Invasion of fall armyworm (*Spodoptera frugiperda*) in India: nature, distribution, management and potential impact

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Fall armyworm (FAW; *Spodoptera frugiperda* (J. E. Smith)) is emerging as the most destructive pest of maize in India since its report in May 2018. Its rapid spread to more than 90% of maize-growing areas of diverse agro-ecologies of India within a span of 16 months presents a major challenge to smallholder maize farmers, maize-based industry, as well as food and nutritional security. FAW has been reported from other crops as well like sorghum and millets with varied proportion of economic damage. In this review, the transboundary movement of FAW, role of ecology, its spread and damage are discussed. Management of FAW by developing and deploying various pest management tools is elaborated. The role of agro-ecological measures for reducing FAW damage with African experiences has also been highlighted.

Keywords: Agro-ecology, fall armyworm, host plant resistance, integrated pest management, transgenics.

MAIZE (*Zea mays* L.) is the most important cereal crop being cultivated in an area of 180.63 m ha in 165 countries across the world with a production of 1134 million tonnes growing at an average annual rate of 3.46% (ref. 1). It is widely valued for its extensive use as feed, fodder and as raw material for a large number of industrial applications[2]. In India, maize is the third most important cereal after rice and wheat, both in terms of area and production, registering maximum growth rate among food crops[3]. Though maize is emerging as an important industrial crop in India, its productivity (3.1 tonne/ha) is much lower than the world average (5.62 tonne/ha)[3]. Besides socio-economic factors like low adoption of hybrids and lack of policy support to the maize farmers, biotic and abiotic stresses are significant bottlenecks in attaining

fullest potential of the yield gains in maize. In India till recently three insect pests, viz. spotted stem borer (*Chilo partellus* Swinhoe), pink stem borer (*Sesamia inferens* Walker) and shoot fly (*Atherigona* spp.) were of major consequences. Since the report of the invasive pest fall armyworm (FAW; *Spodoptera frugiperda* J. E. Smith) in maize in May 2018, it has spread rapidly to all maize-growing ecologies of India, except Himachal Pradesh, and Jammu and Kashmir within a span of 16 months, casting a shadow on maize production in the country. In this article, we discuss the ecology and behaviour, extent of the spread of this insect in India and beyond in the sub-continent, strategies to manage its potential impact on maize production.

Transboundary movement of fall armyworm

Fall armyworm (FAW) is native to tropical and subtropical Americas and is known as a sporadic pest in the United States since 1797. A severe outbreak of FAW on corn and millets was documented in 1912 (ref. 4). In Latin America, FAW was observed to cause up to 73% yield loss in maize[5]. Outside Americas FAW first invaded Africa, as reported from Sao Tome, Nigeria, Benin and Togo in 2016 (ref. 6). In India, its presence was confirmed in May 2018 by the University of Agricultural and Horticultural Sciences, Shivamogga, Karnataka[7]. Since then, it has spread within the country and moved eastwards to countries bordering India, viz. Bangladesh (December 2018), Myanmar (December 2018), Sri Lanka (January 2019), China (January 2019) and Nepal, and to Thailand (December 2018), South Korea and Japan (July 2019). Temporal spread of FAW within India has been documented[8] since its report from Karnataka in May 2018. FAW spread from peninsular India to the North and North East during 2018 and early 2019 respectively. With the
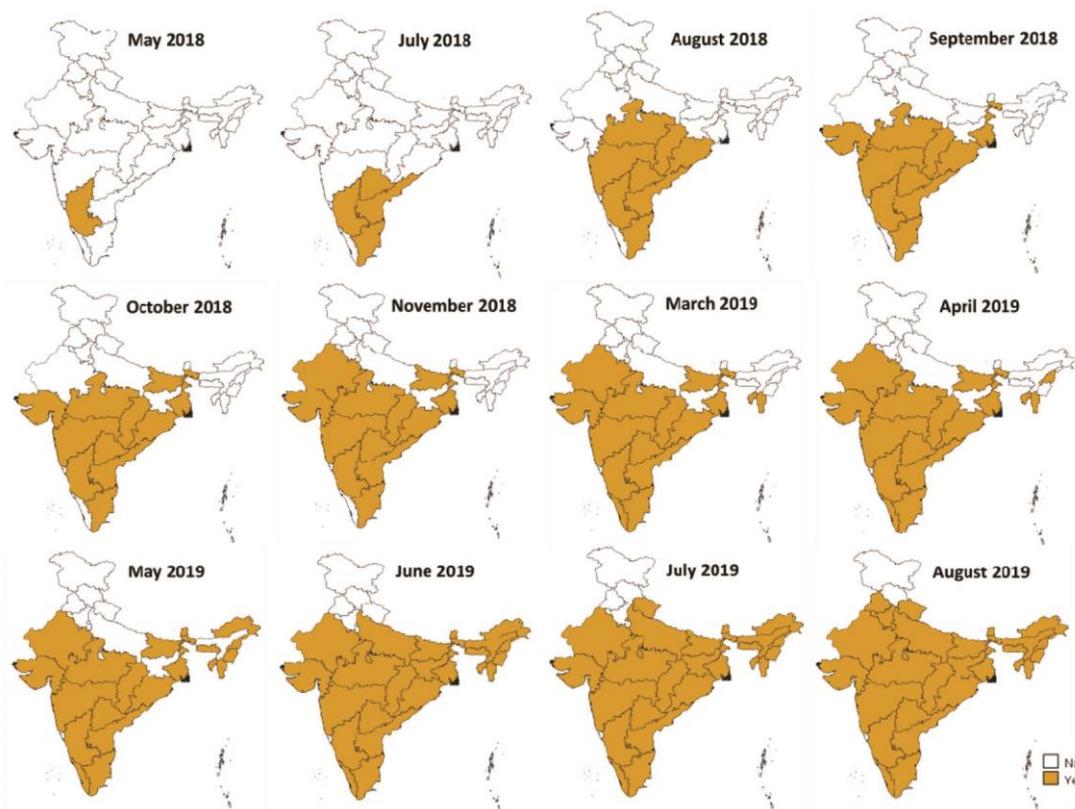
Figure 1. Temporal spread of fall armyworm (FAW) in India from May 2018 to August 2019, colouration of the states indicates reporting of FAW and does not indicate the intensity of damage (reproduced from Rakshit *et al*.)

progression of the 2019 monsoon, FAW incidence has been reported from the northern and northwestern parts of the country as well (Figure 1).

Host preference and economic damage

FAW is a polyphagous pest reported to attack 353 plant species belonging to 76 plant families[9]. However, it is primarily a pest of grasses, preferring maize the most. Besides, it can also cause economic damage to other cereals and millets. FAW attacks maize from seedling emergence to ear development stage. The female lays over a thousand eggs in single or multiple clusters. Upon hatching, the early instar secretes silken thread and is dispersed through wind (Figure 2 *a*). The first and second instar larvae found on the upper surface of the leaves scrape the epidermis resulting in elongated papery windows all over the leaves (Figure 2 *a* and *b*). Third instar onwards, the larvae settle in the whorl and their feeding renders a series of holes and faecal matter in the unfurling leaves. Their feeding rate increases with growth; thus, the size of holes and amount of faecal matter also increase (Figure 2 *c*). The sixth instar larvae defoliate heavily and leave a large amount of faecal matter in the plant whorl. Older larvae sometimes bore the developing internodes of early whorl stage of maize and cause plant death (Figure 2 *d*). The larvae may attack tassel (Figure 2 *e*) and developing ears (Figure 2 *f*) as well. First to third instar larvae of FAW are quiet small and eat 2% of the total foliage consumed in their life cycle, while it is 4.7%, 16.3% and 77.2% for the fourth, fifth and sixth instars which heavily defoliate the crop[10]. Besides maize, FAW incidence was closely monitored in sorghum and other millet fields during both kharif 2018 and rabi 2018–19. Based on the whorl damage, sorghum was found to be the most preferred host among millets (60.1%), followed by pearl millet (41.4%), barnyard millet (22.9%) and finger millet (10.2%)[11].

FAW consists of two strains, viz. corn strain 'C' which feeds predominantly on maize, sorghum and cotton, and rice strain 'R' which prefers rice and turf grass[12]. Molecular genetic diversity studies suggest that the FAW population in India belongs to the 'R' strain based on polymorphisms in the *Cytochrome oxidase subunit I* gene (*COI*)[13]. Later, using other markers the Indian FAW population was found to be predominantly 'C' type by *Tpi* and 'R' type by *COI*, which strongly indicates inter-strain hybrids of FAW in Africa and India, arising from a common small founder population[14]. The FAW genome, as sequenced from Sf21 cell line, is 358 Mb in size with 11,595 genes and shares significant homology with that
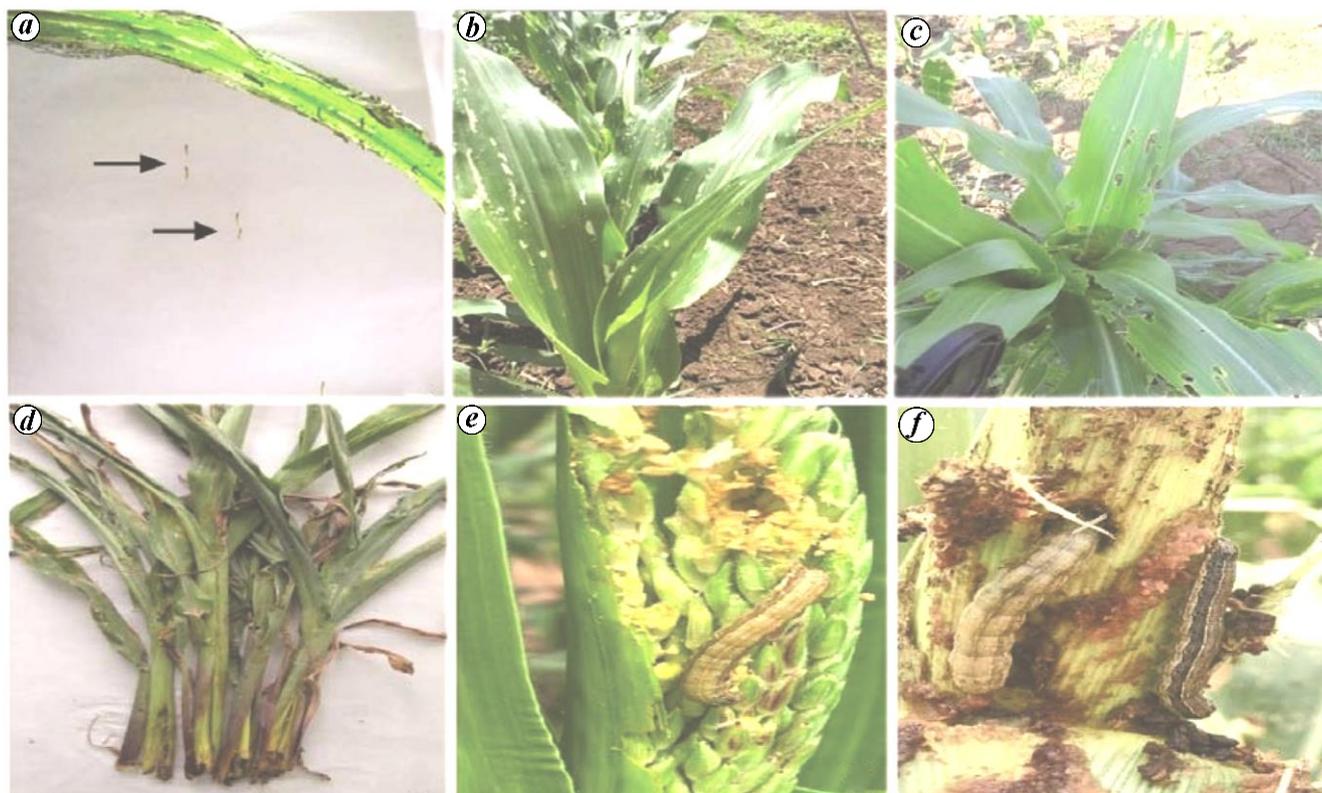
Figure 2. (*a*) Dispersal of FAW 1st instar larvae through ballooning (arrow marks), (*b*, *c*) damage of maize foliage, (*d*) dead maize plants by FAW boring into the developing stalk, (*e*) tassel damage and (*f*) cob damage.

of the silkworm genome [15]. However, FAW genome from Sf9 cell line reported 451 Mb genome size. The genomes of both C and R strains as sequenced are 438 and 371 Mb respectively[16]. The C strain contains 21,700 protein coding genes, whereas the R strain is predicted to have 26,329 genes. Significant expansions of genes associated with chemosensation and detoxification were found in FAW. These expansions are largely attributable to tandem duplications, a possible adaptation mechanism enabling polyphagy. Recently, two chromosome-level FAW genomes were reported using one male and one female adult moth collected from the Yunnan Province, China[17]. The genome size was found to be 542.42 Mb for male and 530.77 Mb for female with 22,201 predicted genes in the male genome. A notable expansion of cytochrome P450 and glutathione *S-transferase* gene families often associated with pesticide detoxification and tolerance was found.

Strategies adopted for management

Host plant resistance

Host plant resistance (HPR) to herbivorous insects is widely involved in crop protection against insect pests. A number of maize germplasm sources of temperate and tropical background have been reported as sources of resistance to FAW due to low foliar damage (Supplementary Table 1). First reported FAW resistant lines were selected from Antigua 2D × (B10 × B14) and Texas Experimental Hybrid 6417 (ref. 18). Classical plant breeding efforts over the years by researchers from USDA-ARS on germplasm of Caribbean origin, particularly Antigua, yielded a number of temperate maize inbred lines combining resistance to FAW and southwestern corn borer. Resistant lines developed are presented in the Supplementary Table 1 (refs 19–32). Since the onset of FAW attack in India, a large set of diverse maize germplasms are being screened for FAW resistance at the Winter Nursery Centre of ICAR-IIMR, Hyderabad under natural infestation, assured with early planting of susceptible lines all around the field. In this process, seven promising maize lines, viz. DMR E63/CML 287-4-14-2B, DMR E63/CML 287-2-3-2⊗⊗⊗⊗⊗, DMR E63/CML 287-3-3-⊗⊗⊗⊗⊗, DMR E63/CML 287-4-14-3B, DMR E63/CML 287-4-89-4B, DMR E63/CML 287-5-4-1B and P31C4S5B-85-##-1-4-5-B*5-1-B-1 have been identified as resistant to FAW, which needs further confirmation.

Resistant sources against FAW have been reported in sorghum at various crop growth stages[33,34]. Sorghum accession, plant introduction (PI) 147573 was resistant to

FAW over MP 708 (resistant check), but at 14 days after infestation all the 9 sorghum accessions were as resistant as MP 708 with significantly less damage than AB24E (susceptible check). This suggests that sorghum possesses induced resistance in the whorl[35]. FAW resistance in pearl millet was also reported in Tifton no. 153 and Tifton no. 240, and antibiosis was attributed to be the resistance mechanism[36].

Mechanisms of host plant resistance

Plants combat herbivorous insects by means of physiological, morphological and biochemical defence mechanisms. Mophological features attributed to FAW resistance include leaf toughness[37], trichome density[38] and thicker cell wall complex of epidermal layer[39] which acts as a barrier to prevent insect feeding. The biochemical traits, viz. abundance of crude and acid detergent fibre[40] were reported to confer FAW resistance in maize. Higher concentration of amino acids, viz. aspartic acid and tyrosine[41] confers FAW resistance in maize, whereas higher concentrations of total nitrogen was highly correlated with FAW resistance in sorghum[34]. Higher amounts of leaf cuticular lipids[41], polyphenol compounds maysin and chlorogenic acid[42] and benzoxazinoids (BXs) play a crucial role in maize defence against insect herbivores[43]. The FAW resistant Antiguan inbred MP 708 contains elevated defensive proteins[44]; higher levels of JA[45] and (E)-β-caryophyllene-JA responsive indirect defence volatile[46].

The myriad mechanisms of FAW resistance reported above in diverse maize germplasms suggest the quantitative nature of resistance. The key genomic regions were identified on chromosomes 1, 5, 7 and 9 in MP 704 and MP 708 (refs 47, 48; these have combined resistance to both FAW and southwestern corn borer). Subsequently, using composite interval mapping (CIM) and multiple interval mapping (MIM), 24 QTLs explaining up to 26.5% of the total phenotypic variation, and 36 QTLs and 10 interactions for FAW leaf-feeding damage in MP 704 were identified[49]. However, no resistance gene (R gene) has been identified to confer tolerance against chewing herbivores in maize or any other crop plant so far.

Transgenics

The advent of transgenic maize expressing *Bt* proteins was a significant progress in insect–pest management. In maize, a total of 179 events have been commercially approved for cultivation with lepidopteran insect resistance trait across 13 countries. All these events harbour one or more combinations of 13 different *cry* genes (Supplementary Table 2). Out of the 13 *cry* genes, 7 have been specifically identified for conferring FAW resistance. These are *vip3Aa20*, *cry1F*, *cry1Fa2*, *cry1A.105*, *cry2Ab2*, *cry1Ab* and *mocry1F*. The plant-expressed *Bt*

proteins confer resistance to lepidopteran insects by selectively damaging their midgut lining. *Bt* maize, especially with *Cry1F* was found to reduce more than 50% of the FAW population[50]. In the last few years, field-evolved resistance to *Cry1F* and *Cry1Ab* expressing maize has been reported in some FAW populations from Puerto Rico, Florida and North Carolina[51,52], Brazil[53] and Argentina[54]. Field observations showed that *Cry1Ab* maize provided partial control of *Spodoptera frugiperda* in field trials conducted with drought-tolerant *Bt* maize varieties in East Africa[55]. The emerging scenario of breakdown of resistance of *Bt* transgenics against some populations of FAW points to the need of greater attention to insect resistance management strategies at the field level.

Management of fall armyworm

Since the occurrence of FAW, chemical insecticides have been widely used for its management in maize. The efficacy of selected synthetic insecticides was tested against FAW in maize[56]. Control of FAW in early instar is more effective than attempting controlling at late stages when they are stronger to resist control measures and the damage caused is also more significant. Therefore, monitoring activities together with need-based application of insecticides is necessary for sustainable management of FAW. Currently, in India, the Central Insecticide Board and Registration Committee (CIB and RC) has recommended the insecticides, namely chlorantraniliprole 18.5 SC @ 0.4 ml/l, spinetoram 11.7 % SC @ 0.5 ml/l, thiamethoxam 12.6% + lambda cyhalothrin 9.5% ZC @ 0.25 ml/l for minimizing the damage in maize. The Government of India (GoI) has recently recommended the use of cyantraniliprole 19.8% + thiamethoxam 19.8% FS @ 6 ml/kg seed as seed treatment against FAW.

Biorational pesticides

Integrated use of various non-chemical management options significantly reduces dependence on chemical pesticides for the management of insect pests. Various options available to manage FAW are discussed below.

Entomopathogenic microbes, nematodes and viruses: Entomopathogens such as fungi, bacteria, nematodes and viruses have shown potential for the control of FAW[57–62] (Supplementary Table 3). Among the naturally occurring insect viruses, multiple nucleopolyhedrovirus (SfMNPV) has potential for use in the management of FAW[63]. Natural epizootics of *Metarrhizium rileyi* (Figure 3) were reported to cause significant larval mortality ranging from 1.87% to 18.30% in Karnataka[64]. It was observed that entomofungal pathogen *Nomuraea rileyi* caused 10–15% larval infection[65,66].

Parasitoids and predators

Surveys have documented large numbers of parasitoids and predator species emerging from FAW larvae from various studies[65–71]. Larval parasitoids *Coccygidium melleum*, *Eriborus* sp., *Exorista sorbillans* and predators *Harmonia octomaculata*, *Coccinella transversalis* were reported[65]. Other parasitoid species that emerged from FAW were egg parasitoids *Telenomus* sp., *Trichogramma* sp., gregarious larval parasitoid *Glyptapanteles creatonoti* and solitary larval parasitoid *Campoletis chloridae*[66]; other than these predators *Forficula* was also reported[66]. Solitary endo-parasitoids *Cotesia marginiventris* (Cresson) and *Chelonus insularis* Cresson. were reported from FAW larvae[69,70] (Supplementary Table 4). Egg larval parasitoid *Chelonus* sp. was found predominant, which has a potential for biological control of FAW[71]. Other common FAW predators observed in maize are pentatomid bugs, spiders, predatory wasps, ladybird beetles, mirid bugs, earwigs and rove beetles[71].

Botanicals

Plant-derived pesticides are attractive alternatives to synthetic insecticides and constitute an affordable tool for insect pest management. Several plant species have shown insecticidal properties against FAW[72–74] (Supplementary Table 5). Extracts of neem, *Azadirachta indica*, boldo *Peumus boldus* Molina[75], *Schinnus molle*, *Phytolacca dodecandra*[56], *Argemone ochroleuca* Sweet (Papaveraceae)[76], garlic + neem[77] showed efficacy against FAW larvae. At present, potent botanicals against FAW have to be identified. Multi-location field studies and compatibility of botanical pesticides with other pest management options should be conducted to assess their efficacy.

Semiochemicals

The pheromone composition of FAW females has been identified as a major and two minor components. (*Z*)-9-tetradecenyl acetate (Z9-14 : OAc) was a major component of the sex pheromone of FAW females[78] and the same has been identified from the moths collected from India. FAW pheromone has been recommended for monitoring and mass trapping. Efforts are being made to utilize the pheromone blends for mating disruption in FAW. The field efficacy of the lures ranges from 20 to 30 days and warrants frequent replacement, which adds to the cost of lure and labour for replacing them. The efficacy and dissipation of the release matrix is to be evaluated across the maize-growing tracts of India.

Agro-ecological interventions for management

Agro-ecological interventions are a core component of IPM integrating with breeding for pest resistance, biological control and safer pesticides. Cultural practices improve crop health, reduce pest population, and also provide shelter and alternative food sources to natural enemies of FAW, thus facilitating natural control[79]. Details of cultural and landscape management options are provided in the Supplementary Table 6 (refs 80–83).

In habitat management through 'push–pull' technology, pest-repelling legumes like *Desmodium* spp. or *Tephrosia* planted as intercrop 'push' the insect outside crop areas, while on the border pest-attractive trap plant species such as napier grass or *Brachiaria* spp. are planted to 'pull' the pest towards them. Intercropping with *Tephrosia* and *Desmodium* was found to reduce the number of FAW eggs laid on maize[84]. Identifying the location-specific intercropping/mixed cropping systems suited to varied agro-ecological regions for India could be the most sustainable technology, especially for smallholder farmers. Similarly, managing FAW by crop rotation, nutrient and water management needs standardization in the Indian conditions.

Integrated pest management strategy for management

An IPM package for FAW in maize was made by ICAR-IIMR in collaboration with ICAR-NBAIR and communicated to various stakeholders. Infestation threshold for the crop growth stages and spray schedule have been documented[8].

Intensity in India and possible impact on maize production

The cumulative data published by the Department of Agriculture Cooperation and Farmers Welfare, GoI on 25 June 2019, indicate that Karnataka has the highest area affected with FAW (211,300 ha), followed by Telangana (24,288 ha), Maharashtra (5144 ha) and others[8]. FAW has

Figure 3. *Nomuraea rileyi* infected FAW larva.

been reported to cause economic damage in Tamil Nadu, Karnataka, Andhra Pradesh, Telangana and Maharashtra during rainy and post-rainy seasons of 2018 and 2019; Tripura during the last week of March 2019 and Mizoram in May 2019. With the behaviour of FAW, the pest may not establish or cause economic damage where the temperature drops below 10°C and rises beyond 40°C. This may be the reason for the mild infestation of FAW in northern Rajasthan, Haryana and Punjab. FAW may not be a threat to the temperate northern hill zone as well, where the temperature drops well below 10°C during winter months. However, effective awareness campaigns coordinated with control measures could effectively contain the damage caused by the insect[8]. FAW is predicted to cause 21–53% loss in annual maize production in the absence of control measures[85], while conservative estimates show yield reduction of 14.3–22.7% (ref. 86). However, rough estimates within India do not suggest damage of more than 5–10% (based on field experience). Good rainfall and better management compensate the initial damage caused by the pest in majority of cases. However, if 5–10% loss in production is assumed in the affected maize areas, this amounts to reduction in total maize output by 37,000–75,000 tonnes in India. The estimate may increase or decrease depending on further spread or containment of FAW. This needs to be studied in detail in different agro-climatic zones of India.

Conclusion

FAW with its remarkable dispersal ability and preference for warmer temperature has spread from its tropical and subtropical habitat of the Americas. With the initial onslaught of FAW, GoI initiated timely strategies at policy level by establishing High Powered Committees both at Central and State levels in the FAW-affected states, extending label claims on insecticides against control of FAW. The research institutes, network projects and agricultural universities under the National Agricultural Research System, GoI, played a proactive role towards creation of awareness and management of FAW. India has taken a major role in managing FAW, which may be extended to other countries in the region under South–South collaboration.

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