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DYNAMICS AND DISTRIBUTION POPULATIONS OF PEST Hypothenemus hampei Ferr. BASED ON THE MATURITY OF COFFEE GAYO ARABICA BEANS

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ABSTRACT

Hypothenemus hampei (Ferrari) or coffee berry borer (CBB) is a major coffee pest that causes serious damage to coffee berry, particularly in the Gayo Arabica coffee production center in the Gayo Highlands, Province of Aceh. This study aims to evaluate the dynamics and distribution populations of coffee berry borer based on maturity level of Gayo Arabica coffee berries at various altitudes. The study was conducted at plantations coffee Arabica in Bener Meriah Regency at altitudes of 750–1500 meters above sea level. The coffee berry borer population was observed on coffee berries categorized into three maturity levels (unripe, semi-ripe, and ripe), and was observed for 12 weeks. The results showed that coffee berry borer attacked coffee berries at all maturity levels, with population distribution varying according to developmental stage and elevation. Egg populations were more numerous in unripe fruit, larvae were dominant in unripe berries, and pupae and adults were more numerous in ripe berries. The distribution pattern of coffee berry borer at all maturity levels showed a clustered pattern in all altitude locations. Regression analysis showed that temperature significantly affected the adult population at all maturity levels. Based on these findings, coffee berry borer control focused on the middle to ripe fruit, particularly in lowlands, and a spatially based monitoring approach was employed. These results provide an important basis for developing an Integrated Pest Management (IPM) strategy based on fruit phenology and pest population ecology.

1. INTRODUCTION

Aceh Province is known as a center of Arabica coffee production, located in the Gayo Highlands, includes the regencies of Bener Meriah, Central Aceh, and Gayo Lues. Gayo Arabica coffee boasts superior quality and a strong reputation, bolstered by the commitment of local farmers to maintaining crop quality (Purba *et al*., 2020; Hendrival *et al*., 2022). Gayo Arabica coffee is a superior Indonesian coffee that has been recognized globally, with its distinctive flavor and high international market value (Meisetyani *et al*., 2021). As a local variety, Gayo Arabica coffee demonstrates optimal adaptation to highland agro-ecosystem conditions, contributing to its distinctive flavor. Cultivation of this coffee has become an essential part of the Gayo people and has developed into a leading export commodity. For the Gayo people, Arabica coffee serves not only as a primary source of income but also as an essential element in the economic and cultural aspects of daily life (Asis *et al*., 2020). The unique characteristics of Gayo Arabica coffee are closely related to the chemical content of its beans, which is influenced by environmental factors, such as the altitude of the cultivation site (Saputri *et al*., 2020). Arabica coffee planting areas are generally located at an altitude of 950 to 1450 meters above sea level (Hulupi *et al*., 2013). However, the low productivity of Gayo Arabica coffee is technically caused by several factors, such as the dominance of old coffee plant and unproductive plants (>30 years), land saturation due to continuous cultivation without rotation, the impact of global climate change that triggers temperature increases in the Gayo Highlands, the presence of heterogeneous varieties, and attacks by coffee berry borer pests (Hendrival *et al*., 2024).

Hypothenemus hampei (Ferrari) (Coleoptera: Curculionidae: Scolytinae), known as the coffee berry borer (CBB), is one of the most destructive pests in coffee cultivation globally, including in Aceh Province, Indonesia (Johnson *et al*., 2020; Ruiz-Diaz & Rodrigues, 2021; Hendrival *et al*., 2022; Fotso Fotso *et al*., 2023). Damage begins after the female beetle bores holes in the coffee berry, constructs galleries in the endosperm, and lays eggs (Vega *et al*., 2015; Constantino *et al*., 2021). Females of CBB beetles can infest unripe fruit during periods of high infestation and wait until the endosperm contains more than 20% dry matter before entering the beans (Pereira *et al*., 2021). After hatching, the larvae begin to feed on the endosperm tissue of the beans (each coffee berry contains two beans), thus reducing yield and marketable product quality. Male beetles have reduced wings and remain inside the coffee berry for their entire life (Damon, 2000), while inseminated females emerge and seek out other berries in which to lay their eggs (Vega *et al*., 2010). A typical sign of PBKo infestation is the presence of a fine powder or pollen around small holes on the surface of the berry. In addition to damaging the berry in the field, PBKo can also attack coffee during post-harvest storage in warehouses (Martínez *et al*., 2012; Moreno-Ramirez *et al*., 2024).

The dynamics of the CBB pest population are influenced by environmental conditions such as coffee plant factors and the physical environment. Plant factors include coffee berry phenology and the coffee growing system, while natural enemies relate to the diversity of natural enemies associated with CBB. Coffee plant phenology has implications for the CBB population, reproductive capacity, and the increase in the abundance of this pest population. The maximum population of this pest occurs at certain stages of the coffee fruit phenological cycle (Fernandes *et al*., 2015). This pest attacks coffee fruit at all developmental stages, from unripe fruit to ripe fruit (Fintasari *et al*., 2018). The development of the CBB population is more infested on ripe fruit than on unripe fruit because the fruit is affected by CBB for a longer period (Dufour *et al*., 2021). Environmental conditions in Arabica coffee plantations allow for continuous fruit production, thus dividing the harvest season into two seasons: a 6-month first half and a 6-month second half. These conditions contribute to the reproduction and development of CBB because coffee fruit is available year-round. The abundance of CBB is highest in monoculture systems, compared to agroforestry systems (Botelho *et al*., 2021). Coffee berry borers are poikilothermic organisms whose development and population size are proportionally dependent on temperature. Consequently, the economic losses caused by this pest to coffee crops are directly related to temperature and other environmental conditions.

Studies on the dynamics of the CBB population provide initial information for formulating an Integrated Pest Management (IPM) strategy aimed at increasing the productivity of Gayo Highlands Arabica coffee. Understanding CBB population dynamics allows for the planning of anticipatory measures against pest emergence throughout the season, identification of critical times for fruit damage, and the design of targeted management strategies. Research on CBB distribution patterns provides important information on spatial distribution and serves as an indicator for designing more effective monitoring strategies (Hendrival *et al*., 2022; Hendrival *et al*., 2024). Therefore, this study was conducted to examine the dynamics of the CBB population in relation to the maturity level of the coffee berry. The findings of this study are expected to be an important component in developing an IPM strategy for CBB pests in Gayo Arabica coffee. Specifically, this study aims to evaluate the dynamics and distribution of CBB populations based on the maturity level of Gayo Arabica coffee berries at various altitudes.

2. MATERIALS AND METHODS

2.1 Research Location and Time

This research was conducted in an Arabica coffee plantation area in Bener Meriah Regency, encompassing three sub-districts: Pintu Rime Gayo, Timang Gajah, and Bukit. The locations were categorized at elevations of 750-1000, 1000-1250, and 1250-1500 meters above sea level (m asl) (Table 1). Observation and sampling locations were selected on smallholder coffee plantations, with the following criteria: coffee plants in the productive phase, aged between 5 and 10 years, organically managed with shade trees, and planted with Arabica coffee of the Gayo 3 variety. Gayo 3 is the dominant variety in the area. In each sub-district, two coffee plantations were selected as observation and sampling points. Sample identification and analysis were conducted at the Plant Pest and Disease Laboratory, Faculty of Agriculture, Malikussaleh University. This research was conducted from July to September 2022.

Table 1. Elevation zoning of the distribution of Gayo Arabica coffee plantation locations in Bener Meriah Regency, Aceh Province

Elevation Zone	Elevation Range (m asl)	Elevation (m asl)	Latitude (LU)	Longitude (BT)	District	Village
High	> 1250	1332	04° 43' 0''	96° 53' 48''	Bukit	Delung Asli
		1361	04° 42' 34''	96° 41' 35''	Bukit	Tingkem Beyer
		1423	04° 43' 33''	96° 51' 26''	Bukit	Bale Atu
		1522	04° 40' 46''	96° 52' 6''	Bukit	Uning Bersah
Medium	1000-1250	1027	04° 45' 36''	96° 45' 37''	Timang Gajah	Lampahan
		1049	04° 45' 29''	96° 45' 54''	Timang Gajah	Lampahan
		1175	04° 44' 45''	96° 47' 2''	Timang Gajah	Kanine
		1215	04° 44' 34''	96° 47' 34''	Timang Gajah	Kanine
Low	750-1000	786	04° 53' 36''	96° 44' 28''	Pintu Rime Gayo	Taman Firdaus
		838	04° 52' 40''	96° 44' 28''	Pintu Rime Gayo	Bener Meriah
		882	04° 52' 47''	96° 45' 11''	Pintu Rime Gayo	Taman Firdaus
		937	04° 52' 15''	96° 45' 21''	Pintu Rime Gayo	Bener Meriah

2.2 Sample Plants

Observations of pest populations on coffee berries began with the determination of sample plants. Sample plants were identified using a transect approach, with five 100-meter transect lines spaced 5 meters apart. Sample plants were systematically selected at fixed intervals, every five coffee plants, resulting in five sample plants per transect. On each plant, four productive branches were designated as observation units, which could be young branches from the shoot or young branches growing from secondary branches. Branch selection was based on cardinal direction orientation, including branches facing north, east, south, and west (Hendrival et al., 2022). From each observation location, 80 ripe coffee berries (red), 80 semi-ripe coffee berries (yellow), and 80 unripe coffee berries (green) were collected, with a distribution of 24 berries per four branches on each effective sample tree (Hendrival *et al*., 2024).

2.3 Population Abundance

Observations of the coffee berry borer (CBB) population were conducted by collecting fruit showing symptoms of infection from sample plants. Fruit assumed to be infected were characterized by the presence of small holes at the tip of the fruit, caused by the activity of the female imago during egg-laying. Observations focused on all developmental stages: egg, larva, pupa, and imago. The coffee fruits observed were grouped based on maturity levels: unripe aged 3–4 months were green, semi-ripe aged 6–7 months were yellow, and ripe aged 8–9 months were red. Pest population identification and counting were conducted by splitting infested coffee berries at the Plant Pest and Disease Laboratory, Faculty of Agriculture, Malikussaleh University. Population data were represented as the number of individuals per branch on each tree. Data collection was conducted periodically at one-week intervals for 12 consecutive weeks.

2.4 Climate Data

All climate data (temperature, relative humidity, and rainfall) were obtained from the Malikussaleh Class III Meteorological Station, Malikussaleh Airport Meteorological Street, Muara Batu, North Aceh, Aceh Province. Daily climate variable data (minimum temperature (°C), average temperature (°C), maximum temperature (°C), minimum relative humidity (%), average relative humidity (%), maximum relative humidity (%), and rainfall (mm) were averaged for each sampling week. Information on climate data during the study is presented in Table 2.

2.5 Data Analysis

The study of the effect of coffee berry maturity on the CBB population was arranged in a randomized block design. The coffee berry maturity treatments consisted of unripe, semi-ripe, and ripe fruit. Each treatment was replicated 10 times (10 sample trees). Data on CBB populations and attacks, as well as coffee yield losses, were analyzed using analysis of variance and Duncan's Multiple Range Test (DMRT) at the 0.05 level. Regression analysis was used to analyze the relationship between the CBB population as the independent variable (x) and the physical factor, temperature as the dependent variable (y), based on the phenology of the coffee berry: unripe, semi-ripe, and ripe fruit. The analysis of CBB pest patterns and distribution used different methods: the variance ratio index, the Morisita index, the Lloyd's index, the Green coefficient, and the Negative Binomial distribution index (Table 3). Each index was calculated using the following formula (Costa *et al*., 2010).

$$\text{Variance Ratio Index } (I) = \frac{s^2}{\bar{x}} \quad (1)$$

$$\text{Lloyd's Index } (\dot{m}) = \bar{x} + \left[\left(\frac{s^2}{\bar{x}}\right) - 1\right] \quad (2)$$

$$\text{Morisita's Index } (I_d) = n\left[\frac{\sum x^2 - \sum x}{(\sum x)^2 - \sum x}\right] \quad (3)$$

$$\text{Green's Coefficient } (C_x) = \frac{\left(\frac{s^2}{\bar{x}}\right) - 1}{(\sum x - 1)} \quad (4)$$

$$\text{Negative Binomial Distribution } (k) = \frac{\bar{x}}{(s^2 - \bar{x})} \quad (5)$$

Table 2. Average temperature (°C), relative humidity (RH) (%), and rainfall (mm) during 12 weeks of sampling (July to September 2022) in Pintu Rime Gayo, Timang Gajah, and Bukit Districts, Bener Meriah Regency, Aceh Province

Time (week)	Rainfall (mm)			Temperature (°C)			RH (%)		
	Pintu Rime Gayo	Timang Gajah	Bukit	Min.	Average	Max.	Min.	Average	Max.
1 (1-7 Jul 2022)	4.63	2.00	2.50	27.00	27.57	28.20	80.00	81.86	87.00
2 (8-14 Jul 2022)	2.00	0.00	0.00	27.00	27.71	28.40	78.00	81.29	84.00
3 (15-21 Jul 2022)	34.00	0.00	4.00	26.00	27.16	27.90	77.00	81.43	88.00
4 (22-28 Jul 2022)	29.29	31.50	16.57	25.80	26.31	26.60	83.00	86.14	90.00
5 (1-7 Aug 2022)	5.75	0.00	4.00	23.60	26.64	28.10	78.00	82.00	86.00
6 (8-14 Aug 2022)	0.00	0.00	2.00	26.70	27.14	27.60	78.00	81.71	84.00
7 (15-21 Aug 2022)	24.13	5.00	3.67	25.70	26.84	27.60	81.00	83.43	87.00
8 (22-28 Aug 2022)	10.29	6.70	4.71	25.50	26.24	26.60	83.00	85.14	88.00
9 (1-7 Sep 2022)	3.88	13.75	3.00	25.60	26.30	26.90	77.00	84.57	93.00
10 (8-14 Sep 2022)	0.00	5.00	8.00	26.10	26.79	27.10	78.00	80.71	84.00
11 (15-21 Sep 2022)	6.50	28.00	1.50	25.70	26.86	27.20	81.00	83.29	86.00
12 (22-28 Sep 2022)	11.00	14.50	3.86	25.50	26.59	27.60	75.00	82.43	88.00

Table 3. Classification of distribution patterns based on various distribution indices (Costa *et al.*, 2010)

Index Distribution	Value Criteria	Pattern of Distribution
Variance Ratio Index (I)	$I = 1$	Random
	$I < 1$	Reguler
	$I > 1$	Aggregated
Lloyd's Index ($\dot{m}/\bar{x}$)	$\dot{m}/\bar{x} = 1$	Random
	$\dot{m}/\bar{x} < 1$	Reguler
	$\dot{m}/\bar{x} > 1$	Aggregated
Morisita's Index (Id)	$Id = 1$	Random
	$Id < 1$	Reguler
	$Id > 1$	Aggregated
Green's Coefficient (Cx)	$Cx = 0$	Random
	$Cx < 0$ (negative)	Reguler
	$Cx > 0$ (positive)	Aggregated
Binomial Index (k)	$k < 2$	High Aggregated
	$2 < k < 8$	Medium Aggregated
	$k > 8$	Random

3. RESULTS AND DISCUSSION

3.1 Population Dynamics

The maturity level of coffee berries significantly influences the CBB population because each stage of fruit development presents different physical and biochemical conditions that influence the pest's oviposition preferences, development, and survival. CBB populations were detected infesting coffee berries at all stages of ripeness, including unripe, semi-ripe, and ripe, at various altitudes. All stages of CBB development, from eggs, larvae, pupae, and imago, were found on unripe and ripe berries. Unripe coffee berries are generally inhabited by eggs, first-instar larvae, and actively laying female imago. Semi-ripe berries are dominated by larvae, while ripe berries contain more pupae and adults. The highest populations were found on unripe, semi-ripe, and ripe coffee berries at lower altitudes (750–1000 m asl), while the lowest populations were found in areas with higher elevations (1250–1500 m asl) (Figure 1). Semi-ripe fruit tends to contain high numbers of larvae, indicating that egg laying by the CBB imago occurs when the endosperm of the fruit begins to harden. Development from egg to larva takes approximately 5–9 days, while the larval stage lasts for 10–26 days (Damon, 2000; Jaramillo *et al*., 2011). The presence of dominant pupal and imago stages in ripe fruit reflects the progress of the CBB development cycle, which has passed the initial egg and larval stages.

The development of the CBB population is related to the maturity levels of the coffee fruit. Pest attacks tend to increase on coffee fruit with hardened endosperm, as this structure serves as the primary nutrient source for the larval and adult stages. Overly immature fruit generally lacks sufficiently soft tissue and provides inadequate nutrient reserves for larval development. Coffee unripe fruit, with its still-soft endosperm, generally serves as an egg-laying site for female imagos (Fintasari *et al*., 2018). Conversely, semi-ripe and ripe fruit have a more stable water and nutrient content, as well as endosperm tissue suitable for larval consumption (Vega *et al*., 2020).

Semi-ripe fruit with a hard endosperm provides an optimal nutritional substrate for larval development and provides a suitable microhabitat for male imago. Female adults that encounter fruit with unhardened endosperm tend to remain in the borehole until the endosperm hardens. However, in some cases, imago may also abandon unripe fruit and move to fruit with a harder endosperm as an ideal site for oviposition. CBB attacks on unripe and semi-ripe coffee generally cause the fruits to drop before reaching maturity, while ripe fruit that is attacked will show symptoms in the form of boreholes that impact the weight and quality of the beans (Susilo, 2008). CBB attacks occur from the unripe fruit stage to the ripe fruit, with a relatively regular level of damage at each stage. Damage occurs when the female imago bores into the surface of the fruit, penetrates the flesh to reach the beans, and continues its life cycle within the fruit. Feeding and reproductive activities by larvae and imago cause degradation of the physical and physiological quality of coffee berries and trigger premature fruit drop (Vega *et al*., 2017; Aristizábal *et al*., 2017; Infante, 2018).

The analysis of variance results showed that the maturity fruit level affected the CBB population at all altitudes. The maturity level of the coffee berry significantly affected the egg, larval, pupal, and adult populations of the pest at altitudes of 750–1000 m asl, 1000–1250 m asl, and 1250–1500 m asl (Table 4). Populations were influenced by differences in coffee fruit maturity across all altitude locations. Egg populations were higher in fruit unripe, compared to partially-ripe and ripe fruit. Coffee unripe fruit was more frequently inhabited by eggs and early instar larvae because females begin laying eggs in the early stages of bean formation. Larval populations were higher in semi-ripe fruit, but fewer in unripe fruit, because this is the stage where the CBB is actively feeding on endosperm tissue (Table 5). Pupal populations were absent in unripe fruit, while they began to appear in partially-ripe and ripe fruit. Ripe fruit tended to be inhabited by pupae and adults, indicating that the life cycle had progressed further (Vega *et al*., 2020). The findings of this study align with those of Fintasari *et al*. (2018), who found that only the egg stage was found in unripe fruit, while all stages were found in semi-ripe and ripe fruit. Semi-ripe fruit was more abundant in larvae, while ripe fruit was more abundant in pupae and adults. Coffee unripe fruit, approximately 3 to 4 months old, generally exhibited egg and early larval stages. In the ripening phase, when the fruit is around 6 to 7 months old, the larval population is more dominant, originating from eggs previously laid on unripe fruit and having hatched. The pupal and imago stages are generally found on ripe coffee fruit at around 8 to 9 months old, which reflects the final development of the CBB life cycle. This infestation process shows that the development of CBB is closely related to the physiological changes of the fruit, especially in the endosperm formation and maturation phase (de Castro & Marraccini, 2006; Salmona *et al*., 2008; Adler *et al*., 2014).

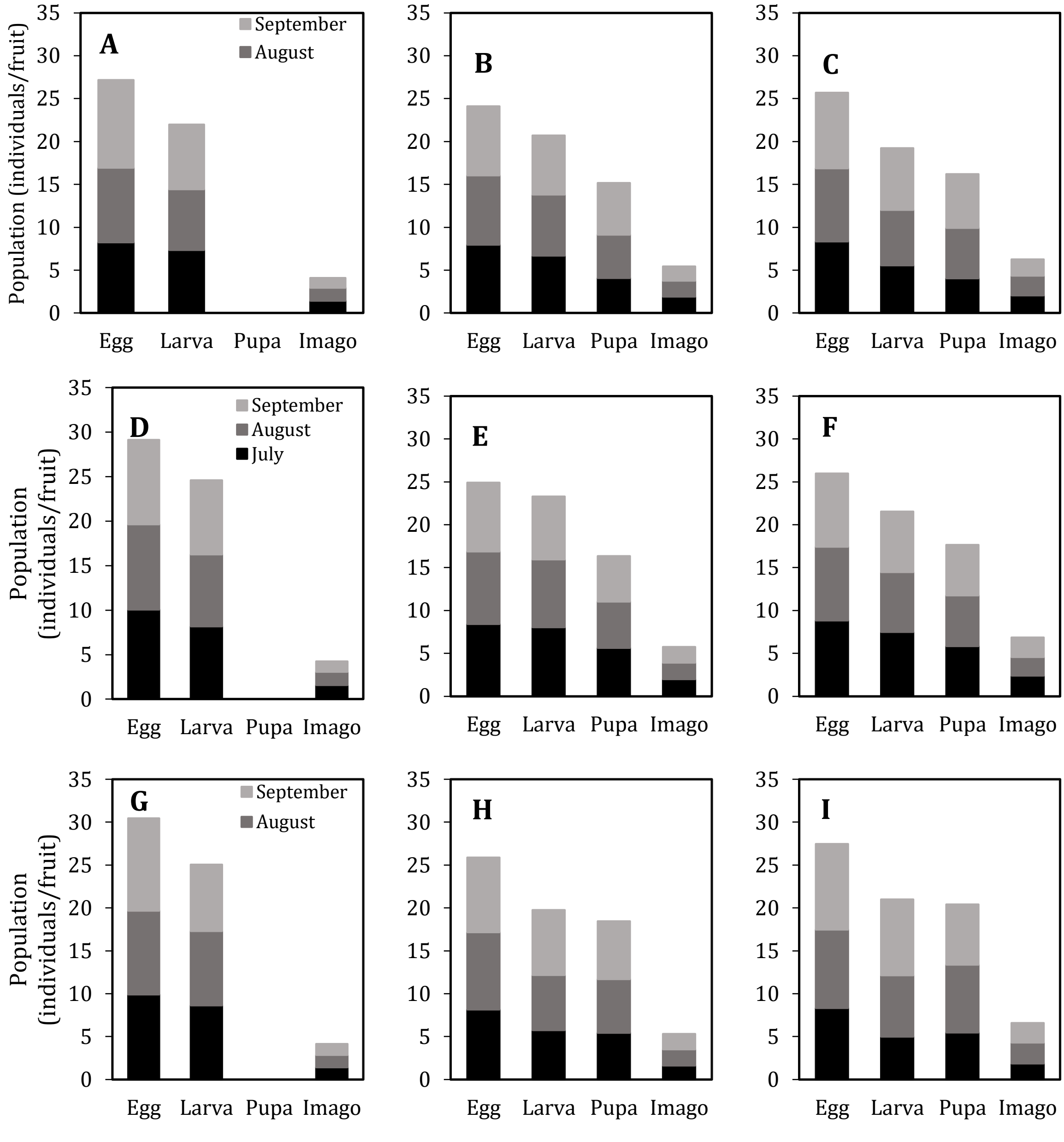

Figure 1. Population development of CBB based on maturity fruit at different altitudes (Figure A-unripe fruit, B-semi-ripe fruit, and C-ripe fruit at an altitude of 1250–1500 m asl), (Figure D-unripe fruit, E-semi-ripe fruit, and F-ripe fruit at an altitude of 1000–1250 m asl), (Figure G-unripe fruit, H-semi-ripe fruit, and I-ripe fruit at an altitude of 750–1000 m asl) in Bener Meriah Regency, Aceh Province

Table 4. Results of the analysis of variance of the effect of coffee berry maturity on the CBB population at altitudes of 750–1500 m asl in Bener Meriah Regency, Aceh Province

Altitudes (m asl)	F-value			
	Egg	Larva	Pupa	Imago
1250–1500	6,44**	5,84**	180,91**	45,21**
1000–1250	44,27**	11,31**	593,11**	41,03**
750–1000	7,42**	6,20**	296,02**	47,33**

Description: The Critical F-value of the 0.05 = 3.44 and 0.01 = 5.72. ** = Very significantly different

Table 5. Results of the analysis of the effect of coffee fruit maturity on the CBB population at an altitude of 1250–1500 m asl in Bener Meriah Regency, Aceh Province.

Altitudes (m asl)	Fruit Maturity Stage	Population (individuals per fruit)			
		Egg	Larva	Pupa	Imago
1250–1500	Unripe fruit	9,06 b	7,33 b	0,00 a	1,36 a
	Semi-ripe fruit	8,06 a	6,91 ab	5,06 b	1,82 b
	Ripe fruit	8,57 ab	6,41 a	5,41 b	2,09 c
1000–1250	Unripe fruit	9,71 c	7,76 b	0,00 a	1,42 a
	Semi-ripe fruit	8,30 a	8,21 b	5,45 b	1,92 b
	Ripe fruit	8,66 b	7,19 a	5,89 c	2,29 c
750–1000	Unripe fruit	10,15 b	6,59 b	0,00 a	1,38 a
	Semi-ripe fruit	8,62 a	8,35 a	6,15 b	1,78 b
	Ripe fruit	9,16 a	7,98 a	6,80 c	2,20 c

Description: The numbers in each column followed by the same letter are not significantly different based on the DMRT test at the 0.05% level.

The CBB pest attacks unripe and ripe coffee berries, causing similar damage to all Arabica coffee varieties. Damage to the coffee berry occurs when the female adult bores a hole and enters the berry, consuming the pulp and seeds, and reproduces within the berry. The imago of CBB and larvae damage the berry, affecting quality and causing fruit drop (Vega *et al*., 2015; Aristizábal *et al*., 2017; Infante, 2018; Johnson & Manoukis, 2020). The differences in coffee berry damage caused by CBB in the three varieties are related to differences in fruit phenology in each variety. Fruit color, ripeness, and aroma are known to influence variations in CBB attacks across coffee varieties (Susilo, 2008). Another factor influencing CBB pest attacks is the content of metabolite compounds in the fruit, so that larvae and imago cannot damage the beans, but only damage the seed coat. Imago of CBB prefer secondary metabolite compounds such as kairomones produced by coffee berries at varying concentrations depending on the maturity fruit (Ortiz *et al*., 2004). The level of maturity fruit, fruit color, and width of the fruit disc are sources of stimulation that can attract CBB to attack the fruit (Soesanthy *et al*., 2016). The thin skin and rather wide fruit disc of the Ateng Super variety make it easily damaged by CBB larvae and adults. However, in all Arabica coffee varieties, the percentage of attacks is still relatively low (0–25%), this is related to the pulp in all varieties containing a lot of sticky mucus. The attraction of the female imago of CBB is also related to changes in the content of biochemical compounds in the fruit during the ripening process. Coffee berries emit chemical signals that are easily detected by olfactory CBB receptor neurons, such as aldehydes, alcohols, and benzyl alcohols. Unripe to ripe coffee berries attract the most CBB and contain the highest concentrations of volatile and semi-volatile compounds (Ruiz-Diaz *et al*., 2023).

The results of the analysis of variance of regression parameters indicated that the temperature factor has a very significant effect on the population of CBB imago at all levels of fruit maturity at an altitude of 750–1500 m asl, while rainfall and humidity factors do not affect the development of the CBB population. The results of the linear regression model estimation showed that the coefficient of determination (R^2) value of the temperature parameter with the CBB imago population indicates that the relationship between temperature parameters and the imago population is relatively strong

(Table 6). The results of the regression analysis indicated that temperature affects the CBB imago population that occurs at all levels of fruit maturity in areas with an altitude of 750–1500 m asl, while the pupa population at an altitude of 750–1000 m asl is found in ripe fruit. The results of the study indicated that temperature has an impact on the development and activity of CBB pupae and imago that occur at all levels of coffee fruit maturity in areas with an altitude of 700–1500 m asl. Arabica coffee plantations located at altitudes ranging from 750–1000 m asl tend to have higher daily temperatures (25–28°C), approaching the optimal range for CBB. Consequently, CBB populations increase due to faster development times, greater generations per season, and higher reproductive rates. In mid- to high-altitude areas (1250–1500 m asl), temperatures tend to be lower (<23°C). This results in slower development rates, decreased egg-laying success rates, and relatively lower CBB populations.

Table 6. Regression parameters of the relationship between CBB population density as the independent variable (x) and temperature as the dependent variable (y) based on fruit maturity at different altitudes in Bener Meriah Regency, Aceh Province.

Altitudes (m asl)	Fruit Maturity Stage	Population	F-value	*P*	*a*	*b*	R^2
1250–1500	Unripe Fruit	Egg	0,547tn	>0,477	23,93±1,23	0,10±0,13	0,052
		Larva	0,170tn	>0,689	27,44±1,46	0,82±0,19	0,017
		Imago	6,596*	<0,013	3,222±0,34	0,15±0,01	0,702
	Semi-ripe Fruit	Egg	0,349tn	>0,568	25,30±2,60	0,19±0,32	0,034
		Larva	3,449tn	>0,093	24,11±1,47	0,39±0,21	0,256
		Pupa	1,207tn	>0,298	26,18±0,61	0,13±0,12	0,108
		Imago	61,496**	<0,000	22,48±0,55	2,40±0,30	0,927
	Ripe Fruit	Egg	0,013tn	>0,912	27,16±3,09	0,41±0,36	0,014
		Larva	2,291tn	>0,161	25,28±1,04	0,24±0,16	0,186
		Pupa	4,856*	<0,050	25,71±0,52	0,21±0,95	0,327
		Imago	110,76**	<0,000	22,77±0,38	1,94±0,18	0,917
1000–1250	Unripe Fruit	Egg	1,997tn	>0,188	30,55±2,63	-0,38±0,27	0,408
		Larva	0,720tn	>0,416	28,67±2,16	-0,22±0,26	0,067
		Imago	120,71**	<0,000	24,59±0,21	1,58±0,14	0,923
	Semi-ripe Fruit	Egg	0,101tn	>0,758	25,74±3,45	1,13±0,41	0,010
		Larva	0,223tn	>0,154	7,621±17,4	1,12±3,41	0,042
		Pupa	0,556tn	>0,473	28,87±2,72	-0,37±0,49	0,083
		Imago	182,150**	<0,000	23,06±0,28	1,97±0,16	0,948
	Ripe Fruit	Egg	0,007tn	>0,933	27,11±3,11	-0,03±0,35	0,001
		Larva	2,495tn	>0,145	30,15±2,09	-0,46±0,29	0,200
		Pupa	0,112tn	>0,744	27,27±1,29	-0,07±0,21	0,011
		Imago	116,217**	<0,000	22,95±0,36	1,70±0,15	0,921
750–1000	Unripe Fruit	Egg	0,063tn	>0,807	27,30±1,83	-0,04±0,18	0,006
		Larva	0,090tn	>0,770	26,22±2,06	0,07±0,24	0,009
		Imago	113,84**	<0,000	22,02±0,45	3,48±0,32	0,919
	Semi-ripe Fruit	Egg	3,249tn	>0,102	25,17±0,93	0,19±0,11	0,245
		Larva	1,288tn	>0,283	25,99±0,76	0,13±0,16	0,114
		Pupa	3,835tn	>0,079	24,85±1,02	0,32±0,15	0,277
		Imago	69,833**	<0,000	23,08±0,45	2,11±0,25	0,875
	Ripe Fruit	Egg	1,207tn	>0,298	25,58±1,15	0,13±0,12	0,108
		Larva	3,768tn	>0,081	26,03±0,43	0,11±0,06	0,274
		Pupa	1,865tn	>0,021	24,66±0,36	0,32±0,05	0,191
		Imago	153,395**	<0,000	23,93±0,23	1,32±0,11	0,939

Description: tn: not significantly different, **: very significantly different

Table 7. Results of parameter analysis to determine the distribution of the coffee berry maturity pest population at an altitude of 750–1500 m asl in Bener Meriah Regency, Aceh Province

Altitudes (m asl)	Stage	Fruit Maturity Stage	S^2/m	$\dot{m}/\bar{x}$	I_d	Cx	k
1250–1500	Egg	Unripe Fruit	7,69	15,75	1,91	6,68	1,15
		Semi-ripe Fruit	38,01	45,05	1,89	37,02	1,03
		Ripe Fruit	48,48	56,05	1,89	47,47	1,02
	Larva	Unripe Fruit	12,91	19,24	1,88	11,90	1,08
		Semi-ripe Fruit	18,32	24,23	1,87	17,31	1,06
		Ripe Fruit	8,95	14,36	1,87	7,93	1,13
	Pupa	Unripe Fruit	nc	nc	nc	nc	nc
		Semi-ripe Fruit	3,50	7,56	1,87	2,48	1,40
		Ripe Fruit	3,14	7,55	1,88	2,13	1,47
	Imago	Unripe Fruit	34,94	35,30	1,30	33,88	1,03
		Semi-ripe Fruit	53,16	53,98	1,48	52,12	1,02
		Ripe Fruit	37,47	38,56	1,56	36,43	1,03
1000–1250	Egg	Unripe Fruit	37,23	45,94	1,91	36,22	1,03
		Semi-ripe Fruit	63,62	70,92	1,89	62,61	1,02
		Ripe Fruit	48,83	56,49	1,90	47,82	1,02
	Larva	Unripe Fruit	26,62	33,83	1,89	25,61	1,04
		Semi-ripe Fruit	27,98	34,75	1,88	26,97	1,04
		Ripe Fruit	33,33	39,51	1,87	32,32	1,03
	Pupa	Unripe Fruit	nc	nc	nc	nc	nc
		Semi-ripe Fruit	62,67	67,12	1,83	61,65	1,02
		Ripe Fruit	12,31	17,20	1,85	11,30	1,09
	Imago	Unripe Fruit	16,96	17,38	1,35	15,90	1,06
		Semi-ripe Fruit	33,99	34,91	1,51	32,95	1,03
		Ripe Fruit	31,55	32,85	1,60	30,52	1,03
700–1000	Egg	Unripe Fruit	14,43	23,58	1,92	13,43	1,07
		Semi-ripe Fruit	5,76	13,38	1,91	4,75	1,21
		Ripe Fruit	7,08	15,24	1,91	6,07	1,16
	Larva	Unripe Fruit	22,48	29,83	1,89	21,47	1,05
		Semi-ripe Fruit	4,24	9,83	1,89	3,23	1,31
		Ripe Fruit	1,49	7,49	1,96	2,48	3,04
	Pupa	Unripe Fruit	nc	nc	nc	nc	nc
		Semi-ripe Fruit	10,10	15,25	1,86	9,08	1,11
		Ripe Fruit	3,86	9,66	1,90	2,85	1,35
	Imago	Unripe Fruit	80,77	81,15	1,30	79,71	1,01
		Semi-ripe Fruit	39,69	40,47	1,47	38,64	1,03
		Ripe Fruit	18,08	19,29	1,59	17,05	1,06

Description: If the value of S^2/m <1–regular distribution, S^2/m = 1–random distribution, and S^2/m >1–aggregated distribution. If the value of $\dot{m}/\bar{x}$ < 1–regular distribution, $\dot{m}/\bar{x}$ = 1–random distribution, and $\dot{m}/\bar{x}$ > 1–aggregated distribution. If the value I_d < 1–regular distribution, I_d = 1–random distribution, and I_d > 1–aggregated distribution. If the value Cx = 0–random distribution, Cx = negative value–regular distribution, and Cx = positive value–aggregated distribution. If the value k < 2–high aggregated distribution, 2 < k < 8–medium aggregated distribution, and k > 8 random distribution. nc: not counted

Microclimatic conditions in Arabica coffee plantations, such as temperature, influence the metabolism of CBB. Extreme temperature conditions for the development of CBB are in the range of 13.9–15 °C, while the optimal temperature for reproduction is in the range of 25–27 °C (Jaramillo *et al*., 2011, Giraldo-Jaramillo *et al*., 2018). At temperatures below or above this range, the development and oviposition of CBB will stop (Jaramillo *et al*., 2011). Temperature is the most important climate variable that directly influences biological life such as insect development, number of generations per year, distribution, interactions with plants and natural enemies, and behavior (Deutsch *et al*., 2008; Thomson *et al*., 2010). The research results of Constantino *et al*. (2021) show that the development of CBB can be faster at lower altitudes as a result of higher daily temperatures. The number of generations of CBB per season is greater in the lowlands compared to the highlands. Temperature changes that occur can support or limit the biological activity, development, and emergence of CBB (Mariño *et al*., 2016; Johnson *et al*., 2019; Hamilton *et al*., 2019). Therefore, there is a relationship between CBB population dynamics and altitude, with faster population development in lower areas (750–1000 m asl). In the appropriate temperature range, imago are able to utilize coffee berries at various stages of maturity as a source of nutrition and a place to lay their eggs, so population of CBB imago is consistently detected in all altitude zones.

3.2 Population Distribution

The results analysis of several spatial distribution parameters based on the stages CBB at different maturity fruit stages indicate that the Variance Ratio Index (*I*), Lloyd's Mean Crowding Index ($\dot{m}$), and Morisita Index (*Id*) are all above 1, while the Green's Coefficient (*Cx*) ranges from 0 to 1, and the Binomial Distribution Index (*k*) shows a positive value with $k < 2.0$ (Table 7). Based on these criteria, it can be concluded that the spatial distribution pattern of CBB shows a tendency toward aggregation. All index parameters used lead to the conclusion that the pest distribution is not random or regular, but rather forms aggregates or groups. The spatial distribution of CBB, based on fruit maturity, shows consistency in the clustered distribution pattern across all elevation groups. The clustered distribution pattern of CBB on Arabica coffee has also been reported by (Wiryadiputra, 2014; Hendrival *et al*., 2022; Hendrival *et al*., 2024). This phenomenon is generally caused by the preference of female imagos in selecting coffee berries as oviposition sites that have optimal conditions, such as a suitable level of fruit maturity and adequate nutrient availability for larval development until they become imago. Coffee berries from unripe to ripe are known to have an endosperm structure that supports pest survival at all stages.

Each insect species has a unique distribution pattern, influenced by biological factors, habitat type, and environmental conditions. The distribution pattern of an insect species is not only influenced by environmental factors but is also closely related to its population density. Generally, at low population levels, insect distribution patterns are random, but as population density increases, this pattern can change to centralized or clustered. The distribution of all stages of CBB shows an aggregated pattern, related to high population of each stage, which is widely distributed across various elevation zones. Thus, pest population concentrations are higher in plants or areas with abundant and optimally ripe coffee berries. This pattern needs to be considered in site-based pest sampling and control strategies, because a clustered distribution indicates that control measures should be focused on central points of attack rather than being applied evenly throughout the plantation. Siswanto *et al*. (2008) reported that *Helopeltis antonii* populations on cashew trees exhibit a clustered distribution pattern when the population is high, whereas at low densities, the distribution pattern tends to be random or regular. Various other studies on the spatial distribution of pests have also shown similar patterns, as reported by Cho *et al*. (2001), Khaing *et al*. (2002), Seal *et al*. (2006), Soemargono *et al*. (2008), Costa *et al*. (2010), Kumar *et al*. (2014), dan Bakry *et al*. (2020). This distribution pattern is important for pest control strategies. CBB attacks were unevenly distributed, monitoring and control should be focused on areas with ripe or developing fruit. Understanding this relationship also supports sampling approaches based on spatial distribution, such as application of cluster-based economic thresholds.

4. CONCLUSION

Coffee berry borer was found to attack Gayo Arabica coffee berries at all stages of maturity fruit, with populations varying according to the pest's developmental stage. Eggs and early larvae were more common on unripe fruit, larvae were dominant on semi-ripe berries, while pupae and imago dominated on ripe berries. The highest CBB populations were found on coffee berries at elevations ranging from 750 to 1,000 m asl. The spatial distribution of CBB at all stages of fruit maturity at different altitudes showed a tendency to cluster.

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