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A new and highly effective sampling plan using attractant-baited traps for the coffee berry borer (*Hypothenemus hampei*)

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Abstract Several sampling plans have been developed for many insect pest species. However, few sampling plans have been based on attractant-baited traps. The coffee berry borer *Hypothenemus hampei* (Coleoptera: Curculionidae: Scolytinae) is a key coffee pest of worldwide importance whose sampling plans usually demand the harvest and inspection of up to 5,000 coffee berries per field, which is labor-intensive, costly, and ineffective. Therefore, this system constitutes a good model for the development of a more cost-effective sampling plan based on attractant-baited traps for capturing adult insects allowing the sustainable management of this pest species. The reported study was performed in 27 coffee fields using berry damage-assessment techniques and capture of adult borers applying attractant-baited traps made of PET-bottles (polyethylene terephthalate bottles). The relationship between trap capture and berry damage was significant allowing the use of the former to estimate coffee loss caused by the borer. The trap capture data from the coffee fields were adjusted to a negative binomial distribution suitable for establishing a single conventional sampling plan for all investigated fields. The required trap density varied from 14 to 355 traps/10 ha, depending on the precision error selected. The sampling plan developed using spatial interpolation (kriging and inverse weighted-distance methods) indicated that using 22 traps/10 ha for sampling of the coffee berry borer, costing US$ 303.24/10 ha and requiring 49.14 min/10 ha for the sampling procedure, was suitable and resulted in cheaper, faster, and more reliable estimates compared to present recommendations.

Keywords *Coffea arabica* · Coffee pest · Trap density · Spatial analysis · Attractant-baited traps

Key message

- Current sampling plans for the coffee berry borer are labor-intensive, costly, and ineffective.
- Here we report a new and effective sampling plan using attractant-baited traps to circumvent such limitation.
- Coffee berry borers were captured with a mixture of ethanol:methanol 1:3 (v/v) with 1 % benzoic acid.
- The developed sampling plan required 22 traps/10 ha and 49.14 min/10 ha for sampling at a cost of US$ 303.24/10 ha.

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Introduction

Sustainable pest management programs require precise and reliable methods for estimating the density of insect pests, and accurate estimates are achieved using suitable sampling plans for pest-control decision-making (Norris et al. 2003; Pedigo and Rice 2006). Sampling plans are either conventional or sequential, and the former is necessary for the development of the latter, serving as a fundamental initial step in establishing a decision-making process (Nault and Kennedy 1996; Pedigo and Rice 2006).

Conventional sampling plans have been developed for several insect pest species, including the coffee berry borer *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae: Scolytinae), a key pest of coffee (*Coffea arabica* L. and *C. canephora* Pierre ex A. Froehner) in several countries (Decaszy et al. 1988; Rémond et al. 1993; Souza and Reis 1997; Damon 2000). These previously reported coffee sampling plans are destructive and have debatable scientific support because they are labor-intensive, time-consuming, costly, and ineffective. Furthermore, the adoption of such sampling plans was unlikely despite their recommendation by official state agencies, which led to the development of alternative (conventional) plans that were less time-consuming (e.g., Bustillo et al. 1998; Echeverry et al. 2006).

The current sampling plans for the coffee berry borer focus on the sampling of coffee branches and berries (CENICAFÉ 1993; Bustillo et al. 1998; Bianco 2000; Duque and Chaves 2000; Aristizábal et al. 2006; Echeverry et al. 2006). In contrast, the use of sampling plans based on attractant-baited traps has been largely neglected, although traps are recognized as a potentially important alternative because they allow recognition of the transition period when the female adult borers leave old, residual berries to infest newly formed berries (Damon 2000).

Attractant-baited traps can be used successfully for pest insect sampling because they are time-saving, easy to use, and allow the capture and confinement of the insects (Jones 1998; Bacca et al. 2006, 2008). Traps are useful for sampling when the density of captured insects correlates with that of the insect infestation and/or consequent plant yield loss (Francke et al. 1988; Gusmão et al. 2005; Pedigo and Rice 2006). Attractant-baited traps for the coffee berry borer were developed using an ethanol-methanol mixture in PET-bottles (polyethylene terephthalate bottles) (Mathieu et al. 1999; Dufour 2002; Saravanan and Chozhan 2003; Barrera et al. 2004; Silva et al. 2006; Dufour and Frérot 2008). Attractant-baited traps have also been used to develop economic injury-level estimates (Fernandes et al. 2011), suggesting their potential for more widespread use in sampling and thus monitoring population densities of this key coffee pest species.

Sampling plans integrating attractant-baited traps and field-management decision-making are desirable additions to insect pest management strategies; however, they must include a suitable number of samples to allow fast, affordable, and precise sampling with a maximum error threshold of 25 % (Bliss and Owens 1958; Southwood 1978; Pedigo et al. 1982; Pedigo and Rice 2006). Spatial interpolation uses geostatistical techniques to determine insect population densities at unsampled sites using neighboring sites as a reference (Strother and Steelman 2001; Nansen et al. 2003; Bacca et al. 2006). Spatial analysis is also useful in determining trap distance and trap placement to improve insect sampling and monitoring (Bacca et al. 2006, 2008).

Suitable sampling plans using attractant-baited traps for the coffee berry borer have yet to be developed, and the previous efforts have involved only preliminary work with a few traps placed in restricted areas. Therefore, the objective of the present study was to develop a sampling plan using attractant-baited traps for the coffee berry borer and to build insect density maps through spatial interpolation techniques.

Materials and methods

Coffee plantations

The study was performed in 27 coffee fields (*Coffea arabica* L.) of approximately 10 ha each, located in the counties of Viçosa and Ponte Nova, in the state of Minas Gerais, Brazil. The coffee plants, planted in the field at a spacing of 0.5 m × 1.5 mm, were eight years old and were from the IAC 15 lineage of the cultivar "Catuaí Vermelho." The coffee plants ranged between 1.7 and 1.9 m in height and were cultivated under intensive light. Conditions in the fields were characteristic of the Atlantic Forest region of coffee cultivation in Brazil, with temperature conditions ranging from 14 to 30 °C, 25–100 % relative humidity, 1,250 mm/year precipitation and an altitude of approximately 650 m above sea level. The plants were fertilized using dolomitic calcarium, macro, and micronutrients following the recommendations for the region (Guimarães et al. 1999; Zambolim 2001). Fertilization and harvest were performed manually, while spraying and other cultivation activities were performed with machines. The timings of the coffee phenological stages in the region were as follows: flowering in September, early berry development between October and November, berry expansion until December, grain development between January and March, berry maturation between April and June, and harvest between July and August.

Insect sampling and berry damage

The adult density of the coffee berry borer was determined using red-painted and attractant-baited traps made of 2-L PET-bottles that each had a rectangular side opening (20 × 15 cm), as described by Fernandes et al. (2011) (Fig. 1). The traps were fixed to the coffee plants 1.5 m above the ground using no. 12 galvanized wire. Each trap received a 10-mL glass vial containing the attractant mixture [ethanol:methanol at 1:3 with 1 % benzoic acid (all reagents were > 99.9 % pure)]. The bottom of the trap

Fig. 1 *Red*-painted and attractant-baited traps made of 2-L PET-bottles on coffee plants *Coffea arabica* with attractant to capture adults of coffee berry borer (*Hypothenemus hampei*). The attractant mixture used was ethanol:methanol at 1:3 with 1 % benzoic acid contained in a diffusor glass flask. (Color figure online)

was filled with 120 mL of water with 5 % neutral liquid soap for insect capture. The trap opening was centrally oriented between crop rows, which allowed the odor plume to spread between the rows (Bacca et al. 2006). Three hundred traps were placed in each coffee field, establishing a spacing grid with 2, 4, 10, 20, 30, and 50 m between traps randomly distributed in each coffee field. This range of trap distances was necessary for the spatial analysis (Isaaks and Srivastava 1989), and the traps were inspected every two weeks from September onward during two consecutive years, 2006/2007 and 2007/2008. The traps captured primarily adult females of the coffee berry borer because the males do not fly (Damon 2000; Barrera et al. 2004; Dufour and Frérot 2008). The insects captured in the traps were transferred to 150-mL plastic containers filled with 70 % ethanol, which were subsequently taken to the laboratory for counting using a stereomicroscope (20× magnification).

Green, mature, and dried berries damaged by the coffee berry borer were recorded by inspecting the parchment of 100 coffee berries from each of five branches located in the mid-canopy of each plant located every 100 m in the coffee row and every 50 m between rows, encompassing approximately 50 plants per field. This assessment was performed in three coffee fields. The total number of berries and the total number of berries damaged by the coffee berry borer were recorded every two weeks, when the attractant-baited traps were inspected. Linear regression analysis between (adult) trap capture and damaged berries was performed to assess the relationship between these two variables using the PROC REG procedure (SAS Institute 2008).

Frequency distribution of insect captures

The mean and variance of adult trap capture were used to estimate the aggregation index of the captured insects, which is the most practical way to determine the frequency distribution of insect capture (Taylor 1961; Myers 1978). A random frequency distribution provides a variance/mean ratio equal to one, while aggregate distribution provides a mean lower than the variance and regular distribution provides a variance lower than the mean. The suggested most suitable data distribution model was confirmed by calculating the expected frequencies based on the negative binomial, Poisson, and positive binomial models and comparing the expected and observed frequencies using the Chi-squared (χ^2) goodness-of-fit test (Pedigo and Zeiss 1996). The best model of frequency distribution was used to guide the selection of the most suitable statistical approach to estimate the necessary number of samples (Young and Young 2002).

The existence of a common K-value (K_c or common aggregation index) was recognized based on the frequency distribution obtained, and it was used to derive a dispersion parameter that suitably described the variability of insect capture observed among coffee fields (Bliss and Owens 1958; Binns 1975; Taylor 1984). The common K-value (K_c) is a parameter of the negative binomial distribution used to determine the number of samples representing the data dispersion in the different fields surveyed. The partial K-values (K_p, or partial aggregation index, refer to the K-values for each coffee field) were calculated, and their independence from the mean was tested by regression with the eventual estimation of K_c following Young and Young (2002).

Required number of samples and sampling costs

The number of samples required for the sampling plan was estimated based on the frequency distribution of insect capture. The estimated K-value for each field used was based on the recognized frequency distribution and a suitable equation was applied as indicated by Young and Young (2002). If no suitable frequency distribution was recognized for a given field, the number of samples was estimated following Pedigo and Rice (2006). The number of traps required to establish a conventional sampling plan was calculated allowing assessment errors (i.e., precision errors) of 5, 10, 15, 20, and 25 %. The common value (CV) of the number of samples required for all fields was calculated using the following equation provided by Young and Young (2002):$CV = \left[\frac{1}{EA^2} \times \frac{1}{\overline{X}} + \frac{1}{K_c}\right]$, where EA is the level of error allowed, $\overline{X}$ is the mean of adults and K_c is the K common.

The general formula proposed by Pedigo and Zeiss was used to estimate the required number of samples (N) for the fields in which no data distribution was recognized. $N = \left[\frac{(t \times S)}{(D \times \overline{X}}\right]^2$, where N is the number of samples, $\overline{X}$ is the mean of adults, D is the error allowed (0.05 to 0.25), and S is the standard deviation.

The sampling costs were estimated by adding the labor costs and sampling material costs. The labor costs considered the time spent in setting up the traps and subsequently collecting and recording their catches, the salary of rural workers, and their social benefits [employment security fund (8 %) and social security (0.027 %)]. The materials used for sampling included pencils, erasers, paper, clipboards, red-painted PET-bottles, 10-mL glass containers, no. 12 galvanized wire, attractant mixture (ethanol, methanol, and benzoic acid), detergent, 500-mL wash bottles, 5-L plastic bottles (to pour water and soap into the traps), and 50-mL plastic containers to store the collected insects. The time spent on data processing was also recorded to provide an idea of the time needed for decision-making. The sampling method recommended by Souza and Reis (1997), where 1.5 % of the plants were subjected to berry harvest for borer inspection in a 10-ha field (replicated 10 times), was employed for comparison.

Spatial distribution

The spatial distribution of the coffee sampling plan was recorded in a 10-ha coffee field in Ponte Nova county between the months of September and November (2009), when the coffee berry borer starts to infest the newly formed coffee berries (Souza and Reis 1997). The capture data from 300 traps (absolute trap density) were recorded in a coffee field and compared with trap capture data using estimated trap densities with precision errors of 15, 20, and 25 %. Isoline maps were used to represent the spatial distribution of adult insect capture when using the absolute trap density (300 traps/10 ha) obtained with ordinary kriging as the interpolation method (Isaaks and Srivastava 1989; Bacca et al. 2008). In contrast, the inverse weighted-distance method was used for interpolation when using smaller trap densities estimated for precision errors of 15, 20, and 25 % (Isaaks and Srivastava 1989; Bacca et al. 2006, 2008).

The nugget (C_0) and sill ($C_0 + C$) parameters of spatial dependence were determined in the geostatistical analysis. The nugget is the semivariogram value in which the model intercepts the y-axis (i.e., the semivariogram axis), and its effect corresponds to measurement errors or spatial sources of variation at distances smaller than the sampling interval (or both). The sill refers to the semivariogram value in which the model flattens out indicating spatial autocorrelation up to this point (and respective distance, referred to as the semivariogram range). The ratio nugget/sill ($C_0/(C_0 + C)$ allows the identification of the level of spatial dependence (LSD). The above estimates were subjected to the classification proposed by Cambardella et al. (1994) in which the semivariograms with a strong spatial dependence exhibit an $LSD \leq 0.25$, those with a moderate spatial dependence exhibit an LSD between 0.25 and 0.75, and those with a weak spatial dependence exhibit an $LSD > 0.75$. The interpolation methods were selected based on the number of samples, as previously explained (Brookers 1991). All of the spatial analyses were performed using the software GS+ (Gamma Design Software 2012).

Results

Insect sampling and berry damage

The coffee berry borer represented approximately 90 % of the insect specimens collected in the attractant-baited traps and the remaining 10 % of the collected insects were Scolytidae and Cerambycidae beetles. The density of coffee berries damaged by the coffee berry borer during the coffee plant reproductive period in the three sampled coffee fields ranged from 0 to 287 berries damaged/plant/15 days, and the borer capture rates in the attractant-baited traps ranged from 0 to 3,854 insects/trap/15 days. The insect capture in the attractant-baited traps was a robust predictor of damaged berries, with a significant and positive relationship ($R^2 = 0.88$, $P < 0.001$) (Fig. 2). These results provide support for the development of a sampling plan using insect capture with coffee borer attractant-baited traps to monitor the attack of this species and allow for decision-making regarding its control.

Frequency distribution of insect capture

The relationship between variance and mean for the trap capture data in each field was higher than one, indicating an aggregated frequency distribution for insect capture (Table 1). The insect capture data were subsequently adjusted to the negative binomial, positive binomial, and Poisson distributions to verify the pattern of frequency distribution. The data did not adjust to the Poisson and positive binomial distributions when using the χ^2 goodness-of-fit test ($P < 0.05$); in contrast, the negative binomial distribution

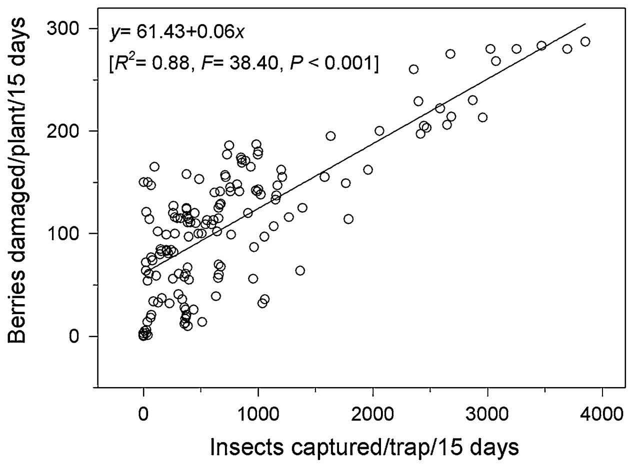

Fig. 2 Relationship between the number of adults of the coffee berry borer (*Hypothenemus hampei*) captured by the attractant-baited traps and the number of berries damaged by the borer

provided good fits for all but two coffee fields (Table 1). This distribution was also confirmed by estimating the partial aggregation indexes *Kp* of the negative binomial distribution, which is usually close to zero with a few exceptions (Table 1). If tending to infinity (i.e., very high values), the aggregation index *K* indicates a more random distribution.

Required number of samples and sampling costs

The prevailing frequency distribution of captured insects was negative binomial; therefore, the number of required traps per area was estimated accordingly using the aggregation index *K* of the corresponding negative binomial distribution (Young and Young 2002). The alternative estimate of the number of required traps, as suggested by Pedigo and Zeiss (1996), was used for the two coffee fields where no suitable frequency distribution of insect capture

Table 1 Mean ($\overline{X}$), variance (σ^2), aggregation index (partial *K*-values) of the negative binomial distribution (*Kp*), χ^2 goodness-of-fit test and degrees of freedom (*d.f.*) for the frequency distribution models of the trap capture data for coffee berry borer adults (*Hypothenemus hampei*) in 27 coffee fields

Coffee field	$\overline{X}$	σ^2	$\sigma^2/\overline{X}$	*K*	Negative binomial		Poisson		Positive binomial	
					χ^2	*d.f.*	χ^2	*d.f.*	χ^2	*d.f.*
1	4,868.7	7,642,715.7	1,569.7	0.9	20.8 ns	23	155*	12	211*	7
2	6,193.8	53,736,659.3	8,675.7	0.7	1.8 ns	6	214*	13	312*	8
3	7,011.4	52,740,707.3	7,522.0	0.9	3.6 ns	3	458*	11	153*	15
4	5,120.9	3,015,917.7	588.9	8.7	6.5 ns	6	591*	12	293*	11
5	1,823.5	4,388,095.2	2,406.3	0.7	7.5 ns	4	151*	22	343*	11
6	1,857.8	4,215,854.9	2,269.2	0.8	7.2 ns	4	242*	12	111*	10
7	1,747.7	3,923,912.0	2,245.1	0.7	6.6 ns	8	783*	4	187*	12
8	5,774.8	13,485.3	2.3	4,325	155*	6	315*	8	124*	7
9	2,768.7	1,860,372.9	671.9	4.1	1.7 ns	2	456*	3	765*	7
10	3,497.8	17,555,234.4	5,018.8	0.7	8.8 ns	4	252*	4	342*	5
11	3,381.3	15,039,399.9	4,447.7	0.8	1.1 ns	6	135*	3	111*	9
12	1,221.2	1,971,029.9	1,613.9	7.6	1.3 ns	3	453*	3	523*	11
13	1,265.3	1,960,606.8	1,549.4	0.8	8.3 ns	6	151*	8	221*	21
14	3,713.8	3,188,704.0	858.6	4.3	6.9 ns	5	954*	12	411*	10
15	1,823.5	4,388,095.2	2,406.3	0.7	1.9 ns	7	136*	2	634*	3
16	877.3	1,118,888.7	1,275.3	0.6	1.6 ns	8	515*	13	811*	12
17	906.9	1,089,510.9	1,201.3	0.7	1.6 ns	3	610*	23	227*	10
18	42.0	2,675.1	63.6	0.6	6.6 ns	3	121*	33	654*	31
19	43.8	2,772.5	63.2	1.0	1.4 ns	4	743*	33	333*	54
20	3,597.8	746,494.5	207.4	17.4	1.2 ns	5	950*	43	811*	11
21	14,161.1	698,758.6	49.3	292.9	212*	10	344*	12	112*	32
22	14,602.9	22,183.3	1.5	2.9	2.4 ns	9	273*	11	98*	7
23	3,964.0	337,207.0	85.0	47.1	5.1 ns	11	135*	9	266*	9
24	3,600.5	937,520.5	260.3	13.8	1.7 ns	7	115*	11	122*	9
25	3,632.7	1,642,465.6	452.1	1.0	1.2 ns	8	655*	6	100*	9
26	1,414.3	2,634,895.1	1,863.0	1.0	1.5 ns	9	520*	4	309*	7
27	86.5	9,166.5	105.9	1.0	1.1 ns	4	321*	9	671*	8

Degrees of freedom (*d.f.*) = number of classes − 1 − number of parameters estimated in the model (Young and Young 2002)

The asterisks indicate significant differences at $P < 0.05$, while "*ns*" indicates no significant differences between observed and expected data using the χ^2 goodness-of-fit test

Table 2 Number of samples (traps) required for sampling adults of *H. hampei* under different precision errors of the conventional sampling plan using attractant-baited traps in 27 coffee fields (10 ha/field)

Coffee field	Level of precision error (%)				
	5	10	15	20	25
1*	349	87	39	22	14
2*	1,516	379	168	95	61
3*	1,161	290	129	73	46
4*	124	31	14	8	5
5*	148	37	16	9	6
6*	1,428	357	159	89	57
7*	1,322	331	147	83	53
8**	1,390	348	154	87	56
9*	75	19	8	5	3
10*	263	66	29	16	11
11*	1,553	388	173	97	62
12*	1,424	356	158	89	57
13*	1,431	358	159	89	57
14*	1,325	331	147	83	53
15*	250	63	28	16	10
16*	1,428	357	159	89	57
17*	1,574	393	175	98	63
18*	1,434	358	159	90	57
19*	1,637	409	182	102	65
20*	1,560	390	173	97	62
21*	62	16	7	4	3
22**	1,415	354	157	88	57
23*	78	20	9	5	3
24*	135	34	15	8	5
25*	1,426	356	158	89	57
26*	1,325	331	147	83	53
27*	1,645	411	183	103	66
Common value	355	89	39	22	14

The required number of samples in fields followed by an asterisk was estimated following Young and Young (2002), while the number of samples required followed by two asterisks was estimated following Pedigo and Rice (2006)

was identified (fields 8 and 21). The number of traps required for sampling each field (approximately 10 ha) decreased with the increase in precision error from 5 to 25 % (Table 2; Fig. 3).

Significant slopes ($F_{1,22} = 60.50$, $P < 0.01$) and non-significant intercepts ($F_{1,22} = 2.96$, $P \geq 0.10$) were obtained in the regression analyses employed to test the homogeneity of the aggregation index K from the binomial distribution of insect capture. The results for the 27 coffee fields indicated the suitability of estimating a common K (K_c) for all fields and estimated an average number of samples necessary (Table 2). A K_c value of 1.13 was obtained, which allowed the establishment of a sole sampling plan for all coffee fields. The required number of traps for sampling the coffee berry borer stabilized at the 25 % precision error level (Fig. 3a). The higher the precision error level, the lower is the residue dispersion (Fig. 3b). At the 25 % precision level, the conventional sampling plan required between three and 66 traps per coffee field (10 ha) and required a time expenditure between 6.70 and 147.40 min for sampling each field at a cost ranging from US$ 41.35 to US$ 909.73/field (Table 3). The common sampling plan design based on the obtained K_c values indicated that 14 attractant-baited traps (per 10-ha field) were necessary for a 25 % precision error when sampling for the coffee berry borer. This common sampling takes 31.27 min/10 ha and costs US$ 192.97/10 ha (Table 3).

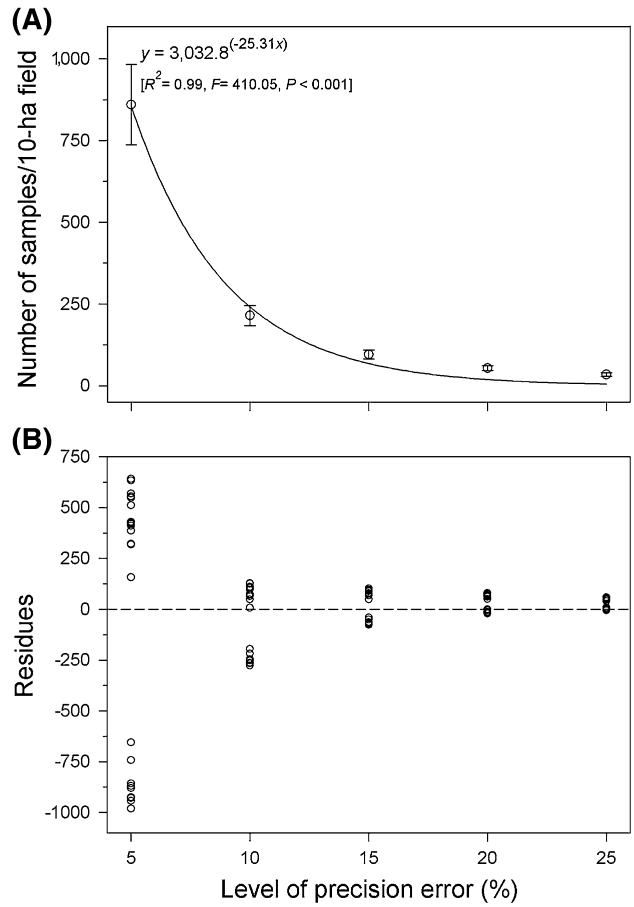

Fig. 3 Number of samples (traps) required for sampling the coffee berry borer (*Hypothenemus hampei*) under different precision errors (**a**) and residual plot exhibiting the dispersion of estimated number of samples required (**b**) for the conventional sampling plan using attractant-baited traps. The estimates were based on determinations from 27 coffee fields

Spatial distribution

The spatial distribution maps of insect capture using the attractant-baited traps showed an aggregated distribution

Table 3 Minimum required number of samples, sampling time (min) and sampling cost (US$) for the conventional sampling plan using attractant-baited traps for the coffee berry borer (*Hypothenemus hampei*) estimated based on a 25 % precision error in 27 coffee fields (10 ha/field)

Coffee field	Number of samples	Sampling	
		Time (min)	Cost (US$)
1	14	31.27	192.97
2	61	136.25	840.80
3	46	102.74	634.04
4	5	11.17	68.92
5	6	13.40	82.70
6	57	127.31	785.66
7	53	118.38	730.53
8	56	125.08	771.88
9	3	6.70	41.35
10	11	24.57	151.62
11	62	138.48	854.58
12	57	127.31	785.66
13	57	127.31	785.66
14	53	118.38	730.53
15	10	22.34	137.84
16	57	127.31	785.66
17	63	140.72	868.37
18	57	127.31	785.66
19	65	145.18	895.93
20	62	138.48	854.58
21	3	6.70	41.35
22	57	127.31	785.66
23	3	6.70	41.35
24	5	11.17	68.92
25	57	127.30	785.66
26	53	118.38	730.53
27	66	147.42	909.72
Common value	14	31.27	192.97

The sampling time encompasses the time walking between sampling sites, counting the female adults, and recording the results on the datasheet

(Fig. 4). The high level of spatial dependence (*LSD*) observed in the coffee fields with 39 (*LSD* = 0.16), 22 (*LSD* = 0.10) and 300 (*LSD* = 0.18) traps (Fig. 5) provides additional support for the data suggesting an aggregated distribution of berry borers. Isolines and different colors in the maps represent grouped areas with similar captures that ranged from 0 to nearly 10,000 insects/trap/15 days, and the aggregate pattern of capture (and infestation) is particularly clear with the use of 300 traps/field (Fig. 4). The same areas of high insect capture were recognized in the maps generated with 22 and 39 traps/field, but not with 14 traps/field, where trap capture was grossly overestimated (Fig. 4). The tests using a smaller number of traps were evenly distributed in the area, and their density corresponded to the estimated (common) number of traps required using estimated precision errors of 15, 20, and 25 % for trap densities of 39, 22, and 14 traps/10-ha field, respectively. Therefore, a minimum of 22 traps/10-ha field was necessary for proper capture estimates and required 49.14 min of sampling/10 ha, costing US$ 303.24/10 ha.

Discussion

Trap-based sampling plans need to exhibit a significant and preferentially robust relationship between pest capture and pest damage to allow for management decisions based on trap capture (Jones 1998), as reported in other studies (Evenden et al. 1995; Asaro and Berisford 2001; Bacca et al. 2012). In the present study, we were able to demonstrate such a relationship between the capture of coffee berry borer in attractant-baited traps and the number of coffee berries damaged by this pest species. Consequently, a sampling plan based on the capture of the coffee berry borer is a potentially suitable tool for pest management decisions regarding this species.

Designing a sampling plan requires knowledge about the frequency distribution pattern of the insect capture data. The relationship between variance and mean of coffee borer capture in the attractant-baited traps suggests a pattern of aggregate distribution, which was confirmed by the aggregation index of the negative binomial distribution and direct testing of this distribution. Only two out of the 27 coffee fields sampled did not exhibit an aggregated pattern of distribution, which is likely due to the great data dispersion observed in these two fields. The aggregated pattern of frequency distribution is common among insects, particularly among borers, including *Diaphania* spp. (Lepidoptera: Pyralidae) and the cigarette beetle *Lasioderma serricorne* (Coleoptera: Anobiidae), as well as other species (Koivula et al. 2005; Bacci et al. 2006; Carvalho et al. 2006). The observed aggregated pattern of distribution of the coffee berry borer has also been reported elsewhere (Ruiz et al. 2000, 2003; Ruiz-Cárdenas et al. 2009). Therefore, such distribution was considered when estimating the number of traps required for sampling for the coffee berry borer in fields (10 ha) of *C. arabica*.

Different populations of a given species may exhibit distinct patterns of aggregation, requiring the use of distinct sampling plans depending on the area being sampled (Young and Young 2002). However, the coffee berry borer exhibited a common pattern of aggregation allowing the use of a sole sampling plan suitable for all 27 sampled coffee fields and establishment of a single sampling plan for the species using attractant-baited traps. The minimum number of traps required to sample for the coffee berry

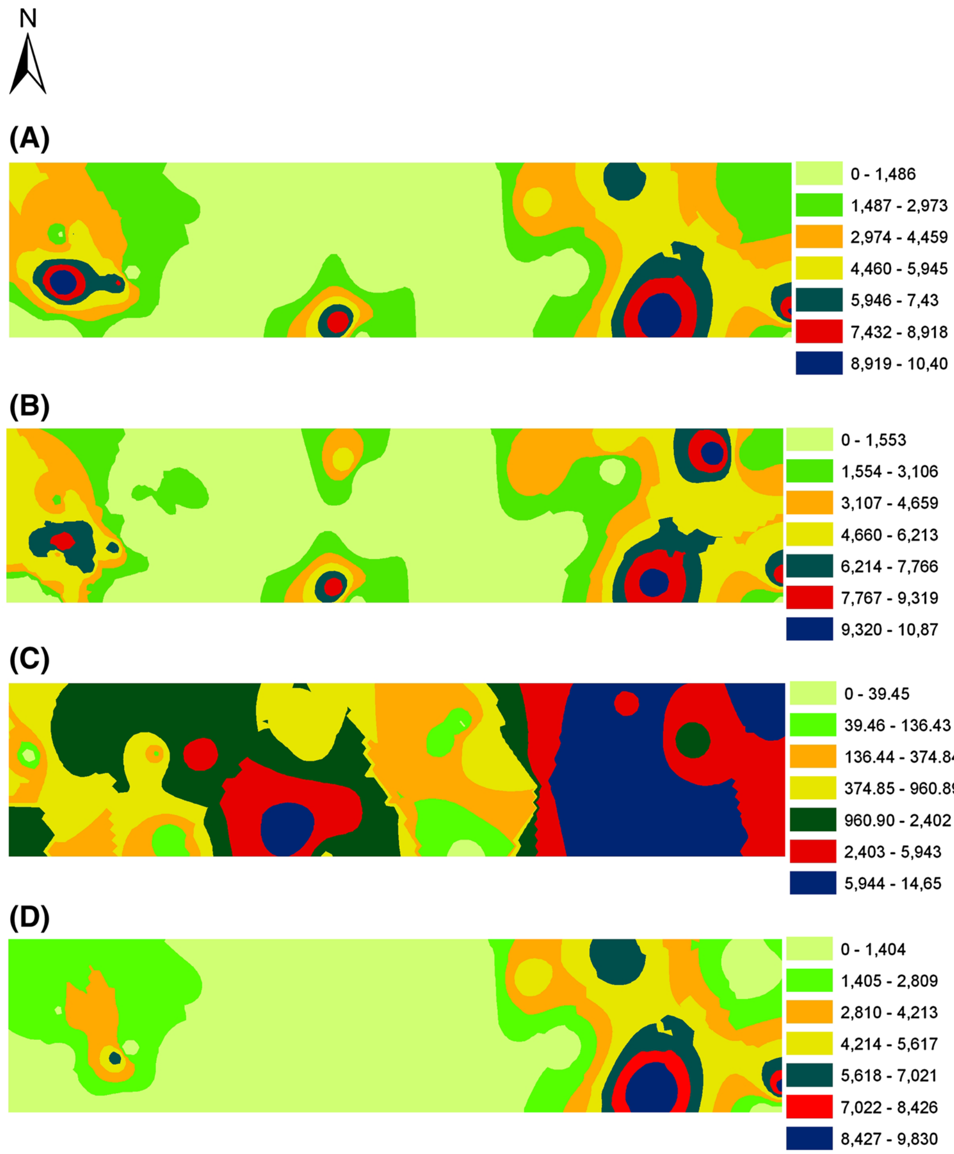

Fig. 4 Map of the spatial distribution of coffee berry borer (*Hypothenemus hampei*) capture generated using 39 (**a**), 22 (**b**), or 14 (**c**) traps per 10-ha coffee field with interpolation using the inverse weighted-distance and 300 traps with (ordinary) kriging (**d**). (Color figure online)

borer was initially estimated at 14 traps/10 ha at a cost substantially smaller (US$ 192.97/10 ha) than the current recommended sampling plan used in Brazil for this species, which is based on berry harvest and inspection and requires 30 samples/ha and takes 3.2 h/ha to sample at a cost of US$ 389.70/ha (Souza and Reis 1997; Fernandes et al. 2011). Based on these results, coffee berry borer sampling with attractant-baited traps is much faster and more cost-effective than conventional sampling. Nonetheless, this initial estimate of the number of traps per field was based solely on the frequency distribution of insect capture data without considering the actual spatial distribution of the insect in the area.

The frequency distribution of trap capture does not always reflect the spatial distribution of the insect populations in the field (Young and Young 2002). This distinction has been reported for the egg distribution of the Mexican bean beetle *Epilachna varivestis* Mulsant (Coleoptera: Coccinellidae) (Barrigossi et al. 2001), but not for the coffee leaf miner *Leucoptera coffeella* (Guérin-Méneville & Perrottet) (Lepidoptera: Lyonetiidae) (Bacca et al. 2008). Geostatistical procedures allow circumventing this potential problem because they can be performed to analyze the spatial relationships among individual insects of a species (Liebhold et al. 1993).

The aggregated pattern of distribution of the coffee borer capture (determined by the relationship between the variance and mean of capture, as well as by the frequency distribution of the insect capture data) was confirmed using spatial analysis, which highlighted discrete foci of infestation typical for an aggregated pattern of field distribution (Bacca et al. 2008). The spatial interpolation used in our study was also helpful in simulating the results generated in the conventional sampling plan with attractant-baited traps

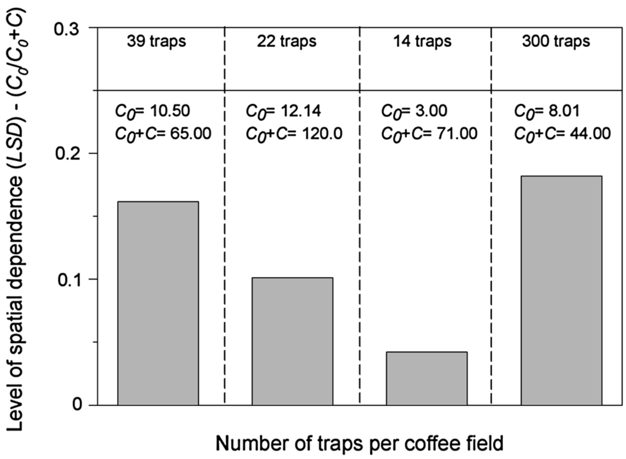

Fig. 5 Level of spatial dependence (*LSD*) of the semivariogram models obtained from the trap capture data of *Hypothenemus hampei* using attractant-baited traps in coffee fields with 39, 22, 14, and 300 traps per 10 ha. The level of spatial dependence was established from the ratio between the nugget effect (measurement error and/or spatial variation smaller than the sampling distance) and sill (semivariogram value bellow which spatial correlation exists)

for the coffee berry borer. The predictions from the captures obtained with 14, 22, and 39 traps/10-ha field (corresponding to prediction errors of 15, 20, and 25 %, respectively) were related to the absolute capture obtained with 300 traps/10-ha field. This approach indicated that a minimum of 14 traps/10 ha, which was predicted based on the required number of traps estimated using the (negative binomial) frequency distribution model, does not provide a good approximation to the capture rates obtained with 300 traps, unlike predictions using the densities of 22 and 39 traps/10 ha. Therefore, the minimum number of traps required for proper sampling of the coffee berry borer using attractant-baited traps is 22 traps/10 ha as opposed to 14 traps/10 ha. This trap density still provides much faster and cheaper sampling (49.14 min/10 ha at US$ 303.24/10 ha) than the conventional sampling method in which damaged berries are harvested and inspected, which is approximately 14× more expensive and time-consuming. The trap method also generates reliable estimates of pest density and of coffee loss.

The sampling plan using attractant-baited traps tested here exhibited robust statistical data and favors the capture of adult females of the coffee berry borer (*H. hampei*) while being non-destructive to the coffee berries, which are both advantages over the current destructive sampling plans employed for this key coffee pest. Although in trap insect density data and the experimental attractants can be affected by environmental conditions such as temperature, relative humidity, and wind, sampling with attractant-baited traps was cheaper and faster than the conventional methods used for sampling the coffee berry borer (Souza and Reis 1997; Bianco 2000; Trujillo et al. 2006). Sampling berries from coffee branches take approximately 42 min (Bustillo et al. 1998), although Trujillo et al. (2006) claimed faster sampling, but did not provide recorded data. Several other former studies did not assess the length of time necessary for sampling (Decaszy et al. 1988; Rémond et al. 1993; Souza and Reis 1997), which is a fundamentally important factor for assessing the cost of sampling (Young and Young 2002).

In summary, the developed sampling plan using attractant-baited traps at a density of 22 traps/10 ha for monitoring populations of the coffee berry borer, *H. hampei*, was fast and reflects pest infestation and berry damage in the coffee fields. Furthermore, the sampling plan allows identification of the main infested areas with high precision, allowing subsequent control efforts to be properly directed to the more heavily infested areas, therefore increasing efficiency and decreasing costs and non-target impacts. This trapping system and sampling plan were developed for relatively large coffee fields, but are potentially useful for small coffee plantations as well using a single trap per field smaller than 2 ha. However, field studies aiming validation for such conditions are necessary.

Author contributions

FLF conceived and designed research. MES conducted experiments. MCP contributed materials and tools. FLF analyzed data. FLF and RNCG wrote the manuscript. All authors read and approved the manuscript.

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