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Research Article

Diversity, Population Dynamics, and Damage Intensity of Insect Pests Associated with Oil Palm (*Elaeis guineensis* Jacq.) in Southwestern Côte d'Ivoire Industrial Plantations

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Abstract

Understanding the composition and dynamics of insect pest communities is crucial for developing effective and sustainable management strategies in oil palm (*Elaeis guineensis* Jacq.) production systems. This study provides an updated inventory and ecological analysis of insect pests associated with industrial oil palm plantations in southwestern Côte d'Ivoire. The objective was to characterize pest diversity, abundance, and damage intensity across plantations of different phenological stages. Sampling was conducted during the late rainy to early dry season (March to July 2024) across three strata: Young Non-Productive Crops (YNPC), Young Productive Crops (YPC), and Mature Crops (MC). A total of 30,380, 717, and 882 palms were respectively examined in these strata. Insects were collected from a single frond per tree and identified using both morphological keys and image-recognition tools, with confirmation at the Entomology and Agricultural Zoology Laboratory of INP-HB (Yamoussoukro). Ecological indices, including species richness (S), Shannon diversity (H′), evenness (E), and similarity (Jaccard and Sørensen), were calculated to compare community structures. Ten pest species belonging to nine families and three orders (Coleoptera, Lepidoptera, and Orthoptera) were recorded. Species composition varied markedly with plantation age. *Oryctes monoceros* dominated in YNPC (Ar = 100%), *Zonocerus variegatus* in YPC (Ar = 72.14%), and *Coelaenomenodera lameensis* in MC (Ar = 91.70%). Species richness and diversity increased with age (S = 1 to 8; H′ = 0 to 0.72), whereas evenness remained low ($E \leq 0.24$), indicating strong dominance by a few species. Similarity indices revealed complete faunal turnover between young and mature strata, confirming a clear ecological succession. Multivariate analyses revealed near-complete faunal turnover between strata (ANOSIM R = 1.0, p = 0.001), with hierarchical clustering perfectly grouping plots according to plantation age. Damage intensity followed the same trend: minimal in YNPC (mainly due to O. monoceros), moderate in YPC, and severe in MC, where *C. lameensis* caused up to 78.68% moderate and 2.49% severe damage. These results demonstrate that pest pressure and community complexity increase with the maturity of oil palm. Effective pest management, therefore, requires a phenology-based integrated approach, combining preventive measures in young plantations with regular entomological monitoring and biological or selective chemical control in mature ones. Continuous surveillance and the conservation of natural enemies are crucial for enhancing the ecological resilience and sustainability of Ivorian oil palm agroecosystems.

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1. Introduction

The oil palm (*Elaeis guineensis* Jacq.), a monocotyledon belonging to the family Arecaceae, is cultivated primarily for its palm oil, which is extracted from the mesocarp of its fruits [1, 2]. In Côte d'Ivoire, oil palm cultivation plays a crucial socioeconomic role, generating both industrial and smallholder income. National production is estimated at approximately 2.7 million tons of fresh fruit bunches per year, yielding around 600,000 tons of crude palm oil from about 290,000 hectares of plantations, of which smallholders account for nearly 70% [3, 4]. The country ranks seventh globally and remains the leading African exporter of palm oil [5].

Despite its economic significance, oil palm cultivation is threatened by a wide array of biotic constraints, among which insect pests are of major concern due to their diversity and the severity of the damage they cause [6, 7]. These pests attack virtually all parts of the plant—from young fronds to roots and inflorescences—resulting in significant yield losses [6, 8]. In addition, several Hemipteran species act as vectors of viral diseases affecting oil palm seedlings and mature stands [9, 10]. The key pest species identified in West African oil palm plantations include *Oryctes monoceros* (Olivier) (Coleoptera: Scarabaeidae), *Coelaenomenodera lameensis* Berti & Mariau (Coleoptera: Chrysomelidae), and *Rhynchophorus phoenicis* (Fabricius) (Coleoptera: Curculionidae), among others [11-15]. Their combined activity can lead to severe defoliation, damage to young shoots, and destruction of reproductive structures, ultimately reducing oil yields and plantation longevity. It should be noted that some known pests, such as *Rhynchophorus phoenicis*, may not be detected in all sampling periods due to their cryptic behavior or seasonal occurrence.

Effective integrated pest management (IPM) strategies require a precise understanding of the pest complex associated with oil palm plantations—specifically, their species composition, population dynamics, spatial distribution, and the extent of damage they cause [7, 16]. Such baseline information is essential for developing adaptive, stage-specific management interventions that sustain productivity while minimizing environmental impact.

The present study contributes to the sustainable management of oil palm insect pests in Côte d'Ivoire by providing a comprehensive inventory and ecological assessment of pest species in industrial plantations located in the South-West region of the country. Specifically, the study aims to (i) identify and catalogue the main insect pest species associated with oil palm, (ii) assess their frequency, abundance, and diversity across different age strata of plantations, (iii) determine similarities among pest communities across strata, and (iv) evaluate the intensity of damage associated with the major pest taxa. The study was conducted during a period of peak pest activity to provide a snapshot of community structure and damage patterns, with the understanding that longer-term monitoring would be needed to capture full seasonal dynamics.

2. Materials and Methods

2.1. Study Site

The study was conducted in the industrial oil palm plantation of *Industrial Agricultural Company* (EAI) located in Bolo, within the Sassandra Department, on the western coast of Côte d'Ivoire (4°57′ N, 6°05′ W). The region is characterized by a humid equatorial climate, with an average annual rainfall ranging between 1,200 and 1,500 mm. The dominant soils are desaturated ferralitic types, generally suitable for perennial crops. The local economy is primarily based on agriculture, with oil palm (*Elaeis guineensis* Jacq.) representing the main cash crop in the area.

2.2. Biological and Technical Material

The biological material consisted of oil palm trees (*Elaeis guineensis* Jacq.), Tenera variety, ranging in age from 3 to 26 years, and insect pest specimens collected from these palms. The technical equipment included sickles, scrapers, hooks, gloves, boots, protective goggles, and data recording sheets used for field sampling and observations.

2.3. Selection of Observation Plots

Observations were conducted within the industrial plantation of EAI-Bolo, which spans a total area of 5,445.51 hectares, divided into blocks comprising multiple plots. These blocks were classified according to the year of establishment and grouped into three age-class strata corresponding to the phenological stages of oil palm development:

1) Young Non-Productive Crops (YNPC) - palms aged 0-3 years,
2) Young Productive Crops (YPC) - palms aged 4-10 years,

and

3) Mature Crops (MC) - palms older than 10 years.

Plot selection followed a stratified random sampling approach, representing 10% of the total 216 plots in the plantation, in accordance with the methodologies of Mariau et al. [17] and Ponnamma et al. [18]. Within each stratum, a purposive sub-selection was made based on ecological criteria such as proximity to forest edges, presence of lowland areas, and previous infestation levels by insect pests [19, 20].

The number of plots selected per stratum (n_i) was determined using Cochran's proportional allocation formula [21], which allocates sample sizes to strata in proportion to their population sizes and variability.

$$n_i = \frac{N_i \cdot s_i}{\sum_{i=1}^{L} N_i \cdot s_i} \cdot n \quad (1)$$

where:

1) N_i= size of stratum i

2) s_i= standard deviation within stratum i

3) n= total sample size

4) L= total number of strata

In total, 20 plots were selected from the 216 available plots, corresponding to 10% of the plantation area. These were distributed proportionally across the three age-class strata (Table 1).

Table 1. *Distribution of Observation Plots According to Age-Class Strata.*

Age-class stratum	Abbreviation	Total number of plots	Number of sampled plots
Young Non-Productive Crops (0-3 years)	YNPC	25	2
Young Productive Crops (4-10 years)	YPC	65	6
Mature Crops (>10 years)	MC	126	12
Total	—	216	20

2.4. Tree Sampling

In the *Young Non-Productive Crop* (YNPC) stratum, insect collection was performed on all palms within the two designated plots, following the protocol described by Appiah [22]. This exhaustive sampling approach was adopted to prevent any potential infestation that could prove fatal to these highly vulnerable young palms. For the *Young Productive Crop* (YPC) and *Mature Crop* (MC) strata, sampling involved observing one palm per hectare [22].

Within each selected plot, palms were chosen systematically and alternately along the southern and northern borders, as well as the south-central and north-central sections, at a frequency of one line out of five (1L/5). From each selected palm, a single frond was collected for entomological examination. Three successive sampling rounds were conducted with regular rotation to ensure optimal representativeness of the data collected (Figure 1).

In total, 30,380 palms were sampled in YNPC, 717 palms in YPC, and 882 palms in MC.

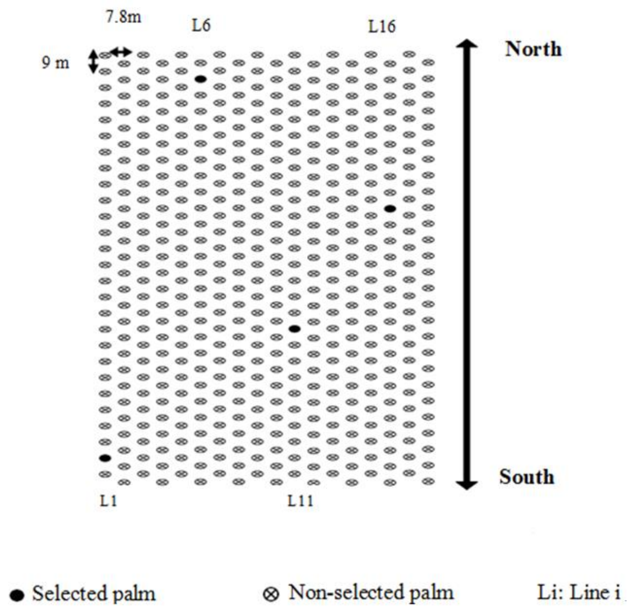

Figure 1. *Schematic Layout of the Palm Sampling Design.*

In YNPC, exhaustive sampling of all palms was conducted due to the high vulnerability of young stands. In YPC and MC, one palm per hectare was systematically selected along alternating north-south transects (1 line in 5) to ensure spatial coverage.

2.5. Data Collection

Sampling was conducted from March to July 2024, encompassing the late rainy and early dry seasons, a period characterized by high pest activity in the region.

Insects were collected from one frond per palm according to the alternating line sampling pattern described above. Observations were conducted biweekly from March to July 2024, in accordance with the procedure of Appiah [22]. Each inspection included meticulous visual examination of the fronds, manual extraction of larvae, and collection of individuals for taxonomic identification [23, 24].

All developmental stages—egg, larva, pupa, and adult—were recorded. The data obtained were used to determine larval and adult counts, frequency of occurrence, specific and relative abundance, species richness, and the level of damage caused [23, 24].

2.6. Insect Identification

Identification followed a stepwise protocol: (1) field sorting by morphotype; (2) laboratory examination using morphological keys [25-29]; (3) cross-validation using image-recognition platforms (iNaturalist, Picture Insect); (4) rearing of larvae to adulthood for problematic taxa; and (5) final confirmation against reference specimens at the INP-HB Entomology Laboratory.

Insect pests were identified from field-collected specimens using a combination of traditional morphological examination and computer-assisted visual recognition. External morphological traits were initially analyzed and compared with descriptions and illustrated identification keys from standard references [25-29].

Subsequently, identifications were refined and cross-validated using online entomological platforms (*Insect Identification* and BugGuide) and mobile image-recognition applications (iNaturalist and Picture Insect), allowing for verification against international photographic databases.

Additionally, caterpillars collected in the field were reared under controlled laboratory conditions until they emerged as adults, facilitating precise species identification. Final identifications were confirmed by comparison with reference specimens housed in the Entomology and Agricultural Zoology Laboratory of the *Higher School of Agronomy (ESA), Félix Houphouët-Boigny National Polytechnic Institute (INP-HB)*, Yamoussoukro, Côte d'Ivoire.

2.7. Observed and Calculated Parameters

Several ecological parameters were used to evaluate the entomological diversity within the industrial oil palm plantation. These included frequency of occurrence, specific and relative abundance, species richness, Shannon diversity index, evenness, and similarity indices. The combination of these indicators provided a comprehensive characterization of the composition, structure, and diversity of insect pest communities.

1) Frequency of occurrence (C)

The frequency of occurrence (C) was calculated as the proportion of samples in which a given species was observed, following Dajoz [30] and applied in similar plantation studies [16]. Species were classified into five categories: Omnipresent (C = 100%), Constant (50% ≤ C < 100%), Frequent (25% ≤ C < 50%), Accessory (5% ≤ C < 25%), and Rare (C < 5%).

$$C(\%) = \frac{P_i \times 100}{P} \quad (2)$$

P_i = number of samples in which species i was observed;
P = total number of samples examined.

2) Relative abundance (Ar)

Relative abundance expresses the proportion of individuals of a given species relative to the total number of individuals recorded [31, 32]. Species were grouped into five classes: Very Abundant (Ar ≥ 50%), Abundant (25% ≤ Ar < 50%), Fairly Abundant (5% ≤ Ar < 25%), Scarce (1% ≤ Ar < 5%), and Very Scarce (Ar < 1%).

$$Ar(\%) = \frac{N_i \times 100}{N} \quad (3)$$

N_i = number of individuals of species i;
N = total number of individuals recorded.

3) Species richness (S)

Species richness corresponds to the total number of species recorded per plot [33, 34].

4) Shannon diversity index (H′)

The Shannon index (H′) quantifies biodiversity heterogeneity by integrating both species number and their relative abundance [35, 36]. It equals zero when only one taxon is present and reaches its maximum when all species are equally abundant.

$$H' = -\sum_{i=1}^{S} P_i \ln(P_i) \quad (4)$$

where S is the total number of species, n_i the number of individuals of species i, N the total number of individuals recorded, and $P_i = n_i/N$, the proportion of species i in the community.

5) Evenness (E)

Evenness reflects the uniformity of individual distribution among species within a community. It is defined as the ratio between observed and theoretical maximum diversity [37, 38].

$$E = \frac{H'}{H'max} = \frac{H'}{\log_2(S)} \quad (5)$$

E = evenness index; H' = observed Shannon diversity index; H'_{max} = maximum theoretical diversity; S = total number of species.

Values close to 0 indicate strong dominance by a single species, whereas values approaching 1 denote a perfectly balanced community.

6) Similarity Indices

Two ecological indices were used to compare species similarity between habitats. The Jaccard Index (S_j) is based on species composition, whereas the Sørensen Index (S_s) relies on shared species presence [39, 40]. Both indices range from 0 (no shared species) to 1 (complete similarity).

$$S_j = \frac{N_c}{(N_a+N_b)-N_c}$$

$$S_s = \frac{2N_c}{S_a+S_b} \quad (6)$$

where Nc = number of species common to both habitats A and B; Na, Nb = total numbers of species in habitats A and B, respectively; Sa, Sb = total number of species recorded in habitats A and B (used for Sørensen).

2.8. Evaluation of Insect Damage

Assessment of damage caused by insect pests was conducted across the three crop strata considered in this study. During each sampling session, a systematic visual inspection of palms was performed to characterize damage symptoms and classify them according to a predefined rating scale: AD (no damage), DF (low damage), DM (moderate damage), and DG (severe damage). This scale was based on the percentage of damage, categorized as follows: AD (0%), DF (10-30%), DM (40-60%), and DG (70-100%). This standardized, observation-based approach enabled an objective quantification of the intensity of insect attacks (Kalidas, 2012).

2.9. Data Processing and Statistical Analysis

Data entry and table organization were performed using Microsoft Excel (Microsoft Office 365). Statistical analyses were carried out in RStudio (version 4.3.1) using the following packages: *vegan*, *FactoMineR*, *ggplot2*, *pheatmap*, and *cluster*.

Non-parametric Kruskal-Wallis tests were used to compare diversity indices—including species richness (S), Shannon diversity (H′), and Evenness (E)—across the three Age-class strata (YNPC, YPC, and MC). When significant differences were detected, Dunn's post-hoc tests were applied for multiple comparisons. Correlations between palm age and diversity parameters were evaluated using Spearman's rank correlation test.

Multiple multivariate approaches were employed to characterize the structure of insect pest communities across strata of oil palm plantations. A Principal Component Analysis (PCA) was performed on log-transformed species abundance data to visualize community patterns and identify species contributing most to inter-strata variation. Hierarchical Cluster Analysis (HCA) using Bray-Curtis dissimilarity and Ward's linkage method was applied to identify homogeneous groups of plots based on pest community composition. Differences in community structure among strata were tested using Analysis of Similarity (ANOSIM) with 9,999 permutations. Species co-occurrence patterns were examined through network analysis based on Jaccard similarity, with associations greater than 0.3 retained for visualization. The relationship between damage intensity (ordinal variable: AD, DF, DM, DG) and abundance of major pest species was modeled using ordinal logistic regression. All multivariate analyses were conducted in R version 4.3.1 using the *vegan*, *FactoMineR*, and *MASS* packages.

Several graphical analyses were generated to summarize and interpret the results:

1) A heatmap illustrating the relative abundance of insect species across sampled plots, with double hierarchical clustering of both species and plots.
2) A PCA biplot showing the joint projection of plots (colored by stratum) and species (as vectors).
3) A dendrogram derived from the HCA, depicting the hierarchical grouping of plots based on community composition.
4) A species co-occurrence network, where nodes represent species and edges indicate statistically significant associations, was analyzed using a Jaccard-based co-occurrence approach.

Finally, the relationship between damage intensity (ordinal response variable: AD, DF, DM, DG) and the abundance of major pest species (*Oryctes monoceros*, *Coelaenomenodera lameensis*, *Zonocerus variegatus*) was examined using an ordinal logistic regression model.

The significance level for all statistical tests was set at $\alpha = 0.05$.

3. Results

3.1. Faunal Composition

The entomological survey conducted within the industrial oil palm plantation recorded ten (10) insect pest species, belonging to nine (9) families and three (3) orders: *Coleoptera*, *Lepidoptera*, and *Orthoptera* (Tables 2-4).

The order Coleoptera comprised two species: *Oryctes monoceros* (Scarabaeidae) (Figure 2a) and *Coelaenomenodera lameensis* (Chrysomelidae) (Figure 2b). The order Lepidoptera included seven species distributed across six families: *Leptonatada sjöstedti* (Notodontidae), *Pteroteinon laufella* (Hesperiidae), *Latoia viridissima* and *Casphalia extranea* (Limacodidae), *Furcivena rhodoneuralis* (Crambidae), *Dasychira pistoides* (Erebidae), and *Elymnias hypermnestra* (Nymphalidae) (Figures 2c-i). The order Orthoptera was represented by a single species, *Zonocerus variegatus* (Pyrgomorphidae) (Figure 2j).

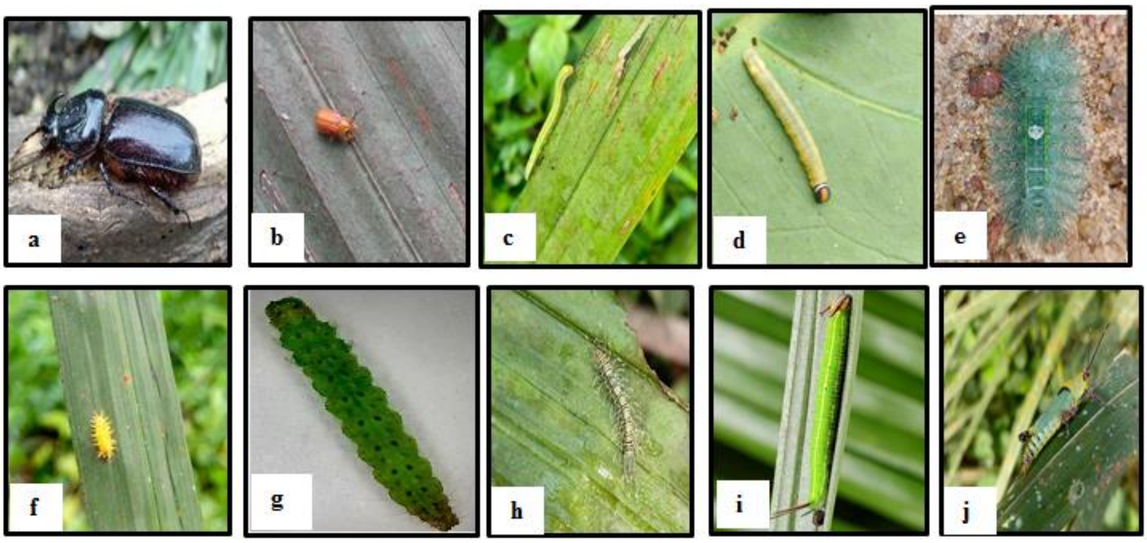

Figure 2. Insect Pest Species Recorded on Oil Palm Plantations.

(a) Oryctes monoceros; (b) Coelaenomenodera lameensis; (c) Leptonatada sjöstedti; (d) Pteroteinon laufella; (e) Latoia viridissima; (f) Casphalia extranea; (g) Furcivena rhodoneuralis; (h) Dasychira pistoides; (i) Elymnias hypermnestra; (j) Zonocerus variegatus.

3.2. Distribution and Abundance of Species Across Plantation Strata

Analysis of species composition and abundance across the three plantation age strata revealed distinct variations corresponding to the developmental stage of the palms.

In the Young Non-Productive Crops (YNPC), among the 30,380 palms sampled, only one species—*Oryctes monoceros*—was recorded, with a total abundance of 1,718 individuals. This species was classified as *accessory* (C = 5.66%) and *very abundant* (Ar = 100%) (Table 2). No other pest species were observed in this stratum.

In the Young Productive Crops (YPC), out of 717 palms sampled, five species were identified, totaling 359 individuals. *Zonocerus variegatus* was the dominant species with 259 individuals, corresponding to a *very abundant* and *accessory* status (Ar = 72.14%; C = 6.42%). *Leptonatada sjöstedti* was *fairly abundant* (N = 69; Ar = 18.22%), while *Furcivena rhodoneuralis* and *Coelaenomenodera lameensis* were *scarce* (N = 12 and 15; Ar = 3.34% and 4.46%, respectively). *Dasychira pistoides* was *very scarce* (N = 3; Ar = 0.84%) (Table 3). The remaining species were absent in this stratum.

In the Mature Crops (MC), eight species were identified among the 882 palms sampled. *Coelaenomenodera lameensis* was the dominant pest in this stratum, classified as *frequent* (C = 57.48%) and *very abundant* (Ar = 91.70%). *Leptonatada sjöstedti* and *Dasychira pistoides* were *accessory* species (C = 7.26% and 14.06%) and exhibited *fair* (N = 257; Ar = 5.20%) and *low abundance* (N = 131; Ar = 2.65%), respectively. Other species, including *Pteroteinon laufella*, *Furcivena rhodoneuralis*, *Latoia viridissima*, *Elymnias hypermnestra*, and *Casphalia extranea*, were *rare* (C < 5%) and *very scarce* (N < 8; Ar < 1%) (Table 4). Neither *Oryctes monoceros* nor *Zonocerus variegatus* were detected in this stratum.

These results highlight a clear ecological succession of pest species along the developmental gradient of oil palm. *Oryctes monoceros* predominated in young, non-productive plantations; *Zonocerus variegatus* became important in young, productive stands; and *Coelaenomenodera lameensis* emerged as the dominant and persistent pest in mature plantations. This progression reflects the dynamic adaptation of insect pest communities to changes in palm age and canopy structure.

Table 2. Relative Abundance and Frequency of Occurrence of Insect Species Recorded in Young Non-Productive Crops (YNPC).

Orders	Families	Species	Total abundance (N)	Relative abundance (Ar%)	Frequency of occurrence (C%)
Coleoptera	Scarabaeidae	*Oryctes monoceros*	1,718	100	5.66
	Chrysomelidae	*Coelaenomenodera lameensis*	0	0	0
Lepidoptera	Notodontidae	*Leptonatada sjöstedti*	0	0	0
	Hesperiidae	*Pteroteinon laufella*	0	0	0

Orders	Families	Species	Total abundance (N)	Relative abundance (Ar%)	Frequency of occurrence (C%)
	Limacodidae	*Latoia viridissima*	0	0	0
		Casphalia extranea	0	0	0
	Crambidae	*Furcivena rhodoneuralis*	0	0	0
	Erebidae	*Dasychira pistoides*	0	0	0
	Nymphalidae	*Elymnias hypermnestra*	0	0	0
Orthoptera	Pyrgomorphidae	*Zonocerus variegatus*	0	0	0
Total			1,718	100	

Table 3*. Relative Abundance and Frequency of Occurrence of Insect Species Recorded in Young Productive Crops (YPC).*

Orders	Families	Species	Total abundance (N)	Relative abundance (Ar%)	Frequency of occurrence (C%)
Coleoptera	Scarabaeidae	*Oryctes monoceros*	0	0	0
	Chrysomelidae	*Coelaenomenodera lameensis*	12	3.34	1.12
Lepidoptera	Notodontidae	*Leptonatada sjöstedti*	69	18.22	4.18
	Crambidae	*Furcivena rhodoneuralis*	16	4.46	1.81
	Erebidae	*Dasychira pistoides*	3	0.84	0.42
Orthoptera	Pyrgomorphidae	*Zonocerus variegatus*	259	72.14	6.42
Total			359	100	

Table 4*. Relative Abundance and Frequency of Occurrence of Insect Species Recorded in Mature Crops (MC).*

Orders	Families	Species	Total abundance (N)	Relative abundance (Ar%)	Frequency of occurrence (C%)
Coleoptera	Scarabaeidae	*Oryctes monoceros*	0	0	0
	Chrysomelidae	*Coelaenomenodera lameensis*	4,531	91.70	57.48
Lepidoptera	Notodontidae	*Leptonatada sjöstedti*	257	5.20	14.06
	Hesperiidae	*Pteroteinon laufella*	8	0.16	0.79
	Limacodidae	*Latoia viridissima*	4	0.08	0.54
		Casphalia extranea	1	0.02	0.14
	Crambidae	*Furcivena rhodoneuralis*	6	0.12	0.68
	Erebidae	*Dasychira pistoides*	131	2.65	7.26
	Nymphalidae	*Elymnias hypermnestra*	3	0.06	0.34
Orthoptera	Pyrgomorphidae	*Zonocerus variegatus*	0	0	0
Total			4,941	100	

3.3. Species Richness, Diversity, and Evenness Across oil Palm Strata

The analysis of ecological indices for insect pests across the different oil palm strata revealed marked variations associated with plantation age and developmental stage (Table 5, Figure 3).

In the Young Non-Productive Crops (YNPC), species richness was minimal, with only one species recorded, resulting in a null Shannon diversity index ($H' = 0$). This indicates the complete dominance of a single species within the stratum.

In the Young Productive Crops (YPC), species richness increased moderately ($S = 5$), but Shannon diversity remained low ($H' = 0.28$), and evenness was very low ($E = 0.12$). This configuration reflects a community strongly dominated by a single taxon, a typical pattern in ecologically simplified habitats.

In contrast, the Mature Crops (MC) exhibited the highest species richness ($S = 8$) and diversity ($H' = 0.72$). However, evenness remained low ($E = 0.24$), indicating an uneven distribution of individuals among species. This structure suggests a higher overall diversity with plantation age, reflecting a gradual ecological stabilization, yet still characterized by the dominance of a few taxa well-adapted to mature oil palm ecosystems.

3.4. Statistical Analysis of Diversity Patterns

The Kruskal-Wallis tests demonstrated highly significant differences in species richness ($\chi^2 = 29$, df = 2, $p = 5.04\times10^{-7}$) and Shannon diversity ($\chi^2 = 14.29$, df = 1, $p = 0.00016$) among plantation strata. Post-hoc analysis revealed three distinct groups characterized by increasing diversity values from YNPC to MC (Table 5, Figure 3).

Spearman correlation analysis revealed strong positive relationships between palm age and diversity indices. Species richness showed a perfect positive correlation with palm age ($\rho = 1.0$, $p < 2.2 \times 10^{-16}$), indicating a linear increase in pest species numbers as plantations mature. Shannon diversity also exhibited a strong positive correlation ($\rho = 0.87$, $p = 7.50 \times 10^{-7}$), demonstrating that both species number and relative abundance distribution become more complex with increasing plantation age.

The consistently low evenness values across all strata ($E \leq 0.25$) confirmed strong ecological dominance in these monoculture systems. The significant increase in evenness from YPC ($E = 0.11$) to MC ($E = 0.25$; $\chi^2 = 14.29$, $p = 0.00016$) suggests a gradual shift toward more balanced community structure in mature plantations, though dominance by key species remains pronounced.

Overall, species diversity (H′) increased with plantation age, whereas evenness (E) remained consistently low across all strata. This pattern highlights a non-uniform distribution of insect populations, suggesting the progressive specialization and differentiation of pest communities along the oil palm developmental gradient. These statistical findings support the concept of ecological succession in oil palm pest communities, with plantation age serving as the primary driver of pest community assembly.

Table 5. *Species Richness, Shannon Diversity, and Evenness Across Oil Palm Plantation Strata with Statistical Comparisons.*

Stratum	Species richness (S)	Shannon diversity (H′)	Evenness (E)	Statistical grouping
Young Non-Productive Crops (YNPC)	1	0	-	a
Young Productive Crops (YPC)	5	0.28 ± 0.05	0.11 ± 0.02	b
Mature Crops (MC)	8	0.74 ± 0.08	0.25 ± 0.02	c
Kruskal-Wallis test	$\chi^2 = 29$, df = 2, $p = 5.04\times10^{-7}$	$\chi^2 = 14.29$, df = 1, $p = 0.00016$	$\chi^2 = 14.29$, df = 1, $p = 0.00016$	
Spearman correlation with palm age	$\rho = 1.0$, $p < 2.2\times10^{-16}$	$\rho = 0.87$, $p = 7.50\times10^{-7}$		

Statistical grouping, indicated by different letters, shows significant differences between strata ($p < 0.05$) based on Dunn's post-hoc tests with the Bonferroni correction.

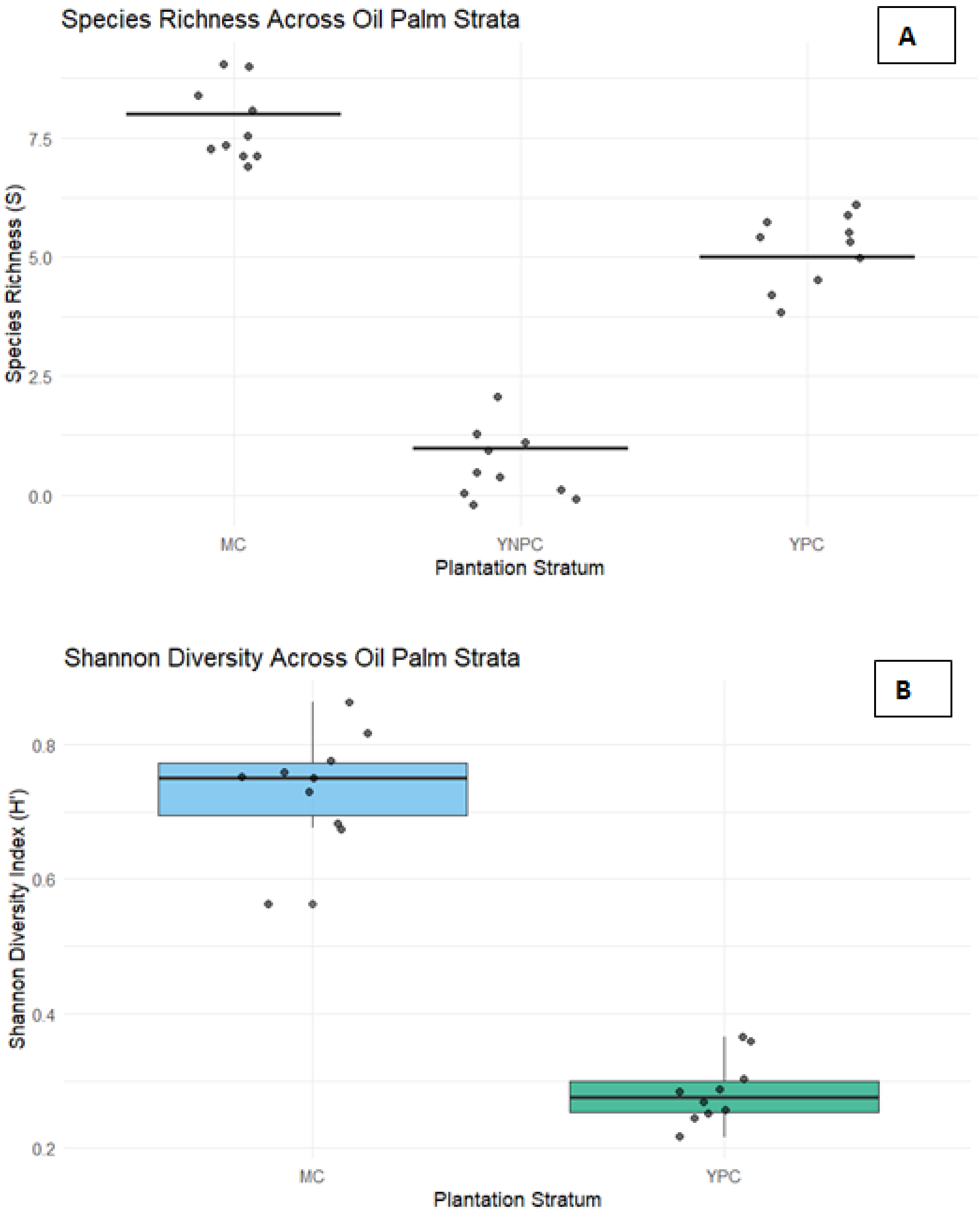

Figure 3. *Diversity Indices of Insect Pest Communities Across Oil Palm Plantation Strata.*

(A) Species richness (S) and (B) Shannon diversity index (H′) in Young Non-Productive Crops (YNPC), Young Productive Crops (YPC), and Mature Crops (MC). Error bars represent standard deviation.

3.5. Similarity Among Oil Palm Plantation Strata

The inter-stratum similarity analysis, based on Jaccard (Sj) and Sørensen (Ss) indices, revealed clear differentiation in pest community composition between young and mature plantations (Table 6).

No similarity was observed between YNPC and YPC (Sj = 0; Ss = 0) or between YNPC and MC (Sj = 0; Ss = 0), indicating the absence of shared species between these strata. In contrast, a moderate similarity was found between YPC and MC (Sj = 0.50; Ss = 0.66), suggesting a degree of ecological continuity between intermediate and mature developmental stages of oil palm.

These findings confirm a progressive ecological succession of pest species along the age gradient of the plantations. As oil palms mature, the complexity and diversity of insect communities increase, reflecting greater ecological stabilization and diversification of faunal niches. Nonetheless, dominance by a few species remains evident in older systems, underscoring the persistence of key pests that have adapted to mature palm environments.

Table 6. Jaccard and Sørensen Similarity Indices Among Oil Palm Plantation Strata.

Strata	Young Non-Productive Crops	Young Productive Crops	Mature Crops
Young Non-Productive Crops (YNPC)	1	0 and 0	0 and 0
Young Productive Crops (YPC)	0 and 0	1	0.50 and 0.66
Mature Crops (MC)	0 and 0	0.50 and 0.66	1

Note: Bold values correspond to Sørensen similarity indices.

3.6. Multivariate Analysis of Insect Pest Community Structure

Multivariate analyses revealed significant structural differences in insect pest communities across the three oil palm plantation strata (Figures 4-7). Principal Component Analysis (PCA) explained 67.6% of the total variance in the first two dimensions, indicating strong structuring of pest communities along plantation age gradients. The first dimension (42.6% variance) clearly separated young non-productive crops, dominated by *Oryctes monoceros*, from mature crops dominated by *Coelaenomenodera lameensis* (Figure 4). The second dimension (25.0% variance) captured compositional variation within strata, particularly among lepidopteran species in mature plantations.

Analysis of Similarity (ANOSIM) confirmed highly significant differences in community structure among the three strata (R = 1.0, p = 0.001), demonstrating near-complete faunal turnover along the plantation developmental gradient. This perfect separation (R = 1.0) represents one of the strongest possible dissimilarity values in ecological studies, underscoring the deterministic nature of pest succession in oil palm agroecosystems.

Hierarchical cluster analysis based on Bray-Curtis's dissimilarity identified three distinct clusters that perfectly corresponded to the plantation strata (Figure 5). All mature crop (MC) plots formed one cohesive cluster, young productive crops (YPC) constituted a second cluster, and young non-productive crops (YNPC) comprised the third cluster. This perfect classification indicates that pest community composition alone can accurately predict the developmental stage of a plantation.

Heatmap visualization of Hellinger-transformed abundance data revealed clear dominance hierarchies across strata (Figure 6). Young non-productive crops exhibited exclusive dominance by *O. monoceros*, while young productive crops showed mixed communities with *Zonocerus variegatus* as the predominant species. Mature crops demonstrated overwhelming dominance by *C. lameensis*, accompanied by a diverse assemblage of lepidopteran species, including *Leptonatada sjöstedti*, *Dasychira pistoides*, and several minor species.

Co-occurrence network analysis based on Jaccard similarity identified 23 significant species associations (similarity > 0.2), with *C. lameensis* serving as a central hub in the interaction network of mature plantations (Figure 7). The network structure revealed greater complexity and interconnectedness among lepidopteran species in mature crops. In contrast, dominant species from younger strata (*O. monoceros* and *Z. variegatus*) showed relatively isolated positions in the network.

Ordinal regression analysis examining the relationship between pest abundance and damage intensity yielded unexpected results. Despite its numerical dominance, *the abundance of C. lameensis* alone did not significantly predict damage intensity in mature crops (p = 0.705). This suggests that additional factors beyond simple pest density, such as environmental conditions, tree physiological status, natural enemy activity, or cumulative exposure effects, may influence damage patterns. Interestingly, ordinal regression revealed no significant relationship between *C. lameensis* abundance and damage intensity (p = 0.705), suggesting that factors beyond simple pest density may influence damage patterns.

Collectively, these multivariate analyses demonstrate a structured and predictable succession of insect pest communities in industrial oil palm plantations. The clear stratification of pest assemblages according to plantation age, coupled with the complex species interactions in mature stands, underscores the necessity for developmental stage-specific pest management strategies. The dissociation between pest abundance and damage intensity in mature plantations further highlights the need for integrated assessment approaches that consider multiple ecological factors in damage prediction and management decision-making.

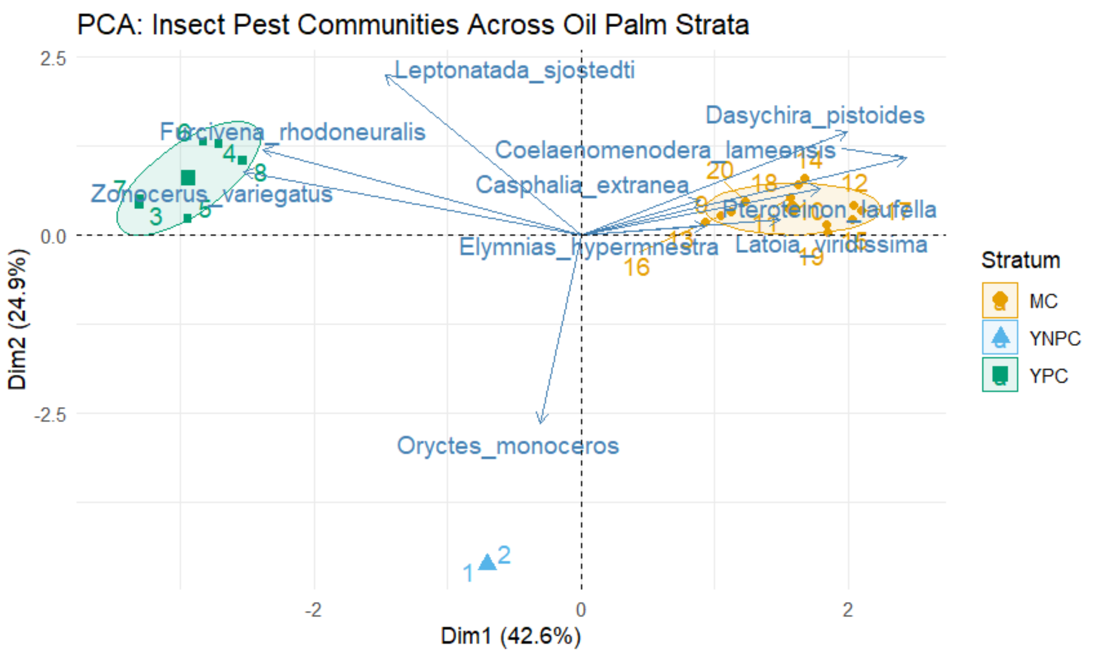

Figure 4. Principal Component Analysis Biplot of Insect Pest Communities Across Oil Palm Plantation Strata.

Ellipses represent 68% confidence intervals for each stratum. Vector length and direction indicate species contributions to the principal components.

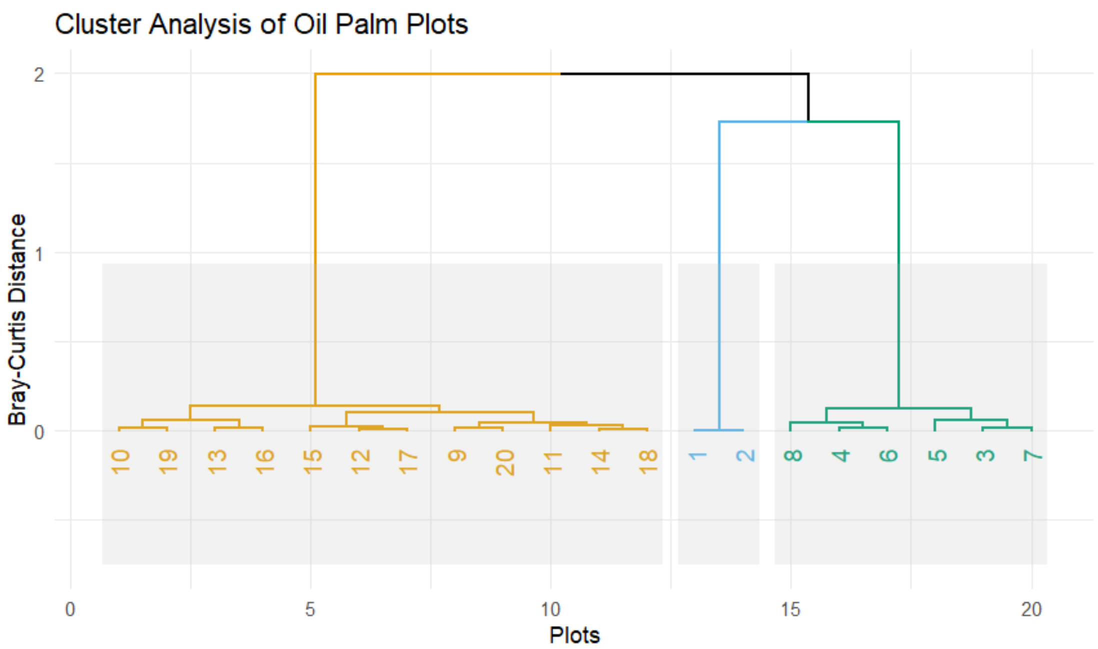

Figure 5. Hierarchical Cluster Analysis Dendrogram of Oil Palm Plots Based on Bray-Curtis Dissimilarity of Insect Pest Communities. Three Distinct Clusters Were Identified: Cluster 1 (blue) Comprises YOUNG Non-Productive Crops (YNPC, plots 1-2), Cluster 2 (green) Comprises Young Productive Crops (YPC, Plots 3-8), and Cluster 3 (Orange) Comprises Mature Crops (MC, Plots 9-20). The Perfect Correspondence Between Clusters and Plantation Strata Demonstrates the Strong Association Between Pest Community Composition and Oil Palm Developmental Stage.

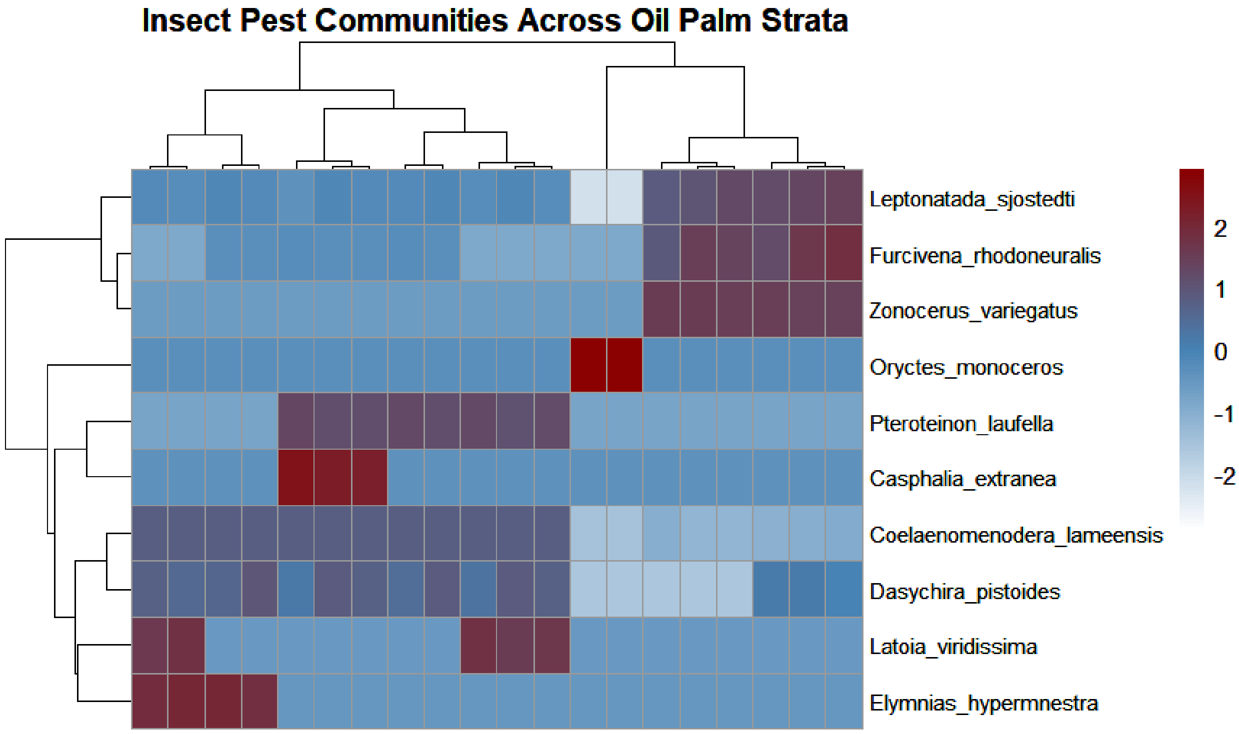

Figure 6. *Heatmap of Hellinger-transformed Insect Pest Abundances Across Oil Palm Plots. Rows Represent Species, Columns Represent Plots, and Colors Indicate Abundance Levels (White = low, red = high). Dendrograms Show Clustering of Species and Plots.*

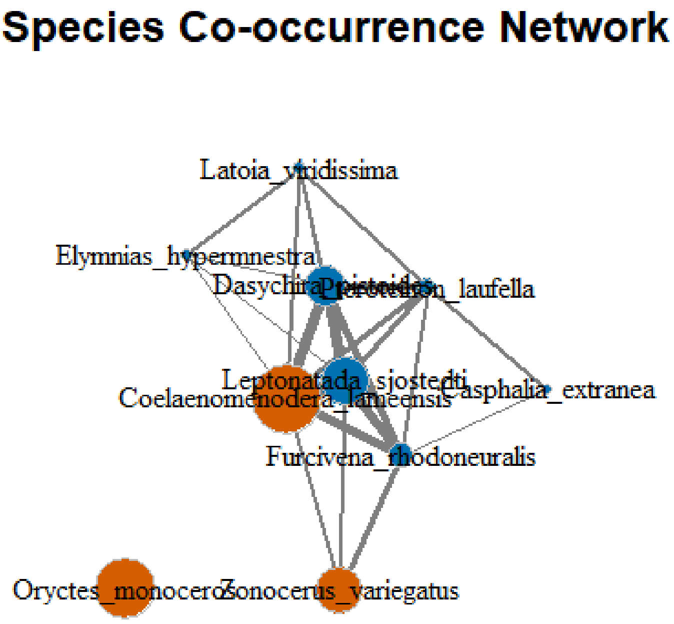

Figure 7. *Species Co-occurrence Network Based on Jaccard Similarity Coefficients Greater Than 0.2. Node Size Represents Relative Abundance, Node Color Distinguishes Dominant (Orange) from Secondary (Blue) Pest Species, and Edge Thickness Indicates Strength of Association.*

3.7. Assessment of Insect Damage

The assessment of damage caused by insect pests of oil palm revealed considerable variation depending on the developmental stage of the plantations and the species involved.

In the Young Non-Productive Crops (YNPC), observed damage was exclusively attributed to *Oryctes monoceros*. Results showed that 70.63% of palms exhibited no visible damage, while 21.65% showed slight injury, 7.67% displayed moderate damage, and only 0.05% suffered severe injury

(Table 7). These findings indicate a low infestation pressure by *O. monoceros* at this developmental stage, despite its constant presence in young plantations.

In the Young Productive Crops (YPC), damage levels varied according to pest species. *Coelaenomenodera lameensis* caused only minor injuries, with 94.18% of palms unaffected and 5.82% showing slight damage. Other species, particularly *Leptonatada sjöstedti* and *Dasychira pistoides*, were virtually harmless, as 98.74% of palms remained undamaged and only 1.26% were slightly affected (Table 8). Similarly, *Furcivena rhodoneuralis* had a minimal impact, with 97.60% of palms remaining unaffected.

In the Mature Crops (MC), damage became markedly more severe, primarily due to *C. lameensis*, which was responsible for a high proportion of moderate damage (78.68%), followed by mild (6.35%) and severe (2.49%) injuries. In comparison, only 12.47% of palms remained intact (Table 9). The group of Lepidopteran species—*Leptonatada sjöstedti*, *Pteroteinon laufella*, *Latoia viridissima*, *Casphalia extranea*, *Dasychira pistoides*, *Elymnias hypermnestra*, and *Furcivena rhodoneuralis*—showed a broader range of damage intensities, with 34.58% of palms undamaged, 35.83% slightly affected, 20.98% moderately damaged, and 8.62% severely attacked.

These findings confirm a progressive increase in pest-induced damage with plantation age, associated with higher pest population densities and prolonged canopy cover in mature plantations, which favor pest persistence and recurrent infestations.

Table 7. *Estimated Damage Caused by Oryctes Monoceros in Young Non-Productive Crops (YNPC).*

Species	No damage (%)	Slight damage (%)	Moderate damage (%)	Severe damage (%)	Total palms observed
Oryctes monoceros	70.63	21.65	7.67	0.05	30,380

Table 8. *Estimated Damage in Young Productive Crops (YPC).*

Species	No damage (%)	Slight damage (%)	Moderate damage (%)	Severe damage (%)
Coelaenomenodera lameensis	94.18	5.82	0.00	0.00
Leptonatada sjöstedti, Dasychira pistoides	98.74	1.26	0.00	0.00
Furcivena rhodoneuralis	97.60	2.40	0.00	0.00

Table 9. *Estimated Damage in Mature Crops (MC)/.*

Species	No damage (%)	Slight damage (%)	Moderate damage (%)	Severe damage (%)
Coelaenomenodera lameensis	12.47	6.35	78.68	2.49
Leptonatada sjöstedti, Pteroteinon laufella, Latoia viridissima, Casphalia extranea, Dasychira pistoides, Elymnias hypermnestra, Furcivena rhodoneuralis	34.58	35.83	20.98	8.62

The pattern of damage across plantation strata demonstrates that *O. monoceros* is primarily associated with early developmental stages, causing moderate to mild injuries in young palms. As plantations mature, *C. lameensis* becomes the principal pest, inducing extensive foliar damage and reducing canopy vigor. Lepidopteran pests, although generally secondary, cumulatively contribute to defoliation pressure in mature plantations, underscoring the need for integrated pest management strategies tailored to plantation age.

4. Discussion

This study demonstrates that the structure and composition of oil palm pest communities vary considerably with the phenological stage of the plantations. This trend reflects a progressive ecological succession driven by plant physiology and the dynamics of the cultivated ecosystem.

The highly significant differences in species richness ($p = 5.04\times10^{-7}$) and Shannon diversity ($p = 0.00016$) across strata, coupled with strong positive correlations between palm age and diversity indices (species richness: $\rho = 1.0$; Shannon diversity: $\rho = 0.87$), provide quantitative support for the successional model of pest community development in oil palm agroecosystems.

In young plantations, *Oryctes monoceros* has been reported as a major pest of young palms, corroborating earlier findings [41]. This coleopteran, recognized as a primary pest of coconut and oil palm in Côte d'Ivoire [42], attacks soft tissues and young shoots, potentially causing severe losses. Its prevalence in newly established plantations is often associated with the plentiful decomposing organic matter produced during land clearing and the inadequate burial or removal of windrows and debris [8, 13].

As plantations mature, a marked shift in pest community composition occurs, with *Coelaenomenodera lameensis* emerging as the dominant defoliator. This species is the most destructive pest of mature oil palm plantations in West Africa, causing substantial defoliation, reduced photosynthetic area, and significant yield losses [11, 43]. The consistently low evenness values observed across all strata reflect strong ecological dominance by one or a few species—a pattern characteristic of industrial monoculture systems, particularly in the context of large-scale mono-crop oil palm plantations, where uniform management and reduced structural complexity tend to favor dominance [44, 45]. This pattern reflects both the high specialization of particular pest species to homogeneous environments and the vulnerability of such systems to outbreaks.

The multivariate analyses provided robust statistical support for this successional pattern, with near-perfect separation of pest communities among strata (ANOSIM $R = 1.0$). This exceptional dissimilarity value highlights the deterministic nature of pest succession in oil palm monocultures, where plantation age is the primary driver of community assembly. The clear clustering of plots according to developmental stage demonstrates that pest community composition can accurately indicate the phenological status of plantations.

The gradual increase in species diversity with plantation age reflects the expansion of ecological niches and greater habitat stability [46, 47]. The presence of secondary species such as *Zonocerus variegatus* and several lepidopterans (*Leptonatada sjöstedti*, *Latoia viridissima*, *Dasychira pistoides*) suggests a latent entomological richness that may play an important ecological role in community interactions. The co-occurrence network analysis revealed that these lepidopteran species form interconnected associations in mature plantations, with 23 significant species interactions identified (Figure 7). Although these species are not quantitatively dominant, they exemplify the coexistence of multiple trophic guilds and contribute to the complexity of interaction networks. Such networks can be deliberately leveraged in conservation biological-control strategies by enhancing natural-enemy populations (e.g., predators, parasitoids, insectivorous birds) within the plantation system [48, 49]. The network structure reveals that *C. lameensis* serves as a central hub, while lepidopterans such as *L. sjöstedti* and *D. pistoides* occupy intermediate positions, suggesting they may play crucial roles in maintaining community stability in mature oil palm ecosystems.

Most weevil larvae (Coleoptera: Curculionidae) are recognized pests of oil-palm; for example, the African palm weevil, *Rhynchophorus phoenicis,* attacks oil-palm (*Elaeis guineensis*) in Africa by boring into the stem and heart of palms, causing leaf yellowing and plant loss [15, 50] and the female inflorescence weevils (*Prosoestus* spp.) [51, 52]. Lepidopteran larvae also contribute to oil-palm damage: for example, the African spear borer *Pimelephila ghesquieri* (Crambidae) attacks spear leaves and young palm bases in West Africa. While other species, such as *Zophopetes dysmephila* (Hesperiidae), are listed as palm-feeding larvae, their impact on oil palm as major defoliators remains less documented [7]. However, none of these species were collected during the present study, which may be attributable to the sampling methodology and the limited duration of the collection period. The absence of *Rhynchophorus phoenicis*, a known stem borer, may reflect its cryptic behavior or low detectability with frond-based sampling. This observation highlights the need for extended entomological monitoring, employing more intensive capture or rearing techniques throughout the entire annual cycle. Further investigations are required to confirm their presence or absence in the study area. Notably, the characteristic damage symptoms associated with *Pimelephila ghesquieri* in mature palms indicate that this pest may occur locally, consistent with its recognized economic significance [7].

The observed damage patterns confirm that pest pressure increases with plantation age. While damage in young plantations was generally low to moderate, mature plantations exhibited moderate to severe damage, predominantly associated with *C. lameensis*. These results are consistent with observations reported from other African oil palm production zones [18, 22].

The lack of a significant correlation between *C. lameensis* abundance and damage intensity may be explained by several ecological factors: (1) non-linear damage thresholds, where severe defoliation occurs only after specific population densities are exceeded; (2) natural enemy activity suppressing damage despite high pest counts; (3) palm compensatory growth masking visible injury; or (4) cumulative or lag effects not captured in snapshot abundance data. This highlights the importance of an integrated damage assessment that considers pest density, plant vigor, and the environmental context.

From a pest management perspective, these findings emphasize the need for an integrated and age-specific management approach. Consequently, we recommend the following stage-specific IPM strategies:

1) YNPC: Implement pheromone trapping for *O. monoceros*, ensure complete burial of organic debris, and conduct monthly visual inspections.
2) YPC: Monitor *Z. variegatus* populations using sweep nets or visual counts; if thresholds are exceeded, apply botanical extracts (e.g., neem) before chemical interventions.
3) MC: Deploy biopesticides (e.g., Beauveria bassiana) against *C. lameensis*, conserve natural enemies through selective insecticide use, and conduct frond damage assessments every 2-3 weeks.

These measures should be supported by continuous entomological monitoring and habitat management to enhance natural regulation.

Finally, promoting biological control through the identification and conservation of indigenous predators and parasitoids of *C. lameensis* and other pest species could enhance the ecological resilience of oil palm agroecosystems, while reducing dependency on chemical insecticides.

Our study provides a robust snapshot of pest communities during a period of high activity. However, long-term, multi-season monitoring is recommended to capture annual population dynamics and the effects of climatic influences.

5. Conclusion

This study provides an updated inventory of insect pests associated with industrial oil palm plantations in southwestern Côte d'Ivoire. A total of ten economically significant species, belonging to nine families and three orders, were identified, indicating a relatively high entomological diversity within the studied agroecosystems.

The results demonstrate that the structure of insect pest communities varies according to the phenological stage of the oil palm. *Oryctes monoceros* predominates in young plantations, whereas *Coelaenomenodera lameensis* becomes the most abundant and destructive species in mature stands. The severity of pest-induced damage increases with palm age, reaching critical levels in mature crops. These findings underscore the necessity of implementing a stage-specific integrated pest management (IPM) approach, tailored to the developmental phase of the plantations. Such an approach should combine preventive measures, biological control, and the targeted use of biopesticides or selective chemical treatments where necessary.

We therefore advocate for a stage-specific, integrated pest management framework:

1) In young plantations, focus on preventive measures (debris management, pheromone trapping).
2) In mature stands, prioritize biological control and selective biopesticides against *C. lameensis*.
3) Across all ages, implement regular entomological monitoring and conservation of natural enemies through reduced insecticide use and habitat diversification.

Beyond curative management, the study highlights the importance of continuous entomological monitoring and diversified control strategies to ensure the ecological and economic sustainability of industrial oil palm plantations in Côte d'Ivoire. Future research should focus on understanding the seasonal dynamics of pest populations, assessing the impact of agroecological practices on natural pest regulation, and testing the efficacy of indigenous biological control agents under local plantation conditions.

Author Contributions

Desire Anicet Kouassi: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing - original draft, Writing - review & editing

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Nahoule Armand Adja: Conceptualization, Investigation, Methodology, Validation, Writing - original draft, Writing - review & editing

Yann Gildas Kouakou: Conceptualization, Data curation, Investigation, Writing - original draft, Writing - review & editing

Yao Casimir Brou: Project administration, Resources, Supervision, Validation, Visualization, Writing - review & editing

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