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Article

# Seasonal and Spatial Distribution of Fall Armyworm Larvae in Maize Fields: Implications for Integrated Pest Management

Karimou Zanzana <sup>1,2,\*</sup>, Antonio Sinzogan <sup>1</sup>, Ghislain T. Tapa-Yotto <sup>2,3,\*</sup>, Elie Dannon <sup>4</sup>, Georg Goergen <sup>2</sup> and Manuele Tamò <sup>2</sup>

<sup>1</sup> Laboratoire d'Entomologie Agricole (LEAg), Faculté des Sciences Agronomiques (FSA), Université d'Abomey-Calavi (UAC), Abomey-Calavi, 01 BP 526 Cotonou, Benin

<sup>2</sup> Biorisk Management Facility (BIMAF), International Institute of Tropical Agriculture (IITA-Benin), 08-01000 Cotonou, Benin

<sup>3</sup> Ecole de Gestion et de Production Végétale et Semencière (EGPVS), Université Nationale d'Agriculture (UNA), 43 Kétou, Benin

<sup>4</sup> Université Nationale des Sciences, Technologies, Ingénieries, et de Mathématiques d'Abomey (UNSTIM), Bénin

\* Correspondence: zkarimou@yahoo.fr (K.Z.); g.tapa-yotto@cgiar.org (G.T.T.-Y.)

**Simple Summary:** The fall armyworm is a destructive pest that severely impacts maize crops. This study focused on understanding how this pest spread in maize fields and how the population fluctuation during both the dry and rainy seasons. We examined maize plants in different regions of southern Benin, tracking the number of larvae, the level of infestation, and the extent of plant damage. The study showed higher infestation and damage in fisheries region during the dry season compared to ferralitic soil region. However, during the rainy season, while more plants were damaged in the fisheries region, the number of larvae was similar between the two areas. By analyzing the way these pests group together, we observed that fall armyworms tend to form small colonies when laying eggs. This behavior influences how they spread and attack crops. Better understanding of how and when fall armyworms attack can help farmers and researchers. With this knowledge, farmers and researchers can plan about how and when to protect their crops more effectively.

**Abstract:** The fall armyworm (FAW), *Spodoptera frugiperda*, a major pest in maize production, was assessed for its temporal and spatial distribution in maize fields during both the off and rainy seasons of 2021 and 2022. In this study, 30 and 50 maize plants were randomly sampled using a "W" pattern during the dry and rainy seasons, respectively. Larval density, infestation rates, and damage severity were monitored over time. Taylor's power law and the mean crowding aggregation index were applied to evaluate the dispersion patterns of the larvae. The results indicate a higher infestation rate and larval density in agroecological zone AZE 8 (fisheries zone of South Benin) compared to AZE 6 (ferralitic soils zone) during the off-season. In the rainy season, while the percentage of damaged plants was higher in AZE 8, no significant differences in larval density between the two zones were observed. The dispersion analysis revealed moderate aggregation (aggregation index = 1.25) with a basic colony of 2.08 larvae, reflecting the aggregation oviposition behavior of FAW. This study provides valuable monitoring data on the FAW's distribution, offering insights for further research on population dynamics and developing predictive models for integrated pest management strategies.

**Keywords:** fall armyworm; climate variability; spatio-temporal distribution; damage; larval dispersion

## 1. Introduction

In the context of mounting concerns over climate change, the global agricultural landscape is facing a new major challenge, the fall armyworm (FAW), *Spodoptera frugiperda* J E Smith, (Lepidoptera: Noctuidae). Native to the tropical and subtropical regions of the Americas, this invasive insect pest has rapidly become a great threat to agriculture in Africa [1] and Asia [2,3]. Its voracious larvae and rapid spread across regions have induced heavy damage to several crops such as sorghum and maize, as reported in various studies [4,6]. Beyond its voracity, FAW is a polyphagous insect species, infesting over 353 host plant species in general, with a clear preference for maize [7]. The combination of its remarkable morphological plasticity and polyphagous feeding habits [8,9] is posing a serious threat to agricultural productivity and food security [10], particularly in developing countries [11,14].

For a better understanding of the bio-ecology of this invasive pest as the basis for developing sustainable management strategies, the current study focuses on the seasonal fluctuations of its larval population density and the factors that affect their spatial dispersion [15,16]. These fluctuations are driven by a combination of ecological and agroclimatic factors, such as competition, natural enemies, resource availability, temperature, precipitation, and relative humidity [17,20]. Additionally, the rate of change in FAW population over time is influenced by its fecundity, speed of development, and survival, all of which are shaped by these environmental variables [16,21].

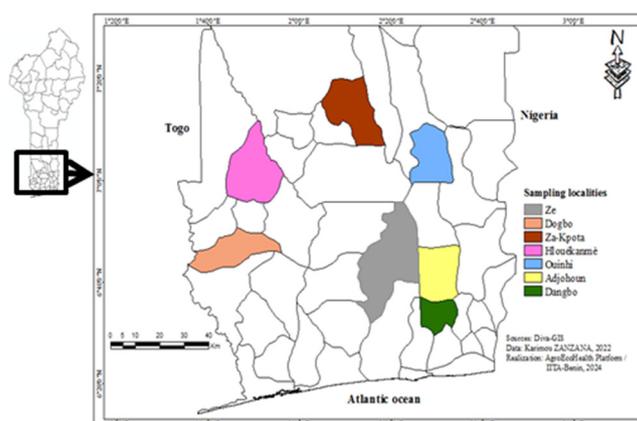
The spatial distribution pattern is an intrinsic factor of species and may reflect their behavioral traits due to the interaction between insects and their environment [22,23]. Thus, effective integrated pest management tactics can benefit from investigations of spatial dispersion data. Several studies have attempted to characterize FAW spatial distribution on maize in Mexico [24,26], and in China [27] documenting various distribution patterns for these pest populations. However, the spatial distribution of FAW in maize fields has not yet been investigated in Africa. Aggregation indexes and distribution frequencies can infer distribution types [28,29]. While non-mathematical, these indexes provide an approximate description of population distributions. Based on observed field data, probability distribution models are crucial for establishing sampling and statistical analysis criteria for pest management [26,30].

The study attempts to elucidate the spatio-temporal distribution of FAW associated with the larvae in maize fields in Benin, where maize is one of the staple food security crops. It capitalizes on recent findings by [21,31,32], whereby temperature, relative humidity, and rainfall were considered important agroclimatic factors affecting FAW populations [33].

## 2. Materials and Methods

### 2.1. Study Area

The study was carried out in the southern region of Benin, more specifically in AgroEcological Zone N°8 (AEZ 8, also known as the fisheries zone), in the municipalities of Adjohoun (6° 42' 43" N / 2° 29' 38" E), Dangbo (6° 34' 49" N / 2° 29' 57" E), Ouinhi (7° 4' 5" N / 2° 28' 5" E), and in the AEZ 6 (dominated by ferralitic soils) in the municipalities of Zè (6° 47' 00" N, 2° 18' 00" E), Dogbo (6° 49' 0" N / 1° 46' 60" E), Klouékanmè (6° 58' 49" N / 1° 50' 32" E), and Zakpota (7° 13' 41" N / 2° 12' 4" E) (Figure 1). These municipalities were chosen because of their high level of maize production and FAW prevalence. Both agroecological zones are also suitable for off-season maize production. With a subequatorial climate featuring two rainy and two dry seasons and a growing season of about 240 days, this region spans 17,920 km<sup>2</sup> and receives between 950 and 1,400 mm of rainfall each year. A plateau with depressions, low valleys, and a coastal region make up the topography, which also includes a variety of soil types such hydromorphic, clayey, and ferralitic soils. Fisheries and crop production, with a particular emphasis on maize, are the main drivers of this region's economy.



**Figure 1.** Study municipalities in southern Benin.

### 2.2. Sampling of Fall Armyworm Larvae in Maize Fields

Larvae were sampled during the maize growing seasons, from January to February in the off-season and from April to May in the rainy season, in 2021 and 2022. Twelve maize fields were targeted in each AEZ. In total, 384 maize fields at the 2–8 leaf stage (V2–V8) were sampled and each field was sampled once.

Maize fields were split into five subplots. Scouting was performed by randomly selecting 6 plants (during the off-season) and 10 plants (during the main rainy season) per subplot while moving along a W-shaped pattern during the off-season and rainy seasons, respectively. In total, 30 plants and 50 plants were randomly sampled per field during the off-season and major rainy seasons, respectively. Inspected maize fields were slightly smaller in size during the off-season (0.5 ha) compared to the rainy season (between 0.5 to 1 ha). The number of larvae and egg masses was recorded per plant. Leaf damage was assessed using a scoring system from 1 to 9, which was first described by [34] and further adjusted by [4] (Table 1). Pesticide-treated maize fields were excluded during sampling.

Score	Description
1	No visible leaf-feeding damage
2	Few pinholes on 1-2 older leaves
3	Several shot-hole injuries on a few leaves (<5 leaves) and small circular hole damage to leaves
4	Several shot-hole injuries on several leaves (6–8 leaves) or small lesions/pinholes, small circular lesions, and a few small elongated (rectangular-shaped) lesions of up to 1.3 cm in length present on whorl and furl leaves
5	Elongated lesions (>2.5 cm long) on 8-10 leaves, plus a few small- to mid-sized uniform to irregular-shaped holes (basement membrane consumed) eaten from the whorl and/or furl leaves
6	Several large elongated lesions are present on several whorl and furl leaves and/or several large uniform to irregular-shaped holes eaten from furl and whorl leaves
7	Many elongated lesions of all sizes present on several whorl and furl leaves plus several large uniform to irregular-shaped holes eaten from the whorl and furl leaves
8	Many elongated lesions of all sizes present on most whorl and furl leaves plus many mid to large-sized uniform to irregular-shaped holes eaten from the whorl and furl leaves
9	Whorl and furl leaves almost totally destroyed and plant dying as a result of extensive foliar damage

### 2.3. Parameters

Plants with either FAW egg masses or larvae were considered as infested. The rate of plant infestation was calculated for each maize field, whereas the mean rate of infested fields was calculated per AEZ by considering the total number of fields sampled over each year. The mean percentages of damaged plants per AEZ were determined by considering the sum of percentages of plants with visual symptoms of FAW attack per field and the total number of inspected fields in a given year. Plants with evidence of visual symptoms of FAW attack were categorized as damaged,

regardless of the presence of feeding larvae. The mean numbers of larvae per plant per week were determined. Damage severity was also assessed.

#### 2.4. Meteorological Data

Monthly average temperatures and precipitations for the study period in the different study locations were obtained from the Agency for Aerial Navigation Safety (Agence pour la Sécurité de la Navigation Aérienne en Afrique et à Madagascar, ASECNA-Bénin). For temperatures, we used data from the weather station of Bohicon which is closest to the locations of Ouinhi, Zakpota, Klouékanmè, and Dogbo, while for the localities of Adjohoun, Dangbo, and Zè we used data from the Cotonou station. For rainfall, we used data from the municipalities of Adjohoun, Dangbo, Ouinhi, and Zakpota, and from the Aplahoué and Allada weather stations for the localities of Dogbo, Klouékanmè, and Zè.

#### 2.5. Data Analysis

##### 2.5.1. Larval Dispersion Model Analysis in Maize Fields

The larval dispersion model was analyzed using the Taylor power law and Iwao regression procedure [23,30,35,38]. Taylor's power law [38] is expressed as follows:

$$S_i^2 = \alpha m_i \beta \quad (1)$$

$S_i^2$  is the variance at a sampling date  $i$ ;  $m_i$  is the mean larval density at sampling date  $i$ ;  $\alpha$  is the sampling factor; and  $\beta$  is the aggregation index. The coefficients  $\alpha$  and  $\beta$  were estimated by performing linear regression on the log-transformed values [39] of  $S_i^2$  (variance sampling date  $i$ ), and the corresponding log-transformed values of the mean larval density. The aggregation index, as defined by [40] and used by [23,30,41], was estimated to analyze larval dispersion. The following formula defines this index:

$$m_i^* = m_i + [(S_i^2/m_i) - 1], \quad (2)$$

where  $m_i^*$  represents the mean of the aggregation index;  $m_i$  is the mean larval density per plant for sampling date  $i$ ; and  $S_i^2$  is the variance of larvae at sampling date  $i$ . According to [36], many biological distribution models exhibit a linear relationship between  $m^*$  and  $m$ :

$$m^* = Y + \delta m, \quad (3)$$

where  $Y$  is the regression coefficient;  $m^*$  is the mean of the aggregation index; and  $m$  is the larval density. The slope  $\delta$  represents the rate of aggregation of the larval population, and  $Y$  indicates the number of individuals constituting the initial colony [41].

##### 2.5.2. Statistical Analysis

Data on percent infestation, and larvae number of AEZ were processed by applying the analysis of variance (ANOVA) based on the General Linear Model (GLM) with SAS software, version 9.3. Means were separated using the Student-Newman-Keuls (SNK). The t-test was used to compare infestation severity and mean number of larvae observed during the two years. The percent damaged plants was analyzed using the least square difference (LSD) test.

### 3. Results

#### 3.1. Infestation of Maize by FAW in Off and Rainy Season

Infestation rates displayed a significant difference between the two AEZs for the years 2021 and 2022 ( $Df=3$ ;  $F=11.69$ ;  $p<0.0001$ ). During the off-season, significantly lower infestation rates were observed in 2022 compared to 2021 in each AEZ (Table 2). In the rainy season, the lowest infestation rate was observed in AEZ 6 compared to AEZ 8 in 2022 ( $F= 3.80$ ;  $P = 0.01$ ) (Table 2). However, no significant difference was obtained between AEZ 6 and 8 in 2021. Infestation rates in AEZ 8 were

higher during the rainy season compared to the off-season; regardless of year. However, no significant differences were observed between plant infestation rates between AEZ 6 and AEZ 8, regardless of season.

**Table 2.** Infestation rates in the AEZ 6 and 8 in 2021 and 2022 during the dry and rainy season.

Season	Agroecological zone	Infestation rate (%) (Mean $\pm$ SE)		F	P
		Year 2021	Year 2022		
Off-season	AEZ 6	36.94 $\pm$ 2.61bB	29.97 $\pm$ 2.25aC	11.69	0.0001
	AEZ 8	36.50 $\pm$ 2.00bB	29.87 $\pm$ 2.27aC		
Rainy season	AEZ 6	42.40 $\pm$ 2.90aB	41.44 $\pm$ 2.32aB	3.80	0.01
	AEZ 8	47.96 $\pm$ 2.87abA	50.94 $\pm$ 1.90bA		
F		3.54	21.49		
P		0.01	0.0001		

AEZ = AgroEcological Zone; SE = Standard Error. Means  $\pm$  SE followed by the same upper letter in the column are not significantly different. Mean  $\pm$ SE followed by the same letter are not significantly different at the 5% threshold ( $P < 0.05$ ); Upper case letters refer to the comparison between seasons for within the same year while lowercase letters refer to the comparison of agroecological zones and years for the same season.

### 3.2. Density of FAW Larvae During the Dry and Rainy Season

Dry and rainy season FAW larval densities in 2021 and 2022 are presented in Table 3. During the off-season, significant differences were observed between weeks within each AEZ for the same year. Weekly recorded larval densities show a decrease in larval densities with time as well, regardless of AEZs. In the rainy season, the larval density of FAW was highest during sampling at weeks 2 and 3 in 2021 in both AEZs and week 4 in AEZs 6 in 2022 ( $F_{5, 2995} = 6.38$ ,  $P < 0.001$ ) and 2022 ( $F_{9, 5391} = 35.88$ ,  $P < 0.0001$ ) (Table 3). When comparing the overall means, larval density was higher in AZE 8 compared to AZE 6 in off-season in 2021. But no significant differences were observed between the AEZs in 2022 during the rainy season for larval density. Between-season comparison shows the highest larval densities in AEZ 8 during the off-season while the lowest larval density was recorded during the rainy season, regardless of agroecological zone and year.

**Table 3.** Weekly larval density of FAW in the two AEZs during the off and rainy season in 2021 and 2022.

Season	Agroecological zone	Sampling week	Larval density (Mean $\pm$ SE)		
			Year 2021	Year 2022	
Off-season	AEZ 6	1	0.88 $\pm$ 0.08abc	0.96 $\pm$ 0.09abc	
		2	0.58 $\pm$ 0.05d	0.68 $\pm$ 0.05cde	
		3	0.71 $\pm$ 0.06cd	0.67 $\pm$ 0.06cde	
		4	-	0.56 $\pm$ 0.05ed	
		5	-	0.43 $\pm$ 0.04e	
	Overall mean			0.73 $\pm$ 0.03B	0.66 $\pm$ 0.02B
	AEZ 8	1	1.11 $\pm$ 0.09a	1.07 $\pm$ 0.11ab	
		2	0.82 $\pm$ 0.07bc	1.20 $\pm$ 0.09a	
		3	0.98 $\pm$ 0.70ab	0.95 $\pm$ 0.07abc	
		4	-	0.87 $\pm$ 0.08bc	
5		-	-	-	

		5	-	0.82 ± 0.07bcd
Overall mean			0.98 ± 0.04A	0.99 ± 0.03A
			F = 7.15; P < 0.0001	F = 10.42; P < 0.0001
Rainy season	AEZ 6	1	0.44 ± 0.03b	0.18 ± 0.03d
		2	0.62 ± 0.04a	0.42 ± 0.03c
		3	0.69 ± 0.04a	0.36 ± 0.03c
		4	-	0.38 ± 0.03c
		5	-	0.77 ± 0.04a
Overall mean			0.59 ± 0.02C	0.43 ± 0.01C
	AEZ 8	1	0.48 ± 0.04b	0.37 ± 0.03c
		2	0.56 ± 0.04a	0.21 ± 0.02d
		3	0.63 ± 0.04a	0.39 ± 0.03c
		4	-	0.45 ± 0.03c
		5	-	0.67 ± 0.03b
Overall mean			0.56 ± 0.02C	0.42 ± 0.01C
			F=6.38; P < 0.0001	F = 35.88; P < 0.0001

AEZ = AgroEcological Zone; SE = Standard Error. Means ± SE followed by the same upper letter in the column are not significantly different. Mean ±SE followed by the same letter in the column are not significantly different at the 5% threshold (P< 0.05). Uppercase letters refer to the comparison of the overall mean between seasons within the same year and lowercase letters refer to the comparison of agroecological zones within the same year regardless of the season.

### 3.3. Percentage of Damaged Plants During the Off and Rainy Seasons

A comparison of the two AEZs shows a slight difference for the percent damaged plants (Df=3; F= 8.09; P<0.0005) (Table 4), regardless of the year.

Percent damaged plants was highest in 2021, regardless of AEZs (Df=3; F=16.61; P < 0.0001) (Table 4). However, in 2022 the highest damage was observed in AEZ 8 compared to zone 6. Comparison between seasons revealed the lowest plant damage rates during the off-season in 2022; regardless of agroecological zone.

**Table 4.** Percentage of damaged plants by FAW in the two AEZs during the off and rainy seasons.

Season	Agroecological zones	Percentage of damaged plants (Mean ± SE)		F	P
		Year 2021	Year 2022		
Off-season	AEZ 6	58.33 ± 1.51bB	51.53 ± 2.31aC	8.09	0.0005
	AEZ 8	55.72 ± 1.82abB	53.73 ± 2.35aC		
Rainy season	AEZ 6	80.92 ± 1.94cA	63.44 ± 2.06aB	16.61	0.0001
	AEZ 8	82.22 ± 2.36cA	72.05 ± 1.86bA		
F		66.42	19.91		
P		0.0001	0.0001		

AEZ = AgroEcological Zone ; SE = Standard Error. Means ± (SE) followed by the same upper letter in the column are not significantly different. SE = Standard Error. Mean ±(SE) followed by the same letter in the column are not significantly different at the 5% threshold Uppercase letters refer to the comparison of the overall mean between seasons within the same year and lowercase letters refer to the comparison of agroecological zones within the same year regardless of the season.

### 3.4. Plant Damage Severity in 2021 and 2022 During the Dry and Rainy Season

Table 5 shows the severity of FAW damage on maize plants during the off-season of 2021-2022. In 2021, the highest damage was observed in the third week-sampling in AEZ 8 compared to AEZ 6 in 2021 (F5, 1795 = 8.60, P<0.0001). But in 2022 even significant differences occurred between weekly

samples ( $F_9, 3231 = 12.91, P < 0.0001$ ), the highest plant damage was obtained in the fourth week in AEZ 6 and from the second to the fifth week in 2022. When comparing damage severity within the same AEZ between seasons, mean values obtained in off-season were significantly higher than those recorded during the rainy season ( $F = 37.95; P < 0.0001$ ), but this trend was only evident in 2021. Plant damage severity was higher in the off-season compared to the rainy season; regardless of agroecological zone in 2021 ( $F = 197.99; P < 0.0001$ ). In 2022, damage severity was lowest in AEZ 8 during the rainy season ( $F = 102.22; P < 0.0001$ ).

**Table 5.** Weekly damage severity in the two AEZs in 2021 and 2022 during the off and rainy seasons.

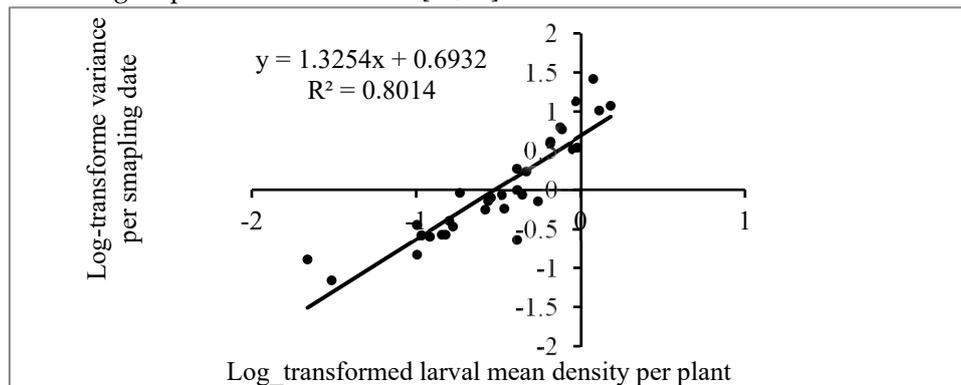
Season	Agroecological zone	Sampling week	Plant Damage Score Per AEZ (Scale 1–9) (Mean $\pm$ SE)	
			Year 2021	Year 2022
Off-season	AEZ 6	1	3.36 $\pm$ 0.10b	2.58 $\pm$ 0.07b
		2	3.17 $\pm$ 0.09bc	2.25 $\pm$ 0.06c
		3	3.30 $\pm$ 0.08bc	2.30 $\pm$ 0.06c
		4	-	2.73 $\pm$ 0.07ab
		5	-	2.24 $\pm$ 0.07c
	Overall mean		3.28 $\pm$ 0.05A	2.42 $\pm$ 0.03BC
	AEZ 8	1	2.95 $\pm$ 0.08c	2.32 $\pm$ 0.07c
		2	3.13 $\pm$ 0.08bc	2.63 $\pm$ 0.07ab
		3	3.82 $\pm$ 0.15a	2.63 $\pm$ 0.06ab
		4	-	2.89 $\pm$ 0.07a
		5	-	2.84 $\pm$ 0.07a
Overall mean		3.30 $\pm$ 0.06A	2.66 $\pm$ 0.03A	
			F = 8.60; P < 0.0001	F = 12.91; P < 0.0001
Rainy season	AEZ 6	1	2.03 $\pm$ 0.05b	1.55 $\pm$ 0.04f
		2	2.10 $\pm$ 0.05b	2.56 $\pm$ 0.07b
		3	2.32 $\pm$ 0.05a	2.70 $\pm$ 0.08b
		4	-	1.98 $\pm$ 0.05e
		5	-	3.48 $\pm$ 0.08a
	Overall mean		2.16 $\pm$ 0.02B	2.46 $\pm$ 0.03B
	AEZ 8	1	2.00 $\pm$ 0.05b	1.84 $\pm$ 0.04e
		2	2.10 $\pm$ 0.05b	1.79 $\pm$ 0.05e
		3	2.32 $\pm$ 0.05a	2.45 $\pm$ 0.07c
		4	-	2.23 $\pm$ 0.05d
		5	-	3.41 $\pm$ 0.08a
Overall mean		2.14 $\pm$ 0.03B	2.35 $\pm$ 0.02C	
			F = 197.99; P < 0.0001	F = 13.53; P < 0.0001

AEZ = AgroEcological Zone; SE = Standard Error. Means  $\pm$  (SE) followed by the same upper letter in the column are not significantly different. Mean  $\pm$ (SE) followed by the same letter in the column are not significantly different at the 5% threshold ( $p < 0.05$ ). Uppercase letters refer to the comparison of the overall mean between seasons within the same year and lowercase letters refer to comparison of agroecological zones within the same year regardless of the season.

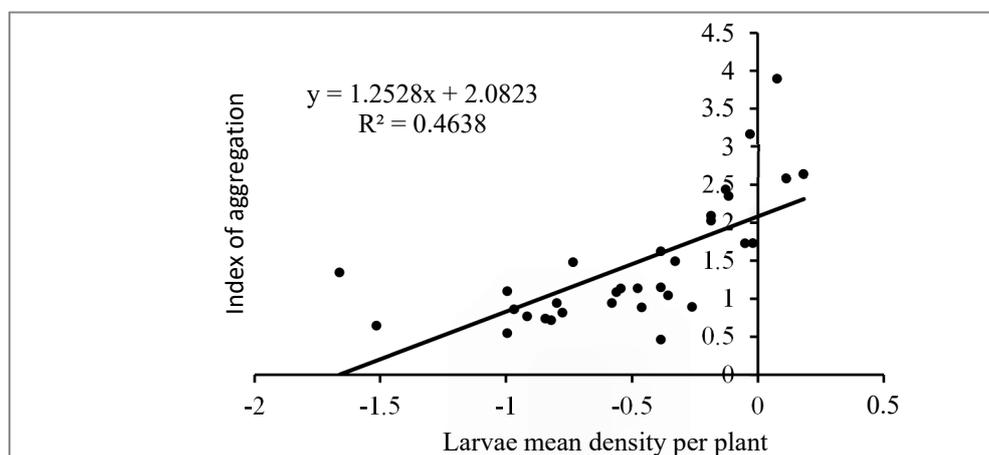
### 3.5. Dispersion Pattern of FAW Larvae

The linear relationship between the logarithm of  $S_i^2$  and the logarithm of  $m_i$ , is depicted in Figure 3 with a determination coefficient ( $R^2$ ) of 0.801. This model fits best to describe the relationship between the two variables ( $P < 0.0001$ ). The slope  $\beta$  of 1.32, exceeding 1, indicates an aggregation trend of larvae. The larval dispersion pattern was found to follow a negative binomial distribution.

Figure 4 shows the linear relationship between the aggregation index and the mean larval density per plant, with a determination coefficient ( $R^2$ ) of 0.463. The slope  $\delta$  of the regression line, equal to 1.25, suggests a moderate aggregation of larvae, while the intercept  $Y$ , equal to 2.08, indicates that FAW larvae were grouped in basic colonies [36,41].



**Figure 2.** Relationship between the log-transformed values of  $S_i^2$ , variance for plant at each sampling date, and the corresponding log-transformed values ( $m_i$ ) of larval mean density per plant.

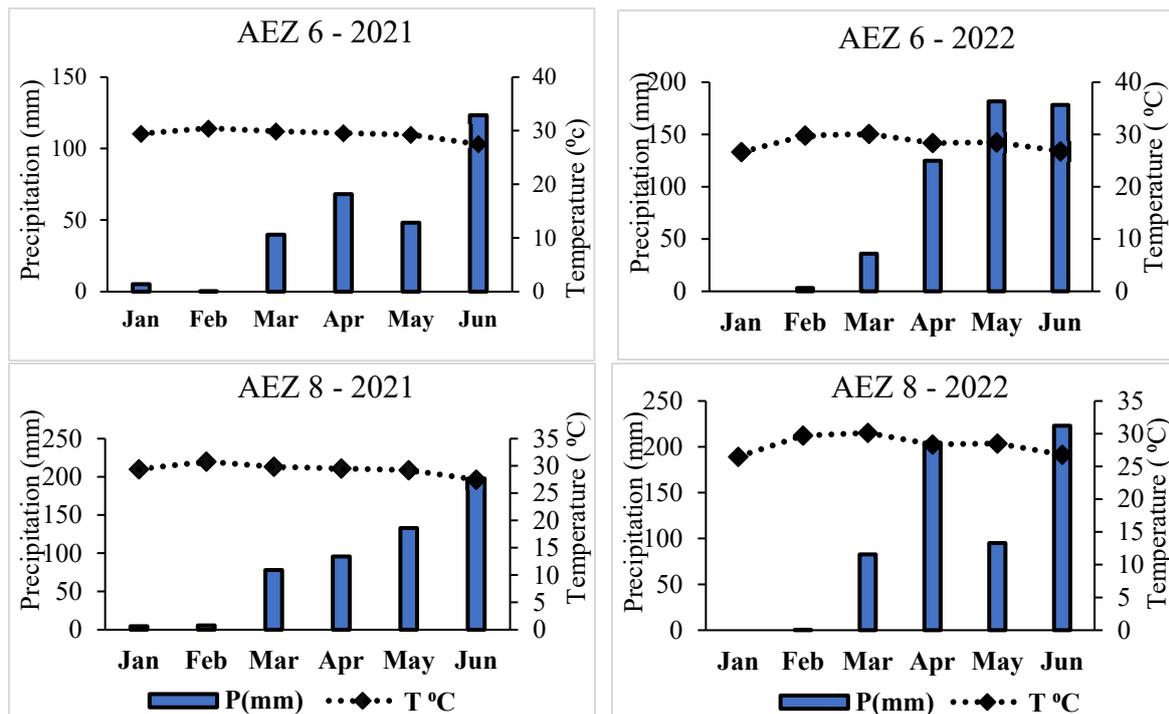


**Figure 3.** Relationship between the index of aggregation ( $m_i^*$ ) and the larval mean density per plant ( $m_i$ ).

### 3.6. Temperature and Precipitation During the Survey

The off-season had higher monthly mean temperatures than the rainy season, yet there were significant variations in precipitation between the two seasons (Figure 2). The temperatures at AEZ 6 in 2021 varied from 29.39 to 30.38°C during the off-season, and 29.21 to 29.52°C during the rainy season. Rainfall varied from 0.25 to 5.12 mm in the off-season, while during the rainy season, it varied from 39.75 to 123.32 mm. For the same area (AEZ 6), temperature variations were observed in 2022, ranging from 26.63 to 29.8°C in the off-season and from 28.36 to 28.5°C during the rainy season. Conversely, in the off-season, precipitation varied from 0 to 3.1 mm, whereas during the rainy season, it ranged from 35.95 to 181.62 mm.

Temperatures in AEZ 8 for 2021 varied from 29.39 to 30.78°C, while rainy season temperatures ranged from 29.21 to 29.52°C. Precipitation ranged from 4.5 to 5.53 mm during the off-season, while it ranged from 78.06 to 198.03 mm during the wet season. Temperatures in AEZ 8 ranged from 26.48 to 29.7°C during the off-season and from 28.35 to 28.5°C during the rainy season in 2022. Precipitation ranged from 82.73 to 222.9 mm in the wet season and 0 to 0.56 mm in the off-season.



**Figure 4.** Monthly mean temperatures (°C) and mean precipitation (mm) in the AEZ at the off season (January to March) and in the rainy season (April and June).

#### 4. Discussion

The current study revealed a variability between seasons and years in the FAW infestation of the two AEZs of Benin (zones 6 and 8). Thus, the infestation of maize in AEZ 8 was higher than that of AEZ 6 during the rainy season in 2022. Globally, infestations were lower during the off-season in 2021, regardless of AEZs. Such findings may be explained by the differences in maize varieties between the two zones and the timing of planting. Furthermore, regional climate may also affect the damage of maize during the two years and within AEZs [17]. In the current context of climate variability, these temperature and precipitation variations affect insect life cycles, including FAW, thereby increasing the potential for damage and spreading to new regions [42,43]. In Africa, for example, it could colonize previously unsuitable areas, taking advantage of migrations from climatically favorable zones, highlighting the importance of continued surveillance, as emphasized by [44].

Infestation rates and percent damaged plants also show variability between seasons or years and within AEZs, which may be due to the FAW life cycle and maize plant phenology [31,45]. Younger maize plant stages (VE-V3) might be more heavily damaged compared to the old ones [46,47]. Another factor could be the interactions of FAW with some of its parasitoid complex occurring in most maize fields, suggesting natural regulation [50,54]. Such regulation should be addressed during future research work.

The mean larval density per plant recorded during the off-season was higher than that of the rainy season. This difference may be attributed to the reduced availability of food during the off-season compared to the rainy season, resulting in more significant foliar damage. Our findings suggest that rainfall played a crucial role in influencing the observed variations in the number of FAW larvae per plant between seasons across all AEZs. The rain likely washed away many larvae from the plants, consequently reducing both larval density and damage to the plants [31,53]. A similar trend was observed in Mozambique by [31], who recorded a higher number of FAW larvae during the off-season.

Studying the spatial distribution of FAW larvae provides crucial insights into understanding the aggregation patterns and population dynamics of this pest. Our analysis of the aggregation index and the mean number of larvae per plant revealed a slope of  $\delta = 1.25$ , indicating a moderate larval

aggregation. These findings had been previously reported by [25] in Mexico, by [54] in America, and by both [24,55] in Brazil. A random spatial distribution has also been reported by Hernández-Mendoza et al., (2008) in Mexico and by [24] in Brazil. These findings were similar to previous observations documenting more pronounced intraspecific aggregation patterns in similar pest species [35,56,57]. The aggregated dispersion of FAW is due to several factors, such as its oviposition pattern resulting in egg masses, as well as behavioral and environmental factors that promote the clustering of individuals, especially when population density is low, as was the case when considering the average density of larvae found for each sampling. Furthermore, the intercept of  $\gamma = 2.08$  supports that FAW larvae evolve in colonies of at least 2 larvae before they disperse.

Understanding this aggregation pattern is essential for developing effective control strategies, developing effective sampling plans, and predicting pest damage, as this pattern could affect the dispersion of FAW larvae. For instance, probability distribution models based on field data help establish sampling and statistical analysis criteria for pest management, aiding in more targeted and efficient interventions [58]. Behavioral patterns and environmental characteristics play a key role in determining the spatial distribution of individuals within a population in a given ecosystem. It has been demonstrated that different plant varieties also impact the spatial distribution of insects [59]. Therefore, further investigations are required to validate the spatial distribution of this pest in maize growth stages. The current study did not explore the range of alternative host plants of FAW. Therefore, there is a need to examine the influence of these host plants on the dispersion and population dynamics of this pest insect. The larval density and aggregation patterns of FAW identified in this study can inform action threshold determination for targeted interventions by providing critical data on population dynamics that help identify when pest populations exceed economically damaging levels, allowing for timely and precise management strategies.

The current study on the FAW in two AEZs reveals seasonal dynamics and key factors influencing its infestation in maize crops. The data shows that FAW is present throughout the year, with higher infestation rates during the rainy season. Larval populations exhibit distinct trends, increasing during the rainy season and decreasing during the off-season, with a particular sensitivity to temperature variations. A significant implication of this study is that the biological control of FAW could be optimized by using biological control agents adapted to the specific conditions of the rainy season. This targeted approach could reduce the impact of FAW on maize crops while minimizing the use of chemical inputs. Furthermore, our data suggests that early planting of maize during the major growing season can significantly reduce the population density of FAW, providing a practical perspective for farmers.

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