Journal of Economic Entomology, XX(XX), 2024, 1–12
https://doi.org/10.1093/jee/toae235
Research

ENTOMOLOGICAL SOCIETY OF AMERICA
SHARING INSECT SCIENCE GLOBALLY

OXFORD

Arthropods in Relation to Plant Disease

Maize plants can recover from fall armyworm damage under optimum crop production conditions in humid tropical agro-ecologies

Albert Fomumbod Abang[1], **Samuel Nanga Nanga**[1], **Mawufe Komi Agbodzavu**[2], **Apollin Kuate Fotso**[1,*], **Christopher Suh**[2,3], **Cargele Masso**[1,4], **Zoumana Bamba**[2], **Komi Kouma Mokpokpo Fiaboe**[1]

[1]Plant Health Department, International Institute of Tropical Agriculture (IITA)-Cameroon, Yaoundé, Cameroon, [2]Plant Health Department, International Institute of Tropical Agriculture (IITA)-DRC, Yaoundé, Cameroon, [3]Annual Crop Department, Institute of Agricultural Research for Development (IRAD), Yaoundé, Cameroon, [4]One CGIAR, Environmental Health and Biodiversity Impact Area, Nairobi, Kenya [*]Corresponding author, email: a.fotso@cgiar.org

Subject Editor: Allan Showler

Received on 19 April 2024; revised on 8 September 2024; accepted on 28 September 2024

Farmers in Africa perceive the impact of fall armyworm (FAW) on maize to be significant, but field assessments have shown that yield losses are not significant enough to warrant pesticide interventions. This suggests that relationships between the crop stages, time, and duration of attack can affect the yield. Therefore, assessing the plant's recovery from damage using individual plants based on defoliation levels could guide whether and when pesticides should be applied. To study this, we selected 120 labeled maize plants corresponding to six levels of FAW defoliation, replicated 20 times, based on an initial damage rating. The rating scale ranged from 1 (no defoliation) to 5 (>75% defoliation) during four planting seasons. Plants with a rating scale of 1 were replicated and treated with a chemical insecticide to keep them undefoliated, and that served as a control. Damage severity was recorded weekly on all plants, starting from emergence until maturity, using the same damage rating scale. Results showed that damage severity varied significantly among different defoliation levels during all seasons. Higher levels of defoliation during dry seasons resulted in significant yield loss only for plants with damage levels 4 and 5, with damage severity ranging from 38.7% to 57.5%. These results indicate that FAW control is unnecessary in the rainy season. In contrast, pesticide interventions should be envisaged in seasons of erratic rainfall, with a significant defoliation threshold level of around 50%, occurring at 8 and 5 wk after planting weeks after planting, respectively for the early and late dry season.

Key words: foliar damage, severity rating scale, percent leaf defoliation, recovery, maize yield loss

Introduction

Stem borers are well-known Lepidopteran pests of maize in Africa. However, research on maize pests must now consider *Spodoptera* species, particularly the fall armyworm (FAW) *Spodoptera frugiperda* (J.E. Smith), and how the crop recovers from its damage and compensates for yield loss. Yield loss due to stem borers across Africa has been estimated between 20 and 40% (Wahedi et al. 2016), and the presence of FAW is likely to affect this rate, especially as spatiotemporal interaction between the two pests has been observed (Ntiri et al. 2019, Abang et al. 2020).

The impact of FAW on maize yield in Africa is significant. According to Day et al. (2017), the impact of FAW on yield in Ghana and Zambia is between 22 and 67%, resulting in millions of US dollars in losses. Similarly, Kumela et al. (2018) estimated that FAW affects 32% of the yield in Ethiopia and 47% of the yield in Kenya. However, these estimates were based on socio-economic surveys that focused on farmers' perceptions rather than rigorous field scouting. There is a lack of rigorous field scouting in Africa to estimate economic yield losses, such as those prescribed by Baudron et al. (2019). Meanwhile, damaged plants remain a concern for farmers as they were not familiar with this type of damage, where the insect eats through so much of the leaves. Farmers know about stem borers, but because they are often hidden in the stems, they are not as scary as FAW, with its monstrous-looking big larvae in the whorl and scary leaves devastating display. However, it is still difficult for most of them to distinguish between the two lepidopteran groups as they often generalize them as the same pest, calling them worms. Even the damage caused by the two pests cannot be separated by farmers. Therefore, attention should also be paid to ear and stem borers when conducting any study about lepidopteran pests on maize so as not to attribute stem borer data to spodopterans and vice versa. Differentiating damage symptoms caused by these lepidopterans is key to the quality of data on damage attributed to the respective pest types and will play a role in determining the intervention threshold based on economic injury levels.

Several farmers and state governments have taken measures to address pest damage, but such interventions have been driven more by emotions than by data. The visible damage inflicted by pests can be quite striking, leading to anxiety among farmers at the mere sight of damaged leaves. Unfortunately, media alarmism and the desire of politicians to take swift action have resulted in some poor decisions, such as the use of highly hazardous pesticides (FAO 2018).

The tendency of farmers and researchers to respond with panic to the appearance of FAW damage may indicate a lack of understanding of the potential impact of such damage and the relationship between damage levels and yield losses. Upon encountering significant-looking damage, the common response is to assume that it will result in dramatic yield reduction. However, it is important to realize that FAW damage does not typically cause destruction, and the leaf damage caused by the pest may result in yield reductions below expectations. As research by Hruska (2019) has shown, defoliation resulting from FAW rarely exceeds 50% and is typically closer to 25%, resulting in some yield reduction but not necessarily to the extent feared.

It has been observed that among the three major parameters (abundance of immature stages, incidence, and severity) recorded for the FAW on maize, the severity of defoliation or damage is the crucial factor that determines the yield response, particularly if the severity is high on a significantly high number of plants. Several studies have been conducted to assess the impact of FAW infestation on maize yield in the field, mainly in the Americas. The review of these studies shows that while a few of them show yield reductions of over 50% due to FAW, most of the field trials show yield reductions of less than 20%, even with high FAW infestation (up to 100 percent of plants infested) and very few plants may have severe damage with big holes and damaged leaves that warrant farmers' action. Various studies demonstrated that maize plants can compensate for foliar damage by armyworms such as corn earworm and FAW, especially if there is good plant nutrition and moisture (Buntin et al. 2001, 2004, Buntin 2008, FAO, 2018). Thus the use of pesticides, whether chemical or biological, should be prudent and restricted only when the pest population exceeds the economic threshold level to avoid their misuse and over-use (FAO and PPD. 2020).

In Africa, where the FAW is a recent pest there is a concern about the inappropriate use of chemical controls as threshold levels are not being used and are not available in determining the need for chemicals (Assefa and Ayalew 2019). This could lead to resistance development, economic inefficiency, and risks to human and environmental health (Togola et al. 2018). Although an intervention guide based on incidence has been provided (Abrahams et al. 2017, FAO and PPD. 2020), its effectiveness has not been demonstrated based on agroecological differences and how yields are affected. In the Americas, several threshold for field corn levels have been reported, such as the presence of egg masses on more than 5% of the plants (Bessin 2004), 50% of the plants having severe leaf damage (Steffey et al. 1999), and 5% of the plants with leaf damage and live larvae still present (Bessin 2004), 20% of plants with pinhole-type damage (Alves De Albuquerque et al. 2006, Cruz et al. 2012), 20% of whorl stage plants infested with 3 living larvae each (Buntin 1986), pheromone trap catches of 10–20 per night (Barlow and Kuhar 2009), 10 days after a cumulative number of three adults or 10% of the plants damaged (Cruz et al. 2010, 2012), and the number of larvae per plant (Jaramillo-Barrios et al. 2020). Recently, Cameroon made efforts to apply the most common and simplest method for farmers, indicated by Andrews (1980) such as damage incidence (10% or 25%) and three-moth capture in pheromone trap (single and double frequency), to determine the need for insecticide treatment (Andrews 1980, Abang et al. 2022). However, there were no significant differences in yield and severity of damage between treated and untreated plots, indicating that geographic location plays a role in setting thresholds.

The level of compensation and the yield are affected by the growth stages at which the infestation occurs and the duration of the infestation (FAO 2018). However, it is important to consider the severity of the damage, the percentage of plants affected by each level of damage, the presence of larvae, and environmental conditions of the field, such as drought. For example, at Purdue University in 2019, pesticide applications were recommended when there was a severe infestation, with 75% of the plants exhibiting whorl feeding damage and larvae were less than 31 mm long, and the plants were under stress (Hruska 2019). The level of foliar damage can also affect the ability to compensate and recover from the damage (Hruska 2019). The level of foliar damage usually varies between plants, but results are usually given as an average of different plants with different initial severity rates. Therefore, damage recovery from a plant with less foliar damage will be different from recovery of a plant with higher foliar damage. We hypothesize that evaluating the ability of plant recovery from damage using individual plants based on the level of foliar damage will help validate strategies to effectively manage FAW in an African context.

This study aimed to assess whether maize plants can recover from damage caused by FAW without significant yield loss while adhering to customary maize cultural practices. The specific objectives were: (i) to evaluate the severity of foliar damage and its impact on plant recovery and/or yield loss; (ii) to evaluate the influence of planting season and weather conditions on plant recovery and yield loss; (iii) to determine the maize growth stage at which foliar damage effects yield; (iv) to determine the level of foliar damage at which significant yield loss occurs and to estimate the economic benefits of interventions against the pest.

Materials and Methods

Experimental Site and Plot Establishment

Four field experiments were conducted from September 2020 to August 2021, at the International Institute of Tropical Agriculture (IITA) in Yaounde, Cameroon, at 03°51.791′N; 011°27.706′E; 747 masl. The experimental site's agroecology is the bimodal warm and humid forest zone characterized by four seasons per year: the long rainy season from mid-March to mid-July (S1), short dry season from mid-July to mid-September (S2), short rainy season from Mid-September to mid-November (S3), and late dry season from mid-November to mid-March of the following year (S4; Fig. 1) (Abang et al. 2021). Temperature ranges from 20°C to 25°C depending on altitude (400–1,000 m), and the rainfall is around 1,500–2,000 mm/year (Blein et al. 2008). Two experiments were conducted in the rainy season (September to December 2020 and April to August 2021), and two in the dry season from October 2020 to January 2021 (early

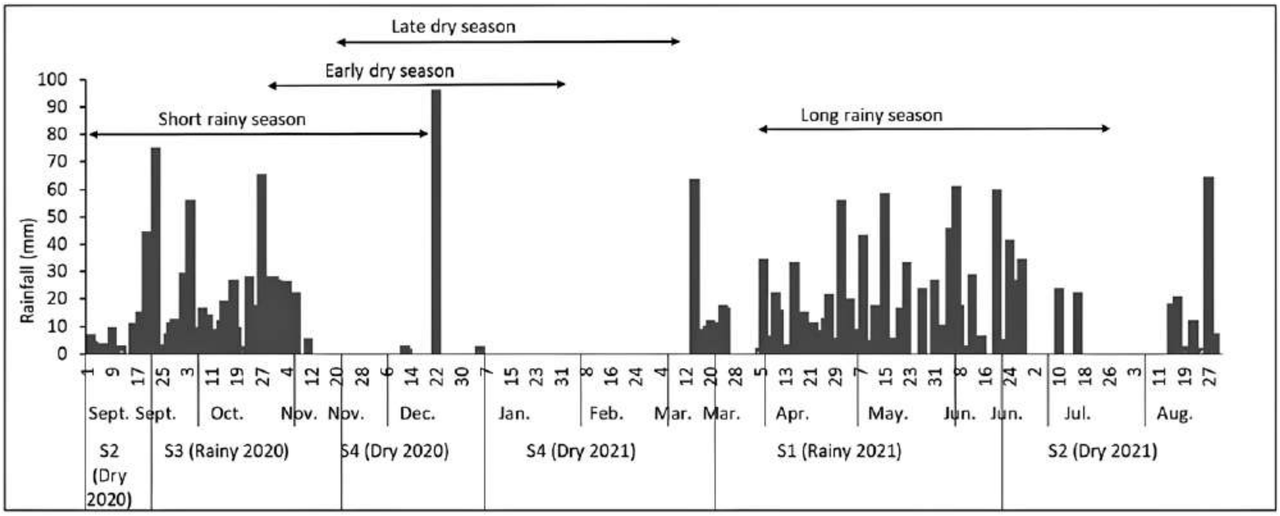

Fig. 1. Distribution of rainfall during the four trials conducted in the years 2020 and 2021. The data is presented with a weekly range, and the trials are classified into Short and Long Rainy, Early and Late Dry, representing the four different experiments. The ecological zone where the experiment was conducted has four seasons, namely S1 (mid-March to mid-June), S2 (mid-June to mid-September), S3 (mid-September to mid-November), and S4 (mid-November to mid-March of the next year).

dry season) and November 2020 to February 2021 (late dry season). The size of the experimental field was 2500 m^2. The high-yielding IITA maize variety ACR 06 TZL COMP4C4F2 (ACRO 6 thereafter) (60–64 days crop cycle from planting to anthesis) (Badu-Apraku et al. 2020) was planted in each plot at 50 cm within rows and 50 cm between rows. The trials were fertilized twice as side-dress: first, NPK (20-10-10) at 11 g/plant 2 wk after planting (soon after thinning), and second, urea at 11 g/plant four weeks after planting (WAP) (after weeding and mounding). Control plants were treated bi-weekly by spraying with insecticide GREMEC (Emamectin benzoate 300 g/ha at 10 g/sprayer in 15 L of water) to keep the plants completely free from FAW.

Experimental Design

Regular scouting was conducted daily in the field, and the experiments started when plants with varying damage levels were available. Plant selection for the treatments was done concurrently for all damage levels at the onset of each experiment. For the long rainy season in March (experiment 1), all 6 damage levels (treatments) were available at 4 WAP, while for the short rainy season in September (experiment 2), they were available at 3 WAP. During the early dry season in October (experiment 3), the experiment was set up at 4 WAP and for the late dry season in November (experiment 4), the experiment plants were available at 2 WAP. Plants were selected and labeled based on damage levels according to a damage rating scale of 1–5 (Silva et al. 2015). The foliar damage levels were score 1 = no leave damage (treatment 1), score 2 = leave damage between 1%–25% (treatment 2), score 3 = leave damage between 26%–50% (treatment 3), score 4 = leave damage between 51%–75% (treatment 4), and score 5 = leave damage > 75% (treatment 5). 20 undamaged control plants were also selected and sprayed bi-weekly to serve as the control. Pegs with labels indicating the treatment were tied at the base of each selected plant in the field. Each treatment was replicated 20 times by selecting 20 plants. In total, 120 plants comprising 6 damage levels (score 1–5, and control) × 20 plants were labeled following a completely randomized design. Plant selection was done along a fertility and slope gradient. Fig. 1 shows the rainfall pattern during the experimental periods.

Data Collection and Calculations

The damage severity by FAW and stemborers (*Busseola fusca* F.) of each of the 120 plants was recorded based on the same scale used for the selection of defoliation treatments (Silva et al. 2015) starting from the day of selection and continued weekly until tasseling. Bigger holes on leaves are characteristic of FAW and are not present in stemborer attacks (for both young and old larvae). FAW larvae produce scattered or clustered pinhole-type damage, small to large, and circular or elongated lesions with cuticle removed or without "windowpanes" and shoot-holes (aligned across the leaf) (Davis et al. 1992, FAO 2018, Prasanna et al. 2018, FAO and CABI 2019). Among stemborers, *Busseola fusca* (Fuller) is the most important. Damage due to young larvae between FAW and *B. fusca* may be confusing, but stemborers often produce smaller shoot-hole damage and extensive feeding on cuticle renders the damaged section elongated, brownish yellow, and the windowpanes and lesions become necrotic when older (Tefera et al. 2011).

Yield was assessed using the grain count method described by Blumenthal and Thompson (2009). During an initial unpublished experiment, we conducted in the same location and under the same conditions, two yield assessment methodologies, the grain count and the grain weight methods, were compared. The treatments included control and local innovations to control FAW, such as detergent, soil, *Thevetia neriifolia* leaf extract, and wood ash. During the harvest, we compared two methods for collecting and calculating the yield data: the first method, as described by Teklewold et al. (2015), directly measures grain weight; the second method is based on counting the number of grains per cob (Blumenthal and Thompson 2009, Agbodzavu et al. 2024). After harvesting, the ears of each of the 20 plants from each treatment were collected, labeled and used for yield calculation.

For the grain weight method, each sub-sample was shelled, and the grain weight was measured to get the shelling percentages as follows:

$$\text{Shelling \%} = \frac{\text{Grain weight (kg)}}{\text{Field weight (kg)}} \times 100$$

The grains were then dried until reaching a stable weight to determine the moisture content (MC).

MC = Initial weight—stable weight after drying.

The grain moisture content was adjusted to 12.5% using the following formula:

$$\text{Adjusted moisture content} \ (\%) = \frac{100 - \text{actual moisture content} \ (\%)}{100 - 12.5} \times 100$$

The final grain yield (t/ha) was presented as adjusted to 12.5% moisture content using the following formula:

$$\text{Yield} \ (\text{t}/m^2) = \frac{\text{Field weight (kg)} \times \text{adjusted moisture content (\%)} \times \text{shelling \%} \times 10}{\text{Sampled plot area} \ (m^2)} / 1000$$

For the grain count method, yield data was collected at the senescence stage from a 1 m² plot, corresponding to four ears with a planting distance of 50 × 50 cm. The number of grain rows in each cob from the sample area and the number of grains in the longest and shortest rows were counted. Using this information, the mean number of grains per row was calculated and multiplied by the number of rows to obtain the total number of grains per ear. The total number of ears for each sample area was multiplied by the average number of grains per ear to determine the number of grains per sampled area. The number of grains per hectare was obtained by multiplying the number of grains for each sample area by 10,000 m² and dividing by 2.25 m² which is the useful area occupied by maize plants in a 1 m²-plot (Agbodzavu et al. 2024). The number of grains per hectare was divided by the bushel factor to calculate the number of bushels per hectare. The authors of the bushel method found that maize subjected to drought stress has approximately 110,000 small grains per bushel, while normal maize has 90,000 medium grains per bushel, and exceptional maize has 70,000 large grains per bushel. Actual grain sizes were determined by measuring a sample of grains. The category of the grains was determined using a key to determine the "grains per bushel factor graph" (Blumenthal and Thompson 2009, Agbodzavu et al. 2024).

We used a Generalized Linear Model (GLM) with the Gaussian distribution to evaluate the effect of treatments on yield for each yield calculation method. Furthermore, we used the student *t*-test to compare the two yield assessment methods for each treatment. Our significance threshold was set at $P = 0.05$.

In Table 1, the results of this initial experiment indicated no significant difference between yields obtained through the two methods. Therefore, the bushel method was selected for the study described in this paper due to its ease of implementation compared to the actual weighing method.

Data Analysis

The Shapiro test did not confirm normality. Therefore, a Generalized Linear Model (GLM) was used to evaluate the effect of initial damage level on final damage levels. This was done for each week and season. Similarly, a GLM was applied to analyze the effect of stem borer damage severity on plant recovery from FAW damage. The same model was used to analyze the effect of initial foliar damage level on plant height and yield but with the Gaussian distribution. The significance threshold was set at $P = 0.05$, using the F test. Similar analysis procedures were applied to assess the effect of the season on each parameter, but a *t*-test was applied to compare the severity of stemborer damage between the two dry seasons during which it was recorded. When differences between foliar damage levels were found, Tukey's test was used for mean separation. R version 3.6.2 was used for all statistical analyses.

Results

Effect of Initial Damage Levels on FAW and Stem Borer (SB) Damage Severity and Yield

The results of the experiments indicate significant differences in the severity of foliar damage over time, as presented in Table 2. The severity of foliar damage over time varied during the different seasons: During the long rainy season, the severity of foliar damage ranged from 0.1 ± 0.1 to 27.1 ± 2.3% ($F = 57.15$; $df = 4.95$; $P < 0.001$); during the short rainy season, it ranged from 1.1 ± 0.3 to 20.6 ± 1.5% ($F = 60.51$; $df = 4.95$; $P < 0.001$); during the early dry season, it ranged from 2.3 ± 1.6 to 55.4 ± 7.3% ($F = 19.193$; $df = 5.114$; $P < 0.001$), and during the late dry season from 3.1 ± 0.6 to 49.6 ± 3.0% ($F = 31.904$; $df = 5.114$; $P < 0.001$). The damage caused by stem borer damage was observed only during the two dry seasons. The damage severity of stem borer ranged from 5.3 ± 2.4 to 31.0 ± 6.6% ($F = 2.858$; $df = 5.114$; $P = 0.018$) during the early dry season and from 0 to 14.5 ± 3.5% ($F = 2.481$; $df = 5.114$; $P = 0.036$) during the late dry season.

It was observed that there was a significant difference in yield between damage levels only during the dry seasons (Table 2). Damage levels did not have any significant effect on the yield during the long rainy season ($F = 0.648$; $df = 4, 95$; $P = 0.631$) with values from 5.0 ± 0.4 to 5.6 ± 0.2 t/ha, and the short rainy season ($F = 0.171$; $df = 4.95$; $P = 0.953$) with values ranging from 5.2 ± 0.5 to 5.8 ± 0.6 t/ha. Variations were significant for early dry season ($F = 4.784$; $df = 5.114$; $P = 0.007$) and late dry season ($F = 3.615$; $df = 5, 114$; $P = 0.006$). The yield ranged from 1.3 ± 0.6 to 2.7 ± 0.0 t/ha in early dry season and from 1.6 ± 0.2 to 3.0 ± 0.3 t/ha in late dry season (Table 2). The data showed that there was significant yield loss during the early dry season ranging from 8.1% to 53.8% and the late dry season ranging from 5.9% to 42.9% (Table 2). On the other hand, the yield loss was lower during the rainy seasons ranging from 4.5% to 11.7% for the long rainy season and −7.5%–4.1% for the short rainy season.

Seasonal Effect on Damage Severity and Yield

There were significant differences observed among the seasons in terms of FAW damage severity ($F = 38.36$; $df = 3.430$; $P < 0.001$), plant stunting ($F = 450.4$; $df = 3.430$; $P < 0.001$), and yield ($F = 76.13$; $df = 3.430$; $P < 0.001$). The severity values were higher

Table 1. Comparison between grain count and the grain weight methods during maize yield assessment

Treatment	Grain count (kg/ha)	Grain weight (kg/ha)	*t*	*P*
Control	2480.0 ± 200.3	1975.0 ± 194.1	−1.811	0.145
Detergent	2640.0 ± 138.7	2383.5 ± 294.1	−0.789	0.491
Soil	2485.1 ± 353.6	1987.2 ± 408.5	−0.922	0.410
Leaf extract	2577.5 ± 168.5	2200.3 ± 222.8	−1.350	0.253
Wood ash	2180.4 ± 068.4	2013.4 ± 140.0	−1.072	0.365
$F_{4.10df}$	0.716	0.436		
P	0.5996	0.7802		

Table 2. Average (±SE) of damage severity by FAW, SB, and of yield and plant parameters for each treatment (initial defoliation levels)

Experiment	Defoliation treatments	FAW damage severity (%)	SB damage severity (%)	Plant height (cm)	Yield (MT/ha)	Actual loss (%)
Long rainy	Control	0.1 ± 0.1c	–	256.5 ± 12.5	5.6 ± 0.2	–
	1 (0%)	0.7 ± 0.3c	–	263.9 ± 11.7	5.4 ± 0.3	4.5
	2 (1%–25%)	13.9 ± 2.7b	–	259.8 ± 6.5	5.2 ± 0.5	6.8
	3 (26%–50%)	27.1 ± 2.3a	–	260.7 ± 5.3	5.2 ± 0.3	7.9
	4 (51%–75%)	26.4 ± 1.4a	–	257.8 ± 6.2	5.0 ± 0.4	11.7
	$F_{4,95df}$	57.15		0.105	0.648	
	P	<0.001		0.981	0.631	
Short rainy season	Control	1.1 ± 0.3d	–	266.5 ± 8.2	5.4 ± 0.5	–
	1 (0%)	5.2 ± 0.8c	–	270.0 ± 7.6	5.5 ± 0.3	−1.9
	2 (1%–25%)	11.3 ± 1.2b	–	251.1 ± 9.5	5.8 ± 0.6	−7.5
	3 (26%–50%)	16.9 ± 11.4a	–	262.9 ± 6.7	5.3 ± 0.6	1.1
	4 (51%–75%)	20.6 ± 1.5a	–	285.6 ± 6.5	5.2 ± 0.5	4.1
	$F_{4,95df}$	60.51		1.324	0.171	
	P	<0.001		0.273	0.953	
Early dry season	Control	2.3 ± 1.6d	5.3 ± 2.4b	120.3 ± 9.0a	2.7 ± 0.0a	–
	1 (0%)	21.7 ± 3.9c	24.0 ± 6.6a	108.6 ± 11.0ab	2.5 ± 0.2ab	8.1
	2 (1%–25%)	20.3 ± 3.8c	31.0 ± 6.6a	115.1 ± 7.8ab	2.5 ± 0.3ab	7.7
	3 (26%–50%)	28.0 ± 3.8bc	16.3 ± 5.4ab	90.5 ± 5.2ab	2.1 ± 0.6ab	22.6
	4 (51%–75%)	47.8 ± 5.6ab	14.8 ± 5.7ab	103.9 ± 7.8ab	1.5 ± 0.0b	46.0
	5 (>75%)	55.4 ± 7.3a	12.3 ± 4.9ab	77.2 ± 10.5b	1.3 ± 0.6b	53.8
	$F_{5,114df}$	19.193	2.858	2.596	4.784	
	P	<0.001	0.018	0.030	0.007	
Late dry season	Control	3.1 ± 0.6c	0b	116.3 ± 9.3	3.0 ± 0.3a	–
	1 (0%)	26.0 ± 2.8b	14.5 ± 3.5a	124.2 ± 7.6	2.8 ± 0.3ab	5.9
	2 (1%–25%)	40.5 ± 4.9a	5.5 ± 2.8ab	103.8 ± 9.4	2.5 ± 0.4ab	15.2
	3 (26%–50%)	42.3 ± 3.3a	4.3 ± 2.9ab	121.0 ± 6.9	2.3 ± 0.3ab	22.1
	4 (51%–75%)	49.6 ± 3.0a	4.0 ± 3.0ab	106.3 ± 8.0	1.6 ± 0.2b	46.1
	5 (>75%)	44.1 ± 4.3a	12.0 ± 5.9ab	112.2 ± 9.7	1.7 ± 0.3b	42.9
	$F_{5,114df}$	31.904	2.481	0.693	3.615	
	P	<0.001	0.036	0.630	0.006	

Comparison is done among treatments within each experiment; values followed by the same letter in a column are not statistically different with Tukey's test ($P = 0.05$). SB = Stem borers, FAW = Fall armyworm, MT = Metric tons, ha = hectare.

in the dry seasons, while the values for both plant height and yield were lower in the dry seasons. There was a statistical difference in the yields obtained between the rainy and the dry seasons, with a 58.3% loss in the dry season. While stem borer damage was not significant during the rainy seasons, it was significantly different between the two dry seasons, which is supported by the statistical analysis ($t = 8.94$; $df = 1.184$; $P < 0.001$; Table 3).

Contrast in the Evolution of Plant Damage Severity With Time or Crop Stage Between Rainy and Dry Season

The following information pertains to two sets of pictures displaying five pictures of maize plants during the rainy season with foliar damage, which was scored 3 at three WAP on April 7th. The damage was present until 5 WAP and no longer visible from 6 WAP onwards as the plant regained its healthy state under optimum humidity conditions (Fig. 2). Fig. 3 displays another picture of maize plants in the dry season, with foliar damage, which was also initially scored 3 at 2 WAP after planting on November 1st. Besides, the damage to the plant occurred throughout the plant growth, with multiple FAW generations, leading to even higher damage severity at 9, 10, and 12 WAP.

Effect of Defoliation Levels on Severity of Damage Over Time

During the long rainy season experiment, there were significant differences ($P < 0.001$) among defoliation levels at the first four observations (4, 5, 6, and 7 WAP), but not during the last three observations at 8, 9, and 10 WAP (Table 4). The short rainy season had similar results to the long rainy season, with significant differences among defoliation levels ($P < 0.001$) at the first four observations (4, 5, 6, and 7 WAP), but contrary to the long rainy season, the sixth observation (8 WAP) also showed significant differences among rating scores but not the fifth and the seventh at 7, and 10 WAP (Table 5). The early dry season showed significant differences among defoliation levels at all eight observations from 4 WAP to 11 WAP ($P < 0.001$; Table 6). Likewise, the early dry season has significant differences among defoliation levels at all eight observations from 2 WAP to 10 WAP. The first seven observations had $P < 0.001$, and the last observation had $P = 0.003$ (Table 7). The data on FAW population dynamic shows the highest abundance at the late vegetative stage compared to the early vegetative and early reproductive stages, with at least four generations of FAW per crop cycle during both seasons (Fig. 4).

Discussion

Effect of Defoliation Levels (Damage Rating Score) on the Severity of Damage

The current study evaluated the effect of different defoliation levels caused by the FAW on maize recovery. The results revealed significant variations among treatments in average percentage of damage severity over the whole cropping period. The damage severity increased with an increase in defoliation levels during all seasons. Higher defoliation levels led to higher damage severity damage (Gazzoni and Moscardi

Table 3. Average (±SE) of fall armyworm (FAW) and stemborers (SB) damage severity, plant height, and yield during the four seasons

Season	FAW damage severity (%)	SB damage severity (%)	Plant height (cm)	Yield (MT/ha)
Early dry	30.5 ± 2.5a	24.4 ± 2.7	103.6 ± 4.2b	2.2 ± 0.2b
Late dry	34.3 ± 2.0a	8.0 ± 1.7	114.6 ± 3.8b	2.3 ± 0.1b
Long rainy	13.8 ± 1.4b	–	259.7 ± 3.8a	5.3 ± 0.1a
Short rainy	11.0 ± 0.9b	–	265.5 ± 4.6a	5.5 ± 0.3a
$t_{1,185}$		8.94		
$F_{3,430}$	38.36		450.4	76.13
P	<0.001	<0.001	<0.001	<0.001

Values followed by the same letter in a column are not statistically different with Tukey's test ($P = 0.05$). SB = stem borers, FAW = fall armyworm, MT = metric tons, ha = hectare.

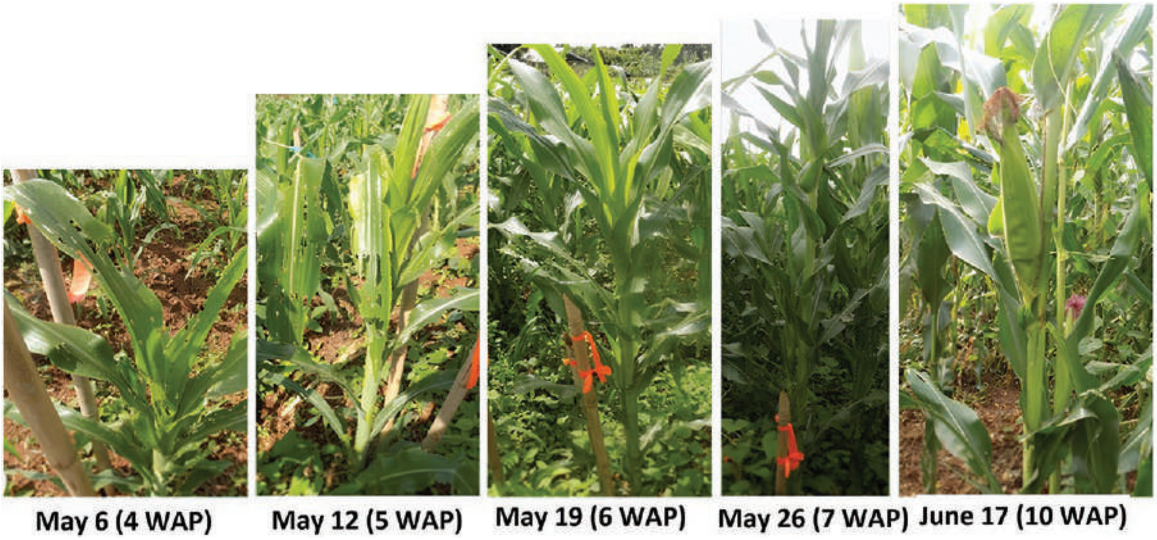

Fig. 2. Recovery pattern in the rainy season. With optimum rainfall, maize damage by FAW does not reach the economic threshold because the injury remains within recovery levels as both soil moisture and rapid crop development accelerate the recovery process (WAP = weeks after planting).

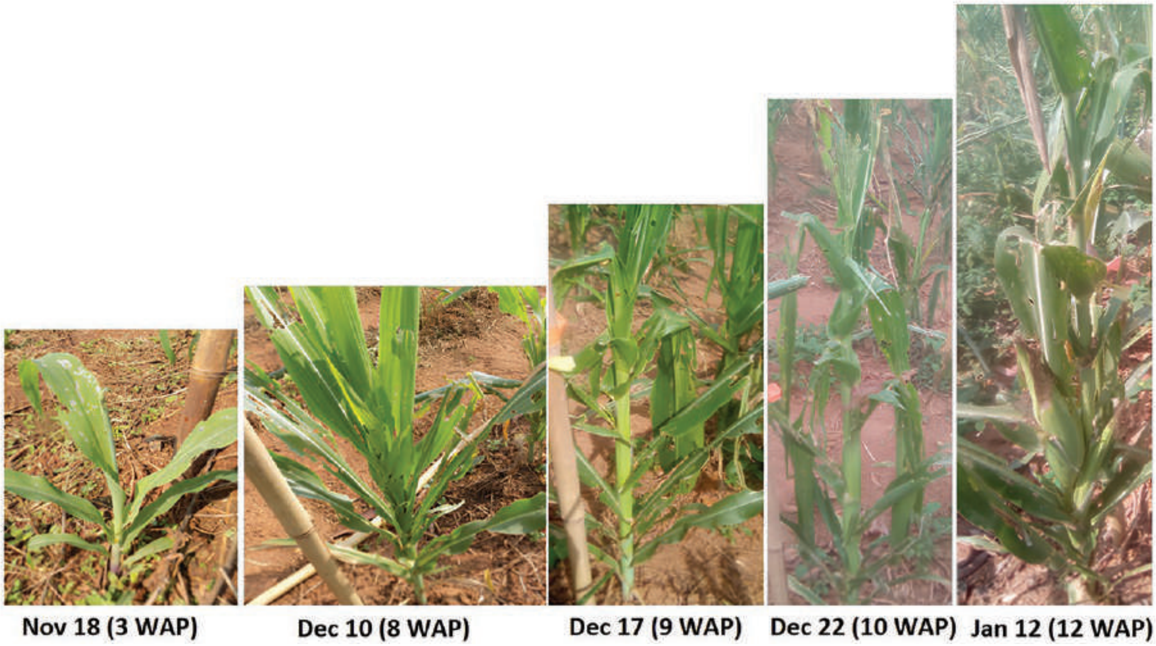

Fig. 3. Recovery pattern in the dry season. Under drought or erratic rainfall, lack of sufficient soil moisture prevents crop recovery, and unperturbed larvae cause increasing damage to crops, reaching economic injury levels (WAP = weeks after planting).

Table 4. Average (±SE) weekly FAW damage severity per treatment during the long rainy season

	Maize development stage						
Defoliation treatments	V6 (4WAP)	V8 (5WAP)	V10 (6WAP)	V13 (7WAP)	V17 (8WAP)	V20 (9WAP)	R1 (10WAP)
Control	0d	0c	0b	0.3 ± 0.3c	0.5 ± 0.3	0.2 ± 0.1	0
1 (0%)	0d	1.1 ± 0.8c	1.1 ± b	0.7 ± 0.4bc	0.9 ± 0.6	0.8 ± 0.5	0
2 (1%–25%)	15.3 ± 2.1c	22.1 ± 5.0b	11.2 ± 3.4a	7.1 ± 2.4a	5.0 ± 1.9	3.3 ± 1.2	1.6 ± 0.8
3 (26%–50%)	39.1 ± 1.5b	41.3 ± 6.0a	20.0 ± 3.6a	8.1 ± 1.6a	6.2 ± 2.0	5.1 ± 1.6	3.9 ± 1.2
4 (51%–75%)	62.3 ± 1.6a	25.8 ± 3.6b	10.9 ± 2.0a	6.6 ± 1.5ab	5.5 ± 2.9	4.7 ± 2.7	3.3 ± 2.5
5 (>75%)	–	–	–	–	–	–	–
$F_{4,95df}$	386.6	20.08	11.65	6.336	2.172	2.133	1.774
P	<0.001	<0.001	<0.001	0.0002	0.078	0.083	0.141

Values followed by the same letter are not statistically different with Tukey's test ($P = 0.05$). V = vegetative stage, R = reproductive stage, WAP = weeks after planting.

Table 5. Average (±SE) weekly FAW damage severity per treatment during the short rainy season

Defoliation treatments	V2 (3WAP)	V5 (4WAP)	V8 (5WAP)	V10 (6WAP)	V12 (7WAP)	V15 (8WAP)	R1 (10WAP)
Control	0a	1.8 ± 0.9a	1.8 ± 0.8a	1.8 ± 0.8a	1.5 ± 0.5	0.8 ± 0.4a	0
1 (0%)	0a	2.0 ± 0.8a	4.0 ± 1.1a	16.0 ± 1.2b	6.3 ± 1.6	6.7 ± 1.6b	1.3 ± 0.6
2 (1%–25%)	18.8 ± 1.1b	20.3 ± 2.4b	18.5 ± 2.8b	9.8 ± 2.3b	6.5 ± 1.8	5.5 ± 1.5b	0.2 ± 0.2
3 (26%–50%)	39.2 ± 1.5c	34.5 ± 4.5c	21.0 ± 3.2b	11.7 ± 2.3b	5.5 ± 1.6	5.0 ± 1.4ab	1.3 ± 0.8
4 (51%–75%)	66.3 ± 1.7d	48.8 ± 5.4c	19.3 ± 3.9b	10.5 ± 2.6b	3.0 ± 1.5	2.3 ± 0.9ab	0.3 ± 0.3a
5 (>75%)	–	–	–	–	–	–	–
$F_{4,95df}$	10.116	38.398	16.612	8.287	2.253	5.292	1.729
P	<0.001	<0.001	<0.001	<0.001	0.069	0.001	0.15

Values followed by the same letter are not statistically different with Tukey's test ($P = 0.05$). V = vegetative stage, R = reproductive stage, WAP = weeks after planting.

1998). Lower levels of defoliation led to quick recovery from lost leaf area and generally lower damage severity. Damage by lepidopteran pests sometimes caused stunted plants, but plants were observed to compensate for damage under conditions of available soil humidity. There were no significant differences among the treatments in plant height, and the capacity to prevent stunting was also achieved in the dry season trial. Similarly, Oyewole and Oluotanmi (2017) did not find any effect of defoliation on plant height. However, similarities in plant height between the two dry seasons provide evidence that it is only at a high level of leaf defoliation that plant height may be

Table 6. Average (±SE) weekly FAW damage severity per treatment during the early dry season

Defoliation treatments	V6 (4WAP)	V8 (5WAP)	V11 (6WAP)	V13 (7WAP)	V15 (8WAP)	V19 (9WAP)	VT (10WAP)	R1 (11WAP)
Control	0a	0.1 ± 0.1a	0a	0a	0.8 ± 0.6a	6.3 ± 3.3a	5.5 ± 2.6a	6.0 ± 2.8a
1 (0%)	0a	5.3 ± 2.5bc	9.5 ± 3.6ab	20.6 ± 5.9ab	26.4 ± 6.0bc	27.3 ± 6.1ac	38.3 ± 7.7bc	46.7 ± 8.1bc
2 (1%–25%)	16.3 ± 2.5b	22.5 ± 4.0bc	19.1 ± 4.7abc	21.0 ± 5.6ac	19.0 ± 5.3ab	17.8 ± 5.6ab	22.3 ± 6.2ab	24.3 ± 6.4ab
3 (26%–50%)	37.5 ± 2.8c	39.8 ± 5.2c	28.8 ± 5.8bd	21.8 ± 5.0ac	20.5 ± 4.9ab	22.7 ± 5.4ab	26.3 ± 5.7ac	17.0 ± 5.3ac
4 (51%–75%)	71.3 ± 1.3d	66.8 ± 5.1d	39.5 ± 7.1cd	38.7 ± 7.4bc	43.0 ± 7.6bc	41.3 ± 7.6bc	42.5 ± 8.1bc	24.5 ± 7.1bc
5 (> 75%)	82.1 ± 4.6e	58.5 ± 7.1d	48.0 ± 8.4d	44.9 ± 8.4c	49.8 ± 8.9c	50.3 ± 9.3c	52.5 ± 9.2c	52.0 ± 9.8c
$F_{5.114df}$	206.3	36.21	10.358	6.922	8.412	6.099	6.360	6.418
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Values followed by the same letter are not statistically different with Tukey's test ($P = 0.05$). V = vegetative stage, VT = tasseling stage R = reproductive stage, WAP = weeks after planting.

Table 7. Average (±SE) weekly FAW damage severity per treatment during the late dry season

Defoliation treatments	VE (2WAP)	V2 (3WAP)	V5 (4WAP)	V8 (5WAP)	V10 (6WAP)	V12 (7WAP)	V15 (8WAP)	R1 (10WAP)
Control	0a	1.8 ± 0.7a	3.9 ± 1.3a	3.6 ± 1.4a	5.4 ± 1.2a	4.0 ± 0.8a	3.0 ± 0.6a	2.3 ± 0.6a
1 (0%)	0a	7.4 ± 2.7a	20.0 ± 3.6b	43.5 ± 6.5b	44.3 ± 5.5bc	38.0 ± 5.7b	27.0 ± 4.7b	26.3 ± 5.1b
2 (1%–25%)	17.5 ± 1.3b	41.4 ± 5.1b	46.4 ± 5.9c	54.8 ± 6.6b	52.0 ± 7.0bc	43.8 ± 7.3b	35.0 ± 7.6b	33.3 ± 8.1b
3 (26%–50%)	41.3 ± 3.3c	53.5 ± 5.7b	43.5 ± 5.4c	48.8 ± 6.9b	46.3 ± 5.4bc	44.8 ± 5.2b	30.0 ± 3.8b	27.8 ± 4.3b
4 (51%–75%)	66.3 ± 1.6d	56.0 ± 5.4b	40.8 ± 5.2c	54.8 ± 6.0b	60.5 ± 5.8c	50.1 ± 6.2b	36.3 ± 5.5b	28.0 ± 5.6b
5 (>75%)	81.6 ± 1.3e	53.8 ± 5.6b	57.5 ± 6.5c	44.0 ± 7.7b	35.6 ± 6.1b	28.8 ± 6.3b	20.5 ± 5.0b	27.0 ± 6.6b
$F_{5.114df}$	428.95	31.68	18.01	11.77	14.04	11.15	8.43	3.90
P	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.003

Values followed by the same letter are not statistically different with Tukey's test ($P = 0.05$). V = vegetative stage, R = reproductive stage, WAP = weeks after planting.

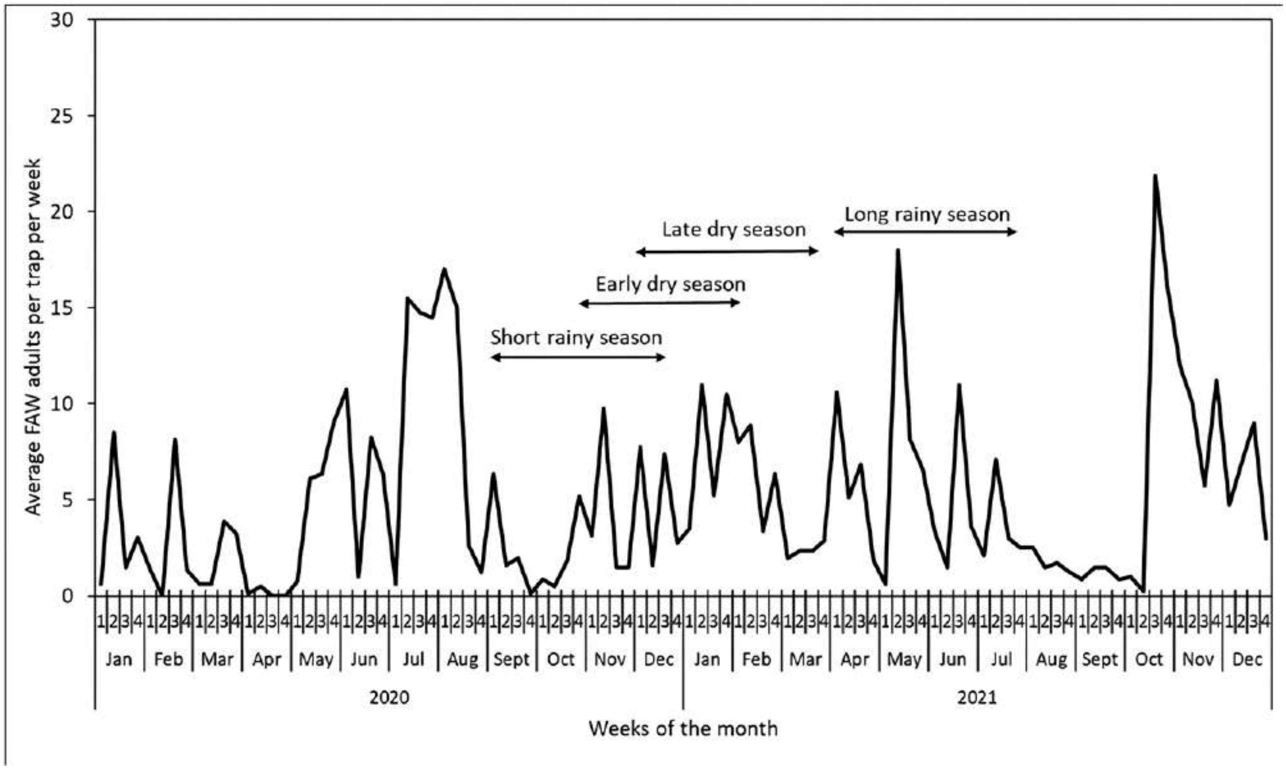

Fig. 4. FAW adult population dynamics during the experiments between 2020 and 2021.

affected and under stress conditions (Hruska 2019). The early whorl stage (EV-V6) of maize crops was found to be susceptible to FAW due to high larval load. On the other hand, the late whorl stage (V7-VT) showed greater leaf damage in both rainy and dry seasons across two years (Pradeep et al. 2022). Although there were no reported effects on yield, susceptibility at the early whorl stage can limit plant height, while greater damage at the late whorl stage can result in significant yield loss, as demonstrated by higher severities at late crop stages in the current study.

Effect of Defoliation Levels on Yield

The yields of maize during the rainy season ranged from 5.0 to 5.8 t/ha, but were lower in the dry season, ranging from 1.3 to 3 t/ha. Foliar damage was higher during the dry season, resulting in more area loss than in the rainy season and lower yield. A study was conducted in Cameroon to compare biological and chemical control of lepidopterans affecting maize. The study reported yields in the rainy season between 4.6 and 7.0 t/ha (Kammo et al. 2019). Maize yields are influenced by leaf area index and efficiency in absorbing solar radiation for photosynthesis (Mouhamed and Ouda 2006). Higher defoliation levels in the dry season led to significant yield loss. The findings are consistent with Oyewole and Oluotanmi (2017), who found that maize yields are affected by defoliation levels. They reported significantly higher yields when no defoliation occurred, and the lowest yield at 100% defoliation by FAW. In the rainy season, low severity did not exceed 26%, resulting in insignificant yield loss. Previous studies indicate that FAW damage on maize is not devastating, with yield reductions of less than 20%, even with high infestation. However, reports from most African countries show higher yield losses ranging from 22% to 67% (Day et al. 2017, Kumela et al. 2018). Chisonga et al. (2023) conducted a screen house experiment to investigate the influence of leaf damage on grain yield in maize. Their study found that infesting maize with one 2nd instar larva at various crop stages had minimal impact on yield under optimal conditions. It also highlighted the potential significance of drought over FAW damage in terms of yield loss. Although FAW damage may be important for yield loss, drought can be more important (Baudron et al. 2019) as it can hamper crop development while promoting defoliation by FAW and other pests such as stem borers. Defoliation levels of 26%–50% during both seasons resulted in about 22% yield loss and beyond this level, yield losses became significant. At this defoliation level, FAW severity was 28.0% while stem borers severity was 16.3% in the early dry season, indicating that stem borers contributed more to yield loss. In the late dry season, FAW severity was 42.3%, while stem borer severity was 4.3%, indicating that FAW contributed more to yield loss. Kamno et al. (2019) showed that the average severity of damage caused by pests was around 25%, with a range of 22.6%–28.8%. Factors such as time of planting, infestation start time, and damage level can affect the severity trend across WAP, and may be more relevant than the average damage severity. Estimating maize yield through the grain weight method may be challenging since grains must be dried to the desired moisture content before weighing. As a consequence, researchers mainly present incidence and severity data from their efficacy trials on maize and rely on socio-economic surveys to estimate yield loss. The grain count method used in this study represents an alternative to the grain weight for maize yield estimation in field trials and should be included in efficacy trials on maize.

Effect of Season or Time of Planting on the Level of Foliar Damage

The dry season resulted in about half of the yield compared to the rainy season, leading to a 58.3% yield loss due to seasonal change alone. Additionally, higher plant damage severity was observed during the dry seasons, indicating that the season can impact crop damage and yield. The highest yield loss during the rainy season was 11.7%, while in the dry season, it was 53.8%. According to Baudron et al. (2019), the yield losses were about 12% under normal cropping conditions with optimum growing conditions. Chisonga et al. (2023) attempted to evaluate the impact of FAW on yield and found no significant effect on yield under control conditions in the screen house. However, the study did not state specific criteria for the number of larvae inoculated per plant, which could explain the lack of significant effect. Recent field evaluation of the impact of FAW on yield revealed that chemical pesticides can decrease the number of larvae and the extent of damage, but do not significantly impact crop yield or farmers' net return (Agbodzavu et al. 2024). Good crop management, such as soil fertility, provides an effective alternative to chemical insecticides (Fiaboe et al. 2024). Rainfall affects the plant's ability to recover from damage, and the availability of water is a key factor in compensating for foliar damage (Varella et al. 2015, Hruska 2019). Drought affects crop growth and grain development, especially during tasseling and cob formation (Farnsworth 2004).

Effect of Season or Time of Planting on Plant Recovery

During the rainy seasons, the damage severity of defoliation levels 3 and 4 did not surpass the damage score of 2, except in the first rainy season. The severity of damage was higher during the dry season for all defoliation levels, reaching level 5. FAW infestation becomes severe when maize plants record whorl feeding damage under stress conditions (Hruska 2019). The experiments were not commenced too soon, as the absence of defoliation level 5 in the rainy seasons, did not go above 75%. Extensive feeding during the rainy season and late defoliation negatively impact plant recovery. Furthermore, this repeated absence of defoliation level 5 is also an indication that the start of the experiment was not delayed, so no significant initial damage was missed, revealing the inability of larvae to feed extensively during the rainy season. It is suggested that injury at advanced crop stages leads to higher plant yield loss (Thomison et al. 2016, Tshiabukole et al. 2021). It is also important to establish the mechanism behind plant recovery. Is it due to the plant's ability to compensate and regenerate damaged tissues, or is there a contribution from the knock-down effect of rainfall? Rainfall has been reported to reduce larval feeding by drowning them in plant funnels or washing them off the plant (Varella et al. 2015).

Time and Level of Foliar Damage at Which There Will be Significant Yield Loss if No Action is Taken

During the rainy seasons, plant leaf damage decreased steadily over time, with all plants showing less than 25% foliar damage after 5 wk. Studies indicate that up to 25% defoliation does not cause more than 9% yield reduction. (Hruska 2019). Therefore, managing FAW during the rainy season seems unnecessary. In the dry season, plants with higher defoliation levels showed initial recovery tendencies that did not exceed the second week, remaining between 26% and 50%. Only the plants with damage levels of 4 and 5 experienced a significant yield reduction at the last observation. In the later part of the dry season, defoliation levels of 2, 3, 4, and 5, with damage severity of about 30%, resulted in significant yield loss. The threshold for significant yield loss is around 50% defoliation (Thomison et al. 2016, Hruska 2019). The plant should not become damaged beyond recovery after previous injuries, or it should have started recovering from previous injuries. Failure to recover may increase damage severity to the next level. At specific growth stages during the dry season, maize plants may be able to compensate for low-level defoliation, but may struggle to recover from higher levels (Hruska, 2019). Pesticide applications for FAW should only be used when necessary, and economic or action thresholds must be determined for each stage of maize growth (FAo and CABI, 2019). The results obtained during the dry season suggest that FAW mitigation plans should be considered in case of erratic rainfall. A study at Purdue University in 2019 recommended pesticide application intervention when there is severe infestation with whorl feeding damage under hydric stress (Hruska 2019). The cutoff point is reached earlier during the late dry season at 5 WAP and 8 WAP for the early dry season. This level varies depending on the start of infestation and damage, which is also influenced by season and planting date. Some studies have shown that infestation and damage during the early and late dry seasons affect compensation and yield (FAO, 2019). Pesticide interventions may be needed during the dry season, but not during the rainy season. Regular scouting is recommended to monitor incidence and economic injury levels. Plants with 50% defoliation experience significant yield loss. This is the level at which recovery stops, and any additional infestation or damage will put the plant either beyond recovery from previous injuries or cause the damage to exceed the economic injury level. Under optimum production conditions, losing below 25% of the leaf surface has no significant impact at any growth stage. Even up to 50% leaf loss is not important for young and later stage leaves. However, this can have a considerable effect for advanced vegetative and inflorescence stages.

Author contributions

Albert Abang (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Software [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), Samuel Nanga Nanga (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Software [equal], Visualization [equal], Writing—original draft [equal], Writing—review & editing [equal]), Komi Agbodzavu (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Visualization [equal], Writing—review & editing [equal]), Apollin Fotso Kuate (Conceptualization [equal], Investigation [equal], Methodology [equal], Visualization [equal], Writing—review & editing [equal]), Christopher Suh (Conceptualization [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Visualization [equal], Writing—review & editing [equal]), Cargele Masso (Funding acquisition [equal], Project administration [equal], Supervision [equal], Writing—review & editing [equal]), Zoumana Bamba (Funding acquisition [equal], Project administration [equal], Writing—review & editing [equal]), and Komi Fiaboe (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Funding acquisition [equal], Investigation [equal], Methodology [equal], Project administration [equal], Visualization [equal], Writing—review & editing [equal])

Funding

Funds used for this research were provided by Maize CRP (CGIAR Research Program). We also received additional funding from the Food and Agricultural Organization (FAO) of the United Nations.

Data availability

The data presented in this study are openly available at https://doi.org/10.25502/jzhj-m192/d

References

Abang AF, Fotso Kuate A, Nanga Nanga S, et al. 2020. Spatio-temporal partitioning and sharing of parasitoids by fall armyworm and maize stemborers in Cameroon. J. Appl. Entomol. 145(1-2):55–64. https://doi.org/10.1111/jen.12827

Abang AF, Nanga SN, Fotso Kuate A, et al. 2021. Natural enemies of fall armyworm *Spodoptera frugiperda*. Insects. 12(6):509–523. https://doi.org/10.3390/insects12060509

Abang A, Nanga SN, Ndanda RMO, et al. 2022. Reliability of pheromone trap catches and maize plant damage as criteria for timing fall armyworm control interventions in humid forest agroecology of central Africa. J. Econ. Entomol. 115(6):1806–1816. https://doi.org/10.1093/jee/toac087

Abrahams P, Bateman M, Beale T, et al. Fall armyworm: impacts and implications for Africa (September 2017). UK: CABI; 2017.

Agbodzavu KM, Nanga SN, Abang AF, et al. 2024. Impact of *Spodoptera frugiperda* (Lepidoptera: Noctuidae), on maize yield in humid tropical zones of Central Africa. J of Econ Entomol. 117(4):1588–1605. https://doi.org/10.1093/jee/toae102

Alves De Albuquerque F, Maestro Borges L, De Oliveira Iacono T, et al. 2006. Eficiência de inseticidas aplicados em tratamento de sementes e em pulverização, no controle de pragas iniciais do milho. Rev Bras Milho e Sorgo. 5(1):15–25.

Andrews KL. 1980. The whorlworm, *Spodoptera frugiperda*, in Central America and neighboring areas. Florida Entomol. 63(4):456. https://doi.org/10.2307/3494530

Assefa F, Ayalew D. 2019. Status and control measures of fall armyworm (*Spodoptera frugiperda*) infestations in maize fields in Ethiopia: a review. Cogent Food Agric. 5(1):1641902. https://doi.org/10.1080/23311932.2019.1641902

Badu-Apraku B, Fakorede MAB, Talabi AO, et al. 2020. Genetic studies of extra-early provitamin-A maize inbred lines and their hybrids in multiple environments. Crop Sci. 60(3):1325–1345. https://doi.org/10.1002/csc2.20071

Barlow VM, Kuhar TP. 2009. Fall armyworm in vegetable crops. Virginia Coop Ext. 444(015):1–3.

Baudron F, Zaman-Allah MA, Chaipa I, et al. 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. Crop Prot. 120(1):141–150. https://doi.org/10.1016/j.cropro.2019.01.028

Bessin R. 2004. Fall armyworm in corn. Kentucky, UK cooperative extension service. ENTFACT. 11(1):1–2. https://entomology.ca.uky.edu/files/ef110.pdf

Blein R, Soulé BG, Faivre-Dupaigre B, et al. Les potentialités agricoles de l'Afrique de l'Ouest (CEDEAO). Paris: Fondation pour l'agriculture et la ruralité dans le monde (FARM); 2008.

Blumentha JM, Thompson WH. 2009. Estimating corn grain yields. AgriLife. 6(09):1–6. Available at https://oaktrust.library.tamu.edu/bitstream/handle/1969.1/87563/pdf_2628.pdf?sequence=1&isAllowed=y

Buntin GD. 1986. A review of plant response to fall armyworm, *Spodoptera frugiperda* (J. E. Smith), injury in selected field and forage crops. Florida Entomol. 69(3):549–559. https://doi.org/10.2307/3495389

Buntin GD. 2008. Corn expressing Cry1Ab or Cry1F endotoxin for fall armyworm and corn earworm (Lepidoptera: Noctuidae) management in field corn for grain production. Florida Entomol. 91(4):523–530. https://doi.org/10.1653/0015-4040-91.4.523

Buntin GD, Lee RD, Wilson DM, et al. 2001. Evaluation of yieldgard transgenic resistance for control of fall armyworm and corn earworm (Lepidoptera: Noctuidae) on corn. In: Florida Entomologist. Florida Entomol. Soc. 84(1):37–42. https://doi.org/10.2307/3496660

Buntin GD, All JN, Lee RD, et al. 2004. Plant-incorporated *Bacillus thuringiensis* resistance for control of fall armyworm and corn earworm (Lepidoptera: Noctuidae) in corn. J. Econ. Entomol. 97(5):1603–1611. https://doi.org/10.1603/0022-0493-97.5.1603

Chisonga C, Chipabika G, Sohati PH, et al. 2023. Understanding the impact of fall armyworm (*Spodoptera frugiperda* J. E. Smith) leaf damage on maize yields. PLoS One 18(6):e0279138. https://doi.org/10.1371/journal.pone.0279138

Cruz I, Figueiredo MLC, Silva RB, et al. 2010. Efficiency of chemical pesticides to control *Spodoptera frugiperda* and validation of pheromone trap as a pest management tool in maize crop. Revista Brasileira de Milho e Sorgo 9(2):107–122. https://doi.org/10.18512/1980-6477/rbms.v9n2p107-122

Cruz I, de Lourdes Corrêa Figueiredo M, da Silva RB, et al. 2012. Using sex pheromone traps in the decision-making process for pesticide application against fall armyworm (*Spodoptera frugiperda* [smith] [lepidoptera: Noctuidae]) larvae in maize. Int. J. Pest Manag. 58(1):83–90. https://doi.org/10.1080/09670874.2012.655702

Davis F, Ng SS, WIlliams W. 1992. Visual rating scales for screening whorl-stage corn for resistance to fall armyworm. Tech. Bull. - Mississippi Agric. For. Exp. Station. 186(1):1–9.

Day R, Abrahams P, Bateman M, et al. 2017. Fall armyworm: impacts and implications for Africa. Outlooks Pest Manag. 28(5):196–201. https://doi.org/10.1564/v28_oct_02

FAO and CABI. 2019. Community-based fall armyworm (*Spodoptera frugiperda*) monitoring, early warning and management. In: Training of trainers manual. 1st ed. p. 112. Licence: CC BY-NC-SA 3.0 IGO.

FAO and PPD. 2020. Manual on integrated fall armyworm management. Yangon: FAO; p. 1–50. https://doi.org/10.4060/ca9688en

FAO. 2018. Integrated management of the fall armyworm on maize: a guide for farmer field schools in Africa. Rome (Italy): FAO; p. 130.

Farnsworth E. 2004. Hormones and shifting ecology throughout plant development. Ecology 85(1):5–15. https://doi.org/10.1890/02-655

Fiaboe KR, Agboka K, Agnamba AO, et al. 2024. Fertilizer-bioinsecticide synergy improves maize resilience to *Spodoptera frugiperda* infestation. Crop Prot. 177:106548. https://doi.org/10.1016/j.cropro.2023.106548

Gazzoni DL, Moscardi F. 1998. Effect of defoliation levels on recovery of leaf area, on yield and agronomic traits of soybeans. Pesqui. Agropecu. Bras. 33(e991):411–424.

Hruska AJ. 2019. Fall armyworm (*Spodoptera frugiperda*) management by smallholders. CAB Rev. Perspect. Agric. Vet. Sci. Nutr. Nat .Resour. 14(43):0–3. https://doi.org/10.1079/PAVSNNR201914043

Jaramillo-Barrios CI, Varón-Devia EH, Monje-Andrade B. 2020. Economic injury level and action thresholds for *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae) in maize crops. Rev. Fac. Nac. Agron. Medellín. 73(1):9065–9076. https://doi.org/10.15446/rfnam.v73n1.78824

Kammo EQ, Suh C, Mbong GS, et al. 2019. Biological versus chemical control of fall armyworm and Lepidoptera stem borers of maize. Agronomie Africaine. 31(2):187–198.

Kumela T, Simiyu J, Sisay B, et al. 2018. Farmers' knowledge, perceptions, and management practices of the new invasive pest, fall armyworm (*Spodoptera frugiperda*) in Ethiopia and Kenya. Int. J. Pest Manag. 65(1):1–9. https://doi.org/10.1080/09670874.2017.1423129

Mouhamed SGA, Ouda SAH. 2006. Predicting the role of some weather parameters on maize productivity under different defoliation treatments. J App Sci Res. 2(11):920–925.

Ntiri ES, Calatayud P-A, Van den Berg J, et al. 2019. Spatio-temporal interactions between maize lepidopteran stemborer communities and possible implications from the recent invasion of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in sub-saharan Africa. Environ. Entomol. 48(3):573–582. https://doi.org/10.1093/ee/nvz024

Oyewole CI, Oluotanmi OR. 2017. Effect of varying rate of leaf defoliation on maize growth, development and yield components and yield. Guigoz Sci Rev. 3(1):1–5.

Pradeep P, Deshmukh SS, Sannathimmappa HG, et al. 2022. Seasonal activity of *Spodoptera frugiperda* (J. E. Smith) in maize agroecosystem of South India. Current Sci. 123(1):81–86. https://doi.org/10.18520/cs/v123/i1/81-86

Prasanna B, Huesing JE, Eddy R, et al. (eds). 2018. Fall armyworm in Africa: a guide for integrated pest management. 1st edn. CDMX (Mexico): CIMMYT.

Silva MS, Broglio SMF, Trindade RCP, et al. 2015. Toxicity and application of neem in fall armyworm. Comun. Sci. 6(3):359–364. https://doi.org/10.14295/CS.v6i3.808

Steffey K, Rice M, All J, et al. 1999. Handbook of corn insects | Entomological Society of America. Am. Phytopathol. Soc. https://search.worldcat.org/title/756983104. Accessed 4 Jan 2021.

Tefera T, Mugo S, Tende R, et al. Methods of screening maize for resistance to stem borers and post-harvest insect pests. Nairobi (Kenya): CIMMYT; 2011.

Teklewold A, Wegary D, Tadesse A, et al. Quality protein maize (QPM): a guide to the technology and its promotion in Ethiopia. Addis Ababa, Ethiopia: CIMMYT; 2015.

Thomison PR, Nafziger ED, Coulter JA, et al. 2016. Response of corn to multiple defoliation events. Information poster presented at the annual meeting of the American society of agronomy, November 2016. https://scisoc.confex.com/scisoc/2016am/webprogram/Handout/Paper99910/2016%20ASA%20NCIS%20Poster%20FV.pdf

Togola A, Meseka S, Menkir A, et al. 2018. Measurement of pesticide residues from chemical control of the invasive *Spodoptera frugiperda* (Lepidoptera: Noctuidae) in a maize experimental field in Mokwa, Nigeria. Int. J. Environ. Res. Public Health. 15(5):849. https://doi.org/10.3390/IJERPH15050849

Tshiabukole JPK, Khonde GP, Phongo AM, et al. 2021. Simulation of fall armyworm (*Spodoptera frugiperda*) attacks and the compensative response of quality protein maize (*Zea mays*, var. Mudishi-1 and Mudishi-3) in southwestern DR Congo. OALib. 08(03):1–14. https://doi.org/10.4236/oalib.1107217

Varella AC, Menezes-Netto AC, De Souza Alonso JD, et al. 2015. Mortality dynamics of *Spodoptera frugiperda* (Lepidoptera: Noctuidae) immatures in maize. PLoS One. 10:6e0130437. https://doi.org/10.1371/journal.pone.0130437

Wahedi JA, David DL, Danba EP, et al. 2016. Yield performance of maize treated with neem seed extracts against stem borers. Am. J. Exp. Agric. 12(6):1–8. https://doi.org/10.9734/AJEA/2016/26485