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The U.S. Government's Global Hunger & Food Security Initiative

Innovation Lab for Integrated Pest Management

Pest Risk Assessment of the Fall Armyworm, *Spodoptera frugiperda* in Egypt

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VIRGINIA TECH

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I. INTRODUCTION

The purpose of this document is to conduct a pest risk assessment of the invasive fall armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) for Egypt. Invasive species are a major cause of crop loss and can adversely affect food security (Cook et al., 2011). Morimoto and Kiritani (1995) defined exotic (invasive) insect species as "those species reproducing naturally in a designated area where they were brought by unusual means, such as air, ocean current, and accidental or intentional introduction". One of the important problems in pest control is that many invasive insects already have resistance to some pesticides and arrive without their natural enemies, which keep them under control in their native countries.

Quantifying the threat presented by the FAW to Egypt and developing effective biosecurity policy requires: 1) an understanding of the potential sources of the FAW; 2) its likelihood of arriving/entering at a particular location in Egypt; 3) the likelihood of its establishment at specific locations within Egypt; and 4) an estimate of the possible impact.

Pest risk analysis and assessment are performed to determine whether a pest should be regulated and the strength of any phytosanitary measures to be taken against it. The assessment is the evaluation of the likelihood of entry, the likelihood of establishment upon arrival, spread of a pest or disease within the country, an estimate of the possible impact, the resources available to tackle the pest, and a road map for its management. It is the evaluation of the potential yield loss and also includes recommendations to reduce the adverse effects on human or animal health and biodiversity arising from the use of toxic pesticides.

The assessment of the economic impact resulting from FAW invasion requires an integration of information on: 1) the biology, ecology and damage caused by the FAW; 2) its entry; 3) establishment; 4) spread; 5) valuation of assets at risk; and 6) market consequences.

II. BACKGROUND

The Fall Armyworm is a polyphagous pest that is native to the tropics in North and South America. In North America, the FAW will move north in the late summer and early fall, which is when it does most of its damage. It then dies off in the cold weather. It affects all stages of plant development and is difficult to control. The pest can survive year-round in the southeastern United States due to the warm and humid climate. In Africa, the FAW was first detected in Nigeria in January 2016. After that, it has spread to other West, Central and East African countries.

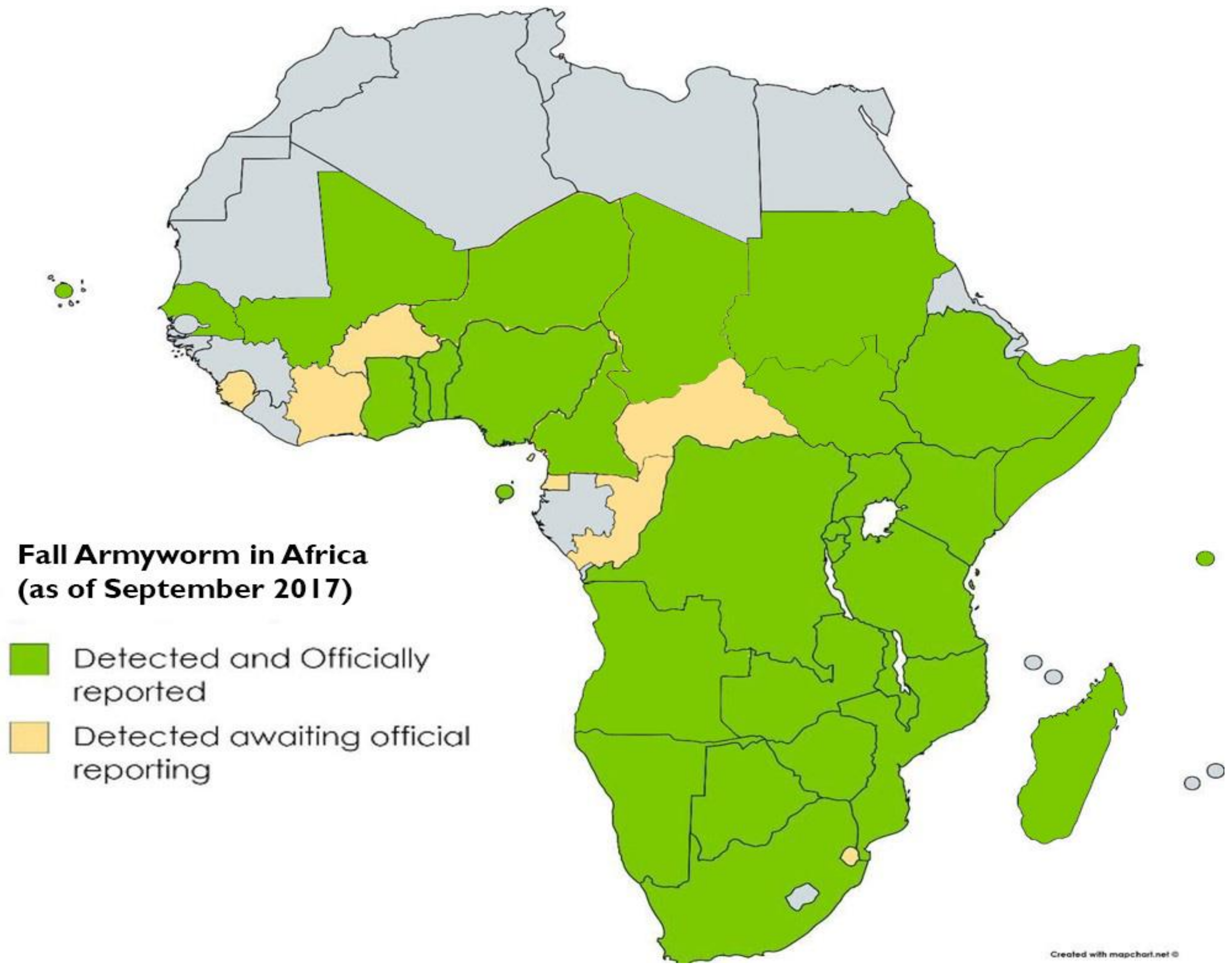

Fig. 1 FAW spread in Africa (CABI)

As of December 2017, 38 countries including Angola, Benin, Botswana, Cameroon, the Democratic Republic of Congo, Ethiopia, Ghana, Guinea, Ivory Coast, Kenya, Madagascar, Mali, Malawi, Mozambique, Namibia, Nigeria, Rwanda, Sao Tome and Principe, Senegal, South Africa, South Sudan, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, and Zimbabwe have confirmed the presence of the FAW (Fig. 1). However, information on FAW presence or absence from the remaining countries is yet to be reported.

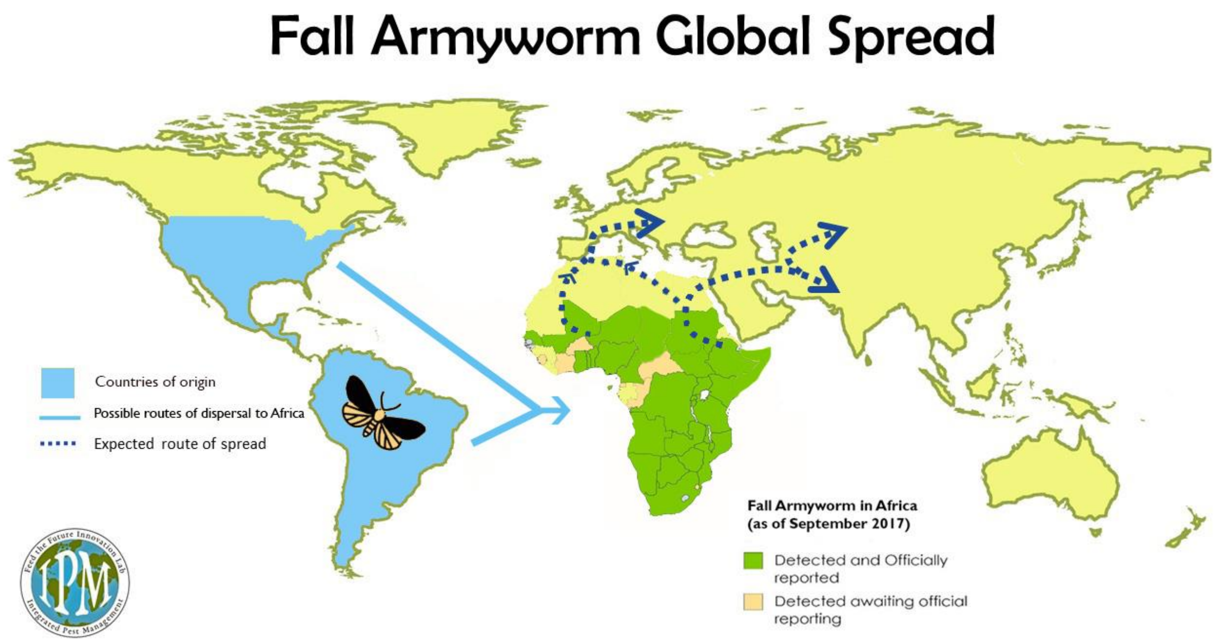

Fig. 2 Potential routes of FAW spread from Africa

S. frugiperda is a transboundary pest, therefore its appearance in some countries in Africa raises the level of threat to other regions of the continent not yet infested and other tropical and subtropical regions of the old world. The environmental suitability on the Mediterranean coast in Morocco, Algeria, Tunisia, and Libya, increases the possible spread of this insect to Southern

Europe, while climatic suitability in East Africa makes the Middle East and Asia more vulnerable to the spread of the FAW (Fig. 2).

III. HOST PLANTS

Although the FAW has a wide host range, with over 80 plant species in 27 families, it shows a preference for the Poaceae. Its preferred host plants are Bermuda grass, crabgrass, maize, millet, rice, sorghum, sugar cane, and wheat. This pest also attacks other non-graminaceaous crops such as apple, cowpea, cotton, grape, groundnut, orange, papaya, peach, potato, soybean, strawberry and a number of ornamental plants. Weeds known to serve as hosts include bentgrass, Johnson grass, morning glory, nutsedge, pigweed and sand spur. It is challenging to manage the FAW due to its polyphagous behavior and ability to survive on diverse alternate hosts. Its impact on cotton, maize, sorghum, sugarcane, tomatoes, wheat, and some ornamental plants in Egypt is likely to be significant (refer to section on Economic Impact).

IV. TAXONOMY

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 'maize 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 (maize), cotton and sorghum. However, 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 feed on maize. The strains are morphologically identical, but can be distinguished using DNA barcodes. The FAW strain in Togo appears to be the haplotype found in southern Florida and the

Caribbean (Nagoshi *et al.,* 2017). However, both the maize strain and the rice strain are now confirmed in Africa (Cock *et al.,* 2017). The knowledge about FAW strains is important for two reasons: 1) different haplotypes have different host ranges, 2) different biotypes carry different pesticide resistance genes.

V. IDENTIFICATION

Identification of larvae in the field requires expertise and skills as the FAW is easily confused with similar species such as the African armyworm (*Spodoptera exempta*), and the cotton leafworm (*Spodoptera littoralis*), as well as species of other noctuid genera, such as the African maize stalk borer (*Busseola fusca*). However, there are certain identification guidelines developed by taxonomists in the United States that are useful for identifying the FAW (Fig. 3).

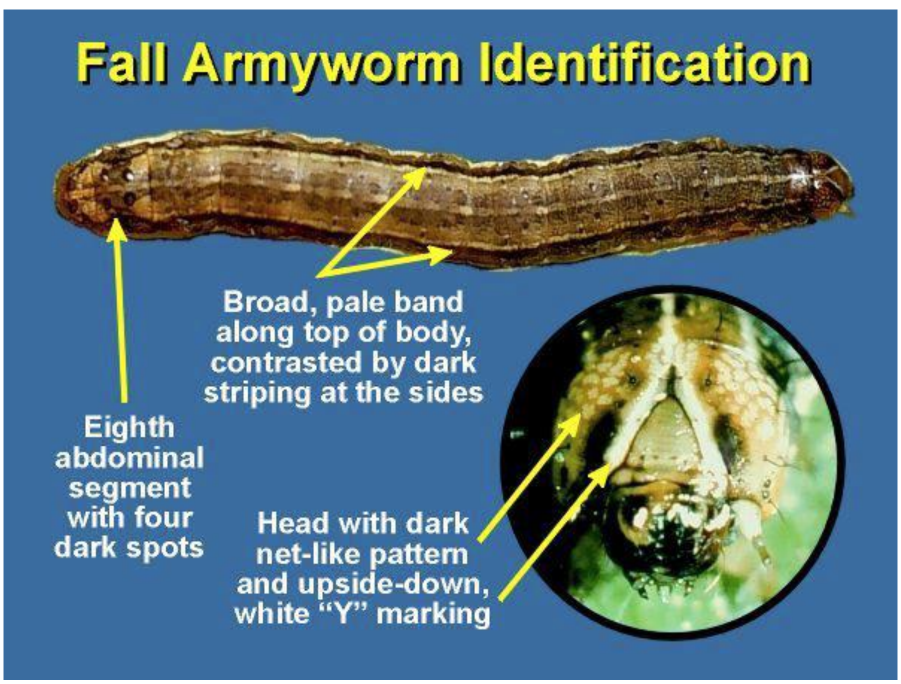

Fig. 3 FAW ID info (Farmbiz Africa / University of Nebraska*)*

VI. BIOLOGY

Eggs are dome shaped and are dirty-white to gray in color (Fig. 4). Eggs are laid in groups or clusters of about 10-200 eggs per egg mass, usually on the underside of leaves. Sometimes the eggs are deposited in layers but usually eggs are laid in a single layer attached to foliage. After oviposition, the female deposits a layer of grayish scales or hairs over the eggs and covers the egg mass giving it a hairy or moldy appearance (Fig. 5). Depending on environmental conditions, eggs hatch in two to five days in optimum temperatures.

Fig. 4 Newly laid FAW eggs (Bugguide.net)

Fig. 5 FAW eggs with hairs (Bugguide.net)

In its native regions, the FAW goes through six larval instars with the final instar being most devastating and consuming up to 80% of the plant material. The newly hatched larvae are greenish with a black head, which turns orange-brown in the 2nd instar. Newly hatched larvae first feed near where the egg mass was laid, then move upwards on the maize plants, and then disperse by wind using silk threads.

The larvae exhibit cannibalistic behavior, and under heavy infestations, larval densities can be reduced to one or two per plant. Cannibalism was found to account for approximately 40% mortality when maize plants were infested with more than one fourth-instar larvae over a three-day period (Chapman *et al.,* 2000).

Fully-grown larvae are 3.1 – 3.8 cm long and vary in color from pale green to almost black, with three yellowish stripes running down the back. There is a wider dark stripe and a wavy yellow-red blotched stripe on each side (Fig. 6). The FAW's head has a predominant white, inverted Y-shaped suture between the eyes (Fig. 3). In its native range, developmental times of immature stages vary with temperature (an acceptable range of between 11°C and 30°C).

Fig. 6 Fully grown FAW larva (Holly Schwarting)

Fig. 7 FAW pupa (Bugguide.net)

Pupation normally takes place in the soil, but may also occur on plant parts under high population densities. The pupa is reddish brown (Fig. 7). The pupal stage is 8-9 days in the summer and longer than 2 weeks under winter conditions. The adult moths have a wingspan of 32 to 40 mm. The male moth has dark gray and brown shaded mottled forewings with conspicuous triangular white spots at the tip and near the center of the wing (Fig. 8). These markings are less distinct in female moths (Fig. 9). The hind wing is iridescent, silver-white, with a narrow dark border in both sexes.

Fig. 8 FAW adult male
(Lyle J. Buss, University of Florida)

Fig. 9 FAW adult female
(Lyle J. Buss, University of Florida)

Adults are nocturnal, and are most active at dusk when they mate. Like other noctuids, FAW adult females have a high fecundity rate. Females deposit most of their eggs during the first four to five days of life, but some eggs may be laid for up to three weeks. Females can mate multiple times during this period and lay multiple egg masses, with a potential fecundity of up to 1,000 eggs per female. At low population densities, females normally lay eggs on the underside of leaves. However, at high densities, oviposition is indiscriminate over the entire plant or on non-host plant objects. Adults can live up to an average of 10 days but sometimes the duration extends up to three weeks in the temperate region of the U.S. The larvae are nocturnal feeders. Unlike other armyworm species, FAW larvae are typically found damaging maize in patches throughout a field. In the northern parts of the U.S. they appear in maize fields late in the season, from mid-July through the fall harvest, but in Africa/Egypt, due to the tropical climate, it can multiply year-round.

In the summer months, the FAW completes its life cycle in about 30 days (Fig. 10); however, during winter months in the southern U.S. it takes 80 to 90 days to complete its life cycle. Development is slow in cooler climates and the number of generations in an area varies. The FAW does not have the ability to diapause and frost kills the insect. Since frost is not an issue in the African continent, this fact needs to be considered when conducting surveys and seeking better understanding of FAW biology in Africa.

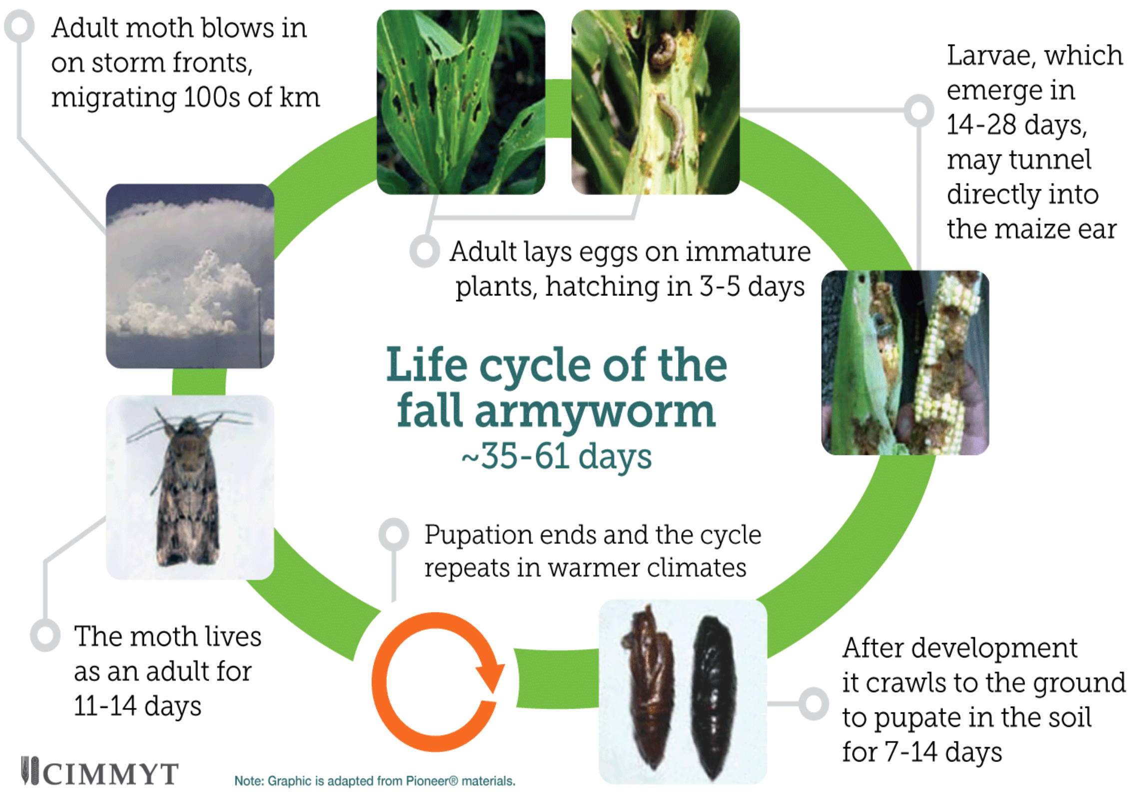

Fig. 10 Typical life cycle of the FAW

Natural Enemies

In its native region, FAW eggs, larvae, and pupae are attacked by several species of parasitoids (Table 1). Among several groups of parasitoids, the egg parasitoids *Telenomus* spp. (Hymenoptera: Platygastridae) and *Trichogramma* spp. (Hymenoptera: Trichogrammatidae), are deemed important in several countries. Egg parasitoid *Telenomus remus,* an introduced parasitoid from the Pacific, has proven very effective in South America and Florida. These egg parasitoids *Trichogramma* spp. and *Telenomus* spp. are easy to rear under laboratory conditions. However, the presence of scales/hairs over the egg masses acts as a barrier against parasitism by *Trichogramma* spp. but not to *Telenomus* spp. This physical barrier could be overcome by selecting a more aggressive species of *Trichogramma*, capable of breaking the physical barrier imposed by scales on the eggs. It is therefore essential to know the species/strains present in the agro-ecosystem when choosing the *Trichogramma* species to be used for applied biological control of the FAW. The wasp parasitoids most frequently reared from larvae in the U.S. are *Cotesia marginiventris* and *Chelonus texanus* (Hymenoptera: Braconidae). In Argentina, larval parasitoids collected were *Campoletis grioti* (Hymenoptera: Ichneumonidae), *Chelonus insularis* (Hymenoptera: Braconidae), *Archytas marmoratus* and *A. incertus*, (Diptera: Tachinidae) *Ophion* spp. (Hymenoptera: Ichneumonidae), *Euplectrus platyhypenae* (Hymenoptera: Eulophidae), and *Incamyia chilensis* (Diptera: Tachinidae). In Mexico, 13 genera of hymenopteran larval parasitoids, belonging to three families-Braconidae, Ichneumonidae and Eulophidae were recovered.

Table 1. Common parasitoids of FAW found worldwide

Parasitoid	Type	Country
Telenomus spp. Hymenoptera: Platygastridae	Egg	Antigua, Barbados, Brazil, Colombia, Dominican Republic, Guadeloupe, Ecuador, Guyana, Honduras, Nicaragua, Puerto Rico, Suriname, Trinidad, U.S., Venezuela, Israel, Cuba, Mexico
Trichogramma spp. Hymenoptera: Trichogrammatidae	Egg	Barbados, Nicaragua, Brazil, Chile, Colombia, Argentina, Cuba, U.S., Guadeloupe, Mexico
Chelonus spp. Hymenoptera*:* Braconidae	Egg, Larval	Barbados, Nicaragua Honduras, Mexico, Trinidad, Argentina, Brazil, Chile, Colombia, Cuba, Haiti, Puerto Rico, U.S., Uruguay, Venezuela
Agathis stigmatera Hymenoptera: Braconidae	Larval	Argentina, Peru, U.S.
Archytas spp. Diptera: Tachinidae	Larval	Argentina, Barbados, Honduras, Mexico, Nicaragua, U.S., Venezuela, Brazil, Chile, Puerto Rico, Suriname, Trinidad, Uruguay, Cuba, Ecuador, Guadeloupe, Lesser Antilles, Peru
Campoletis grioti (Hymenoptera: Ichneumonidae)	Larval	Argentina
Cotesia marginiventris Hymenoptera: Braconidae	Larval	Honduras, Barbados, Nicaragua, Argentina, Brazil, Chile, Lesser Antilles, Mexico, Puerto Rico, Suriname, U.S., Uruguay, Venezuela, Trinidad & Tobago, Colombia, Guyana
Euplectrus spp. Hymenoptera: Eulophidae	Larval	Nicaragua, U.S., Argentina, Puerto Rico, Panama, Honduras, Barbados, Brazil, Chile, Colombia, Cuba, Guyana, Lesser Antilles, Mexico, Trinidad, Venezuela, Honduras
Lespesia spp. Diptera: Tachinidae	Larval	Brazil, Honduras, U.S., Argentina, Brazil, Chile, Cuba, Guadeloupe, Guatemala, Honduras, Lesser Antilles,

		Mexico, Nicaragua, Puerto Rico, Uruguay, Venezuela, Colombia
Ophion spp. Hymenoptera: Ichneumonidae	Larval	Argentina, Uruguay, Chile, U.S., Brazil, Honduras, Mexico, Nicargua, Peru,
Brachymeria spp. Hymenoptera: Chalcididae	Pupal	Argentina, U.S.
Cryptus albitarsis Hymenoptera: Ichneumonidae	Pupal	U.S.
Diapetimorpha introit Hymenoptera: Ichneumonidae	Pupal	Honduras, U.S.
Ichneumon promissorius, *I. ambulatorius*. Hymenoptera: Ichneumonidae	Pupal	U.S.
Trichospilus pupivora Hymenoptera: Eulophidae	Pupal	Barbados

Five species of Ichneumonidae: *Diapetimorpha introit*, *Cryptus albitarsis*, *Ichneumon promissorius*, *Ichneumon ambulatorius* and *Vulgichneumon brevicinctor*, two species of Chalcididae: *Brachymeria ovata* and *B. robusta* and one Eulophid species, *Trichospilus pupivora* have been reported on FAW pupae from the U.S., Argentina, and Barbados but they are of limited effectiveness. Another biological control agent, *Doru luteipes* (Dermaptera: Forficulidae) has been used as an agent for the biological control of FAW eggs in Brazil.

Although several pathogens have been shown to reduce the abundance of FAW larvae in maize, only *Bacillus thuringiensis* (Bt) is currently used, and success depends on having the product on the foliage when the larvae first appear. Bt sprays tend to be short-lived as they are very susceptible to UV degradation and require multiple sprays. Another option for biological control of FAW is *S. frugiperda* nuclear polyhedrosis virus (SFNPV). A large number of isolates of NPV have been obtained from the field and some have been detected as promising isolates. A commercial formulation for *S. frugiperda* NPV, SPOBIOL, prepared by CORPOICA, the Colombian public-private ag research partnership, is available and has been licensed with Certis LLC, a U.S company. Some studies have also shown that *Metarhizium anisopliae* and *Beauveria bassiana* have potential as microbial control agents against FAW.

There are a number of egg and larval parasitoids found in Africa that could attack FAW eggs and larvae. There are 11 species of *Telenomus* and 26 species of *Trichogramma*/ *Trichogrammatoidea* found in Africa (Tables 2 and 3). There are two larval parasitoids, *Habrobracon hebetor* in Niger, and *Cotesia* spp. in Kenya that can attack FAW larvae. Another parasitoid, *Bracon mellitor* was introduced into Egypt to control *Spodoptera littoralis* may also attack FAW.

Table 2: List of *Telenomus* spp. recorded in Africa

***Telenomus* spp.**	**Host**	**Distribution**
T. applanatus	*Eldana saccharina*	Gabon, Ghana, Ivory coast
T. bini	*Maliarpha separratella*, *Chilo* spp., *Scirpophaga* spp.	Ghana, Ivory Coast, Madagascar, Malawi, Senegal, Tanzania.
T. busseolae	*Busseola fusca*, *Sesamia* spp., *Coneista ignefusalis*	Cameroon, Egypt, Ghana, Kenya, Nigeria, Reunion, Senegal, South Africa, Sudan, Uganda
T. creusa	*Chilo diffusilineus*	Malawi
T. etielliphaga	*Etiella zinckenella*,	Senegal
T. nemesis	*Chilo orichalcociliellus*	Ghana, Kenya, Mozambique, Senegal

T. nephele	*Scirpophaga melanoclista, S. occidentella, S. subumbrosa*	Cameroon, Ghana, Ivory Coast, Malawi, Mali, Senegal.
T. procas	*Antigastra catalaunalis*	Senegal, Sudan
T. soudanensis	*Chilo zacconius*	Niger
T. thestor	*Chilo orichalcociliellus*	Ivory Coast, Kenya, Senegal, Uganda, Zaire
T. versicolor	*Scirpophaga melanoclista*	Ghana, Ivory Coast, Malawi, Senegal

Table 3. *Trichogrammatidae* egg parasitoids recorded in Africa

Trichogrammatidae	**Host**	**Distribution**
Trichogramma bourarachae	*Helicoverpa armigera*	Morocco
Trichogramma bournieri	*Chilo partellus*	Comoros, Kenya
Trichogramma cacoeciae	-	Morocco
Trichogramma chilonis	*Eldana saccharina, Busseola fusca, Chilo partellus*	South Africa
Trichogramma ethiopicum	-	Cameroon
Trichogramma evanescens	*Chilo Agamemnon, Helicoverpa armigera, Pectinophora gossypiella, Spodoptera littoralis*	Egypt, Madagascar
Trichogramma japonicum	*Chilo partellus*	Malawi
Trichogramma kalkae	*Diopsis macrophthalma*	Malawi
Trichogramma sp. nr *kalkae*	-	Zimbabwe
Trichogramma kayo	-	Sudan
Trichogramma mandelai	*Diparopsis watersi*	Chad
Trichogramma sp. nr *mwanzai*	*Chilo diffusilineus, Chilo partellus, Busseola fusca, Eldana saccharina, Sitotroga cerealella*	Malawi, Kenya

Trichogramma ostriniae	*Busseola fusca, Chilo partellus*	South Africa
Trichogramma papilionidis		Angola
Trichogramma pretiosum	*Apple leaf roller*	South Africa
Trichogramma pinneyi	*Diopsis macrophthalma*	Malawi
Trichogramma spp. nr *exiguum*	*Chilo partellus*	Kenya
Trichogramma voegel	-	Morocco
Trichogrammatoidea armigera	*H. armigera,* *Heliocheilus albipunctella*	Kenya, Niger
Trichogrammatoidea bactrae	*P. gossypiella*	Egypt
Trichogrammatoidea citri	-	Madagascar
Trichogrammatoidea combreti	-	Senegal
Trichogrammatoidea cryptophlebia	*Cryptophlebia batrochopa,* *C. leucotreta*	Malawi, South Africa
Trichogrammatoidea eldanae	*E. saccharina, Sesamia calamistis*	South Africa, Nigeria, Kenya
Trichogrammatoidea lutea	*C. partellus, B. fusca,* *H. armigera*	South Africa, Kenya, Ivory Coast, Ethiopia, Mali, Mozambique, Senegal
Trichogrammatoidea simmondsi	*Diopsis macrophthalma,* *C. partellus,* *Thaumatotibia leucotreta,* *H. armigera, Atherigona soccata*	Malawi, South Africa, Kenya, Burkina Faso

VII. DAMAGE

The developing larvae feed on different parts of the host plant, depending on the crop, the stage of crop development, and the age of the larvae. The FAW generally feeds on foliage, but during heavy infestations, larvae also feed on maize ears. Young larvae initially feed near where the egg mass was laid and superficially feed on one side of the

Fig. 11a Young FAW larvae feeding on a maize leaf. (D Visser ARC-VOP)

Fig. 11b Young FAW larvae dispersing by using silk threads (D Visser ARC-VOP)

leaves leaving the epidermis intact on other side (Fig. 11a). Then the larvae disperse using silk threads blown by wind, a phenomenon known as ballooning (Fig.11b).

Fig. 12 Ragged appearance of leaves due to FAW larval feeding (CABI)

Foliar damage to maize is usually characterized by ragged feeding (Fig. 12), and moist sawdust-like frass near the whorl and upper leaves of the plant (Fig. 13).

Fig. 13 Sawdust-like frass near the whorl due to FAW feeding (CABI)

Later instars feed by making holes in leaves and eat from the edge of the leaves inward. Feeding in the whorl of maize often produces a characteristic row of perforations in the leaves. Due to young larval dispersal and the cannibalistic behavior by late instars, larval numbers are reduced to few larvae per plant. Fully-grown larvae cause extensive defoliation, often leaving only the ribs and stalks of maize plants. Larvae can also burrow into the growing point and affect the growth of plants. In maize, larvae sometimes also bore into the ear through the husk and feed on the tip of ears (Fig. 14) and on kernels (Fig. 15). When boring through the husk they produce holes (Fig. 16).

Fig. 14 FAW larva feeding at tip of a maize ear (P. Chinwada)

Fig. 15 FAW larvae feeding on a maize ear. (CABI)

Fig. 16 FAW feeding hole in maize ear (P. Chinwada)

VIII. HOW TO IDENTIFY AND DIFFERENTIATE THE FAW FROM OTHER SIMILAR SPECIES IN EGYPT

Spodoptera littoralis - Eggs are translucent with few hairs or scales (Fig. 17).

Fig. 17 *Spodoptera littoralis* eggs. (EPPO.int)

The larvae are usually brown colored with distinct black spots. Sometimes the larvae may be yellowish or blackish with light spots. Caterpillars have dark and light longitudinal bands and two dark, semi-

Fig. 18 *Spodoptera littoralis* larva (Pyrgus.de)

circular spots laterally on each segment, except for the prothorax (Fig. 18). Moths are grey-brown and have a characteristic "scratch like" pattern on forewings. The tip of the forewing is light brown, with a distinct white marking shaped like an "A" and a white, three-branched, fork-like pattern. Hind wings are whitish with grayish-brown margins and veins as well as fringe hairs (Fig. 19).

Fig. 19 *Spodoptera littoralis* adult (CABI)

Spodoptera exempta- Young larvae are light colored, while the older ones are usually blackish in color. They are velvety-black on the upper body surface with green, black, yellow, and white lateral stripes. The underside of the body is green or yellow and the larvae do not have hairs on the body (Fig. 20).

Fig. 20 *Spodoptera exempta* larvae (CABI)

The adult moths are similar in appearance to the FAW and lay eggs in groups or layers covered with hairs.

Spodoptera exigua: Larvae are pale green or yellow in color when young (Fig. 21). Older larvae are darker in color and develop lateral stripes and sometimes dots (Fig. 22). Sometimes a characteristic pink line or spots are seen on the sides of larvae. The larvae are smooth without any hairs. The adults have a mottled grey and brown forewings

Fig. 21 Young *Spodoptera exigua* larva (John Capinera)

Fig. 22 Mature *Spodoptera exigua* larva (Pyrgus.de)

with an irregular banding pattern and a characteristic light colored bean shaped spot (Fig. 23). Eggs are laid in groups covered with hairs or scales.

Fig. 23 *Spodoptera exigua* moth (John Capinera)

IX. MOBILITY AND DISPERSAL

Noctuids are generally considered strong fliers and are assumed to migrate at night and downwind. Fall armyworm adults are nocturnal and their early evening movement near fields is generally with the wind. There are records of 16-30 hour tethered flight by FAW males (van Handel, 1974).

In Central America, FAW moths generally disperse about 500 km before oviposition, from seasonally dry habitats to wet habitats (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. The data indicates that FAW follow this pattern and can move variable distances on weather fronts (Rose *et al.*, 1975, Young, 1979). There is one documented incidence of long-distance migration by FAW on a weather front where FAW travelled 1,600 km from Mississippi to southern Canada in 30 hours (Rose *et al.*, 1975). Therefore, FAW has the potential to spread rapidly and has already spread to the western, eastern and southern regions of Africa in a span of around 18 months since its discovery in the western region.

X. SPREAD AND ESTABLISHMENT

Using multiple modeling methods, and data sources, we identified different routes and pathways of possible FAW introduction to Egypt, its spread within the country, and the threat this scenario poses to other countries. To this end, we have accounted for ecological factors, spatiotemporal variation in vegetation, and production of major hosts of FAW, its flying capacity, wind patterns, and international trade and travel. To study its spatiotemporal spread, we developed a cellular automata model (CA) based on a recent work by Guimapi and others (Guimapi *et al.*, 2016). To study the role of wind, we used the TAPPAS (Tool for Accessing Pest and Pathogen Ariel Spread) (Durr *et al.*, 2015) interactive framework for modeling pest and pathogen spread through wind. This work derives from a recent study of migration patterns of FAW by Westbrook and others (Westbrook *et al.*, 2016). To analyze international trade and travel, we used datasets from Food and Agricultural Organization (FAO) and WorldPop (http://www.worldpop.org.uk/).

Establishment potential

To assess the suitability of FAW to establish in different parts of Egypt, work by Abrahams *et al.* (2017) was adopted. They used seven species distribution models to assess the environmental suitability of Africa for the establishment of FAW (Fig. 24a). The models account for climatic factors and the biological properties of the pest. Overall, their results indicate that most southern parts of Egypt are less suitable for FAW, while the central and northern parts are moderately suitable.

However, there seems to be high variation in the predictions across the models for this African region (see Fig. 24(b) inset) (Abrahams *et al.*, 2017). Also, to the best of our knowledge, their approach does not seem to account for crop production or man-made diversity. For example, several hosts of FAW are grown along the Nile River (suitable for establishment), even though, in general, the areas some distance from the Nile may not be suitable for establishment.

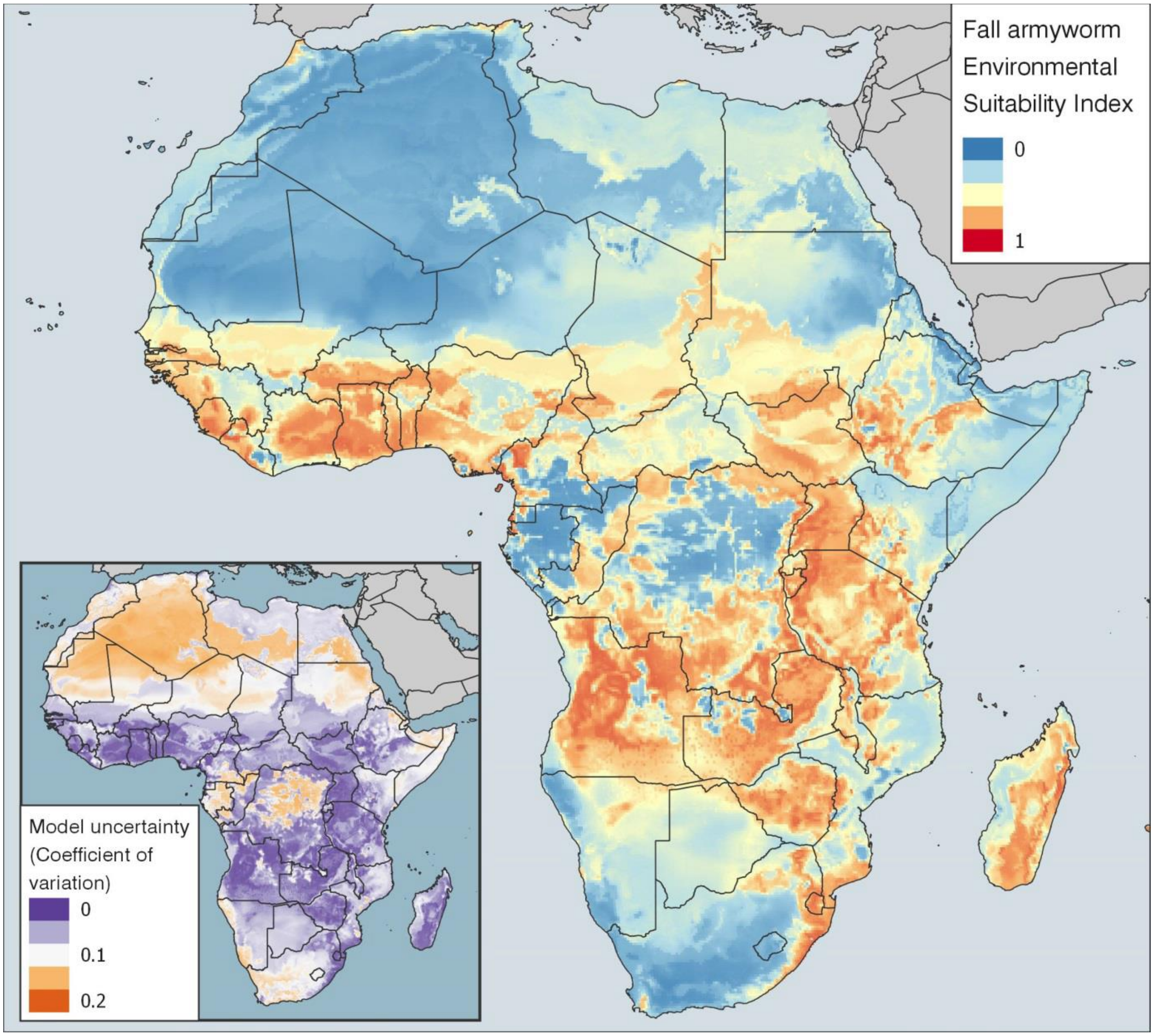

Fig. 24 Environmental suitability for the establishment of FAW in Africa including Egypt and surrounding countries (a) and 24 (b) (inset) Model uncertainty Abrahams *et al.* (2017). In fig. 24a dark blue is least suitable and dark red, the most suitable to the establishment of the FAW. Notice that Abraham's model does not take into account the crop areas suitable for FAW movement north along the Nile River running from Sudan to the Nile Delta.

Pathways of introduction and spread

There are three potential pathways of introduction into Egypt that we accounted for: 1) natural spread; 2) travel; and 3) trade. We first predicted the natural spread (unaided dispersal) from

Sudan and Ethiopia to Egypt based on the flight biology of the insect in North America and wind directions from the sources in Sudan and Ethiopia. This exercise was followed by modeling the flight of the FAW from Ethiopia and Sudan to Egypt.

Natural spread (unaided dispersal) based on flight biology

The FAW has spread onward to southern and eastern parts of Africa since its introduction in West Africa in 2016. There is no documented evidence on the possible methods or pathways of its spread within Africa. It seems likely that of the three pathways; 1) unaided dispersal through flight, 2) as a stowaway in aircraft or other transportation or 3) through trade. Unaided dispersal through insect flight may be the most probable means of introduction into Egypt. In order to assess the risks of the FAW spread into Egypt, it is appropriate to assess the potential pathways of entry, especially when the pest is already in Sudan and other countries in East Africa.

The following calculations were employed to determine the rate of migration (flight) movement from a source point (nearest source locations to Egypt) to a specific location in Egypt and the rate of FAW movement within Egypt once it arrives.

A= Distance from a source to a potential location in Egypt (miles)

B= Migration potential [X miles/generation (30 days)]

C= Number of months to reach a specific destination in Egypt

C= A/B

Note **(A)** In the US, movement from S. Texas to Canadian border (1,740 mi.) occurs in 105 days or 3.5 months (***C***) where **B** =1740 /105= 16.5 mi./day = 497mi./mo. or one insect generation (1740/497) = 3.5 months. or 3.5 insect generations

A conservative estimate for the US would be 250 miles /generation /month. (Johnson 1987). In North America, moths fly downwind above the boundary layer, 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). The FAW clearly, has the potential to spread rapidly from Ethiopia and Sudan to Egypt, if the prevailing winds are in a northerly direction and of sufficient speed. There is no published research however, as to the factors affecting FAW movement in Africa. Indeed, the FAW may already be near Egypt or approaching Egypt soon.

Based on wind movements, the migration potential [(X miles/generation (30 days)] from Sudan is expected to be lower than that in the US. Because the FAW is expected to move from Lake Tana, Ethiopia to Khartoum via the Blue Nile, and is already in Khartoum, we only calculated the migration potential from Khartoum to Lake Nasser and from Lake Nasser to the Nile Delta.

Calculations:

1. Khartoum, Sudan to Lake Nasser in Egypt

A= Distance from source (Khartoum, Sudan) to Lake Nasser in Egypt= 700 miles

B= Migration potential: Miles/generation-Conservative= 150/Liberal=300

Conservative estimate= C= A/B= 700/150= **4.7 months** or 4.7 generations

Liberal estimate = C= A/B= 700/300= **2.3 months** or 2.3 generations

2. Lake Nasser (Aswan) in Egypt to the Nile Delta near Cairo

A= Distance from source (Lake Nasser in Egypt) to Nile River Delta (near Cairo)= 500 miles

B= Migration potential: Miles/generation-Conservative= 150/ Iiberal=300

Conservative estimate= C= A/B= 500/150= **3.3 months** or 3.3 generations

Liberal estimate= C= A/B=500/300= **1.7 months** or 1.7 generations

Sudan is one potential source of FAW to invade Egypt from the south. It would follow the watershed of the Nile River as suitable crops for feeding and reproduction of the FAW are only available along the watershed (Fig. 25). Beyond the irrigated areas along the Nile there is no availability of crops for the FAW to feed on.

Fig. 25 Possible routes of introduction and spread of FAW in Egypt based on model output and suitability.

The movement from Sudan is expected to follow the watershed of the White Nile River as suitable crops are only grown along the watershed. Other areas do not have crops on which the FAW can feed as it moves north. The FAW feeds on 80 different host plants and the most suitable host plants along the Nile are cotton, cowpeas, groundnut, maize, millet, rice, sorghum, sugarcane, tomatoes, and wheat. At the upper portion of the White Nile, near Khartoum, where the White Nile and the Blue Nile merge, the Gezieira Scheme has extensive areas of cotton, maize, sorghum and sugarcane, the preferred hosts. From Khartoum, the FAW would be expected to follow the Nile moving north, as the watershed has extensive irrigated areas providing the required host plants for the FAW. The FAW would be expected to enter Egypt just south of Lake Nasser. The wind direction in Sudan is north, northwest or northeast 89 % of the time on an annual basis (N-32%, NW- 44% and NE- 13%). The distance from Sudan to Lake Nasser is approximately 700 miles.

The distance from Lake Nasser to the Nile River Delta at Cairo is approximately 500 miles. A conservative estimate is that it will take 3.3 months (500 miles.÷ 150 miles per 30 days) and a liberal estimate is 1.7 months (500 mi. ÷ 300 mi. per 30 days). There is also a slight possibility that the FAW from Ethiopia could enter Egypt via Yemen and Saudi Arabia to the east side of the delta in Egypt (Fig. 26).

Modeling the natural spread based on ecological suitability, hosts etc.

To assess the threat of FAW through natural spread, we developed a cellular automata model accounting for vegetation and availability of host crops. The output of the model is the spatiotemporal spread of the FAW. The model parameters include vegetation and production thresholds that determine establishment potential, the pest's flying capacity and time to complete a life cycle. One of the instances of the model output (which was a close fit to pest reports) is shown in Fig. 26.

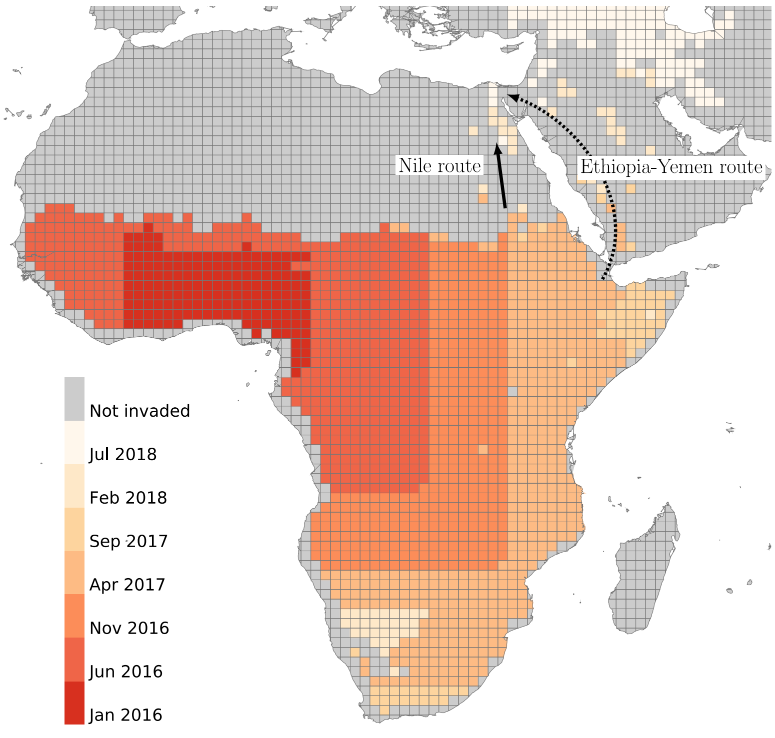

Fig. 26 Spatiotemporal spread of the FAW as predicted by the cellular automata model for 36 months starting January 2016.

The country closest to Egypt with reports of the FAW is Sudan (Muniappan, personal communication). The movement from Sudan would be expected to follow the watershed of the White Nile River. This is because suitable crops are grown only along the watershed. Also, areas further from it have very low vegetation in general. At the upper portion of the White Nile, near Khartoum, where the White Nile and the Blue Nile, coming from Ethiopia merge, the Gezieira Scheme has extensive areas of cotton, maize, sugarcane and sorghum as preferred hosts. Fig. 26 illustrates this route. According to our models, it will take between 4-8 months for FAW to reach Lake Nasser through this route.

The movement from Ethiopia can happen in two ways (Fig. 25). The most probable one would start near Lake Tana and follow the Blue Nile watershed to Kartoum where it merges with the White Nile and then move north up the Nile watershed to Lake Nasser, similar to the Sudan population (Fig. 26). There are suitable food crops for the FAW along the Blue Nile. The other route is along the coastal regions of Yemen and Saudi Arabia. The latter would take longer (greater than 9 months) and directly affect the Nile Delta.

Our models also indicate the possibility of the FAW spreading to Southeastern Europe and Western Asia within 3-4 months after establishing in the Nile Delta region. This is under the assumption that these regions are not already invaded from other sources or routes.

Wind patterns and its effect on the spread of FAW

As mentioned earlier, the FAW has been known to cover thousands of miles aided by wind. Recently, Westbrook *et al*. (2016) studied the wind aided migratory flight of FAW in the continental USA using the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1997). Our study is based on this work. For simulations, we used the TAPPAS online software tool (Durr *et al*., 2015) which is developed to simulate the long-distance spread of pests and pathogens. It uses the HYSPLIT framework in the backend.

We studied monthly wind patterns with particular emphasis on wind directions from pest reported areas of Sudan and Ethiopia. In the simulations, the insect population was initiated at two places: one in the Khartoum area of Sudan and the other near Addis Ababa in Ethiopia. Each insect is modeled as a particle. The properties of the particles were set based on the work of Westbrook *et al*. (2016). These include the release altitude which is between 500m-AGL (Above

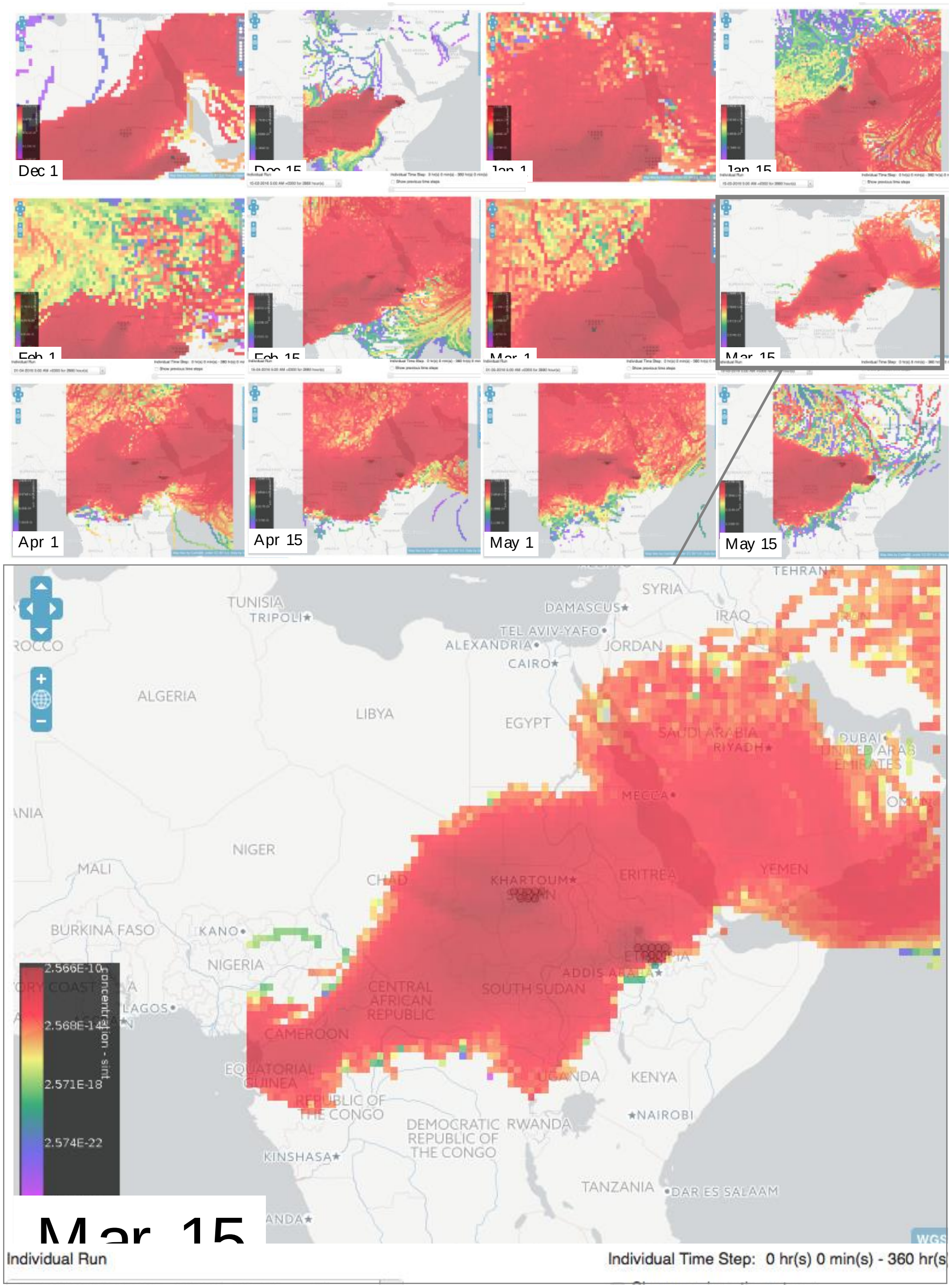

Figure 27. Wind patterns studied using the TAPPAS simulation tool: The results of 12 simulations are presented. Each simulation is identical except for the start date which varies from December 1 to May 15 in 15-day interval. For clarity, one of the results is expanded. The concentration of insect population is color coded (from red, yellow, blue to violet in descending order of concentration). This is the concentration 120 days after the start date.

Ground Level) to 3000m-AGL, diameter, release quantity and release time. Each simulation was run for a duration of 120 days with different start dates accounting for multi-generational migration.

Here, we would like to note that in addition to biology and physical properties of the pest, Westbrook *et al*. (2016) incorporate many other details including but not limited to production cycles of corn in the continental USA, time to complete life cycle in terms of degree days, presence of water bodies, etc. Also, in their framework, after every 12-hour flight the moths were run through a biological model tied to corn growth. However, to mimic such a detailed spread model, we do not have required data for Africa. Hence, in this work, we focus only on the effect of wind on particles which are endowed with the properties of the insects.

The results are shown in Fig. 27. We note a general trend of Northeasterly wind flow from Sudan and Ethiopia towards Southern and Central Egypt, Yemen and Saudi Arabia. This observation strongly suggests that wind can aid in the introduction and spread of FAW in Egypt. In particular, it can help the pest in two ways: 1) enable it to cross the low vegetation areas between Northern Sudan and Southern parts of Egypt and, 2) speed up the spread process.

Travel

From a travel perspective, Egypt's air travel passenger volume, when restricted to Africa, is dominated by domestic flow, followed by other countries from Northern Africa (Fig. 28a). Among the countries with highest passenger inflow, Nigeria (13%), Sudan (10%), and South Africa (8%) report the presence of FAW. It accounts for 20% of the inflow among countries in this region, excluding Egypt (approximately 900,000 passengers per year). Cairo accounts for the highest inflow of passengers from the rest of Africa (around 2,000,000 or 75%) followed by Alexandria (12%) and Hurghada (6%). However, for a more accurate assessment, it is important to consider the type of travelers. If most travelers are tourists visiting Egypt, it is possible that the risk of introduction through baggage is much less. However, if the introduction is through flights, then these passenger flow volumes are a good indication of relative threat. Most of the international air travel from Egypt is to Asia (40%), Europe (31%) and Africa (28%) (Fig. 28 b).

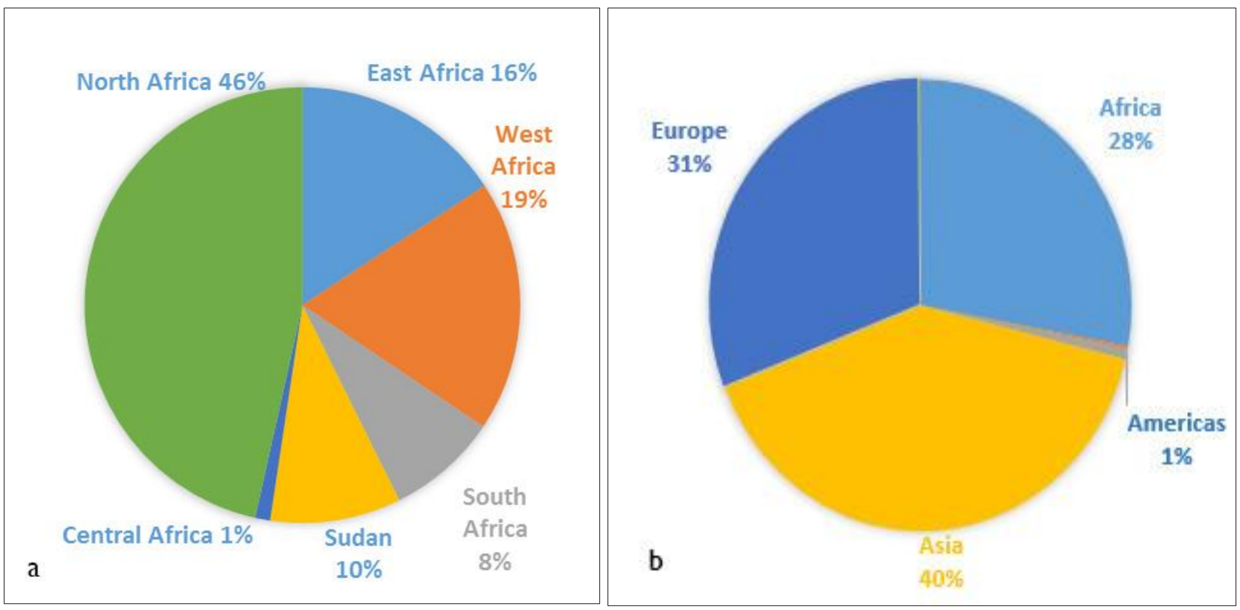

Fig. 28. International air travel: Volume of passengers travelling annually (a) to Egypt from different parts of Africa and (b) from Egypt to different regions of the world. (Most travelers from the Americas travel through Europe or the Middle East, therefore the America account for low percentage)

Trade

Among the identified host crops of FAW, Egypt imports less than 1% from Africa. Though more than 30% of its imports are from the Americas, historically, it does not seem to be a threat. Hence, trade does not appear to be an important pathway.

XI. RISK TO OTHER COUNTRIES

We assessed the possible risk of FAW spread from Egypt to other parts of the world that are currently free from FAW. Here again, we considered the three possible pathways: natural spread, trade, and travel.

Natural spread

Our models also indicate the possibility of the FAW spreading from Egypt to Western Asia within 3-4 months after establishing in the Nile Delta region. This prediction is based on the assumption that these regions have not already been invaded as of this writing.

Travel

Based on the volume of passenger flow from Egypt, several countries in Western Asia, Western and Europe and Northern Africa are at risk from air travel (Fig. 27 b). The top countries are Saudi Arabia (11%), United Arab Emirates (9%), Germany (7%), United Kingdom (6%), and Italy (5%). Again, as discussed previously, the risk would depend on the type of traveler and whether the mode of invasion is baggage or as a stowaway on a flight.

Trade

The region under major threat of FAW due to imports from Egypt is Western Asia, in particular the Middle-Eastern countries and Russia. Several countries import from Egypt. Among these countries, Saudi Arabia (21%) and Russia (18%) are the top importers. It is of interest to note here that FAW eggs have been detected in quarantine, in the Netherlands, on cut roses and vegetables shipped by plane from Kenya, and Zambia (EPPO, 2017).

XII. ECONOMIC IMPACT OF FAW

To compute the impact, we will explore two different measures: 1) the direct impact and, 2) the total impact, following the methodology in Soliman *et al.*, 2012. The direct impact measures the direct revenue loss from the invasion of FAW on each of the crops. This depends on the loss encountered by each crop, the total cultivated area, yield per unit of land, and the price of the crop. The cultivated area multiplied by the yield equals total production. The direct impact, however, does not account for the change in the market price of the crops due to crop loss (hence drop in market supply) or the impact of price change on consumers' and producers' welfare.

To calculate a more comprehensive economic impact, we use the partial equilibrium approach. This approach assumes that the price for substitute and complementary goods remain unchanged. The partial equilibrium method accounts for the shift in the supply curve and the resulting change in market clearing price. To calculate the new equilibrium price, data is needed on demand and supply elasticities for each crop. Once the new price is determined, changes in consumer and producer surplus can be calculated.

Table 4 provides the input data used in the calculation of the economic impact for each crop. Table 5 shows the direct and total economic impact of FAW on each of the eight crops. The economic impact is measured in terms of change in social welfare from before to after the pest invasion. The change in social welfare is measured by the sum of change in consumers' surplus and change in producers' surplus. In order to calculate the change in surplus, we first find the new equilibrium price. Table 5 shows the new equilibrium price for all crops, which is higher than the original price. The consumers' surplus drops for all the crops. The producers' surplus (profits) increases for all crops except for sorghum and soybean.

The reason producers' surplus drops for sorghum and soybean is that the increase in revenue due to higher price is more than compensated by the decrease in revenue due to reduced demand, resulting in net drop in revenue and hence profits. The change in profits depends upon the interplay between supply and demand elasticities, the change in price, loss due to invasion and the amount sold. Note that even though the profits are higher for all other crops, the total social welfare still drops because it is the sum of consumers' and producers' surplus, and the drop in consumers' surplus is higher in magnitude than the increase in producers' surplus. This model does not consider the impact of exports and imports. Only the domestic demand and supply of each crop is considered.

Direct economic loss from a crop = production*proportion lost due to FAW

Total direct economic loss across all 8 crops = $2.68 billion/year (first year of infestation)

Total (direct plus indirect) economic loss= $37.5 billion/year (first year of infestation)

Table 4. Input data used in the calculation of economic impact.

Crop	Proportion lost due to FAW	Production (in tons)	Original Price (USD/ton)	Demand Elasticity	Supply Elasticity
Wheat	0.2	9,279,804	387	0.47	0.38
Maize	0.2	8,059,906	321	0.24	0.57
Rice	0.3	5,467,392	301	0.66	0.21
Sorghum	0.075	804,051	308	0.44	0.5
Sugarcane	0.4	16,055,013	55	0.57	0.09
Cotton	0.3	252,504	1028	0.59	0.67
Soybean	0.1	39,872	565	0.44	0.5
Tomato	0.3	8,288,043	200	0.12	0.5

Data sources:

Production, original price: "Market Information" file.

Proportional loss: These figures are estimates. Same as given in "FAW risk assessment" file.

Demand and supply elasticity: https://www.ers.usda.gov/data-products/commodity-and-food-elasticities/ ; http://ageconsearch.umn.edu/bitstream/59510/2/10-WP_506.pdf

Table 5. Direct and total economic impact of FAW on each of the eight crops.

Crop	New Equilibrium Price (USD)	Direct Loss (millions of USD)	Total Loss (millions of USD)
Wheat	503	718.26	6,769.60
Maize	423	517.45	14,411.04
Rice	454	493.71	1,298.31
Sorghum	335	18.57	670.54
Sugarcane	119	353.21	502.59
Cotton	1,364	77.87	5,592.15
Soybean	632	2.25	85.35
Tomato	356	497.28	8,177.43
Total Loss		**2,678.60**	**37,507.02**

XIII. DEVELOPMENT OF A MANAGEMENT PLAN FOR THE FAW IN EGYPT

The invasion of Egypt by the FAW is inevitable. It may only be a matter of a few months as it has already invaded Sudan, a country south of Egypt. It is expected that the FAW will reach Aswan in the south and then proceed to spread northwards to the Nile Delta. There is also a slight possibility that it could reach the eastern part of the Delta through Yemen and Saudi Arabia east of the Red Sea.

In the development of a management plan, we recommend organization of a network of administrators, scientists, NGOs, extension personnel, and farmers to develop and communicate FAW management strategies. This should be coordinated by the value chain project (ACDI VOCA). To prepare government officials and farmers to combat this pest invasion, it is suggested that awareness workshops be conducted at Aswan, Luxor, and Alexandria and in the eastern part of Delta (Port Said or Mansour) as soon as possible. Workshop participants should include officials from the Ministry of Agriculture, scientists from the Agricultural Research Center, and universities and members of farmers associations.

Outline for an awareness and management workshops in Egypt (Before and after FAW arrival)

1. Taxonomy of *Spodoptera* species
2. FAW biology, distribution in the new world and Africa
3. FAW strains and identification
4. FAW host plants
5. FAW monitoring (see Appendix 2)
6. FAW field observations
7. Phytosanitary and sanitary measures to mitigate the risk
8. Control measures (See appendix 3)
    - Cultural control
    - Mechanical control:
    - Host plant resistance
    - Biological control
    - Botanical pesticides
    - Microbial pesticides
    - Chemical insecticides
9. PERSUAP (Pesticide evaluation report and safer use action plan)

XIV. PREPAREDNESS STEPS

a) Organize a network of administrators, scientists, NGOs, extension personnel and farmers to develop and communicate FAW management strategies.

b) Organize awareness and management training workshops at Aswan, Luxor, Alexandria and Port Said or Mansoura.

c) Farmer training.

d) Strengthen existing biocontrol laboratories in the production and distribution of natural enemies.

e) Provide FAW alerts as it spreads through Egypt.

f) Prepare bulletins and other print media and distribute.

g) Utilize mass media for dissemination of information on management of FAW to the public.

h) Identify safe pesticides to be used in the IPM program (PERSUAP).

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Appendix 1

Data

We used diverse datasets in this analysis: vegetation, climate, production, international trade, and travel. For natural vegetation, we used the normalized difference vegetation index (NDVI) (NEO 2017). NDVI is a numerical indicator that uses near-infrared radiation (NIR) and visible radiation (VIS) of the electromagnetic spectrum. The time resolution for this dataset is one month at a resolution of 0.1 arc degree x 0.1 arc degree. For production, we used spatial distribution data from MAPSPAM. The data is obtained by using machine-learning techniques to estimate global distribution of more than 40 crops using partially available data on production and climatic factors. We identified five major hosts among the data available: wheat, rice, maize, sorghum, and sugarcane. Harvest area was used as an indicator of presence of host. The resolution is 5 minutes x 5 minutes.

We used FAOSTAT's database (FAOSTAT 2017) to analyze Egypt's trade with other countries. For exports, we considered a number of fresh fruits and vegetables: cauliflowers, peppers, cucumbers, eggplants, tomatoes, apples, grapes, oranges, papaya, strawberries and peaches. For international travel, we used the Worldpop and open flights datasets (Mao *et al.*, 2015), which provide information on passenger flows between airports and information about the airports (location, country, etc.) respectively. Finally, to group figures according to regions, we used the UN country grouping scheme.

Spatiotemporal spread model using cellular automata

We adapted a cellular automata (CA)-based diffusion model developed by Guimapi and others (Guimapi *et al.*, 2016). It is intended to capture the natural spread of the FAW accounting for environmental factors, presence of natural vegetation, production of major host plants, the pest's flying capacity, and time to complete a lifecycle.

Role of temperature and humidity

Our model assumes that host presence is an indicator of the suitability for the pest to establish. As discussed by (Abrahams *et al.*, 2017), it is not adequate to consider only temperature data to reasonably estimate the environmental suitability of the pest. Therefore, we used the presence of vegetation and host plants as the indicator of suitability.

Model description

The Cellular Automata (CA) model consists of four components: 1) a grid of cells overlaid on the focus region, 2) cell states, 3) cell state transition rules, and 4) time steps. The focus area is the bounding box -20° to 60° latitude and -40° to 40° longitude encompassing the continent of Africa and parts of Europe and West Asia adjacent to Africa (Fig. 26). A grid of cell size 1°✕1° (approximately 110km✕110km at the equator) was overlaid on the focus region. Each cell can be in one of the following two states: susceptible (S) or invaded (I). Susceptible means the region covered by the cell has not been invaded by the FAW and invaded state corresponds to the situation that the region is infested.

The simulation proceeds in discrete time steps. Each time step corresponds to *t* months, where t can range from 0.5 to 2 months. At any time step, a cell's state is influenced by its closed Moore neighborhood of range *r*. Here, "closed" implies that the current cell's state is also taken into account. When range *r=1*, it corresponds to the 3°×3° cell that includes the current cell and its eight neighbors, when *r=2*, it is the 5°×5° cell including the current cell, its neighbors and all their neighbors, and so on. The current cell's state can change only if its closed Moore neighborhood has an invaded cell, and if this is true, the state transition is governed by a set of simple transition rules. To evaluate the cell's state, the corresponding month's data is applied.

Parameter choices

The model is determined by four inputs: The threshold for vegetation and production, range *r*, the parameter *t* that determines the length in months a simulation step corresponds to.

CA transition rules

A cell is evaluated only if it has a neighbor (depending on range *r*) in state I. If the cell has a NDVI greater than the threshold and if at least the harvested area of one crop (maize, rice, sorghum, sugarcane, and wheat,) is greater than that of the production threshold, the cell is assigned an invaded status. Also, if the NDVI is greater than a second threshold (higher than the first threshold), its state is set to I following Guimapi *et al.* (2016).

Metric for evaluating models

To calibrate our models and compare them we adapt the maximum-likelihood approach of Carrasco *et al.* (2010). Uncertainties and delays in identifying and reporting of the pest's presence (or absence) depends on several factors. This can be mainly attributed to lack of knowledge and infrastructure to monitor and report, which varies from one country to another. Typically, pest reports become more accurate as awareness of invasion spreads. We use the following general framework to compare the model output to pest reports.

Let $t(x, S)$ denote the probability that the pest invades location *x* at time *t* in the simulation output. In our case, *x* corresponds to an administrative region (state, governorate, province, etc.) and *t* corresponds to a month. Let $t(x, G)$ denote the probability that the pest actually invaded *x* at time *t* (G denoting ground truth). While it is impossible to ascertain this value exactly, we can model this based on expert judgement. There are three types of locations;

1) those which are invaded in both simulation output as well as ground-truth, 2) those which are invaded in simulation output, but do not yet report pest presence (false positives), and 3) those which report pest presence, but are not invaded in the simulation output (false negatives).

We evaluated each simulation output based on false positives, false negatives and a score that is computed as follows for locations that correspond to case 1) Let w_u denote the uncertainty interval. Greater the w_u , the lesser the penalty for mismatch between $t(x, G)$ and $t(x, S)$. Let c_x denote the confidence we place in the report from the location. For all locations x such that both $t(x, S)$ and $t(x, G)$ exist, the total score is $score(S, w_u) = \sum c_x fl(|t(x, S) - t(x, G)|/w_{u)}$ where $fl()$ corresponds to the floor function. If the model matches the ground truth, then the score is 0. Therefore, lower the score, the better the fit.

For ground truth, we chose administrative regions of two or more countries each from West, East and Southern Africa. The criteria were confidence in reports based on a several factors: reports from EPPO and FAO, monitoring quality (Early *et al.*, 2016), and general awareness in the region. In addition, we also included some administrative regions of Egypt, Morocco, and even Oman as regions that FAW has not invaded. We used the same confidence for all locations that report FAW ($c_x = 1$).

Appendix 2

FAW monitoring

Populations can be sampled using blacklight traps and pheromone traps. Pheromone traps are very efficient and should be suspended at canopy height during the whorl stage of maize growth. Insect catches indicate the presence of moths in the area but are not necessarily good indicators of density. Once the moths are detected, it is recommended to search for eggs and larvae. A random sampling of 20 plants in five locations, or 10 plants in 10 locations, is generally considered to be adequate to assess the proportion of plants infested. Sampling to determine larval density often requires large sample sizes, especially when larval densities are low or larvae are young, so it is not often used. Traps containing the FAW pheromone should be set up along the Nile riverbanks starting at Aswan (20 traps), Luxor (15 traps), Alexandria (10 traps) and the eastern part of the Delta (10 traps). The traps should be examined weekly. Collected moths should be sent to a specialist for identification and confirmation of FAW. When the FAW is found in a trap(s), neighboring maize fields should be surveyed for FAW infestation. Suspected FAW larvae should be collected, placed in alcohol vials and sent to a specialist for identification and confirmation. Other crop fields such as cotton, rice, sorghum, and sugarcane should also be examined for FAW infestation, as these are also potential host crops

Appendix 3

Control measures

a) **Cultural control**:

1. Planting border rows with maize, a month after planting the main field.

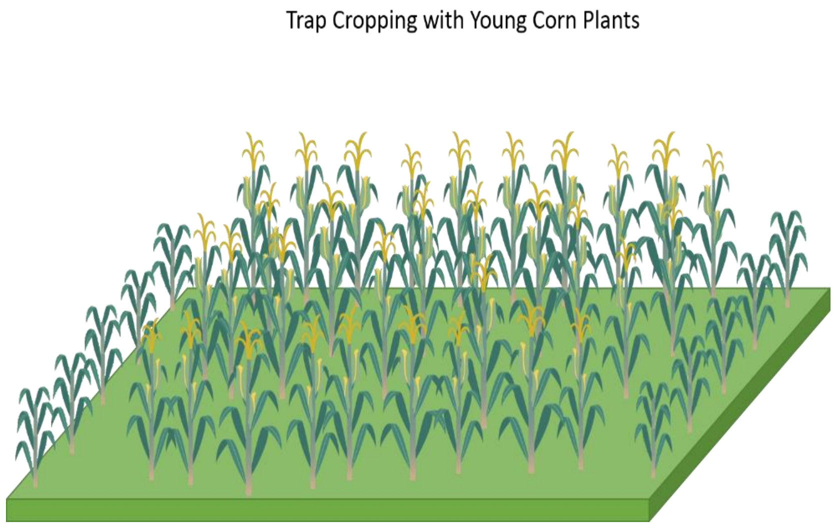

Fig. 29 Trap cropping with young plants

2. Planting a couple of plants taller than maize (such as castor) in the middle of the field to attract moths to lay eggs on them.

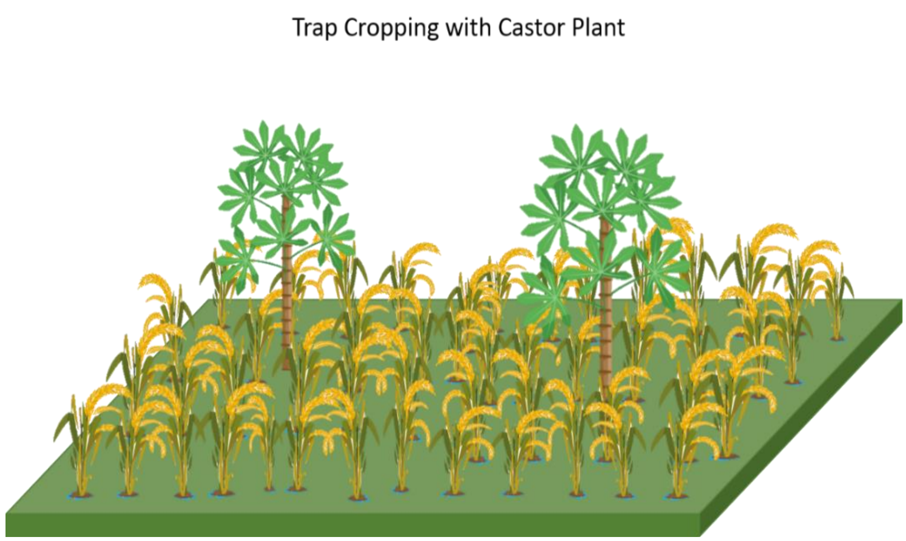

Fig. 30 Trap cropping with Castor plants

3. Intercropping with beans has shown to reduce the FAW infestations by 20-30 percent.

4. Push and pull technique (ICIPE).

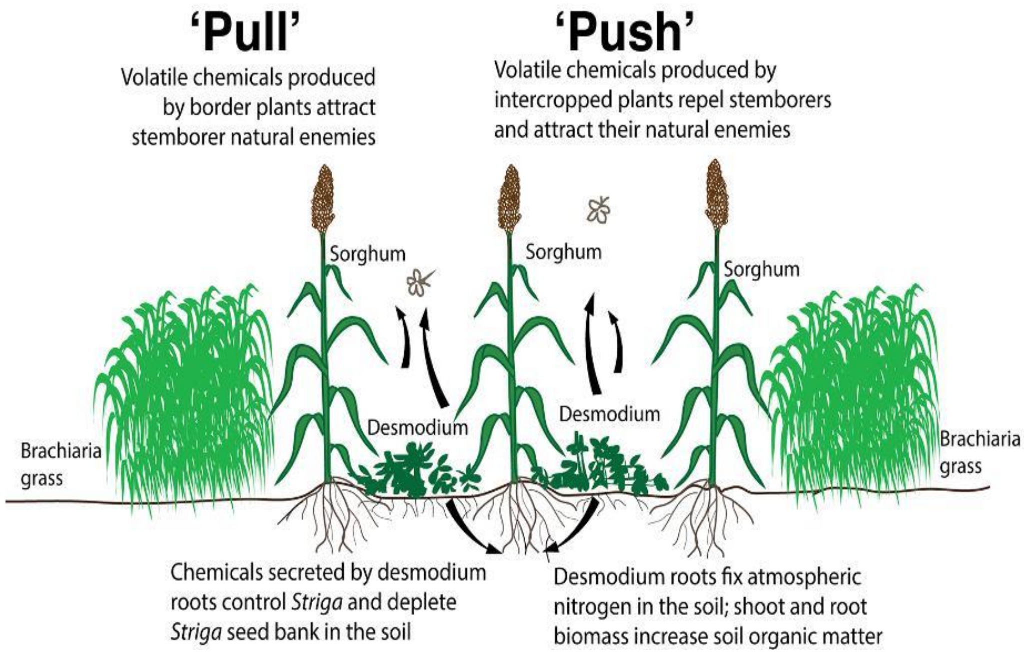

Fig. 31 Push-pull strategy for managing FAW in Africa

b) Mechanical control

Hand picking and squashing eggs and caterpillars of FAW.

c) Host Plant Resistance

(CIMMYT is developing resistant varieties but it will take a couple of years at the minimum)

d) Biological Control

Classical biological control*:* Classical biological control is not to be considered at this stage. Augmentative and conservation biological control options are to be tested before resorting to classical biological control. Egypt is more advanced in augmentative biological control compared to other countries in Africa.

Augmentative biological control*:* There are 24 government and private laboratories in Egypt that produce and supply *Trichogramma* spp. and other natural enemies to farmers for control of various pest species. The biological control laboratory at the Department of Economic Entomology and Pesticides in Cairo University, headed by Dr. Ashraf Arnaouty, is producing *Trichogramma acheae, T. euproctides, Chrysoperla* sp., *Orius* sp., coccinellids, and other natural enemies. Additionally, parasitoids *Trichogrammatoidea bactrae*, *Trichogramma evanescens* and *Telenomus busceola* have been recorded from Egypt. These could be field collected, multiplied and tested for parasitism efficacy on FAW. This laboratory is capable of providing training to technicians from government and private agencies on production of the natural enemies. It could even serve as a regional center for providing training for technicians from East and North African countries. In the past, the IPM Innovation Lab has arranged technicians from Niger and Mali to undergo training on *Trichogramma* spp. production at this facility.

Trichogramma spp. and *Chrysoperla* sp. should be released immediately after the discovery of FAW in an area to minimize the damage caused by FAW. Surveys for local natural enemies recruited by FAW should be started and continued. Natural enemies collected should be identified and evaluated for their efficacy against FAW. Effective ones can be mass multiplied and released in the field.

Conservation biological control*:* Broad spectrum chemical pesticides should be avoided. Pesticides that are compatible with natural enemies should be selected and used.

e) Botanical Pesticides

One of the private pesticide companies in Egypt producing neem extract and using it for control of pests in the fields. This company should be supported to enhance its production of neem products and their quality control and distribution. Experiments need to be conducted to integrate neem products in the management of FAW in the maize IPM program.

f) Microbial Pesticides

Use of *Beauveria bassiana*, *Metarhizium anisopliae*, *Bacillus thuringiensis*, and NPVs should be explored.

g) Chemical insecticides

Insecticides are considered a main control option in response to FAW outbreaks. However, there are major limitations to the use of chemicals. The FAW larvae are often inaccessible to insecticides because of their tendency to hide in the whorls and reproductive parts of the host plant, limiting the efficacy of spraying.

Under African conditions, insecticides can be expensive and many subsistence farmers cannot afford chemical control methods. Spraying large areas of food crops and pastures with insecticides can be problematic in low income countries, as appropriate safety procedures may not be implemented on a regular basis. Personal protective equipment may not be widely available or affordable to subsistence farmers, which increases the risk of pesticide exposure and pesticide poisoning. Management using insecticides should be considered when substantial damage occurs on at least 25 percent of the plants. If high levels of damage are noted in isolated areas of a field, spot treatments may be warranted. For an effective control and an adequate penetration by insecticides, spraying should be done in the late afternoon or early evening, before the larvae burrow into the whorls or ears. Various insecticides recommended for FAW include pyrethroids, carbamates, and organophosphates. Granular insecticides can also be applied over the young plants because the particles fall deep into the whorl. However, a reliance on chemical control to manage pest populations has become increasingly ineffective as regional populations develop resistance to several toxicological groups of insecticides.

PERSUAP (Pesticide evaluation report and safer use action plan). A PERSUAP for the FAW in Africa has been developed by IPM Innovation Lab and has been approved by the Bureau of Food Security, USAID. If needed, it could be modified for use in Egypt.