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Article

Vertical trapping of the coffee berry borer, *Hypothenemus hampei* (Coleoptera: Scolytinae) in coffee

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Simple Summary: Globally, Coffee Berry Borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae: Scolytinae) severely affects the quality and production of coffee. To understand how to control this pest, we studied their flight patterns and captured them at different trapping heights. Baited column traps captured more coffee berry borers at 0.5m height than at higher heights irrespective of temperature changes, rainfall, and relative humidity. Understanding the height position for the most efficient insect capture is useful for developing future cost-effective management strategies to control this coffee pest.

Abstract: The coffee industry loses millions of dollars annually worldwide due to the Coffee Berry Borer (CBB); these losses imply a decrease in quality and production. Traps are used to monitor their flight and for pest control. The main objective was to determine the flight pattern and trap capture percentages of the CBB population over time using column traps (CTs) in two independent field experiments. CTs were composed of four traps installed at four different heights 0.5, 1.5, 2.5, and 3.5m above ground. Our results demonstrated a significant difference in CBB capture by traps placed at different heights above the ground. The CT capture maintained a pattern throughout this study's lag; the lower the height, the greater the percentage of CBBs captured. In Experiments A and B, the traps placed at 0.5m caught 67% and 85% of the CBBs captured, respectively. Furthermore, the trap set at 1.5m above the ground in the multi-level CT showed a higher capture percentage than the individually placed trap (also at 1.5m). The pattern of the capture and proportion of the CBB in the CTs were maintained throughout the study despite the season, changes in temperature, and relative air humidity. We suggested that CTs could be explored as a useful tool for capturing the CBB, considering its monitoring and management.

Keywords: *Coffee arabica*, *Hypothenemus hampei*, baited traps, IPM

1. Introduction

The Coffee Berry Borer (CBB), *Hypothenemus hampei* (Ferrari, 1867) (Coleoptera: Scolytidae is a major invasive species in coffee [1,2]. Trapping is one of the most traditional and well-known Integrated Pest Management (IPM) strategies on coffee plantations worldwide for monitoring and direct pest control [3, 4, 5, 6, 7, 8]. The alcohol-baited traps are primarily used to monitor flight activity and control the CBB [1, 3, 9, 10]. The CBB uses the coffee berries for shelter, feeding and reproduction, causing a decrease in coffee bean quality

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and production [6, 11]. Around the world, the coffee industry loses more than US$500 million annually as a consequence of CBB damage [12].

A relationship has been reported between the number of CBBs captured by the traps baited with a methanol: ethanol solution and the infestation of the coffee berries [5, 8, 13, 14, 15, 16]. Different trap designs and proportions of ethanol and methanol have been tested worldwide in search of a combination that captures the most significant number of CBBs [3, 5, 10, 13, 15, 16, 17]. In most trapping designs, the traps are placed at a height between 1.5 and 2.0m with a single unit and a bait container of 17 to 40 mL with a 3:1 solution methanol: ethanol [5, 10, 18]. Also, the rate of emission of the solution is essential to attract and capture CBBs. In 1997, Mathieu et al. [3] suggested that the trap's emission rate is inversely proportional to the number of CBB captures for methanol: ethanol mixture in funnel traps. Mathieu and collaborators recommended that a single trap might be a better control option for the CBB.

Wind, rain, temperature, and availability of the berries directly influence the flight range of the CBBs [14]. For a trapping system, several questions remain about interactions among characteristics and behavior of the CBB, climate factor, density and phenology of the coffee plants. How much the insect will disperse and move horizontally or vertically is important to improve CBB control and monitoring. What would be the ideal height to capture the largest number of CBBs [5, 14, 15, 18, 19]? The main objectives in this work were: (1) to establish the relationship between field infestation and the capture by the traps, and (2) to determine the capture of the CBB by standard Brocap traps installed in columns at four different heights (0.5m, 1.5m, 2.5m, and 3.5m) vs single traps (at 1.5m), over distinct stages of the coffee phenology and weather periods, Figure 1.

Figure 1: Representative illustration of column traps (CT). Each CT comprised of four traps placed at 0.5m, 1.5m, 2.5m and 3.5m above ground and a single trap (ST) at 1.5m above ground. Field experiments conducted at Adjuntas, Puerto Rico.

2. Materials and Methods

2.1 Study sites

The field experiments were conducted at the Agricultural Experiment Station of Adjuntas, PR (18 10'28.89" N 66 47' 52.27" W) at 585 meters above sea level (masl) in *Coffee arabica* "Limani" and "Catuaí". Coffee plants averaged 2.5m height in the study plots. Experiment A (Exp A, "Limani") was conducted between April and September 2019 in the first plot, which has an area of 2,280m²; Experiment B (Exp B, "Catuaí"), conducted between October 2019 and March 2020, was established in a second plot that has an area of 2,800m². In the adjacent referential coffee plot (Ref 1 and Ref 2) with an area of 1,200m², single traps (Brocap®) at 1.5m height were installed. Meteorological data was recorded by a Remote Monitoring Weather Station Data Logger HOBO RX3000 (Onset, Bourne, MA, USA).

2.2 Column Trap Designed

A column trap (CT) design held four traps (Brocap®) placed at four heights above ground. Five CTs (repetitions) were positioned 25 m from each other in a zig-zag pattern in each plot. Each trap contained a 30mL container with a chemical lure (3:1, methanol: ethanol). The lure was replaced every six weeks or sooner if it was observed to have evaporated. The traps were fixed one above the other at 3.5m, 2.5m, 1.5m, and 0.5m above the ground; and five single traps (ST) at 1.5m above the ground were placed at the adjacent reference plot Figure 1.

2.3 Data Collection

CBBs captured were duly separated and identified by the number of the CT and its corresponding height; then the samples were taken to the laboratory to identify and quantify. For the infestation, we first randomly selected three branches from trees around each CT, recorded the total number of berries per coffee branch (each branch chosen had a minimum of 33 berries), also counting how many perforated berries were on the branch, for a total of fifteen branches per plot for each sampling date. The same was done for the reference coffee plot (Ref 1 and Ref 2).

2.4 Data Analysis

All of the data was collected from two experiments and two referential coffee plots. Exp A and Ref 1 were carried out from March to September 2019, and Exp B and Ref 2, from October 2019 to March 2020. CBB capture rate pattern was monitored by the height of each of the traps in the CTs. We also monitored the percentage of infestation of the coffee berries in each plot. The percentage of infestation was calculated by the ratio of perforated berries to whole berries. To fit a normal distribution, the data were transformed according to Warton [20]. The CBB capture rate per trap was normalized per day and transformed according to [21]. Furthermore, we used the proportions of CBB capture at each height over the total number of CBBs captured by the CTs to analyze the capture pattern at each height through time. Such analysis was done with a generalized linear model. To evaluate data normality, we used the Shapiro-Wilk test and Spearman's rank correlation test for Infection and CBB capture rate by CT. The statistical analysis was performed using RStudio Team V1.2.1335 [21, 22], and for Figures, we used the package ggplot2 [23].

3. Results

A total of 72,172 CBBs were captured using CTs during the periods of the two studies: Table 1, 32,899 CBBs in the Exp A and 39,273 in Exp B. In addition, 7,635 CBBs in Ref 1 and 2,665 in the Ref 2 were captured by single traps at the adjacent reference plot. Also, in dissected coffee berries, we found 363 CBBs in Exp A, 405 in Exp B, 398 in Ref 1 and 515, Ref 2. A similar pattern could be observed at the two study sites and in all CTs. The traps placed at 3.5 m and 2.5 m height were the ones that collected the least CBBs, and the most significant collection of CBBs was at 0.5 m, followed by 1.5 m height, Figure 2. The trap placed at 0.5 m height collected 67.0% and 84.7% of the total CBBs for Exp A and Exp B, respectively. The trap at 1.5 m collected 11.2% and 26.3%, in Exp A and Exp B, respectively. The traps at 2.5 m and 3.5 m combined represented 6.7% in Exp A and 4.1% in Exp B, Figure 2.

Table 1: Summary of environmental variables and total CBBs captured by the CTs at the study sites (Agricultural Experiment Station of the University of Puerto Rico at Adjuntas). Temperature and relative humidity (RH), and the total rainfall during the trapping interval.

Experiment A										
Date	Temp∘C	Max	Min	RH%	Max	Min	R	RE	DD	CBB
3-Apr-19	20.7±4.4	30.5	12.1	85.1	100	44.7	52.0	11	8	7588
15-Apr-19	20.8±4.3	30.6	12.3	83.8	100	42.4	10.4	14	3	9563
2-May-19	21.2±4.5	31.4	12.6	85.1	100	44.7	95.6	20	7	7577
22-May-19	22.2±4.2	31.5	13.8	85.1	100	55.1	144.0	13	9	5092
5-Jun-19	22.2±3.6	31.3	16.1	89.1	100	55.6	84.6	29	13	1406
19-Jun-19	23.2± 4.4	33.9	15.3	85.8	100	53.5	17.4	12	8	452
2-Jul-19	23.5±4.3	33.0	15.9	85.5	100	50.7	52.8	8	7	261
19-Jul-19	23.0±3.7	32.1	15.3	87.2	100	49.8	222.6	28	6	224
5-Aug-19	23.5±3.8	32.4	16.0	87.8	100	46.9	40.0	19	5	155
21-Aug-19	23.7±3.9	32.2	16.0	86.7	100	54.4	78.6	17	7	228
4-Sep-19	23.5±4.4	33.7	15.0	86.2	100	45.8	20.4	10	4	353
Mean±SD	**22.5±4.1**	**32.1**	**14.6**	**86.1**	**100.0**	**49.4**	**818.4**	**181.0**	**77.0**	**32899.0**
Experiment B										
18-Oct-19	21.8±4.6	32.9	14.7	89.9	43.9	100	270.4	32	3	250
30-Oct-19	22.0±3.7	30.9	16.1	91.7	50.2	100	75.0	28	1	365
13-Nov-19	21.9±3.8	29.7	15.8	90.1	57.2	100	89.8	16	4	286
27-Nov-19	20.9±3.9	30.3	13.8	92.0	58.4	100	103.2	19	6	821
11-Dec-19	21.1±3.8	29.6	13.5	90.9	56.3	100	30.0	18	1	441
22-Jan-20	20.8±3.3	29.3	13.6	90.0	53.8	100	111.2	77	16	9574
5-Feb-20	20±4.2	29.7	12.2	91.5	50.1	100	79.2	24	4	11101
19-Feb-20	21.6±3.8	29.4	13.3	90.5	55.1	100	12.4	12	6	9368
4-Mar-20	20.3±4.1	29.7	12.7	89.1	42.2	100	95.4	30	6	7067
Mean±SD	**21.2±3.9**	**30.2**	**14.0**	**90.6**	**51.9**	**100.0**	**866.6**	**256.0**	**47.0**	**39273.0**

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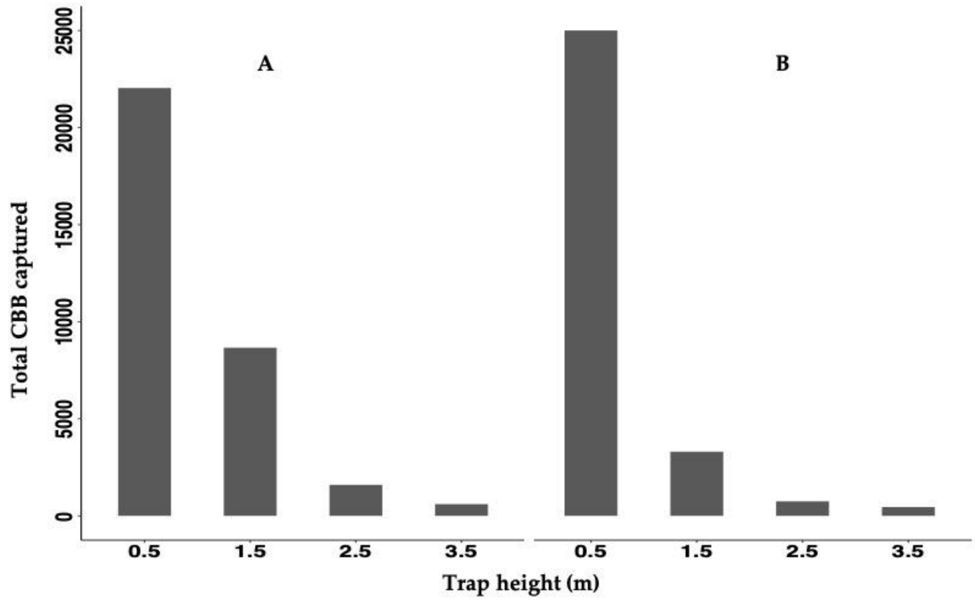

Figure 2: The total CBB captured at each height in each experiment. Experiment A was established from March 2 to September 4, 2019, and Experiment B, from October 2 to March 4, 2020, at Adjuntas, Puerto Rico.

Results from general linear model for Exp A showed that the percentage of each trap's capture, according to height for the total CBB captured by a column, was statistically different by height over time with (43) =177.1, *P-value=0.001*, and Akaike Information Criterion (AIC) of the 365.55. These results suggested that the best height to capture CBB for all the periods was 0.5 m above the ground, see Table S1 and Figure 3. The results from Exp B showed that the percentage of each trap's capture, according to height for the total CBB captured by a column, was statistically different by height and by the interactions between height but not by sampling dates. Whereas the percentage of the CBB catches by sampling dates were not statistically different $X^2(31)$ =10.13, *P-value=0.001*, and AIC = 112.23.

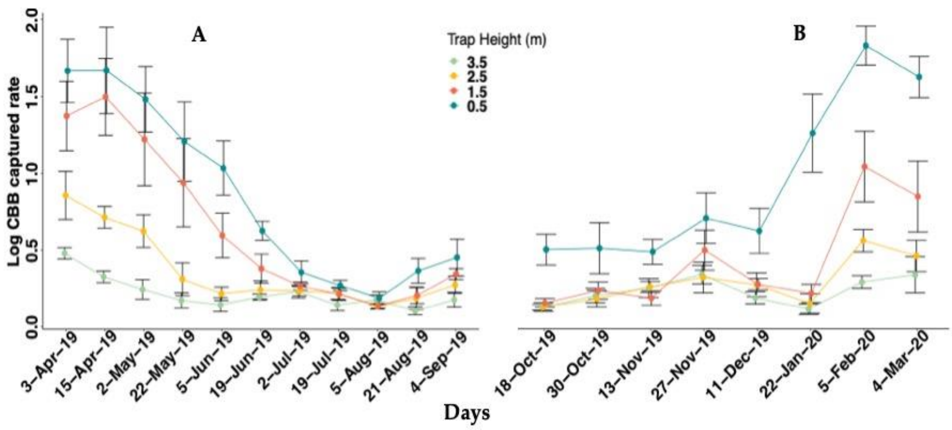

Figure 3: (A) Average and standard error per collection date for each height through time of Experiment A. (B) Average and standard error per collection date for each height through time of Experiment B. Adjuntas, Puerto Rico.

We compared the capture rate of CBB traps, placed at 1.5 m height from the ground in both CT and ST, see Figure S1 in both experiments. The results show the significance of (22) = 20.8, $Pvalue$ = 0.001, AIC= 94.43 for Exp A, see Table S1. These findings suggest that the traps at 1.5m in CT were more efficient at capturing CBB throughout the year than were the reference single traps (only one trap at 1.5m, ST), see Table S1 and Figure S1-A. Likewise, in Exp B the traps at 1.5m compared with ST showed significant differences of = 10.85, $Pvalue$ = 0.001, AIC= 41.62, see Table S1 and Figure S1-B. On the other hand, the infestation rate in the adjacent plots in Exp A and Exp B decreases through time. For Exp A, the initial infestation rate was 27.21% but ended up being 4.63%. For Exp B, the initial infestation rate was 3.81% and ended up 1.77%. Nonetheless, in the plot adjacent to Ref 1, the infestation rate started at 20.23% and ended at 8.50. For Ref 2, the infestation rate started at 10.18% and ended at 20.12%. This decrease in the infestation rates of the adjacent plots where the CTs were installed could result from the increased capture by CTs, Figure S1.

The regression analysis results showed a significant positive correlation between infestation in the coffee crop of the study plots and the CTs' capture rate for Exp A and Exp B, Figure 4. These results suggest that CTs are a good predictor of the flight activity of the CBB population. Likewise, the caught rate of CBB in CT is linked with the coffee crop's infestation, Figure 4. Additionally, the infestation rate of the adjacent referential plot decreased through time, Figure S1.

Also, the results showed that independent of the season and coffee variety ('Limani' or 'Catuaí'), the height that collected more CBB was 0.5 m above the ground. The total rain events by the trapping period correlates with the total capture of CBB in Exp A; a significant difference is observed (*T(10)=2.48, Pvalue=0.033*).

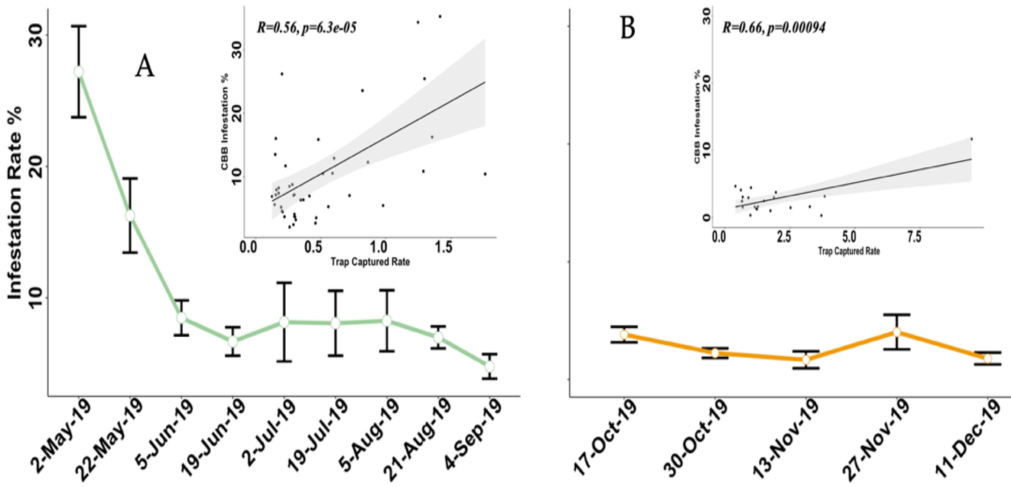

Figure 4: The average and standard error (vertical bar) of infestation rate during experiments A and B at the adjacent plots. The regression analysis shows a significant positive correlation between the percentage of infestation and trap capture. Experiment A was conducted from March 2019 to September 2019, and B, performed from October 2019 to March 2020, at Adjuntas, Puerto Rico.

4. Discussion

Bait traps have been used worldwide, primarily to monitor CBB populations' flight on coffee plantations [3, 8, 13, 15, 17, 24]. However, the significant fluctuation in the number of CBB captured through time at the four different heights of the CTs in our study suggests that CTs themselves could be beneficial as a pest management control strategy. The height at which each trap is placed is crucial; our results establish a significant difference among the CT heights. It was the lowest height trap sites (0.5m) that captured the highest number of CBB. Usually, to monitor CBB flight activity, the traps are used individually at 1.5 m above ground and not in columns [18, 25]. Considering these results, if the traps are placed at 0.5m from the ground, their capacity to catch CBB throughout the year will be much higher than at the height commonly placed.

The berries remaining on the ground after the harvest are a potential refuge for the CBBs in the following months and in future coffee production. During this period, a significant number of the population of the CBBs are close to the ground [25, 26]. Therefore, the height at which the trap is placed is critical in this period. Our results support this idea; we found that a significant number of CBBs collected in this season came from the ground, i.e., from berries that fell to the ground at harvest time see Figure 4 and Figure 5. However, CT collected CBBs at all four heights during the entire studied periods with significant differences between the four heights over time. These results suggest that most of the CBB population has preferred a short or low flight. CBBs that survived in the dry berries ("raisins") on the ground, when they fly again, and depending on the availability of an attractant, they will first colonize berries in branches closer to the ground.

Both chemicals (Ethanol: Methanol) used in the trapping are heavier than the air. The CT design under normal conditions would produce an expanded zone of influence with an overall increase in attractiveness towards the lower areas. Our experiment also observed a positive column attraction in the CBB captures (4 traps, four pro-column attractants) as indicated in the results. This design would likely increase CBB capture in the lower height trap throughout the study period.

5. Conclusions

CT is useful in indicating CBB infestation density and population distribution by height. Figure 3 shows how the traps placed at a lower height always maintained the pattern of highest capture of CBB throughout the study period. However, different environmental conditions, the coffee crop stage, plant density, variety, the crop cultivation system could influence the results. Under the environmental conditions of this study, the traps with the maximum capacity to capture the CBB throughout the evaluation periods were those placed at 0.5 m from the ground accounting for 67% (Exp 1) and 84% (Exp 2) of the total insect captures. Further studies on column trapping design should be conducted to optimize and explore their use as a proper pest management tool. Additional work should investigate CT effectivity during young coffee plant stages.

Supplementary Materials: Figure S1: **Figure S1**, Table S1: **Analysis of variance to columns traps in Experiment A and Experiment B**.

Author Contributions: Conceptualization, C.P.R.D. and J.C.V.R.; methodology, C.P.R.D. and J.C.V.R.; formal analysis, C.P.R.D. and J.C.V.R.; investigation, CPRD and J.C.V.R.; resources, J.C.V.R.; writing—original draft preparation, C.P.R.D.; writing—review and editing C.P.R.D. and J.C.V.R.; supervision, J.C.V.R.; project administration, J.C.V.R.; funding acquisition, J.C.V.R. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest

Appendix A

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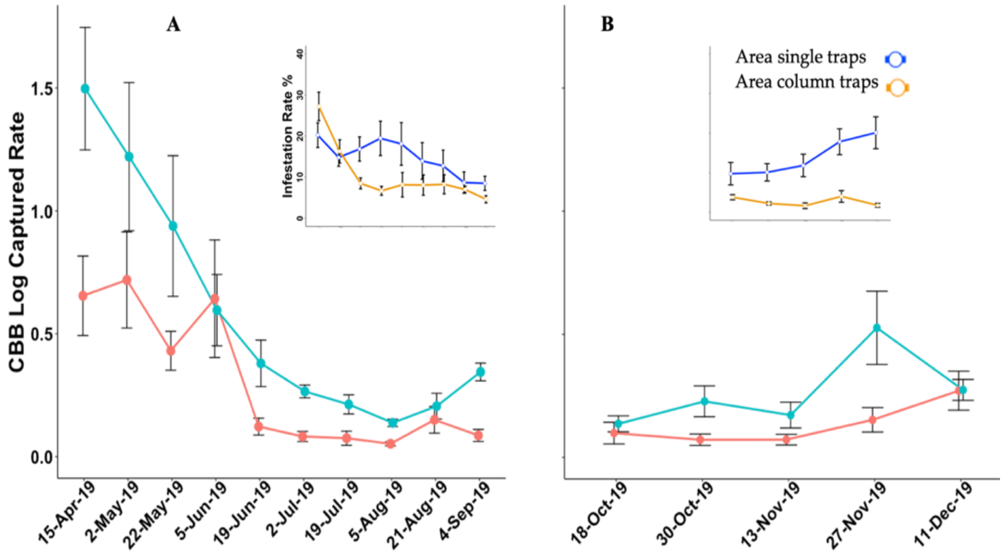

Figure S1: Comparison between traps placed at 1.5m in the single (red) and in the column trap design (blue). The top insert, infestation rate of the coffee berries in the Experiment A and B plots (blue) and berries infestation rate at the referential single trap plots (yellow).

Table S1: Analysis of variance to column traps in Experiment A and Experiment B

Experiment A		
	df	Pr(>Chi)
Trap-Height	*3*	*< 2.2e-16* ***
Date Sampler	*10*	*7.867e-11* ***
Trap-Height: Date Sample	*30*	*< 2.2e-16* ***
Experiment B		
Trap-Height	*3*	*< 2.2e-16* ***
Date Sampler	*7*	*0.0814435*
Trap-Height: Date Sample	*21*	*0.0001252* ***

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