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Spatiotemporal Dynamics of Cotton Bollworms and Associated Yield Losses in Côte d'Ivoire

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Abstract

Cotton is integral to the rural economy of Côte d'Ivoire, yet yield stability is increasingly threatened by shifting pest complexes. Following the recent incursion of the leafhopper *Amrasca biguttula biguttula* (Ishida), cotton protection strategies were reoriented toward sap-feeding pests, and renewed infestations of boll-feeding Lepidoptera were reported. This study assessed the spatiotemporal dynamics (2021-2024) of the main cotton bollworms across production areas and sowing periods and quantified their associated boll damage and yield losses. *Helicoverpa armigera* (Hübner) remained the most prevalent exocarpic Lepidoptera, followed by *Earias* spp. and *Diparopsis watersi* (Rothschild). Infestations of *H. armigera* were more severe in late sowing periods, and this species occurred throughout the cotton-growing region. In contrast, *Earias* spp. and *D. watersi* larvae were more abundant in the northeastern production area. Among endocarpic bollworms, *Pectinophora gossypiella* (Saunders) was more prevalent than *Thaumatotibia leucotreta* (Meyrick). A significant negative correlation ($r = -0.45$; $p = 0.001$) was observed between bollworm damage and seed cotton yield, underscoring the economic importance of these pests. Overall, the results highlight the need to tailor surveillance intensity and protection strategies to the prevailing species, production area characteristics, and sowing period to mitigate yield losses.

Keywords

Cotton, Bollworms, Spatiotemporal Dynamics, Boll Damage, Yield Loss

1. Introduction

In Côte d'Ivoire, cotton is a pivotal component of the rural economy, providing cash income to more than 106,000 farming households and supporting national ginning and textile value chains. Cotton is cultivated from the central region to the northern borders, covering more than 392,000 ha [1]. However, sustaining cotton productivity is increasingly challenged by soil fertility decline [2] and by climate variability and change [3]. These constraints can also modify pest phenology, survival and dispersal, leading to spatially heterogeneous and seasonally shifting pest pressure that complicates evidence-based crop-protection decisions.

Cotton productivity and fibre quality are strongly affected by arthropod pests, including sap-feeding insects (notably aphids, whiteflies and leafhoppers) and boll-feeding Lepidoptera. Bollworms are considered among the most damaging pests because they attack flower buds and bolls directly, thereby converting pest pressure into immediate yield loss and reduced marketable quality. In West Africa, the principal bollworms include *Helicoverpa armigera*, *Diparopsis watersi*, *Earias* spp., *Pectinophora gossypiella* and *Thaumatotibia leucotreta*, which are consistently associated with economic losses when outbreaks occur [4] [5]. Their relative importance can vary across production areas and sowing windows, making local, season-specific information essential for targeting scouting and protection efforts.

During the 2022-2023 cotton season, the invasive leafhopper *Amrasca biguttula biguttula* [6] [7] was reported on cotton in Côte d'Ivoire and was associated with production losses exceeding 50% [8]. This incursion altered the operational priorities of cotton protection, which had previously focused largely on bollworms (especially *H. armigera*), by shifting attention toward sap-feeding pests. In the 2023-2024 season, intensified use of leafhopper-targeted insecticides coincided with reduced control pressure on Lepidoptera larvae and was followed by renewed bollworm infestations [9]. Such shifts in pest complexes are of particular concern under changing climatic conditions because they may expand the spatial extent of outbreaks, affect their timing across sowing periods, and undermine the effectiveness of calendar-based spray programs.

In this context, updated evidence is needed on (i) which bollworm species dominate across cotton-producing areas and sowing periods, and (ii) how their larval pressure translates into boll damage and yield loss under current protection practices. Here, "spatiotemporal dynamics" refers to variation among years (2021-2024), among production areas, and among sowing periods within the cotton-growing region. Therefore, this study assessed the spatiotemporal dynamics and damage of the major bollworms of cotton in Côte d'Ivoire (*D. watersi*, *H. armigera*, *Earias* spp., *P. gossypiella* and *T. leucotreta*) during four consecutive seasons (2021-2024) in the context of the invasion of the leafhopper *A. biguttula biguttula*. Specifically, we aimed to: (1) Quantify annual and spatial variation in larval abundance; (2) Evaluate the effect of production area and sowing period on pest densities; (3) Determine relationships between larval pressure, boll damage and seed cotton yield.

The study area, sampling strategy, and analytical approaches used to address these objectives are described below.

2. Materials and Methods

2.1. Study Area

This research was conducted in 50 localities from the cotton-producing region of Côte d'Ivoire, which extends from the central to the northern part of the country between latitudes 7˚5 to 12˚N and longitudes 3˚ to 8.5˚W (**Figure 1**). This region spans both sides of the 9th parallel. The area north of the 9th parallel is characterized by a Sudanian climate featuring an extended dry season from October of one year to May of the subsequent year. Conversely, the southern area situated below the 9th parallel experiences greater precipitation and is characterized by a sub-Sudanian climate with two distinct rainy and dry seasons. The rainy season occurs from March to July and from October to November, whereas the dry season occurs from August to September and from December to February. The annual rainfall in this region varies between 1300 and 1700 mm [10]. Fifty localities were selected from the entire cotton-growing region.

2.2. Plot Selection for Survey

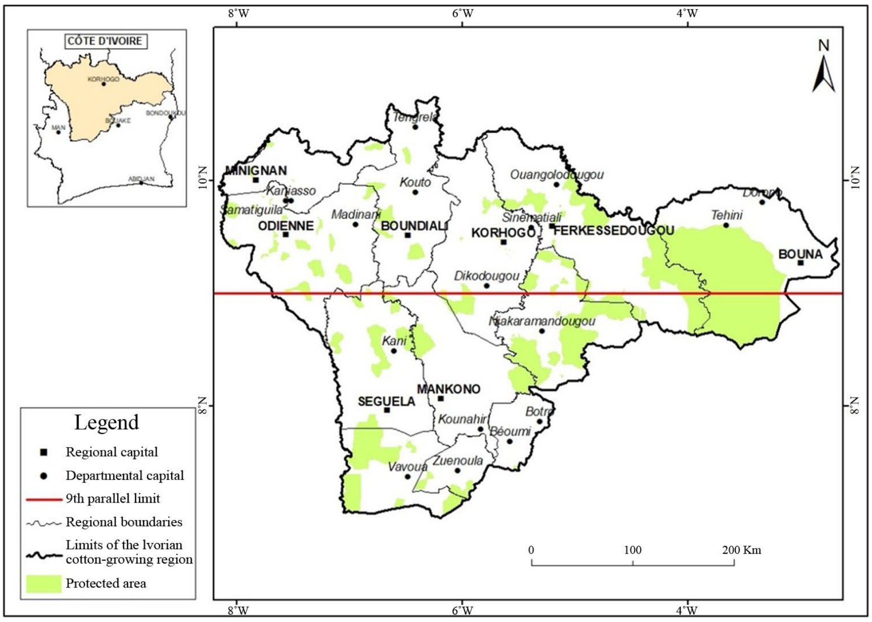
Surveys were conducted during four consecutive cotton-growing seasons (2021-2024). For each season, field observations were carried out from July to November, covering the main vegetative and reproductive stages of the crop. Each year, 50 localities were monitored across the cotton-producing region of Côte d'Ivoire (*i.e.*, the same 50 localities were followed over the four years). In each locality, 10 farmers' cotton fields were selected (500 fields per year). When a selected farmer did not cultivate cotton each year, a replacement field was selected within the same locality and within a radius of ≤1 km to maintain spatial comparability.

Within each locality, the 10 selected fields were distributed to capture local variability while remaining feasible for weekly monitoring. Two criteria guided selection: (i) spatial coverage within the locality (North-South and East-West directions), and (ii) sowing period. To limit spatial autocorrelation, sampled fields within a locality were separated by at least 300 m whenever possible (and never less than 100 m), as determined by road distance or GPS tracks during field visits. Sowing dates were recorded for all selected farmers, grouped into 10-day intervals (decades), and fields were then sampled across these sowing decades proportionally to the number of farmers who sowed within each decade, followed by a random draw within each decade.

To ensure valid comparisons among years, the same monitoring protocol was applied in each season (2021-2024). The same 50 localities were followed annually, with the same target sampling intensity (10 fields per locality per year). In every field, observations were conducted within a standardized 0.25 ha central area using identical plant- and boll-inspection procedures, the same observation frequency (weekly plant inspections and five boll dissections per field), and the same observation window (approximately 30 - 122 days after sowing). All monitored fields were managed under the standard national cotton protection program (six insecticide sprays at 14 day intervals), thereby reducing inter-annual variability due to differences in control practices.

In each selected field, a 0.25 ha usable area was delimited at the plot centre to reduce edge effects and standardize observations across visits and years. The cotton variety cultivated in monitored fields was Gouassou Fus [11]. The crop was protected according to the standard national program recommended to farmers in Côte d'Ivoire, consisting of six insecticide applications at 14 day intervals from approximately 45 to 115 days after emergence.

In addition to pest and damage observations, the following variables were recorded for each field and visit: locality name, field identity (farmer/plot), sowing date (used to classify sowing period), and sampling date (expressed as days after sowing). This survey did not directly measure climatic variables (e.g., temperature, rainfall, humidity) at the field level, nor did it quantify cotton acreage by region. Therefore, statements regarding climatic drivers or regional changes in planted areas are treated as contextual interpretation and are supported by published sources where cited rather than inferred from the present dataset.



Source: Base map data from: National Bureau of Technical Studies and Development (BNETD). 2014.Updated using ArcGIS 10.6.

Figure 1. Study area.

2.3. Sampling and Observations

2.3.1. Counting of Bollworms on Cotton Plants

Weekly direct observations were conducted from 30 to 122 days after sowing. At each visit, 30 cotton plants were inspected within the 0.25 ha observation area. Plants were selected as six groups of five consecutive plants along a diagonal transect of the field [12], as shown in **Figure 2**, to ensure representativeness. The position of the diagonal was changed each week to improve field coverage across the season.

Each plant was meticulously examined to count *D. watersi*, *H. armigera*, and *Earias* spp. larvae. These species are classified as exocarpic because the larvae inhabit and develop external bolls on the cotton plant.

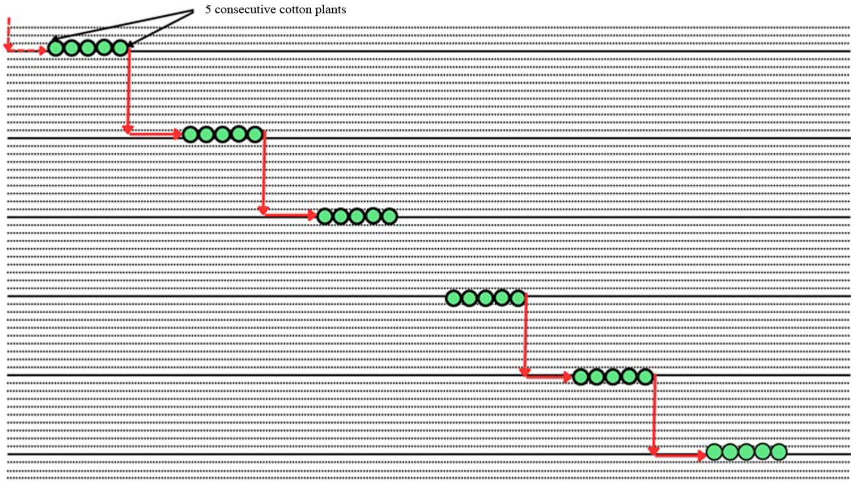


Figure 2. Method for selecting six groups of five plants along the diagonal.

2.3.2. Sanitary Analysis of Green Bolls

The larvae of *P. gossypiella* and *T. leucotreta* develop within bolls and are thus categorized as endocarpic. Consequently, a sanitary analysis of bolls is imperative for their detection. Starting on the 80th to 108th day after sowing, five health evaluations were conducted weekly. During each evaluation, 50 green bolls were randomly collected within the 0.25 ha plot, with a maximum of one boll per plant. However, the cotton plants in the four central rows were spared as they were reserved for yield estimation. These bolls, which were approximately the same age, were sampled from the middle of the plant and close to the main stem. After collecting, the bolls were examined and categorized into several classifications: healthy, perforated bolls, and bolls that appeared healthy but had internal damage.

During the sanitary analysis, larvae of *P. gossypiella* and *T. leucotreta* found inside bolls were counted.

2.3.3. Harvest and Estimation of Cotton Yield

Harvesting was performed in the four central rows of each plot when bolls were fully open. Seed cotton was weighed after harvest, and yield was expressed in kilograms per hectare.

2.4. Data Analysis

Analyses were performed to assess temporal (year) and spatial (locality/production area) variability in bollworm abundance, and to quantify relationships between pest pressure, boll damage and seed cotton yield.

Because larval counts are discrete and repeatedly collected, larval abundance data were analysed using generalized linear mixed models (GLMMs), with a Poisson or negative binomial distribution depending on dispersion. To account for the hierarchical sampling design and repeated measurements, the random effects Locality and Field were included in the models to evaluate their influence on pest dynamics. A linear regression analysis was performed between the percentage of damaged bolls and seed cotton yield to identify the relationships between these two variables.

Statistical analyses were carried out using GenStat (10th edition), and distribution maps were produced using ArcGIS 10.6.

3. Results

3.1. Average Abundances of Cotton Bollworms

Overall mean densities of the five bollworm taxa recorded during 2021-2024 are summarized in Table 1. For exocarpic larvae, the mean numbers (±SD) per 30 plants were 0.038 ± 0.011 for *D. watersi*, 0.14 ± 0.061 for *H. armigera*, and 0.06 ± 0.012 for *Earias* spp. For endocarpic larvae, mean densities per 100 green bolls were 0.014 ± 0.003 for *P. gossypiella* and 0.001 ± 0.00 for *T. leucotreta*.

Table 1. Average densities of bollworms on plants and in cotton bolls.

Groups	Species	Minimum	Maximum	Average	Standard Deviation
Exocarpic Lepidopteran Larvae	*Diparopsis watersi* (mean/30 plants)	0.000	1.000	0.038	0.011
	Helicoverpa armigera (mean/30 plants)	0.000	2.923	0.143	0.061
	Earias spp (mean/30 plants)	0.000	0.909	0.064	0.012
Endocarpic Lepidopteran Larvae	*Pectinophora gossypiella* (mean/100 green bolls)	0.000	0.667	0.014	0.003
	Thaumatotibia leucotreta (mean/100 green bolls)	0.000	0.429	0.001	0.000

3.2. Annual Variations in the Abundance of Cotton Bollworms

3.2.1. Variation of Exocarpic Bollworms

Annual mean densities of exocarpic bollworms differed significantly for all three taxa (Table 2). For *D. watersi*, mean density increased from 0.03 ± 0.00 larvae per 30 plants in 2021 to a maximum of 0.07 ± 0.01 in 2024. For *H. armigera*, density decreased in 2022 (0.06 ± 0.03) relative to 2021 (0.11 ± 0.04), peaked in 2023 (0.22 ± 0.09), and then declined in 2024 (0.13 ± 0.05). For *Earias* spp., density was lowest in 2022 (0.05 ± 0.01) and was higher in 2021 and 2024 (0.07 ± 0.02 and 0.07 ± 0.01, respectively), with intermediate values in 2023 (0.06 ± 0.00).

Table 2. Trends in the average densities of bollworms on cotton plants and within green bolls from 2021 to 2024.

Years	**Exocarpic Lepidopteran Larvae** (mean/30 cotton plants)			**Endocarpic Lepidopteran Larvae** (mean/100 green bolls)	
	D. watersi	*H. armigera*	*Earias* spp	*P. gossypiella*	*T. leucotreta*
2021	0.03 ± 0.00 a	0.11 ± 0.04 b	0.07 ± 0.02 b	0.006 ± 0.00 a	0.000 ± 0.00
2022	0.04 ± 0.01 ab	0.06 ± 0.03 a	0.05 ± 0.01 a	0.009 ± 0.00 a	0.002 ± 0.00
2023	0.03 ± 0.01 a	0.22 ± 0.09 c	0.06 ± 0.00 b	0.02 ± 0.01 b	0.002 ± 0.00
2024	0.07 ± 0.01 b	0.13 ± 0.05 b	0.07 ± 0.01 b	0.01 ± 0.00 ab	0.000 ± 0.00
F	3.97	31.14	3.38	5.75	0.14
p	0.008	<0.001	0.018	<0.001	0.332

3.2.2. Variation of Endocarpic Bollworms

For *P. gossypiella*, mean density varied among years, with the highest value observed in 2023 (0.02 larvae per 100 bolls) and the lowest values in 2021 and 2022 (0.006 and 0.009 larvae per 100 bolls, respectively). Overall, densities showed an increasing tendency from 2021 to 2024. In contrast, *T. leucotreta* was consistently rare, with mean densities close to zero in all years and no significant inter-annual variation.

3.3. Impact of the Production Area on the Larval Densities of Cotton Bollworms

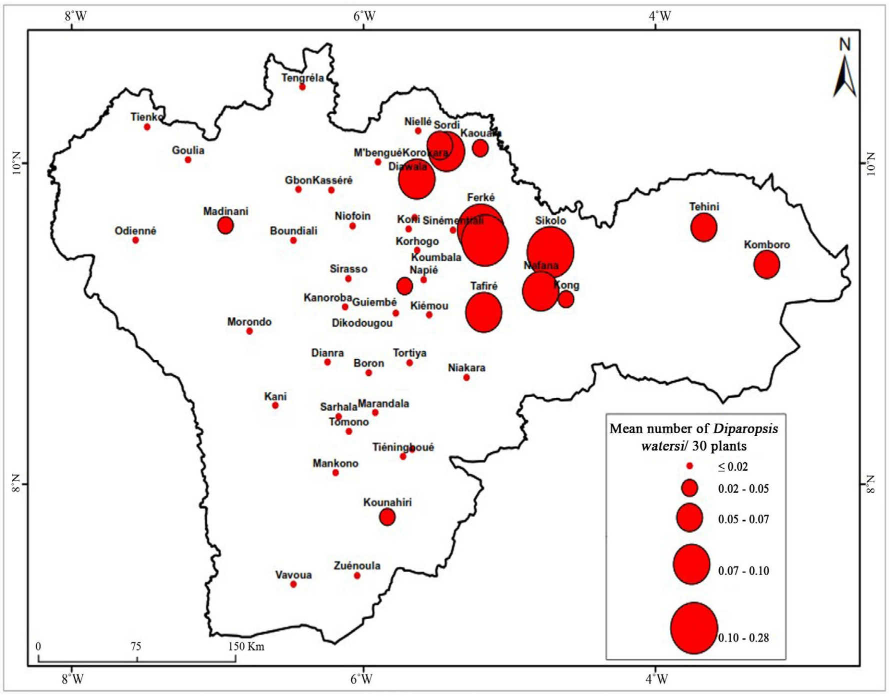
3.3.1. Impact of the Production Area on Exocarpic Bollworms

Figure 3 shows notable variations in the distribution of *D. watersi* across different locations. The highest larval densities were recorded in the northeast, specifically in Ferké (0.46 larvae per 30 plants), Koumba (0.22 larvae per 30 plants), and Sikolo (0.20 larvae per 30 plants). Conversely, densities approaching 0 larvae per 30 plants were observed in Bouandougou, Boundiali, Boron, Niofoin, Odiéné, Sarhala, Sinématiali, Tienko, Tomono, Vavoua and Zuénoula. The comprehensive analysis presented in **Table 3** indicates that this species predominantly inhabits northern cotton-growing areas.

Figure 4 illustrates the distribution of *H. armigera* across production areas. This species occurred in all production areas, with the highest mean density recorded in Sordi (0.81 larvae per 30 plants), followed by Napié (0.47 larvae per 30 plants) and Diawala (0.41 larvae per 30 plants). In contrast, lower densities were observed in localities such as Boundiali, Ouéllé, Goulia and Gbon, with means close to 0.00 larvae per 30 plants. The comparative analysis in **Table 3** indicates a significant difference between the northern and southern parts of the cotton-growing region, with higher densities in the north (0.16 larvae per 30 plants) than in the south (0.10 larvae per 30 plants).

Significant spatial variation in *Earias* spp. densities was observed (**Figure 5**), with the highest mean densities in the northeastern region. The largest mean density was recorded in Diawala (0.45 larvae per 30 plants), followed by Ferké and Sikolo (0.24 larvae per 30 plants each). Conversely, very low densities (approximately 0.00 larvae per 30 plants) were recorded in Boundiali, Bouandougou and

Sinématiali. The analysis in **Table 3** confirms that mean densities of *Earias* spp. were higher in the northern region than in the southern region.



Source: **Figures 3-7** are all sourced from field survey data (primary data).

Figure 3. Spatial variation in the mean density of *Diparopsis watersi* larvae within cotton-growing areas of Côte d'Ivoire based on surveys from 2021 to 2024.

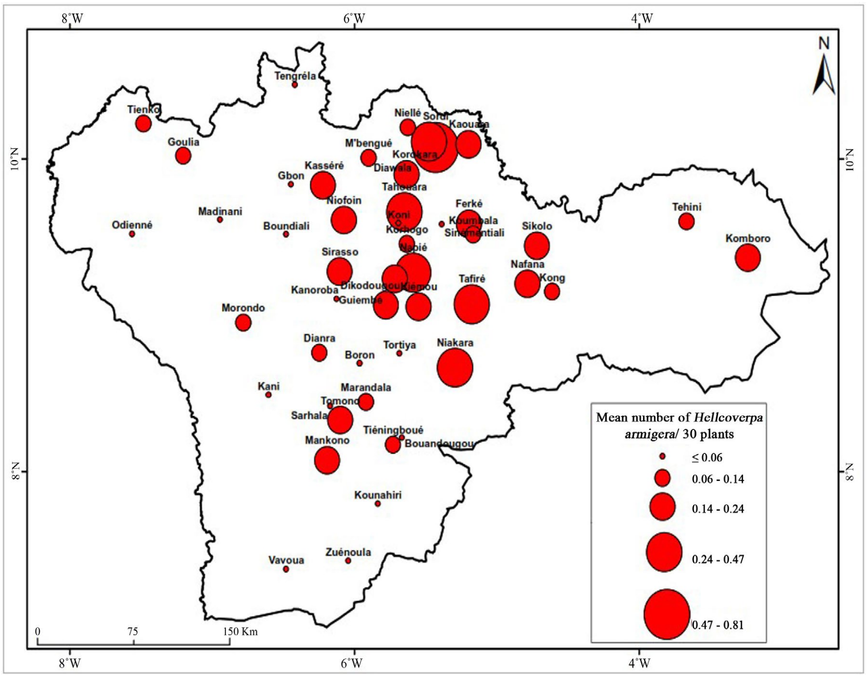


Figure 4. Spatial variation in the mean density of *Helicoverpa armigera* larvae within cotton-growing areas of Côte d'Ivoire based on surveys from 2021 to 2024.

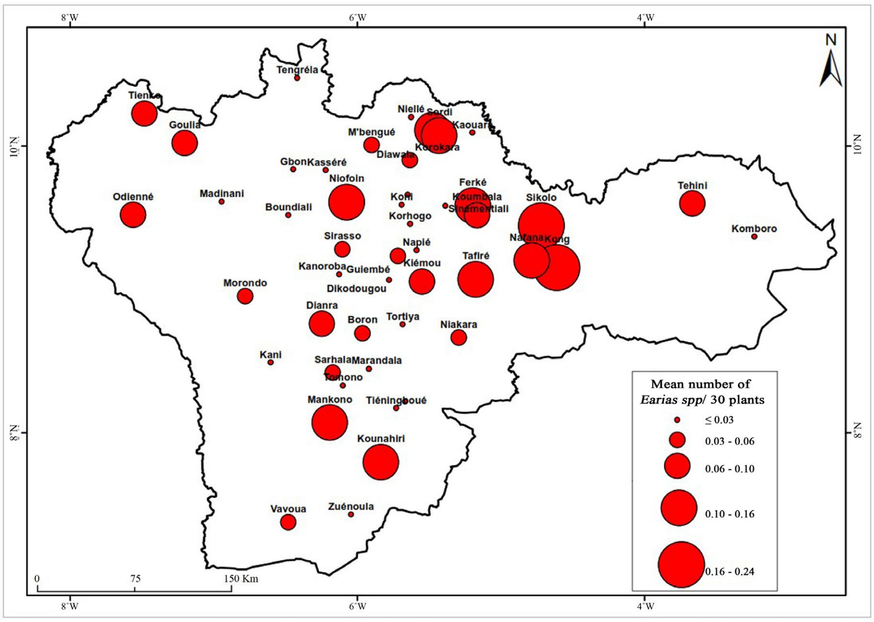


Figure 5. Spatial variation in the mean density of *Earias* spp. larvae within cotton-growing areas of Côte d'Ivoire based on surveys from 2021 to 2024.

3.3.2. Impact of the Production Area on Endocarpic Bollworms

Figure 6 illustrates the notable variation in larval densities of *P. gossypiella* across different localities. This species is predominantly observed in southern regions, specifically in the localities of Zuénoula (0.22 larvae/100 bolls), Kounahiri (0.21 larvae/100 bolls). Vavoua (0.14 larvae/100 bolls) and Koumbala (0.06 larvae/100 bolls). The analytical results presented in **Table 3** suggest a higher abundance of these species in the southern cotton-growing basin.

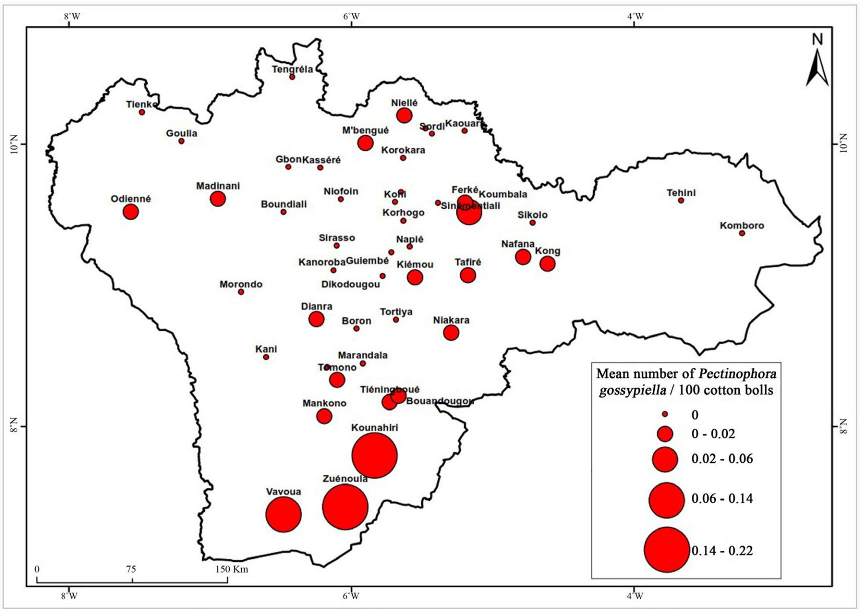


Figure 6. Spatial variation in the mean density of *Pectinophora gossypiella* larvae within the cotton cultivation areas of Côte d'Ivoire based on a survey from 2021 to 2024.

Figure 7 depicts the overall low density of *T. leucotreta*. The highest densities were recorded in Boundiali (0.05 larvae/100 bolls) and Mankono (0.02 larvae/100 bolls). This species did not exhibit a distinct distribution pattern between the northern and southern regions (**Table 3**).

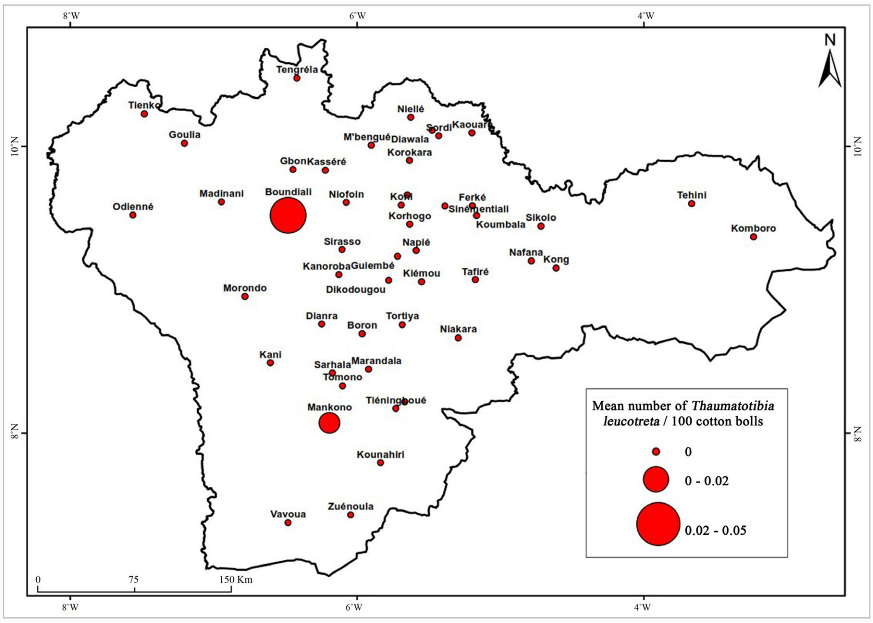


Figure 7. Spatial variation in the mean density of *Thaumatotibia leucotreta* larvae within cotton-growing areas of Côte d'Ivoire based on surveys from 2021 to 2024.

Table 3. Comparison of bollworm densities between the northern and southern production areas of the cotton-growing region.

Production area	Exocarpic Lepidopteran larvae (mean/30 cotton plants)			Endocarpic Lepidopteran larvae (mean/100 green bolls)	
	D. watersi	*H. armigera*	*Earias* spp	*P. gossypiella*	*T. leucotreta*
North	0.06 ± 0.01	0.16 ± 0.07	0.07 ± 0.01	0.01 ± 0.00	0.00 ± 0.00
South	0.00 ± 0.00	0.10 ± 0.03	0.05 ± 0.01	0.03 ± 0.01	0.01 ± 0.00
t	8.51	4.35	2.64	7.55	0.75
p	<0.001	<0.001	0.008	<0.001	0.454

3.4. Influence of the Sowing Period on the Density of Cotton Bollworms

Table 4 summarizes bollworm (fruit-feeding Lepidoptera) densities according to sowing period.

No statistically significant differences were detected in the average densities of *Diparopsis watersi*, *Earias* spp., *P. gossypiella*, and *T. leucotreta* across the various sowing periods. In contrast, a significant variation in the density of *H. armigera* was observed depending on the sowing period. The highest density (0.18 larvae per 30 plants) was recorded during the D4 sowing period (June 21 to 30), whereas the lowest density was noted during the D1 sowing period (May 20 to 31). Overall, there was an observable trend indicating a progressive increase in *H. armigera* density from the early to the late sowing periods.

Table 4. Variation in the densities of bollworms in relation to the timing of cotton sowing in Côte d'Ivoire.

Sowing period	Exocarpic Lepidopteran larvae (mean/30 cotton plants)			Endocarpic Lepidopteran larvae (mean/100 green bolls)	
	D. watersi	*H. armigera*	*Earias* spp	*P. gossypiella*	*T. leucotreta*
D1 (20 - 31 May)	0.01 ± 0.00	0.06 ± 0.01 a	0.09 ± 0.02	0.00 ± 0.00	0.000 ± 0.00
D2 (01 - 10 June)	0.03 ± 0.01	0.11 ± 0.03 a	0.07 ± 0.01	0.02 ± 0.00	0.003 ± 0.00
D3 (11 - 20 June)	0.04 ± 0.01	0.13 ± 0.04 ab	0.06 ± 0.01	0.01 ± 0.00	0.001 ± 0.00
D4 (21 - 30 June)	0.05 ± 0.01	0.18 ± 0.11 b	0.07 ± 0.01	0.01 ± 0.00	0.001 ± 0.00
D5 (01 - 10 July)	0.04 ± 0.02	0.13 ± 0.07 ab	0.07 ± 0.02	0.02 ± 0.00	0.002 ± 0.00
D6 (11 - 20 July)	0.04 ± 0.01	0.11 ± 0.03 a	0.03 ± 0.00	0.03 ± 0.01	0.000 ± 0.00
F	1.22	3.59	0.83	0.84	0.73
p	0.299	0.003	0.529	0.524	0.598

3.5. Influence of Bollworms on the Sanitary Condition of Green Bolls and Cotton Yield

3.5.1. Influence on the Rate of Perforated Bolls

Table 5 presents the multiple regression model relating the mean number of perforated bolls to larval densities. The model was significant ($p < 0.001$) and indicated that Lepidopteran larvae explained approximately 10.5% of the variation in boll perforation ($R^2 = 0.105$). Significant predictors were *D. watersi*, *H. armigera*, *Earias* spp. and *P. gossypiella*. All regression coefficients (β) were positive, indicating increased boll perforation with increasing larval density. Standardized coefficients suggested that *D. watersi* had the strongest association with boll perforation, followed by *P. gossypiella* and *H. armigera*.

3.5.2. Influence on the Rate of Internal Damage in Cotton Bolls

Table 6 presents the regression analysis of internally damaged bolls in relation to larval densities. The model was significant ($p < 0.001$) and indicated that approximately 3% of the variation in internal boll damage was explained by bollworm larval densities ($R^2 = 0.03$). Coefficients (β) were positive for *P. gossypiella* and *T. leucotreta*, indicating higher internal damage with increasing densities of these endocarpic larvae. In contrast, coefficients were negative for *D. watersi*, *H. armigera* and *Earias* spp., consistent with their primarily external feeding on bolls. Standardized coefficients suggested that *D. watersi*, *P. gossypiella*, and *T. leucotreta* contributed most to the model.

Figure 8 illustrates a significant negative correlation ($r = -0.45$) between seed cotton yield and the percentage of damaged green bolls. Approximately 20% of yield losses are related to damage caused by bollworms ($R^2 = 0.20$).

Table 5. Regression coefficients of the rate of perforated bolls as a function of bollworm densities ($F = 29.62$, $p < 0.001$).

Variables	β	SE	t	Pr > |t|	IC (95%)	β std
Intercept	0.82	0.069	11.791	<0.0001	[0.68; 0.95]	
Diparopsis watersi (mean/30 plants)	4.10	0.545	7.508	<0.0001	[3.03; 5.17]	0.21
Helicoverpa armigera (mean/30 plants)	0.90	0.225	4.002	<0.0001	[0.46; 1.34]	0.11
Earias spp (mean/30 plants)	1.32	0.528	2.505	0.012	[0.29; 2.36]	0.07
Pectinophora gossypiella (mean/100 green bolls)	5.40	0.942	5.724	<0.0001	[3.546; 7.24]	0.15
Pectinophora gossypiella (mean/100 green bolls)	0.80	3.210	0.248	0.805	[−5.50; 7.09]	0.01

$R^2 = 0.105$; SE: standard error; 95% CI: confidence interval; β std: standardized coefficients.

Table 6. Regression coefficients for the rate of bolls with internal damage as a function of bollworm densities ($F = 9.94$, $p < 0.001$).

Variables	β	SE	t	Pr > |t|	IC (95%)	β std
Intercept	7.001	0.270	25.893	<0.0001	[6.47; 7.53]	
Diparopsis watersi (mean/30 plants)	−7.540	2.133	−3.535	0.000	[−11.73; −3.36]	−0.10
Helicoverpa armigera (mean/30 plants)	−1.843	0.878	−2.099	0.036	[−3.57; −0.12]	−0.06
Earias spp (mean/30 plants)	−3.849	2.066	−1.863	0.063	[−7.90; 0.21]	−0.05
Pectinophora gossypiella (mean/100 green bolls)	12.066	3.686	3.273	0.001	[4.83; 19.30]	0.09
Pectinophora gossypiella (mean/100 green bolls)	37.836	12.554	3.014	0.003	[13.21; 62.47]	0.08

$R^2 = 0.03$; SE: standard error; 95% CI: confidence interval; β std: standardized coefficients.

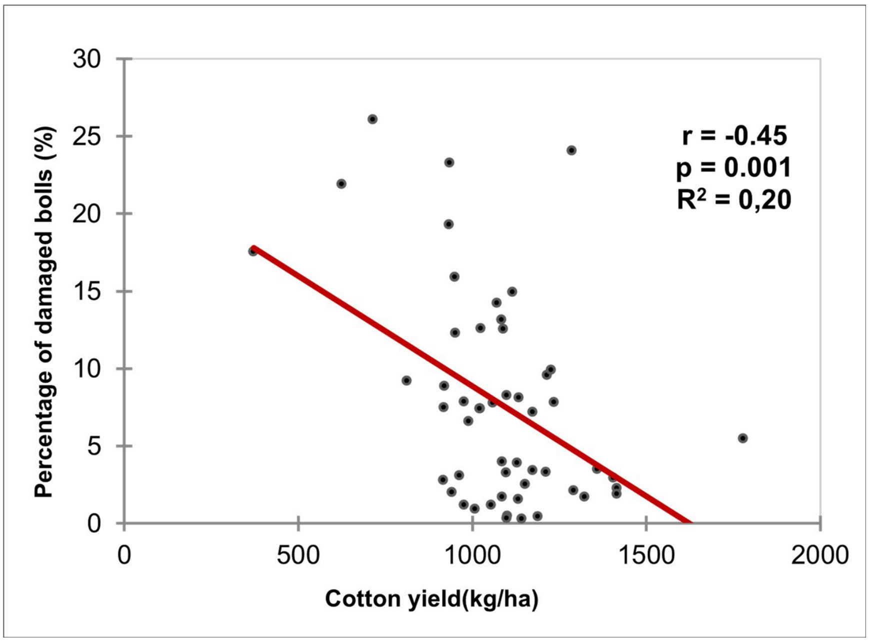


Figure 8. Variation in seed cotton yield in response to bollworm damage on green bolls.

4. Discussion

This study showed that *H. armigera* was the predominant exocarpic bollworm, followed by *Earias* spp. and *D. watersi*. The dominance of *H. armigera* may be favoured by the diversity of host plants in the production landscape. This species is cosmopolitan and has been reported to feed on more than 300 plant species across over 68 families [13]. Although *H. armigera* is a major pest of cotton, several other crops can be highly attractive, including tobacco, maize and sunflower [14], which may act as relay hosts and contribute to population persistence. Consequently, effective management should consider the broader cropping system and the availability of alternative hosts. In contrast, *D. watersi* has a narrower host range and survives unfavourable periods through diapause; environmental cues such as temperature, relative humidity and photoperiod have been implicated in diapause regulation [15]-[17].

Among the two endocarpic species, *P. gossypiella* was the most abundant. Indeed, previous studies have shown difficulties in controlling these two species. Previous work on *P. gossypiella* demonstrated that larval development inside bolls greatly limits the effectiveness of insecticide products [18]. Furthermore, studies on sensitivity have revealed a strong presence of insecticide detoxification enzymes in *P. gossypiella* and levels of resistance, particularly to organophosphates [19]. It would thus be advisable to consider integrated management strategies. Alternative methods such as mating disruption [20], mass trapping [21], and other integrated management strategies have been evaluated [22] [23].

Regarding the spatial distribution of the studied pests, exocarpic species (*H. armigera*, *D. watersi*, and *Earias* spp.) were more abundant in areas located above the 9th parallel, whereas endocarpic species (*P. gossypiella* and *T. leucotreta*) were higher in the area situated below the 9th parallel. These results confirm previous studies [24]. This geographic pattern is consistent with differences in agro-ecological conditions between the Sudanian and sub-Sudanian zones described for Côte d'Ivoire [3]. Nevertheless, because field-level weather variables were not measured in the present survey, the contribution of specific climatic factors (temperature, rainfall and relative humidity) should be interpreted as a hypothesis supported by the literature rather than as a direct result of this dataset [25] [26].

From the perspective of year-to-year evolution, infestation levels fluctuated for all species. Such inter-annual variation may reflect changes in agroclimatic conditions and biotic interactions reported for cotton pest complexes. However, because this survey did not directly record field-level weather variables, climate is discussed here as a plausible contributing factor based on the published literature. In addition, the 2022-2023 period coincided with the invasion of the leafhopper *Amrasca biguttula biguttula*, which disrupted the composition of the insect fauna on cotton [7] [27]. Cottoning this invasion, cotton protection recommendations and farmer practices increasingly emphasized leafhopper control, including the use of leafhopper-targeted active ingredients (e.g., flonicamid), which have limited activity against boll-feeding Lepidoptera. This shift in control focus, documented in recent studies and efficacy trials [9] [28], likely contributed to the resurgence of fruit-feeding Lepidoptera observed in subsequent seasons.

The study also highlighted the impact of bollworms on boll health and seed cotton yield. These pests accounted for approximately 3% - 10% of the boll damage observed and were associated with nearly 20% yield loss, despite plant protection measures. These results confirm the status of fruit-feeding Lepidoptera as major pests of cotton in West Africa [4] [5]. Despite the leafhopper invasion in 2022, fruit-feeding Lepidoptera therefore remain key pests. Their importance stems from direct feeding on reproductive organs (flower buds, flowers, and bolls). The resurgence of fruit-feeding Lepidoptera after the leafhopper invasion underscores the complexity of cotton protection and the need to implement integrated approaches that consider the full pest complex.

Overall, the year-to-year fluctuations observed in bollworm densities highlight the need for sustained surveillance in cotton-growing areas. Future work should explicitly integrate agroclimatic measurements and document farmer-level pest-management practices to better explain inter-annual variability and to quantify the contribution of control programs to pest resurgence. In parallel, periodic insecticide-susceptibility monitoring across the main taxa would help maintain the effectiveness of the national protection program and support evidence-based adjustments.

5. Conclusions

Across four cotton-growing seasons (2021-2024) in Côte d'Ivoire, fruit-feeding Lepidoptera remained major pests, with measurable impacts on boll damage and seed cotton yield. The findings further suggest that protection programs strongly focused on the invasive leafhopper *Amrasca biguttula biguttula* may reduce control pressure on bollworms and favour their resurgence.

These results underscore the necessity of sustaining continuous surveillance of bollworms and adjusting control strategies according to the prevailing species, geographic regions, and planting schedules. Integrated pest management, which encompasses suitable cultural practices and targeted phytosanitary interventions, is essential for mitigating yield losses attributable to these pests.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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