0	558.9	1,391.1	1,134.1	163.7	407.5
Tanzania	5,732.6	1,679.1	1,301.3	3,239.0	2,365.6	381.2	948.8
Zambia	2,913.0	500.9	728.1	1,456.1	1,154.0	125.2	250.4
Zimbabwe	1,104.1	360.7	234.8	584.4	455.6	76.7	190.9
Total	**38,971**	**11,590.5**	**8,319.3**	**20,556.7**	**16,104.7**	**2,481.7**	**6,187.3**

The estimates indicate that for these countries taken together, without use of control options, the potential impact of FAW on continental wide maize yield lies between 8.3 and 20.6

million tonnes per year of total expected production of 39 million tonnes per year and with losses lying between US$ 2, 481 and US$6,187 million per year of total expected value of US$ 11,590.5 million per year.

Table 9. The estimated lower and upper economic losses for the 12 countries expressed as percentages of their agricultural GDP; the three average (FAO stats) GDP and agricultural GDP also shown for comparison (figures in US$ million)

Country	% agricultural GDP loss (lower)	% agricultural GDP loss (upper)	GDP	Agricultural GDP	% ag GDP of GDP
Benin	3.93	9.78	9,005	2,205	24.5
Cameroon	2.00	4.99	29,363	6,668	22.7
Democratic Republic of Congo	1.10	2.75	30,502	6,749	22.1
Ethiopia	1.34	3.34	48,857	21,828	44.7
Ghana	1.40	4.24	42,787	9,871	23.1
Malawi	12.50	31.12	5,867	1,802	30.7
Mozambique	2.10	5.00	15,838	4,174	26.4
Nigeria *	0.69	1.72	514,806	108,274	21.0
Uganda	2.36	5.88	25,441	6,932	27.3
Tanzania	2.68	6.67	43,872	14,223	32.4
Zambia	5.41	10.82	26,899	2,315	8.6
Zimbabwe	4.54	11.31	15,038	1,688	11.2

***suspected under-reporting of FAW impacts**

From Table 9, it can be seen that FAW has the greatest impact on the agricultural GDP of Benin, Malawi, Zambia and Zimbabwe. It is particularly worrying in Benin and Malawi, where the agricultural GDP contributes to 24 and 31% of the overall GDP respectively.

The impact of controlling the FAW at a household level in Ghana and Zambia

Context

Having understood the impacts of FAW at the national level for Ghana and Zambia, and at the continental level for a further subset of 10 countries, it is important to consider the individual household-level impacts. FAW will impact many different aspects of household livelihoods. As seen through the prism of the DFID livelihood framework, the pest is likely to directly affect human capital, through labour and knowledge availability and the access to communication channels; natural capital, through yield losses and the ability of agricultural lands to respond to shocks; and financial capital, through increasing the cost of control (defined as the cost of technology and its application), and its effect on income. It will also indirectly affect households' social and physical capital (the household's assets).

The survey given to 512 households enables this report to focus on the cost of control of FAW in the field.

466 participants had seen FAW on their maize crop in the last cropping season, and only 11 had not acted on the problem. The major control measures were as set out in the table below:

Table 10: most popular FAW control measures used by farmers in Ghana and Zambia

Top five control methods for Ghana and Zambia	Ghana	Zambia
	%	%
Chemical control	72	60
Hand-picking egg masses and caterpillars		36
Ash on larvae		7
Frequent weeding	23	6
Improve soil fertility	16	
Uprooting and burning infected plants		5
Early planting	13	
Removing crop residues	8	

Chemical control is by far the most utilised control measure: 72% of the participants in Ghana and 60% of participants in Zambia used chemical measures to control FAW. Hand-picking egg masses and caterpillars was also popular in Zambia (36% of positive responses), whilst frequent weeding was popular in Ghana (23% of positive responses). Three participants mentioned the use of biological control (two had used Bt pesticide, whilst one mentioned biological control).

This section focuses on the cost and use of conventional pesticides to control FAW. More specifically, it considers how much the cost of control adds to other costs for maize farmers. In this analysis, the study has managed to find many variables to use for the theoretical costs of the technology, as well as its application. We assume that labour and chemical costs are constant across the country. We also assume that the minimum wage is being disbursed to the informal sector for daily labour in the field. We have also costed household members in the field at the same cost, as the work would have to be done irrespective of whether this is by a household member or an external labourer.

In this analysis, the data focuses on the most popular chemicals used: these are products with the active ingredients cypermethrin, lambda cyhalothrin and chlorpyrifos in Zambia, and Cypemethrin, lambda cyhalothrin and emamectin benzoate in Ghana. Their use does not show any specific preference according to a particular region. Indeed, the map below shows they are all widespread across the countries (see figure 11 below).

Table 11: Most popular use of chemicals in the household survey in Ghana and Zambia

Active ingredient	Ghana	Zambia
Cypermethrin	29	52
Lambda cyhalothrin	11	48
Chlorpyrifos	4	13
Emamectin benzoate	9	6

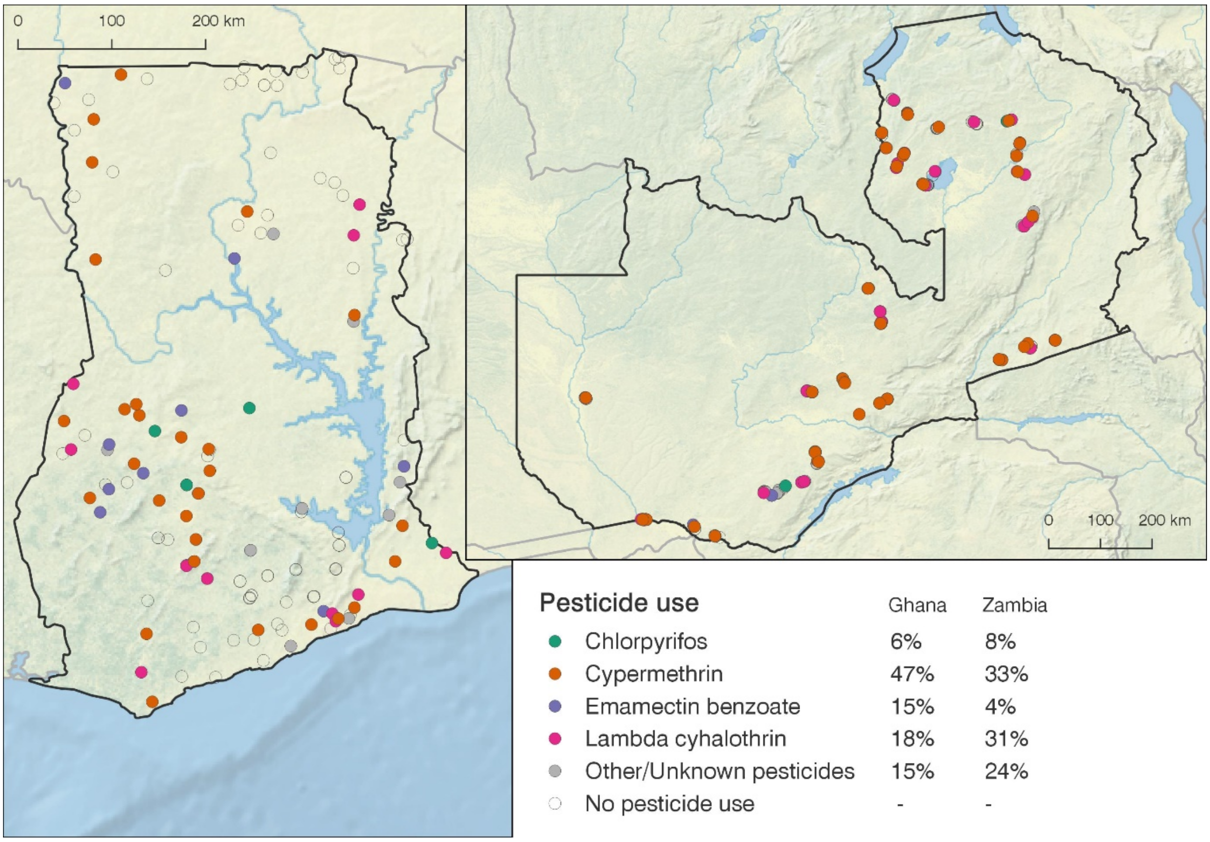


Figure 11. Location of use of most popular chemicals in Zambia and Ghana (note: some points are obscured due to the close geographic nature of the survey points in Zambia).

For the analysis, we have chosen to use cypermethrin and lambda cyhalothrin in Zambia and Ghana. we could not use emamectin benzoate due to the inconsistency in the small sample size.

Information gathered in the field, reported on in other sections, has allowed this study to use these cost estimates for the theoretical exercise (table 12).

Table 12. Cost estimates for chemicals in Ghana and Zambia

	Ghana	Zambia
Cypermethrin-based chemical	Cymethoate (cypermethrin and dimethoate)	Fastac (alpha cypermethrin)
Retail cost (local/US$) per litre	30 cedis or $7/litre	K250 or $27 / litre
Label recommendation	70 ml per 15 litres	100 ml per 15 litres per hectare
Availability	Country-wide	Country-wide
Lambda cyhalothrin based chemical	Efforia 45 SC (lambda cyhalothrin and Thiomethoxam)	Bolt (lambda cyhalothrin and chlorpyrifos
Retail cost (local/US$) per unit	72 cedis / $16/litre	ZMK 65 or $7 / litre
Label recommendation	35 ml/15 litres; but recommendation for FAW is 50 ml per 15 litres	1 litre per 15 litres per ha
Availability	Country-wide	Country-wide
Daily minimum wage	8 cedis a day	ZMK 30

Based on these costs, table 13 below shows the overall costs of labour and chemical application per unit area. It will cost a farmer in Zambia US$14.7 a hectare to control FAW with cypermethrin, or US$12.7 a hectare with lambda cyhalothrin. In Ghana, a farmer will spend US$5 per hectare to control FAW with cypermethrin, and US$17 per hectare for lambda cyhalothrin. Therefore, in Zambia, it is more economical to use lambda cyhalothrin than cypermethrin, and the opposite is the case in Ghana. The number of sprays were considered but unfortunately the data could not be extracted adequately. We have assumed that the quantity used and the hours of labour are enough to explain the control costs

Table 13. Cost estimates per hectare of control and application in Zambia and Ghana on cypermethrin and lambda cyhalothrin

Zambia	Chemical cost	Average chemical bought	Cost of chemical	Area average	Cost/unit area	Cost of household and external labour	Total cost per unit area
Cypermethrin **N=44**	US$27 a litre	1 litre	US$27	3.1 hectares	US$8.7 /hectare	US$6	**US$14.7 per hectare**
Lambda cyhalothrin **N=43**	US$7 a litre	2.4 litres	US$17	3.25 hectares	US$5.2 / hectare	US$7.5 per hectare	**US$12.7 per hectare**
Ghana	**Chemical cost**	**Average chemical bought**	**Cost of chemical**	**Area average**	**Cost/unit area**	**Cost of household and external labour**	**Total cost per unit area**
Cypermethrin **N=28**	US$7 a litre	1.4	US$10	12.3 acres = 5 hectares	US$2 per hectare / US$1 per acre	US$3 per hectare	**US$5 per hectare**
Lambda cyhalothrin **N=43**	US$8 a litre	3.8	US$30	6.7 acres = 2.7 hectares	US$11.1 per hectare / US$4.5 per acre	US$6 per hectare	**US$17.1 per hectare**

On average, the mean annual household income in Ghana is 16,644 cedis, or US$3,804, although there is large disparity between the regions (GLSS6 2014). For example, in the Upper East region, the mean household income is 7,240 cedis, or US$1,654, while in the Ashanti region, the income is approximately 23,000 cedis per year, or US$5,257. For the next calculations, this study will establish a range based on the poorest and richest areas, to give a more precise overview.

On average, the mean annual household income in rural areas in Zambia is ZMK 810 per month, or a yearly income of US$1,068. Small-scale farmers have a monthly income of ZMK 693, or US$913 a year, while medium-scale farmers have a monthly income of ZMK 1,862, or US$2,460 a year (Zambia statistical services 2016). For the next calculations, this study will establish a range based on the average rural and small-scale farm incomes, to give a more precise overview.

Scenarios[2]:

In the poorest region of Ghana (Upper East), assuming an average yearly income per household of US$1,654

[2] It is important to note that the following expenditure comparisons must not be taken as a recommendation to use a particular pesticide or any other pesticide

A small-scale farmer, with less than or equal to two hectares, could expect to pay approximately **1%** of the average yearly income in his region towards FAW control if he/she uses cypermethrin. With the same chemical, a farmer with 10 hectares could pay up to **3%** of the average yearly income in his region towards FAW control. In the same region, and assuming the same average household income, a farmer with two hectares could spend up to **2%** of the average yearly income in his region using Lambda cyhalothrin, and a farmer with 10 hectares could spend up to **10.5%** of the average yearly income in his region on FAW control.

In the richest region of Ghana (Ashanti), assuming an average yearly income per household of US$5,257

A small-scale farmer, with less than or equal to two hectares, can expect to pay approximately **0.2%** of the average yearly income in his region towards FAW control if he/she uses cypermethrin. With the same chemical, a farmer with 10 hectares could pay up to **1%** of the average yearly income in his region towards FAW control. In the same region, and assuming the same average household income, a farmer with two hectares could spend up to **0.5%** of the average yearly income in his region using lambda cyhalothrin, and a farmer with 10 hectares could spend up to **3.2%** of the average yearly income in his region on FAW control.

For average rural household in Zambia, assuming an average yearly income per household of US$1,068

A small-scale farmer, with less than or equal to two hectares, can expect to pay approximately **2.5%** of an average rural household yearly income towards FAW control if he/she uses cypermethrin. With the same chemical, a farmer with 10 hectares could pay up to **13.7%** of an average rural household yearly income towards FAW control. In the same region, and assuming the same average household income, a farmer with two hectares could spend up to **2.3%** of an average rural household yearly income using lambda cyhalothrin, and a farmer with 10 hectares could spend up to **11.9%** of an average rural household yearly income on FAW control.

For an average small-scale household in Zambia, assuming an average yearly income per household of US$913 and a medium-scale household in Zambia, assuming an average yearly income per household of US$2,460

A small-scale farmer, with less than or equal to two hectares, can expect to pay approximately **3.2%** of an average small-scale household income towards FAW control if he/she uses cypermethrin. With the same chemical, a farmer with 10 hectares could pay up to **5.9%** of an average medium-scale household income towards FAW control. In the same region, and assuming the same average household incomes, a farmer with two hectares could spend up to **2.7%** of an average small-scale household income using lambda cyhalothrin, and a farmer with 10 hectares could spend up to **5.1%** of an average medium-scale household income on FAW control.

These scenarios also assume that a farmer with 10 hectares will have the same budget as a farmer with two hectares in Ghana, which is not the case. However, a literature search could not identify individual figures for each case, hence the average income per region in Ghana.

Note that this figure only refers to the cost of control, and does not take into account any loss of yield. For a better understanding of these costs, please refer to the section on national estimates of losses according to AEZs.

Control measure success

Table 14, below, seeks to identify the degree of success of each chemical approach, as well as the second most popular (ie 'somewhat successful' control measure in each country.

Table 14. Degree of success of each active ingredient perceived by farmers

	Ghana			Zambia		
	Successful	**Somewhat successful**	**Not successful**	**Successful**	**Somewhat successful**	**Not successful**
Cypermethrin		83%	17%		90%	10%
Lambda cyhalothrin Ghana N=11; Zambia N= 48	**91%**			67%	32%	1%
Emamectin benzoate **Ghana N=9**	75%	10%	15%			
Chlorpyrifos **Zambia N=13**					100%	
Hand-picking egg masses and caterpillars Zambia N=74				4%	82%	14%
Frequent weeding **Ghana N=20; Zambia N=17**	30%	45%	25%	18%	64%	18%

Although cypermethrin was the most common chemical used in both countries, Lambda cyhalothrin was much more successful. In Ghana, emamectin benzoate was fairly successful, whilst 100% of farmers who used Chlorpyrifos deemed it 'somewhat successful'.

The majority of farmers who used cultural control techniques, such as hand-picking egg masses and caterpillars, and weeding, on the most part stated that these measures were 'somewhat successful'.

Whilst lambda cyhalothrin was reported by the survey participants to be a successful product against FAW, it is more expensive. Indeed, cypermethrin is three times cheaper in Ghana than lambda cyhalothrin. However, it has a much lower success rate according to the participants in this survey. In Zambia, lambda cyhalothrin is almost four times cheaper than cypermethrin and 14% cheaper by hectare, including cost of purchase and application. Moreover, the majority of farmers stated that Lambda cyhalothrin was more successful than cypermethrin. It seems that farmers with FAW in Zambia should use lambda cyhalothrin where possible (whilst adopting the strategy of utilising and regularly interchanging different pesticides with alternative modes of action in order to reduce risk of resistance). In Ghana, the situation is less clear cut.

It is also important to understand what success represents for a farmer. Does it mean the control measure has been successful, by increasing the household's final yield – and therefore producing a higher income? Or was it simply a success in controlling the pest, and did not change the final yield (for example, the pest might already have damaged most of the crop such that it could not survive, and even if the chemical was successful in controlling FAW numbers in the field, the damage was already done)? These questions unfortunately could not be answered by the survey, and will need to be looked at in more detail in the future.

Impacts on trade

International trade carries the risk of introducing pests to countries where they are not yet present – consignments of food and agricultural products being a particular risk. Thus, the arrival of FAW in Africa creates a new risk for countries importing from affected African countries, if FAW is absent from the importing country. This includes countries in North Africa, Asia and Europe. For the purposes of this analysis we focus on Europe as a major importer of agri-food products from Africa and for which good data is available, although the same principles would apply to countries in Asia for which FAW now poses a significant risk.

The World Trade Organisation's Agreement on the Application of Sanitary and Phytosanitary Measures (SPS Agreement, 2017) lays out rules under which importing countries can manage such risks, allowing countries to achieve the level of protection they wish, provided the measures they institute to manage the risk do not constitute an unjustifiable restriction on trade.

Before FAW invaded Africa, Europe had already identified the species as a risk, as large volumes of agricultural produce are imported to Europe from the Americas where the pest is present. Directive 2000/29/EC sets out FAW as a harmful organism whose introduction into and spread within all member states is banned, it not being present in any member state. Jeger *et al.* (2017) have recently undertaken a pest categorisation of FAW: they concluded that it can be regarded as a 'Union quarantine pest'. Specific measures in Directive 2000/29/EC are set out in Table 15.

Table 15. Special requirements listed in Directive 2000/29/EC relating to *Spodoptera frugiperda*

Annex IV, Part A	Special requirements which must be laid down by all member states for the introduction and movement of plants, plant products and other objects into and within all member states	
Section 1	Plants, plant products and other objects originating outside the community	
	Plants, plant products and other objects	Special requirements

27.2	Plants of *Dendranthema* (DC.) Des Moul., *Dianthus* L. and *Pelargonium* l'Herit. ex Ait., other than seeds	Without prejudice to the requirements applicable to the plants listed in Annex IV(A) (I)(27.1), official statement that: (aa) the plants originate in an area free from *Spodoptera eridania* (Cramer), *Spodoptera frugiperda* Smith and *Spodoptera litura* (Fabricius), established by the national plant protection organisation in accordance with relevant International Standards for Phytosanitary Measures, or (a) no signs of *Spodoptera eridania* (Cramer), *Spodoptera frugiperda* Smith, or *Spodoptera litura* (Fabricius) have been observed at the place of production since the beginning of the last complete cycle of vegetation, or (b) the plants have undergone appropriate treatment to protect them from the said organisms

In practice, this can result in increased costs to traders, in two ways. If consignments arriving in Europe are found to contain FAW, treatment may be required, import may be refused, or the consignment could even be destroyed, so there is a cost when contaminated consignments are intercepted by importing countries. To reduce the likelihood of this happening, additional measures may be required in the exporting country, including those listed in Table 15 above. This will also incur a cost to the producers and the national plant protection organisation. Together, these additional costs could make the trade less profitable, potentially reducing the volume.

Data from Europhyte show that there is a risk of FAW being imported with agricultural produce from Central and South America, although the number of consignments found to contain the pest is fairly small (Table 16). Note, however, that in June 2017 the first interception of FAW in a consignment from Africa took place. Of particular note is the fact that it was found in a consignment of roses, not listed as a host of FAW, but a major export from East Africa.

Table 16. Number of interceptions of *Spodoptera frugiperda* in Europe, 1995–July 2017, for country of export and plant species (from Europhyte database). Note that the single entry for Zambia was in June 2017

	Commodity								
	Asparagus	**Capsicum**	**Eryngium**	**Momordica**	**Rosa**	**Solanum**	**Tillandsia**	**Vigna**	**Total**
Brazil					1				**1**
Dom. Rep.		5							**5**
Ecuador			1						**1**
Guatemala							1		**1**
Mexico		2							**2**
Peru	4								**4**
Suriname		14		3		14		1	**32**
Zambia					1				**1**
Total	**4**	**21**	**1**	**3**	**2**	**14**	**1**	**1**	**47**

To illustrate the potential scale of this problem for Africa, Table 17 shows interceptions in Europe of the related *Spodoptera littoralis* in consignments from Africa. Note that these are absolute numbers of interceptions, rather than a rate. Nevertheless, the following observations can be made:

- Roses are a major export crop from East Africa, and the crop for which most *S. littoralis* interceptions have occurred. The first *S. frugiperda* interception from Africa having been in relation to roses suggests the species could present additional problems for exporters

- Where efficient export certification schemes are in place that effectively reduce *S. littoralis* interceptions they should be able to cope with *S. frugiperda*

- As a result of efforts to tackle the problem of *S. littoralis* interceptions, in 2016/2017 there have been relatively low numbers of interceptions on roses (maximum of four per country per year)

- Most interceptions from South America relate to *Capsicum* and *Solanum*. These do not seem to be a major pathway for *S. littoralis* from Africa, but it remains to be seen whether they provide a significant pathway for *S. frugiperda*. A number of countries in Africa export these crops to Europe and so will need to exercise caution

Table 17. Number of interceptions of *Spodoptera littoralis* in Europe, 1995–July 2017, for country of export (African countries) and plant species (from Europhyte database)

	Amaranthus	Aster	Begonia	Capsicum	Celosia	Chrysanthemum	Corchorus	Cotoneaster	Dianthus	Echeveria	Eryngium	Eustoma	Gypsophila	Ipomoea	Mentha	Ocimum	Pelargonium	Rosa	Solanum	Solidago	Talinum	Telfairia	Vernonia	Total
Burundi																		3						**3**
Ethiopia						1									2	2		5						**10**
Ghana							1							1					1				1	**4**
Kenya						1			1		5	1	2			5		27		7				**49**
Malawi																		4						**4**
Mozambique				1																				**1**
Nigeria				1	1																1	2		**5**
Rwanda																		4						**4**
South Africa			1							1														**2**
Tanzania											1	1					1	20		1				**24**
Uganda	1					3		1								1		93						**99**
Zambia																		22		10				**32**
Zimbabwe		3									7							327		17				**354**
Total	**1**	**3**	**1**	**2**	**1**	**5**	**1**	**1**	**1**	**1**	**13**	**2**	**2**	**1**	**2**	**8**	**1**	**505**	**1**	**35**	**1**	**2**	**1**	**591**

NPPOs in Africa with significant exports to Europe are aware of this risk (pers. comms.) and are taking the appropriate measures to reduce the risk of FAW-contaminated consignments being shipped. Well-organised NPPOs supporting major export sectors should be able to cope with this situation, but it could be problematic for countries where export certification is weaker and the export horticulture sector is less developed.

Table 18 shows the value of agri-food exports to Europe from a number of countries in Africa. While some countries have major export sectors, the costs of FAW in terms of additional operational costs or reduced/lost trade are not likely to be of the same order of magnitude as the losses to crop yield reported above.

Table 18. Mean annual export value (2012–2016) of agri-food products to Europe from selected African countries (data from COMTrade)

	Annual export value per commodity code*, US$ million		
Country	**06**	**07**	**08**
Ethiopia	440.4	700.9	6.3
Ghana	0.3	17.5	536.0
Kenya	538.0	262.9	79.6
Malawi	0.0	1.3	17.8
Nigeria	78.3	2.7	340.2
Senegal	1.2	48.1	27.4
South Africa	66.5	182.0	2707.6
Zimbabwe	2.1	2.7	13.2
Uganda	54.6	42.9	2.3
Tanzania	38.3	214.8	284.3
Zambia	20.8	17.5	0.9

***Commodity codes:**

06. Live tree and other plant; bulb, root; cut flowers etc
07. Edible vegetables and certain roots and tubers
08. Edible fruit, nuts, peel of citrus fruit, melons

Section 4 Control

In this section we consider the evidence from the Americas regarding control of FAW, and its possible application in Africa. While there is a large volume of literature on, and experience of, FAW control in the Americas, the agricultural systems there are often very different from those in Africa. For example, few areas in the Americas have the small farm and field sizes that predominate in Africa (fig. 13).

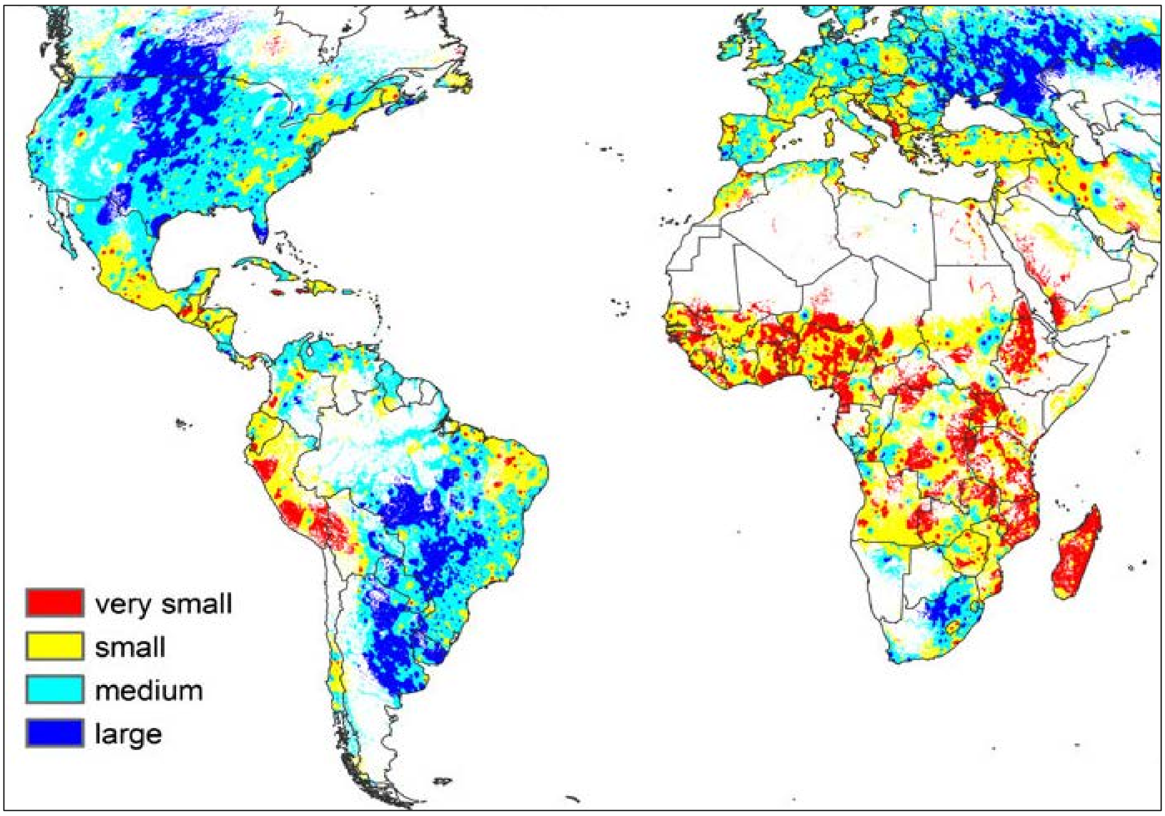


Figure 13. Field size (from Fritz et al., 2015).

Related to this, yields are much higher in the Americas, averaging over eight tonnes per hectare for maize, compared with around two tonnes per hectare in Africa. Genetically modified (GM) crops are also widespread in the Americas (in Brazil over 80% of maize is GM) but are used in only a few countries in Africa. Thus, GM crops and pesticide application are the most used approaches to control FAW in both North America and South America. Additionally, most of North America is only infested seasonally by FAW migrants, with populations dying out when the temperature falls. Where possible, we therefore emphasise evidence from Central America and South America.

We first discuss aspects of FAW damage and monitoring which impinge on control decisions (section 4.1), before considering the control methods themselves (section 4.2). We then look in more detail at the availability and safety of biological pesticides for controlling FAW (section 4.3), before considering the uptake of pest control solutions (section 4.4), particularly the IPM approach that FAO and others are promoting. Finally, we provide a summary evaluation of the control methods that are being recommended for Africa (section 4.5).

4.1 Damage, monitoring and action thresholds

4.1.1 Damage

FAW causes damage by feeding on both vegetative and reproductive structures. For crops such as maize, where the reproductive structure is harvested, damage to the vegetative parts does not necessarily cause a loss of yield. This is because the plant is able to compensate for at least some loss of leaf area: an effect which may lead to inaccurate perceptions of loss, as well as modifying the level of damage at which investment in control becomes worthwhile. The relationship between level of attack and yield loss can be further complicated by the moment in time at which an attack occurs, with earlier loss of leaf area allowing more time for compensation than later loss. Older larvae cause more damage than younger larvae as they consume more material, and can feed on the developing cobs. However, early attack may also result in the growing point being killed (dead heart), which causes yield loss. This damage relationship can be further modified by growing conditions and soil fertility, and is different for different species.

At the plot or farm level, yield loss is estimated experimentally by allowing some plots to be attacked while protecting others, with the difference in yield being the loss due to the pest. Using this approach on maize in Nicaragua, van Huis (1981) reported yield losses of 30% to 60%, and Hruska & Gladstone (1988) reported 45% loss when all plants were infested. While localised studies would be needed to precisely determine economic injury levels for particular crops in particular situations (Cruz et al., 1999), farmers need to make decisions on the basis of broad estimates, particularly in diverse agroecosystems where many factors affect yields and the damage due to pests.

Although FAW attacks a large number of crops, it is much more serious when it attacks some compared to others. In Latin America, rice is rarely treated for FAW attack, which usually occurs from larvae moving in from grasses at the edge of the field, although sometimes eggs are laid directly on the rice. The main concern with FAW in rice is the protection of the upper canopy leaves (the flag leaf and the next leaf down) and the panicles themselves. When feeding is on the lower canopy leaves, yield loss is minimal, but if the larvae feed on the flag leaves, they are more problematic. Of greater concern is when they move into rice during grain fill and move to the panicle to feed directly on the high moisture, filling grains. Heavy attacks on very young plants also cause more damage.

Sorghum is relatively tolerant of defoliation, so thresholds for treatment are generally higher than for maize, and pesticide application is much less frequently justifiable. However, Andrews (1988) reported that FAW infestations in the whorl reduced sorghum grain yields of susceptible lines by 55%–80%, while studies by Diawara *et al.* (1991) showed a grain yield reduction of 76%–85% on the susceptible sorghum line Huerin Inta, but losses of only 0% to 33% on several resistant lines.

4.1.2 Monitoring

Monitoring the health of a crop is always useful, but becomes more important when decisions are required regarding whether or not to intervene. Three approaches to monitoring are used in Latin America: scouting, pheromone traps and light traps.

Scouting. Scouting involves visual inspection of the crop to assess the level of damage and/or the presence/abundance of the pest. A commonly used scheme is to examine 20 consecutive plants from five different locations in the field. Some or all of the following information can be recorded:

- Growth stage of the plants
- Number of plants with damage symptoms. Specific symptoms can be recorded if desired
- Number of plants with egg masses
- Number of plants with larvae. Size of larvae can be recorded if desired

There are two practical difficulties with scouting FAW. The damage symptoms can be confused with those caused by other pests, and the eggs and young larvae may be difficult to find – particularly for farmers who have not seen them before. Thus, it is not clear how many small-scale farmers undertake scouting in Latin America, or at least undertake it accurately.

Scouting can begin not long after germination, and should continue until the silks begin to dry. More frequent scouting allows earlier detection of infestations, though it takes more time. Some authors recommend scouting every two days, but once or twice a week should be adequate. More frequent scouting is appropriate in hotter areas where the pest develops more rapidly.

If scouting aims to count larvae, then it should be undertaken in the early morning or late afternoon, when the larvae are more likely to be visible.

Pheromone traps. Female FAW moths attract males by emitting a pheromone. The chemical composition of this has been determined, and synthetic pheromone can be used as a lure in a trap to monitor the moth population. However, not all the chemical components of the natural pheromone are required to make an effective lure, and different manufacturers market lures with different blends of usually two to four different chemicals. Russell IPM, one of the companies selling FAW pheromone lures in Africa, uses four components and has tested the product in southern Africa (Nayem Hassan, pers. comm.).

A kit containing synthetic pheromone plus a trap is marketed in various countries in South America, including Brazil. According to one manufacturer the trap should be placed in the centre of the planting area and used at a density of one trap for every five hectares of crop (BioControle). Traps with the lures should be hung approximately 1.5 metres above the ground. If the planted seed has not been treated, monitoring should start soon after emergence (Cruz *et al*. 2011). The trap should be checked twice a week and the number of moths counted. One lure lasts a month, so several lures are required for one trap per season.

In Brazil, a trap plus pheromones costs Brazilian Real BRL 20 (BioControle), equivalent to a little over US$6. However, some farmers in Peru and Colombia make their own traps, which reduce the cost. Even so, the use of pheromone traps for monitoring FAW is more common for medium and larger growers than for smallholders. Some experts in Latin America report that pheromone traps are the best way of monitoring FAW, and are the best method of determining if a maize crop requires insecticide treatment (Cruz *et al.* 2012) or treatment with biological control agents (Figueiredo *et al*. 2015). However, in North America, the number of moths caught in a trap is a poor predictor of crop damage (Johnson, undated), although this does not necessarily mean that trap catches are giving a poor estimate of the adult population.

Light traps. Since the 1960s light traps have been used, principally at research stations. They catch many different kinds of insects so the catch has to be sorted and identified, and this makes them difficult to use for monitoring FAW. They may have a role to play in monitoring in cases where they are also being used with the aim of reducing the moth population (see mass trapping). Unlike pheromone traps they catch both male and female moths. Some small-scale farmers in Latin America make their own light traps, but it is not clear how effective or practical these are.

4.1.3 Action thresholds

A major reason for monitoring FAW at farm level is to decide whether an intervention, such as chemical application, is required. An intervention is economically justifiable if the value of the crop loss it reduces is more than the cost of the intervention. If one has information on the costs of control, the expected yield with and without the intervention, the relationship between the parameter monitored and expected yield loss, and the value of the crop, it is possible to define a threshold value of the monitored parameter at which an intervention should be made. For example, if a farmer expects a yield of 1 tonne/ha which fetches a price of $200, a pesticide application costing $10/ha would need to reduce yield loss by over 5% to be economically worthwhile.

In commercial farms, where the damage relationship has been well researched, this approach is feasible, but in small-scale systems it may be less suitable due to the many factors affecting yield. Also, small-scale farmers may have other goals apart from profit maximisation: for example they might seek to reduce risk of low yield, or minimise the cost of inputs.

Nevertheless, it is still appropriate to define action thresholds that can guide on-farm decision-making. Van Huis (1981) evaluated thresholds of 20% and 50% of maize whorls damaged and concluded that the 20% threshold generally performed better. This depended on the subsequent rate of increase in the number of injured whorls: as infestation is difficult to forecast, the 20% level was deemed most appropriate for small-scale farmers in Nicaragua. This threshold may be applicable up to 30–40 days after planting, while for plants between 40 and 60 days after planting the threshold can be reduced to 10% (Afonso-Rosa and Barcelos 2012; Grützmacher *et al.* 2000). Another example is in Ontario, where a 15% damage threshold is advised prior to tassel emergence, and after the corn has reached late-whorl 5% feeding injury warrants an insecticide application (Ontario Crop IPM 2017). However, for small scale farms in Honduras, Pitre *et al.* (1997) recommended pesticides when 40% of plants were infested with FAW.

If pheromone traps are being used, the threshold will be in terms of number of moths caught. Cruz (2010) proposed a minimum of three moths per trap per hectare in Brazil, but, as with a threshold based on the percentage of plants damaged, this needs testing in Africa.

Given that several of the parameters used to define the action threshold at different times of crop development are not known in Africa, there is an immediate need for work in this area.

4.2 Control methods in Latin America and lessons for Africa

4.2.1 Biological considerations

Aspects of the biology and ecology of a pest affect what control strategies or tactics may be appropriate. Section 1 reviewed the biology and ecology of FAW; here we highlight specific aspects that are pertinent for control.

Young FAW larvae hide in the funnel during the day but emerge at night to feed on the leaves. Thus, spray applications are more likely to be effective if undertaken around dawn or dusk. Older larvae tend to stay inside the funnel and so are protected. Therefore, where possible, pesticide applications should be timed to coincide with the presence of the younger larvae.

As FAW has the capacity to migrate long distances, a relevant question for control strategies in Africa is under what conditions migration will occur. This could affect the extent to which populations build up in an area, and whether control strategies that have inter-seasonal, as well as intra-seasonal, impacts on the pest population are beneficial. For example, there would be little value in spending time and effort ploughing up pupae if the emerging moths would in any case migrate elsewhere.

In most areas of North America FAW arrives seasonally, and then dies out in the cold weather, but in Central and South America generations are continuous where host plants are available and climatic conditions are favourable (Andrews 1980). When adults emerge from pupae, if there are food plants available, they are likely to stay in the same area, mate and lay eggs, unless the population density is high, in which case migration to other areas is more likely (Regiane Bueno, pers. comm.). This contrasts with the African armyworm, *Spodoptera exempta*, which almost always migrates away from its emergence site, and is considered an obligate migrant (Rose *et al*. 2000). Johnson (1987) proposed that migration in *S. frugiperda* evolved in Central America as an adaptation to the bimodal rainfall pattern, and it can therefore be described as a facultative migrant. The patterns of population persistence, dispersal and migration in Africa have yet to be determined.

In Brazil, the level of infestation in one season is said to be poorly correlated with the level in the previous season (Regiane Bueno, pers. comm.), but this may be because of the widespread use of *Bacillus thuringiensis* (Bt) crops and pesticide spraying. In contrast, in Central America a high infestation in one season is likely to be followed by a high infestation the next season, unless control is effected (Patricia Castillo, Gregorio Varela, pers, comm.). Thus, coordinated area-wide control efforts are worthwhile, including methods that limit survival from one season to the next. This could include synchronised planting, although this would be difficult to achieve over large areas with many smallholders.

Infestation also tends to be spatially patchy rather than uniformly distributed in fields (Patricia Castillo, Luis Medina, Juan José Lagrava, pers. comm.). Thus, if possible, direct control methods can be targeted at affected areas rather than generally across a farm – something that is more feasible on a small farm than on a large one. Farms where planting takes place later tend to show a more uniform distribution of the larvae (and higher levels of damage).

There may also be interactions between FAW and other pests that have an effect on control needs. van Huis (1981) described interactions between FAW and *Diatraea lineolata*, so it is possible that FAW will interact in some way with other pests attacking maize – particularly stem borers.

4.2.2 Chemical control

Method: Chemical control involves the application of poisons to the pest and/or crop that kill the FAW through a variety of mechanisms, including on contact or through ingestion. Most commonly, the pesticides are diluted with water and sprayed on growing plants at around 200–400 litres per hectare, though this can vary considerably with the age of the plant and the application method. A knapsack, hand-operated sprayer can be used to spray selected plants, whereas a tractor mounted boom sprayer is less targeted. Aerial spraying is also possible. Less frequently used approaches are to treat the seed with a pesticide before planting, and the use of dry pesticide applied to the plant funnel.

Effectiveness: Numerous synthetic pesticides are able to kill FAW, and many are registered and recommended in Latin America. These include pesticides from several different modes of action spanning the various WHO hazard categories, including some classified as highly hazardous (Class 1b). As well as inorganic molecules, a number of products are based on products of microorganisms (such as spinosad), so are sometimes classified as biopesticides (see below).

Seed treatment is reported as effective with thiamethoxam (Albuqurque *et al*.,2006), but Azevedo *et al.* (2004) found it not to be effective. Several highly or extremely hazardous compounds are effective as seed treatments, but these should not be used. Thrash *et al.,* (2013) reported use of chlorantraniliprole and cyantraniliprole as seed treatments in soya reduced the need for foliar sprays against FAW in soya. In laboratory tests, thiodicarb and clothianidin reduced the number of plants cut or insured by FAW, but chlorpyrifos, fipronil and thiamethoxam were not effective (Camillo *et al.,* 2005). Kerosene is ineffective as a seed treatment (Portillo *et al.*, 1994).

Another approach is to apply pesticide to the soil at planting, though this is likely to be less efficient than seed treatments. Van Huis (1981) concluded that in experiments in Nicaragua, soil treatment did not exert any control on FAW.

Pesticides applied to the growing crop are most effective when used at the right time and in the correct way. This includes spraying when the larvae are still young; spraying in the early morning, later afternoon or night when the larvae are more active; and directing the spray into the funnel (when using knapsack sprayers) of affected plants. It is likely that the many reports from farmers of pesticides “not working” are due to inappropriate application methods, or application when it is too late.

Feeding stimulants or attractants mixed with pesticides can increase effectiveness at lower concentrations, although they are not widely used.

The Peruvian Ministry of Environment recommends mixing dry formulations of trichlorfon with sand, and applying the mixture into the whorl with a plastic bottle. This is considered effective and is widely used by smallholder farmers in Peru. In trials in Nicaragua van Huis

(1981) found that a mixture of sawdust and chlorpyrifos reduced the amount of pesticide needed by 20%, without loss of control.

In several parts of the Americas FAW has become resistant to pesticides: resistance has been reported to mode-of-action categories 1A (Carbamates) 1B (Organophosphates), and 3A (Pyrethroids-Pyrethrins). In these cases, larger doses or alternative chemicals or methods have to be used.

Cost: The cost of pesticides in Africa is variable. Converting the cost of a bottle of pesticide to a cost per hectare treated requires assumptions to be made regarding the dilution and volume applied. While the dilution should be in accordance with the manufacturer's label, the volume of spray applied per hectare will be affected by the size of the plants, whether all or only visibly damaged plants are treated, and the preference of the spray operator. However, assuming a fixed volume of application, some observations on costs can be made.

Not surprisingly, small packets/bottles are more expensive than larger ones, which makes the effective cost higher for small-scale farmers. (This can also lead to the dangerous practice of unlicensed repackaging).

Neem-based products, the most widely available botanical, are generally more expensive. For example, in Uganda the recommended pesticides cost around US$3.5–5 per hectare, while neem products can cost US$10–15. This price differential makes it very unlikely that resource poor farmers, if they can afford pesticides, will purchase anything other than the cheap inorganic chemicals.

In Ghana, it was noted that cheaper products were made from generic formulations of the active ingredients, and that the binary products (containing more than one active ingredient) are more costly than those made from a single active ingredient. Products using novel adjuvants to enhance adherence or solubility cost more.

In Kenya, a retailer noted that a number of products recommended by the government are not stocked, due to low demand. This is either due to a perception that the product is ineffective, or to it being too expensive.

Considerations for Africa: A key issue around pesticide use in Africa is the risk to human health. Pesticides are frequently applied without appropriate safety precautions being taken, and there is growing evidence of pesticide poisoning – although so far not as a result of FAW control. Resource-poor farmers are often unwilling or unable to buy the appropriate safety equipment and in some cases they use pesticides without appropriate application equipment. In Ghana 'Hosanna' application refers to pesticide application using a palm frond dipped in pesticide and waved over the crop. Farmers may also be disinclined to use safety equipment when hot weather can make this extremely uncomfortable. Recognising that farmers will still want to use pesticides, specific measures are needed to make lower risk pesticides more accessible.

Many of the cheapest and most widely used pesticides in Africa fall into the mode-of-action classes, to which resistance has developed in the Americas. It is not known whether the FAW populations in Africa were already resistant on arrival, but, regardless, strategies should be devised and implemented to reduce the likelihood of resistance developing.

The following information is adapted from a leaflet produced by the International Resistance Action Committee (IRAC 2016, see www.irac-online.org). Pests develop resistance to pesticides through repeated exposure of successive generations to chemicals with the same mode of action, so the following strategies should be implemented.

- Where possible, a combination of management methods should be used, rather than relying entirely on pesticides.
- Treating successive generations using products with the same mode of action must be avoided.
- Pesticide application should be based on monitoring and thresholds, rather than being used as a prophylactic or preventative measure.
- The manufacturer's recommended dose and concentration should be followed.
- Pesticides should be purchased from registered dealers.

The International Code of Conduct on the Pesticide Management includes detailed Guidelines on Prevention and Management of Pesticide Resistance (FAO 2012), which national authorities should become familiar with and follow as far as possible.

A widespread problem with pesticides (and other inputs) in Africa is adulteration or selling of fake products. This may increase the risk of pesticide resistance developing, and wastes farmers' money, making them more cautious about buying inputs in the future. There are already frequent reports of pesticides 'not working' in Africa, but it is not clear whether that is due to inappropriate use, substandard pesticides, or the presence of resistance. In our survey in Ghana and Zambia, of the farmers who had used pesticides for FAW control, only 27% reported total success, with 57% and 16% reporting the control as somewhat or not successful, respectively.

4.2.3 Microbial biopesticides

Method: A range of microbial organisms attack FAW in its native range, and these can be multiplied and used in a similar way to chemical pesticides. *Beauvaria bassiana* is a fungus used in multiple products worldwide. Bt products are suitable for lepidopterous pests, such as FAW, and a number of products are available in Africa as well as in the Americas. *Spodoptera frugiperda* multiple nucleopolyhedrovirus (SfMNPV) has been known about for some time, but only recently have products come to market. A joint venture between EMBRAPA and Vitae Rural Group has just launched a product in Brazil, and AgBiTech has recently achieved registration of a similar product in the US. A product is also being commercialised in Nicaragua (Patricia Castillo, pers. comm.). No SfMNPV products are available in Africa yet. Landazabal *et al.* (1973) applied the nematode *Neoaplectana carpocapsae* for FAW in Colombia and achieved good reductions in larval populations, but only under high humidity, and no products are commercialised.

Effectiveness: Early trials with Bt on FAW were not successful, but improvement in the active ingredients and formulations since then have made Bt an effective product. As with chemical pesticides, application methods can play a major part in determining the effectiveness of microbial pesticides. They are often slower to act than chemical pesticides, which can result in damage being done after application, even if the insects eventually die. This can reduce their attractiveness to farmers and can be interpreted as failure.

How effective the new products based on the SfMNPV will be remains to be seen. Ultraviolet light and high temperatures can destroy the virus, so the formulation as well as application time affects their efficacy. It is possible that they will be less efficacious than chemical pesticides but still be a cost-effective component of an integrated approach. Their high level of host specificity is an advantage, in that no non-target organisms are affected, but where there are other pests that farmers want to control at the same time as FAW this specificity can also be seen as a disadvantage. Products containing several different viruses to control the major pests can be produced.

Cost: Microbial pesticides may be more expensive than the older pesticides. A critical determinant is the cost of production, so where efficient production systems can be established, the product can be marketed at competitive rates. The cost of the virus is estimated at around US$10/hectare.

Considerations for Africa: Having lower risk than chemical pesticides, microbial pesticides are suitable for Africa. However, they can be adversely affected by climatic conditions and suboptimal application procedures, both of which could occur in Africa. Their widespread use would need to be supported by effective awareness-raising/communication campaigns. There are a number of microbial pesticides registered for use in Africa, and some countries are recommending the use of Bt.

4.2.4 Macrobials: Inundative release

Method: Macrobials (predatory insects and parasitic wasps or parasitoids) have been used in inundative releases in Latin America for FAW control. Indundative releases involve repeatedly releasing large numbers of agents to depress the current FAW population. There is no expectation that the high populations of the agent will persist and affect any control the following season.

Trichogramma spp are egg parasitoids that can be reared relatively easily in very large numbers and have been used for controlling insect pests in crops such as corn, sugarcane, tomatoes, rice, cotton, sugar beet, apple, prune, vegetables, and forests (Parra *et al*. 2002). In Latin America, *Trichogramma pretiosum* is produced commercially and releases of around 100,000/hectare are recommended for FAW, although this may be adjusted between 50,000 and 350,000 according to the pest density. Around four releases might be required in a season, at weekly or shorter intervals. There are several methods for releasing the parasitoid: one is through the release of adult wasps that have already emerged; another is by placing cards containing parasitised hosts in the field, from which the adults then emerge. Capsules containing parasitised eggs can also be distributed. In addition to commercial insect factories, in Brazil there are *Trichogramma* production units run by farmers' associations.

Telenomus remus Nixon (Hym., Scelionidae) is another egg parasitoid that is suitable as a control agent for *Spodoptera* spp, although *S. frugiperda* was not its original host. It is reported to be mass-reared for commercial or experimental purposes in several Latin American countries (Cave 2000). However, in Brazil it is still not commercially available, though Koppert is developing a product which could be available in 2018 (Lais Cristina da Silva, pers. comm.).

Some predatory insects can also be used in inundative releases. The earwig *Doru luteipes* is an important mortality factor for FAW (Sueldo *et al.* 2010), and has also been recommended by the Maize and Sorghum Agricultural Research Center of the Brazilian Agricultural Research Corporation for augmentative rather than inundative releases in Brazil (Cruz 2007). Luginbill (1928) recognised *Orius insidiosus* as a primary predator of the FAW, preying upon both eggs and larvae. The presence and abundance of *O. insidiosus* in maize has been reported by several authors (Isenhour *et al.* 1990; Mendes *et al*. 2008), and *Orius* is produced commercially. However, it is particularly effective for control of thrips, and it is not clear whether it is released specifically for FAW control.

Effectiveness: Effective inundative release of macrobials requires sufficient numbers to be released at the right time, which must be based on good monitoring of the pest population. If egg parasitoids are released a few days late, most of the FAW eggs may have hatched. Research suggests that if *T. pretiosum* are released within three days of detecting male moths in pheromone traps, the method achieves similar results to those achieved with pesticides.

Telenomus remus is more effective than *T. pretiosum*, in that it can penetrate all layers of the FAW egg mass – leading to potentially much higher rates of parasitism. Thus, release of only 5,000–8,000 parasitoids per hectare can cause up to 90% parasitism of S. *frugiperda* eggs (González and Zocco 1996; Cave 2000). As with *T pretiosum*, three to four releases are required. In maize in Venezuela, Hernández *et al*. (1989) released 5,000 *T. remus* per hectare per week for three weeks, and parasitism reached 78%–100% at distances of 1,400 metres from the release point up to two months after the releases. *T. remus* is not commercially available.

While there is evidence of the importance of both *Doru* and *Orius* as natural enemies in the field, we have not found any reports that releasing large numbers has an impact on FAW damage.

Cost: The estimated cost for *Trichogramma pretiosum* in Brazil is around USD$15–18 per release (including labour costs), but excluding the cost of monitoring that is required for effective timing of releases. This probably makes it unattractive for smallholders, where yield is much lower than on large-scale commercial farms.

Mendesi *et al*. (2005) estimated the cost of laboratory production of *Orius insidiosus* in a system producing only 33,000 individuals/month as US$0.069/insect. Commercial cost is approximately US$40 for a container of 1000 insects.

Considerations for Africa: Production would need to be based on studies of the natural enemies attacking FAW, which are only just beginning. Distribution and timely release of macrobials amongst multiple smallholders could pose logistic difficulties. However, some macrobials could be produced in local rearing units, reducing such difficulties.

4.2.5 Macrobials: Classical biological control

Method: Classical biological control involves one or more releases of a biological control agent not already present in the area, with the aim of establishing a permanent population that reduces the pest population on a continuous basis. It is particularly suitable for a pest that has invaded a new area, where the natural enemies that attack it in its native range are absent. In the Americas, the parasitic wasp *T. remus* has been introduced to several countries (following earlier introductions from Papua New Guinea to Asia for the control of *S. litura*), the first introduction being in Barbados in 1971. Later releases were made in several other Caribbean countries, and Central and South America. Attempts were made in 1975–77 to establish the agent in Florida, USA.

Effectiveness: In Barbados, the parasitoid was credited with substantial reductions of *Spodoptera* spp. In El Salvador and Nicaragua, it appears not to have been established. Similarly, in Florida, once releases stopped, the parasitoid disappeared.

Cost: Classical biological control can be viewed as a one-off investment, the size of which depends on how soon a successful agent is found. Very high returns on investment have been reported for a number of successful classical biological control problems: for example, Zeddies *et al.* (2001) reported a benefit:cost ratio of 200 or more for the biological control of cassava mealy bug in Africa, in a famously successful programme covering much of sub-Saharan Africa.

Considerations for Africa: Provided the appropriate procedures are followed to minimise risks (as laid out in International Standards for Phytosanitary Measures No. 3), there should be no reason why a classical biological control for FAW cannot be initiated immediately, at the same time as studies take place on natural enemies already attacking FAW in Africa.

Apart from *T. remus*, there are many other parasitoids that attack FAW in the Americas, among the most frequent being *Cotesia marginiventris* and several *Chelonus texanus* spp. These would also be candidates for classical biological control agents.

4.2.6 Plant extracts/botanicals

Method: Extracts of many plants show insecticidal activity against FAW (Batista-Pereira 2007), but relatively few have been successfully commercialised. Azadirachtin (from neem) and pyrethrins (from pyrethrum) and the most widely found product, although in Latin America there are only a handful of registered products. Globally, there are registered products based on rotenone, garlic, nicotine, rianodine, quassia and other extracts (ISMAN 1997). The products may be formulated to be diluted with water and sprayed in the same way as chemical pesticides, although dust formulations are also available.

Home preparations of neem or other botanicals are also possible. In Brazil, EMBRAPA provides guidance on how to prepare the neem aqueous extract, and extension material published by FAO Bolivia recommends the use of neem extract as a control agent for the FAW. In Colombia, CORPOICA provides step-by-step guidance on how to prepare extracts from dried seeds, leaves and neem fruits, tobacco and chinaberry leaves. Extract of chinaberry is used by Paraguayan farmers for FAW control. In Costa Rica a preparation of garlic extract, neem and detergent is reported to be effective (Helga Metzler, pers. comm.).

Effectiveness: One problem with the use of neem on a large scale is the high photosensitivity of azadirachtin, which breaks down or isomerises under sunlight; thus, neem has a low residual effect under field conditions. Moreover, the lack of standardisation and quality control in neem-based formulations produced affect the reproducibility of the insecticide effect (Forim *et al*. 2010). Viana and Prates (2003), using an aqueous extract from neem leaves at 1%, found that the mortality level of *S. frugiperda* caterpillars was low during the first three days, after initial feeding, and high by 10 days, indicating that protocols for testing the efficacy of conventional pesticides may not be suitable for testing neem extracts.

The effectiveness of home-prepared concoctions based on neem or other plants is variable, as there are unavoidable variations in the raw material and the processing.

Cost: Commercially available neem-based products are often more expensive than conventional pesticides. Home-prepared botanicals may require family labour only, for which the opportunity costs are hard to estimate.

Considerations for Africa: Botanicals have the advantage that they are generally lower risk than many other pesticides, in terms of human health – an advantage in a context where safety precautions are often not taken. However, they are not entirely hazard-free (see section 4.3), and, as with many pesticides, they may kill non-target beneficial insects as well as the pest. A wide range of home-made pesticides are used and recommended in Africa. In Kenya, for example, www.theorganicfarmer.org recommends mixing chilli powder with ash and dropping it into maize funnels.

In Ghana, two botanicals are being recommended: maltodextrin and ethyl palmitate. Maltodextrin is registered as an insecticide and is used for controlling various pests, especially in horticulture (Root et al. 2008), while ethyl palmitate is reported to have acaricidal properties but is not registered as a pesticide.

The most widely available botanicals should be tested for efficacy against FAW so that clear and authoritative recommendations can be made.

4.2.7 Pest-resistant crops

Method: Different varieties of a crop may show more or less tolerance or resistance to a particular pest. Traditional host plant breeding seeks to produce lines that combine this trait with other desirable traits, such as high yield. However, iin the Americas, a large proportion of maize (and some other FAW-susceptible crops) is genetically modified to produce one or more Bt proteins. Thus, there is less demand for pest-resistant crops produced by conventional approaches. Nevertheless, there is good evidence of variation between maize varieties (and other crops) in susceptibility to FAW, though given the predominance of Bt maize the opportunities this provides have probably not been explored in full.

Ferreira *et al*. (2003) assessed 10 different maize genotypes and concluded that, in general, the taller genotypes with greater ear insertion height suffered less damage. Williams *et al*. (1998) reported that maize that is resistant to FAW sustained less leaf-feeding damage, and larvae feeding on resistant maize grew more slowly. They also reported that both susceptible and resistant varieties sustained less damage as the plants grew older, but resistant varieties completed the transition from juvenile to adult plant earlier than susceptible varieties. Hemicellulose levels were higher in resistant genotypes and in older plants of all genotypes, and appear to be associated with FAW resistance. This may explain the observation by Pitre *et al.* (1997), in Honduras, that early maturing maize varieties suffered less damage. Resistance may manifest itself in various ways, including antibiosis, resulting in reduced survival, reduced feeding rate resulting in reduced size and fitness, and lower attractiveness of the plants, resulting in reduced oviposition (Viana *et al*. 2000).

A more widespread approach to FAW-resistant maize in the Americas is the use of GM crops containing Bt genes. Modifications have been engineered that lead to production of several different Bt proteins, and as these provide control of more than one pest species, without the cost of intervention, they are generally popular – especially with commercial farmers.

Effectiveness: There is little evidence or suggestion that resistant varieties can provide adequate control on their own, but if varieties can be produced that have some measure of resistance, alongside other desirable traits, they can be an important part of an integrated approach.

Bt maize was initially very effective at controlling FAW and other pests. However, resistance to maize containing the Cry1F gene has appeared in FAW, with some cross resistance to the Cry1Ab gene. FAW resistance to Bt cotton has also been found. Pyramiding multiple Bt genes in the same crop variety is now being used. To hinder the development of resistance, a proportion of maize in an area should be non-Bt, to act as a 'refuge' in which Bt-susceptible insects can reproduce.

Cost: Traditional breeding takes time, but this does not necessarily greatly increase the cost of seeds. Bt maize is considered to be cost-effective (aside from the problem with resistance) in the Americas, but in South Africa it is reported to be expensive for smallholders (Fischer *et al.* 2015). However, under the Water Efficient Maize for Africa (WEMA) programme, GM maize will be royalty-free, and so will cost no more than non-GM varieties. The cost to farmers of GM seeds thus depends on the approach taken by the owners.

Considerations for Africa: Many farmers in Africa save their own seed, so achieving wide uptake of new varieties can be slow. However, for maize, farmers are much more likely to spend money on improved seed (McGuire and Sperling 2016), so if FAW-resistant varieties can be produced that contain the other characteristics farmers look for, it is likely they would be taken up. Some such varieties may already be present, so a first step is to test existing varieties for resistance to FAW. In South Africa, Van Rensburg *et al.* (1998) assessed 19 genotypes for resistance to the maize stalk borer, *Busseola fusca*, and found that one line provided high-level leaf-feeding resistance to the borer that was resistant to FAW (in the Americas).

GM crops have only been approved in a few countries in Africa, and most of the GM crops are in South Africa, which is the only country where Bt maize is grown in Africa. It will be important to determine whether FAW shows any resistance to the Bt maize grown there. Several countries are starting field trials of Bt maize, and these trials will now need to factor in FAW. While GM crops may have a role to play in FAW management, they are unlikely to provide the sole solution. In South Africa, there is ongoing debate about whether Bt maize is appropriate for smallholders: some authors contending that traditional breeding of open pollinated varieties is more cost-effective and appropriate (Fischer *et al.* 2015), with others envisaging Bt maize playing a key role in achieving increased food security in Africa (Keetch *et al.* 2005).

4.2.8 Mass trapping

Method: The same pheromones that can be used for monitoring FAW (section 4.1) can also be used as a control method. If sufficient male moths can be captured, not all females will be able to find mates, thus reducing the number of fertilised eggs that are laid. This method has not been widely used for *Spodoptera spp.* (Geuerrero *et al*. 2014), but Andrade *et al*. (2000) reported that the method had been used in Costa Rica for FAW control since 1992 in over 2000 hectares of melon fields, deploying four to five traps per hectare. Personal communications suggest that small-scale farmers in Latin America are using four to ten home-made traps per hectare. Some farmers in Peru use home-made light traps to attract and kill FAW (Edison Hidalgo, pers. comm.).

Effectiveness: As one male can mate with several females, a high proportion of males needs to be trapped for this approach to be effective. It is also usually more effective over a large area, to reduce the impact of immigrating moths. A report by Andrade *et al*. (2000) suggested that use of mass trapping reduced the need for expensive applications of *B. thuringiensis* by 30%–70%. Effectiveness depends in part on how attractive the artificial pheromone is, and there is evidence that this may vary amongst different geographic populations (Meagher *et al.* 2013). We have not found evidence that light traps are effective.

Cost: Above, it was reported that in Brazil a trap plus pheromone costs around US$6. However, for mass trapping, one trap could be used multiple times, and some farmers make their own traps. In Kenya, one company is selling FAW lures for approximately US$16 for a pack of four lures only, or around US$4/lure, with a trap costing around US$4, and the sticky plates that are inserted into the trap for catching the moths costing US$9 for a pack of 10. If pheromone lures are renewed every month, and with a trap density of five per hectare, the cost for pheromone alone would be $20/hectare/month.

Considerations for Africa: With many small-scale farms, use of mass trapping would probably require area-wide coordination and implementation for it to be successful, yet the cost may be more than many farmers would be willing to pay, especially if additional control measures were still required. Work would also be needed to confirm the most cost-effective blend of chemical components in the lure.

4.2.9 Agronomic practices

There are multiple practices that have been suggested as beneficial (or detrimental) in the management of FAW. Table 19 provides a brief description, with comments on effectiveness, cost and considerations for Africa. Some of the methods are likely to have some beneficial impact, and if they can be implemented at low cost to the farmer, they are worth doing, even though they will probably not provide full control. Research is required to determine which methods should be highlighted as most important for farmers.

Table 19. Agronomic practices for FAW control

Method	Description	Effectiveness	Cost	Considerations for Africa
Don't plant near infested crop	Reduces the chance of caterpillars moving into the new crop	Reduces risk of local FAW immigration but not from further afield.	Low	May be impractical
Early/prompt/delayed planting	Assumes that FAW pest populations build up during the season, and for delayed planting, that weeds are attractive for egg-laying.	Some evidence that late planted crops are more likely to be damaged. Short delay of 5 days after weed emergence was beneficial in Honduras, followed by delayed weeding 10-14 days after crop emergence.	Low, but risks if rains late.	Unpredictability of rains a constraint
Synchronised planting	"Dilutes" immigrant FAW, and reduces availability of preferred host age through the season.	Not clear how effective.	Organisational costs	Difficult to organise where many smallholders. Easier for commercial farms
Overplanting/thinning	Plant at above the recommended density, then thin 2-3 weeks after emergence, removing those that have been severely attacked by FAW or are otherwise weak. This would reduce need for intervention at this stage.	van Huis (1981) reported that it should be effective for smallholdings in Nicaragua. Little recent mention, perhaps due to cost.	For seed costs of $50/ha, a 20% overplanting would cost $10/ha plus labour, roughly equivalent to a pesticide treatment.	Providing the thinning is done, no harmful effect so worth trying. Research needed in Africa.
Maintain healthy crop	Plant at correct spacing, fertilise correctly. Healthy plants are generally better able to resist pest attack.	Not clear. Some evidence that fertilised crops are more attacked and fertiliser application is only worthwhile if FAW is controlled. Control of FAW during drought did not increase yields.	Low as should be happening anyway	Fertiliser use is generally low in Africa.
Intercropping	Planting rows of other crops between the maize.	Likely to be most effective when non-host plants used (eg cassava). Crop diversity may encourage natural enemies, although this may be context specific. Maize-bean intercrop in Nicaragua reduced FAW attack on maize by 20-30% (beans were attacked).	Low. Possible opportunity cost of not planting preferred crop.	As in smallholder systems of Central America, intercropping is a traditional approach for reducing risk. Common intercropping practices need evaluating in relation to FAW attack.
Soil/ash/lime/sand in whorl	The dry mixture is put inside the top of the whorl.	Not clear. Van Huis (1981) said farmers use soil but in experiments it did not work. Where nematodes or other pathogens are present in the soil, it may enable them to infect the	If material easily available, low apart from labour	For small scale farmers worth trying. Research needed in Africa.

Method	Description	Effectiveness	Cost	Considerations for Africa
		larvae.		
Plant trap crops	Planting crops that are attractive to ovipositing females that lay on the trap crop instead of the main crop	Partially effective in non-maize crops where maize is planted as the trap crop. Some weeds may act as trap crops.	Cost of growing the trap crop.	Used as part of the "push-pull" approach; see Section 4.4
Rotate with non-host plants	Plant non-host crops after host-crops (such as maize).	Rotation is a good general practice. Specific benefit in FAW management not clear. Main benefit may be in having an unsusceptible crop rather than affecting pest population, unless synchronised implementation of a large area.	Opportunity costs	There are likely to be other reasons why a farmer would or wouldn't rotate.
Ploughing	FAW pupae are in the soil, so ploughing could kill them and/or expose to the weather and natural enemies	Not clear. Depends on the relative importance of locally emerging moths and immigrants in causing infestations.	Cost of ploughing, and negative effects of ploughing on soil.	Not compatible with low/zero tillage approaches, so likely to be unsuitable in many instances.
Weeding	Some authors recommend regular weeding; others partial or delayed weeding.	Conflicting evidence. Possible contrary effects, sum of which will depend on context (including weed species). Weeding removes potential FAW breeding sites, but could also act as a trap crop early on. Weeding may reduce natural enemies. Delaying initial weeding may be beneficial.	Labour cost, though weeding may already be done in some cases	Context specific research required
Don't move infested materials	Avoiding moving infested plant materials is a good general practice to limit a pest's spread.	Given FAW's flight capacity, unlikely to halt spread unless movement of materials is over a long distance.	Costs for enforcement (eg at borders)	A consideration for slowing spread to countries where it is not yet present, eg Madagascar.
Spraying sugar solution	Sugar can attract natural enemies, which then attack the FAW.	Not clear. Reported to be used by smallholders in Honduras. Latin America. It might also encourage growth of harmful fungi.	Cost of sugar and labour.	Other ways of encouraging natural enemies likely to be more acceptable.
Destroy/remove stubble	Destroys any caterpillars still in the stubble.	Unlikely to have much effect on FAW as larvae do not diapause (like some species) and pupae are in soil.	Labour cost, unless stubble already removed for other uses	Probably not worth recommending.

4.2.10 Sterile insect technique (SIT)

Method: Irradiation of insects at the right dose can cause them or their offspring to become sterile. The approach has been tried for several types of insect, but is less widely used for moths (Bloem and Carpenter 2001). As part of a large programme investigating the potential of SIT for moth pests, studies were conducted in Brazil on irradiating FAW, which showed that the approach was technically feasible (Arthur *et al*. 2002). However, it has not been developed as a control method.

Effectiveness: SIT has not been deployed for FAW control, although the method can be effective for some species of pest.

Cost: SIT is only economically viable if large numbers of sterile insects can be produced at low lost. SIT also requires a special facility.

Considerations for Africa: SIT is used in South Africa for control of false codling moth (*Thaumatotibia leucotreta*) in fruit orchards (Boersma and Carpenter 2016), but only as part of an integrated approach in relatively small areas. Control of FAW in Africa using SIT is not likely to be feasible for many years.

4.2.11 Integrated Pest Management

Box 1. Definition of Integrated Pest Management (IPM) (FAO & WHO, 2014)

The careful consideration of all available pest control techniques and subsequent integration of appropriate measures that discourage the development of pest populations and keep pesticides and other interventions to levels that are economically justified and reduce or minimise risks to human and animal health and/or the environment. IPM emphasises the growth of a healthy crop with the least possible disruption to agro-ecosystems and encourages natural pest control mechanisms.

Method: IPM is variously defined, but usually involves a combination of methods that minimises use of pesticide use (Box 1). The International Code of Conduct on Pesticide Management (FAO and WHO, 2014) is ‘designed to promote Integrated Pest Management (IPM)’ (article 1.7.6). ‘FAO promotes IPM as the preferred approach to crop protection and regards it as a pillar of both sustainable intensification of crop production and pesticide risk reduction. As such, IPM is being mainstreamed in FAO activities involving crop production and protection.’ (From FAO website http://www.fao.org/agriculture/crops/thematic-sitemap/theme/pests/ipm/en/).

In taking a more holistic view of pest management, IPM also takes into consideration other pests in the crop. Thus, in identifying and evaluating control methods for FAW, it is also necessary to consider the positive or negative effects that these methods might have on the management of other pests. There may also be biological interactions between the different pests, so this too needs to be investigated.

An important element of IPM is encouraging – or at least avoiding killing – the natural enemies of the pest. In Latin America, large numbers of parasitoids, predators and pathogens of FAW have been reported: for example, Molina-Ochoa (2003) listed over 40 species of parasitoid, with Figueiredo *et al.* (2006) adding further species to the list. Naturally occurring diseases include bacteria, fungi, viruses and nematodes. Various studies have therefore sought to assess not only the contribution that natural enemies make to regulating FAW populations, but also the extent to which they may be damaged by other control methods, particularly pesticides and GM crops.

Ni *et al*. (2011) examined the resistance of maize lines to FAW, including some that were resistant to other root and ear-feeding pests. They also assessed the extent to which the different lines attracted predators. However, there was no direct correlation between FAW damage and predator abundance, although some lines showed resistance to FAW as well as other pests.

Effectiveness: IPM is effective, almost by definition. Its effectiveness for a particular pest depends on the availability, cost and effectiveness of the different component control methods, and the socio-economic context of the farmers. The element of natural control also depends on the presence of natural enemies that exert some level of control.

Cost: The costs for IPM are variable. If more than on input is required (such as spraying a biopesticide and releasing parasitoids), then costs can become high. But other elements of IPM, particularly agronomic practices, have low input costs. However, there may be additional labour costs for crop monitoring and agronomic practices. While labour itself may not have a high cost, if family labour is used, there can be significant opportunity costs.

Considerations for Africa: What IPM might look like for FAW in Africa will depend on a number of factors, including what natural enemies attack the pest. Studies on what natural enemies are attacking FAW in Africa, what level of mortality they can exact, and how they can be encouraged, are therefore required.

IPM is widely promoted as the most appropriate approach to pest management in Africa. For control of FAW in Latin America, IPM is seen most commonly in smallholder systems that are more similar to African farming systems than the large monocultures where Bt crops and/or calendar spraying are used. See section 4.4 for further discussion on the uptake and adoption of IPM in Africa.

4.3 Biopesticides for FAW

Given the dangers of chemical pesticides, the development of lower-risk approaches using biological pesticides for FAW is high on the list of near-term priority activities. An analysis is therefore being conducted of biopesticides registered in 30 countries: 10 in FAW’s native range and 20 in Africa, most of which have already been invaded by FAW. The analyses of the lists of registered pesticides and biopesticides for Argentina, Benin, Bolivia, Brazil, Burkina Faso, Colombia, Costa Rica, Ecuador, Ethiopia, Kenya, Mail, Malawi, Mexico, Mozambique, Nigeria, Peru, Togo, the USA and Zambia is supported by the German Gesellschaft für Internationale Zusammerarbeit (GIZ), as part of its support to the Grüne Innovationszentren in der Agrar-und Ernährungswirtschaft (in English: ‘Green innovation centres for the agriculture and food sector’). The analyses for Côte d’Ivoire, the Democratic Republic of Congo, Rwanda and Uganda were supported by funding from DFID.

Preliminary findings of the analysis for 25 of the countries is presented here. The analysis for all 30 countries and more detailed information on the findings will be presented in the forthcoming report, which will be published by GIZ.

Lists of registered products were analysed for the following biologically-based active ingredients (AI):

- Biochemical biopesticides – plant extracts / botanicals
- Biochemical biopesticides – synthetic pheromones / semiochemicals
- Biochemical biopesticides – microbial extracts / fermentation products
- Biochemical biopesticides – insect growth regulators
- Biochemical biopesticides – compounds synthesised by other organisms
- Biochemical biopesticides – inorganic compounds
- Biochemical biopesticides – synthetically derived equivalents to naturally occurring substances
- Microbial biopesticides – bacteria
- Microbial biopesticides – fungi
- Microbial biopesticides – protozoa
- Microbial biopesticides – viruses
- Microbial biopesticides – oomycetes
- Microbial biopesticides – yeast
- Microbial biopesticides – algae
- Macrobials – natural enemy – insect predators and herbivores
- Macrobials – natural enemy – parasitoids
- Macrobials – entomopathogenic nematodes

CABI software was used to mine and process large datasets to extract registration data from government sources, such as online databases and files containing documents in pdf, Excel, Word format, etc. Where lists of registered products do not include information on target pests, CABI databases were used to identify the biopesticides which are likely to be effective against FAW. In both cases, biopesticides which are specifically registered for FAW were identified, as well as biopesticides which are more generally registered for the *Spodoptera* genus, Noctuidae, and Lepidoptera. The data extraction was undertaken in July and August 2017, so it represents a snapshot of what was registered at that time. In some countries, some products of interest are exempted from the requirement for registration. For example, in the USA, macrobials, such as *Trichogramma* wasps and pheromones which are used exclusively as attractants in traps, do not require registration.

Profiling the biopesticides. For each registered active ingredient, detailed profiles of the human health and environmental hazards were developed in order to verify whether they would indeed provide a lower-risk option compared to chemical pesticides. The profile included the chemical class, use type, the pest designation for which the biopesticide was flagged (eg whether it was flagged specifically for *Spodoptera frugiperda* or more generally for Lepidoptera), and any associated hazards to human health and the environment. In particular, it was noted whether any of the identified AI were highly hazardous pesticides. Highly hazardous pesticides are defined as pesticides that are acknowledged as presenting particularly high levels of acute or chronic hazards to health or the environment, according to internationally accepted classification systems (FAO 2016). Pesticides that cause severe or irreversible harm to health or the environment under the conditions of use in a country may also be considered highly hazardous.

For all chemicals, including pesticides, the *Globally Harmonized System of Classification and Labelling of Chemicals* (GHS, UN 2015) describes the classification criteria and the hazard communication elements by type of hazard, covering physical hazards (eg flammability), human health hazards (eg acute toxicity, carcinogenicity) and environmental hazards (eg aquatic toxicity, potential for bioaccumulation). Hazard statements associated with each biopesticide AI were collected and 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 highly hazardous pesticide (HHP) criteria were categorised 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. AI were grouped into five categories, as shown in Table 20.

Table 20. Description of the method applied for grouping the AI into overall hazard categories based on the GHS hazard statements associated with each AI.

Hazard category	Basis for inclusion in the hazard category
HHP	AI which satisfy one or more HHP criteria
Danger	One or more of the associated human health hazard statements indicates that the AI is 'toxic' or 'Fatal if inhaled' (in the case of inhalation hazards)
Warning	None of the human health hazard statements indicates that the AI is 'toxic' One or more of the associated human health hazard statements indicate that the AI is 'harmful'
Low toxicity	No known human health hazard statements associated with the AI
Missing data	Data not available on one or more of the criteria used for identifying HHPs

The analysis identified over 900 products, containing a total of 54 AI registered in at least one country. Over half of the identified biopesticide AI are either botanicals or microbial biopesticides (Figure 14). Likewise, the biopesticide products are most frequently botanicals (N=391), microbials (N=246) or microbial extracts / fermentation products (N=177). With respect to macrobials, only one parasitoid species (*Trichogramma pretisoum*) and two entomopathogenic nematode species (*Steinernema carpocapsae* and *S. feltiae*) are registered. It is highly likely that macrobials are under-represented since most countries do not include macro-organisms in their lists of registered pesticides.

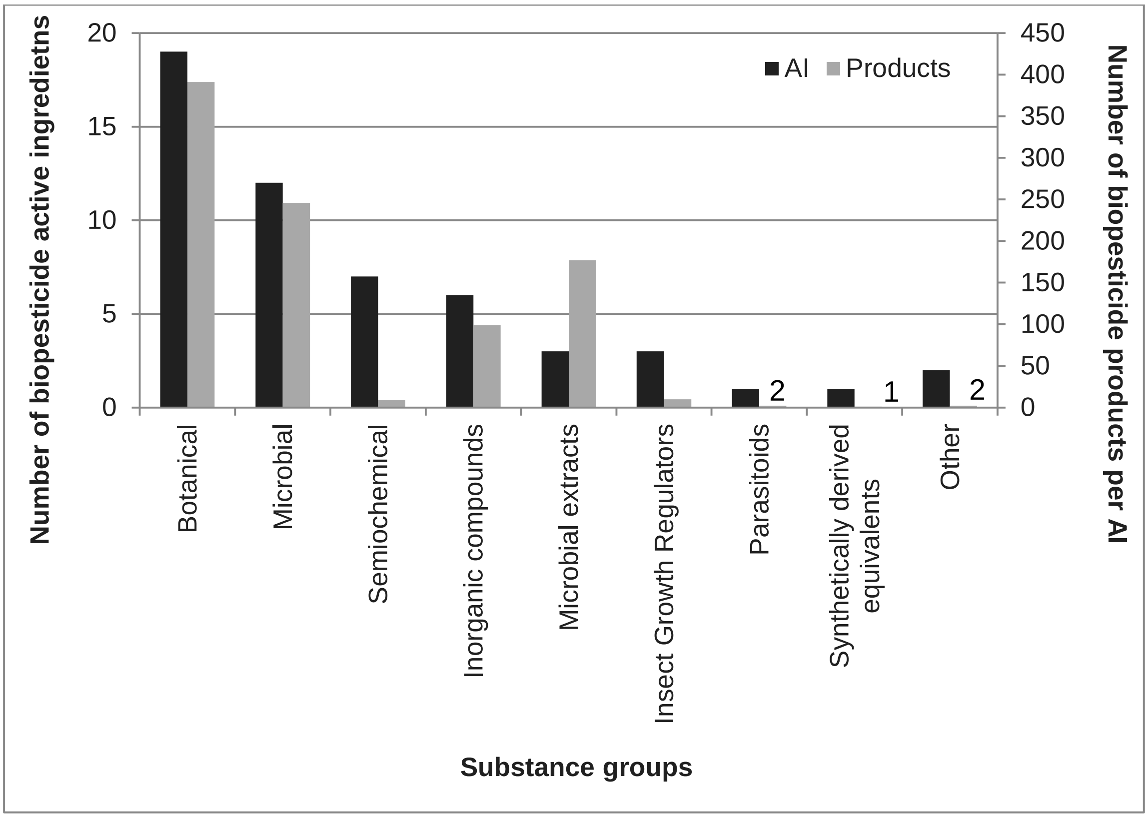


Figure 14. The number of AI and products identified per biopesticide substance group.

The biopesticide AI which are registered and are potentially allowed for use for FAW management in three or more countries are listed in Figure 15 The highest number of products registered is for biopesticide products containing pyrethrins, *Bacillus thruingiensis,* neem and spinosad:

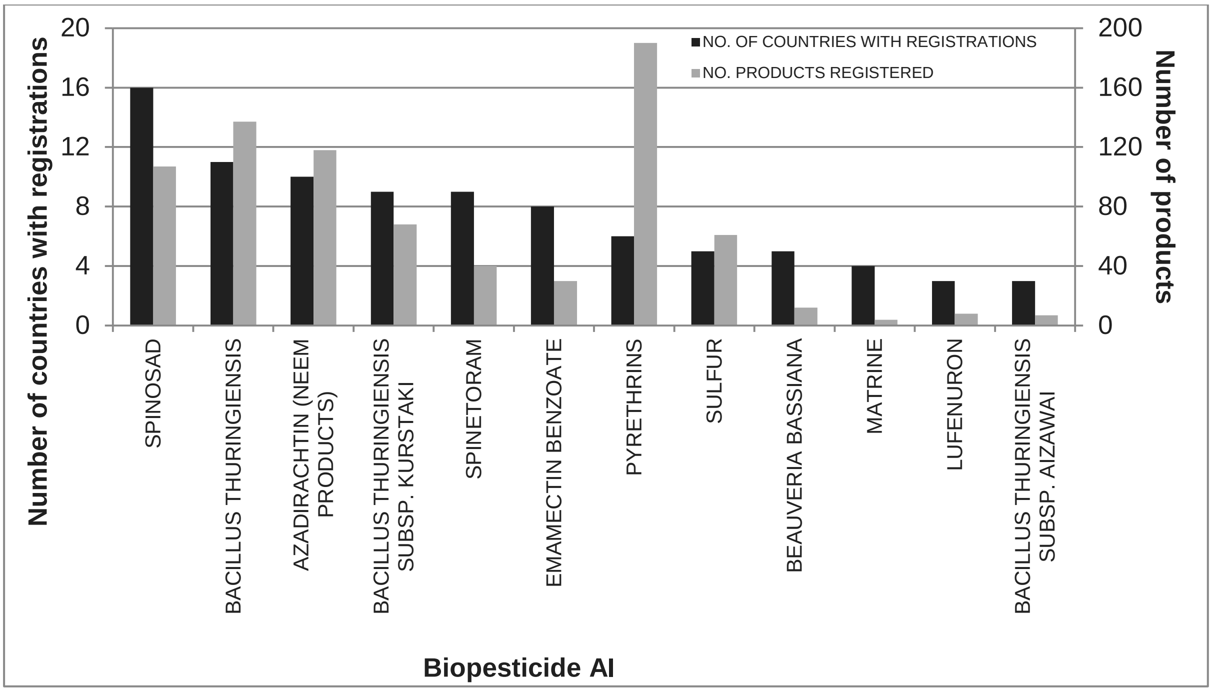


Figure 15. AI which are registered in three or more countries and the corresponding number of products which are registered for each AI in the 30 study countries (different entries for *B. thuringiensis* represent different subspecies).

In FAW's native range, the countries with the highest numbers of AI registered for use against it are the USA (40 AI, Figure 16). The USA also has significantly higher numbers of products registered (549 products); Mexico has the next highest number (118 products).

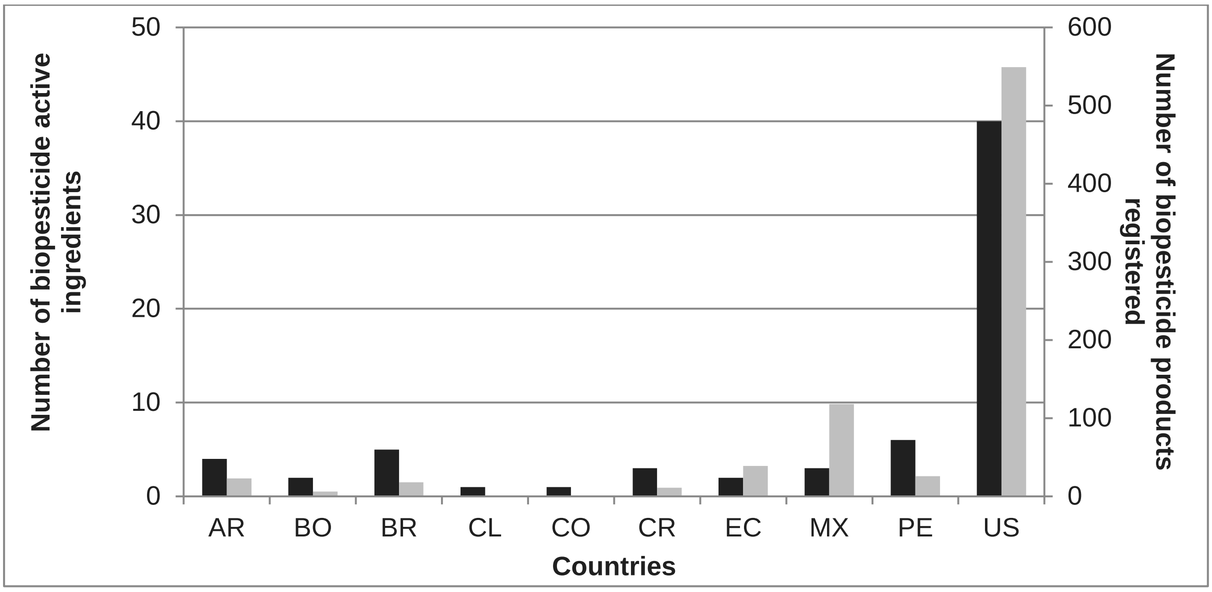


Figure 16. Numbers of biopesticide AI and corresponding products registered in 10 countries in FAW's native range.

In the 20 countries in Africa, 18 AI were identified which are registered and would be allowed for use for FAW management, although none is yet specifically registered for use against

FAW. The countries with the highest number of AI and products which could potentially be used against FAW are Kenya (11 AI and 51 products), Mozambique (9 AI and 28 products) and South Africa (7 AI and 17 products, Figure 17).

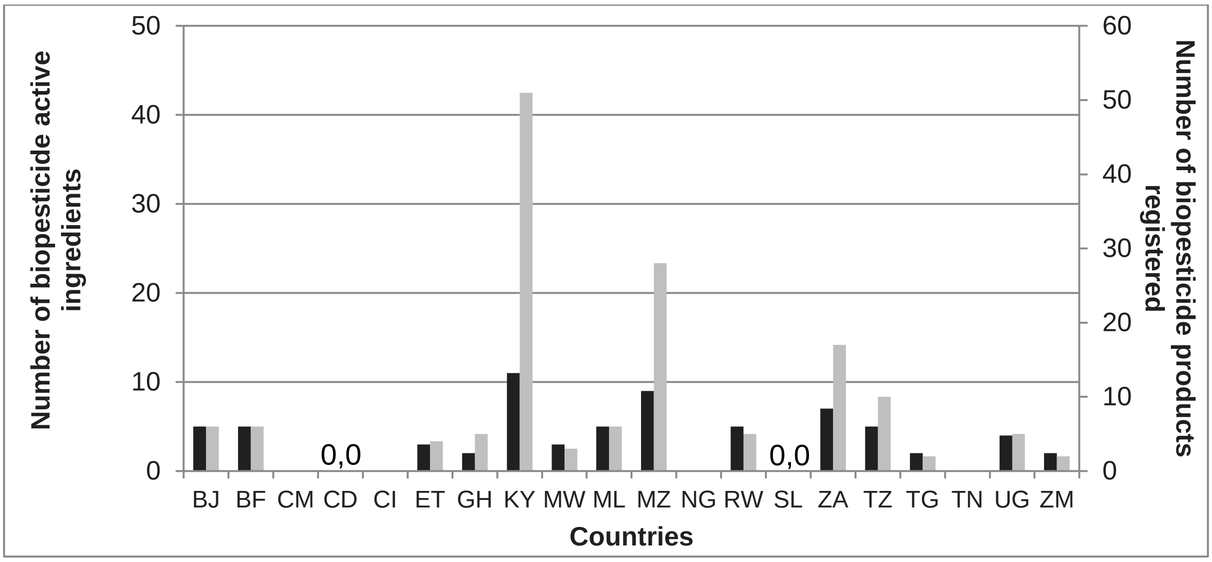


Figure 17. Numbers of biopesticide AI and corresponding products registered in 20 countries in Africa. Analyses for Democratic Republic of Congo, Ivory Coast, Rwanda, Sierra Leone and Uganda are supported by DFID.

Hazard profiles of identified biopesticides AI

The 53 biopesticide AI all present relatively low levels of hazard. However, two of the AI meet one or more of the HHP criteria; 12 AI are categorised as ‘danger’ (one or more of the associated human health hazard statements indicate that the AI is ‘toxic’ or ‘fatal if inhaled’); 14 AI are categorised as ‘warning’; 10 AI are categorised as ‘low hazard’ (there are no known human health hazard statements associated with the AI); and data was not available for one or more of the criteria used for identifying HHPs for 16 (‘missing data’).

Discussion

For many of the countries in Africa which were evaluated, a relatively small number of the identified biopesticide AI are registered for use. For the most part, the hazard profiles do not suggest that the identified AI will pose an undue risk to human health or the environment. The two active ingredients identified as HHP were classified as such based on the technical grade or pure AI. In practice, the formulated products containing these AI are likely to be much lower risk. The overall toxicological profiles of the biopesticide AI as a group tend to be much less hazardous than the average group of conventional pesticides. Because of FAW’s biology, quite often the synthetic pesticides which are registered for its management are significantly more hazardous than those which are most often used. Many of the conventional pesticides which are registered for FAW management in the study countries are in fact HHPs.

The final report being prepared for GIZ will provide detailed information on the study findings and recommendations for follow-up action.

Some next steps will include the following.

Assess macrobial biocontrol options. In most countries regulation of the use of macro-organisms does not fall under the mandate of the national regulatory authority for pesticides. For example, the USA's regulations relating to the registration of pesticides explicitly exempts 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 and Kenya. For most countries, introduction and use of non-native macro-organisms is regulated by the national plant protection organisation, following the *Guidelines for the export, shipment, import, and release of biological control agents and other beneficial organisms* (ISPM 3 2005), though requirements and procedures for risk assessment, import permits, documentation, etc vary by country. Within a macro-organism's native range, most countries allow their use as biocontrol agents. As one of its next steps, CABI will review the available information on the use of microbial biocontrol agents to manage FAW. To assess whether a microbial biocontrol agent would be allowed for use in a country, the organism's bio-geography will be determined by referencing the *CABI Crop Protection Compendium*, the *Plantwise Knowledge Bank* and the Fifth Edition of *The Manual of Biocontrol Agents* (print edition) and other sources as relevant.

Prioritise candidate biopesticides through literature reviews. A literature review will be conducted to assess the efficacy of the identified biopesticide active substances. National experts who are known to CABI will also be contacted to learn about successful management approaches, based on local experiences. In addition, CABI will link into the existing global working group of the International Organisation of Biological Control, which is focusing on maize insect pests, in order to obtain additional scientific expert advice.

Technical support for biopesticide trials for FAW management. The above analyses will be used to identify the most promising candidate biopesticides for follow-up testing, in order to assess efficacy against FAW and support registration. In collaboration with appropriate regulators and other local organisations, the most promising biopesticides will be tested. In addition, advice will be provided on conducting rapid assessment through laboratory bioassays of biopesticide products that are already in the country and registered for other Lepidoptera. CABI will provide guidance for the experimental design, implementation and analysis of laboratory and field trials to test the efficacy of the identified biopesticides against FAW under in-country conditions.

Technical support for risk assessments and subsequent regulatory decision-making. For the biopesticides which are proven to be effective in the biopesticide trials, the next step will be to carry out risk assessments and consider registration (or the issuing of import permits for macro-organisms which are biocontrol agents). CABI will provide regulators with technical support for risk assessments and it will facilitate liaison for the registration of biopesticides.

4.4 Uptake of pest control solutions

The question of how pest control solutions can be delivered effectively is part of a long-standing yet ongoing wider discourse on how to increase the impact of agricultural research in Africa. For example, Meijer *et al*. (2015) noted that, despite the potential of agricultural innovations, uptake by smallholder farmers in sub-Saharan Africa is low. They concluded that uptake is a complex process that is influenced by both extrinsic and intrinsic variables. We do not attempt to review that literature here but focus instead on the uptake of pest management methods. The evidence from Latin America indicates that an IPM approach is necessary, in which pesticide use is minimised, natural enemies are encouraged in various ways, crops are monitored, and one or more interventions are made only when necessary. This is clearly more complicated than calendar spraying at predetermined times – an approach used in some large-scale farms in Latin America – as the advice to farmers is unavoidably more complex. After considering the use of IPM in Africa, we then briefly review some of the ways in which adoption of pest management methods can be promoted.

4.1.1 IPM in Africa

When the term IPM was first coined, the approach was seen as a 'new technology' (Huffaker 1980), that was expected to solve the problems caused by pesticide overuse – particularly in the New World. It was thus seen as a technical solution to a technical problem. In contrast, the development of IPM in rice in Asia, also triggered by pesticide-induced pest problems, emphasised the empowerment of farmers to make pest management decisions, and pioneered the use of Farmer Field Schools (FFS). IPM and FFS have been championed in Africa by FAO, especially in the last two decades, and FAO has already started developing FFS curricula and activities focused on FAW.

However, while there has been much enthusiasm for IPM in Africa – the principles are not really ones that can be argued with – there is a widespread view that IPM is still not living up to its promise, prompting questions such as 'can we make IPM work for resource-poor farmers in sub-Saharan Africa?' (Van Huis and Meerman 1997). Nwilene *et al.* (2008) stated that 'the potential of IPM to contribute to poverty alleviation and food security is still poorly realised in Africa due to a myriad of factors'. Way and van Emden (2000) observed that there are few examples of significant IPM advances in food crops in sub-Saharan Africa. The example that is often cited (eg Nwilene *et al.* 2008; Way and van Emden 2000; SP-IPM 2010) is the classical biological control of cassava mealy bug (Neuenschwander *et al.* 2003). Yet in that case there was relatively little involvement of resource-poor farmers, and a single control method was unusually effective in reducing the pest population. Thus, while it was a highly successful programme, it is not really a good example of IPM.

A number of elements of IPM involve habitat management or ecological engineering (Gurr *et al.* 2004). The structure of the agroecosystem is managed to reduce pest damage though a variety of mechanisms, but often by the encouragement of natural enemies. Mixed cropping, intercropping, rotations, trap crops, companion crops and agroforestry can all be viewed as habitat management – techniques that are used in Africa for a variety of reasons, often with little or no understanding of the mechanisms involved. Much of the increasing research on habitat management has been in developed countries, where the reintroduction of heterogeneity into agroecosystems at a range of scales can have multiple benefits. However, the push-pull strategy for managing cereal pests in Africa is a well-researched and documented example of this approach (Box 2). By 2016 it had been adopted by at least 125,000 farmers in eastern Africa (Khan *et al.* 2016). However, *Desmodium uncinatum,* the repellent or ‘push’ species in the system, is exotic to Africa (originating in South America) and is reported to be invasive (Witt and Luke 2017).

Box 2: Push-pull approach in cereals (summarised from Hassanali *et al.* (2008))

Stem-borers, such as Busseola fusca (Noctuidae) and Chilo partellus (Crambidae), can cause serious damage to maize and sorghum. This can be reduced by planting trap crops, such as Napier grass (Pennisetum purpureum), next to the crop: the stem-borers are more attracted to the Napier grass for oviposition, reducing oviposition on the adjacent crop. In contrast, Desmodium uncinatum repels the pests, so, intercropped with cereals, it reduces pest damage. The ‘push-pull’ system thus combines two to three rows of napier grass around the edge of a field, with alternate rows of cereal and Desmodium. Yields are substantially increased, due to a combination of factors. As well as reduced oviposition on the crops, parasitism by natural enemies is higher in push-pull fields. In addition, Desmodium has an allelopathic or allelobiotic effect on African witchweed, Striga hermonthica, another serious pest of cereals. ICIPE and Rothamstead Research have developed a detailed understanding of the semiochemicals involved in this system, and suggest that the knowledge could be used in conventional breeding or genetic modification to produce plants which are more or less attractive to the pests. In principle, the approach is possible for many pests, including FAW.

The US-funded IPM Innovation Lab (formerly IPM-CRSP) has supported considerable research on IPM in a number of countries in Africa. As well as addressing technical issues, the programme has promoted socio-economic and participatory approaches, and has been notable for its work on gender (Hamilton and Norton 2001; Heinrichs 2005). Its research in Uganda, for example, has suggested that women have a greater appreciation of the benefits of IPM, and that targeting women can improve IPM adoption.

Various explanations for the relatively low rates of adoption of IPM by resource-poor farmers in Africa have been proposed, including the following (Orr 2003).

- Inadequate extension systems. In many countries, there are too few extension personnel to provide comprehensive advisory services.
- Complexities of IPM. Because IPM can involve the collection of information (such as about pest density) and decisions requiring evaluation of information, training farmers on how to use IPM can be more expensive than promoting a technology such as a new seed variety.
- Farmers are encouraged by industry to use pesticides. Agro-input dealers obviously promote methods that involve the purchase of their products.
- Policies do not support IPM. There are various policies that can intentionally or unintentionally promote pesticide use rather than IPM, such as the widespread government provision of pesticides for FAW control.

IPM methods are developed that are not appropriate to farmers' needs. Recognition of this issue has driven the involvement of farmers in research, from prioritisation of needs to design and evaluation of trials.

However, while all these may be the case to a lesser or greater extent, Orr (2003) argues that these are 'supply-side' issues, and that what we really should be looking at to explain low rates of adoption is the demand and need for IPM. Because much small-scale farming in Africa is often low-input and low-output, the benefits of crop protection do not justify the costs. Orr (2003) points out that although IPM may be labour-, rather than capital-, intensive, the opportunity costs in terms of farmers' time is not as low as is commonly assumed. He contrasts conditions for successful IPM (adapted from Morse and Buhler 1997) with those pertaining in smallholder farming in Africa (see Table 21).

Table 21. Contrast between conditions for successful IPM and conditions in African smallholder agriculture (Orr 2003, adapted from Morse and Buhler 1997)

Component	Conditions for successful IPM	Smallholder farming systems in Africa
Prices	High-value crops plus a stable market Stable prices for crop protection inputs	Low-value staples Input price hikes following structural adjustment
Agro-ecosystem	Monoculture over wide areas	Mixed cropping systems
Soil fertility	Stable	Declining
Productivity	Green Revolution increases yields of staple food crops	Low yield of staple food crops
Pest complex	A small number of important pests	Multiple pests
Pesticide use	Pesticide treadmill caused by excessive use	Low pesticide use on staple food crops
Research/extension base	Strong	Weak

The differences highlighted in Table 21 thus provide another suite of explanations as to why IPM uptake is likely to be difficult in resource-poor farming systems. Thus, some of the best examples of the adoption of IPM are found where at least some of these conditions hold. The high-value horticultural export sector in eastern and southern Africa does not involve many smallholders, but it does illustrate how market demand for higher value products can stimulate the adoption of IPM (Okello and Okello 2010; Ekesi *et al.*, 2011). There are now a number of companies marketing various IPM products in East Africa, and this perhaps provides opportunities for spill-overs into lower-valued crops.

4.4.2 Promoting uptake of pest management methods

As described above, there are various reasons why IPM might not be taken up, particularly by small-scale farmers, and these provide pointers to possible interventions that would promote uptake.

Financial incentives, subsidies

Despite the evidence showing that agricultural input subsidies are not always effective, due to flaws in programme design as well as implementation (Dorward and Chirwa 2014), there is still considerable interest in the approach, with more recent programmes attempting to provide ‘smart’ subsidies . In most more recent programmes the subsidy is for fertiliser and seeds, and so is not explicitly concerned with pest control.

Historically, pest control has been subsidised through pesticide price subsidies – in some cases reaching 100% of the price. As with other inputs, the rationale was that subsidy would enable resource-poor farmers to gain experience of using pesticides, and the additional yield derived would convince and enable them to purchase the inputs once the subsidy was withdrawn. There were several problems with this approach, and in the 1980s and 1990s, with a reduction in external support to agriculture in Africa, input subsidies were scaled back. For example, price subsidies for pesticides were removed in Benin in 1991, in Ethiopia in 1995, and in Ghana in 1996 (Williamson 2003).

Other subsidies can take various forms and may include: donations of pesticides from developed countries; subsidised credit; preferential tax rates; and emergency responses to outbreaks of migrant/transboundary pests. In this latter category, government support for control of outbreaks of locusts, quelea birds and African armyworm is common. Several governments have responded to the arrival of FAW in a similar fashion, providing pesticides and application equipment free.

So if control of FAW is to be subsidised in the future, what would be the best way to do this? Clearly, this will depend on the availability of effective alternative methods, and ones which can be effectively subsidised. In the short term, subsidies could be provided for registered biologically-based pesticides (such as Bt or botanicals), or the lower-risk inorganic pesticides. These are generally more expensive than the higher-risk inorganic pesticides, which are the ones that are usually subsidised. A not dissimilar case occurred in 2001 when the government of Senegal subsidised a new and more expensive insecticide (Prempt, containing fenpropathrin and pyriproxyfen), to control whiteflies on cotton, which had become resistant to existing chemicals (Williamson 2005).

In the longer run, subsidies to support the establishment of enterprises that can produce biologicals, such as *Trichogramma*, could be considered. Given the risks associated with price subsidies, the subsidy might best be deployed to reduce the cost of market development and entry, assuming a sustainable business model can be achieved without price subsidy.

In Zambia, a pilot subsidy scheme was launched during the 2015/16 season, to replace the Farmer Input Support Programme (FISP), based on “e-vouchers”. Based on lessons learned (Kuteya *et al.* 2016; Kuteya and Chapoto 2017), the scheme is being extended. The e-voucher allows a farmer to choose which products on which to use the subsidy. In the pilot, 5.5% redeemed their vouchers for insecticides and herbicides. Such a scheme could be adapted to promote the purchase of lower-risk pest control products.

Agricultural advisory services

The provision of agricultural advice to small-scale farmers has traditionally been seen as a public sector function, usually provided by a department within a ministry of agriculture, and crop protection is one of the main areas in which farmers need advice. In the 1970s the World Bank led efforts to strengthen agricultural extension in developing countries, promoting the training and visit (T&V) approach (Howell 1988). The effectiveness of T&V was a topic of much debate, but since then a consensus has developed that a pluralistic approach is necessary, involving many players in the private and public sectors (Swanson and Davis 2014). Farmers usually report that a main source of advice is other farmers, but beyond that, they receive information and advice from agro-input dealers, financial service providers, NGOs, and private companies running outgrower schemes, as well as from government extension agents.

The dissemination of information and advice on FAW control therefore involves many actors, and with FAW being a new pest, this presents a challenge to ensure that farmers receive sound advice. While government may not be able to provide advice to all farmers, an important role in FAW control is to try and ensure some consistency of advice, while at the same time updating the advice as new information is collected.

Aside from the structure of agricultural advisory services, the way in which advice is communicated to farmers has also become much more diverse. Many efforts are being made to improve the communication and provision of pest management information, and there is debate over which channels are the most effective. However, different channels have different advantages and disadvantages, depending on various factors, including the complexity of the pest management information to be transferred, the desired reach (number of farmers), and the intended target audience (men/women, young/old). For example, mass media can deliver information cheaply, but is more suitable for relatively simple messages, such as raising awareness of a new pest. In contrast, demonstration plots involving face-to-face interaction between an extension agent and groups of famers over a period of time can develop a deeper understanding of pest management, but cost more per farmer (Figure 18).

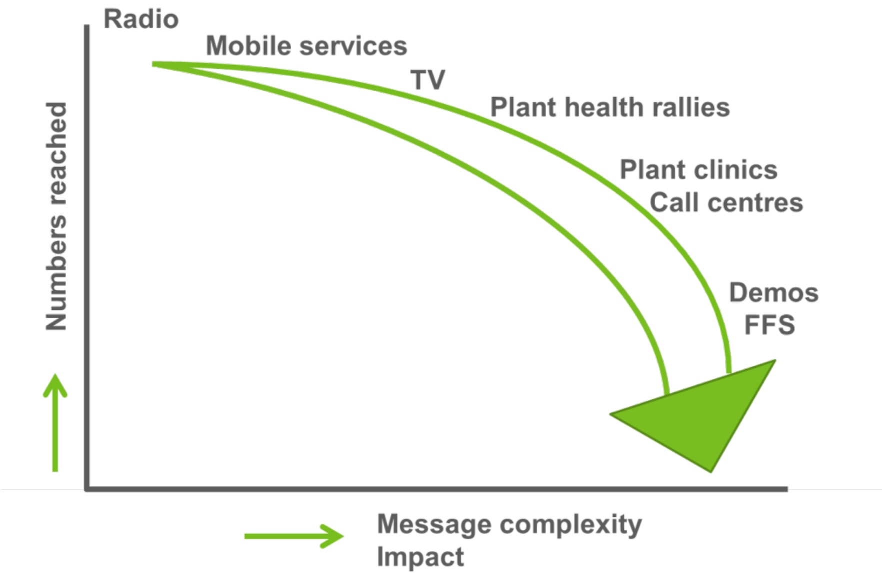


Figure 18. Trade-off between reach and complexity of pest management information communicated (from Romney et al. 2017).

FAO is promoting FFS as a key approach, and evidence shows that FFS can have significant impact (Settle and Garba 2009), particularly as IPM can involve complex messaging. However, as depicted in the figure above, FFS can be relatively costly per farmer 'reached' (Bentley 2009).

In practice, a combination of methods (in both the public and private sectors) is likely to be required, taking into account the information to be communicated and the control methods being promoted. Again, there is an important role for government in regard to monitoring whether farmers are receiving the advice they need, and finding ways of addressing gaps. Communication methods, such as radio phone-ins and plant clinics, can provide useful feedback in this context.

Policy and regulatory environment

Policy can affect the way in which pests are controlled, and, as noted above, in general policy should promote IPM. In practice, it is not uncommon for policy to intentionally or unintentionally promote pesticides. Waibel (1991) identified a range of obvious and hidden price and non-price factors that encourage pesticide use (Table 22).

Table 22. Factors encouraging pesticide use (Waibel 1991)

	Price factors	Non-price factors
Obvious factors	Government sells or gives pesticides Donors provide pesticides at low or no costs Government refunds pesticide companies' costs Subsidised credit for pesticides Preferential rates for tax and exchange rate	Misguided use of governments' activities in reducing pesticide damage Governments' investments in pesticide research Inadequate government research in environmentally benign pest management
Hidden factors	Plant protection service outbreak budget Pesticide production externalities Pesticide use externalities	Lack of adequate procedures for: • pest definition • crop loss definition Lack of information on agroecological parameters Lack of transparency in regulatory decision-making Curricula of agricultural education and extension Dominance of pesticide industry in the market for crop protection information

In response to the appearance of FAW, several governments are, understandably, providing or subsidising pesticides. However, there may be wider impacts of this in terms of encouraging pesticide use that in the long run is not sustainable, so the perceived short-term benefits must be weighed carefully against the potential long-term costs. Hruska & Gladstone (1988) reported that pesticide subsidy reduced the action threshold at which chemical control became cost effective to just 2% plants infested, which illustrates the potential impact of subsidy.

An important part of pesticide policy is the pesticide registration regime: registration is a legal requirement for a pesticide to be imported, sold, stored, distributed, advertised, packaged or used. To register a pesticide, data must be submitted, including the product's identity, formulation, biological properties, toxicology, and environmental impact. Data from field trials of efficiency may also be required, but the more data that is required, the higher the cost. Products that are lower risk but are for smaller or niche markets may therefore be effectively excluded from registration. A registration system designed to reduce risk may thus end up promoting the use of broad-spectrum mass-market products, and prevent lower-risk products from entering the market.

One way to improve pesticide registration is therefore to use harmonised procedures across a number of countries. SADC and EAC have developed draft guidelines for registration of crop protection products, but so far these have not been fully implemented. In contrast, the Comité Sahelién des Pesticides (CSP) is a fully operational sub-regional pesticide registration system. In 1992 CILSS adopted the 'Réglementation commune aux états membres du CILSS de l'homologation des pesticides' (CILSS, 1999). Under this regulation, the CSP was established as the pesticides regulation body for all member states, and countries are directed to set up national pesticide management committees for implementing CSP decisions.

A regulatory environment that encourages the registration of lower-risk, biological pest control products is one way to provide a favourable business environment for IPM enterprises. Where the private sector can make money out of IPM, there is a much greater chance of it being adopted, so policies that favour the establishment of small- or medium-scale IPM enterprises should have a positive effect. In Kenya, there are now several IPM enterprises producing and distributing IPM products and services (such as biopesticides of various sorts), although at the moment they cater mainly for the high-value export market.

4.5 Control recommendations

4.5.1 Country recommendations in Africa

Many countries are already providing recommendations to their farmers, and a sample of these is shown in Table 23.

Table 23. Examples of recommendations issued by countries in Africa

	Countries					
Control method	**[1]Kenya**	**[2]Burundi**	**[3]Ghana**	**[4]Zambia**	**[5]Mozambique**	**[6]Rwanda**
Pesticides						
Synthetic pesticides	Y		Y	Y	Y	Y
Biopesticides	Y		Y		Y	
Botanical pesticides	Y		Y	Y		Y
Biological						
Trichogramma release	Y					
Pheromone trapping	Y					
Varieties						
Plant early maturing varieties			Y			
Plant maize with hard husk	Y					
Agronomic practices						
Hand picking	Y	Y	Y	Y		Y
Don't plant near infested crop	Y					
Early planting	Y		Y		Y	Y
Plant at correct spacing	Y					
Soil/ash/sand in whorl	Y			Y		
Fertilize correctly	Y					
Rotate with non-host plants			Y			Y
Plough to destroy pupae	Y		Y			Y
Weeding	Y		Y			Y
Destroy stubble			Y		Y	Y
Don't move infested materials	Y					

Notes

[1] **Kenya: Fall Armyworm Pest Management Decision Guide. Otipa M. *et al.***
[2] **Burundi : Pers comm. National Plant Protection Organisation**
[3] **Ghana: Ministry Poster**
[4] **Zambia: Pers comm. Ministry of Agriculture**
[5] **Mozambique: Ministry of Agriculture leaflet**
[6] **Rwanda: Factsheet for farmers**

The Pest Management Decision Guide for Kenya was produced under the auspices of CABI's Plantwise programme. However, it is not clear that all the recommendations are appropriate, and the list is likely to be revised. The US Agency for International Development (USAID) and CIMMYT are holding a workshop in Uganda in mid-September to develop a set of technical recommendations, which countries can draw on and package for their own situations.

Table 24 shows the control methods that farmers reported having used in Ghana and Zambia during our surveys. Nearly two-thirds of farmers who had attempted control reported using pesticides, and nearly a third had tried hand-picking. No other methods had been tried by more than 10% of farmers.

Table 24. Use of FAW control methods reported by farmers in Ghana and Zambia, and how successful they were

	Using the method		How successful? (% farmers)		
Control method	**No. of farmers**	**%**	**Extremely**	**Somewhat**	**Not**
application of pesticide	229	63	27	57	16
hand-picking egg masses and caterpillars	105	29	5	72	23
frequent weeding	37	10	24	54	22
improve soil fertility	22	6	27	55	18
ash on larvae	19	5	16	74	11
early planting	15	4	27	67	7
remove crop residues	14	4	14	86	0
uproot and burn infected plants	14	4	7	79	14
detergent application	14	4	21	71	7
do nothing	16	4	0	6	94
crop rotation	7	2	14	57	29
replanting	9	2	0	78	22
neem-based products	4	1	0	75	25
intercrop with non-host non-legumes	3	1	0	67	33
intercrop with non-host legumes	3	1	0	67	33
push-pull	2	1	0	0	100
biocontrol options	1	0	100	0	0
plant-resistant varieties	0				
trap cropping	0				

Table 25 shows the AI recommended for FAW control in a number of African countries. It also shows the AI registered for FAW control in two South American countries.

Table 25. Pesticides registered for FAW in South America and recommended for FAW in Africa

			Registered		Recommended								
Active Ingredient	**[1]Mode of Action Category**	**[2]WHO Class**	**Brazil**	**Peru**	**Kenya**	**Ethiopia**	**Malawi**	**Burundi**	**Rwanda**	**Ghana**	**Zambia**	**Mozambique**	**Uganda**
Abamectin	6	n	Y									Y	
Acephate	1B	2	Y	Y	Y			Y				Y	
Acetamiprid	4A	n	Y							Y			
Alpha-cypermethrin	3A	2	Y	Y	Y								
Azadiractin	UN	n	Y	Y	Y					Y			
Bacillus thuringiensis	11A	3	Y	Y	Y					Y		Y	
Beauvaria bassiana	-	n										Y	
Beta-cyfluthrin	3A	1b	Y	Y								Y	
Beta-cypermethrin	3A	n	Y	Y									
Bifenthrin	3A	2	Y	Y								Y	
Carbaryl	1A	2		Y									
Carbofuran	1A	1b	Y										
Carbosulfan	1A	2	Y		Y								
Chlorantraniliprole	28	U	Y	Y	Y							Y	
Chlorfenapyr	13	2	Y	Y									
Chlorfluazuron	15	U	Y	Y									
Chlorpyrifos	1B	2	Y	Y		Y	Y	Y		Y	Y	Y	
Chromafenozide	18	n	Y										
Cyantraniliprole	28	n	Y									Y	
Cyfluthrin	3A	1b		Y									
Cypermethrin	3A	2	Y	Y			Y	Y	Y	Y	Y	Y	Y
Deltamethrin	3A	2	Y	Y						Y	Y	Y	
Diazinon	1B	2		Y		Y							
Diflubenzuron	15	3	Y	Y								Y	
Dimethoate	1B	2				Y				Y			
Emamectin benzoate	6	n		Y						Y		Y	
Esfenvalerate	3A	2	Y										
Ethyl palmitate	-	n								Y			
Etofenprox	3A	U	Y										
Fenitrothion	1B	2	Y	Y							Y		
Fenpropathrin	3A	2	Y										
Flubendiamide	28	n	Y	Y	Y							Y	
Gamma- cyhalothrin	3A	n	Y	Y									
Imidacloprid	4A	2	Y	Y						Y	Y	Y	
Indoxacarb	22A	2	Y	Y	Y					Y		Y	
Lambda- cyhalothrin	3A	2	Y	Y	Y					Y	Y	Y	Y
Lufenuron	15	n	Y	Y	Y							Y	
Malathion	1B	3	Y	Y		Y					Y		
Maltodextrin	-	n								Y			
Methamidophos	1B	1b		Y									
Methomyl	1A	1b	Y	Y									
Methoxyfenozide	18	U	Y	Y									
Methyl parathion	1B	1a										Y	
Novaluron	15	U	Y	Y									
Permethrin	3A	2	Y	Y							Y		
Phenthoate	1B	2		Y									
Profenofos	1B	2		Y					Y			Y	Y
Pyrethrum	3A	n							Y				
Spinetoram	5	U	Y	Y									
Spinosad	5	3	Y	Y	Y							Y	
Sulfur	UN	3	Y										
Tebufenozide	18	U	Y	Y									
Teflubenzuron	15	U	Y	Y									
Thiacloprid	4A	2		Y									
Thiamethoxam	4A	n		Y					Y			Y	Y
Thiodicarb	1A	2	Y	Y									
Trichlorfon	1B	2		Y									
Triflumuron	15	U	Y									Y	
Zeta-cypermethrin	3A	1b	Y	Y								Y	

Notes

[1]Mode of Action Category. From Insecticide Resistance Action Committee www.irac-online.org/modes-of-action/

[2]WHO Class. From www.who.int/ipcs/publications/pesticides_hazard/en/ (1a – Extremely hazardous; 1b – Highly hazardous; 2 – Moderately hazardous; 3 – Slightly Hazardous; U – Unlikely to present acute hazard; n – not listed, as list published in 2009)

The following observations are made.

- Most of the pesticides being recommended in Africa have already been registered for uses other than for FAW, and have been given emergency registration for FAW.
- Of the pesticides being recommended in Africa, the following are not registered in either Brazil or Peru:
- *Beauvaria bassiana*: This is a fungal biopesticide so there is no risk to health; it is reported to affect FAW in South America, but it is not known if the product recommended in Mozambique has been tested against FAW
- Dimethoate: An organophosphate that is likely to be effective
- Ethyl palmitate: A plant extract that is reported to have some acaricidal properties (Bu *et al.* 2012), but no reports have been found of its efficacy against FAW. It is anecdotally reported to be effective in Ghana
- Maltodextrin: A plant-derived starch that is registered for control of some insects in Europe. Its mode of action is physical, blocking the insect's spiracles. It is anecdotally reported to be effective in Ghana
- Methyl parathion: An extremely hazardous chemical that is registered for control of FAW under specific circumstances in the US where strict safety measures can be applied
- Pyrethrum: A plant extract with good insecticidal properties
- Although a number of Class 1 insecticides are registered for use against FAW in the Americas, in Africa it is highly inadvisable to recommend or use Class 1 pesticides under any circumstances. Of the countries listed, only Mozambique has recommended any Class 1 chemicals, and once alerted to this, are revising the recommendation.
- Several of the most widely recommended insecticides in Africa are Class 2 – moderately hazardous.

4.5.2 Summary and recommendations on control methods

Table 26 summarises the authors' recommendations in relation to control for smallholder farmers, commercial farmers and government. Recommendations are made on the basis of available evidence and technologies, and, where good evidence is not available, on the basis of reasonable assumptions. As the results of research become available, recommendations will need to change.

Table 26. Recommendations on control (focus on maize)

Method	Availability in Africa	Recommendations for smallholders	Recommendations for commercial farms	Recommendations for government
Monitoring: scouting, pheromone traps and action thresholds	• Field scouting protocols available from Latin America; action thresholds need defining. Pheromone traps/lures commercially available in Africa; best trap/lure needs determining, and significance of trap catches.	• Scout in farm at least weekly once plants have emerged • In each field record percentage of 100 plants with FAW damage • Consider treatment if more than 20% whorls damaged and small larvae still present.	• Establish monitoring system based on scouting for damage and FAW eggs and caterpillars • Score 20 plants at each of 5 random points in each field • Try pheromone traps; keep good records to link trap catches to scouting data and subsequent yield • Estimate an action threshold based on expected value of crop, expected loss if untreated, cost of treatment.	• Commence research to refine action thresholds for different situations (crop, growth stage) • Establish national monitoring system; extensionists or others to conduct regular field scouting and run a pheromone trap; data should be sent by app to central database
Chemical control	• Many are recommended but are not always available – especially lower risk, more expensive products. Most products are foliar sprays; a few seed treatment and other formulations available.	• Use pesticides as a last resort • Use pesticides recommended by the government • Select lower risk pesticides if affordable • Avoid spraying in the first 2-3 weeks of the crop • Follow all advice on safety, dilution, etc on the product label • Buy only from registered pesticide dealers	• If heavy infestation expected, consider using seed treatment • Do not spray as a preventative measure • Use pesticides recommended by the government, especially those with lower impact on natural enemies • Avoid spraying in the first 2-3 weeks of the crop • Follow all manufacturer's instructions • Spray in early morning or late	• Establish standard pesticide efficacy testing procedure • Monitor for pesticide resistance to most popular active ingredients • Publish list of pesticides registered for fall armyworm (full or temporary registration) • Develop a resistance management strategy

Method	Availability in Africa	Recommendations for smallholders	Recommendations for commercial farms	Recommendations for government
		• Spray in early morning or late afternoon • Spray into the whorl • Only spray affected plants	afternoon • Spray into the whorl if using knapsack sprayers • Don't use pesticides with same mode of action twice in a row	
Biopesticides: Microbials. Bt, *Beauvaria*, SfMNPV	Bt products are available in many countries; *Beauvaria* less widely available; SfMNPV not yet sold in Africa.	• Use registered Bt products instead of pesticides if possible	• Use registered microbial biopesticides if recommended by government and effective against caterpillars. (In most cases this will be Bt formulations).	• Accept supporting data from other countries for emergency/temporary registration. • Do not register products without supporting data. • Provide temporary registration for products already registered for FAW use in Americas (eg SfMNPV)
Macrobials for inundative release	Some macrobials are available in Africa for uses other than for FAW. None available specifically for FAW.	• Can't be recommended yet.	• Can't be recommended yet.	• Work with private sector to facilitate product development
Classical biological control	Not available yet. Candidate agents have been identified.	• Not available	• Not available	• Work with international agencies to test candidate agents
Botanicals	Neem products are commonly available; some pyrethrum products. Various other imported and local products available in some countries; mostly	• Use neem products recommended by government instead of pesticides, if possible • If no alternative, consider using home-made pesticide made from	• Consider using neem instead of chemicals; conduct own trials. • Assess other products if available.	• Accept supporting data from other countries for emergency/temporary registration. • Do not register products without supporting data.

Method	Availability in Africa	Recommendations for smallholders	Recommendations for commercial farms	Recommendations for government
	unproven.	neem or other plants known to have pesticidal effect.		• Test efficacy of locally manufactured and homemade botanical pesticides.
Planting material	Variation in FAW susceptibility available in germplasm collections. Bt Maize available.	• If using self-saved seed, save seed from plants that are least damaged • Use varieties if/when recommended as providing some resistance/tolerance, including short duration varieties	• Ascertain from seed providers level of susceptibility of preferred and other available varieties and use less susceptible ones. • Use short duration varieties where appropriate	• Facilitate multiplication of any current varieties showing resistance • Work with international partners to screen available germplasm • Incorporate FAW resistance in breeding programmes. • Assess/monitor susceptibility of Bt maize lines in country
Hand-picking	Already commonly used in Africa	• Check crop twice a week. • If feasible, use immediately first eggs/larvae seen.	• Not suitable.	• Conduct public awareness on the pest, how to spot it, and how to kill it
Other agronomic practices	• Many available but largely untested.	• Intercrop maize with non-host (eg cassava) or less susceptible crops • Plant promptly • Consider planting extra seeds so that damaged ones can be removed 2-3 weeks later, leaving good stand. • Put soil/ash/sand mixture into funnel of attacked plants • Consider short term diversification of	• If planting over a large area, synchronise planting as far as possible • Plant promptly	• Research on options listed for smallholders

Method	Availability in Africa	Recommendations for smallholders	Recommendations for commercial farms	Recommendations for government
		crops, to non-host plants if feasible		
Mass trapping	• Pheromones and traps are commercially available. Little evidence that mass trapping is economically viable.	• Not worth trying yet. Seeing dead moths in a trap does not necessarily mean less damage.	• Probably not worth trying yet.	• Do not promote as control method yet. Assess data from research on pheromones for monitoring to decide whether trials on mass trapping merited.
Sterile insect technique	• Not available for FAW anywhere yet	• Not applicable	• Not applicable	• Low priority as would take years to develop, and successful outcome unlikely.
Integrated pest management	• Components available (monitoring, control options) but basis for integrating components not. • Integration of FAW control with other pest control not available	• Visit and observe fields regularly for presence/damage due to FAW and other pests. • Use non-chemical methods wherever possible for all pests	• Maintain good records of agronomy, monitoring, interventions, yield etc and review regularly	• Include FAW in maize IPM research programmes • Consider subsidies or other mechanisms for encouraging use of lower-risk control products

Section 5: Information resources

Table 27: Selected FAW information resouces

Information	Source	Provider	Notes
General pest biology / ecology / utilising current pest management knowledge	Invasive Species Compendium	CABI	Expert-written and peer-reviewed datasheet. The ISC also includes 156 bibliographic records relating to FAW
	Plantwise Knowledge Bank	CABI	Technology factsheets and identification photosheets
	CIMMYT, MaizeDoctor	CIMMYT	Factsheet introducing simple, stepwise method for identifying maize production problems and providing possible solutions
	EPPO Global Database	EPPO	Factsheet maintained by the Secretariat of the European and Mediterranean Plant Protection Organisation (EPPO)
	Fall Armyworm as a pest of field corn	Penn State College of Agri Sciences	PennState College of Agricultural Sciences Extension Factsheet
Current awareness and up-to-date information on spread of pest	CABI Invasives Spodoptera frugiperda curated twitter list	CABI	Current awareness of news, shared content and activities concerning fall armyworm as shared on Twitter
	PestLens	USDA-APHIS	PestLens collects and distributes new information on exotic plant pests and provides a web-based platform for documenting safeguarding decisions and resulting actions. It is used as an early-warning system supported by USDA's Animal and Plant Health Inspection Service (APHIS) to protect U.S. agriculture and natural resources against exotic plant pests.
	PestNet Listserve	PestNet	PestNet is an email network that helps people worldwide that obtains rapid advice and information on crop protection, including the identification and management of

			plant pests.
	Emergency Transboundary Outbreak Pest (ETOP) Situation Updates, monthly	USAID	Monthly updates on Emergency Transboundary Outbreak Pests (ETOP), including latest distribution records and news on surveillance and mitigation activities.
	FAO News	FAO	News Service of FAO
	FEWSnet	USAID	Famine Early Warning Systems Network is a leading provider of early warning and analysis on food insecurity. Created by USAID in 1985 to help decision-makers plan for humanitarian crises, FEWS NET provides evidence-based analysis on some 34 countries. Implementing team members include NASA, NOAA, USDA, and USGS, along with Chemonics International Inc. and Kimetrica
	IITA News	IITA	News Service of the CGIAR centre, International Institute of Tropical Agriculture (IITA).
	CIMMYT	CIMMYT	News service of the CGIAR centre, International Maize and Wheat Improvement Center (Centro Internacional de Mejoramiento de Maíz y Trigo, CIMMYT)
	IAPPS News	IAPPS	News Service of the International Association of Plant Protection Sciences (IAAPS News)
	National news websites	News Ghana; Ethiopian News Agency; The Southern Times; BBCnews	National and regional news websites are vital to keep updated on spread of disease. These may not always be accurate, but they are important to consider
	Armyworm network	Lancaster University	Resource provides up to date information on both the endemic African armyworm (*Spodoptera exempta*) and the new invasive FAW (*Spodoptera frugiperda*) - both of which are important pests of staple crops and pasture grasses in sub-Saharan Africa. Resources available on this website include the latest armyworm forecasts, press reports of armyworm outbreaks, photos, videos, publications, and lots of useful

			information on the biology, ecology and control of these important African crop pests
Official reporting services	IPPC	IPPC	IPPC Official Pest Reports
	EPPO Reporting Service	EPPO	The EPPO Reporting Service is a monthly information report on events of phytosanitary concern. It focuses on new geographical records, new host plants, new pests (including invasive alien plants), pests to be added to the EPPO Alert List, detection and identification methods etc
	EPPO Pest Alerts via Scoop.it	EPPO	A news aggregator site for EPPO pest alerts curated by Anne-Sophie Roy of EPPO.
Research and identification	CAB Direct	CABI	Search engine containing 4,795 records on FAW dated between 1915 and 2017
	PubMed	US National Library of Medicine National Institutes of Health	Search engine containing 2,372 records on FAW dated between 1968 and 2017
	Bugwood	Center for Invasive Species and Ecosystem Health, University of Georgia	Bugwood Image Database System (images.bugwood.org), Center for Invasive Species and Ecosystem Health, University of Georgia, with 463 images
	Diagnostic protocol for Spodoptera sp.	EPPO, John Wiley & Sons, Inc	This protocol provides guidance for the identification of Spodoptera species
	Armyworm identification keys	Center for Systematic Entomology,	A key to *Spodoptera frugiperda, S. exigua, S. latifascia, S. ornithogalli, S. dolichos, S. sunia and S. eridania* with color illustrations of rare and typical forms is presented. Potential problems in identifying Spodoptera species are discussed.

		Gainesville,	
Management and control	Homologa	Homologa	Homologa™ is a database containing registration information of agrochemical products for more than 60 countries, including information about active ingredients, companies, approved crops, maximum dose rates, Pre-Harvest Interval (PHI), risk and safety phrases and approval status of agrochemicals in the EU.
	Koppert Side effects database	Koppert B.V.	Presents data on indirect effects of pesticides (based on a once-only application of the pesticide at the authorised dose) such as killing natural enemies or pollinators. Can be used as a guideline for the use of chemical pesticides in combination with biological crop protection and/or natural pollination.
	Spodoptera frugiperda v2; In: ensembl.lepbase	Lepbase	Lepbase: the Lepidopteran genome database
	SPODOBASE	INRA	An integrated database for the genomics of the Lepidoptera Spodoptera frugiperda
	HarvestChoice	HarvestChoice	Host distribution data for use in modelling spread of FAW HarvestChoice is cultivating a novel hub of geographically tagged datasets organised into a matrix of 10km x 10km grid cells spanning sub-Saharan African. This data-rich platform allows more fine-grained visualisation of the enormous mix of farming, cultural, and socio - economic conditions that exist across Africa. Specific User License needed and aimed at promoting non-commercial use of the data

Section 6. Conclusions

6.1 Conclusions – FAW in Africa and its broader implications

Evidence suggests that potential annual economic damage to maize – without control – could be in the range of US$,481m – US$6,187m in 12 maize-growing countries. Damage to other crops, such as sorghum, whilst lower at $827 million (figure taken from the CABI evidence note, published April 2017) taken together will have significant impacts on household food security across Africa, even if damage only occurs at the lower end of expectations. We do not yet understand enough about FAW behaviour in Africa, in terms of its interaction with other crops, pests and natural predators to predict larvae populations and their damage. These, and other factors such as caterpillar cannibalism, may result in deviation from the upper levels of forecast impact in maize. Such factors need to be tested with further research and ground-truthing from activities such as field scouting, which will help to confirm the accuracy or otherwise of the forecasts made in this study. However, this does not change the reality that FAW is here to stay in Africa: environmental conditions are generally suitable to its ongoing reproduction.

We expect FAW to spread to the limits of its viable African habitat within the next few cropping seasons. This may include northern Africa and Madagascar, though, respectively, the barriers caused by desert and the latter's predominant south-easterly winds may act as a brake. Our models agree on forecasts of high predicted risk in areas of environmental suitability. We expect more reports of FAW in western Africa, Central African Republic, Sudan, Angola and Nigeria.

Better research insights in the following areas will help us to better understand FAW's behaviour and the risks it poses for Africa in coming years. A comprehensive range of actions for the short, medium and long term was identified at an international meeting organised by AGRA, FAO and CIMMYT in Nairobi in April 2017. This has subsequently been developed by FAO and partners into a framework containing four components:

1. FAW management, including early warning and control methods
2. Assessment of the impact of the pest
3. Communication, information sharing and awareness raising
4. Coordination. The Nairobi meeting agreed that FAO should be responsible for overall coordination.

FAO will be publishing the final version of the framework in September 2017, which will provide a guide for development of projects and programmes by the various stakeholders in the areas of their mandates (see Briefing Note on FAO Actions on Fall Armyworm in Africa, FAO 1 September 2017). We consider these elements, contained within the framework deliberations, to be of particular importance:

- Assessment of microbial biocontrol options, to determine if agents would be allowed in a country based on the bio-geography of the organism/agent

- Research into, and identification and development of, prioritised candidate biological pesticides for FAW and others, initially through literature reviews

- Test candidate biopesticides through lab bioassays, measuring for efficacy against FAW; utilise data to support (or decline) registration

- Execute biopesticide risk assessments at regional level, with an expectation of accelerated national legislative approval (including for import permits of macro-organisms)

- Subsidy schemes (or donor support) considered for biologically-based biopesticides and/or biocontrol-rearing factories (eg temporary tax breaks) to reduce cost of market development and entry; and/or farmer input supply subsidy programmes (eg FISP, Zambia)

- Conducive policy frameworks, promoting IPM-led approaches (and which minimise unsustainable purchase of chemical pesticides)

- Regional adoption of harmonised pesticide and biopesticide registration procedures to reduce repeat costs for manufacturers in introducing new and effective, specific-use or lower-risk narrow spectrum products.

Specifically, this report has identified clustered areas of research which would assist future impacts of FAW:

FAW biology, behaviour, distribution

- Impact of density-dependent mortality of FAW caterpillars (cannibalism) on FAW population and damage levels

- Trigger mechanisms for dispersal and migration of the corn and rice strains

- Assess feeding preferences of either strain

- Impacts on other crops

- Distribution status in Africa:

- Testing forecast models via ground-based observations in multiple countries, to reduce risk of over-extrapolation from Ghana/Zambia to Africa-wide

- FAW relationship with other pests and natural predators over time

Impacts

- Detailed examination of yield loss on range of crops and across AEZs

- Test reasons for differences in predicted impacts between AEZs
- Societal impact at farm level, & beyond
- Impacts on household food security

Control methods

- Understanding differences in control options for each FAW strain
- Agronomic practices: impact of growing other crops on FAW population
- Comparative impact and cost-benefit analyses of control and monitoring options, for example, pheromone traps, seed treatments, use of pest-resistant varieties, push-pull, botanicals, SfMNPV and other biopesticides, etc
- Action thresholds for small-scale and larger farmers: to treat or not treat, ie balancing costs of losses versus cost of control

More immediately, what is required is national coordination (as recognised within the FAO stakeholder framework), to ensure consistent messaging to farmers. Advice may need to include avoidance of spraying early on, if at all possible, to allow natural enemies to build up. Potentially of relevance, though perhaps unattractive for farmers because of its cost implications, is for maize growers who expect an early infestation to 'overplant' ie to plant more seeds than necessary or normal, then to thin out later, removing the FAW-damaged plants (van Huis 1988). This could also help to avoid early spraying. Pilot studies to evaluate this strategy would be worthwhile.

It is important to encourage farmers to maintain plant diversity on the farm – for example by intercropping – since this should encourage natural enemies.

- Monitor susceptible crops at least weekly, with the aim of detecting egg masses and/or small larvae (<0.5 cm). Large-scale farms could consider using pheromone traps for monitoring twice weekly but visual inspection is also advised.
- On detecting FAW or early damage (windowing of leaves) consider treatment when suggested action thresholds are reached (eg 20% of whorls damaged in plants <40 days on small-scale farms; 10% on plants 40–60 days post-planting – noting that other threshold levels have been suggested):
- Small farms, depending on resource availability: hand-picking; placing sand/soil mixed with ash/lime into the whorl; pesticide application at dawn/dusk directly into the funnel
- Large farms: pesticide application in affected fields at dawn/dusk
- Pesticides: use WHO Class 3 or U if possible (though lower-risk products tend to be more expensive), from a nationally recommended list. Use personal protective equipment and follow manufacturer's instructions

- After treatment, continue monitoring and consider further treatment if more young larvae appear.

In the immediate term, it is suggested that national authorities undertake the steps set out below as far as possible; many have begun to do so.

- Promote awareness of FAW, its identification, damage and control, particularly integrated pest management

- In consultation with agro-input suppliers, prepare and communicate a list of recommended, regulated pesticides and biopesticides. The pesticides should be available, and preferably already registered for the crop in which they are to be used, and/or for use on other caterpillars. Pesticides registered/recommended for FAW control in the Americas could be selected, but WHO Class 1a or 1b pesticides should never be recommended (recommendations in the US are for very specific uses)

- Provide emergency/temporary registration for the recommended pesticides and microbial biopesticides. Registrants should provide supporting data from the Americas within a specified period. The International Code of Conduct for Pesticide Management provides detailed guidance. Regulators should adopt protocols and procedures that encourage the registration of lower-risk pest control products

- Arrange for laboratory efficacy tests of recommended pesticides to be conducted by authorised national laboratories

- Regularly review recommendations (eg avoid treating FAW generations with the same mode-of-action pesticides) and publicise changes promptly and widely, simultaneously monitoring FAW populations for resistance

- Assess preferred crop varieties for resistance or tolerance to FAW

Consider short-term subsidies for small-scale farmers – for example to reduce prices for lower- risk products

In the longer term, experiences with FAW in Africa will provide lessons on how other invasives need to be dealt with on the continent. Also, how other continents like Asia should prepare for FAW through the establishment of early detection and rapid response networks, potentially prioritising them around major transport hubs, needs consideration from regional stakeholders.

It is to be hoped that stakeholders will be able to resource an effective response to FAW. In Africa, different countries have responded to FAW in different ways, using many different agencies and departments. International cooperation, in terms of sharing of information, has happened but to what extent this has been coordinated as opposed to serendipitous is open to interpretation. Whilst responsibility for decisions regarding how (or if) to manage a particular invasive species must remain with a country’s government, within the constraints of its own finances and priorities, FAW’s demonstration of how quickly an invasive problem can jump borders emphasises to us the need for a cross-sectoral and regional approach to invasive species, which is currently either absent or under-performing. FAW is just one invasive amongst many which collectively are causing poverty, yield loss, health impacts in people and animals, displacement and conflict (see Annex 1). Coping with FAW on its own will not be sufficient to deal with the bigger problem that invasives annually cause – causing more than US$1.4 trillion damage each year (Pimentel *et al*. 2000). Dealing with this problem therefore requires better joined-up thinking and actions. It is questionable whether invasive species are being considered seriously enough in terms of their threat to poor rural households, due to a lack of coordination, know-how, or awareness amongst stakeholders. In particular, at a regional level, there needs to be political will to approve and implement known control solutions to the problems posed by major invasives pests.

If biological invasions could be managed across sectors (including not only agriculture and the environment, but health, trade and tourism as well) a much-improved chance to improve rural livelihoods would exist. This will require a number of coordinated procedural interventions:

- Making information and data available: such as, for example, confirmed and reported distribution records, potentially utilising an EMPRES-type system of mapped and tracked invasives; crop damage forecasts; identification and diagnostic apps or tools for field-use; and shared risk assessment and efficacy data of control methods, to enable more rapid approval of product registrations. This should mean that it not only becomes possible to track biological invasion distributions and monitor the scale and impact of best practice implementation on the ground, but that those most affected by invasive outbreaks are enabled to take preventative action, and know which control measures work best.

- Facilitating cross-sectoral partnerships – for example, between trade, environmental and plant health groups – so that a collaborative group of concerned stakeholders can act or react quickly to mounting crises caused by biological invasions. In the long term, these partnerships will enable better communication within the national/regional system.

- Building capacity at national and regional level to publicise, to train and to deliver best practice solutions – particularly IPM approaches – so that control methods are sustainable, affordable, accessible, and used rationally.

- Facilitating the adoption of best practices at scale, so that participatory large-scale implementation plans are developed and validated to increase local production of a tested best practice (for example, support for stations for mass rearing of approved biocontrol agents).

Ideally, extension systems need to be able to undertake systematic surveillance, comprising a mix of general knowledge gathering from multiple sources (eg plant doctors) and specific surveillance coordinated by the relevant NPPO, potentially including scouting for forecast/non-forecast invasive species which have been prior-modelled as a risk to countries in a region. Rapid reporting via information and communication technology, crowd-sourcing etc, may support such a process, though this must be balanced against the risk of overwhelming NPPOs and a country's principal extension agency. Establishment or strengthening of adequately coordinated national plant health systems, drawing upon a consortium of partners which build extension capacity collectively, may offer part of a solution.

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Annex 1 Considerations – Beyond FAW

Lessons from the African FAW outbreak

This report has focused on reporting the evidence of FAW's distribution in Africa, as well as the experiences and control approaches taken in the Americas. We have reported how these approaches might be transferable, and we have discussed issues such as the need for particular aspects of research to understand fully the future impact of FAW in Africa, and beyond. What does the African experience of FAW tells us about our preparedness for managing economically-damaging invasive species in future?

The rapidity of FAW's onset, spread and impact caught the headlines and brought many agencies together to develop emergency response plans, working together to coordinate and leverage their activities. If maintained, this will certainly be beneficial. However, FAW is just one of many invasive species having a fundamental impact on livelihoods and the health of ecosystems upon which smallholder farmers disproportionately depend. It is worth considering to what degree the FAW outbreak was an invasives disaster waiting to happen, simply because invasives management has not been treated sufficiently seriously so far.

Whilst the FAW situation may be rare – given FAW's mobility, specific impact on a key staple crop but polyphagous nature, and so forth – there are causes for concern which must be addressed. How do we prepare for the 'next' FAW entering Africa? What measures are required in Europe and Asia to minimise any entry of FAW there? How do we deal with other invasives (see below) that are already present in Africa (and beyond), given limited budgets and resources?

Beyond FAW: other invasives of concern in Africa

As a result of increased trade and travel more and more species are being moved within and between countries, and further afield to other continents. Many of these introduced species become established in their new environments to the detriment of biodiversity, crop and livestock production, human and animal health, water resources and economic development. These biological invasions are being exacerbated by increased disturbance and climate change.

Because these invasive species know no boundaries we need a regional approach in order to tackle them effectively – we cannot work in isolation, we need to work together to manage shared problems. To that end, CABI is developing a new regional programme to address the issue of shared invasive species, focusing on prevention, early detection and rapid response, and the development and implementation of best management practices – especially IPM.

Below are just some example of the many invasive crop pests, diseases and weeds that need to be tackled in Africa.

Invasive	Cause for concern	Current distribution	Countries at high risk
Maize lethal necrosis disease (MLND)	Much of the land areas of Uganda (88.1%), Tanzania (65.9%), Ethiopia (59.8%), Malawi (53.8%), Madagascar (45.1%), and Kenya (41.1%) are climatically suitable (Isabirye and Rwomushana 2016). In terms of proportional potential loss, Rwanda, Burundi, and Swaziland might lose their entire potential maize yield. In Kenya alone, losses by 2012 amounted to **US$52 million**. Current annual losses to smallholder farmers in eastern Africa are **US$339 million** (Pratt *et al.* 2017)	Ethiopia, Kenya, Tanzania, Rwanda, Uganda	Angola, Burundi, Cameroon, Central African Republic, Congo, Democratic Republic of Congo, Equatorial Guinea, Gabon, Madagascar, Malawi, Mozambique, South Africa, Swaziland
***Fusarium oxysporum* f. sp. *cubense* Tropical Race 4 (Panama disease TR 4**	The impact of the first Panama epidemic (Race 1 and 2) in the Americas in the 1950s was at least **US$2.3 billion** – it wiped out the Gros Michel varieties, which were replaced by the more resistant Cavendish varieties. In 1992, a new strain of the Fusarium wilt (TR 4) was discovered in Southeast Asia. Since then, tens of thousands of hectares of Cavendish plantations have been wiped out in China, Indonesia, Malaysia and the Philippines. The damage caused by this second outbreak has already surpassed **US$400 million.**	Mozambique	Most banana-producing countries in Africa
***Candidatus* Liberibacter asiaticus (CLas) (Citrus greening)**	Greening was first detected in Florida in 2005 and threatens to destroy Florida's citrus industry. Florida has lost about **US$7.8 billion** in revenue, 162,200 citrus acres and 7,513 jobs to citrus greening since 2007. Orange production dropped from 242 million to 104 million boxes in 2014.	Ethiopia – the vector, the Asian citrus psyllid – is now present in Kenya and Tanzania	Refer to Narouei-Khandan *et al.* 2015 for distribution maps
***Tuta absoluta* (Tomato leafminer)**	Crop losses can reach 100%. A total of 84.9% (3.7 million hectares) and 87.4% (133.7 million tonnes) of world tomato-cropped surface and world tomato. production, respectively, are now directly threatened and could be infested in the near future. In the worst case scenario, future invasions by *T.*	Algeria, Egypt, Ethiopia, Kenya, Libya, Morocco, Mozambique,	Refer to Tonnang *et al.* 2015 for distribution maps

Invasive	Cause for concern	Current distribution	Countries at high risk
	absoluta in the world would result in an increase of around US$240–420 million (based on the Spanish case, ie €100–150 per hectare) and US$487 million (based on the Argentinean case, ie US$175 per hectare) per year for pest management in tomato crops (see Garzia *et al*. 2012). This amounts to approximately US$500 million/year in additional management costs.	Niger, Nigeria, Senegal, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia	
Paracoccus marginatus (Papaya mealybug)	Papaya mealy bug is a devastating papaya pest in Asia, Africa, and North America, and also attacks more than 60 other crops, particularly horticultural species. In 2010, Ghana reported papaya yield losses of up to 65%, reducing plantations to 380 hectares, with 1,700 people in the sector losing their jobs. Introduction of natural enemies in India reduced potential losses in the first year by **US$309 million**, and **US$1 billion** over five years.	Benin, Ghana, Kenya, Malawi, Mozambique, Tanzania, Togo	Most of tropical Africa
Bactrocera dorsalis **(Oriental fruit fly)**	A major pest of avocado, banana, guava and mango. In California, USA, it has been estimated that the cost of not eradicating Oriental fruit fly would range from **US$44 to 176 million** in crop losses, additional pesticide use, and quarantine requirements. The cost for the eradication programme in northern Queensland (1995–1999) was **AUS$33 million**, but the estimated annual cost to control the pest, had it been left established, was estimated to be **AUS$7–8 million** (Cantrell *et al*. 2002). In Hawaii, annual losses in major fruit crops caused by *B. dorsalis* may exceed 13%, or **US$3 million** (Culliney 2002). Trade bans to Africa alone are causing around **US$2 billion** losses annually (FAO 2017).	Tropical Africa	Refer to Villiers *et al.* 2015 for distribution maps
Bactrocera zonata **(Peach fruit fly)**	It is one of the three most destructive flies in India, causing crop losses of 25% to 100% in peach, apricot, guava and figs. In Egypt, *B. zonata* causes an estimated **€190 million** damage annually. Current annual costs of damage in the Near East are estimated at **€320 million** (Soomro *et al*. 2017).	Egypt and Libya	Refer to Ni *et al.* 2012 for distribution maps Images: Russel IPM
Xanthomonas campestris **pv.**	The disease attacks all banana cultivars and can cause up to 100% yield losses. In Rwanda in 2009, the estimated area affected by BBW was 2,000	Burundi, Democratic	Banana-growing areas in Africa

Invasive	Cause for concern	Current distribution	Countries at high risk
musacearum **(Banana bacterial wilt) (BBW)**	hectares, equivalent to economic losses of **US$2.95 million**. Banana production losses caused by BBW were valued at **US$10.2 million** and **US$2.95 million** in Tanzania and Rwanda, respectively (Nkuba *et al*. 2015). In Uganda, without any control, losses were expected to reach **US$295** million annually, which equates to **US$200** per household (Kalyebara *et al*. 2006).	Republic of Congo, Ethiopia, Rwanda, Tanzania, Uganda	
Cassava brown streak virus (CBSV)	Cassava brown streak causes substantial root yield loss of up to 100%. Field trials in Tanzania showed that CBSV can decrease root weight in the most sensitive cultivars by up to 70% (Hillocks *et al*. 2001). In 2001, losses in Malawi alone were estimated to be **US$6 – 7 million** (Gondwe *et al*. 2002).	Burundi, Democratic Republic of Congo, Equatorial Guinea, Kenya, Rwanda, South Sudan, Tanzania, Uganda	Potential to spread throughout cassava-growing areas in Africa
Candidatus Phytoplasma palmae (Coconut lethal yellowing disease)	Coconut yellowing disease is known to cause up to 90% mortality. In Ghana 6,500 hectares have been devastated by the disease. An outbreak in Ivory Coast destroyed over 350 hectares of plantations, with a loss of 12,000 tonnes of copra/year, with a further 7,000 hectares under threat (Arocha-Rosete *et al*. 2014). Between 1994 and 2004 annual export losses in Mozambique were **US$3.36 to 7 million** (FAO, 2011).	Cameroon, Ghana, Ivory Coast, Kenya, Mozambique, Nigeria, Tanzania, Togo (Gurr *et al.* 2016)	Throughout tropical Africa
Striga asiatica **(Witch weed)**	A recent survey by Groote *et al*. (2008) suggests over 1 million hectares of maize (80% of the crop) is affected by *S. asiatica* in Malawi and over 250,000 hectares in Angola, with smaller areas in Zimbabwe, Zambia, Mozambique, Namibia and South Africa. Average losses of maize due to *S. asiatica* in Malawi were estimated at 28% in infested fields and 4.5% for the country as a whole (Kroschel *et al.* 1996). In Kenya the annual economic	Native to tropical Africa	Refer to Mohamed *et al.* 2006 for distribution maps

Invasive	Cause for concern	Current distribution	Countries at high risk
	loss is estimated to be **US$46 million** (Andersson and Halvarsson 2011).		
***Striga hermonthica* (Witch weed)**	Over 5 million hectares of crops – mainly sorghum, millet and maize – are affected in six countries of West Africa alone (Sauerborn 1991): possibly 10 million hectares in Africa as a whole. One plant of *S. hermonthica* per host plant is estimated to cause approximately 5% loss of yield (Parker and Riches 1993) and large infestations can cause total crop failure. Overall yield losses are estimated at 21% of all sorghum in northern Ghana, 10% of all cereals in Nigeria, 8% in Gambia and 6% in Benin (Sauerborn 1991). Witch weed costs billions of USD in reduced yields across Africa.	Senegal across to Ethiopia and south to South Africa (native to Ethiopia and Sudan)	Refer to Mohamed *et al.* 2006 for distribution maps
***Chromolaena odorata* (Siam weed)**	Siam weed threatens biodiversity by displacing native plant species, inducing allelopathy, altering soil properties, increasing shading, reducing grazing potential for wildlife and livestock, and increasing the intensity and frequency of fires in natural forested areas. It also has negative impacts on livelihoods, largely because of the loss of grazing and agricultural land. In Indonesia, *chromolaena* reduces yields of oil palm, rubber, coffee, forestry species, fruit orchards, rice paddies and tobacco, and has been noted to be a key driving factor behind field abandonment. Can reduce livestock carrying capacities from 6 hectares per large livestock unit to more than 15 hectares per unit.	Angola, Kenya, Mozambique, Swaziland, South Africa, Tanzania, Uganda and most of West and Central Africa.	Refer to Kriticos *et al.* 2005 for distribution maps
Cryptostegia grandiflora (Rubbervine)	In Australia, in 1990 *C. grandiflora* was estimated to occupy more than 30,000 km^2, 'being described as the single biggest threat to natural ecosystems in tropical Australia' (McFadyen and Harvey 1990). Dense infestations can reduce livestock carrying capacities by as much as 100%. The plant contains toxic glycosides which cause heart malfunction as well as stomach and intestinal disorders in both humans and animals. Economic losses to farmers in the north Queensland (Australia) beef industry alone, through increased management costs and reduced cattle-carrying capacities, have been put at **AUS$18 million annually** (Agriculture and Resource Management, 2001). Biological control has significantly reduced	Botswana, Ethiopia, Namibia, South Africa	Refer to Kriticos *et al.* 2003 for distribution maps

Invasive	Cause for concern	Current distribution	Countries at high risk
	impacts.		
Parthenium hysterophorus (Famine weed)	In field trials in Ethiopia, where fields were infested with high densities of famine weed, sorghum yields were reduced by 97%. In India, parthenium infestations have resulted in yield losses of up to 40% in several crops and up to a 90% reduction in pasture carrying capacities. Famine weed costs Australia's beef industry **AUS$16.5 million per year** and cropping industries several million dollars per year (Biosecurity Queensland 2007). Estimated losses in East Africa to small holder farmers are estimated to be **US$81,9 million/annum** (Pratt *et al*. 2017).	Botswana, Egypt, Ethiopia, Kenya, Mozambique, Rwanda, Swaziland, South Africa, Tanzania, Uganda, Zimbabwe	Refer to McConnachie et al. 2010 for distribution maps
Lantana camara (Lantana)	Lantana is toxic to livestock, causing pastoral losses that in Queensland, Australia, were in 1985 estimated at **AUS$7.7 million**, which included 1,500 animal deaths, reduced productivity, loss of pasture, and higher control costs. In India, lantana impact and control costs amount to almost **US$1 billion annually**. In South Africa, lantana poisoning accounts for about 25% of all reported cases of livestock poisoning by plants.	Throughout most of tropical Africa	Refer to Taylor *et al.* 2012 for distribution maps
Prosopis spp. (Mesquite)	In Ethiopia, *P. juliflora* has reduced understorey basal cover for perennial grasses from 68% to 2%, and has reduced the number of grass species from seven to two (Kebede and Coppock 2015). *P. juliflora* also has a dramatic negative impact on underground water resources. Other negative impacts include encroachment on paths, villages, homes, crop- and pasturelands, and injuries inflicted by the thorns. Infestations have contributed to the abandonment of agricultural land, and in some cases of homes and small villages as well. The pollen has been identified as a major allergen (Killian and McMichael 2004). In semi-arid parts of Africa, *P. juliflora* has depleted the natural resources on which many thousands of people depend, spawning conflict between communities over the diminishing resources.	Botswana, Djibouti, Ethiopia, Kenya, Malawi, Mozambique, Namibia, North African countries, Somalia, South Africa, Tanzania, Uganda	Majority of countries in Africa
***Opuntia stricta* (Erect prickly**	The small spines (known as glochids) on the fruit, when consumed by livestock, lodge in their gums, on their tongues or in their gastrointestinal	Eritrea, Ethiopia, Ghana, Kenya,	Semi-arid regions throughout Africa

Invasive	Cause for concern	Current distribution	Countries at high risk
pear)	tracts, causing bacterial infections, while the hard seeds may cause rumen impaction, which can be fatal, and which often leads to excessive, enforced culling of affected animals (Ueckert *et al.* 1990). People who consume the fruits develop diarrhoea and may suffer from serious infections caused by the glochids (Larsson 2004). In Kenya, *O. stricta* infestations have resulted in the abandonment of farmlands. In Kenya, annual economic losses of **US$500–1,000 per household** have been recorded.	Morocco, Namibia, Swaziland, South Africa, Tanzania, Tunisia, Uganda	
Eichhornia crassipes **(Water hyacinth)**	Across Africa costs due to water hyacinth may be as much as **US$100 million annually** (UNEP 2006). It is estimated that the flow of water in the Nile could be reduced by up to one-tenth due to increased losses from evapotranspiration by water hyacinth in Lake Victoria (Ndimele *et al*. 2011). In Lake Victoria, fish catch rates have decreased because water hyacinth mats blocked access to fishing grounds, delayed access to markets and increased costs in effort and material.	Water bodies across most of Africa	Water bodies across most of Africa
Tithonia **spp.**	In Nigeria, where it is displacing native vegetation in the wetlands of the Apete River, Eleyele Lake and Oba Dam near Ibadan, *T. diversifolia* is considered to be one of the most damaging of all invasive species (Borokini 2011). There, it is reported to be out-competing even the formidable invasive shrub *Chromolaena odorata* (L.) King and H.E. Robins (Asteraceae) (Olubode *et al*. 2011). Mexican sunflower has the ability to compete with agricultural crops (Illori *et al.* 2010) and is contributing to the local extinction of valued native species, including some important medicinal plants (Olubode and Muoghalu 2014). Infestations have reportedly led to the abandonment of some farms in the Copperbelt region of Zambia.	Angola, Botswana, Burundi, Cameroon, Central African Republic, Chad, Congo, Democratic Republic of Congo, Egypt, Eritrea, Kenya, Malawi, Mozambique, Namibia, Nigeria, Rwanda, Swaziland, South Africa, Tanzania,	Rapidly expanding range across most of tropical and sub-tropical Africa

Invasive	Cause for concern	Current distribution	Countries at high risk
		Uganda, Zambia	
Hyptis suaveolens	Regarded as one of the world's most noxious weeds. It is believed to be allelopathic, impeding the germination of other plant species, and as such it threatens natural succession processes (Padalia *et al*. 2014). It also physically competes for space and nutrients in grain crops and peanuts (Parsons and Cuthbertson 2001). Near Materi, Kenya, farmers are alarmed by the rapid rate at which it is spreading, and by the impacts it is having on crop and pasture production. Widely naturalised in the savannahs of northern Australia, it is there considered to pose the greatest threat to 'rangeland biodiversity'. It is also unpalatable to livestock and wildlife. In addition, it is becoming increasingly invasive in India, and is naturalised in Papua New Guinea and on several Pacific islands.	Ethiopia, Kenya, Malawi, Tanzania, Uganda, Zambia (probably also other countries)	Refer to Padalia *et al.* 2005 for distribution maps
***Mimosa pigra* (Giant sensitive plant)**	In the Tram Chim National Park, Vietnam, declining densities of native plant species in infested habitats are threatening the sarus crane (Triet and Dung 2001), which is listed as vulnerable. *M. pigra* thickets in Australia have been found to support fewer birds and lizards, less herbaceous vegetation, and fewer tree seedlings than native vegetation (Braithwaite *et al*. 1989). In Lochinvar National Park, Zambia, infestations have reduced bird diversity by almost 50% and bird abundance by more than 95% (Shanungu 2009). In Cambodia, farmers have ranked mimosa as the most significant problem affecting rice farming, 'ahead of rodents, other pests, and drought' (Chamroeun *et al*. 2002). *M. pigra* also hampers fishing activities, and blocks access to water bodies.	Ethiopia, Malawi, Mozambique, Rwanda, South Africa, Tanzania, Uganda, Zambia and a host of countries in West and Central Africa	Refer to Walden *et al.* 2004 for distribution maps
***Mimosa diplotricha* (Creeping sensitive plant)**	Dense stands may prevent or inhibit the movement of livestock and wildlife. In Nigeria, *M. diplotricha* densities have reached 630,000 plants per hectare, reducing cassava-root yields, 12 months after planting, by 80% (Alabi *et al*. 2001). The species readily invades orchards and rice paddies, reducing yields and increasing management costs (Waterhouse 1993). Invaded cattle ranches in the Markham Valley, Papua New Guinea, are spending up to US$130,000 annually on chemical control (Kuniata 1994). *M. diplotricha* is	Burundi, Cameroon, Cote d'Ivoire, Ethiopia, Ghana, Guinea, Mauritius, Malawi, Mozambique,	Most of tropical and sub-tropical Africa

Invasive	Cause for concern	Current distribution	Countries at high risk
	apparently also toxic to livestock. In Thailand, 22 swamp buffaloes died 18–36 hours after eating *M. diplotricha* (Tungtrakanpoung and Rhienpanish 1992). Trials in Queensland, Australia, have indicated its toxicity to sheep, and a report from Flores, Indonesia, suggests that it is also toxic to pigs (Parsons and Cuthbertson 1992).	Nigeria, Reunion, Rwanda, Tanzania, Togo, Uganda, Zimbabwe	
Acacia mearnsii **(Black wattle)**	By shading out plants of native species, and by shedding large quantities of litter, black wattle reduces plant diversity (Weber 2003), including grass communities, and reduces the carrying capacity of the land (Sanakaran and Suresh 2013). By fixing nitrogen, the species alters nutrient cycling, making soils unsuitable for some native plant species. In South Africa, problems associated with black wattle infestations include reduced stream flows, a heightened fire risk, increased erosion, destabilisation of riverbanks, loss of grazing, nitrogen pollution, impairment of recreational activities, and diminished aesthetic appeal (de Wit 2001). Losses in water runoff in South Africa, attributed to infestations of *A. mearnsii*, amount to an estimated 577 million m^3 of water annually (Versfeld *et al*. 1998). *A. mearnsii* is considered to be the 'most aggressive invader' of stream banks, forest margins and miombo woodlands above 1,600 metres above sea level in the mist belts of the eastern highlands of Zimbabwe. It has already invaded large tracts of land in the Nyanga and Chimanimani National Parks, and in the botanical gardens of La Rochelle and Vumba. Black wattle is also extremely invasive in India, having invaded shola forests and associated grasslands.	Algeria, Burundi, Ethiopia, Kenya, Mozambique, Morocco, Namibia, Rwanda, South Africa, Sudan, Swaziland, Uganda, Zimbabwe and possibly others – widely grown as an agro-forestry species	High-lying areas throughout eastern and southern Africa and possibly elsewhere

Annex 2 Methodology for FAW impact estimation

National yield loss methodology

The national yield loss (per unit time) for Ghana and Zambia was estimated from the general formula:

National yield loss (NYL) = Expected total gross production (TGP) * Proportion lost from FAW (PLFAW).....(1)

Total national economic loss is then estimated by factoring into this equation the current producer price/tonne:

National economic loss (NEL) = TGP * PLFAW * Producer price (PC)....(2)

As the FAW has been reported in sub-Saharan Africa since late 2016 (see earlier sections of this report), estimates were made for the last completed growing season in the two countries. In Zambia, the last completed growing season for maize ended in April. In Ghana, the growing seasons are staggered according to the AEZ. Approximately two-thirds of the respondents in Ghana stated that the last growing season took place in 2016, whilst the remaining third were currently growing their maize in 2017.

In the analysis, it was assumed that FAW losses were of a similar magnitude on smallholder and commercial maize plots, and that producer prices were similar between sectors. Costs of controls implemented in different areas of the two countries were not estimated nationally because of the variability in existing data and the potential difference in costs of inputs and labour; these costs are considered under the impacts at the household level.

The expected total maize production for each country was estimated by taking a three-year mean total production from FAOSTAT (FAOSTAT 2017) to provide a more balanced figure, considering Zambia's 2017 bumper crop season and Ghana's huge seed and fertiliser subsidy programme. The mean proportion lost as a result of FAW was assumed to vary across each country in relation to a number of variables: for example, the suitability of the climate, the crop variety grown and the length of time that the FAW had been present and invading. Thus, each country was divided by national AEZ and estimates of proportion lost were derived for each.

The procedure for estimating model (1) parameters is as follows:

- The proportion of national maize production for each AEZ was taken from literature sources and calculated using Harvest Choice maize production datasets. Modelled production values at a 10 km grid square resolution for 2005 were spatially processed and grouped at the AEZ level. These production values were then scaled to more recent values, maintaining the same proportions. Sources – Ghana: Amanor-Boadu 2012 and Harvest Choice 2015; Zambia: Harvest Choice 2015.

- The proportion of yield loss per AEZ was estimated from data collected from the household survey of male and female farmers. This was a questionnaire survey of smallholder farms conducted in July 2017, covering 156 households over nine regions of Ghana, and 355 households over 11 provinces of Zambia. 94% of the total grew maize. More information on the household survey methodology is found in the household section of the impact chapter. Information was obtained from each maize farmer about the proportion of maize lost due to FAW in the last completed growing season. The actual time of planting in each county depended on the start of the rains in each AEZ. In Ghana, the dates are extremely flexible and staggered across the year, whilst in Zambia the major planting efforts occurred between November 2016 and May 2017.
- Thus, the proportion of yield loss per household was derived using the following formula:

Total production in season expected without FAW* - Total actual production in season
Total production in season expected without FAW…..(3)

***Farmers were specifically asked about the losses due to FAW. Whilst we cannot be completely certain regarding accuracy with study participants' articulated responses, the training of the enumerators specifically asked them about losses directly attributable to the FAW in their field, and to disregard any other pests or diseases that usually caused yield losses.**

Producer prices were collected from each household and averaged across all AEZs for each country.

Analysis of area affected by FAW

Data on the area affected by FAW at each household was collected during the household survey (table 28). Answers were placed into five categories:

Table 28: impact categories in the household survey

1	<10%
2	10% – 40%
3	40% – 60%
4	60% – 90%
5	>90%

The individual estimates of proportion of yield loss per household were analysed using R software (R Core Team 2017). Differences in yield loss per household across AEZs and time FAW was first seen was analysed in a linear model per country. For the estimation of mean, low and high total yield losses for each AEZ, the data was grouped by frequency for each AEZ and the mean and the interquartile range (ie the lower (25%) and upper (75%) values of the frequency distribution classes) was calculated.

Methodology for continental estimates

The expected total maize production for each country was estimated by taking a three-year mean total production from FAOSTAT (FAOSTAT 2017).

The proportion of maize lost as a result of FAW was estimated using the pooled data on this from Ghana and Zambia. The proportion of maize lost was, as for Ghana and Zambia, assumed to vary across each country in relation to a number of variables (suitability of the climate, the crop variety grown etc), as this is likely to affect the proportion of maize lost. To allow the estimates from Ghana and Zambia to be extrapolated to other parts of Africa, the data from these two countries was split, this time by Africa-wide AEZs – the latter were taken from Harvest Choice (2014) (see Annex 3). The proportion of maize lost (lower and upper) were then estimated for each Africa-wide AEZ represented in these two countries, and were then combined. Following this, the presence of the Africa-wide AEZ in each of the other 10 countries, together with the amount of maize grown in each AEZ per country, was taken from Harvest Choice (2005). This information was then combined with the yield loss proportion to estimate yield and economic loss totals for each AEZ in each country.

Producer prices for each country were taken from FAOSTAT (2017); where this information was not available for a country, the average of the other countries was used.

The Africa-wide AEZ identified in Ghana and Zambia are listed in Table 29, together with the lower and upper proportion of yield loss; these figures are the same for the two countries as the data was pooled. The analysis indicates that three zones are particularly susceptible to FAW attack: humid – tropics – warm, semiarid – tropics – warm, and sub-humid – tropics – warm. Only the 'all zones' figures were used in the estimations.

Table 29. Africa-wide AEZs present in Ghana and Zambia

Africa-wide AEZs	Ghana		Zambia	
	Proportion yield loss (lower)	Proportion yield loss (upper)	Proportion yield loss (lower)	Proportion yield loss (upper)
Humid – tropics - warm	0.25	0.60	0.25	0.60
Semiarid – tropics - cool	0.20	0.48	0.20	0.48
Semiarid – tropics - warm	0.25	0.60	0.25	0.60
Sub-humid – tropics - cool	0.14	0.40	0.14	0.40
Sub-humid – tropics - warm	0.25	0.60	0.25	0.60
All zones	0.23	0.57	0.23	0.57

Although these five AEZs represent the major growing areas in all of the 10 additional countries, some maize is grown in other AEZs in five of the countries, and thus is not included here (because these AEZs were not represented in Ghana and Zambia); however, in these five countries, over 80% of maize was represented.

Household survey methodology

Household surveys were conducted in July 2017, in both Ghana and Zambia. These were useful not only to understand FAW's potential national- and continental-level effects on food security, but also to understand how it affects the household. The questionnaire was designed and developed by CABI based on previous household impact assessments in

Africa. The survey concentrated on many different aspects: screening questions, household composition and farming activities, FAW control practices, FAW impacts, information resources, external shocks and access to credit. Some elements of pest scouting were included in the household survey activities, but only if the field was within a ten-minute walk from the interview site (due to observed FAW presence in the field being a secondary objective to its impact analysis). After a first round of feedback from external collaborators at the FAO (headquarters and regional offices), the final version was developed and coded for an open source Android Application (Open Data Kit). This app enables data to be collected by digital means. 24 tablets were then used by the enumerators to enter data collected during the interviews, and sent via data packages to a central data platform (https://ona.io/). The survey was organised through CABI's regional offices in Accra, Ghana, and Lusaka, Zambia, and conducted in conjunction with Ghana's Plant Protection and Regulation Services Directorate (PPRSD), and the Zambian Agricultural Research Institute (ZARI). In total, 12 PPRSD officers and 12 officers from ZARI participated in the training given by CABI staff in Accra and Lusaka. In Ghana, each region was divided into four blocks, with the exception of the Northern Region and the Brong Ahafo Region, which were divided into eight blocks. Within each block, all the districts were listed and three were selected randomly. In Zambia, 21 districts were surveyed in 11 different provinces across the country.

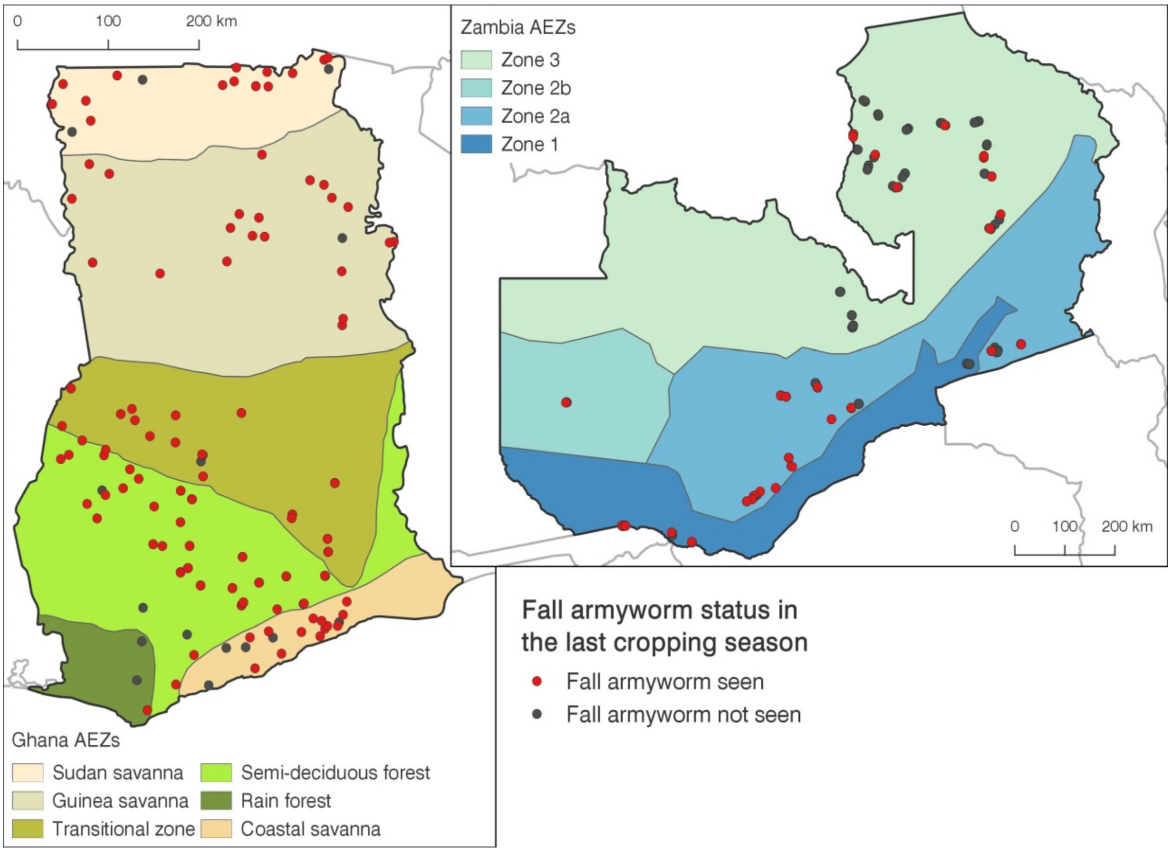

Figure 12. The distribution of survey farm records of the presence in last season of FAW across the AEZs of Ghana and Zambia.

Within the selected districts, the communities were also selected randomly and the first household on a randomly selected street or lane was picked. Households were also selected according to stratified sampling strategy, choosing every third household on the street/lane. In cases were the presence of the FAW for maize was not recorded, the enumerator recorded only section 1 (data handlers) and part of the screening section 2 of the survey, before moving to the next household in the lane. In total, the 24 enumerators conducted 511household interviews, 156 in Ghana and 355 in Zambia.

GPS coordinates were automatically collected in each farmer survey, using a smartphone or tablet. These coordinates were plotted using QGIS software. This allowed us to visualize the survey information geographically and to search for spatial patterns in the data. By using this GIS software we were able to link the survey data with other spatial datasets, including sub-national administrative regions, economic datasets, AEs, and FAW environmental suitability model outputs.

Impact of FAW at the household level – methodology

The 466 positive survey results in relation to the likely presence and impacts of FAW was a big enough sample size to measure the cost of control. The cost of control was defined as the cost of the technology in the countries, as well as its application in the field through labour. This formula was utilised solely for chemical pesticide use, seeing as this was a major focus of the survey. The survey did take into account fertiliser use, but the amount of data that gave us an indication of these results was negligible, and therefore conclusions could not be drawn. Indeed, of the 466 participants, only 22 participants stated they had used fertiliser specifically for FAW. Moreover, none stated what specific fertiliser had been used, so the study could not approximate costs.

The costs of different chemicals were obtained through agro-dealer surveys in Zambia and Ghana. The selection of the cypermethrin (Cymethoate and Fastac) and Lambda cyhalothrin (Efforia and Bolt) products was due to the existence of more complete information about their retail prices, availability and label recommendations.

The cost of labour was based on the daily minimum wage, acquired by World Bank data. These are constantly changing, and indeed the study took eight Ghanaian cedis as the minimum wage based on local discussion in the last month, compared to the World Bank's six cedis in 2014.

The survey asked participants to give the number of hours in a day, number of days in a week, and number of weeks they had sprayed the relevant chemical. The cost of household labour was assumed to be the same as external labour, and it was assumed that it was paid for at the daily minimum wage.

Annex 3 Agro ecological zones in Ghana and Zambia

Ghana Agro ecological zone statistics (Aquastats 2005)

Zone	Rainfall	Portion of total area	Length of growing season	Dominant land use systems	Main food crops
	(mm/yr)	(%)	(days)		
Rain forest	2 200	3	Major season: 150-160 Minor season: 100	forest, plantations	roots, plantain
Deciduous forest	1 500	3	Major season: 150-160 Minor season: 90	forest, plantations	roots, plantain
Transition zone	1 300	28		annual food and cash crops	maize, roots, plantain
Guinea savannah	1 100	63	180-200	annual food and cash crops, livestock	sorghum, maize
Sudan savannah	1 000	1	150-160	annual food crops, livestock	millet, sorghum, cowpea
Coastal savannah	800	2	Major season: 100-110 Minor season: 50	annual food crops	roots, maize

Zambia Agro ecological zone statistics (Institute for African studies, 1996)

Agro Ecological Regions	Avg. rainfall (mm/ Year)	Min. (Dec - Feb)	Elevation (meters)	Growing Season (days)	Risk of Drought	Occurrence of Frost in Dry Season	Agricultural Importance
Region I	< 800mm	19 – 21	300 - 900; 900 - 1,200	80 – 129	Medium to High	Risk in Plateau Areas	Suitable for production of small grains and livestock rearing
Region II a	800 - 1,000 Mm	17 – 18	900 - 1,300	100 – 140	Medium to Low	Risk in the Central Plateau	Most productive areas in the country in both food and cash crops
Region II b							High potential for Cassava and rice production as well as cattle rearing
Region III	> 1,000 mm	14 – 16	1,100 - 1,700	120 - 150	Very Low	Some risk in the South-West	High Cassava growing and consuming region

Glossary

Section 1	**Lepidoptera.** The group (order) of insects containing moths and butterflies. **Noctuidae.** A family of moths containing the armyworms, cutworms and other major crop pests worldwide. **Polyphagous.** Of an insect, able to eat many different plants. **Instar.** One of the several stages that a caterpillar goes through. The first instar caterpillar emerges from the egg, and in the case of FAW, the 6th turns into the pupa. **Pupa.** The inactive stage of some insects including Lepidoptera between the last larval instar and the adult. **Haplotype.** A combination of markers on a single chromosome.
Section 4	**Bacillus thuringiensis.** A naturally occurring bacterium that produces proteins toxic to insects, used as a biological pesticide, and genes from which have been used to engineer maize and other crops that produce the toxins and so are resistant to pests. **Diatraea lineolata.** The neotropical corn stalk borer, a pest of maize and other crops in Central America **Carbamates.** A category of synthetic pesticide (Category 1) derived from carbamic acid that work by inhibiting the enzyme acetylcholinesterase in the nervous system **Organophosphates.** A category of synthetic pesticide (Category 1) derived from phosphoric acid that work by inhibiting the enzyme acetylcholinesterase in the nervous system **Pyrethrins.** Insecticidal compounds normally derived from Chrysanthemum flowers. **Pyrethroids.** A category of synthetic pesticide (Category 3A) similar to natural pyrethrins that work by modulating sodium channels in the nervous system. **Neem.** A tree (scientific name Azadirachta indica) native to Asia, introduced elsewhere and now considered a weed in many places including Africa, long used medicinally, and containing compounds, particularly Azadiractin, with insect repellent and antifeedant effects. Many pest control products based on neem are commercially available. **Macrobial**. Natural predators and parasites of insects, that are larger than microbes **Inundative release**. The release of large numbers of natural enemies for

	immediate reduction of a pest population. **Macrobial**. Natural predators and parasites of insects, that are larger than microbes **Inundative release**. The release of large numbers of natural enemies for immediate reduction of a pest population. **HHP.** Highly hazardous pesticide. A pesticide meeting at least one of a set of criteria covering physical hazards, human health hazards and environmental hazards. **Entomopathogenic.** Pathogenic to insects. **Allelopathic.** Negatively affecting the growth and survival of another species of organism through production of one or more chemicals. **Allelobiotic.** Affecting the biology of another species of organism through production of one or more chemicals.

Acronyms

AEZ	Agroecological Zone
AI	Active ingredient
Bt	Bacillus thuringiensis
CABI	CAB International (Centre for Agriculture & Biosciences International)
CGIAR	Consultative Group on International Agricultural Research
CIE	Commonwealth Institute of Entomology
CILSS	Comité Inter-Etate pour la Lutte contre la Sécheresse au Sahel / Permanent Inter-State Committee for Drought Control in the Sahel)
CIMMYT	Centro Internacional de Mejoramiento de Maíz y Trigo / International Maize and Wheat Improvement Centre (Mexico)
CORPOICA	Corporación Colombiana de Investigación Agropecuaria / Colombian Corporation for Agricultural Research (Colombia)
DFID	Department for International Development (UK)
EAC	East African Community
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária / Brazilian Agricultural Research Corporation (Brazil)
EMPRES	Emergency Prevention System for Transboundary Animals and Plant Pests and Diseases (FAO)
EPPO	Search Results
ETOP	Emergency Transboundary Outbreak Pest
EUROPHYT	European Union Notification System for Plant Health Interceptions
FAO	Food and Agricultural Organisation of the United Nations
FAO-SFE	FAO Sub-regional Office for Eastern Africa
FAOSTAT	FAO statistics service
FEWSNET	Famine Early Warning Systems Network
FFS	Farmer field school
FISP	Farmer Input Support Programme
GDP	Gross Domestic Product
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
GIZ	Gesellschaft für Internationale Zusammerarbeit (Germany)
GM	Genetically Modified
HHP	Highly Hazardous Pesticide
IAPPS	International Association for the Plant Protection Sciences
ICIPE	International Centre for Insect Physiology and Ecology
IITA	International Institute of Tropical Agriculture
INRA	L'Institut National de la Recherche Agronomique, France
IPM-CRSP	Integrated Pest Management Collaborative Research Support Program
IPPC	International Plant Protection Convention
IRAC	International Resistance Action Committee
ISPM	International Standard for Phytosanitary Measures
JAICAF	Japan Association for International Collaboration of Agriculture & Forestry
NGO	Non Governmental Organisation
NPPO	National Plant Protection Organisation
OFDA-AELGA	Office of US Foreign Disaster Assistance/Assistance for Emergency Locust/Grasshopper Abatement
PPRSD	Plant Protection and Regulation Services Directorate (Ghana)
QGIS	Quantum Geographic Information System (software)
SADC	Southern African Development Community
SDM	Species Distribution Model
SfMNPV	Spodoptera frugiperda multiple nucleopolyhedrovirus

SIT	Sterile Insect Technique
SPS	Sanitary and Phytosanitary
T&V	Training and Visit
TOT	Training of Trainers
UN	United Nations
USAID	United States Agency for international Development
USD	United States Dollar
USDA	United States Department of Agriculture
USDA-APHIS	USDA Animal and Plant Health Inspection Service
WEMA	Water Efficient Management for Africa
WHO	World Health Organisation
ZARI	Zambian Agricultural Research Institute
ZMK	Zambian Kwacha

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