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Spatiotemporal Dynamics and Climate Drivers of Major Maize Insect Pests Across Agroecological Zones in Morocco

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ABSTRACT

Maize (*Zea mays* L.) in Morocco faces diverse insect pests, yet their seasonal patterns and climatic responses remain unclear; weekly surveys (2023–2025, weeks 18–30) were conducted in Zemamra, Mettouh, and Oulad Saïd zones using multiple trapping methods. Eight major pests were monitored: *Sesamia nonagrioides, Ostrinia nubilalis, Agrotis segetum, Rhopalosiphum padi, Sitobion avenae, Oscinella frit, Agriotes lineatus*, and *Diabrotica virgifera virgifera*. Pest composition was consistent, with *R. padi* (15.8–18.4%), *S. avenae* (14.3–16.5%), and *S. nonagrioides* (15.4–17.3%) dominating, while O. frit was least abundant (6.7–7.2%). Abundance consistently peaked during weeks 20–21 across all years and sites, with the highest levels recorded in Zemamra (342.5–357.3), followed by Mettouh (336.9–352.8) and Oulad Saïd (298.4–309.0). Diversity indices remained stable (Shannon–Wiener (H') ~1.4–1.6; Margalef (D) ~0.9–1.0; Pielou's (J) indices ~0.8) with little variation across sites or years. Aphids correlated positively with humidity (*R. padi* Spearman's coefficient (r) = 0.877; *S. avenae* r = 0.851) and rainfall (*R. padi* r = 0.924; *S. avenae* r = 0.958); other pests showed weak, non-significant climatic associations. Moroccan maize pests peak in late May, with aphids rising under humid, rainy conditions, emphasizing the importance of climate-based pest management strategies.

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1. Introduction

Maize (*Zea mays* L.) is a major cereal crop cultivated worldwide due to its adaptability to diverse agro-ecological conditions, making it vital for food security [1]. It is used for human consumption, livestock feed, fodder, and as a raw material for industrial products such as starch and oil [2]. Global maize production exceeds one billion metric tons annually, with about 197 million hectares cultivated, yielding approximately 1,148 million metric tons [3, 4]. It is grown in 165 countries across the Americas, Asia, Europe, and Africa, serving as a staple food for over 900 million people in developing regions [5, 6]. The United States produces about 31.54% of the world's maize, followed by China (23.37%), Brazil (10.28%), the European Union (4.86%), and Argentina (4.45%) [7]. In Morocco, cereals occupy roughly half of the agricultural land (about 4.6 million hectares), with maize representing 9% of cereal crops and 6% of the total cultivated area [8]. Maize was cultivated on approximately 29,678 hectares in 2023, with an average yield of 714.2 kg/ha, ranking the country 152nd worldwide. Maize production in 2022 totaled 35.8 thousand tonnes, which was 26.4% lower than in 2021 [8, 9].

Globally, approximately 10% of maize production is lost annually due to biotic factors, particularly insect pests [10]. Maize is attacked by numerous pests throughout its various growth stages [11]. More than 140 insect species are known to infest maize, including aphids, thrips, shoot flies, stem borers, fall armyworm, corn earworm, and corn leafhopper, all causing varying levels of damage [6, 12]. Of these, only about twelve species are considered major pests, as they inflict significant damage from sowing to harvest and during storage [13, 14]. In Morocco, the primary maize pests include the Mediterranean corn borer *Sesamia nonagrioides* Lefèbvre (Lepidoptera: Noctuidae), the European corn borer *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae), the turnip moth *Agrotis segetum* (Denis & Schiffermüller) (Lepidoptera: Noctuidae), the bird cherry-oat aphid *Rhopalosiphum padi* (Linnaeus) (Hemiptera: Aphididae), the grain aphid *Sitobion avenae* (Fabricius) (Hemiptera: Aphididae), the frit fly *Oscinella frit* (Linnaeus) (Diptera: Chloropidae), the common click beetle *Agriotes lineatus* (Linnaeus) (Coleoptera: Elateridae), and the western corn rootworm *Diabrotica virgifera virgifera* LeConte (Coleoptera: Chrysomelidae); yield losses can reach economically damaging levels when appropriate control strategies are not implemented [15].

Developing effective pest management approaches requires understanding the biodiversity and population dynamics of these insect species [16]. Arthropod diversity in maize fields is influenced by several factors, including crop management practices, phenological stage, surrounding habitats, and climatic conditions [17]. Knowledge of seasonal pest dynamics helps producers align monitoring with critical life stages [18], enabling timely application of pesticides or other control methods. Proper timing increases effectiveness, reduces costs, and minimizes environmental impact [19, 20]. Integrated Pest Management (IPM) strategies applied at optimal stages can also reduce the need for repeated insecticide treatments [21-23].

Insect communities associated with maize cultivation play a crucial role in agroecosystem stability [24]. Understanding their richness, diversity, and seasonal patterns is essential for designing sustainable management strategies. While these pests reduce maize yields, they are also part of broader ecological networks, serving as prey for natural enemies. Any significant reduction in pest populations may disrupt ecological interactions, potentially affecting ecosystem stability even if such effects are not immediately apparent [25]. Maintaining pest densities below economic threshold levels (ETL) is therefore necessary to ensure stable maize production while preserving natural trophic relationships that support biodiversity and long-term ecosystem resilience [26].

Despite the growing body of research on maize pest monitoring, most existing studies are limited to single seasons, single locations, or focus on individual pest species, which constrains a comprehensive understanding of pest community dynamics over time and space. In addition, studies integrating ecological diversity indices with long-term field observations remain scarce, particularly under North African and Moroccan agroecological conditions. Therefore, this study aims to (i) assess the richness and diversity of maize insect pest communities, (ii) analyze their seasonal population dynamics, and (iii) compare their temporal and spatial distribution across major maize-producing regions over multiple years. The novelty of this work lies in its multi-year, multi-site approach combined with the application of ecological diversity indices to characterize pest assemblages, providing a more integrated understanding of pest dynamics than conventional monitoring studies. By doing so, this study advances current knowledge beyond species-specific or short-term assessments and offers a robust scientific basis for improving pest surveillance and optimizing IPM strategies in maize agroecosystems.

2. Materials and Methods

2.1. Study Areas

This study was conducted over three consecutive years (2023–2025) in three maize-producing areas of Morocco. The first site was in Zemamra, Sidi Bennour Province (32°37' N, 8°42' W); the second in Mettouh, El Jadida Province (32°52'48" N, 8°10'12" W); and the third in Oulad Saïd, Settat Province (33°00'08" N, 7°37'11" W) (Fig. **1**). The distances between the sites were approximately 57.6 km between Zemamra and Mettouh, 109.8 km between Zemamra and Oulad Saïd, and 53.2 km between Mettouh and Oulad Saïd, with an overall average distance of about 79.3 km. All three localities studied have Mediterranean climates characterized by mild, wet winters and hot, dry summers. Oulad Saïd experiences colder winters with average temperatures around 8°C and very hot summers reaching up to 38°C. It receives about 320 mm of rainfall annually. Zemamra and Mettouh, both located nearer the Atlantic coast, have milder conditions, with winter temperatures averaging 12°C and summer highs around 30°C. Annual rainfall in Zemamra averages 350 mm, while Mettouh receives approximately 340 mm. Soil types differ across the sites: Zemamra's soil is a vertisol with an angular structure extending up to 15 cm deep, which retains moisture and becomes difficult to work with during dry periods. In contrast, the soils of Oulad Saïd, and Mettouh are lighter, composed mainly of clay, sand, and lime, exhibiting hydromorphic characteristics and alkaline pH.

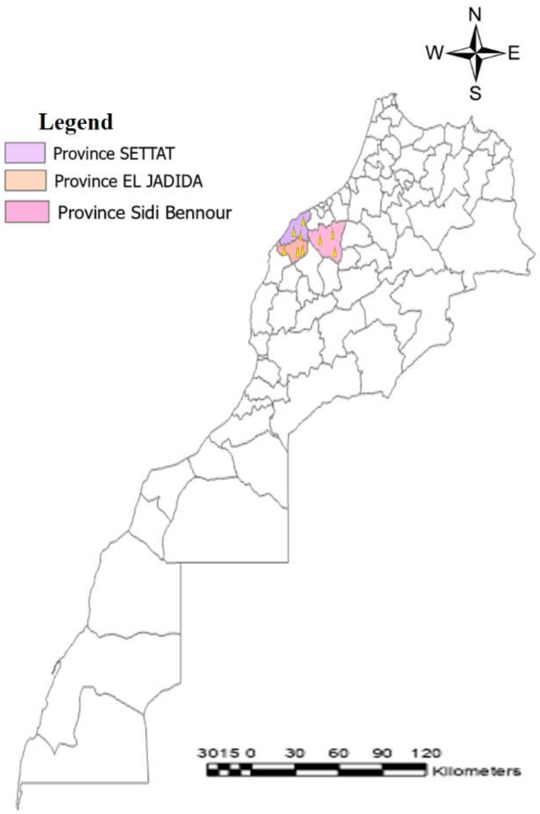

Figure 1: Map of the studied site.

In all study sites, experiments were conducted on three plots of 5,000 to 6,000 m². Sowing took place on April 10, 2023, April 19, 2024, and April 19, 2025. The soil was prepared by one deep plowing followed by two passes with a tractor-mounted cultivator. The hybrid maize variety "Cecilia" was used. Seeds were sown manually on ridges spaced 70 to 80 cm apart, with 20 to 40 cm between plants, resulting in a density of 8 to 10 plants per square meter. Crop management followed conventional local practices without insecticide application. Nitrogen fertilization totaled 180 units: 40 units were applied before or at sowing, and the remainder at the 4–6 leaf stage. Phosphorus was applied at 120 units, with 70 units before or at sowing and 30 units at the 6–8 leaf stage. Potassium was applied at 110 units, with one-quarter before or at sowing and three-quarters at the 6–8 leaf stage. Magnesium, sulfur, zinc, and copper were also supplied to prevent deficiencies that could reduce yield and nutritional quality. Biostimulants and deficiency correctors were mixed with foliar treatments after compatibility testing. Twelve irrigations were applied based on crop water needs, especially during critical stages such as tasseling, silking, cob formation, and grain filling. Irrigation was delivered through a drip system, with a total water requirement of approximately 5,000 m^3. Weed control was done manually by handpicking and hoeing, with no herbicides used at any site. Regarding previous crops and surrounding vegetation, in Zemamra, the site was surrounded by maize and preceded by soft wheat in 2023; surrounded by alfalfa and preceded by faba bean in 2024; and surrounded by maize and preceded by sugar beet in 2025. In Mettouh, the site was surrounded by maize and preceded by sugar beet in 2023, and in 2024 and 2025, it was surrounded by maize and preceded by alfalfa. In Oulad Saïd, the site was surrounded by maize and preceded by soft wheat in 2023 and 2024, and in 2025 it was surrounded by soft wheat and preceded by potato.

2.2. Sampling Procedures

A three-year field study (2023–2025) was conducted to monitor the seasonal dynamics of major maize pests in Morocco and North Africa (*S. nonagrioides*, *O. nubilalis*, *A. segetum*, *R. padi*, *S. avenae*, *O. frit*, *A. lineatus*, and *D. virgifera virgifera*). Sampling occurred weekly from early May (week 18 of the year) to late July each year (week 30 of the year), corresponding to the onset of maize vegetative growth and the initial activity period of key pest species under local climatic conditions. Flying and mobile pests (aphids, hemipterans, dipterans, and adult lepidopterans/coleopterans) were collected using sweep nets (30 cm diameter). At each site, 25 sweeps were performed per plot between 10:00 and 16:00. This time window was selected to standardize sampling efficiency under stable environmental conditions (light intensity, temperature, and wind), which improves visibility and capture consistency during active sampling. Although pest activity may continue after 16:00, complementary passive trapping methods (pitfall traps, sticky traps, and pan traps) were used to ensure continuous 24-hour monitoring of pest activity, including late afternoon and nocturnal species. Captured insects were transferred into labeled containers for counting and identification. Ground-dwelling arthropods, particularly coleopterans, were monitored with 10 pitfall traps per field (20 cm in long × 7 cm in wide, spaced 5 m apart). Each trap was buried flush with the soil and filled one-third with a 70% ethyl acetate–30% water solution plus detergent. A transparent Plexiglas cover was placed 5 cm above each trap. Samples were collected every two days, filtered, and preserved in 75% ethanol. To capture small, actively moving pests such as winged aphids, hemipterans, and dipterans, locally made yellow pan traps (15 × 24 cm; 5 cm deep) were positioned 15 cm above the canopy, and 5 yellow sticky traps coated with grease were placed in each maize plot. Canopy-dwelling pests were also sampled using the beating sheet method. A white inverted umbrella was positioned beneath plants, which were gently shaken—particularly during tasseling and maturity stages. Additional visual counts and handpicking improved detection accuracy. Twenty-five randomly selected plants per plot (RCBD design) were inspected, examining leaves from top to bottom with the naked eye or a 4× magnifier. Fast-moving insects were often counted visually before they escaped.

2.3. Specimen Preservation and Morphological Identification

Insects collected weekly from each field site were placed in 25 mL glass vials filled with 80% ethanol and a small amount of glycerin, adjusted according to specimen size. Each vial was labeled with the collection site, date, and other relevant details. Samples were initially frozen, then rinsed briefly with 75% ethanol to remove debris, and then preserved in 95% ethanol under refrigerated storage. Slide preparations followed the method described by Noyes [27]. Species identification was performed using a stereo zoom microscope (SWIFT Trinocular Stereo Zoom Microscope with 56-bulb LED ring light, 3.5×–90× magnification; SWIFT, USA) equipped with a digital camera (AmScope MU1403, 14MP USB Microscope Camera; AmScope, USA). Morphological features were compared with standard taxonomic keys and catalogs including [28-31]. Data from the Barcode of Life Data Systems (BOLD) were also used to assist in confirmation. Voucher specimens were archived at the Insectarium of the National Institute of Agricultural Research (INRA), Zemamra, Morocco.

2.4. Weather Conditions

Weather parameters—including mean air temperature, and relative humidity, were recorded using an iMetos electronic station (AG/CP/DD 280, Pessl Instruments GmbH, Weiz, Austria) at each study site for each year (from May to July). Data were analyzed on an annual basis. The station was located within 3 km of the experimental maize fields.

2.5. Statistical Analysis

Differences in the abundance of the eight main maize pest species among the four study sites (Zemamra, Mettouh, and Oulad Saïd) were evaluated using a one-way ANOVA at a significance level of $P < 0.05$, followed by Tukey's LSD post hoc test to identify significant pairwise differences between sites and sampling dates. All analyses were performed using IBM SPSS Statistics 23.0 (SPSS Inc., Chicago, Illinois, USA). Community structure was assessed by calculating species diversity, richness, and evenness using the following indices:

Shannon–Wiener index (H'): evaluates diversity by incorporating both species richness and their relative abundances, calculated as:

$$H' = -\sum(Pi \times lnPi) ,$$

where *Pi* is the proportion of individuals belonging to species *i*.

Margalef richness index (D): estimates species richness while accounting for sample size:

$$D = \frac{S-1}{Ln\ N},$$

Where *S* is the number of species and *N* the total number of individuals.

Pielou's evenness index (J): measures how evenly individuals are distributed across species:

$$\mathrm{J} = \frac{\mathrm{H}'}{\ln S},$$

where *H'* is the Shannon–Wiener index and *S* the number of species.

All indices were calculated using Paleontological Statistics software (PAST), Version 3.15 [32]. The Shannon index is widely recognized as a standard tool for measuring biological diversity in both plant and animal communities [33].

To analyze dissimilarities in pest community composition between years and sites, a one-way ANOSIM test was performed with PAST software using the Bray–Curtis similarity index and 9,999 permutations. The effects of sampling year, site, and their interaction (year × site) on insect pests diversity parameters were tested using one-way and two-way ANOVA ($p < 0.0001$) in Statistica software (Version 6; StatSoft, USA). When significant differences were detected, Tukey's post hoc test was applied for pairwise comparisons. Spearman's rank correlation coefficient was used to examine the relationships between pest species abundance and meteorological variables (temperature, relative humidity, and Rainfal), also using IBM SPSS Statistics 23.0.

3. Results

3.1. Abundance and Composition of Maize Insect Pests Across Three Study Sites

Eight maize insect pests were recorded in the Zemamra, Mettouh, and Oulad Saïd localities during the three-year study period (2023–2025) under field conditions. These species were identified and confirmed by the authors as follows: *Sesamia nonagrioides* Lefèbvre, 1827 (Lepidoptera: Noctuidae), *Ostrinia nubilalis* (Hübner, 1796) (Lepidoptera: Crambidae), *Agrotis segetum* (Denis & Schiffermüller, 1775) (Lepidoptera: Noctuidae), *Rhopalosiphum padi* (Linnaeus, 1758) (Hemiptera: Aphididae), *Sitobion avenae* (Fabricius, 1775) (Hemiptera: Aphididae), *Oscinella* *frit* (Linnaeus, 1758) (Diptera: Chloropidae), *Agriotes lineatus* (Linnaeus, 1767) (Coleoptera: Elateridae), and *Diabrotica virgifera virgifera* LeConte, 1868 (Coleoptera: Chrysomelidae). In the Zemamra locality, *S. nonagrioides* and *R. padi* were the most abundant pests, with *R. padi* representing 15.9–16.0% and *S. nonagrioides* 16.9–17.3% of the total population across years. *S. avenae* and *D. v. virgifera* followed closely (14.3–14.6% and 12.7–12.9%, respectively), while *A. segetum*, *O. nubilalis*, and *A. lineatus* showed intermediate abundances (9.9–12.5%). *O. frit* was consistently the least abundant pest, representing only 7.1–7.2% of the total (Table **1**). In the Mettouh locality, *R. padi* dominated the pest complex (17.6–18.0%), followed by *S. avenae* (15.9–16.5%) and *S. nonagrioides* (15.4–16.5%). *D. v. virgifera* and *O. nubilalis* contributed 11.3–12.7% of the total, whereas *A. segetum* and *A. lineatus* accounted for 9.3–10.1%. *O. frit* remained the least represented species, at 6.7–6.9% (Table **1**). In Oulad Saïd, *R. padi* and *S. avenae* were again the most abundant pests (18.1–18.4% and 16.3–16.5%, respectively), followed by *S. nonagrioides* (15.8–16.3%). *D. v. virgifera* and *O. nubilalis* each represented 11.5–12.0% of the total. *A. segetum* and *A. lineatus* maintained similar proportions (9.2–9.8%), whereas *O. frit* consistently showed the lowest abundance (6.7–6.9%) (Table **1**). Overall, the results revealed notable consistency in pest composition across localities and years, with *R. padi*, *S. avenae*, and *S. nonagrioides* comprising the dominant group, while *O. frit* remained the least prevalent.

Table 1: Total number and percentage of maize insect pests in the Zemamra, Mettouh, and Oulad Saïd localities.

Site	Insect Pests	Study Years					
		2023		2024		2025	
		No. of Insects	Percentage(%)	No. of Insects	Percentage(%)	No. of Insects	Percentage(%)
Zemamra	*Sesamia nonagrioides*	5226.7	17.2	5308.9	16.9	5712.5	17.3
	Ostrinia nubilalis	3690.7	12.1	3920.9	12.5	4100.4	12.4
	Agrotis segetum	3126.5	10.3	3252.4	10.3	3463.3	10.5
	Rhopalosiphum padi	4848.0	15.9	5029.3	16.0	5263.8	15.9
	Sitobion avenae	4390.7	14.4	4608.0	14.6	4723.9	14.3
	Oscinella frit	2183.9	7.2	2247.3	7.1	2364.3	7.1
	Agriotes lineatus	3033.9	10.0	3115.6	9.9	3266.1	9.9
	Diabrotica virgifera virgifera	3909.4	12.9	4006.2	12.7	4188.2	12.7
Mettouh	*Sesamia nonagrioides*	4694.2	15.4	5109.5	16.5	5117.8	16.2
	Ostrinia nubilalis	3433.7	11.3	3587.1	11.6	3723.7	11.8
	Agrotis segetum	2931.7	9.6	3114.1	10.1	3109.9	9.8
	Rhopalosiphum padi	5497.6	18.0	5452.8	17.6	5654.3	17.9
	Sitobion avenae	5013.0	16.5	4918.0	15.9	5109.0	16.2
	Oscinella frit	2108.9	6.9	2113.2	6.8	2127.3	6.7
	Agriotes lineatus	2925.8	9.6	2891.5	9.3	2932.6	9.3
	Diabrotica virgifera virgifera	3858.9	12.7	3773.8	12.2	3818.9	12.1
Oulad Saïd	*Sesamia nonagrioides*	4395.4	16.3	4349.0	15.8	4450.2	16.1
	Ostrinia nubilalis	3119.0	11.6	3155.0	11.5	3213.8	11.6
	Agrotis segetum	2629.6	9.7	2670.8	9.7	2721.0	9.8
	Rhopalosiphum padi	4913.0	18.2	5037.8	18.4	5017.6	18.1
	Sitobion avenae	4413.2	16.4	4536.4	16.5	4517.0	16.3
	Oscinella frit	1803.8	6.7	1860.1	6.8	1901.8	6.9
	Agriotes lineatus	2492.8	9.2	2534.5	9.2	2567.5	9.3
	Diabrotica virgifera virgifera	3205.4	11.9	3298.0	12.0	3312.0	12.0

3.2. Seasonal Abundance of Maize Insect Pests Across Three Study Sites

Weekly abundance of maize insect pests in the three studied sites during 2023 is presented in Table **2**. Pest numbers followed a similar seasonal trend in Zemamra, Mettouh, and Oulad Saïd, increasing from week 18 and peaking between weeks 20 and 21, followed by a sharp decline towards week 28, with no captures recorded in weeks 29 and 30. In Zemamra, the highest abundance was recorded in week 20 (337.4 [16.6%]), followed closely by week 21 (335.4 [16.5%]). The results revealed highly significant differences among weeks ($F_{12,182}$ = 195.5, P < 0.001), with Tukey's test separating the peak period (weeks 20–21) from intermediate weeks (weeks 19, 22–24) and low-abundance weeks (weeks 25–28). In Mettouh, pest abundance also peaked in week 20 (339.8 [16.7%]) and week 21 (337.8 [16.6%]). The differences among weeks were highly significant ($F_{12,182}$ = 79.2, P < 0.001), with weeks 20–21 forming the highest group, followed by weeks 19 and 22, and a progressive decline to near-zero levels in weeks 28–30. In Oulad Saïd, maximum abundance occurred in week 20 (304.5 [16.9%]) and week 21 (298.7 [16.6%]). Here too, weekly variation was highly significant ($F_{12,182}$ = 386.8, P < 0.001), with weeks 20–21 significantly higher than all other weeks except week 22. Between-site comparisons for each week showed no significant differences during the peak period (weeks 18–22, P > 0.05). However, from week 23 onwards, differences became significant, notably in week 23 ($F_{2,42}$ = 3.6, P = 0.036), week 24 ($F_{2,42}$ = 3.6, P = 0.037), and week 25 ($F_{2,42}$ = 3.610, P = 0.036). No significant differences were detected in the late-season period (weeks 26–30).

Weekly abundance of maize insect pests in the three studied sites during 2024 is presented in Table **2**. Populations followed a clear seasonal pattern, increasing from week 18 and peaking between weeks 20 and 21 before steadily declining to near-zero levels by week 28, with no captures recorded in weeks 29 and 30. In Zemamra, abundance varied significantly among weeks ($F_{12,182}$ = 192.2, P < 0.001), with the highest means in week 20 (348.4 [16.6%]) and week 21 (341.2 [16.3%]). Mettouh showed a similar trend ($F_{12,182}$ = 57.7, P < 0.001), peaking in week 20 (347.7 [16.8%]) and week 21 (339.6 [16.5%]). Oulad Saïd also exhibited significant temporal variation ($F_{12,182}$ = 362.4, P < 0.001), with maxima in week 20 (307.7 [16.8%]) and week 21 (305.7 [16.7%]). Comparisons among sites within each week showed that during the peak period (weeks 18–22), site differences were not significant (P > 0.05). However, from week 23 onwards, differences became evident. In week 23, abundance was significantly higher in Zemamra than in Oulad Saïd ($F_{2,42}$ = 3.8, P = 0.030), with Mettouh showing intermediate values. Similar patterns were observed in week 24 ($F_{2,42}$ = 4.9, P = 0.012) and week 25 ($F_{2,42}$ = 4.0, P = 0.027), where Zemamra recorded higher pest numbers than Oulad Saïd. This trend persisted into week 26 ($F_{2,42}$ = 4.1, P = 0.024), week 27 ($F_{2,42}$ = 4.7, P = 0.015), and week 28 ($F_{2,42}$ = 4.1, P = 0.023), with Mettouh generally showing intermediate abundance.

Weekly abundance of maize insect pests in the three studied sites during 2025 is presented in Table **2**. Pest populations exhibited a clear seasonal pattern, increasing from week 18 and peaking between weeks 20 and 21, followed by a gradual decline to near-zero levels by week 28, with no captures recorded in weeks 29 and 30. In Zemamra, abundance varied significantly among weeks ($F_{12,182}$ = 473.1, P < 0.001), with the highest mean values observed in week 20 (357.3 [16.2%]) and week 21 (356.1 [16.1%]). Mettouh showed a similar trend ($F_{12,182}$ = 379.6, P < 0.001), peaking in week 20 (352.8 [16.8%]) and week 21 (351.9 [16.7%]). Oulad Saïd also exhibited significant temporal variation ($F_{12,182}$ = 373.5, P < 0.001), with maxima in week 21 (309.0 [16.7%]) and week 20 (308.5 [16.7%]). Comparisons among sites within each week revealed distinct patterns. During the early weeks (18 and 19), Zemamra and Mettouh had similar pest abundances, both significantly higher than Oulad Saïd (week 18: $F_{2,42}$ = 4.28, P = 0.020; week 19: $F_{2,42}$ = 6.46, P = 0.004). This trend continued through the peak weeks 20 to 22, where Zemamra and Mettouh maintained comparable high abundances, significantly exceeding those recorded in Oulad Saïd (week 20: $F_{2,42}$ = 6.0, P = 0.005; week 21: $F_{2,42}$ = 6.0, P = 0.005; week 22: $F_{2,42}$ = 8.3, P < 0.001). From week 23 onwards, site differences became more pronounced. In weeks 23 and 25, Zemamra and Mettouh showed similar abundances, both significantly higher than Oulad Saïd (week 23: $F_{2,42}$ = 11.9, P < 0.001; week 25: $F_{2,42}$ = 11.4, P < 0.001). Week 24 presented a clear gradient, with Zemamra recording the highest pest numbers, Mettouh intermediate, and Oulad Saïd the lowest ($F_{2,42}$ = 15.5, P < 0.001). A similar pattern persisted in week 26, where Zemamra and Mettouh again had comparable and significantly higher abundances than Settat ($F_{2,42}$ = 14.3, P < 0.001). In week 27, all three sites differed significantly from each other, with Zemamra showing the highest pest abundance, followed by Mettouh, and then Oulad Saïd ($F_{2,42}$ = 20.8, P < 0.001). Finally, in week 28, Zemamra and Mettouh had similar low abundances, both significantly higher than Oulad Saïd ($F_{2,42}$ = 7.0, P = 0.002). Overall,

Table 2: **Weekly abundance of maize insect pests in the three sampling sites (Zemamra, Mettouh, Oulad Saïd) during 2023–2025.**

Year	Week of the Year	Zemamra		Mettouh		Oulad Saïd	
		Total	Mean ± SE	Total	Mean ± SE	Total	Mean ± SE
2023	Week 18	2819	188.0±7.7 dA	3004	200.3±19.0 cdA	2689	179.3±5.8 deA
	Week 19	3577	238.5±8.9 cA	3773	251.6±22.7 bcA	3336	222.4±6.7 cA
	Week 20	5062	337.4±15.8 aA	5096	339.8±27.5 aA	4567	304.5±8.3 aA
	Week 21	5031	335.4±15.8 abA	5067	337.8±24.1 aA	4480	298.7±10.7 aA
	Week 22	4400	293.4±12.8 bA	4345	289.7±16.4 abA	3879	258.6±8.9 bA
	Week 23	3499	233.3±11.6 cA	3386	225.7±10.9 bcdAB	2954	196.9±7.2 cdB
	Week 24	2696	179.7±8.6 dA	2598	173.2±8.6 deAB	2280	152.0±5.3 eB
	Week 25	1815	121.0±6.7 eA	1736	115.7±5.4 efAB	1516	101.1±3.9 fB
	Week 26	1036	69.0±4.9 fA	1001	66.7±3.9 fgA	869	57.9±2.1 gA
	Week 27	432	28.8±2.1 fgA	413	27.5±1.8 gA	370	24.7±0.7 hA
	Week 28	42	2.8±0.3 gA	44	2.9±0.4 gA	33	2.2±0.1 hA
	Week 29	0	0.0±0.0 gA	0	0.0±0.0 gA	0	0.0±0.0 hA
	Week 30	0	0.0±0.0 gA	0	0.0±0.0 gA	0	0.0±0.0 hA
2024	Week 18	2971	198.1±8.2 dA	3016	201.1±18.1 cA	2767	184.5±6.1 dA
	Week 19	3718	247.9±11.4 cA	3748	249.9±23.8 bcA	3398	228.5±7.8 cA
	Week 20	5226	348.4±15.1 aA	5216	347.7±32.7 aA	4616	307.7±10.5 aA
	Week 21	5118	341.2±16.7 abA	5095	339.6±29.9 aA	4586	305.7±10.5 aA
	Week 22	4475	298.4±14.3 bA	4417	294.5±21.2 abA	3895	259.7±8.8 bA
	Week 23	3667	244.5±10.2 cA	3474	231.6±15.7 bcAB	3012	200.8±6.6 cdB
	Week 24	2793	186.2±8.5 dA	2702	180.1±13.2 cdA	2319	154.6±5.5 eA
	Week 25	1877	125.2±6.5 eA	1756	117.1±8.3 deA	1550	103.3±3.5 fA
	Week 26	1099	73.3±4.6 fA	1045	69.7±3.8 efAB	890	59.3±1.8 gB
	Week 27	500	33.4±2.5 fgA	448	29.8±1.7 fAB	383	25.5±0.8 hB
	Week 28	43	2.9±0.3 gA	43	2.8±0.1 fA	33	2.2±0.1 hB
	Week 29	0	0.0±0.0 gA	0	0.0±0.0 fA	0	0.0±0.0 hA
	Week 30	0	0.0±0.0 gA	0	0.0±0.0 fA	0	0.0±0.0 hA
2025	Week 18	3116	207.7±6.9 dA	3109	207.2±6.9 deA	2761	184.1±5.8 deB
	Week 19	3961	264.1±6.3 cA	3829	255.2±8.7 cA	3396	226.4±8.0 cB
	Week 20	5360	357.3±10.9 aA	5292	352.8±11.9 aA	4627	308.5±10.1 aB
	Week 21	5341	356.1±9.4 aA	5279	351.9±12.2 aA	4635	309.0±10.1 aB
	Week 22	4767	317.8±9.2 bA	4508	300.6±9.8 bA	3970	264.7±9.1 bB
	Week 23	3834	255.6±8.9 cA	3503	233.5±7.0 cdA	3043	202.9±6.9 cdB
	Week 24	3013	200.9±4.8 dA	2730	182.0±5.6 eB	2392	159.5±5.5 eC
	Week 25	1955	130.3±4.7 eA	1809	120.6±3.7 fA	1560	104.0±3.4 fB
	Week 26	1157	77.1±2.8 fA	1042	69.5±2.0 gA	899	59.9±2.0 gB
	Week 27	530	35.4±1.4 gA	448	29.9±0.8 hB	391	26.1±0.8 hC
	Week 28	49	3.2±0.3 hA	45.	3.0±0.1 hA	34	2.3±0.1 hB
	Week 29	0	0.0±0.0 hA	0	0.0±0.0 hA	0	0.0±0.0 hA
	Week 30	0	0.0±0.0 hA	0	0.0±0.0 hA	0	0.0±0.0 hA

Means in rows followed by the same capital letter are not significantly different (Tukey's test, $P < 0.05$). Means in columns followed by the same small letter are not significantly different (Tukey's test, $P < 0.05$).

temporal variation was highly significant within each site, characterized by distinct periods of peak (weeks 20–21), intermediate (weeks 18–19 and 22–25), and low pest abundance (weeks 26–28). Early-season pest levels were comparable across sites, while late-season persistence was consistently greater in Zemamra and Mettouh compared to Oulad Saïd.

3.3. Diversity and Richness Indices of Maize Insect Pests Across Sites and Years

A summary of the Shannon Diversity Index (H’), Margalef Richness Index (D), and Pielou’s Evenness Index (J) for maize insect pests across the three sampling sites during the three studied years is presented in Table **3**. Results showed consistent values among the sites over the years. Shannon diversity was similar in Zemamra, Mettouh, and Oulad Saïd, with mean values ranging from 1.4 to 1.6. Specifically, Zemamra had the highest diversity in 2023 (H’ = 1.6 ± 0.03), which slightly decreased to 1.4 in 2024 and 2025. Both Mettouh and Oulad Saïd maintained steady Shannon index values of approximately 1.4 throughout the study period. Margalef’s Richness Index was comparable across sites, with Zemamra showing a slightly higher richness in 2023 (D = 1.0) compared to 0.9 in 2024 and 2025. Mettouh and Oulad Saïd maintained values close to 0.9 consistently over the years. Pielou’s Evenness Index values were stable across sites and years, with all sites reporting around 0.8, indicating a relatively even distribution of maize insect pests within the communities. Analysis of variance (ANOVA) applied to these diversity indices and abundance parameters (Table **4**) revealed that the sampling site significantly affected pest abundance, while the year and interaction between year and site were not significant. Neither Shannon diversity nor Margalef Richness indices showed significant differences among years, sites, or their interaction. However, Pielou’s Evenness Index varied significantly across years, but was not significantly influenced by site or the year-site interaction.

Table 3: Shannon diversity index (H’), Margalef Richness Index, and Pielou’s Evenness Index (J) computed for maize insect pests in the three sampling sites among the three studied years.

Site	Shannon Diversity Index (Means ± SE)			Margalef Richness Index (Means ± SE)			Pielou’s Evenness Index (Means ± SE)		
	2023	2024	2025	2023	2024	2025	2023	2024	2025
Zemamra	1.6±0.03 Aa	1.4±0.04 Aa	1.4±0.0.04 Aa	1.0±0.02 Aa	0.9±0.03 Aa	0.9±0.03 Aa	0.8±0.01 Aa	0.8±0.01 Aa	0.8±0.01Aa
Mettouh	1.4±0.04 Aa	1.4±0.04 Aa	1.4±0.04 Aa	0.9±0.03 Aa	0.9±0.03Aa	0.9±0.03 Aa	0.8±0.01 Aa	0.8±0.01 Aa	0.8±0.01 Aa
Oulad Saïd	1.4±0.04 Aa	1.4±0.04 Aa	1.4±0.04 Aa	0.9±0.03 Aa	0.9±0.03 Aa	0.9±0.03 Aa	0.8±0.01 Aa	0.8±0.01Aa	0.8±0.01 Aa

Means in rows followed by the same capital letter are not significantly different (Tukey’s test, P < 0.05). Means in columns followed by the same small letter are not significantly different (Tukey’s test, P < 0.05).

Table 4: Analyses of variance (ANOVA) applied to the diversity indices parameters of maize insect pests in the three sampling sites among the three studied years.

Diversity Indices	Factors	df	F	P
Abundance	Year	2	0.2	0.791
	Site	2	9.4	9.0×10^{-5}
	Year*Site	4	0.2	0.932
Shannon index	Year	2	0.4	0.692
	Site	2	1.5	0.223
	Year*Site	4	1.5	0.190
Margalef Index	Year	2	1.8	0.167
	Site	2	0.4	0.687
	Year*Site	4	1.3	0.276
Pielou’s Evenness Index	Year	2	6.4	1.6×10^{-3}
	Site	2	0.8	0.470
	Year*Site	4	0.3	0.910

3.4. Correlation between Major Maize Insect Pests and Climatic Factors

Table **5** shows the correlation between major maize insect pests and climate factors from 2023 to 2025. Most pests (*S. nonagrioides*, *O. nubilalis*, *A. segetum*, *O. frit*, *A. lineatus*, and *D. virgifera virgifera*) had weak, non-significant correlations with temperature, humidity, and rainfall ($p > 0.05$). In contrast, aphids (*R. padi* and *S. avenae*) showed strong positive correlations with humidity ($r = 0.877$ and 0.851, $p < 0.01$) and rainfall ($r = 0.924$ and 0.958, $p < 0.001$), and negative but non-significant correlations with temperature ($r \approx -0.5$, $p > 0.1$). This indicates that aphid populations increase with humidity and rainfall, while other pests are less influenced by these climatic factors.

Table 5: The association of maize major insect pests species with temperature, humidity, and rainfall during maize growing seasons (2023-2025).

Insect Pests	Temperature		Humidity		Rainfall	
	r	P value	r	P value	r	P value
Sesamia nonagrioides	-0.250	0.521	-0.043	0.913	0.297	4.4×10^{-1}
Ostrinia nubilalis	-0.233	0.552	0.077	0.845	0.449	2.3×10^{-1}
Agrotis segetum	-0.233	0.552	-0.043	0.913	0.331	3.9×10^{-1}
Rhopalosiphum padi	-0.517	0.162	0.877	0.002	0.924	3.7×10^{-4}
Sitobion avenae	-0.567	0.121	0.851	0.004	0.958	4.9×10^{-5}
Oscinella frit	-0.217	0.581	-0.043	0.913	0.331	3.9×10^{-1}
Agriotes lineatus	-0.233	0.552	-0.043	0.913	0.305	4.3×10^{-1}
Diabrotica virgifera virgifera	-0.267	0.493	-0.043	0.913	0.280	4.7×10^{-1}

* Correlation is significant at the 0.05 level based on spearman's rank correlation coefficient (r).

4. Discussion

The present study provides a comprehensive assessment of maize insect pests across three Moroccan localities—Zemamra, Mettouh, and Oulad Saïd—over three consecutive years (2023–2025). Our findings reveal a relatively stable pest complex comprising eight major species, with *R. padi*, *S. avenae*, and *S. nonagrioides* consistently dominating pest populations. The seasonal dynamics, diversity patterns, and correlations with climatic factors observed align closely with findings from other maize-producing regions, including Pakistan, Ethiopia, and China [34, 35], thereby highlighting common ecological patterns and pest management challenges in maize agroecosystems globally. The dominance of *R. padi* and *S. avenae* aphids and the noctuid stem borer *S. nonagrioides* as primary pests confirms their significance as major threats to maize in Morocco. These results are consistent with previous studies in Punjab, Pakistan, where sucking pests such as maize aphids (*Rhopalosiphum maidis*) and leafhoppers (*Cicadulina mbila*) formed a substantial pest complex targeting vegetative stages of maize [14, 36]. The high representation of noctuid moths within pest complexes, notably *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae), *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae), and *Helicoverpa zea* Boddie (Lepidoptera: Noctuidae), reported in Pakistan [14], Ethiopia [34], and China [35], resonates with our findings of *S. nonagrioides* and *A. segetum* as key chewing pests. These species are known to inflict considerable yield losses by damaging maize stalks and ears [37, 38]. Although *S. frugiperda*, a major invasive pest in many maize-growing regions globally [39, 40], was not recorded in our Moroccan sites, the structural similarities of pest complexes underscore the broad threat posed by noctuid pests. The presence of *Spodoptera frugiperda* in Pakistan and many countries in West, Central, and Sub-Saharan Africa, with damage levels reaching up to 100% in fodder maize [41, 42], along with its migration from neighboring crops [43], highlights the importance of early detection and monitoring in other maize-growing regions, including Morocco. Our study's detection of intermediate abundances of *O. nubilalis*, *A. lineatus*, and *D. virgifera virgifera* aligns with their known pest status in other maize systems, though these species appeared less abundant than aphids and stem borers. The consistent low abundance of *O. frit* matches observations from previous works where this species plays a minor role in maize pest complexes [36].

A clear and significant, seasonal peak of pest abundance occurred between weeks 20 and 21 (mid to late May) each year across all sites, with pest populations rising sharply from week 18 and declining toward zero by week 29–30. This pattern is consistent with the findings of Khan *et al*. [14] and Murtaza *et al*. [44], who documented similar seasonal trends in Pakistan, where insect pest populations increase from mid-March, peaking in April and May, coinciding with maize vegetative growth stages. The rapid decline in pest numbers after the peak weeks likely corresponds to maize crop phenology, particularly the progression from vegetative to reproductive stages and eventual senescence, which reduces host availability and suitability [45]. Comparable temporal dynamics have also been reported in Ethiopian maize fields, indicating that climatic and phenological factors exert strong control over pest population fluctuations across diverse agroecological zones [34, 46].

Importantly, the similarity in pest composition and the consistently high prevalence of the eight maize insect pests across the three sites, despite climatic variation among them, can be explained by several interacting ecological and agronomic factors. Maize is cultivated under similar cropping calendars and agronomic practices in each place, resulting in synchronized crop phenology and continuous host availability across all sites. In addition, most of the recorded pest species are highly polyphagous and exhibit broad ecological tolerance, allowing them to persist under different environmental conditions in each locality. Moreover, the high mobility of key insect pests, particularly noctuid moths and aphids, facilitates regional dispersal and contributes to homogenization of pest communities among sites. These combined factors likely outweigh local climatic differences, resulting in similar pest assemblages and consistently high abundance levels in each place studied. Significantly higher late-season pest abundance in Zemamra and Mettouh compared to Oulad Saïd suggests microclimatic or agronomic differences among sites that may influence pest survival and recolonization. Soil composition, vegetation structure, and land management practices likely contribute to these spatial variations, as proposed by Duan *et al*. [47].

The stable Shannon Diversity Index (H'), Margalef Richness (D), and Pielou Evenness (J) values across years and sites indicate a relatively temporally stable pest community with balanced species distributions. This is indicative of a mature agroecosystem where pest assemblages maintain ecological equilibrium despite seasonal and environmental fluctuations [48]. However, this temporal stability should not be interpreted as ecological resilience, but rather as consistency in community structure over the study period. The minor variation in Pielou's Evenness Index across years suggests subtle changes in species dominance that could reflect localized environmental or agronomic influences [49]. In addition, the Shannon diversity values (approximately 1.4–1.6) indicate a moderate level of diversity rather than high diversity, suggesting that the pest community is dominated by a few key species. Incomplete species accumulation curves reported in other studies [50, 51] suggest that despite comprehensive sampling, some pest species with sporadic or cryptic activity may have been missed. Therefore, future studies employing additional trapping methods and extended sampling durations could improve pest inventories [52].

The correlation analysis between major maize insect pests and key climatic variables—temperature, humidity, and rainfall—across the three-year period (2023–2025) reveals important insights into how environmental conditions influence pest populations during maize growing seasons. For most chewing pests including *S. nonagrioides*, *O. nubilalis*, *A. segetum*, *O. frit*, *A. lineatus*, and *D. virgifera virgifera*, the Spearman correlation coefficients with temperature, humidity, and rainfall were weak and statistically non-significant. These results suggest that the abundance and activity of these chewing pests are relatively stable across typical seasonal temperature and moisture fluctuations, possibly due to their physiological adaptations and life stages protected from immediate climatic effects [37, 53]. For instance, the larval stages of *S. nonagrioides* and *D. virgifera virgifera* develop inside maize stems and soil respectively, which buffer against external weather variability [36].

In sharp contrast, the two aphid species, *R. padi* and *S. avenae*, exhibited strong positive and statistically significant correlations with humidity and rainfall. These high correlation coefficients indicate that aphid populations increase markedly with elevated moisture levels, consistent with their biology as soft-bodied insects vulnerable to desiccation [44, 54]. Rainfall likely enhances host plant sap quality and promotes microclimatic conditions conducive to rapid aphid reproduction and survival. This finding aligns with other studies where aphid outbreaks coincide with rainy and humid periods during early vegetative stages of maize [14, 36]. No statistically significant correlation was detected between temperature and aphid abundance, indicating that temperature was not a primary driver of aphid population variation within the observed range. These contrasting patterns between aphids and chewing pests highlight distinct ecological niches and environmental sensitivities. While aphid populations are tightly linked to moisture availability and thus to rainfall and humidity regimes, chewing pests' populations appear more influenced by other factors such as host plant phenology, soil conditions, and biotic interactions rather than direct climatic parameters measured at the macro scale [38, 45].

From a pest management perspective, these findings emphasize the importance of incorporating climatic monitoring—particularly rainfall and humidity forecasts—into early warning systems for aphid outbreaks. Anticipating aphid population surges based on rainfall patterns could allow for timely deployment of control measures, potentially reducing crop damage and reliance on broad-spectrum insecticides [44, 48]. Conversely, management of chewing pests may require an emphasis on crop phenology-based interventions and habitat management to disrupt pest lifecycles, as direct climatic predictors appear less informative for their population dynamics [37, 53]. The consistent dominance and seasonal synchrony of key pests across sites suggest that regionally harmonized IPM programs can be developed focusing on aphids and stem borers, incorporating climatic monitoring to predict aphid outbreaks and optimize control timings. Given the aphids' sensitivity to moisture, forecasting tools integrating rainfall and humidity data could improve early warning systems [48]. For chewing pests, cultural controls, resistant varieties, and biological control may offer sustainable options, especially considering their relative independence from short-term climatic fluctuations [37, 38]. The documented presence of multiple pests at varying abundances further supports an integrated approach addressing the complex pest assemblage rather than single species control.

While the study captured a broad spectrum of pest species and temporal dynamics, some rare or cryptic pests may have escaped detection due to methodological constraints and limited sampling periods, as suggested by species accumulation analyses [50, 51]. Expanding sampling techniques (e.g., pheromone traps, night sampling) and extending monitoring across multiple cropping seasons would enhance completeness and robustness of pest community assessments [52]. Moreover, correlations with climatic factors, although suggestive, are correlative; experimental studies are required to elucidate causal relationships and to understand the mechanistic bases of pest responses to environmental variables [47]. Inclusion of natural enemy dynamics, pesticide usage, and landscape context in future investigations will help elucidate complex ecological interactions shaping pest populations, thereby informing more effective and ecologically sound pest management strategies [48].

5. Conclusion

This three-year study (2023–2025) in Zemamra, Mettouh, and Oulad Saïd revealed a stable maize pest complex dominated by *Rhopalosiphum padi*, *Sitobion avenae*, and *Sesamia nonagrioides*, with *Oscinella frit* consistently least abundant. Pest populations exhibited a clear seasonal peak in weeks 20–21, coinciding with early vegetative growth stages, and declined sharply thereafter. Diversity indices showed relatively similar values across sites and years, suggesting limited variation in pest community structure under the studied conditions. Aphid abundance was strongly and positively correlated with humidity and rainfall, while chewing pests showed no significant relationships with the climatic variables measured. These findings highlight the potential of integrating climatic monitoring—especially humidity and rainfall forecasts—into early warning systems for aphids, alongside phenology-based and habitat management strategies for chewing pests. These interpretations are limited to observed patterns in the present dataset and do not imply long-term ecological stability or resilience of the pest community. Regionally harmonized integrated pest management programs targeting both dominant pest groups are recommended to improve maize protection.

Conflict of Interest

There authors declare no conflict of interest.

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Author Contributions

Mohamed El Aalaoui: Conceptualization; data curation; formal analysis; investigation; methodology; validation; visualization; writing – original draft; writing – review and editing. Mohamed Sbaghi: Conceptualization; visualization; writing – review and editing.

Availability of Data and Materials

Original data for the manuscript can be obtained from the corresponding author upon reasonable request.

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