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Emergence and Infestation Level of *Hypothenemus hampei* (Coleoptera: Curculionidae) on Coffee Berries on the Plant or on the Ground During the Post-harvest Period in Brazil

Adriano E. Pereira,[1,4,5] Pablo C. Gontijo,[2] Andreza K. Fantine,[1] Ricardo S. Tinoco,[1] Mark R. Ellersieck,[3] Geraldo A. Carvalho,[2] José C. Zanuncio,[1] and Evaldo F. Vilela[1]

[1]Departmento de Entomologia/BIOAGRO, Universidade Federal de Viçosa, Viçosa, Minas Gerais, 36571–900, Brasil, [2]Departmento de Entomologia, Universidade Federal de Lavras, Lavras, Minas Gerais, 37200-000, Brasil, [3]Agriculture Experiment Station Statistician, University of Missouri, Columbia, MO 65201, USA, [4]Current address: Division of Plant Sciences, University of Missouri, Columbia, MO, 65211, USA, and [5]Corresponding author, e-mail: pereiraa@missouri.edu

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Abstract

The coffee berry borer (CBB), *Hypothenemus hampei* Ferrari (Coleoptera: Curculionidae), is the most important coffee pest in most of the coffee growing countries. CBB females leave old dry berries after harvest and search for dry noninfested berries on the plant or on the ground to lay eggs or to use as refuge until new berries are available on the coffee trees in the following season. The CBB infestation level and emergence from berries on the ground or on the plants were evaluated in two fields post-harvest in the Spring in Brazil over two seasons. Twenty infested or noninfested berries in separate cages (250 ml plastic cups) were placed on the plants or on the ground under the tree canopy, in each field. The number of infested berries and CBB females that emerged from the infested berries were recorded weekly. CBB emergence was higher from berries on the ground than those on the coffee trees in both seasons, whereas CBB infestation was higher on coffee berries on the plants than those on the ground in season I. Insolation (hours of sunlight) and temperature were the main covariates that affected emergence and infestation by this insect. The results are discussed for monitoring CBB during the time of dispersal with implications on integrated management of this pest.

Key words: *Hypothenemus hampei*, *Coffee arabica*, coffee berry borer, monitoring, infestation level, emergence

In Brazil, coffee is one of the most important commodities, generating approximately US$ 3 million in full- or part-time jobs directly and indirectly during the harvest alone (Matiello et al. 2010). The state of Minas Gerais, located in the Southern region, produces around 65% of the Arabica variety (*Coffea arabica* L.) in Brazil. In 2018, Brazil exported over 32 million coffee bags (60 kg) generating over US$ 5 billion in income (Agrianual 2018, USDA 2018).

The coffee berry borer (CBB) *Hypothenemus hampei* Ferrari (Coleoptera: Curculionidae: Scolytinae), introduced in Brazil over a hundred years ago (Infante et al. 2014), is the most important coffee pest worldwide (Vega et al. 2009, Infante 2018) and one of the most destructive coffee pests in Brazil (Souza and Reis 1997, Vega et al. 2009). This pest along with the coffee leaf miner, *Leucoptera coffeella* Guérin-Méneville (Lepidoptera: Lyonetiidae) (Souza et al. 1998), cause over a quarter billion U.S. dollars in losses annually (Escobar-Ramírez et al. 2019). Damage by CBB limits the coffee production and integrated pest management programs are essential for control of this pest (Wegbe et al. 2003; Aristizábal et al. 2012, 2015, 2016, 2017b; Escobar-Ramírez et al. 2019). CBB adult females mate with sibling males and leave the coffee berries to infest and colonize healthy ones by making multiple galleries inside the coffee seed to lay eggs (Souza and Reis 1997, Vega et al. 2009). CBB adult males have reduced, atrophied wings and stay inside the coffee berries during their lifetime (Mathieu et al. 1997, Damon 2000). The CBB larvae feed on the seed endosperm, reducing the seed weight and quality in addition to allowing opportunistic microorganisms to infect the coffee endosperm (Baker et al. 1992a, Baker 1999, Damon 2000). CBB infestation increases production costs due to the necessity of intense labor to remove as many infested berries as possible from coffee plants and to spray with insecticides when the infestation level reaches economic threshold (Brun et al. 1989, Souza and Reis 1997, Pereira et al. 2012). Females of the CBB can infest green coffee berries in periods of high infestation and they wait inside them for the optimal dry matter rate (>20%) to colonize the seeds

(Baker et al. 1992a, Souza and Reis 1997, Mathieu et al. 1999, Cárdenas and Baker 2010). These green berries, after damaged, may become deteriorated by opportunistic microorganisms and fall off from the trees, thus reducing yield (Souza and Reis 1997, Damon 2000). In addition, total defects on processed coffee berries are increased due to CBB damage, which reduces their value in the market (Souza and Reis 1997).

The CBB control relies on monitoring coffee berries on the plants and then on insecticide sprays if the infestation reaches 3% or 5%, based on high or low coffee market value, respectively (Souza and Reis 1997). The insecticides are efficient and recommended during CBB flight activity from old to new berries (Souza and Reis, 1997), usually applied at the beginning of rainfall in September/October in Brazil (Pereira et al. 2012), in Colombia (Aristizábal et al. 2015), and in Hawaii (Aristizábal et al. 2017a). The coffee harvest has to be performed as thorough as possible to reduce CBB populations in the field, because dry berries are refuge and food source for the CBB females (Baker et al. 1992b, Mathieu et al. 1997, Cárdenas and Baker 2010, Pereira et al. 2012). CBB monitoring in post-harvest periods with ethanol:methanol baited traps can indicate if berries left on the plants and on the ground are infested (Pereira et al. 2012; Aristizábal et al. 2015, 2017a). Temperature, rainfall, and/or relative humidity are important for the CBB flight activity as they trigger the females to leave old and infest new berries (Baker et al. 1992a, b; Jaramillo et al. 2009, 2010; Aristizábal et al. 2017a). Heavy or low infestation can occur in the next growing season depending on the rainfall of the previous one (Souza and Reis 1997).

The objectives of this work were to compare the CBB adult female infestation and emergence from coffee berries on the plants and on the ground and to correlate the CBB infestation and emergence from coffee berries on the plants and on the ground with insolation (hours of sunlight), rain, relative humidity, and temperature during the post-harvest period in the southern region of Brazil.

Material and Methods

Experimental Fields

A field experiment was carried out in two commercial coffee fields of the 'Catuaí' variety, *Coffea arabica* L., in the municipality of Viçosa, Minas Gerais state, Brazil during the post-harvest period from September to December, in 2005 (season I) and 2006 (season II). In Brazil, the harvest occurs between July and September/October, depending on the size of the farm, during which CBB movement increases until January/February (Pereira et al. 2012). The experiments simulate a food and/or refuge shortage situation in the field where the CBB females could survive and wait in the old berries for the next season, or could emerge and search for noninfested berries. Fields 1 and 2 were planted in 1990 and 1992 at 737 m and 669 m above sea level with 2.70 m × 0.70 m and 3.50 m × 0.70 m space between rows and plants (with 5,200 and 4,000 plants/hectare, respectively), at a latitude of (S) 20°48′24″ and (S) 20°43′34″ and longitude of (W) 42°52′56″ and (W) 42°51′30″, respectively. Both fields had ~1 hectare, were planted in full sunlight and had not been sprayed with insecticide to control CBB since the previous season (~14 mo before). Agronomic practices such as weed management and harvest were standard as adopted in the area. The rain (mm), insolation, relative humidity (%), and temperature (°C) were recorded every minute by an automatic Meteorological Station (Vaisala, model MAWS 301; Finland) at the Federal University of Viçosa, in Viçosa, Minas Gerais, Brazil in season I and season II, and the means are presented in 7-d periods (Supp Fig. S1 [online only]). The areas were approximately between 2 and 4 km away from the Meteorological Station.

Containers

The emergence and colonization behavior of the CBB females were evaluated in 20 infested or 20 noninfested dry berries per container in a total of 10 trees (replicates), 20 m apart from each other in a row in each of the two experimental fields. Two containers (250-ml plastic cups), one containing 20 dry, healthy berries, and another containing 20 dry, infested berries, were placed on each of the 10 coffee trees at approximately 1.5 m above the ground (Fig. 1A), and two additional containers, each one with the same proportion of infested and noninfested berries, were placed on the ground under the canopy of the same coffee tree, in each field (Fig. 1B). The containers containing the infested berries were covered with a mesh held fixed by a rubber band to trap the emerging females for the weekly recordings. Infested berries were obtained from a CBB colony kept in dry coffee berries in a Laboratory of the Department of Entomology at the Federal University of Viçosa. Healthy dry berries were allowed to be infested for 4–5 d until the CBB females entered the exocarp about 2 wk before the beginning of the experiments. The females of this insect protect and defend the entry hole of the berry against other females that try to colonize the same berry (Baker et al. 1992a); thereby, we considered that each berry contained one CBB female. The noninfested dry berries (~10–14 mo old), which had no entry holes, were collected from the plants in the field to supply the containers. The bottom of the containers placed on the trees with non-infested berries was perforated and the bottom of those set on the ground was removed to avoid accumulating rainfall water that would kill or prevent CBB emergence or infestation. It is assumed that the berries on the ground decay faster than those on the plants; however, during the time of this study, the berries remained on the ground in perfect condition.

Sampling Methods

To estimate infestation level, the infested berries in the containers on the plant or on the ground were counted, removed from the cups and replaced with healthy dry berries found in the field (~10–14 mo old) each week to complete 20 berries. CBB females counted from the emergence containers were recorded and removed. Percentage of infestation was calculated by dividing the number of infested berries by 20 and multiplying by 100. The emergence containers were closed with a mesh to trap the CBB, so they could be counted and removed. The sampling was done weekly (except in a few samplings in season II that were done biweekly, when heavy rains prevented the access to the areas). In the season I, there were 13 samplings and, in the season II, 10 samplings.

Statistical Analysis

CBB infestation level

Coffee berry borer infestation on berries on the plant and on the ground was analyzed as a complete randomized design split-plot in time (repeated measures). The linear statistical model contained the fixed effects model of field, site (plant or ground), and Julian date (judate), and all possible interactions of these three fixed effects. The random effect of replicates (within field and site) was used as the denominator of 'F' for testing the fixed effects of field, site, and field × site. The distribution of the data was binomial; thus, a logit link function was used. The mean differences (±SE) were determined by using Fisher's protected Least Significant Differences (LSD) in PROC GLIMMIX at $P < 0.05$, using SAS 9.4 (SAS Institute, Cary, NC).

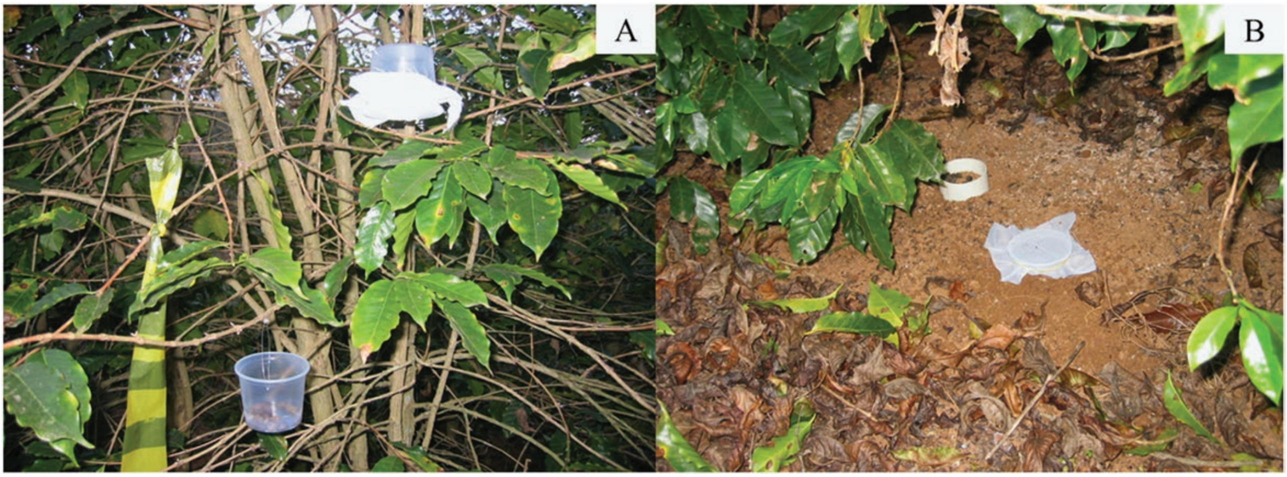

Fig. 1. Containers (plastic cups) placed on the trees (A) and on the ground under the coffee tree canopy (B) containing infested and healthy coffee berries to estimate the coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera: Curculionidae), emergence (mesh-closed container) and infestation level (open container), respectively.

CBB emergence

Coffee berry borer beetle emergence data were analyzed with the same method as for the infestation level. However, the distribution of the data fit a Poisson distribution. The mean (±SE) differences were determined by Fisher's protected Least Significant Differences (LSD) in PROC GLIMMIX using SAS 9.4, at $P < 0.05$. The cumulative emergence data means (±SE) were compared by t-test between CBB emerged from the containers on the plant or on the ground in Student's t-test in PROC TTEST using SAS 9.4, at $P < 0.05$.

Pearson's correlation

Pearson's correlation was performed separately for CBB infestation level or emergence with temperature, rain, relative humidity, and insolation in both fields in season I and II, using PROC CORR in SAS 9.4, at $P < 0.05$.

Results

CBB Infestation Level

In both seasons, the interaction field × site × judate was highly significant (Table 1). In season I, the overall CBB infestation level was higher in both fields on the plant (field 1 = 29.4% ± 2.8; field 2 = 33.6% ± 5.7) than on the ground (field 1 = 12.1% ± 2.1; field 2 = 10.9% ± 2.2; Table 1; Fig. 2). In season II, the overall average of CBB infestation levels were higher in both fields on berries on the plant (field 1 = 17.2% ± 1.5; field 2 = 11.7% ± 2.8) than on the ground (field 1 = 12.3% ± 1.9; field 2 = 9.8% ± 1.1; Fig. 2), though not significantly different (Table 1).

Field and interaction field × judate in season I, and field, site (plant or ground), and interaction field × judate in season II did not differ significantly (Table 1).

CBB Emergence

In both seasons, the interaction field × site × judate was highly significant (Table 2). In both fields in season I, the overall mean of CBB females that emerged from berries in containers on the ground (field 1 = 2.1 ± 0.9; field 2 = 2.9 ± 0.9 CBB/cage/week) was higher than those that emerged from the containers on the plants (field 1 = 0.5 ± 0.2; field 2 = 1.6 ± 0.5 CBB/cage/week, respectively). In season II, the average of CBB females emerged from coffee berries on the ground (2.4 ± 0.9 CBB/cage/week) was higher than those that emerged from the berries on the plants (0.9 ± 0.2 CBB/cage/week) in field 2 (Table 2; Fig. 3). The field, site (plant or ground), and sampling dates (judate) differed between treatments as well as the interactions for CBB emergence in season I (except field × site), whereas 'field' and interaction 'field × judate' did not differ in season II (Table 2). The cumulative number of CBB females emerged from the containers on the ground was higher than those emerged from the plants in both seasons, but statistically different (t = −3.06; df = 38; P = 0.0040) only in season II (Fig. 3).

Table 1. Effects of the variables field, site, and Julian date (Judate) and possible interactions on the percentage of infestation level of coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera,: Curculionidae), in berries located on the plant or on the ground in two crop seasons (I and II)

Season/Effect	F	df	P
Season I			
Field	0.63	1, 36	0.4326
Site (plant, ground)	28.0	1, 36	<0.0001*
Field × site	0.61	1, 36	0.4391
Judate	19.8	12, 432	<0.0001*
Field × judate	17.9	12, 432	<0.0001*
Site × judate	9.83	12, 432	<0.0001*
Field × site × judate	14.8	12, 432	<0.0001*
Season II			
Field	2.55	1, 36	0.1191
Site (plant, ground)	1.08	1, 36	0.3063
Field × site	0.27	1, 36	0.6058
Judate	5.45	9, 324	<0.0001*
Field × judate	4.28	9, 324	<0.0001*
Site × judate	6.77	9, 324	<0.0001*
Field × site × judate	3.80	9, 324	0.0001*

*Statistically different at $P < 0.05$.

Pearson's Correlation

The results documented that the meteorological parameters, especially insolation, followed by relative humidity, temperature and rain, played an important role in CBB emergence or infestation level,

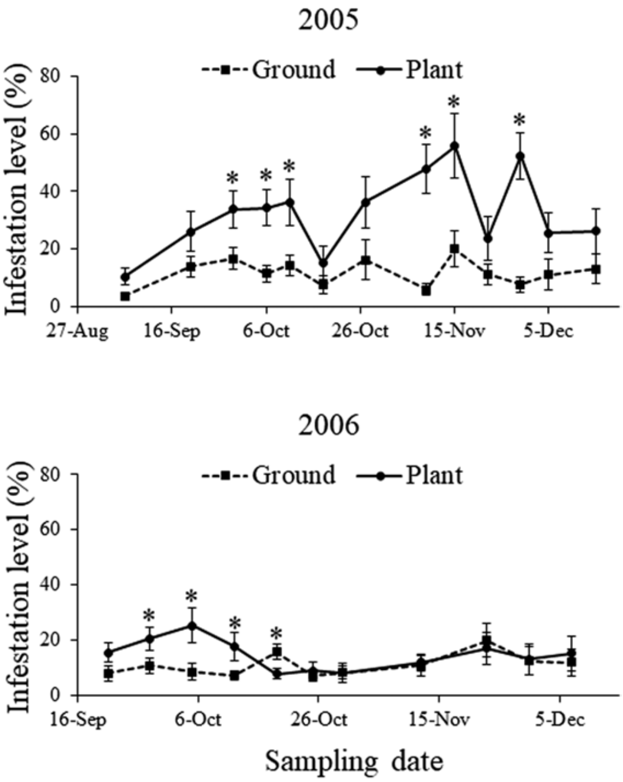

Fig. 2. Percentage of *Hypothenemus hampei* (Coleoptera: Curculionidae), infestation level (means ± SE) on coffee berries on the plant and ground, during the post-harvest period from September to December in two fields during two crop seasons (I and II). Each value corresponds to the mean (± SE) percentage of infestation in berries from 10 containers located on the plant and 10 containers on the ground, per sampling date. *Significantly different in Fisher's LSD, at $P < 0.05$.

regardless of whether the correlation was positive (+) or negative (–) (Table 3).

CBB Infestation Level

In season I, relative humidity (+) and temperature (–) significantly correlated with CBB infestation on the plant, whereas insolation (–) significantly correlated with infestation on the ground (Table 3). In season II, rain (–), temperature (–), and insolation (+) significantly correlated with CBB infestation on the plant, whereas rain (+) and humidity (–, marginally significant at $P = 0.0524$) significantly correlated with CBB infestation on the ground (Table 3).

CBB Emergence

In season I, all four meteorological parameters, rain (–), humidity (–), temperature (+), and insolation (+), significantly correlated with CBB emergence from the plant (Table 3). In season II, humidity (–) and insolation (+) significantly correlated with CBB emergence from the ground (Table 3).

Discussion

This study is, to our knowledge, the first to compare CBB emergence and infestation levels simultaneously on coffee berries located on the plants and on the ground, in two seasons post-harvest. The results showed that CBB females can infest berries on the plants and also on the ground, even when covered by fallen dry leaves. The availability of food and/or refuge for CBB females in the field during the post-harvest season in Brazil can be scarce because few dry berries remain on the ground or on coffee trees after harvest. The best CBB management is the removal of the coffee berries from the plants during the harvest and avoid leaving the minimum number of berries on the ground. However, this tactic can be laborious, which prevents many coffee growers from adopting it (Benavides et al. 2003, Aristizábal 2018). Significant differences between the two fields regarding the CBB emergence were observed only in season I. Therefore, the fields were combined to allow better and easy data interpretation for both seasons. The overall CBB emergence was higher from berries on the ground than on the trees, whereas the CBB infestation was higher in mostly sampling on coffee berries located on the plants than on the ground in 2005. Higher number of CBB individuals inside berries located on the plants when compared to those on the ground have been reported in Ethiopia (Mendesil et al. 2004), Puerto Rico (Mariño et al. 2017), and Hawaii (Johnson et al. 2019). However, similar as in our results, Johnson et al. (2019) also reported higher CBB infestation on berries located on the plants when compared to those on the ground. Therefore, our results corroborate with these and other studies that coffee berries left in the field, regardless if on the plants or on the ground, can be suitable hosts for CBB individuals when available, following optimal climate conditions.

Our results support other studies that recommend the harvest to be performed as efficient as possible to reduce the number of coffee berries left that could serve as CBB refuge (Baker et al. 1992b, Mathieu et al. 1997, Cárdenas and Baker 2010, Pereira et al. 2012, Johnson and Manoukis 2020). The adoption of 'sanitary harvest' (as best as possible) or 'strip-picking' (Aristizábal et al. 2017a) along with baited traps and entomopathogens or predators are some of the best management strategies against the CBB (Dufour et al. 2007). This study also indicates the possibility of predicting the CBB females' flight activity based on emergence and infestation during the rainy season in September–December for this insect.

The lower CBB infestation on berries on the ground than on those on the plants could be due to the difficulty of the CBB females to find those berries on the ground hidden under the dry leaves or covered by soil/dirt, or because coffee berries may decay faster on the ground due to the high relative humidity and high precipitation

Table 2. Effects of the variables field, site, and Julian date (Judate) and possible interactions on the emergence of coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera: Curculionidae), from berries on the plant or on the ground in two crop seasons (I and II)

Season/Effect	*F*	df	*P*
Season I			
Field	4.85	1, 36	0.0344*
Site (plant, ground)	0.23	1, 36	<0.0001*
Field × site	0.56	1, 36	0.4586
Judate	9.74	12, 432	<0.0001*
Field × judate	6.1	12, 432	<0.0001*
Site × judate	4.63	12, 432	<0.0001*
Field × site × judate	12.9	12, 432	<0.0001*
Season II			
Field	2.76	1, 36	0.0974
Site (plant, ground)	12.8	1, 36	0.0004*
Field × site	10.7	1, 36	0.0012*
Judate	13.2	9, 324	<0.0001*
Field × judate	0.89	9, 324	0.5332
Site × judate	2.43	9, 324	0.0107*
Field × site × judate	3.97	9, 324	<0.0001*

*Statistically different at $P < 0.05$.

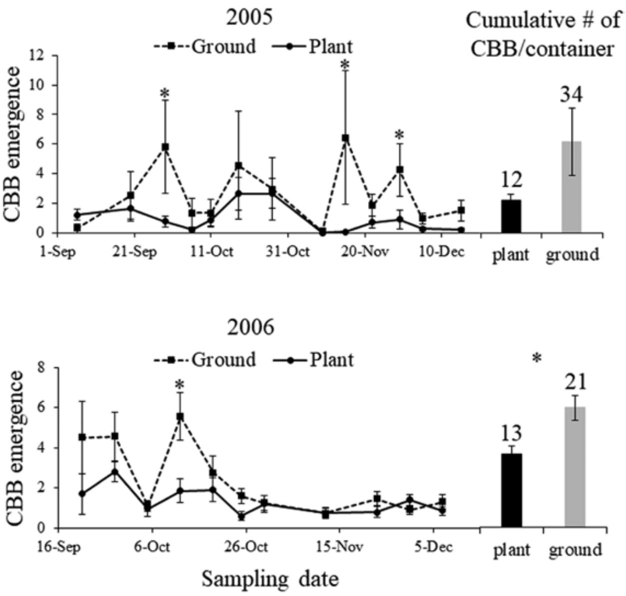

Fig. 3. Number of coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera: Curculionidae), adults that emerged (means ±SE) from coffee berries located on the plant or on the ground, during the post-harvest period from September to December, in two fields during two crop seasons (I and II) as well as the cumulative number of CBB that emerged per container. Each value corresponds to the mean (±SE) number of adults that emerged from 10 containers located on the plant and 10 containers on the ground, per sampling date. *Significantly different in Fisher's LSD, at $P < 0.05$.

(Baker et al. 1992a, Jaramillo et al. 2009). CBB females tend to fly at higher altitudes after the harvest, which may help them to find berries easier on the trees than on the ground (Barrera et al. 2005). Besides, the CBB can find and infest new berries by walking on the branches, and higher percentage of infested berries was found on the plants (49%) than on the ground (29%) (Dufour et al. 2007, Román-Ruiz et al. 2018). In contrast, Teixeira et al. (2006) evaluated coffee berries on the plant and those that fell onto a tarp on the ground and reported higher CBB infestation on those berries when compared with berries on the coffee trees. The authors concluded that the CBB infestation triggered the plants to abort those infested berries (Teixeira et al. 2006). The premature fall (abort) of coffee berries is one of the symptoms caused by CBB infestation especially in green berries with low maturation (Souza and Reis 1997).

The higher CBB infestation in coffee berries located on the plants in season I compared to season II (Fig. 2) was probably due to higher insolation peaks (October), slightly higher mean temperature that started with a peak in late October, and higher cumulative rain in late season I (December) that could have affected the CBB emergence in search for new berries for the season II (Supp Fig. S1 [online only]). Additionally, in late October and late November of season II (Supp Fig. S1 [online only]), there were peaks of cumulative rain that, again, could have impacted CBB infestation by accelerating coffee berry decay. Rodríguez et al. (2013) modeled the relationship between CBB, coffee berry phenology, and climatic factors in Colombia and reported a decrease of CBB infestation in coffee plants during rainy seasons. Similarly, Constantino et al. (2011) reported higher CBB infestation and increased larval development inside the coffee berries during a dry season with higher temperatures caused by El Niño when compared with a rainy season caused by La Niña in Colombia. In Puerto Rico, Mariño et al. (2016) documented higher CBB infestation on plants under shade when compared with plants under the sun likely due to more stable temperatures and higher humidity reported under shade conditions when compared to sunny conditions. These studies contribute to the fact that temperature along with rain/relative humidity are important climatic factors affecting CBB population dynamics.

The overall lower numbers of CBB females that emerged from the coffee berries located on the trees and on the ground may be due to abandon or death caused by pathogens. Baker et al. (1992a) performed a life-history study of CBB in Mexico and reported that CBB death and abandon from coffee berries were caused by pathogens. Considering that each female lays an average of 50 eggs during its lifetime, the expected CBB emergence would be around 45 females per berry, approximately 30 d after the infestation depending on the temperature and considering a sex ratio of 10 females to 1 male (Bergamin 1943, Baker et al. 1992a). However, a female may leave the coffee berry without reaching the endosperm, depending on berry dry weight and weather conditions (Baker et al. 1992b, Cárdenas and Baker 2010). The low CBB emergence from the berries placed on the plants compared to those on the ground was probably due to the high temperatures in the afternoon in some days when the black outer layer (exocarp) of the berries would reach high temperatures, thus killing or forcing the CBB to leave the coffee berry. In addition, large number of leaves fall from the coffee plants during the harvest; thus, reducing the amount of shading within the canopy. Several studies have reported similar results as found in this research. For instance, higher number of eggs was found in coffee berries on the ground compared to those on the plant, in temperature at the entry hole of the coffee berries on the plant reaching as high as 39°C (Baker et al. 1992a). The number of CBB inside coffee berries at temperatures above 27°C start to decrease sharply, especially above 32°C, and those berries on the plants do not get sufficient moisture from rain to stimulate CBB development and emergence (Jaramillo et al. 2009). Coffee berries on the ground are more likely to get saturated with higher relative humidity after rainfall, triggering CBB emergence (Baker et al. 1992b). The survival strategy in CBB of staying inside dry berries on the trees until the next season could also explain the low CBB emergence (Jaramillo et al. 2006, Dufour et al. 2007). CBB infestation was higher in berries on the trees than on those on the ground under the coffee tree or in the center line between the coffee rows (Johnson et al. 2019). Baker et al. (1992a) also reported low number of CBB inside berries that were infested and placed on the ground.

We observed some ants walking on the plant and on the ground around the containers during the berry sampling; however, neither predation nor predator identity was evaluated in this study. Several studies have reported natural control of CBB performed by ants (Perfecto and Vandermeer 2006, Armbrecht and Gallego 2007, Varón et al. 2007, Gonthier et al. 2013, Jiménez-Soto et al. 2013, Morris et al. 2018, Aristizábal and Metzger 2019, Escobar-Ramírez et al. 2019, Beilhe et al. 2020), flat bark beetles (Follett et al. 2016, Brill et al. 2021), and other predators or pathogens (Baker et al. 1992a, b, 1994). In fact, ants can reduce CBB damage by 40% (Aristizábal and Metzger 2019). The lower CBB infestation in berries on the ground compared to those on the trees observed in our study could be due to pathogens and other organisms that removed or killed the CBB in the berries (Cárdenas and Baker 2010).

The correlation between infestation level and emergence of CBB females and insolation, rain, relative humidity, and temperature without a uniform pattern but with positive and negative correlations in all covariates studied can be explained by a weather-dependent emergence from old, and search for new coffee berries. Due to complex relationships among weather conditions, coffee plant

Table 3. Pearson's correlation between coffee berry borer (CBB), *Hypothenemus hampei* (Coleoptera: Curculionindae), emergence or CBB infestation level on coffee berries located on the ground or on the plants and rain (mm), temperature (°C), relative humidity (%), or insolation (days) in two fields combined during two seasons (I and II)

Season	Infestation	Parameter	Rain	Humidity	Temperature	Insolation
I	Plant	*r*	−0.00220	0.16801	−0.08815	−0.19111
		P	0.9713	0.0056*	0.1486	0.0016*
		N	270	270	270	270
	Ground	*r*	0.06666	0.09126	−0.26733	−0.07538
		P	0.2751	0.1347	<0.0001*	0.2170
		N	270	270	270	270
II	Plant	*r*	−0.19500	0.08120	−0.16274	0.15889
		P	0.0046*	0.2414	0.0183*	0.0213*
		N	210	210	210	210
	Ground	*r*	0.14402	−0.13408	−0.08068	0.08741
		P	0.0370*	0.0524*	0.2444	0.2071
		N	210	210	210	210
Season	**Emergence**	**Parameter**	**Rain**	**Humidity**	**Temperature**	**Insolation**
I	Plant	*r*	−0.20643	−0.23880	0.15682	0.14070
		P	0.0006*	<0.0001*	0.0099*	0.0207*
		N	270	270	270	270
	Ground	*r*	0.02037	0.00186	−0.02719	−0.02718
		P	0.7389	0.9757	0.6565	0.6566
		N	270	270	270	270
II	Plant	*r*	0.00023	−0.02309	0.00011	0.12726
		P	0.9973	0.7394	0.9987	0.0657
		N	210	210	210	210
	Ground	*r*	−0.02934	−0.16153	−0.09339	0.35605
		P	0.6725	0.0192*	0.1776	<0.0001*
		N	210	210	210	210

r: Pearson's correlation between CBB infestation level or emergence from plant or soil and rain, relative humidity, temperature, or insolation.

P: *p*-value generated by correlation between infestation level or emergence from plant or soil and rain, temperature, insolation, or relative humidity; *N*: number of observations.

*Pearson's correlation significantly positive/negative at $P < 0.05$.

phenology, and berry development, it is difficult to find strong correlations that explain the behaviors of CBB and its relationship with the coffee plant and weather conditions. Therefore, additional field studies are recommended to fully understand those complex relationships. The high effect of insolation on CBB emergence or infestation level of CBB females followed by temperature and relative humidity, regardless if positive or negative, agree with other studies that reported the importance of these parameters in CBB movement from coffee berries (Baker et al. 1992b, Mathieu et al. 1997, Cárdenas and Baker 2010, Aristizábal et al. 2017a). The CBB emergence and flight activity is triggered by rainfall, that starts in September during the Spring in Brazil, along with increasing relative humidity and temperature in search for new berries as refuge, especially on the ground (Fig. 3). Jaramillo et al. (2010) reported that colonizing CBB females emerge in higher numbers at temperatures between 25°C and 30°C, with ideal relative humidity of > 93% in the laboratory. An example of this behavior was reported by Aristizábal et al. (2017a) in commercial coffee fields in Hawaii, where high CBB flight activity (>2,000 CBB/trap/week) was observed at the end of the harvest season (December–January). Rainfall during the early December followed by more than three weeks of dry period in November triggered high emergence of CBB females from infested berries on trees or fallen on the ground (Aristizábal et al. 2017a). However, this scenario was observed with lower temperatures of 20–22°C during December–January (Aristizábal et al. 2017a).

The CBB infestation exceeded the threshold to control this pest at the end of the experiment, which is between 3% or 5% of infested berries, depending on the coffee price (Souza and Reis 1997). The infestation level reached more than 50% in 2005 (Fig. 2), which could lead to extensive losses, besides increasing the risk of CBB infestation in the next season. This result strengthens the recommendation to remove all possible coffee berries on the plants and on the ground, as the CBB females can locate and colonize them as refuge. Studies conducted in Colombia by Bustillo et al. (1998), Benavides et al. (2003), and Aristizábal et al. (2011) reported that cultural control (frequent and effective harvesting and sanitation) are the most relevant practices to reduce CBB populations in the following season.

In conclusion, the removal of coffee berries remaining on the trees and especially those on the ground is highly recommended as one of the best practices to manage CBB populations after harvest. These berries allow CBB females to colonize them and survive in a refuge and search new coffee berries to lay eggs and begin a new generation. Coffee berries on the ground may be previously infested while on the plants, but heavy rains may accelerate their decay, preventing CBB infestation (Cárdenas and Baker 2010). The sustainable management program for CBB has to consider the concept of integrating other methods, such as the use of *Beauveria bassiana* which has successfully been used in Colombia (Bustillo et al. 1998) and Hawaii (Greco et al. 2018, Hollingsworth et al. 2020), the use of baited traps with semiochemicals to monitor flight activity and control and, if possible, using natural enemies (such as parasitoids, predatory ants, and flat bark beetles) that may be present in the area, with adoption of cultural control practices such as sanitation.

Supplementary Data

Supplementary data are available at *Journal of Insect Science* online.

Supplementary Fig. 1. Weekly average temperature (°C), rain (mm), insolation (hours), and relative humidity (%) during the post-harvest period between September and December in two crop seasons, in Viçosa, Minas Gerais state, Brazil

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Author Contributions

Conceptualization- AEP, EFV; Data curation- AEP, PCG; Formal analysis- AEP, PCG, MRE; Funding acquisition- EFV; Investigation- AEP, AKF, RST; Methodology- AEP, EFV; Project administration- AEP, EFV; Resources- EFV; Supervision- AEP; Validation- AEP, EFV; Visualization- AEP, EFV, AKF, RST; Roles/Writing - original draft- AEP; Writing - review & editing- AEP, JCZ.

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