Fall Armyworm: Current Status in Nepal, its Management and Way Forward

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ABSTRACT

Fall armyworm (FAW), *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), is an economically important invasive pest species primarily infesting maize. It is highly polyphagous and migratory in nature, posing a threat to several economically important crops. This pest has traveled a long journey from the American continent to Asia via Africa. This insect has inflicted substantial damage to Maize's crop productivity of Maize in Nepal, since its introduction in May 2019 and has now become widespread from plain regions to hilly regions of the country. Therefore, this pest problem is considered a major issue for research and development in the country. The lessons from world research and development in the fall armyworm management could be adapted and used in Nepal after its proper validation. In order to identify the current status of fall armyworm in Nepal and the management of the insect species, we have discussed overviews on biology, ecology, origin and distribution pathway, management, and way forward, focusing on sustainable measures which could be useful for designing integrated pest management of fall armyworm in Nepal since knowledge gap is large.

Keywords: Invasive, Lepidoptera, Maize, Pest

1. INTRODUCTION

Fall Armyworm, *Spodoptera frugiperda* (Lepidoptera: Noctuidae), is an invasive insect species native to the tropical and subtropical regions of the American continent (Capinera 2020), but has already invaded Africa, Asia, and Oceania (Overton *et al.* 2021). This notorious pest has also invaded Southeast Asia, including Nepal (Bajracharya *et al.*, 2020). The host range of fall armyworm comprises around 353 plant species, including 76 families of various grain and vegetable crops, including maize, rice, millet, sorghum, wheat, sugarcane, millet, cotton, soybean, cowpea, potato, groundnut, etc. (Montezano *et al.* 2018; Pogue 2002; Goergen *et al.* 2016). However, this pest has more preference over Poaceae, particularly maize (Luginbill 1928; Ayra-Pardo *et al.* 2021).

When an abundant population gets built up in any crop, this pest starts to disperse in masses like the army of the battlefield for searching plant food, so these insects got the name armyworm. The evilest ones to inflict damage on the crop are the late instars whereas the early ones could not cause significant damage or the plant could revive the damage (Ayra-Pardo *et al.* 2021), but it also depends on the crop growth stages. These insect's larvae feed on whorls of young leaves, tassels, and ears, inflicting significant damage to maize. Larvae of fall armyworms can cut the stem base of seedlings and may result in a total loss (Goergen *et al.* 2016). They also bore the base of the seedlings of the young maize plant so that the infestation of fall armyworm can cause the premature death of the plant (Harrison *et al.* 2019). Whereas adult moths are benign in feeding and sipping the nectar of plant flowers.

Fall armyworm has caused huge economic damage to agricultural production in many parts of the world. This pest has been seen as a major threat to the food security and income of the rural population of Africa and Asia and mainly to the maize growers. An estimation done in 2018 for 12 countries in Africa has reported that this pest alone has caused 17.7 million tons of losses in maize production (Ayra-Pardo *et al.* 2021). It is also estimated that this insect alone has the probability of causing US $ 13 billion crop losses in sub-Saharan Africa, which could worsen the food supply in the region (Harrison *et al.* 2019). Yield loss due to infestation of this pest is reported to be higher. In Honduras only, maize production declined by 40% (Wyckhuys and O'Neil 2006) and 72% in Argentina (Murúa *et al.* 2006).

After the introduction of fall armyworms in Nepal, the pest started to disperse throughout the country. With the rise of fall armyworm as a key pest for cereal crops, it is anticipated that the pest could significantly lower the production of the major cereal crops of Nepal and may risk the food security in the country. This would especially hamper the small-scale farmers of the country, which are in the majority. It is estimated that this pest could lower the 34% yield in cereal grains (Lima *et al.* 2010) and pose a serious threat to the country's food security. Among cereal crops, maize is the second most important crop of Nepal after rice, grown in all major climatic regions of the country from the foothills to the mountains (Sharma *et al.* 2019) and immensely consumed as a staple in the mid-hills of Nepal, while productivity is reported to be much less (2.84 mt/ha). Since the insect, i.e., fall armyworm, targets the maize crop, the productivity of the maize crop could be greatly reduced. This will undermine the food supply, food security, and profitability of the farmers from maize farming in the region. Therefore, the present review work was carried out to highlight the current status of fall armyworms in Nepal, its management, and future recommendations to help to design appropriate management techniques suitable to Nepal.

2. BIOLOGY OF THE FALL ARMYWORM

Fall armyworm does have complete metamorphosis with subsequent egg, larval, pupal, and adult stages, as depicted in Fig.1. The adult female lays eggs on the ventral side of the leaves, usually near the base of the plant, but when the population is high they lay eggs on the whorls or the stems. They lay eggs in batches with 6-10 egg batches, each containing about 100-200 eggs. One mature female can lay about 1200 to 2000 eggs for 2-3 weeks (CABI

2017; FAO 2018). The incubation period of an egg is 4-6 days, whereas that of a larva is 14-17 days (Firake *et al.* 2019). The larva does have six instars, and the matured one is about 38-51 mm in length. The larval stage is voracious and the most destructive with biting and chewing mouthparts. The distinguishing character of the larvae has a darker head with a pale-colored Y-shaped mark on the front. Newly hatched larvae feed the tissues where the eggs have been deposited and then move towards the top of the plants where light is plenty and disperses all around the plant with the help of thread they develop (van Huis 1981). Once larger, these larvae start migrating to other host plants (CABI 2017). The pupal stage is found underground, mostly 2-8 cm beneath the soil, and the cocoons are made from the soil and silk, which is reddish-brown (PQPMC 2019). When the soil is too hard to penetrate, they can also pupate in the leaf debris (FAO 2018). Generally pupal period ranges from 7-8 days (Firake *et al.* 2019). The adult is greyish brown with the capacity to have long flights (PQPMC 2019). Their longevity ranges from 7-9 days (Firake *et al.* 2019). This insect has a nocturnal habit. Life cycle durationlife cycle duration can vary according to different seasons, i.e., 30 days during the summer, 60 days in the spring and autumn, and 80 to 90 days during the winter (Capinera 2020). Their growth and development are highly influenced by the temperature they are exposed to.

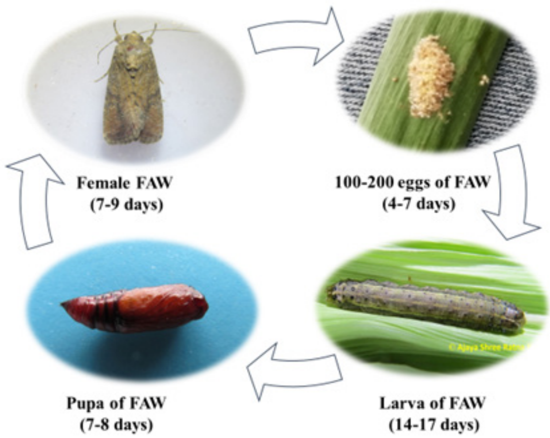

Fig.1 Life cycle of Fall Armyworm (FAW)

3. ECOLOGY OF FALL ARMYWORM

3.1 Host Range and Nature of Damage

The two strains of fall armyworm have been reported, i.e., rice strain (R-strain) prefers rice and maize strain (C-strain) prefers maize, while both strains feed on maize (Harrison *et al.* 2019; Sparks1979). They are morphologically identical but could be detected by molecular technique i.e., DNA barcoding (Cock *et al.* 2017). These strains are different in terms of genetics and behavior (Frerot *et al.* 2017). However, both strains are polyphagous in feeding habit, requiring many plant species to feed on (Casmuz *et al.* 2010; Montezano *et al.* 2018). The first and second instar of the insect is usually found on the leaves, which scrape the epidermal tissues making papery windows to the leaves (Fig. 2a). But, later ones make a hole through the leaf. The damage of matured larvae could besimilar to the cutworms because these insects' larvae also separate the stems from the base of young seedlings of maize plants (Goergen *et al.* 2016). During the day,, the caterpillar hides on the whorls of the maize plant; at night, they feed inside, the caterpillar hides on the whorls of the maize plant, and at night, they feed inside whorls and eat developing silks and tassels (Fig 2b). Due to this, fertilization may also be hampered in the maize. Damage to cobs by the fall armyworm (Fig. 2c) may cause fungal infection and deterioration of the quality of grains (Malo & Hore 2019).

a. FAW initial infestation in leaf

b. FAW infestation in maize whorl

c. FAW infestation in maize cob

Fig. 2 Nature of damage of Fall Armyworm in maize crop

3.2 Migratory Capacity of Fall Armyworm

Like other noctuid moths, fall armyworms are good fliers. Migration through flight enables them to go off from the places where they have been hatched and developed into the places where they can reproduce. In the native region, this insect can fly over a long distance in a single night, i.e., about 100 kilometers. On average, these insects migrate 300 miles (500 kilometers) and produce a generation (Johnson 1987). It is also reported that this insect flies even more during egg lay i.e., almost 500 km (Padhee & Prasanna 2019). The strong migratory capacity of the insects enables them to use the available food resources more efficiently and find new food resources if the food becomes depleted. Fall armyworms cannot survive the cold, freezing winter, but they migrate to a suitable habitat.

4. DIFFERENCES IN INFESTATION OF FALL ARMYWORM AND OTHER INSECTS

Like other insects (for instance, maize stem borer), its infestation in only vegetative stages can be tolerated by the plant. However, feeding damage at the reproductive stage of maize is primarily responsible for reducing the yield. So, the yield loss is basically influenced by the growth stages of maize (Abrahams *et al.* 2017; Capinera 2020; Sisay *et al.* 2019). When fall armyworm infests the maize, it primarily causes serious leaf damage. Although these insects can damage all the stages of maize, i.e., from seedling emergence to the ear development stage, they are more concentrated on the vegetative stage before silk emergence. Young caterpillars feed superficially on the underside of leaves, resulting in the semitransparent patches in the leaves, i.e., windowpanes. This sort of damage is similar to the damage caused by maize stem borer, but generally, big holes are made by fall armyworm infestation compared to stem borer (Goergen *et al.* 2016; FAO 2018). However, later on, instars of fall armyworm infestation become more severe, causing skeletonized leaves and highly windowed whorls (Goergen *et al.* 2016). Later, when maize leaves become more matur, they prefer leaf whorls of maize, whereas leaves near the cob silks are preferred later (PQPMC 2019). When these insects attack the leaf whorl, dead heart, drying, and wilting of the growing leaveare observed (Day *et al.* 2017). Matured stem borer larvae are more present in the stem than whorl, and holes in the stem, and excreta could be seen at the entrances (FAO 2018). Farmers in Kenya and Ethiopia have reported that fall armyworm infestation is even more severe than the maize stem borer (Kumela *et al.* 2018).

5. NATIVE CHARACTERISTICS OF FALL ARMYWORM IN NORTH AMERICA, MIGRATION HISTORY ACROSS AFRICA AND ASIA

In the United States, the fall armyworm population migrates from the eastern and central regions, which are the warmer regions of the country (Nagoshi *et al.* 2012). Typically, they survive during the winter in Texas and Florida, and with the onset of the spring season, they start to move northwards (Wiseman 1985). In North America, it has been recorded that this insect has flown to Canada from Mississippi in 30 hours (Abrahams *et al.* 2017). It should have originated from the tropics, as evidence suggests that it could not survive in the northern temperate region of the USA (Johnson 1987). This insect is well established in the region, and due to the check down of natural enemies, they could not damage at an outbreak level.

This first migrated to the African continent in early 2016 but quickly spread throughout Africa and started to cause a major decline in maize production. This pest firstly appeared in Nigeria, and Western Africa (Goergen *et al.* 2016). It has rapidly spread over 30 countries in the same year, including southern, northern, and eastern Africa (Kumela *et al.* 2018; Rioba & Stevenson 2020). In the Sub-Saharan region of Africa, this pest is causing significant damage (US $ 13 billion) to crops such as rice, maize, sorghum and sugarcane (Abrahams *et al.* 2017).

It is speculated that this insect did not migrate on its own but landed in Africa as an airplane passenger (Early *et al.* 2018; Cock *et al.* 2017). Molecular data suggests that this insect came to Togo from an area in between Eastern USA, Caribbean and Lesser Antilles (Early *et al.* 2018; Nagoshi *et al.* 2017). Both the strains of fall armyworm are found in Africa now (Early *et al.* 2018; Cock *et al.* 2017; Nagoshi *et al.* 2017) It may be true that the rapid spread in between African countries was possible due to inter-national transportation (Faulkner *et al.* 2017). The population of fall armyworm keeps increasing in case of finding suitable host plants and lack of natural enemies and entomopathogens (FAO 2017).

Fall armyworm was recorded in Karnataka of India in May of 2018 and started to spread quickly (Sharanabasappa et al. 2018; Firake *et al.* 2019). In Nepal, this pest has been identified in Gaindakot of Nawalpur district ((N 27042’16.67”, E 084022’50.61”) on 9 May, 2019 and this pest’s arrival has been confirmed by the meeting of National Plant Protection Organization (NPPO) held on August 12, 2019 (Acharya *et al.* 2019). It was also seen in higher altitude shortly after its arrival in Nepal i.e. 1700 meter above sea level, Kabre of Dolakha district (Bajracharya *et al.* 2019). Now, this pest has been reported in various districts of Nepal which includes Chitwan, Sindhupalchowk, Udayapur, Ramechhap, Sindhuli, Khotang, Okhaldhunga, Dolakha, Kavrepalanchowk, Bhaktapur, Lalitpur, Rolpa, Pyuthan, Salyan, Dailkeh, Banke, etc. (MoALD 2020). As reported of July 2020, this pest has been observed in 52 districts of Nepal and in all provinces of Nepal (Sah *et al.* 2020). Another survey done on summer and winter maize has reported the presence of fall armyworm in 21 districts of Nepal (Bajracharya *et al.* 2020). On an average, this pest has reduced the maize yield by 32% (Shrestha 2020). Since this pest favors the climate where there is little frost occurrence and annual temperature of 18-26 °C with rainfall of 500-700 mm (Early *et al.* 2018), this can easily become established in most parts of Nepal excluding upper northern regions of Nepal.

6. MANAGEMENT APPROACHES FOR FALL ARMYWORM AND POTENTIAL IMPLICATIONS TO NEPAL

Insect identification and monitoring is crucial in implementing integrated pest management approaches. Monitoring of this pest could be done using light trap and pheromone trap. Monitoring is very important in terms of assessing its movement, presence and determining its abundance. Pheromone based traps are very effective for trapping the male fall armyworm moths (McGrath *et al.* 2018). Different formulations of lures have been formulated commercially to attract the males and it may vary according to different geographical regions. If its presence is confirmed, then strategies such as cultural, biological, physical/mechanical and chemical should be deployed to manage the pest.

6.1 Fall armyworm Monitoring and Surveillance

It is crucial to monitor fall armyworm for understanding the population dynamics and various ecological factors which govern the insect abundance in any ecosystem. Monitoring of this insect means keeping eye on distribution and abundance of insect and various biotic and abiotic factors which influence the pest dynamics.

All the activities related to monitoring help growers forecast and assess the insect pests in any ecosystem and helps to make better decisions either to manage pests or not (Dhaliwal & Arora 2003). Once they are detected in the crop, farmers should be instructed to follow proper scouting techniques. The damage of insects also depends on the crop growth stages and management of pests at an early stage would be much more effective, which infers the importance of proper monitoring and surveillance of those insects (McGrath *et al.* 2018).

6.2 Cultural Method

This may include different set of practices to lower the insect pest populations or damages such as sanitation, tillage, maintaining plant diversity, ensuring optimum irrigation and fertilizers, destruction of hosts, crop fallowing and crop rotation, use of traps and following timely harvesting (Schellhorn *et al.* 2000). So, fall armyworm cycles of development could not be aligned with the host species with the introduction of new cropping systems which simply do not allow the harboring of those pests on the host. Push-pull strategy is one of the strategies under cultural methods of control. In the push-pull cropping system, crops which emit repulsive volatiles as a push crop and pest attractive crops around the border of the main crop as the pull crops are grown. Following this principle, insects which come around the pull crops are either sprayed by chemicals or their survival is low in those host crops. In East Africa, use of *Desmodium intortum* (Mill.) as the push crop and *Brachiaria* cv Mulato II as the pull crop decreased fall armyworm infestation and helped to increase the yield significantly (Midega *et al.* 2018). One of the strategies employed for managing fall armyworm could be planting of maize early so that fall armyworms do not get the host for growth and development (Assefa *et al.* 2019). Early harvesting also lowers the fall army worm infestation in case of maize (Mitchel 1978). So, it would be better to avoid late planting and staggered planting as it would give the ground for fall armyworm infestation. Planting of maize with the beans in periphery or intercropping with any leguminous crops, would lower the fall army worm infestation in maize compared to mono-cropped maize (Hilau *et al.* 2018; Bhusal & Chapagain 2020; CABI 2019).This is primarily due to inhibition of larval movement especially young ones and by the effect of natural enemies which are supported by the legume intercropping (Van Huis 1981; Harrison *et al.* 2019).

Additionally, smashing the eggs of fall armyworm, killing the larvae and putting the dust of clay mixed with the ash or sawdust in the whorl of corn would also have some effects for minimizing the fall army worm infestation culturally (Abrahams *et al.* 2017; Gebreziher 2020). Planting insect and disease free and healthy seed/ saplings is also one of the recommended practices for avoiding the infestation of fall armyworm (FAO 2017; Gebreziher 2020). Avoiding excessive use of nitrogenous fertilizers could reduce the chance of oviposition by fall armyworm adults. It is reported that organically grown crops have less abundance of fall armyworm due to less plant nitrogen content (Figueroa-Brito *et al.* 2013). But, it is crucial to maintain optimum amount of nutrients and moisture in the soil for healthy crop stands (FAO 2018).

Research in Dominican Republic reported that zero tilled land has lower fall armyworm infestation compared to conventional tilled land. Similar results were observed in Costa Rica and Florida, USA. Further, predator's abundance was much enhanced by the effect of mulch. Mulch also inhibits the pest larvae to enter soil to pupate which would ultimately help predators to predate these pest species (Harrison *et al.* 2019). Use of crop residues as mulch and no-till practice in maize cultivation could be beneficial in case of Nepal not only to conserve natural resources but to minimize the fall army worm infestation with increase of natural predators. But, due to integrated farming systems i.e. with livestock production, these crop residues or fodder resources could not be used for feeding the livestock.

Removing weeds and grasses from the field helps to reduce fall armyworm establishment (Luginbill 1928). Weeds would favor the fall armyworm egg laying on those weed species, in case of lack of suitable crop or crop stages. In Nicaragua, it was found that when weeds were cleared off from either side of the maize row, fall armyworm larvae were very limited to damage the crop (van Huis 1981). But, it was also found that there are a higher number of predators and parasitoids on weedy plots. Weeds also compete with the crops and reduce yield of crops. This aspect of weed should also be taken in account while managing the fall armyworm. Insect's predators and parasitoids prevalence also depends on the species of weeds. All these considerations should be taken in account so that fall armyworm infestation could be lowered down.

6.3 Host-Plant Resistance (HPR)

Using resistant crop varieties is one of the best methods against fall armyworm which infest the crops, particularly maize (Luginbill 1969). One of the techniques for increasing resistance in maize is increasing the thickness of the epidermis of the leaf (Davis *et al.* 1995) so that insect infestation could be tolerated.

6.4 Biological Control

Biological control uses predators, parasitoids and insect pathogens to keep fall armyworm below economic threshold level. But, due to its migratory nature it can easily escape various predators, parasitoids, parasites and pathogens (Hardke *et al.* 2015). Common predators of fall armyworm are birds, rodents, ants, beetles, earwigs and other predatory insects (Sparks 1979). *Bacillus thuringiensis* is found effective for managing the larval stage and should be sprayed in the leaves of plants, when these pests appear in the field. Genetic modification of this strain has been found more effective rather naturally found (All *et al.* 1996).

When fall armyworm eggs are visible to the plant parts, egg parasitoids such as Trichogramma or Telenomus could be released to the field as a biocontrol agent. The field should be regularly monitored after the presence of moths in the trap and soon after larvae emergence in the field it should be prioritized to manage effectively. Bio-pesticides such as *Metarhizium, Beauveria, Bacillus, Baculovirus*, etc. could be used, which are safer to the environment and human health. But, these formulations should be sprayed directly to the maize whorl (Prasanna *et al.* 2018). Some effective biological control agents are presented in Table 1.

Table1. Some effective biological control agents against fall armyworm

S.No.	Treatment details	Recommended dose / application	References
Predators			
1	*Hippodamia convergens*, Lady bird beetle	Eggs and larvae	Cruz *et al.* 2018
2	Forficula spp., Earwig	Eggs and larvae	Shylesha *et al.* 2018; Firake and Behere 2020
3	Zelus spp., Assassin bug	Eggs and larvae	Cruz *et al.* 2018
4	*Geocoris punctipes* , Big-eyed bug	Eggs and larvae	Cruz *et al.* 2018
5	*Eocanthecona furcellata*, Pentatomid predator	Larvae	Firake and Behere 2020
6	*Calosoma Granulatum*, Ground beetle	Larvae	Cruz *et al.* 2018
7	*Cicindela spp.*, Tiger beetle	Eggs and larvae	Firake and Behere 2020
8	*Cosmolestes spp.*, Reduviid bug	Larvae	Firake and Behere 2020
9	*Oxyopes birmanicus,* Spider	Larvae	Firake and Behere 2020
10	*Rhene flavicomans,* Spider	Larvae	Firake and Behere 2020

Parasitoids/parasites			
1	*Chelonus formosanus Sonan*	Egg-larval parasitoid	Firake and Behere 2020
2	*Telenomus cf. remus Nixon*	Egg parasitoid	Firake and Behere 2020
3	*Trichogramma spp.*	Egg parasitoid	Shylesha *et al.* 2018
4	*Ichneumon promissorius (Erichson)*	Pupal parasitoid	Firake and Behere 2020
Insect pathogens			
1	*Metarhizium anisopliae*,	Larvae	Firake and Behere 2020
2	*Beauveria bassiana,* White muscardine fungus	Larvae and pupae	Firake and Behere 2020
3	*Spodoptera frugiperda,* Nuclear Polyhedrosis Virus (SpfrNPV)	Larvae and pupae	Firake and Behere 2020
4	*Bacillus thuringiensis*, Bacteria	Larvae	Firake and Behere 2020

6.5 Botanicals

Plants produce various secondary metabolites which have insecticidal properties and are less toxic to non-targeted species compared to chemical pesticides (Pérez-Gutiérrez *et al.* 2011). Research report stated that fall armyworm larvae are sensitive to the neem if treated before the arrival of fall armyworm in the crop field (NRC 2002). Neem Seed Extract (NSE) has been found more effective against fall armyworm larvae compared to neem leaves extract (Silva *et al.* 2015). Throughout the Latin America, Pyrethrins and Azadirachtin (chemical constituents of neem) are the most commonly used against fall armyworm (Assefa *et al.* 2019). Other formulations based on garlic, tobacco, chrysanthemum, basil, pepper etc. are registered worldwide and have been used against fall armyworm (Isman 1997; Alves *et al.* 2014, Phambala *et al.* 2020). The detail of botanicals used to manage fall armyworm is depicted in Table 2.

Table 2. Some botanicals tested either from laboratory bioassays or field experiments to fall army worm

S. N.	Treatment details	Recommended dose	References
1.	Neem (*Azadirachta indica*) seed cake extracts	0.13%	Silva *et al.* 2015
2	Neem (*Azadirachta indica*) oil	0.25%	Tavares *et al.*2010
3	Neem leaves aqueous extract	2.67 mg/ml.	Prates *et al.* 2003
4	Ethanolic extracts of leaves of Chinaberry (*Melia azedarach*)	1.4 g/lit.	Bullangpoti *et al.*2012
5	Ethanolic extracts of leaves of Bellyache bush (*Jatrophagos sypifolia*)	2.6 g/lit.	Bullangpoti *et al.*2012
6	Ethanolic extracts of mixture of dried stems, leaves and flowers of Pale Mexican prickly poppy (*Argemone ochroleuca*)	30%	Martinez *et al.* 2017

7	Tobacco (*Nicotiana tabacum*) leaves extract	10% w/v	Phambala *et al.*2020
8	Lemon grass (*Cymbopogan citratus*) leaves extract	10% w/v	Phambala *et al.* 2020
9	Basil (*Ocimum basilicum*) leaves extract	10% w/v	Phambala *et al.* 2020
10	Fever tea (*Lippia javanica*) leaves extract	10% w/v	Phambala *et al.*2020
11	Castor bean (*Ricinus communis*) methanol extract of seeds	0.75×10^3 ppm	Ramos-López *et al.*2010
12	Seed extract of Papaya (*Carica papaya*)	1600 ppm	Pérez-Gutiérrez *et al.*2011
13	Essential oil from seeds of Long pepper (*Piper hispidinervum*)	30 and 50 mg/ml	Alves *et al.*2014
14	Ethanol leaf extracts of Marigold (*Tagetus erecta*)	500 ppm	Salinas-Sánchez *et al.*2012

6.6 Chemical Method

Despite knockdown effect of pesticides, they have been recommended to use as a last resort considering threshold level, pest stage, crop type and application area because of and its negative side effects on human, environment or its biological diversity (Assefa *et al.* 2019; FAO 2018) and increasing pest resistance against applied insecticides (Gebreziher 2020).

Many insecticides have been recommended and used for managing fall armyworm considering their toxicity, hazardous level, accessibility, user friendliness. Emamectin benzoate (5 SG, 0.4 g/lit.), Spinosad (45 SC, 0.3 ml/lit.), Chlorantraniliprole (18.5 SC, 0.4 ml/ lit.) etc. are recommended as most effective, if applied at early larval stages (Gebreziher 2020).

Chemical pesticides may not be available to the resource poor farmers or subsistence farmers. Lack of knowledge about the safety procedures while applying pesticides is also one of the constraints of the farmers especially of the developing countries. In Nepal, most of the farmers who use chemicals primarily rely on broad spectrum insecticides so they are facing lots of negative consequences (GC 2015).

6.7 Next Generation Pest Control Strategies for Fall Armyworm

The awareness of consuming safer food products is increasing more than ever (Ali *et al.* 2019). Outbreaks of serious pests like fall army worm in the African region have resulted in the widespread use of insecticides. This could be equally true in Nepal where fall armyworm has recently invaded. So, next generation pest control strategies should be emphasized so that natural enemies' population could be enhanced. Use of flowering plants can ensure food resources i.e. either nectar or pollen and habitat for the natural predators/ pollinators/ natural enemies. This enables the pest management by biological agents in a natural ecosystem, which is also called ecological engineering (Lu *et al.* 2014). Use of local knowledge and ecology-based options are much cheaper to the small holder farmers who can't afford to purchase chemical pesticides or other commercial formulations (Harrison *et al.* 2019).

Agro-ecological concepts of pest management involve the use of soil fertility management to ensure plant resistance and maintain crop health, ensuring sufficient biodiversity so that natural enemies can act and some specific operations designed to deter the pest infestation (Harrison *et al.*2019). It has been seen that the region which follows monoculture as a cropping system, the pest is more damaging compared to the region with having forest trees in patches of the field. This was observed in Honduras and Guatemala where farmers did not report fall armyworm as a serious pest (Morales *et al.* 2001; Wyckhuys and O'Neil 2010; Blanco *et al.* 2014; Harrison *et al.* 2019). It was also seen in Nicaragua that the maize plants grown alongside cotton and the region where chemical pesticides were sprayed heavily, noticed greater damage of fall armyworm compared to regions where pesticides were not used (Van Huis 1981).

7. THREATS POSED BY THE INVASION OF FALL ARMYWORM IN NEPAL

Fall armyworm prefers the region having mean annual temperature in between 17-35 °C and annual rainfall ranging from 0-400 mm (Lamsal *et al.* 2020). Due to the favorable environment, this pest would persist in Nepal and pose a serious threat to Nepalese agriculture. Due to climate change, the country has become hotter by 0.70 °C if we look at the trend of temperature from 1978 to 2008 (Maharjan & Joshi 2013). This suggests that this pest could expand its distribution range slowly over the years. With the rise of temperature, insect development would be accelerated, and they would produce more generations in a year.

Due to high adult fecundity in coupled with short life cycle and some typical larval characteristics including voracious feeding habit (Pogue 2002), ability to dominate intra- and inter- specific competitors (Chapman 1999), fall armyworm larva is expected to survive throughout the year in Nepal as in Africa. Further, Nepal's vegetation offers a wide range of host plants including grain crops, vegetables and wild plants or other grasses. fall army worm primarily prefer maize however it can develop its development cycle in rice, sugarcane, cabbage, soybean, onion, cotton, barley, buckwheat, oat, millets, tomato, cotton and potato (Prasanna *et al.* 2018), most of them are common crops of Nepal. Besides, the country offers suitable climatic conditions or agro-ecology for continuing pest life cycle. Being a new species in Asian continent including Nepal, it might get enemy-free space to spread and establish. These overall might increase the chance of being endemic pests in Nepal and this pattern has been observed since its entry to Nepal.

Although this insect is polyphagous in feeding habit, it is causing more damage in maize and sorghum in African countries (Du *et al.* 2020). Nepal is predominantly agrarian country with small holder's farming where maize is the second important crop after rice in terms of area and production. Maize is primarily a summer crop in the inner terai and mid-hills region of Nepal. Summer season offers optimum temperature, humidity and overall environment for fall armyworm, growth and survival. Fall armyworms could not survive well in all seasons but they get a very amenable environment in pre-monsoon, monsoon and post-monsoon season (PQPMC 2019). This insect also does not have a diapause stage so it could not thrive well in the cooler regions (Du *et al.* 2020). This implies that fall armyworm could not damage the crops in winter maize especially in upper climatic zones of Nepal. Still, these pests have the chance to become the key pests in the seasons other than winter i.e. spring and summer in those regions. In the winter time, it is also probable that these insects could migrate to the terai regions from the mid-hills and hilly regions to infest the maize. The temperature of the terai region, even in winter, favors the growth and development of these insects and with the onset of the spring these insects could start to migrate northwards. While it is expected that the rainfall during the crop season in monsoonal maize in hills and uplands of terai would support to control the pest naturally to some extent, some opportunistic off-season crops like September-planted maize and spring-planted maize have been highly affected by the pest attack. However, greater loss would be observed in kharif maize due to highest area coverage of maize in the season.

Therefore, these insects are one of the challenges to ensure food security in these regions (PQPMC 2019). In terms of food security, more than two-thirds of the districts face food deficit each year. If we talk about the productivity of agricultural crops, it is lowest among south Asian countries (Paudel *et al.* 2019). Overall trend of agricultural production in Nepal is subsistence type. The trends of climate change of Nepal i.e. increase in temperature and summer rain has contributed to decline in yield growth of maize (Maharjan & Joshi 2013). Since Nepal's agriculture primarily depends upon natural climatic conditions, the change in those conditions could affect the agriculture sector of the country largely. So, the challenge posed by this insect, which is devastating mainly to maize, would be serious if it gets uncontrolled. Due to the fall army worm infestation, maize production would be lowered significantly as serious pest infestations have been reported in various maize growing districts of Nepal. Furthermore, fall armyworm damage to any crop has unprecedented consequences and it is well depicted in Fig. 3. For instance, upon higher infestation, farmers become compelled to use higher amount of pesticides which not only increases the cost of cultivation of the resource poor farmers but also has unintended consequences to the human health and the environment. Pesticide exposure to the farmers, their family members, community members and nearby livestock, birds and other animals could be the issue which could be hazardous to the health of the concerned ones. Furthermore, not only the agriculture produce but also the soil, air and water would have residues of insecticides due to higher application of insecticides which is obviously not good for various flora and fauna including humans. Loss of beneficial insects and natural enemies would be another detrimental effect to the agro-ecosystem upon the use of conventional insecticides. Last but not the least, insect itself becomes resistance to the insecticides which could be even harder to manage. These all are the problems faced by many countries where fall armyworm has been the curse of the farmers and Nepal could not be the exception.

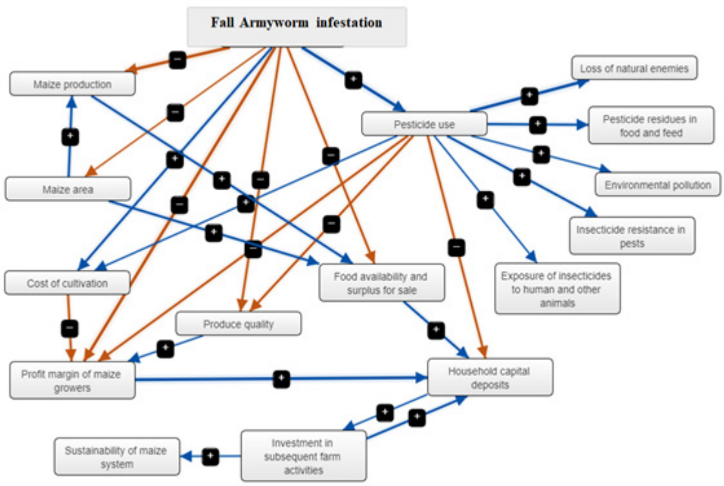

Fig. 3 Relationship of fall armyworm damage to the different components prepared through consultation with concerned experts by using mental model. '+' sign indicates positive correlation and '–' sign indicates negative correlation.

8. THE FUTURE: IMPORTANCE OF NEW MONITORING SYSTEMS, ITS IMPLICATIONS IN RECENT STRUCTURAL CHANGES IN ADMINISTRATION

Since this is an invasive insect species, proper monitoring systems should be developed by the Ministry of Agriculture and Livestock Development of the government of Nepal so that governmental technicians could be directly involved in this task. They can monitor the pest dispersal, their density and other associated factors which govern the pest dynamics in any given geography (McGrath *et al.* 2018). Recent structural changes in administration of Nepal Government due to federalism, new structures of governmental agricultural institutions should be more prioritized to reach to the farmers at local level. Coordination of extension agents, farmers, research institutions and universities are needed for proper monitoring of this invasive insect species. Since this is an invasive insect species, many farmers are not familiar with this insect species so proper identification techniques of all stages of this insect, proper surveillance and scouting at the field level and rational management practices should be taught to the Nepalese farmers by the extension agents. Since Nepal has local, provincial and federal governments, it would be better to act by all these governments and their respective agricultural departments and agencies to tackle this pest. Upon havoc damage of crops in various districts of Nepal especially in maize fields, could end up in widespread use of toxic chemical insecticides to the field. This condition will lead to destruction of natural enemies, predators, parasitoids in the field which will further exacerbate the condition. So, management of this invasive pest by integrated pest management or by ecological based pest management could be better to save the crop, humans and the environment where we live.

Use of digital technologies to monitor the fall army worm population could be applied in the context of Nepal since this pest recently invaded the country and is distributed to different geographical regions. Various advices could be given to the farmers about this insect and its effective management strategy through digital media. Farmers should also be able to express their opinion and effective management strategy tested by them locally and they should be able to access information about these access online and offline from digital applications. The Food and Agriculture Organization (FAO) of the United Nations has developed the Fall Armyworm Monitoring and Early Warning System (Hruska 2019) and this could be better extended to farmers in Nepali language with the partnership of Government of Nepal and FAO, if possible. Centre for Agriculture and Bioscience International (CABI) has also developed invasive species compendium with Fall Armyworm Information portal which also gives updates about this pest invasion and all information related to it (Feldmann *et al.* 2019). Government of Nepal could collaborate with these internationally recognized institutions working on fall armyworm and could devise a digital platform to disseminate experiences and knowledge about this insect. But, this should be started soon so that this insect could not cause serious damage to Nepalese agriculture.

9. CONCLUSION

Since fall armyworm is a highly invasive insect species, this one is becoming a serious threat worldwide. Strong migratory nature, higher fecundity, wide host range and short generation period are some of the features which enable this insect so successful in an agro-ecosystem. This insect has invaded Nepal in 2019 but since then, it has become widespread in the region and threatening production of cereal crops, mainly maize. Strong migratory nature, higher fecundity, wide host range and short generation period are some of the features which enable this insect so successful in agro-ecosystem. Furthermore, climatic suitability and preferred host availability of Nepal has given the opportunity for well establishment in the region. To manage the insect, integrated pest management or ecological based management options should be relied upon rather than specific recommendation of conventional chemicals. Since this is a new insect species introduced to the country, so far limited researches are done and very less information available to the various research and development agencies and ultimately to the farming community. This should be reversed by coordinated action of governmental and non-governmental agencies working on 3 tier federal system of Nepal i.e. federal, provincial and local governments. All the action should be oriented to effective surveillance, monitoring and early warning system, capacity enhancement of technicians and awareness raising program to the farmers and coordinated action to mitigate the fall armyworm invasion. Urgent action of concerned stakeholders is crucial for safeguarding food security, crop production and profitability of farmers.

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