# Major biotic stresses affecting maize production in Kenya and their implications for food security

**Faith Njeru** Corresp., [1], **Angeline Wambua** [2], **Edward Muge** [3], **Geert Haesaert** [4], **Jan Gettemans** [5], **Gerald Misinzo** [6]

[1] Veterinary Microbiology, Parasitology and Biotechnology,, SACIDS Foundation for One Health, Sokoine University of Agriculture, Morogoro, Tanzania
[2] Department of Physical Sciences, Chuka University, Chuka, Kenya
[3] Department of Biochemistry, University of Nairobi, Nairobi, Kenya
[4] Department of Plants and Crops, Ghent University, Ghent, Belgium
[5] Department of Biomolecular Medicine, Ghent University, Ghent, Belgium
[6] SACIDS Foundation for One Health, Sokoine University of Agriculture, Morogoro, Tanzania

Corresponding Author: Faith Njeru
Email address: wanjikunjeru2012@gmail.com

Maize (*Zea mays*) is a staple food for many households in sub-Saharan Africa (SSA) and also contributes to the gross domestic product (GDP). However, the maize yields reported in most SSA countries are very low. The low yields are due to biotic and abiotic stresses. These stresses have been exacerbated by climate change which has led to long periods of drought or heavy flooding and the emergence of new biotic stresses. Few reports exist which compile the biotic stresses affecting maize production in SSA. Here, five biotic stresses of maize in Kenya are presented. Maize lethal necrosis and fall armyworm are new biotic stresses to the Kenyan maize farmer while gray leaf spot, and turcicum leaf blight are endemic to the region. The invasion by the desert locusts is speculated to be caused by climate change. The biotic stresses cause a reduction in maize yield of 30- 100 % threatening food security. There should be deliberate efforts from the government and researchers to control biotic stresses affecting maize yields as the effect of these stresses is being exacerbated by the changing climate.

## Introduction

According to data from the Food and Agriculture Organization of the United Nations (FAO), the total maize yield in Kenya ranged from 1.43 to 1.82 t/ha from 2010 to 2018 (FAOSTAT, 2018) (Table 1). The average maize yield in Kenya of 1.66 t/ha is very low compared to other maize growing regions in some developing and developed countries such as Brazil that has maize yield of 5.1 t/ha (FAOSTAT, 2018). Data collected from farmers in five counties of Kenya reported average maize yields of 1.48 t/ha for the 2020/2021 cropping season (Njeru et al., 2022).

The annual maize consumption in Kenya was 4,300,000 tons in 2018 (Indexmundi, 2018). The deficit from local production is imported from East African countries with a significant portion of imports being contributed by informal cross-border trade. In 2018, a total of 529,558 tons of maize were imported into Kenya at a value of 118,554,000 US dollars (FAOSTAT, 2018). Studies done have shown that potential exists for increasing maize yield to over 6 t/ ha through increased use of improved seeds and good crop husbandry (Odendo et al., 2001). Therefore, there is need to invest in innovative agricultural practices to increase maize yield to be able to meet the demand.

Maize is an important cereal crop in SSA critical for food security as well as a source of income for millions of small-holder farmers (Prasanna et al., 2020). The importance of maize is evidenced by the fact that 90% of the Kenyan population depends on maize for food, income, and employment (Kusia, 2014). Maize is cultivated under diversified climatic and agroecological zones mostly by resource-poor farmers with limited access to inputs such as fertilizers and pesticides (Gudero et al., 2019).

Several biotic and abiotic factors have been shown to significantly affect maize production. Abiotic factors such as drought, and poor fertile soils contribute to low maize yields in Kenya. Biotic factors such as stem borers, and weeds such as *Striga*, have been shown to contribute up to 30% yield loss in maize production (Kusia, 2014). Pathogens such as *maize dwarf mosaic virus*, *sugarcane mosaic virus*, and *wheat streak mosaic virus* have also been reported to cause significant reductions in maize yields in the affected farms.

Globalization and international trade have increased significantly in recent years, subsequently increasing the spread of transboundary pests and diseases. This has led to the emergence of new diseases such as Maize Lethal Necrosis (MLN) and the introduction of new pests such as fall armyworm (FAW) *Spodoptera frugiperda* in Kenya. These new pests and diseases further contribute to low maize production and puts a strain on the agricultural sector.

East Africa is projected to have an increase in annual rainfall which will be of high intensity and sporadic due to climate change (Thompson et al., 2010). The impact of climate change on food security in Kenya is a major concern due to the marginal climatic conditions in the country, the dependence on rain-fed agriculture, and limited resources available for adaptation (Thompson et al., 2010). A study by Njeru et al. (2022) collaborates the findings that maize cultivation in Kenya is mainly rain-fed.

The population in Kenya is expected to continue increasing in the coming decades reaching 66 million in 2030; however, food production is not expected to be on pace. Hence, the purpose of this review paper is to present the major biotic stresses affecting maize production in Kenya, with a focus on fall armyworm, maize lethal necrosis (MLN), desert locusts, gray leaf spot (GLS), and Turcicum leaf Blight (TLB).

This review paper targets plant breeders, pathologists, scientists in the seed companies and students in agricultural research. Several previous review papers have been written on different aspects of biotic stresses affecting maize production such as (Redinbaugh & Stewart, 2018; B. M. Prasanna et al., 2022; Shiferaw et al., 2020). These previous review papers have focused on a single specific biotic stress. The current review paper combines several biotic stresses affecting maize production.

## Survey methodology

The studies used to write this review paper were identified from science direct, research gate and web of science. Only papers written in English were reviewed. The inclusion criteria included original articles and previous review articles on biotic stresses. The search terms used included maize lethal necrosis, fall armyworm, desert locusts, gray leaf spot; turcicum leaf blight. The search terms were used with the Boolean operator "AND" maize production. This enabled to focus the search to articles written in reference to maize cultivation.

**Biotic stresses**

Plants encounter abiotic or biotic environmental stresses which limit their productivity. Abiotic stresses that affect plants are either physical or chemical while the biotic stresses are caused by pathogens. In Kenya, the main abiotic stress affecting maize production is drought. In 2022, Kenya was reported to experience the worst drought with 4.1 million people estimated to be food insecure (FAO, GIEWS). Economic losses to biotic stresses vary depending on the stress and the affected crop. A study by Pratt et al., (2017) reported that biotic stresses in Kenya cause losses of between 3.8 to 123.6 million USD.

Maize is cultivated in 40 % of the total crop area in Kenya and its production is often affected by biotic stresses. Below we discuss in detail the main biotic stresses of maize.

**Fall Armyworm**

**History of FAW**

Fall armyworm (FAW) *Spodoptera frugiperda* is a type of caterpillar that is native to the tropical regions of the western hemisphere from the United States to Argentina (Goergen et al., 2016). It is a strong migratory pest that disperses to long distances annually (Zaman-Allah et al., 2019). The female moth lays eggs in masses on the leaves of many plants (Groote et al., 2020). After hatching, the larvae, which is the most destructive stage of the pest, disperses throughout the crop field consuming vegetation they come across (Capinera, 1999). FAW is a polyphagous pest that attacks over 60 plants, but its major effects have been on a few crops such as rice, millet, sorghum, and maize (Sisay et al., 2018).

FAW is relatively new in Africa, where its first report was in 2016 in West Africa following distress calls by maize producers of high armyworm populations (Goergen et al., 2016). Subsequently, FAW was reported in other African countries including Kenya in 2016 (Mutyambai et al., 2022) and by 2018, FAW had affected 86 % of the maize farmers in Kenya (De Groote et al., 2020).The fast spread of FAW is attributed to its natural distribution capacity (strong migratory pest, producing many eggs) and the increase in international trade (Tambo et al., 2020). Additionally, its preference for maize, the major cereal crop in Africa also aids in the fast spread of this pest which has been reported in all Sub-Saharan African countries except Lesotho (Tambo et al., 2020).

**Impact of FAW on maize production**

Damage on maize by FAW is observed on all plant parts and at all maize developmental stages, with the pest reported to affect the stem base of maize plantlets, the leaves of maize at the vegetative stage, and also on grown maize plants with the pest able to feed on tassels or bore into ears (Goergen et al., 2016). It has been identified mostly in the Southeastern U.S. as a regular and serious pest destroying maize crops (Zaman-Allah et al., 2019) causing yield losses of up to 57 % in Latin America, depending on the crop season and the maize variety planted (Burtet et al., 2017).

Results based on socioeconomic surveys and farmer estimates of yield loss, undertaken in different countries in Africa have estimated maize yield loss due to fall armyworm to be in the range of 22–67% (Kansiime et al., 2019). For example, in Ethiopia and Kenya, Kumela et al. (2019) reported FAW-induced maize yield reductions of 32 % and 47 % respectively, based on a survey of maize farmers while maize yield reductions of 27 % and 35 % were reported in Ghana and Zambia respectively (Rwomushana et al., 2018). However, in Zimbabwe, a study by Braudron et al. (2019) estimated FAW-induced maize yield reductions of 12 % based on a rigorous field scouting method.

Groote et al. (2020), estimated the losses of maize production due to FAW in all the agroecological zones in Kenya through a community based survey, to be one-third of the potential production. The study extrapolated estimates from a survey conducted between June and July 2018, involving 121 group discussions in communities randomly selected to represent the major maize-growing zones. These extrapolated estimates were compared to the production estimates of the different zones before the arrival of FAW (FAO, maize production statistics).

The results of the study gave estimated losses of maize production of 924,000 tons (34%), 883,000 tons (32%), and 257,000 tons in the long rains of 2017 and 2018 and the short rains of 2017 respectively; however, the relative losses in the short season were 32%. These losses due to FAW are similar to results reported by a farmer survey in Ghana and Zambia which reported yield losses of 26-40% and 35-40% respectively (Nboyine et al., 2020) and 32% in Ethiopia (Baudron et al., 2019).

The presence of this new pest in most SSA countries adds to the threat caused by native lepidopteran maize stalk or ear borers such as African maize stalk borer (*Busseola fusca*). Besides its direct effect on agricultural production, FAW also has the potential to significantly affect access to foreign markets (Georgen et al., 2016). Maize is an important crop as a source of food and income to millions of smallholder farmers in Sub-Saharan Africa, FAW, therefore, poses a significant threat to food security in SSA and the attainment of sustainable development goal 2 to end hunger by 2030.

**FAW detection and control**

An assay based on loop-mediated isothermal amplification (LAMP) has been reported for the species specific diagnosis of FAW (Osabutey et al., 2022). However, for the small scale farmer, scouting protocols which looks for the signs of egg hatch and feeding by egg larvae instar have been developed to allow early detection of FAW for better management (Prasanna et al., 2018). Besides scouting, sex pheromone traps have been developed to track the presence and movement of FAW in a certain region (B. Prasanna et al., 2018).

FAW is new to the African continent, therefore control measures are limited and little is known about the most effective agronomic practices for FAW control (Baudron et al., 2019; De Groote et al., 2020). Therefore, most farmers are left with the option of using chemical pesticides for FAW control. This option is expensive and poses risks to health and the environment (Sisay et al., 2018). A study done across 5 African countries of Ghana, Rwanda, Uganda, Zambia and Zimbabwe showed that use of pesticides for FAW control was the most preferred management option among the surveyed farmers (Tambo et al., 2020). The common pesticides used by the farmers in Africa include profenofos, cypermethrin, and lambda-cyhalothrin. Unfortunately, some farmers reported using pesticides such as monocrotophos, dichlorvos, methomyl, and methamidophos which are highly toxic and prohibited products (Tambo et al., 2020).

In addition, the use of pesticides has been reported to be ineffective due to the larval behavior of this pest; larval stage bores into the host plant developing under a protected environment, making it difficult to reach with target insecticidal sprays (Burtet et al., 2017). FAW has also been reported to have evolved resistance to several insecticides used including carbamates, organophosphorus, and pyrethroids (WAN et al., 2020). FAW have been shown to develop resistance to insecticide by metabolic detoxification mechanism (Wang et al., 2022). The increased activity of glutathione S-transferases (GSTs) resulted in FAW resistance to pyrethroids. Another mechanism that has been reported for FAW resistance to insecticides is the target resistance mechanism (WAN et al., 2021).

In Brazil, the control of FAW has been through the use of transgenic plants encoding the Cry1F gene from *Bacillus thuringiensis* (Bt) (Bernardi et al., 2015). However, some studies done in Brazil have shown Bt maize plants expressing the Cry1 proteins to be affected by FAW as a consequence of field evolved resistance to Cry1 proteins (Burtet et al., 2017). Maize plants expressing the Vip3A gene product from Bt were shown to be effective against FAW due to the high toxicity of Vip3A protein to FAW (Burtet et al., 2017).

Though the use of Bt maize expressing the Cry1 and Vip3A proteins have been shown to have significant success in the control of FAW, the use of this technology need to be monitored and integrated with other control options to control the evolution of resistance against the Cry1 and Vip3A proteins by FAW.

However, the ethical concerns for use of genetically modified (GM) plants still restrict the use of such plants where legal restrictions are imposed on GM plants. Therefore, in most SSA countries, more research is being carried out to identify alternative control strategies that are effective, adaptable, and applicable to the smallholder farmer's in SSA.

These mitigation strategies include cultural, the use of bioagents, and the use of resistant plant genotypes as extensively reviewed by Kasoma et al. (2020). Natural enemies of FAW which include parasitoids that are small insects that develop attached to the host and eventually kill the host, have been reported for FAW. Sisay et al. (2018) reported several species of parasitoids for

FAW in Ethiopia, Kenya and Tanzania with parasitism ranging from 4 to 45.3 %. The parasitoids that have been reported for FAW include *Cotesia icipe* , *tachinid fly*, *Palexorista zonata*, *Charops ater* and *Coccygidium luteum* (Sisay et al., 2018). It has also been shown that intercropping with plants such as Tephrosia or desmodium which produce repugnant chemicals help to repel the adult female moths, reducing the number of eggs laid on host plants (Prasanna et al., 2018).

A study by Baudron et al. (2019) in Zimbabwe, reported that FAW damage was frequently reduced by frequent weeding and by minimum and zero tillage. However, pumpkin intercropping was found to significantly increase FAW damage. Further research is needed to determine which crops are the most efficient in controlling FAW and acceptable to farmers. Farmers' have also been shown to employ a range of cultural and physical practices, based on indigenous knowledge e.g. hand picking of egg masses and caterpillars, and application of ash/sand on the larvae, some with considerable levels of success (Kansiime et al., 2019).

Some maize varieties were found by Baudron et al. (2019) to be tolerant to FAW damage. Therefore, there has been research to identify quantitative trait loci (QTL) for application in Marker-assisted selection (MAS) to facilitate the breeding process. Womack et al. (2020) identified two important QTLs explaining 37 % of the phenotypic variance of leaf-feeding damage by FAW in maize. The resistant variety used, Mp705 was responsible for the leaf-feeding damage-reducing alleles for both large-effect QTL and most of the small-effect QTL identified in the study by Womack et al. (2020).

Mycotoxins such as aflatoxins and fumonisins contamination of grains (maize, sorghum, groundnuts) have been reported to be a challenge in SSA due to poor pre harvest, post harvest practices, and the hot and humid climatic conditions (Wokorach et al., 2021). Mycotoxins are toxic metabolites with mild to chronic health effects to humans and animals. The larvae of FAW has been shown to cause damage to corn ears and the kernels (Herrington et al., 2014). The damage caused by FAW to maize kernels has been shown to increase the growth of certain fungi that cause mycotoxins (Devi, 2018).

There is a need for the development and implementation of evidence based efforts to control this pest. Development of alternative control and preventive methods for FAW, based on agronomic management would be more affordable to resource-constrained small holder farmers with less risk to health and environment. But studies are still ongoing to understand the unknown dynamics of establishment, spread, and environmental conditions favoring the survival of FAW in the continent.

**Maize Lethal Necrosis**

**History of MLN**

Maize lethal necrosis (MLN) (Fig. 1) is a disease of maize that was first reported in Peru in 1973 and then in Kansas, USA in 1976 (Hutchens, 1978). It's a viral disease caused by the synergistic interaction of *Maize Chlorotic Mottle Virus* (MCMV) and any of the viruses belonging to the potyviridae family (Antonio *et al.*, 2008). The first report on MLN in the African continent was in Kenya in 2012 (Wangai et al., 2012). The disease was later reported in several other African countries (Semagn et al., 2015) including Uganda, Tanzania, Ethiopia, Rwanda, D.R Congo, and South Sudan (Antonio et al., 2008). These countries are known as MLN endemic countries.

Studies have shown *maize dwarf mosaic virus* (MDMV) and *wheat streak mosaic virus* (WSMV) as the main potyviruses combining with MCMV to cause MLN in the USA (Uyemoto et al., 1980) while *sugarcane mosaic virus* (SCMV) has been implicated in MLN infections in Africa (Mahuku et al., 2015). Recently, a study by Stewart et al. (2017) showed the *Johsongrass mosaic virus* (JGMV) to cause MLN in co-infections with MCMV in East Africa. *Maize yellow mosaic virus* (MaYMV) has been discovered in deep sequencing studies in MLN-infected maize plants, however, it was shown that it does not cause MLN but it significantly enhances MLN symptoms such as stunting (Stewart & Willie, 2021).

Maize is the main natural host for MCMV; however, it has also been detected in millet, Johnsongrass, *Digitaria* sp., sedge, *Setaria* sp., and sugarcane (Mahuku, 2019). Common SCMV hosts reported in Africa include sugarcane, maize, sorghum, Kikuyu grass as well as other Poaceous plant species.

A study conducted on the metagenomic analysis of viruses causing MLN in Kenya showed MCMV as the most prevalent virus in maize-growing regions in Kenya (Wamaitha et al., 2018). SCMV population in Kenya was shown to be diverse, consisting of numerous strains distantly related to isolates from other parts of the world (Wamaitha et al., 2018). Limited sequence divergence among MCMV isolates has been reported in population genetics studies (Braidwood et al., 2018). The majority of MCMV genome divergence has been shown to occur between sub-populations (Braidwood et al., 2018). Phylogenetic analysis has shown similarity between MCMV isolates found in East Africa to those found in China (Braidwood et al., 2018).

**Losses caused by MLN on maize production**

Maize plants infected with MLN show more severe symptoms than plants infected with MCMV or SCMV alone (Mengeshe et al., 2019). Maize plants are susceptible to infection by MLN at all stages of crop development (Beyene et al., 2017). MLN-infected plants show a wide range of symptoms depending on the maize variety, time of infection, and prevailing environmental conditions (Miano, 2014). The symptoms are: chlorotic mottle on leaves, developing from the base of young whorl leaves upward to the leaf tips; mild to severe leaf mottling; and necrosis (Prasanna et al., 2020). Necrosis of young leaves leads to a “dead heart” symptom, and plant death (Wangai et al., 2012). Severely affected plants have small cobs with little or no grain set (Fig. 1) (Wangai et al., 2012).

Results from a community-based survey done by Groote and his team (2013), estimated the proportion of maize lost in the community, at 0.5 million tons per year, or 22% of the average annual production before MLN, with an estimated economic loss of $180 million (Beyene et al., 2017). The most affected region by MLN in maize production is Western Kenya with more than half of the farmers affected and with a 58% loss of maize (Beyene et al., 2017). Central and Eastern Kenya, had up to a third of the farmers affected and with 19% maize yield loss (Beyene et al., 2017). Many studies have estimated the losses due to MLN in different maize agro-ecological zones in Kenya to be between 23-100% (Njeru et al., 2022).

Different studies have shown than MLN disease can completely wipe out maize plants leading to 100% loss in yield. This is especially devastating to millions of families and small holder farmers who depend on maize as a source of food and income. The effect of MLN is also felt by small and medium enterprises (SME's) seed companies and processors (Prasanna et al., 2020). Demand for seed of commercial seed varieties declined when MLN was major epidemic with losses of sales for the companies (Prasanna et al., 2020).

Due to the significant impact of MLN on the maize sector, International Maize and Wheat Improvement Center (CIMMYT) in collaboration with National Agricultural Research System (NARS) and National Plant protection Organization (NPPO) have put in place several mechanisms to prevent its further spread to the MLN non endemic countries where MLN/MCMV has not yet been reported (Prasanna et al., 2020). The mechanisms that have been put in place include diagnosis of MLN-causing viruses in maize seed, monitoring and surveillance of MLN across Africa, production and exchange of MLN pathogen free commercial maize seed (Prasanna et al., 2020)

**MLN epidemiology**

Sustainable control of plant diseases requires an understanding of the disease including the biology of the pathogens causing the disease, suitable environmental factors favoring host-pathogen interactions and vectors or any other means involved in the spread of the disease. Epidemiological studies on the spread of MLN have identified the spread of the disease from plant to plant and from field to field to be mainly through insect vectors (Mangesha et al., 2019).

Several insect vectors such as thrips, maize rootworms, leaf beetles and leaf hoppers have been associated with the spread of MCMV (Mangesha et al., 2019). Aphids on the other hand are the main insect vectors associated with the spread of SCMV (Brault et al., 2010). Seed transmission of MCMV has been reported though at very low rates (0.03-0.33%). This may partly explain how MCMV has managed to travel across continents and countries. MLN has also been shown to be in the soil, irrigation water, and infected plant debris ((Kinyungu et al., 2019; Miano, 2014).

**Disease diagnostics**

To detect MLN, you have to be able to detect both MCMV and SCMV (causative viruses for MLN). Commercial enzyme linked immunosorbent assay (ELISA) kits based on polyclonal antibodies are available for MCMV and SCMV detection. Monoclonal antibodies have also been developed and shown to have sensitive and specific detection of MCMV (Wu et al., 2013). Gene amplification techniques including reverse-transcriptase polymerase chain reaction (RT-PCR) (L. et al., 2019) and reverse transcriptase loop mediated isothermal amplification (RT-LAMP) (Francis et al., 2020) have been developed for MCMV and SCMV detection.

Use of symptoms to tell the presence of MLN is challenging because symptoms caused by MLN viruses vary depending on the age of maize plant and environmental conditions. In addition, symptomless plants have been found to be MCMV positive. Therefore, diagnostic methods are significant to validate the presence of MCMV and SCMV.

**Control of MLN**

A study conducted by CIMMYT in collaboration with Kenya Agricultural and Livestock Research Organization (KALRO) between 2012 and 2014 found that, most of the maize germplasm had low levels of resistance to MLN (Semagn et al., 2015). Therefore, more than 95% of the inbred lines and hybrids grown by farmers in Kenya are susceptible to MLN (Semagn et al., 2015). With the continuous cultivation of maize throughout the year, this exacerbates the problem caused by MLN. Therefore, more research is needed to generate and release resistant hybrids to MLN.

Breeding for resistance following the conventional method is time consuming and costly. Therefore, many researchers are applying genomic selection as a promising breeding tool to improve the efficiency and speed of the breeding process. MCMV resistance has been shown to occur in different chromosomal locations and 5 QTLs for MCMV resistance have been found in chromosomes 3, 5, 6 and 10 (Jones et al., 2018).

Both large QTL effects and multiple small effects QTL for MCMV resistance were identified (Jones et al., 2018). Similar observations were made in a subsequent study by Awata et al. (2020) that identified QTL for resistance to MCMV in 7 bi-parental populations where some QTLs showed major effects in some populations and minor effects in other populations.

To further understand the resistance mechanism of MCMV, Jones et al. (2018), tested systemic leaf tissue from five inbred lines for the presence of MCMV and determined that ELISA responses for tissue of inoculated plants from the five lines and the susceptible control (Oh28) were similar. Therefore, only tolerance to MCMV have been identified rather than resistance. The responses of MCMV and SCMV viruses are not linked as the SCMV-resistant line Pa405 had no resistance to MCMV (Jones et al., 2018).

MLN is a complex disease with multiple reservoirs and transmission pathways. There is need for continued investigation on the molecular basis for resistance to MLN, interactions between MCMV and SCMV for deployment of resistant varieties especially in areas where subsistent farmers' depend on continuous maize crop for food.

## Desert Locusts

### Emergence of desert locusts

The Desert Locusts, *Schistocerca gregaria,* are mainly found in arid and semi-arid areas spanning regions from West Africa to India. Desert locusts' outbreak and invasion date back to 1860. Since then, different outbreaks have been recorded over the years some even lasting for over 22 years (Lecoq, 2003). The recent outbreak can be traced back to the 2018 cyclones coupled with the warm weather and heavy rainfall experienced at the end of 2019 (Roussi, 2020). In this outbreak, Kenya has experienced its worst invasion in 70 years where a large swarm occupied an area of about 2,400 square kilometers (Roussi, 2020).

Current outbreaks are worsened by the current state of political instability, under-financed control centers, Covid-19 pandemic and poor early detection strategies (Roussi, 2020). Therefore, with the recent advances in technology and remote sensing, there is need to devise better and effective early sensing tools for arresting the situation before much damage is done.

### Losses caused by desert locusts

At a local level, desert locusts can cause desertification due to the raged soils caused by depletion of vegetation cover. Development of irrigation schemes in SSA have also aggravated the situation by providing a favorable environment for breeding sites of the desert locusts, consequently leading to recurrent outbreaks (FAO, 1994a). Desert locust can migrate over very long distances attacking all types of vegetation cover hence posing great threat to agro-sylvo-pastoral production (Lecoq, 2003). In times of favorable weather conditions of high rainfall (favorable environment for laying eggs), outbreaks, upsurge and invasions usually occur threatening food security.

On the flip side, insects have over the years been used as an alternative source of high-quality proteins, energy, fats and mineral elements. Together with migratory locusts, desert locusts are consumed for proteins and fats although research on its actual nutritive value has not been reported (Mohamed, 2015; Mariod, 2020). There is, therefore, need to investigate the actual nutritive value and the data obtained used to sensitize the society on the importance of such sources of food. Moreover, specific elements of the same can be used in fortification of staple foods like maize and rice in poor communities where malnutrition is rampant.

**Control of desert locusts**

Over the years, the control for desert locust outbreaks and invasion has been the use of organo-phosphorous insecticides such as the widely used chlorpyrifos. These compounds are not only harmful to humans and other living organisms but also pollute the environment contributing to the Chlorofluorocarbons (CFCs) and global warming at large (Gillespie et al., 2000). Therefore, researchers are advocating for better monitoring and alternative measures to synthetic pesticides to control these insects.

First in the list of alternatives, are biopesticides. Research had shown that a fungus, *Metarhizium anisopliae* can kill desert locust by growing in the insect's body. Gillespie (2000) and his team reported that these entomopathogenic fungi kill the desert locust around day 4 and 5 of infection. Therefore, this bio control strategy although it is environmentally friendly, does not offer immediate results but can be used in combination with other control methods. Hence, further research on the appropriate combination of control strategies need to be done to establish the ones that will give optimal results.

Recently, Galal and Seufi (2020) characterized the microbial community present in the desert locust's body. Using morphological data and molecular identification techniques, 9 bacteria species were identified from the *S. gregari* adult body. The identified bacteria species were *E. faecalis, L. paracasei Bacillus sp., S. epidermidis, Escherichia sp., Salmonella sp., Pluralibacter* *sp., Shimwellia spp*; while one species was unclassifies. However; further research on the role of the identified microbes on the survival of the locusts can give an insight on whether the said microbes can be used in the control of the locusts. In addition, further studies are needed to establish the inter-relationship between these microbes and the entomopathogenic fungi *Metarhizium anisopliae.*

Another environmental friendly control strategy is the use of crude extracts from Jatropha (*Jatropha curcas L.*) and neem (*Azadirachta indica A. Juss*) which have been demonstrated to be toxic, antifeedant, and growth regulating compounds against nymph stage of the desert locusts (Bashir and Shafie, 2014). However, further investigation and fractionation of the extracts is required to characterize the specific compounds which are effective against desert locusts in these plants. There is also need to establish, the effectiveness of these plant extracts on hopper stages of the locusts. Moreover, studies on the effect of combined extracts from both plants on the effect on the nymph and hopper stages of the locusts are yet to be reported.

## Gray Leaf Spot and Turcicum Leaf Blight

### History and impact of GLS and TLB to maize production

Gray Leaf Spot (GLS) caused by *Cercospora zea-maydis* (Tehon and Daniels, 1925) and *cercospora zeina-maydis* (Groenewald et al., 2006), is a maize leaf disease that is a global threat to maize production. Molecular research shows that *C. zeina-maydis* is mainly distributed in Brazil and African contries, whereas *C. zeae-maydis* is predominant in the United States of America (Ward et al., 1999, Korsman et al., 2012). In Kenya, the disease was first reported in 1993 and in 1995, it had contributed up to 15% maize yield loss in the western region of Kenya. Since then, it has been reported in other regions such as Rift valley, Eastern and Central regions (Danson et al., 2008).

Documented yield losses attributed to GLS range from 11% to total yield loss in cases of severe infection (Liu et al., 2016). GLS disease is characterized by necrotic lesions leading to leaf senescence hence reducing the photosynthetic capacity of the plant. This reduced photosynthetic capacity is linked to poor grain filling and stalk lodging which ultimately lead to poor maize yield (Gethi et al., 2013).

Turcicum Leaf Blight (TLB) on the other hand, is a serious foliar disease distributed widely around the world and is caused by *Helminthosporium turcicum* affecting maize plants from seedling to harvest stages (Karavina et al., 2014). It is a serious problem in North Eastern United States, sub-Saharan Africa, and areas of China, Latin America, and India (Adipala et al., 1995, Dharanendraswamy, 2003). TLB is characterized by elliptical grey-green lesions which turn to tan with dark spots of sporulation as maturation continues and eventually leads to defoliation affecting grain yield as seen in GLS (Hooda et al., 2017). Yield losses range from 0% to 70% depending on the onset and severity of the infection (Levy, 1996). Crop yield losses threaten global food security especially in sub Saharan Africa where farming is the main source of livelihood.

**Control strategies for GLS and TLB**

The common control methods deployed for these two maize diseases are mainly cultural, chemical and host plant resistance. In the cultural approach, crop rotation and effective burying of the infected plants debris, have reduced the severity of infection in the subsequent round of planting. In addition, effective removal of the over-wintering infected debris, reduced the inoculum available for the next season hence reducing the infection pressure. Fungicides have also been used to control TLB and GLS though it's less cost effective, leads to fungicide resistance and the continued use of chemicals has raised environmental concerns. Due to these drawbacks, cultural and chemical methods have proved to be uneconomical and unreliable especially for the poor small scale farmers.

Host plant resistance therefore, remains the most viable and reliable method for the management of TLB and GLS. Breeders and researchers around the world have hence embarked on research aimed at identifying host resistant varieties for different biotic and abiotic stresses in different economically important crops. For instance, Karavina and the team (2014), identified three maize hybrid lines (053WH54, ZS225 and SR52) which were resistant to TLB diseases. In addition, GLS resistant genes were established in various researches (Gethi et al., 2013).

Due to increasing population and climate change, the demand for food is expected to increase. Therefore, there is need to search for more resistant maize lines for both biotic and abiotic stresses and give farmers a wide variety of maize lines. In recent decades, the invention of Next-Generation Sequencing (NGS) technology and high throughput phenotyping platforms have paved ways for fast and effective means of identifying host resistance, molecular breeding and marker assisted selection. In addition, new biotechnological tools have made it possible to perform gene editing and produce superior breeds.

## Conclusions

Maize is a key cereal crop in Kenya and it associated with food security not only in Kenya but also in Sub-Saharan Africa. The average maize yield in Kenya is far below the global average because of biotic and abiotic stresses which puts a strain on production. Transboundary diseases and pests are significantly increasing putting a strain on food and income security of millions of small-holder farmers.

In as much as these new diseases have previously been reported elsewhere, research is needed in Kenya so that the extent of the economic losses can be clearly defined and also new strategies to control and prevent these disease which are adaptable to the small holder setting in Kenya can be adapted.

With the lifting of the ban on use and cultivation of GMO in Kenya on October 2022, it is expected that researchers will use this technology to fast-track the release of improved maize varieties resistant to pests and diseases.

## Future Perspectives

Maize is an important crop not only in Kenya but sub Saharan Africa at large. Therefore, the effect of biotic stresses has become a burden to especially the small-scale farmers. Hence, sustainable means of dealing with these are important for a food secure country. First, the available new technological advances and breeding methods should be applied to provide farmers with plant host resistance breeds and environmentally friendly control measures. Also, in most instances, these biotic stresses are detected too late. Improved technologies should therefore be used to develop early detection methods.

There is also a need to build a regional collective response to invasive pests and trans-boundary diseases.

Finally, there is a need to sensitize society on alternative crops to maize which is more tolerant to the pest and have superior nutritive value such as sorghum and millet.

**ACKNOWLEDGEMENT**

We would wish to acknowledge Dr. Erik Ohlson of Agricultural Research Service, US department of agriculture, corn, soybean and wheat quality research, Wooster, Ohio for reading the review paper and giving his inputs and corrections and Dr. Alexander Mzula of Sokoine University of Agriculture (SUA) for his inputs and review of the paper.

**Funding**

This manuscript is part of a Ph.D. project (Application of Nanobody as a diagnostic tool against Maize Lethal Necrosis) funded by the Partnership for Skills in Applied Sciences, Engineering and Technology (PASET), Regional Scholarship and Innovation Fund, (RSIF).

**References**

Ali F, Yan J (2012) Disease resistance in maize and the role of molecular breeding in defending against the global threat. J. Integr. Plant Biol. 54(3), 134–15

Antonio, F., Rafael, L., & Sampaio, L. (2008). 4 5 6 7, 3–5.

Awata, L. A. O., Beyene, Y., Gowda, M., Suresh, L. M., Jumbo, M. B., Tongoona, P., Prasanna, B. M. (2020). Genetic analysis of QTL for resistance to maize lethal necrosis in multiple mapping populations. Genes, 11(1), 1-22. https://doi.org/10.3390/genes11010032

Bashir, E. M., & El Shafie, H. A. (2014). Toxicity, Antifeedant and Growth Regulating Potential of Three Plant Extracts against the Desert Locust Schistocerca gregaria Forskal (Orthoptera: Acrididae). Journal of Experimental Agriculture International, 959-970.

Beyene, Y., Gowda, M., Stephen, L. M. S., Olsen, M., Oikeh, S. O., Juma, C., Prasanna, B. M. (2017). Genetic analysis of tropical maize inbred lines for resistance to maize lethal necrosis disease. Euphytica, 213(9), 1–13. https://doi.org/10.1007/s10681-017-2012-3

Braidwood, L., Quito-Avila, D. F., Cabanas, D., Bressan, A., Wangai, A., & Baulcombe, D. C. (2018). Maize chlorotic mottle virus exhibits low divergence between differentiated regional sub-populations. Scientific Reports, 8(1), 1173. https://doi.org/10.1038/s41598-018-19607-4

Brault, V., Uzest, M., Monsion, B., Jacquot, E., & Blanc, S. (2010). Aphids as transport devices for plant viruses. Comptes rendus biologies, 333(6-7), 524-538.

Burtet, L. M., Bernardi, O., Melo, A. A., Pes, M. P., Strahl, T. T., & Guedes, J. V. C. (2017). Managing fall armyworm, Spodoptera frugiperda (Lepidoptera: Noctuidae), with Bt maize and insecticides in southern Brazil. Pest Management Science, 73(12), 2569–2577. https://doi.org/10.1002/ps.4660

Capinera J.L. 1999. Fall Armyworm, Spodoptera frugiperda (J.E. Smith) (Insecta: Lepidoptera: Noctuidae). Florida Entomologist

Danson, J., Lagat, M., Kimani, M., & Kuria, A. (2008). Quantitative trait loci (QTLs) for resistance to gray leaf spot and common rust diseases of maize. African Journal of Biotechnology, 7(18).

De Groote, H., Kimenju, S. C., Munyua, B., Palmas, S., Kassie, M., & Bruce, A. (2020). Spread and impact of fall armyworm (Spodoptera frugiperda JE Smith) in maize production areas of Kenya. Agriculture, Ecosystems & Environment, 292, 106804.

Devi, S. (2018). Fall armyworm threatens food security in southern Africa. Lancet (London, England), 391(10122), 727. https://doi.org/10.1016/S0140-6736 (18)30431-8

Dharanendraswamy, S. (2003). Studies on turcicum leaf blight of maize caused by Exserohilum turcicum. M.Sc. (Agri.) Thesis. Dharwad: University of Agricultural Sciences.

Galal, F. H., & Seufi, A. M. (2020). Molecular characterization of cultivable bacteria associated with adult Schistocerca gregaria, using 16S rRNA. Journal of Taibah University for Science, 14(1), 605-614.

Gethi, J., Mukunya, D. M., Githiri, S., & Nzuve, F. (2013). Combining abilities of maize inbred lines for grey leaf spot (GLS), grain yield and selected agronomic traits in Kenya. Journal of Plant Breeding and Crop Science, 5(3), 41-47.

Gillespie, J. P., Burnett, C., & Charnley, A. K. (2000). The immune response of the desert locust Schistocerca gregaria during mycosis of the entomopathogenic fungus, Metarhizium anisopliae var acridum. Journal of Insect Physiology, 46(4), 429-437.

Gowda, M., Das, B., Makumbi, D., Babu, R., Semagn, K., Mahuku, G., & Prasanna, B. M. (2015). Genome-wide association and genomic prediction of resistance to maize lethal necrosis disease in tropical maize germplasm. Theoretical and Applied Genetics, 128(10), 1957-1968.

Groenewald, M., Groenewald, J. Z., Harrington, T. C., Abeln, E. C., & Crous, P. W. (2006). Mating type gene analysis in apparently asexual Cercospora species is suggestive of cryptic sex. Fungal Genetics and Biology, 43(12), 813-825.

Gudero Mengesha, G., Kedir Mohammed, B., & Sultan Salo, K. (2019). Management of maize lethal necrosis disease through hand weeding and insecticide applications at Arba Minch in

Southern Ethiopia. Cogent Food & Agriculture, 5(1). https://doi.org/10.1080/23311932.2019.1705746

Herrington, D., Schuster, G., Ag.Bldg, K., & Lewis, A. (2014). Mycotoxin Levels Associated with Fall Armyworm (Spodoptera frugiperda) and Corn Earworm (Helicoverpa zea) Infested Corn.

https://doi.org/10.2135/cropsci2014.09.0646

https://www.fao.org/giews/countrybrief/country.jsp?code=KEN&lang=en

Hutchens, N. J. (1978). LD2668T41981H87.pdf. Kansas state University.

Indexmundi. (2018). https://www.indexmundi.com/agriculture/?country=ke&commodity=corn&graph=domestic-consumption

Jones, M. W., Penning, B. W., Jamann, T. M., Glaubitz, J. C., Romay, C., Buckler, E. S., & Redinbaugh, M. G. (2018). Diverse chromosomal locations of quantitative trait loci for tolerance to maize chlorotic mottle virus in five maize populations. Phytopathology, 108(6), 748–758. https://doi.org/10.1094/PHYTO-09-17-0321-R

Karavina, C., Mandumbu, R., & Mukaro, R. (2014). Evaluation of three-way maize (Zea mays L) hybrids for yield and resistance to maize streak virus and turcicum leaf blight diseases. J Anim Plant Sci, 24(1), 216-220.

Kinyungu, T. N., Muthomi, J. W., Subramanian, S., Miano, D. W., Olubayo, F. M., & Maobe, M. A. (2019). Role of maize residues in transmission of maize chlorotic mottle virus and effect on yield, 6655, 338–349.

Korsman J, Meisel B, Kloppers F, Crampton B, Berger D (2012) Quantitative phenotyping of grey leaf spot disease in maize using real-time PCR. Eur J Plant Pathol. 133: 461–471.

Kuki MC, Scapim CA, Rossi ES, Mangolin CA, Amaral Júnior ATd, Pinto RJB (2018) Genome wide association study for gray leaf spot resistance in tropical maize core. PLoS ONE 13(6): e0199539.

Kumela, T., Simiyu, J., Sisay, B., Likhayo, P., Mendesil, E., Gohole, L., Tefera, T., 2019. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (Spodoptera frugiperda) in Ethiopia and Kenya. International Journal of Pest Management 65 (1), 1–9.

Kump, K. L., Bradbury, P. J., Wisser, R. J., Buckler, E. S., Belcher, A. R., Oropeza-Rosas, M. A., ... & Balint-Kurti, P. J. (2011). Genome-wide association study of quantitative resistance to southern leaf blight in the maize nested association mapping population. Nature genetics, 43(2), 163.

Kusia, E. S. (2018). Characterization of Maize chlorotic mottle virus and Sugarcane mosaic virus causing maize lethal necrosis disease and spatial distribution of their alternative hosts in Kenya (Doctoral dissertation, JKUAT-PAUSTI).

Lecoq, M. (2003). Desert locust threat to agricultural development and food security and FAO/international role in its control. Arab Society for Plant Protection.

Lehmensiek, A., Esterhuizen, A. M., Van Staden, D., Nelson, S. W., & Retief, A. E. (2001). Genetic mapping of gray leaf spot (GLS) resistance genes in maize. Theoretical and Applied Genetics, 103(5), 797-803.

Liu, L., Zhang, Y. D., Li, H. Y., Bi, Y. Q., Yu, L. J., Fan, X. M., ... & Kang, M. S. (2016). QTL mapping for gray leaf spot resistance in a tropical maize population. Plant disease, 100(2), 304-312.

Mahuku, G. (2019). First Report of Maize chlorotic mottle virus and Maize Lethal Necrosis on Maize in, (July 2014), 15–17. https://doi.org/10.1094/PDIS-04-15-0373-PDN

Mahuku, G., Lockhart, B. E., Wanjala, B., Jones, M. W., Kimunye, J. N., Stewart, L. R., … Redinbaugh, M. G. (2015). Maize Lethal Necrosis (MLN), an Emerging Threat to Maize-Based Food Security in Sub-Saharan Africa. Phytopathology, 105(7), 956–965. https://doi.org/10.1094/phyto-12-14-0367-fi

Mariod, A. A. (2020). Nutrient Composition of Desert Locust (Schistocerca gregaria). In African Edible Insects As Alternative Source of Food, Oil, Protein and Bioactive Components (pp. 257-263). Springer, Cham.

Mengesha, G. G., Mohammed, B. K., & Salo, K. S. (2019). Management of maize lethal necrosis disease through hand weeding and insecticide applications at Arba Minch in Southern Ethiopia. Cogent Food & Agriculture, 5(1), 1705746.

Miano, D. W. (2014). Maize lethal necrosis disease: A real threat to food security in the eastern and central Africa region.

Mohamed, E. H. (2015). Determination of nutritive value of the edible migratory locust Locusta migratoria, Linnaeus, 1758 (Orthoptera: Acrididae). Int. J. Adv. Pharm. Biol. Chem, 4, 144-148.

Nboyine, J. A., Kusi, F., Abudulai, M., Badii, B. K., Zakaria, M., Adu, G. B., & Yahaya, A. (2020). A new pest, Spodoptera frugiperda (JE Smith), in tropical Africa: Its seasonal dynamics and damage in maize fields in northern Ghana. Crop Protection, 127, 104960.

Njeru, F., Mwaura, S., Kusolwa, P. M., & Misinzo, G. (2022). Maize production systems, farmers' perception and current status of maize lethal necrosis in selected counties in Kenya. All Life, 15(1), 692–705. https://doi.org/10.1080/26895293.2022.2085815

Odendo, M., De Groote, H., & Odongo, O. M. (2001). Assessment of farmers' preferences and constraints to maize production in moist midaltitude zone of Western Kenya. Paper Presented at the 5th International Conference of the African Crop Science Society, 21–26.

Pant, S. K., Pramod, K., & Chauhan, V. S. (2001). Effect of turcicum leaf blight on photosynthesis in maize. Indian Phytopathology, 54, 251–252.

Prasanna, B., Huesing, J. E., Peschke, V. M., & Eddy, R. (2018). Fall Armyworm in Africa : Situation & Programme, (April), 10–21.

Prasanna, B., Suresh, L. M., Mwatuni, F., Beyene, Y., Makumbi, D., Gowda, M., & Molnar, T. (2020). Maize lethal necrosis (MLN): Efforts toward containing the spread and impact of a devastating transboundary disease in sub-Saharan Africa. Virus Research, 197943.

Roussi, A. (2020). The battle to contain gigantic locust swarms. Nature, 579, 330.

Rwomushana, I., Bateman, M., Beale, T., Beseh, P., Cameron, K., Chiluba, M., Tambo, J., 2018. Fall Armyworm: Impacts and Implications for Africa Evidence Note Update, October 2018. Report to DFID. CABI, Wallingford.

Semagn, K., Beyene, Y., Babu, R., Nair, S., Gowda, M., Das, B., & Warburton, M. L. (2015). Quantitative Trait Loci Mapping and Molecular Breeding for Developing Stress Resilient Maize for Sub-Saharan Africa. Crop Science, 55(4), 1449-1459.

Semagn, K., Magorokosho, C., Vivek, B. S., Makumbi, D., Beyene, Y., Mugo, S., & Warburton, M. L. (2012). Molecular characterization of diverse CIMMYT maize inbred lines from eastern and southern Africa using single nucleotide polymorphic markers. BMC genomics, 13(1), 113.

Sisay, B., Simiyu, J., Malusi, P., Likhayo, P., Mendesil, E., Elibariki, N., & Tefera, T. (2018). First report of the fall armyworm, Spodoptera frugiperda (Lepidoptera: Noctuidae), natural enemies from Africa. Journal of Applied Entomology, 142(8), 800-804.

Stewart, L. R., & Willie, K. (2021). Maize Yellow Mosaic Virus Interacts with Maize Chlorotic Mottle Virus and Sugarcane Mosaic Virus in Mixed Infections, But Does Not Cause Maize Lethal Necrosis. Plant Disease, 105(10), 3008–3014. https://doi.org/10.1094/PDIS-09-20-2088-RE

Stewart, L. R., Willie, K., Wijeratne, S., Redinbaugh, M. G., Massawe, D., Niblett, C. L., Asiimwe, T. (2017). Johnsongrass mosaic virus contributes to maize lethal necrosis in East Africa. Plant Disease, 101(8), 1455–1462. https://doi.org/10.1094/PDIS-01-17-0136-RE

Tambo, J. A., Kansiime, M. K., Mugambi, I., Rwomushana, I., Kenis, M., Day, R. K., & Lamontagne-Godwin, J. (2020). Understanding smallholders' responses to fall armyworm (Spodoptera frugiperda) invasion: Evidence from five African countries. Science of the

Total Environment, 740, 140015. https://doi.org/10.1016/j.scitotenv.2020.140015

Tehon, L. R., & Daniels, E. (1925). Notes on the Parasitic Fungi of Illinois—II. Mycologia, 17(6), 240-249.

Thompson, H. E., Berrang-Ford, L., & Ford, J. D. (2010). Climate change and food security in sub-Saharan Africa: a systematic literature review. Sustainability, 2(8), 2719-2733.

Uyemoto, J. ., Bockelman, D. ., & Claflin, L.  (1980). Severe outbreak of Corn Lethal Necrosis Disease.PDF.

Wamaitha, M. J., Nigam, D., Maina, S., Stomeo, F., Wangai, A., Njuguna, J. N., & Djikeng, A. (2018). Metagenomic analysis of viruses associated with maize lethal necrosis in Kenya. Virology journal, 15(1), 90.

WAN, J., HUANG, C., LI, C. you, ZHOU, H. xu, REN, Y. lin, LI, Z. yuan, WAN, F. hao. (2021). Biology, invasion and management of the agricultural invader: Fall armyworm, Spodoptera frugiperda (Lepidoptera: Noctuidae). Journal of Integrative Agriculture, 20(3), 646–663. https://doi.org/10.1016/S2095-3119 (20)63367-6

Wang, H. H., Zhao, R., Gao, J., Zhang, L., Zhang, S., Liang, P., Gu, S. H. (2022). Genetic architecture and insecticide resistance in Chinese populations of Spodoptera frugiperda. Journal of Pest Science, (October). https://doi.org/10.1007/s10340-022-01569-2

Wangai, A. W., Redinbaugh, M. G., Kinyua, Z. M., Miano, D. W., Leley, P. K., Kasina, M., & Jeffers, D. (2012). First report of maize chlorotic mottle virus and maize lethal necrosis in Kenya. Plant Disease, 96(10), 1582-1582.

Ward JMJ, Stromberg EL, Nowell DC, Nutter FW (1999) Gray leaf spot: a disease of global importance in maize production Plant Dis. 83: 884–895. 8.

Wisser, R. J., Balint-Kurti, P. J., & Nelson, R. J. (2006). The genetic architecture of disease resistance in maize: A synthesis of published studies. Phytopath, 96, 120–129.

Wokorach, G., Landschoot, S., Anena, J., Audenaert, K., Echodu, R., & Haesaert, G. (2021). Mycotoxin profile of staple grains in northern Uganda: Understanding the level of human exposure and potential risks. Food Control, 122, 107813. https://doi.org/10.1016/j.foodcont.2020.107813

Womack, E. D., Williams, W. P., Smith, J. S., Warburton, M. L., Bhattramakki, D., & Hesler, L. (2020). Mapping Quantitative Trait Loci for Resistance to Fall Armyworm (Lepidoptera: Noctuidae) Leaf-Feeding Damage in Maize Inbred Mp705. Journal of Economic Entomology, 113(2), 956–963. https://doi.org/10.1093/jee/toz357

Zaman-allah, M. A., Chaipa, I., Chari, N., Chnwada, P. (2019). Understanding the factors influencing fall armyworm (Spodoptera frugiperda J. E. Smith) damage in African smallholder maize fields and quantifying its impact on yield. A case study in Eastern Zimbabwe, 120, 141-150. https://doi.org:10.1016/j.cropro.2019.01.028

# Figure 1

MLN affected maize

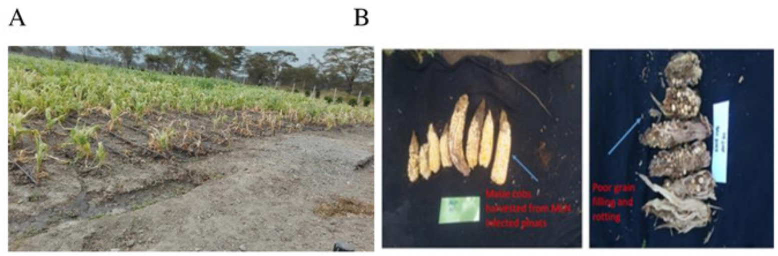


*Fig. 1: A) MLN infected field under artificial inoculation at CIMMYT-KALRO MLN screening facility B) Maize cobs harvested from mechanically inoculated maize (Photo taken by Faith Njeru and Paul Njau)*

# Figure 2

Desert locusts in farmers field

*Fig. 2: A local resident in Kenya trying to ward off desert locusts from her farm. Photo taken from: https://grist.org/climate/climate-change-helped-spawn-east-africas-locust-crisis/.*

# Table 1(on next page)

Average maize production in Kenya 2010-2018

| MAIZE PRODUCTION | | |
|---|---|---|
| **YEAR** | Area harvested (ha) | yield (t/ha) |
| **2010** | 2008346 | 1.73 |
| **2011** | 2131887 | 1.58 |
| **2012** | 2159322 | 1.74 |
| **2013** | 2123138 | 1.69 |
| **2014** | 2116141 | 1.66 |
| **2015** | 2098240 | 1.82 |
| **2016** | 2337586 | 1.43 |
| **2017** | 2086178 | 1.53 |
| **2018** | 2273283 | 1.77 |

*Table 1: Average maize production in Kenya 2010-2018*