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Land type drives pest infestation patterns in smallholder cocoa (*Theobroma cacao* L.) agroecosystems

Pengaruh tipe lahan terhadap pola infestasi hama pada agroekosistem kakao (*Theobroma cacao* L.) pekebun kecil

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ABSTRACT
Pest infestation remains a major constraint in smallholder cocoa (*Theobroma cacao* L.) production, particularly in tropical agroecosystems where environmental heterogeneity can influence pest dynamics. However, the role of land type in shaping pest infestation patterns under field conditions is still insufficiently understood. This study examined how land type influences pest infestation patterns in smallholder cocoa agroecosystems. Observations were conducted across three land types, including sloping, flat, and shaded areas, in a farmer-managed cocoa plantation. A total of 265 cocoa pods were evaluated across three observation periods, and infestation was assessed based on visible damage and pest presence. The results showed that pest infestation differed across land types, with higher infestation rates observed in sloping and shaded areas (approximately 43–44%) compared to flat land (approximately 29%). Statistical analysis indicated a weak association between land type and infestation level, while pairwise comparison revealed significantly lower infestation in flat areas. These findings suggest that land type contributes to shaping pest infestation dynamics, likely through differences in microenvironmental conditions such as moisture, canopy cover, and habitat suitability. These findings highlight the importance of incorporating land characteristics into site-specific pest management strategies in tropical cocoa agroecosystems.

ABSTRAK
Serangan hama masih menjadi salah satu kendala utama dalam produksi kakao (*Theobroma cacao* L.) pada perkebunan skala pekebun kecil, khususnya di agroekosistem tropis yang memiliki heterogenitas lingkungan yang dapat memengaruhi dinamika hama. Namun, peran tipe lahan dalam membentuk pola infestasi hama di kondisi lapangan masih belum dipahami secara memadai. Penelitian ini bertujuan untuk mengkaji pengaruh tipe lahan terhadap pola infestasi hama pada agroekosistem kakao skala pekebun kecil. Pengamatan dilakukan pada tiga tipe lahan, yaitu lahan miring, datar, dan teduh, di kebun kakao yang dikelola oleh petani. Sebanyak 265 buah kakao diamati dalam tiga periode pengamatan, dan tingkat infestasi ditentukan berdasarkan kerusakan visual serta keberadaan hama. Hasil penelitian menunjukkan bahwa infestasi hama berbeda antar tipe lahan, dengan tingkat infestasi yang lebih tinggi pada lahan miring dan teduh (sekitar 43–44%) dibandingkan dengan lahan datar (sekitar 29%). Analisis statistik menunjukkan adanya hubungan yang lemah antara tipe lahan dan tingkat infestasi, sementara analisis perbandingan berpasangan menunjukkan bahwa infestasi pada lahan datar secara signifikan lebih rendah. Temuan ini menunjukkan bahwa tipe lahan berperan dalam membentuk dinamika infestasi hama, yang kemungkinan dipengaruhi oleh perbedaan kondisi mikro lingkungan seperti kelembapan, tutupan tajuk, dan kesesuaian habitat hama. Hasil penelitian ini menegaskan pentingnya mempertimbangkan karakteristik lahan dalam pengembangan strategi pengendalian hama yang spesifik lokasi pada agroekosistem kakao tropis.

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INTRODUCTION

Cocoa (*Theobroma cacao* L.) is a high-value plantation commodity that plays a crucial role in supporting rural livelihoods and regional economies in many tropical countries, including Indonesia (Effendy et al., 2019; Ingesti & Kusumawati, 2022; Silalahi et al., 2024). As one of the main export commodities, cocoa contributes significantly to income generation for smallholder farmers and to national economic development. However, cocoa productivity remains highly variable and is often constrained by both biotic and abiotic factors, particularly pest infestations, which can lead to substantial yield losses and reduced bean quality (Lea et al., 2022; Kongor et al., 2024). In many tropical production systems, pest pressure is considered one of the most critical limiting factors affecting sustainable cocoa production (Cilas & Bastide, 2020).

The dynamics of pest infestation in cocoa agroecosystems are strongly influenced by environmental heterogeneity, including variations in topography, vegetation structure, and microclimatic conditions (Acheampong et al., 2019). Differences in land characteristics such as slope, elevation, and canopy cover can significantly modify key environmental variables, including light intensity, air temperature, humidity, and soil moisture. These microenvironmental changes can directly or indirectly affect pest development, reproduction, and survival, as well as plant physiological responses and susceptibility to pest attacks (Zignol et al., 2023). In addition, variations in habitat complexity associated with different land types may influence the availability of shelter and food resources for pests, thereby shaping their population dynamics and infestation patterns.

Previous studies have demonstrated that changes in microclimate and physical land conditions can increase plant vulnerability to major cocoa pests, such as cocoa pod borer (*Conopomorpha cramerella*), sap-sucking insects including mealybugs, and defoliating caterpillars (Yudiansyah et al., 2021; Sembiring & Dinata, 2024; Triwidodo & Supramana, 2025). These pests can cause significant damage to cocoa pods and leaves, leading to reduced productivity and economic losses for farmers. However, most of these studies have focused on specific pest species or controlled environmental conditions, and less attention has been given to how broader land characteristics influence overall pest infestation patterns under real field conditions in smallholder systems (Meilin et al., 2024).

In Indonesia, particularly in regions such as Mangunan, Bantul, Yogyakarta, cocoa is predominantly cultivated under smallholder management systems characterized by diverse land conditions, including sloping areas, flat lands, and shaded environments (Sitohang et al., 2024). These heterogeneous landscapes create distinct microclimatic environments that may influence pest incidence and severity (Kesumawati et al., 2023; Ramos et al., 2024). However, despite the ecological importance of these variations, information on how different land types affect pest infestation levels in cocoa plantations in this region remains limited. This knowledge gap is critical, as understanding the relationship between land characteristics and pest dynamics is essential for developing effective and site-specific pest management strategies in smallholder cocoa agroecosystems.

Therefore, this study aims to analyze and compare pest infestation levels across three different land types (sloping, flat, and shaded areas) in smallholder cocoa plantations, and to evaluate how land characteristics contribute to variations in infestation patterns. The findings of this study are expected to provide both scientific insights and practical implications for the development of adaptive, ecologically based pest management strategies, and to support decision-making by farmers, extension agents, and future research in tropical cocoa production systems.

MATERIALS & METHODS

This study was conducted in November 2025 over three observation periods in the Mangunan area, Bantul, Yogyakarta, Indonesia, to assess pest infestation levels in cocoa across three land types: sloping, flat, and shaded areas. The study area is characterized by a tropical climate with heterogeneous land conditions and varying canopy cover typical of smallholder cocoa systems. Pest sampling was performed using two approaches: direct visual observation and manual collection, and yellow sticky traps.

Direct observation involved inspecting each tree in the morning and recording pests found on leaves, fruits, stems, and canopies, following established entomological sampling procedures (Gonthier et a, 2014; Gullan & Cranston, 2014; Altieri et al., 2009). Yellow sticky traps (e.g., 20 × 25 cm) were installed on each sample tree at approximately 1.5–2 m above ground within the canopy and left in place for 12 hours before counting captured insects. One trap was used per tree.

In each land type, cocoa trees were selected as sampling units using a systematic approach along plantation rows. Trees were selected at regular intervals based on field accessibility and the availability of productive plants, to reflect actual farmer-managed conditions. A total of 14–26 trees were observed in each land type due to differences in tree availability across sites. The same trees were repeatedly observed across the three sampling periods to ensure consistency. Each tree served as an observation unit for fruit counts and pest assessment.

Infestation level was determined by recording the total number of fruits and the number of infested fruits per tree. Infested fruits were identified based on consistent visible symptoms, including boreholes, discoloration caused by sap-sucking insects, and other pest-related damage. Infestation percentage was calculated as the proportion of infested fruits relative to the total fruit count. Pest observations were used as supporting data to confirm infestation presence.

All data were systematically recorded for analysis. This approach allowed comparison of infestation levels among land types through comparative observational sampling across distinct land typologies using stratified sampling based on land characteristics. Such an approach is supported by previous studies showing that agroecological factors, including canopy structure and environmental conditions, significantly influence pest incidence in cocoa systems (Rizali et al., 2022; Hernández-Nuñez et al., 2024). A Chi-square test of independence ($\alpha = 0.05$) was used to evaluate the association between land type and infestation status. Post-hoc pairwise comparisons were conducted using 2 × 2 contingency tables to identify differences between specific land types.

RESULTS & DISCUSSION

Clear differences in pest infestation intensity were observed across the three land types—sloping, flat, and shaded cocoa areas. Observed parameters included total pod number per tree, number of infested pods, and infestation percentage. Among the pests recorded, mealybugs (Pseudococcidae) were the most dominant across all land types and were associated with the highest proportion of infested fruits. *Helopeltis* spp. were also frequently observed but showed lower infestation intensity, while nettle caterpillars (*Sethora nitens*) and bagworms (*Mahasena* spp.) occurred sporadically. Detailed pest occurrence in shaded, sloping, and flat areas is presented in Supplementary Tables S1, S2, and S3, respectively.

As shown in Table 1, shaded and sloping areas exhibited higher infestation intensity (43.86% and 43.56%, respectively) compared to flat areas (28.97%). This pattern was consistent across observation periods. The higher infestation levels in sloping and shaded areas suggest that land characteristics may influence pest incidence, potentially through differences in plant condition and habitat suitability. The difference in infestation between flat and other land types reached approximately 14–15%, indicating a substantial reduction in infestation under flatter conditions.

Table 1. Pest attack intensity by land type

Land type	Total fruits	Infested fruits	Mean attack (%)
Shaded	57	25	43.86
Sloping	101	44	43.56
Flat	107	31	28.97

The dominance of mealybugs indicates that sap-sucking pests play a major role in shaping infestation patterns in the study site. This dominance highlights the importance of targeting sap-sucking pests as a priority in cocoa pest management strategies. Mealybug infestations were observed on both young and mature pods and were often associated with ant activity. *Helopeltis* spp. caused characteristic necrotic lesions on pod surfaces, indicating potential economic damage despite lower infestation levels. In contrast, nettle caterpillars and bagworms contributed minimally to direct pod damage but may still affect plant performance through defoliation. At the tree level (see Tables S1-S3), substantial variability in infestation intensity was observed, with several trees exhibiting complete infestation (100%), particularly under low fruit load conditions, indicating increased vulnerability at the individual plant level. Representative field observations are shown in Figure 1.

Figure 1. Representative field observations illustrating pest occurrence, biological interactions, and monitoring tools in cocoa agroecosystems. (a) Yellow sticky trap used for insect monitoring; (b) nettle caterpillar (*Sethora nitens*) feeding on cacao leaf; (c) weaver ants (*Oecophylla smaragdina*) associated with biological control activity; (d) mealybug infestation on cacao pod.

Observations from yellow sticky traps indicated that most captured organisms were non-target arthropods such as spiders, ants, and mosquitoes, with relatively few individuals belonging to key cocoa pests. This suggests that yellow sticky traps may have limited effectiveness for detecting major cocoa pests under the observed conditions. However, as

no statistical comparison between sampling methods was conducted, these observations should be interpreted cautiously.

Ecologically, the higher infestation observed in sloping and shaded areas may be associated with differences in plant condition, canopy structure, and habitat suitability that favor pest development. Sloping areas, in particular, may experience increased plant stress due to soil instability and drainage dynamics, potentially increasing susceptibility to pest attack. Meanwhile, shaded environments may provide favorable microhabitats for sap-sucking insects. This interpretation is supported by the heterogeneous infestation patterns observed at the tree level (Tables S1-S3), where both pest presence and infestation intensity varied substantially within and across land types.

However, environmental variables such as temperature, humidity, and light intensity were not directly measured in this study. Therefore, these explanations should be considered as ecological interpretations supported by previous studies (Holthouse et al., 2021; Böckmann et al., 2021; Stevania et al., 2024; Nagaraj et al., 2025) rather than direct causal evidence. These findings provide field-based evidence that land type can act as a practical ecological indicator for pest risk in smallholder cocoa systems.

The presence of beneficial insects such as the weaver ant (*Oecophylla smaragdina*) suggests a potential ecological role in pest suppression. Weaver ants are known to function as effective predators, contributing to biological control in cocoa ecosystems, whereas certain ant species associated with mealybugs may facilitate pest proliferation through mutualistic interactions (Peng & Christian, 2004; Falahudin, 2012; Offenberg et al., 2013; Gonthier et al., 2014; Correa et al., 2023). These interactions highlight the importance of considering ecological complexity in pest management strategies.

Statistical analysis using the Chi-square test indicated a marginal association between land type and infestation level (χ^2 (2, N = 265) = 5.87, p = 0.053). However, pairwise comparisons revealed that infestation in flat areas was significantly lower than in sloping areas (p = 0.029), while no significant differences were observed between shaded and sloping or shaded and flat areas. These findings indicate that, although the overall association is weak, land type may still influence infestation through specific ecological contrasts between sites.

Variability in infestation levels among individual trees was also observed, where trees bearing fewer fruits tended to exhibit higher proportional infestation, in some cases reaching up to 100%. This suggests that low-yield trees may be more vulnerable to complete loss under pest pressure. Taken together, the findings indicate that pest infestation in smallholder cocoa systems is strongly influenced by land characteristics and associated ecological interactions. Shaded and sloping environments likely provide more stable humidity and temperature conditions, which are known to enhance pest survival and reproduction rates. In addition, increased canopy cover may reduce exposure to natural enemies, thereby facilitating higher infestation levels. These ecological mechanisms highlight the importance of implementing site-specific Integrated Pest Management (IPM) strategies, particularly in sloping and shaded areas where infestation risk is elevated. Practices such as targeted pruning to reduce excessive shading, removal of infested pods (sanitation), and conservation of natural enemies (e.g., predatory ants) should be prioritized based on land-specific conditions to improve pest control effectiveness.

CONCLUSIONS

Field observations in Mangunan, Bantul, Indonesia, confirm that cocoa pest infestation is influenced by land type, with higher infestation levels consistently observed in shaded and sloping areas compared to flat areas. Mealybugs (Pseudococcidae) were identified as the dominant pest across all sites, followed by Helopeltis spp., while nettle caterpillars (Sethora nitens) and bagworms (Mahasena spp.) occurred at lower frequencies. These findings indicate that land characteristics play a significant role in shaping pest infestation patterns, likely through their influence on plant condition and habitat suitability within smallholder cocoa systems. Although the overall statistical association was

marginal, specific differences between land types highlight ecologically relevant patterns that warrant further investigation. From a practical perspective, the results emphasize the importance of site-specific Integrated Pest Management (IPM), particularly in sloping and shaded areas where infestation risk is higher. Management strategies should prioritize canopy regulation, plantation sanitation, and conservation of natural enemies to improve pest control effectiveness. Future research should focus on directly measuring environmental variables such as microclimate and soil conditions to better understand the mechanisms underlying land type–pest interactions and to refine adaptive management strategies for sustainable cocoa production.

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