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The effect of shade and full-sun coffee plantation on coffee berry borer, *Hyphothenemus hampei* (Coleoptera: Curculionidae) population dynamics

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Abstract. The coffee berry borer (CBB), *Hypothenemus hampei* (Ferrari), is a significant pest impacting coffee-producing regions globally, causing substantial yield and economic losses. Various factors, including the host plant, environmental conditions, and farm management practices, influence CBB infestation. In particular, smallholder farmers often employ different shade management techniques, creating distinct biotic and abiotic conditions that affect CBB damage, distribution, and reproduction. This study aims to assess CBB populations in coffee berries across different locations within the plots, specifically on branches during harvest, post-harvest, and on the ground. The study was conducted in Pangalengan District, Bandung Regency, West Java. The study indicated that both shade and full-sun areas had a significant effect on CBB population dynamics. Coffee has significantly increased infestation rates in full-sun areas, and rapid populations were established, especially adult CBB. However, the shaded area was not suitable for CBB breeding. Nevertheless, though the populations of adult stages decreased markedly, the number of larval CBB with these two periods was still quite appreciable. Based on these findings, the shaded areas are suggested as an effective ecological strategy for managing CBB populations and reducing crop losses in coffee farming.

Keywords: harvest and post-harvest period, life stage composition, pest management, shade management, West Java

1. Introduction

Coffee holds a central position as the primary agricultural product for millions of smallholder farmers in Indonesia, contributing significantly to the nation's economic development. Smallholder farmers deal with declining coffee margins, labor shortages, pest infestations, and climatic unpredictability [1]. One of the most important insect pests affecting coffee plantations in Indonesia is coffee berry borer (CBB), *Hypothenemus hampei* Ferrari [2]. CBB does not attack other crops. It causes losses of as much as 22-73% in Indonesia [3] and in different countries, it could even reach 90-100% [4]. Adult female insects lay eggs by creating a hole in coffee berries, allowing the larvae to feed on the seeds. This feeding behavior compromises crop yields, diminishes seed quality, and may lead to the premature detachment of the berries [5].

The CBB completes its life cycle within coffee berries, making it especially difficult to control through chemical and non-chemical methods. An Integrated Pest Management (IPM) approach involves multiple components, such as monitoring, cultural harvesting practices, using *Beauveria bassiana*, parasitoid release, post-harvest control, and pest management during rejuvenation processes [6]. Other obstacles to CBB management are intricate and stimulated by ecological limitations such as temperature, humidity, and altitude, which enforce limits on CBB infestations. Warm weather counterparts with shortened life cycles will have more generations yearly, whereas cooler conditions at higher elevations slow their development. On the other hand, CBB management is further hindered by microclimates within the coffee plantations, such as shade management.

There are countless types of shade management practices associated with coffee production, especially by smallholder farmers. Shade and full-sun coffee areas exhibit different biotic and abiotic environments affecting the damage, distribution, and reproduction of agronomic-important pests of coffee [7,8]. Several empirical studies have explored the impact of coffee agroecosystems on the expression or suppression of CBB incidence. There are reports in the literature some authors mention the shade favors CBB infestation [8,9], and others state that the positive effect of the shade on CBB is also influenced by differences between shade levels, canopy tree species [10], and coffee management [11]. By contrast, others have discovered more CBB infestation in full-sun coffee [7] or no significant impacts [12]. Understanding how shade and full-sun environments affect CBB populations is crucial for developing IPM strategies. Grasping this mechanism is also essential for fostering sustainable coffee production and potentially reducing reliance on chemical control methods.

The coffee berries are found in different supports inside the areas: berries in branch nodes, residual berries on the ground, and remaining berries on trees after harvesting. Coffee berries that naturally wither on trees or fall to the ground after harvest can serve as a reservoir for adult CBB beetles for up to 156 days [13]. CBB may also survive on the berries (drying berries) or the beans (post-harvest treatment). These different supports are the sites of origin from which females CBB will move to colonize new berries. As mentioned in the IPM strategy, residual berries present on various support- branch and ground supports which are encouraged to manage training to boost the overall population of CBB into farms were picked by hand. To achieve a more accurate understanding of the impact traditional farming practices have on CBB population dynamics, this study examined the effects of shaded versus full-sun areas on the CBB population within coffee berries on various supports in local coffee plantations in Pangalengan District, Bandung Regency, West Java, Indonesia.

2. Materials and Methods

2.1 Study site

This study was conducted in Pangalengan District, Bandung Regency, West Java, from June to December 2023. On this site, the minimum and maximum temperatures range from 18.29 to 26.17 °C, with an average temperature of 22.33 °C. Additionally, the area experiences an average cumulative rainfall of approximately 188.97 mm in a tropical climate. Based on the survey, the elevation of coffee plantations in Pangalengan is between 1000 and 1600 m asl (meters above sea level) by various varieties: Sigarar Utang, Lini S, Ateng Super, Prianger Andungsari, and Tim-Tim. The Sigagar Utang variety has greater resistance to CBB infestations compared to other coffee varieties. Coffee is grown within the coffee agroforestry system, a multi-strata agroforestry system that includes pine forests (*Pinus merkusii*) and teak forests (*Eucalyptus* sp.). The main shade trees used in the coffee plantations are generally *Inga* spp, *Cedrela lilloi*, and *Persea americana*. Some coffee farms are grown in full-sun areas using poli-culture with horticulture. Coffee farms are easily within reach of each other, just a thin sliver of 1 to 2 meters spaces. Coffee flowering is between October and November, and harvest season is from May to August, peaking around June most often. Conventional, organic, and integrated management are coffee management practices used in the Pangalengan district.

2.2 Selecting plots

The study plots were decisively selected based on the presence of Arabica coffee plantations at the farm level. In total, ten study plots were selected in full-sun area (exposed to full-sunlight) and shade area distributed along a gradient between 1000 and 1400 m asl in three subdistricts (Lamajang, Margamulya, and Pulosari). This elevation is especially linked to catastrophic CBB infestation on Arabica and Robusta coffee plantations. See the information on the selected plot in Table 1:

Table 1. Information on plot selection

Plots	Subdistrict	Coordinate	Elevation (m asl)	Type of management
P1	Lamajang	7°07'44"S107°33'02"E	1000	Shade
P2	Lamajang	7°07'53"S107°33'04"E	1048	Shade
P3	Pulosari	7°10'26"S107°33'20"E	1389	Shade
P4	Margamulya	7°09'26"S107°33'50"E	1275	Shade
P5	Margamulya	7°09'30"S107°33'39"E	1261	Shade
P6	Lamajang	7°07'58"S107°32'53"E	1086	Full-sun
P7	Pulosari	7°10'30"S107°33'23"E	1400	Full-sun
P8	Margamulya	7°09'37"S107°33'43"E	1263	Full-sun
P9	Margamulya	7°09'43"S107°33'37"E	1256	Full-sun
P10	Margamulya	7°09'33"S107°33'27"E	1214	Full-sun

2.3 Sampling of coffee berries

The coffee berry samples were selected using purposive sampling to ensure that only berries infested with CBB were included. As many as 100 infested coffee berries were collected from different supports: branches and ground. The dataset was built in two different types of coffee management, full-sun, and shade area, which let us contrast how its infestations differ by different microclimates. To obtain a representative sample of CBB infestation at various phenological stages of the coffee plant, the sampling process was divided into several phases. This involved both the active harvesting season, when berries were being picked, and the post-harvest period, which increased the likelihood of leftover and overripe berries falling to the ground.

2.4 The level of damage coffee berries

To determine the degree of infestation, the percentage of damage made by CBB was proportionally evaluated for each coffee berry. In the laboratory, each collected berry is sliced lengthwise and thoroughly assessed for damage. The damage score of coffee berries is as follows:

Table 2. Damage score of coffee berries infested by CBB

Score	**Criteria**
0	No damage to coffee berries
25	Light damage (minor signs of CBB infestation, minimal tunneling or scars)
50	Partially damaged (half of the coffee berries are infested by CBB)
75	Severely damaged (at least three-quarters of the coffee berries are infested by CBB)
100	Completely damaged (the entire coffee berry is infested and destroyed by CBB)

2.5 CBB population per berry

The evaluation of CBB internal damage throughout its lifecycle is identified by the presence of CBB within the berry. This activity aims to assess the CBB population in coffee berries on various supports within the plots, specifically on branches and ground during harvest and post-harvest. Each coffee berry is split in the laboratory and all CBB stages, including egg, larvae, pupae, and adults (male and female), are observed.

2.6 Ripeness of coffee berries

Additionally, data on the external characteristics of coffee berries' color are also observed. The color of the coffee berry is a good indicator of ripeness, which in turn has been correlated with how much CBB likes berries at different degrees of ripeness. The berries are categorized into various stages of ripeness (table 3), and we can begin to correlate berry maturation with CBB population density.

Table 3. The ripening scale of coffee berries

Scale	Color Grade
Unripe	All parts of the coffee berries are green.
Semi-ripe	All parts of the coffee berries are yellow and some parts of the coffee fruit are red, including greenish-red or yellowish-red
Ripe	All parts of the coffee berries are red.
Overripe	All parts of the coffee berries are dark or blackish-red.

2.7 Statistical analysis

A comprehensive statistical analysis of the data was undertaken to evaluate a relationship between the damage level of coffee berries, coffee berry ripeness, shading areas, and the population dynamics of CBB. Pearson correlation coefficients were calculated to assess the strength and direction of associations between shading type (shaded vs. full-sun) and total CBB populations across all life stages. Descriptive statistics were also computed to summarize the mean population counts of CBB life stages—eggs, larvae, pupae, and adult females—under both shaded and full-sun areas during harvest and post-harvest periods. Data were analyzed and visualized using the RStudio program version 2023.06.2.

3. Results and Discussions

3.1 The level of damage berries infested by CBB

Coffee berry damage caused by CBB infestation is significantly higher in full-sun areas compared to shaded areas (Figure 1). The mean damage percentage in all phases was higher in the full-sun area, ranging from 40.25% for branches in the harvest to 100% post-harvest. Ground samples in the full-sun area during harvest showed an 85.45% damage rate, indicating slightly less damage than the post-harvest ground samples, which had a 76.9% damage rate. Damage levels were consistently highest in full-sun areas starting from post-harvest, while significantly lower at all post-harvest stages in shaded areas, with mean percentages ranging from 43.3% (harvest - branch) to 88.25% (post-harvest - branch). These findings might be due to the impact of microclimatic variables, such as lower temperatures and relative humidity, which are regulated in the shaded areas. These areas do not support the rapid population growth of CBB [14–16].

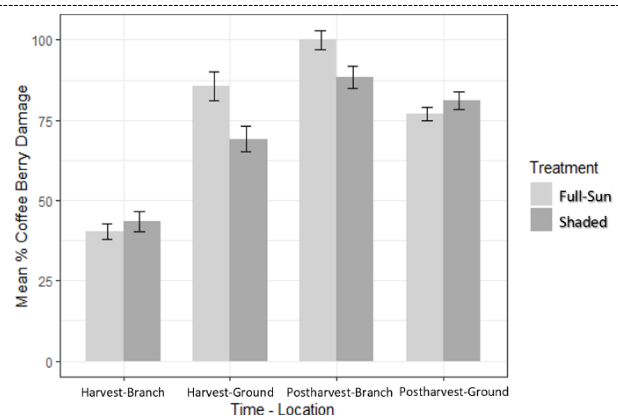

Figure 1. Mean percentage of coffee berry damage caused by CBB infestation.

These differences between full-sun and shaded areas indicate that higher temperatures associated with lower humidity in areas more exposed to sunlight could provide CBB with an environment where it can thrive. It aligns with previous studies indicating that higher temperatures can reduce the generation times of the CBB, thereby accelerating its population growth [17]. By contrast, shaded coffee plantations may support a less conducive environment for the development of the CBB population, since their cooler microclimates impact the life cycle and infestation rates of this pest [18]. Shade-grown coffee systems, where coffee is cultivated under a canopy of trees such as agroforestry systems, create relatively favorable conditions that provide habitats and support abundant and diverse communities of native natural enemies, thereby enhancing the potential for CBB suppression [19,20,21]. According to [22], open farming systems, such as pastures and full-sun coffee plantations, can promote the dispersal of CBB. This increased movement facilitates infestation across nearby coffee farms, especially when suitable host plants are available and environmental conditions favor CBB survival and reproduction. All this evidence strongly supports implementing shade-grown coffee systems as a critical strategy to manage CBB and minimize crop losses. This aligns with sustainable agriculture by reducing the damage to berries from pest issues, boosting biodiversity, and supporting ecosystem balance.

3.2 Composition of CBB stage within the coffee berries in the shaded and full-sun area

The stages of CBB in coffee berries were analyzed under shaded and full-sun areas during the harvest and post-harvest periods. The data show distinct spatial patterns of CBB life stages among coverage, which carry ecological meaning — shaded vs. full-sun effects on CBB population dynamics (Figure 2).

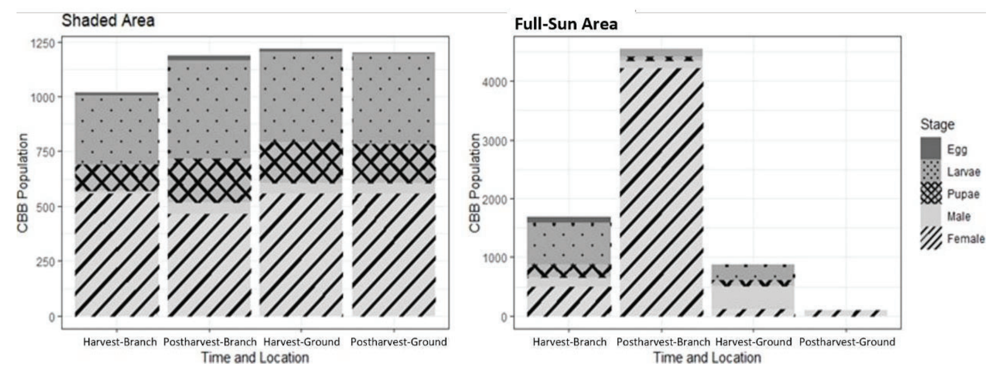

Figure 2. Composition of CBB stages within the coffee berries in shaded and full-sun areas.

During the collection period, the average population of CBB life stages consisted of 27 eggs, 726 larvae, 306 pupae, and 1,095 adult females, with their sex noted on both branches and the ground. It suggests an increased number of larvae, implying that a microhabitat has developed that supports the larval stages. It could be due to the more moderate temperatures and humidity conditions in shaded areas, promoting larval survival [23]. The adult female population in the field, particularly in shaded areas, significantly influenced the total CBB population due to the high reproduction rates of CBBs in these environments. Full-sun treatments also showed slight differences in CBB stages compared to the shaded treatment. The harvest data showed that the branches and ground samples recorded 102 eggs, 712 larvae, 222 pupae, 487 adult females, and 36 adult males, while for ground samples — there were found only a few numbers of eggs (5); larvae (265), pupae (86), female adults (399) and male adults (117). During post-harvest, the adult female count in the branch samples reached a remarkable 4,222, indicating a rapid and dense population buildup. Indeed, these results align with studies showing that the CBB may mature more quickly and have a higher survival rate in adult stages under full-sun areas, likely due to the favorable microclimate [7].

The results indicate that larvae thrive better in shaded areas, while more adult CBBs were observed in full-sun areas. Our findings show new aspects in the demographic trends related to CBB, highlighting that adopting agronomic practices to minimize CBB dispersal may reduce economic losses from these infestations. Nevertheless, the significant rise in adult females in full-sun areas is alarming for those developing control strategies in these systems, as the rapid population growth could pose a serious threat to coffee production. This aligned with [5,14] that coffee cultivation in full-sun areas can support the rapid population growth of CBB.

The Pearson correlations were analyzed between the type of coverage (Shade = 0, Full-sun = 1) and the total CBB population, which included all life stages: egg, larva, pupa, adult female, and male. This regression analysis (Figure 3) revealed a significant positive association between full-sun coverage and total CBB population (p-value = 3.52e-04), as demonstrated by the fitted line shown with its associated 95% confidence interval. This trend indicates that when shade is lost, the coverage of the total CBB population tends to increase. It is probably due to the environmental conditions in full-sun areas being more favorable for the survival and reproduction of adult CBBs. Such dynamics are consistent with previous research that has demonstrated the impact of abiotic factors, such as temperature and humidity, on pest development rates and population density in coffee systems [5]. Shade also has antagonistic effects on CBB. According to a previous study [11], this fungus is highly effective in controlling CBB populations by infecting and killing the beetles. In shaded areas applied with *B. bassiana*, fewer coffee berries were damaged, while the absence of this biological control can lead to increased CBB populations even in shaded areas. It highlights the importance of integrating shade with effective pest management practices to maximize the benefits of shade-grown coffee in controlling CBB populations and minimizing crop losses.

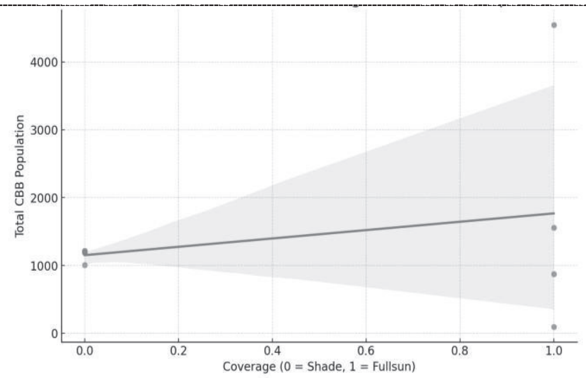

Figure 3. Correlation between coverage and total CBB population.

3.3 Relationship between coffee berry ripeness and CBB population in the shaded and full-sun area

The ripeness of coffee berries explained the majority of the variation in infestation rates of CBB, and there is a clear relevance through different ripeness stages for pest management strategies. The results (Figure 4) show that overripe berries consistently have the highest CBB population. There is a noticeable increase in the CBB population post-harvest, particularly in full-sun areas, with a total of around 4500–5000 CBBs, compared to approximately 2500–3000 CBBs in shaded areas. Conversely, ripe and semi-ripe berries exhibited declining rates of CBB infestations, with unripe berries showing little to no CBB population. It is a well-known fact that CBB can do its worst on overripe berries, providing ideal conditions for CBB reproduction and survival in the post-harvest period, when berry moisture levels and environmental features all contribute to an environment conducive to pest multiplication. [24] investigated postharvest CBB population reservoirs in Hawaii, discovering that leftover berries on trees had significantly higher CBB populations.

Several studies in various coffee-producing regions have shown that the CBB infestation selectively targets ripe and overripe berries, occupying the space between larger seeds and providing more resources for their development [17]. CBB females tend better toward ripeness compared to immaturity because of emitting attractive kairomones, which draw the highest levels of infestation. Ripe berries draw up to 30% more CBB than other stages [25], primarily due to the higher levels of alcohol, such as ethanol, emitted during ripening. Alcohols are significant volatiles released by coffee berries throughout their maturation stages [26]. Ripeness is a critical factor for CBB infestation; thus, managing the ripeness of coffee berries, especially ripe and overripe ones, may be essential in reducing CBB infestations and ensuring higher production standards for this crop, as suggested by recent research studies. The significant increase in CBB populations within overripe berries and during post-harvest emphasizes the need for an IPM approach that considers berry ripeness. This finding highlights the critical importance of early harvesting and improved post-harvest practices to effectively minimize CBB infestations, particularly in full-sun coffee systems.

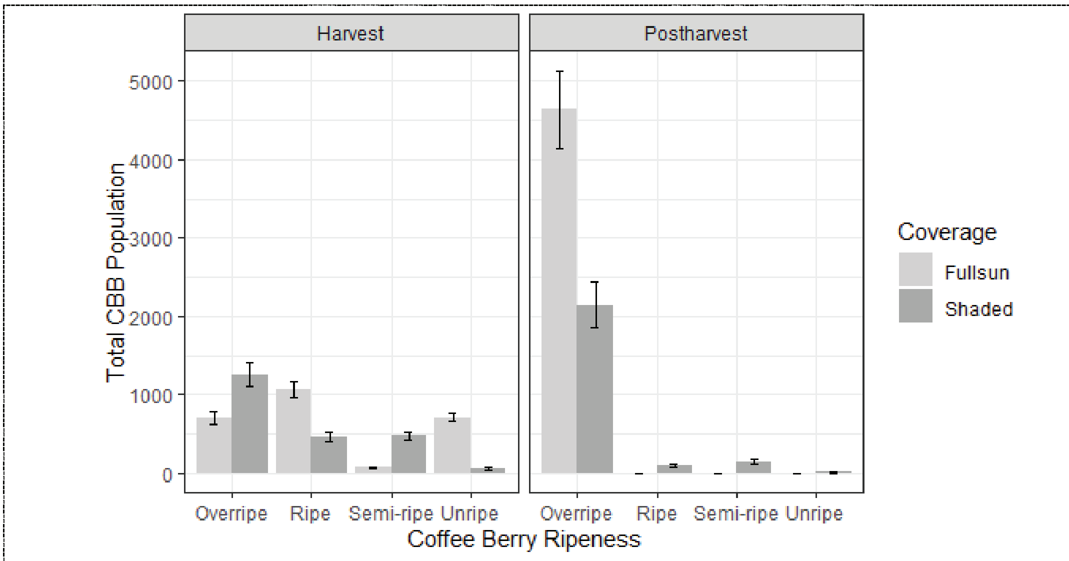

Figure 4. CBB population densities in coffee berries at different ripeness in shaded and full-sun areas.

This result also shows that full-sun areas are much more likely to support increases in CBB populations than shaded ones. Environmental factors, such as sunlight exposure, significantly influence CBB dynamics. The shaded area showed fewer CBB infestations than the full-sun area. This variation was influenced by microclimatic differences, which can affect the behavior and reproductive success of the CBB [8]. Furthermore, the data indicates that berry ripening and environmental factors may affect the decision to implement an IPM program. Due to the strong correlation between the stage of ripeness and the rates of infestation by CBB, we concluded that coffee production management should focus on implementing effective control strategies for CBB. It is especially significant in full-sun and shaded areas, which coffee growers often prefer. Effective pest population management in these environments can lead to overall improvements in both coffee yields and quality. It aligned with [27] that effective management systems can sustain the important pest and disease regulation services within coffee plantations. By managing coffee farms, it is possible to reduce the negative impacts of climate change on pest and disease control services.

4. Conclusion

This study underscores that the shade-grown coffee systems are key to minimizing CBB infestations and timely post-harvest management is essential for preventing crop losses, suggesting that shading and timely management may serve as an effective ecological strategy for controlling CBB populations and minimizing crop losses in coffee production. The application of shade-based management strategies not only contributes to the control of CBB but also supports sustainable coffee farming practices in the long term.

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