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Dispersion Models and Sampling of Cacao Mirid Bug *Sahlbergella singularis* (Hemiptera: Miridae) on *Theobroma Cacao* in Southern Cameroon

D.H.B. BISSELEUA,^{1,2,3} YEDE,³ AND STEFAN VIDAL⁴

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ABSTRACT The spatio-temporal distribution of *Sahlbergella singularis* Haglung, a major pest of cacao trees (*Theobroma cacao*) (Malvaceae), was studied for 2 yr in traditional cacao forest gardens in the humid forest area of southern Cameroon. The first objective was to analyze the dispersion of this insect on cacao trees. The second objective was to develop sampling plans based on fixed levels of precision for estimating *S. singularis* populations. The following models were used to analyze the data: Taylor's power law, Iwao's patchiness regression, the Nachman model, and the negative binomial distribution. Our results document that Taylor's power law was a better fit for the data than the Iwao and Nachman models. Taylor's b and Iwao's β were both significantly >1 , indicating that *S. singularis* aggregated on specific trees. This result was further supported by the calculated common k of 1.75444. Iwao's α was significantly <0 , indicating that the basic distribution component of *S. singularis* was the individual insect. Comparison of negative binomial (NBD) and Nachman models indicated that the NBD model was appropriate for studying *S. singularis* distribution. Optimal sample sizes for fixed precision levels of 0.10, 0.15, and 0.25 were estimated with Taylor's regression coefficients. Required sample sizes increased dramatically with increasing levels of precision. This is the first study on *S. singularis* dispersion in cacao plantations. Sampling plans, presented here, should be a tool for research on population dynamics and pest management decisions of mirid bugs on cacao.

KEY WORDS distribution, negative binomial distribution, population ecology, *Sahlbergella singularis*, spatial dispersion model

The "chocolate tree" *Theobroma cacao* (Malvaceae) is cultivated as an economic crop in the humid tropics worldwide, with $\approx 72\%$ of the production in West and Central Africa. It is largely a "smallholder crop," cultivated on ≈ 5.2 million ha with individual farms ranging in size from 0.5 to 7 ha (Clay 2004). Despite the economic importance of cacao, yield remains low. The main cause of the low yield in this area is the damage caused by the cacao mirid *Sahlbergella singularis* Haglung (Hemiptera: Miridae) (Lavabre 1977). This hemipteran mostly occurs at low densities but may aggregate in "pockets" where conditions are particularly favorable (e.g., openings in the shaded canopy). There are five nymphal instars before maturity, and all feed on cacao seedlings, young shoots, cherelles, pods (immature and mature), and trees. Damage by *S. singularis* often or sometimes causes 30–40% pod loss

(Entwistle 1972). However, under high feeding intensity of 0.7 *S. singularis* per cacao tree, gradual wilting and possible tree death occur (Crowdy 1947, Decazy and Essono 1979).

In the past, researchers studying *S. singularis* concentrated on its ecology (Williams 1953, Lotodé 1969, Bruneau De Miré 1977, Nwana and Youdeowei 1978), or on control options by using chemicals (Decazy 1979, Bruneau De Miré 1985, Coulibaly 1988). However, since the late 1980s, most chemical options for controlling *S. singularis* on cacao became less effective or less desirable because the pesticides selected for resistance in *S. singularis* harmed nontarget beneficial organisms.

Studies on the life cycle of *S. singularis* in many cacao growing countries in West and Central Africa (Lotodé 1969, Bruneau De Miré 1977, Nwana and Youdeowei 1978, Babin et al. 2008) have not yet characterized the dispersion of the insect. Knowledge of *S. singularis* dispersion will increase our understanding of the relationship between *S. singularis* and its environment, and will provide basic information for interpreting spatial dynamics, thus allowing the design of efficient sampling programs for population estimation and pest management. Moreover, a thorough understanding of dispersion is crucial for understanding

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when *S. singularis* enters cacao plantations and when numbers sufficiently increase to warrant control measures (Van-Emden 1996).

Methods that are commonly used to describe dispersion of arthropod populations have been summarized by Southwood (1978). Several estimates are based on sample means and variances (Taylor 1961, 1984; Iwao 1968, 1975) or on mean and the proportion of plants not infested (Nachman 1981, 1984). The models of Taylor and Iwao depend on the relationship between the sample mean and the variance of insect numbers per sampling unit through time, and provide a stable relationship from one year to another based on only the observed sampling mean (Kuno 1969, 1991). The Nachman model describes the relationship between the sample mean and the proportion of sampling units not infested with the specific insect. If a constant relationship exists between mean and proportion of sampling units, the calculation of the mean population is based on the presence or absence of insects rather than on individual counts of insects during subsequent sampling, significantly reducing the cost of sampling. The calculations are used as indices for the aggregation and dispersion parameter k of the negative binomial distribution (Southwood 1978). Moreover, these indices are often interchangeable with one another. Sampling plans based on appropriately characterized dispersion (Kuno 1969, Green 1970) reduce sampling effort and minimize variation of sampling precision (Hutchison et al. 1988, Trumble et al. 1989, Kuno 1991).

As noted earlier, little is known about the dispersion pattern of *S. singularis* in cacao plantations, yet there is a great demand for such information. To address this dearth of information, and provide cacao pest managers, researchers, extension officers, and cacao farmers with a cost-effective sampling method for *S. singularis*, we collected data on the dispersion of *S. singularis* on cacao trees in the humid area of southern Cameroon in 2003 and 2004. The first objective was to analyze the dispersion of this insect in cacao plantations. The second objective was to develop sampling plans based on fixed levels of precision for estimating *S. singularis* populations.

Materials and Methods

Study Sites. This study was conducted in semideciduous rain forests of southern Cameroon in cacao plantations around Ngomezap (Ngom), Bakoa (Bak), Obala (Obl), Talba (Tabl), and Kedia (Ked). The plantations were located between 2° 35' N and 4° 15' N and 11° 48' and 11° 15' E with a minimum distance of 1,000 m. The altitude ranged from 450 m to 715 m above sea level and was characterized by a subequatorial climate with a bimodal rainfall regime. Cultural practices and vegetational composition of these farms have been previously published by Bisseleua and Vidal (2008). The soils were Oxisols and Ultisols, which make up ≈80% of the soils in the humid forest region of Cameroon; the pH of the soils ranged from 4.29 to 5.43 (Kotto-Same et al. 1997, Kanmegne et al. 2006).

In March of 2003, we selected 20 cacao plantations in the region. In each plantation, we selected 30 randomly planted cacao trees in 600 m² (30 m long by 20 rows wide) plots. The mean tree height was 4.4 m (SEM = 0.63) and the diameter was 0.4 m (0.04). The mean distance between two consecutive cacao trees was 1.78 m (SEM = 1.4) and the mean distance between cacao trees and forest tree species was 2.63 m (SEM = 0.4). Cacao planting materials were dominated by traditional varieties and hybrids. We identified a total of 102 forest tree species belonging to 56 families within the selected plots. The most common tree species were *Albizia adianthifolia* (W. F. Wight); *Ficus exasperata* (Vahl) (20% of the total species, respectively); *F. mucosa* (Welw. ex Ficalho); *Disco-glyprena caloneura* (Prain); (11%); *Newbouldia lewisii* (P. Beauv) Seem; *Pterocarpus soyauxii* (Taubert); *Terminalia superba* (Engler & Diels); and *Ceiba pentandra* (Gaertner). Most of the trees were intentionally introduced as shade species (Bisseleua and Vidal 2008). We also measured temperature using a Six's thermometer (Littoclimate S.A., Caen, France) placed 2 m below the tree canopy in each plantation, and measured rainfall with a pluviometer (Littoclimate S.A., Caen, France).

Sampling. On each of the selected cacao trees in each of the 20 cacao plantations, we performed a daily visual assessment (212 d per year for a total of 636 d during the 3-year period). We registered the number of *S. singularis* from pod set to harvest in 2003 (year 1) and 2004 (year 2). We assessed insect numbers on each selected tree by carefully inspecting all plant parts and pods of the tree from the base up to 2 m. *S. singularis* are photophobic and are very active in the night or early in the morning before sunrise. During the day, *S. singularis* generally hide below canopy between the base up to 2 m underneath cacao pods peduncle and at contact zones of cacao pods with the trunk (Entwistle 1972). This hiding behavior aims to avoid exposure to direct sunlight, extreme temperature, and relative humidity, or to escape predators. An hour before sun set, *S. singularis* move to feeding and oviposition sites (i.e., pods, branches, and young shoots) above canopy (>2 m). *S. singularis* inspections were done between 6:30 and 8:30 a.m. The sampling unit was individual cacao trees where adult stages of *S. singularis* were found and counted. No chemical treatments for insect and fungal control were applied in the selected plots during the entire period of study.

Statistical Analysis. We used simple polynomial regression to assess the relationship between temperature, rainfall, and mean number of *S. singularis* and to analyze the relationship between forest tree species richness and number of *S. singularis*. Forest tree species richness was calculated as the total number of species at each sampling site. The density of each tree species was calculated as the number of individuals per sampling site. GLM by using Systat 11 was used for analysis involving forest tree species richness. When the model found statistically significant differences between sites, Tukey's posthoc tests were used to

determine which were significantly different. Because we did not find any relationship between mean number of *S. singularis* per cacao tree and forest tree species, we pulled all data on number of *S. singularis* for the dispersion analyses.

Spatial Dispersion. We used and compared several common methods for describing the dispersion of *S. singularis* in the study sites.

Taylor's Power Law. m (mean densities *S. singularis* per tree) and S^2 (variances) were calculated for trees in each field for each sampling date, and variance to mean relationship was quantified using Taylor's power law (Taylor 1961, 1971; Taylor et al. 1978). Taylor's power law states that the variance (S^2) of a population is proportional to a fractional power of the arithmetic mean (m): $S^2 = am^b$. To estimate a and b , the values of $\ln(S^2)$ were regressed against those of $\ln(m)$ using the following formula:

$$\ln(S^2) = \ln(a) + b\ln(m) \tag{1}$$

where the parameter a is largely a sampling factor related to sample unit size (Southwood 1978), and the slope b is an index of aggregation that indicates a uniform, random, or aggregated dispersion when $b < 1$, $b = 1$, or $b > 1$, respectively.

Iwao's Method. The Iwao's patchiness regression method quantifies the relationship between the mean crowding index (m^*) and the mean (m) by the following formula:

$$m^* = \alpha + \beta m \tag{2}$$

where m^* was determined as $[m + (S^2/m - 1)]$ (Lloyd 1967). The intercept (α) is the index of the basic component of a population or basic contagion (where $\alpha <, =,$ and >0 represent regularity, randomness, and aggregation of populations in spatial patterns, respectively), and the slope (β) is the density contagiousness coefficient interpreted in the same manner as b of Taylor's regression.

Nachman Model. We also determined the goodness-of-fit of our data to the Nachman model. This model reduces the time required for monitoring by using incidence counts (presence or absence) instead of direct counts. This relationship is between the mean density (m) and the proportion p statistical units with no *S. singularis*:

$$p_0 = \exp(-fm^g) \tag{3}$$

where f is a scale parameter and g is a dispersion parameter of the model. If $f = g = 1$, the distribution of individuals is random. The model is linearized with the mean density regressed on p_0 (Nyrop et al. 1989) as follows:

$$\ln(m) = A + B\ln(-\ln(p_0)) \tag{4}$$

where p_0 is the proportion of trees with no *S. singularis* for different means using the two incidences and mean relationships. When a stable relationship is observed between p_0 and m , the regression curve is used to forecast the values of m from p_0 .

Calculation of Common k . The estimates of the dispersion parameter k , computed as $m^2/(S^2 - m)$, were linearly regressed on m ,

$$k = c + dm \tag{5}$$

to test for the existence of a common k (k_c) for each of the data sets (Southwood 1978, Feng and Nowierski 1992). A d value significantly >0 indicates the dependence of k on the mean density. The variance and mean within each area where the variance exceeded the mean were used to estimate k_c for a negative binomial distribution (Fleischer et al. 1991). Estimates of k_c were made using the techniques of Elliot (1977), which estimates k_c by regressing $y' = (S^2 - m)$ on $x' = (m^2 - S^2/n)$, and k_c was defined by $k_c = 1/\text{slope}$. An index for spatial aggregation of arthropod populations, $1/k$, which is equal to $m^*/m - 1$ (Southwood 1978), was calculated to evaluate the dispersion patterns.

Negative Binomial Distribution Model (NBD). The relationship between the proportion of trees with one or more *S. singularis* (the incidence, p_1) and the density of *S. singularis* (m) per tree was developed by assuming that a negative binomial distribution (NBD), with the dispersion parameter k calculated as $(m^2/[S^2 - m])$, would describe the distribution of *S. singularis* on trees. The NBD-based relationship was chosen because of the close relationship between NBD and Taylor's power law (Binns 1986). The calculated S^2 was described as a function of m (Taylor 1961). The incidence is then calculated as 1 minus the 0 term of the NBD (Wilson and Room 1983, Nyrop et al. 1989):

$$p_1 = 1 - [k(k + m)^{-1}]^k \tag{6}$$

Sampling Plans. Based on the sample counts, we calculated the optimal sample sizes (n) with a and b from Taylor's Power Law to develop the enumerative sampling plan of Green (1970) with precision levels of 0.10, 0.15, and 0.25 for ecological and pest management purposes, respectively, as suggested by Southwood (1978):

$$n = am^{b/D^2} \tag{7}$$

where a and b are Taylor's power law coefficients, m the *S. singularis* density and D is the desired precision. Precision measures the degree of error in making population estimates and was expressed as a proportion standard error of the mean.

Because Taylor's Power Law gave the best description of the data and densities estimates of *S. singularis* were within certain limits with a defined error probability, we developed sampling recommendations using Green's formula (Green 1970) but we could have developed sampling recommendations using the other measures of dispersion if they had a better fit. The sampling stop line is calculated as:

$$T_n = \left[\frac{D^2}{a} \right]^{1/(b-2)} n^{(b-1)/(b-2)} \tag{8}$$

Table 1. Mean no. of *S. singularis* and forest tree species richness within selected cacao plantations in southern Cameroon

Sites	Mean ± SE			
	SS		Tree richness	Family
	Year 1	Year 2		
Ngo	0.65 ± 0.22c	0.46 ± 0.13ab	11.0 ± 1.0c	6.5 ± 1.0b
Bak	0.08 ± 0.06a	0.18 ± 0.8a	6.5 ± 0.6b	3.5 ± 0.7a
Obl	0.47 ± 0.16b	0.15 ± 0.06a	9.0 ± 0.6bc	6.3 ± 0.3b
Talb	0.07 ± 0.03a	1.55 ± 0.79b	7.5 ± 0.6b	4.0 ± 0.5a
Ked	0.81 ± 0.38c	1.61 ± 0.79b	5.3 ± 0.8a	3.30 ± 0.3a

Results

Temporal Population Dynamics. We recorded 241 adult *S. singularis* in year 1 and 471 in year 2. The mean number of *S. singularis* per tree was 0.42 (SEM = 0.09) in year 1 with a variance of 5.32. In year 2 we recorded a mean of 0.79 (0.23) and a variance of 30.70 (Table 1). The highest number of *S. singularis* on a tree was 91 and this number was recorded twice in year 2. Mean annual rainfall ranged from 33.0 mm (SEM = 4.6) to 51.3 mm (6.6) and mean temperature was 26.6 (SEM = 0.44). Mean numbers of *S. singularis* increased between June and October in both years. Months with higher precipitation did not systematically lead to greater numbers of *S. singularis* in the following weeks or months. *S. singularis* population fluctuations may actually be linked to cacao tree phenology, in other words, to food availability (Fig. 1). Thus, numbers of

S. singularis were not correlated with temperature ($r^2 = 0.004$) or rainfall ($r^2 = 0.16$).

Impact of Forest Tree Species on Mirids Distribution. Forest tree species richness per study site is summarized in Table 1. A significant difference ($P < 0.01$) was observed between sites when analyzing tree species richness. We observed that the number of *S. singularis* per cacao plantation decreased significantly with increased tree species richness ($y = 15.42 - 0.9x$, $F = 19.78$; $r^2 = 0.52$, $p < 0.001$). However, we did not find any effect of tree species richness on the mean number of *S. singularis* per cacao tree.

Variance to Mean Relationships as Determined by Taylor, Iwao, and Nachman Models. *S. singularis* has a very slow population growth with little variation over time. Results presented are not single values for each field but based on Taylor and Iwao equations. Variation over time was not factored into each mean and variance calculation. Calculation was made based on sample unit as per Taylor and Iwao equations.

Taylor's power law confirmed a positive significant relationship between variance (S^2) and mean density (Fig. 2). When the mean density increases, the variance also increases. Taylor's intercept was greater >0 in years 1 and 2 (in year 1, $a = 1.11$, $t = 3.43$, $df = 49$, $P < 0.001$; in year 2, $a = 1.12$, $t = 1.57$, $df = 59$, $P < 0.001$). The slope b was significantly >1 (in year 1, $b = 1.50$, $t = 7.82$, $df = 49$, $P < 0.001$; in 2004, $b = 1.50$, $t = 19.71$, $df = 59$, $P < 0.001$). Taylor's model was $S^2 = m^{1.5}$ for years 1 and 2, respectively.

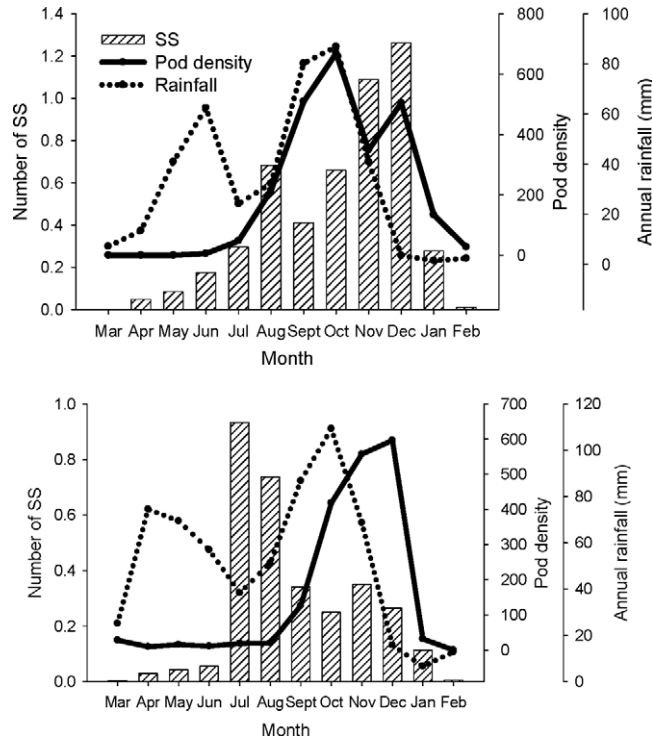


Fig. 1. Relationships between mean number of *S. singularis* per tree (*S. singularis*), mean number of pod per tree and mean annual rainfall (right offset) in all 20 cacao plantations in year 1 (above) and 2 (below).

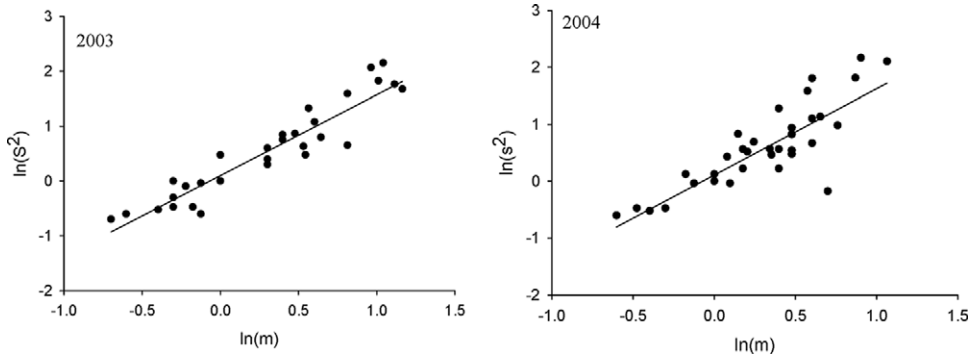


Fig. 2. Regression analysis of Taylor's power law ($\ln (S^2) = 1.10 + 1.50\ln (m)$ in year 1 and $1.11 + 1.50\ln (m)$ in year 2 for *S. singularis* populations on cocoa trees (Cf. Equation 2).

Iwao's patchiness regression revealed that the intercept value (α) was <0 ($\alpha = -0.18, t = -0.30, df = 49, P < 0.001$) in year 1 and >0 ($\alpha = 0.41, t = 1.46, df = 49, P < 0.001$) in year 2 (Fig. 3), indicating that for adult *S. singularis* the basic component of the population tends to be a single individual. Estimates for β , the density contagiousness coefficient, were significantly >1 ($\beta = 1.73, t = 3.76, df = 49, P < 0.001$ in year 1; and $\beta = 2.45, t = 15.29, df = 59, P < 0.001$ in year 2).

Nachman's model provided a fit to the relationship between the proportion of trees without *S. singularis* (p_0) and the mean density (m) of *S. singularis* (Table 1; Fig. 4). Using these parameter calculations (Table 1), we were able to calculate mean density based on the proportion of trees with or without *S. singularis*. However, the coefficient of determination (r^2) was weaker than in the models of Iwao and Taylor.

Calculation of the Common k for NBD. Fig. 5 shows the relationship between k and the mean number of *S. singularis* from samples with variances exceeding the mean in years 1 and 2. The value of k was 3.21 in year 1 and 2.50 in year 2, with the corresponding index of spatial aggregation ($1/k$) of 0.31 in year 1 and 0.40 in year 2. Regression of k on the mean density per tree, using all data, was not significant in year 1 or 2 (in year 1: $F = 0.24, r^2 = 0.007, P = 0.62$; in year 2: $F = 0.77, r^2 =$

$0.02, P = 0.39$) (Table 1). Moreover, the slope of the regression (d) was not significantly different from 0 (in year 1: $t = 0.49, df = 37, P = 0.62$; in year 2: $t = 0.88, df = 40, P = 0.39$). Independence of k from the mean density suggests a common k for the NBD of the *S. singularis* populations. The calculation of a common k , using the method of Elliot (1977), was 1.7544.

Sampling Plans. Optimal sample sizes for fixed precision levels of 0.10, 0.15, and 0.25 are presented in Fig. 6. The optimal sample size for a precision of 0.25 ranged from 18 to 193 trees, depending on *S. singularis* density. For a precision level of 0.10, the sample size ranged from 110 to 1205 trees at the same mean interval. At a precision level of 0.25, the number of sample trees needed for a mean density of 0.42 (year 1) was 27 and for a mean density of 0.79 (year 2), ≈ 20 trees. However, if the level of precision was set to 0.10 the number of samples required for a mean density of 0.42 and 0.79 became 170 and 124 trees, respectively.

The number of samples required for a precision level of 0.25 peaked at 11 and 16 trees for mean values of 0.42 and 0.79 *S. singularis* per cacao tree respectively. For precision level of 0.10, the number of samples required was 73 and 98 trees at the same mean interval.

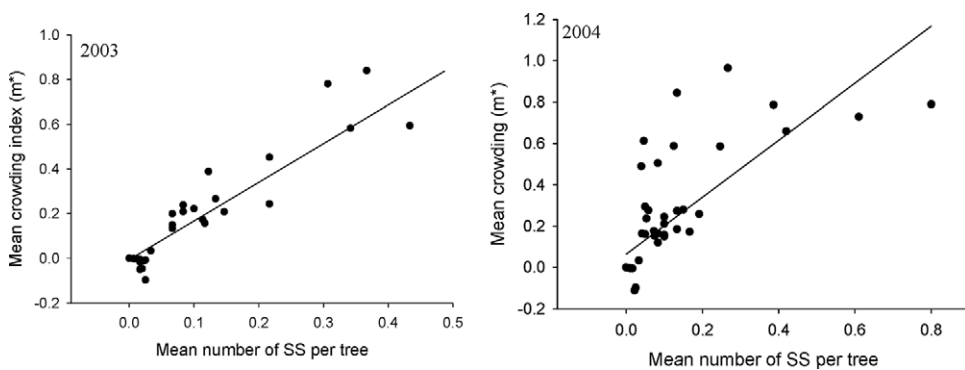


Fig. 3. Regression analysis of Iwao's mean crowding index (m^*) on mean density (m) for *S. singularis* populations on cocoa ($m^* = -0.18 + 1.73m$ in year 1 and $m^* = 0.41 + 2.45m$ in year 2; (Cf. Equation 1).

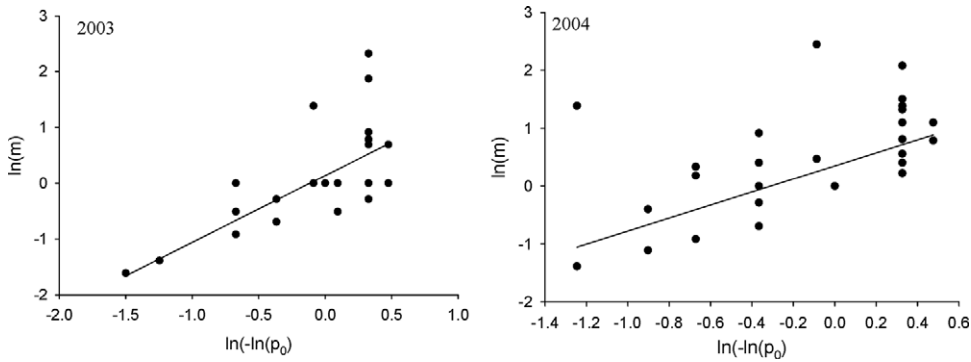


Fig. 4. Regression analysis of Nachman's model ($\ln(m) = -0.15 + 0.51\ln(-\ln(p_0))$ in year 1 and $\ln(m) = -0.25 + 0.39\ln(-\ln(p_0))$ in year 2 for *S. singularis* populations on cocoa (Cf. Equation 3).

Discussion

This study was performed to provide cacao researchers, extension officers, cacao pest managers, and cacao farmers with a cost-effective sampling method of the mirid bugs *S. singularis* in cacao plantations that could be easily integrated into integrated pest management programs. Our results document that differences in shade management between cacao plantations strongly impact cacao landscapes and the distribution of *S. singularis*. Shading practices, number of shading trees, and shading tree species differ significantly between sites. We observed that shading and choice of shading trees are separate variables in the management choices of cacao plantations, and consequently, these factors are correlated only to some extent. Changes in land-use management resulted in a loss of $\approx 70\%$ of plant species, with a stronger effect on the distribution of *S. singularis* at the landscape level than on the individual cacao tree.

Our study documents that Taylor's power law fits the data better than the Iwao's and Nachman models, and *S. singularis* were aggregated on cacao trees with the individual insect as the basic distribution component. A comparison of the negative binomial and Nachman models also indicated that the negative binomial model was appropriate for studying *S. singularis* dispersion. Optimal sample sizes for fixed precision levels of 0.10, 0.15, and 0.25 were estimated with

Taylor's regression coefficients. Required sample sizes increased dramatically with increased levels of precision.

S. singularis populations exhibited almost seasonal patterns in years 1 and 2, with the first peak in abundance occurring between June and September, and the second occurring between November and January. Similar results were reported by Bruneau De Miré (1977), who recorded an increase in *S. singularis* numbers between July and September in cacao plantations near the Mbalmayo forest reserve in southern Cameroon. The second peak in abundance in our study could be attributed to young cacao plantations with the main pod production between September and December. Moreover, increases in *S. singularis* numbers were generally noticed one month after intensive rain in the first year (i.e., in mid-June and mid-November). Philpott et al. (2006) observed very high insect activity in tropical regions during wet seasons. Although our findings suggest that rainfall explains the increase in *S. singularis* numbers, rainfall was not statistically related to the increase in the *S. singularis* population.

Iwao's patchiness regression characterized the relationship between mean crowding and density for *S. singularis* (Table 2; Fig. 3). The intercept value (α) was negative in year 1 (-0.18 ± 0.041), and positive in year 2 (1.73 ± 0.010), suggesting a spatial distribu-

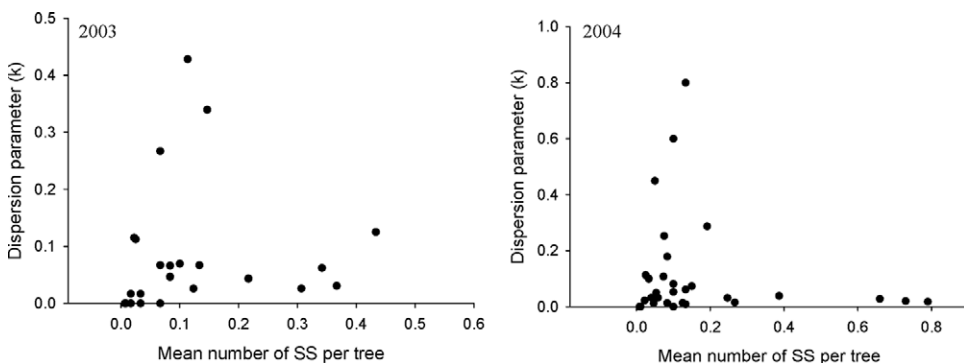


Fig. 5. Scatter plots of k for the NBD against means (m) for *S. singularis* populations on cocoa trees in year 1 and 2.

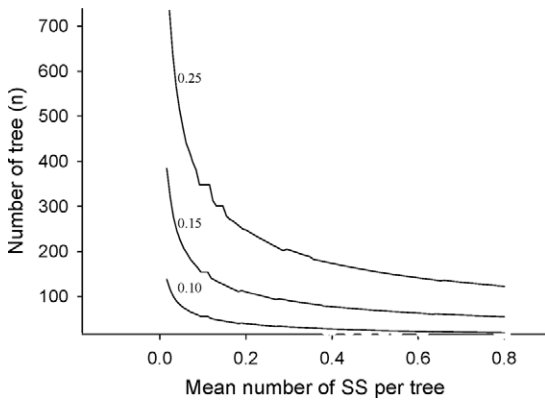


Fig. 6. Number of cacao trees required to achieve given precision level of 0.10, 0.15, and 0.25 at different mean densities of *S. singularis* on cacao tree.

tion of regularity with the tendency to crowding (+ve). This result also indicated that an individual *S. singularis* forms the basic component of the population defined as the “Index of Basic Contagion” by Iwao (1970).

S. singularis dispersion patterns were better described by Taylor’s power law ($r^2 = 0.90$ in year 1 and 0.80 in year 2) than by Iwao’s model ($r^2 = 0.87$ in year 1 and 0.63 in year 2) and Nachman’s model ($r^2 = 0.60$ in year one and 0.44 in year 2). The aggregation indices (slopes, b and β) of Taylor’s power law were all significantly >1 ($P < 0.001$), indicating an aggregated distribution of *S. singularis*. Because the variance was greater than the mean of the observed data, a clumped pattern was likely. Hence the negative binomial distribution was tested. The results confirmed that the negative binomial distribution was a good fit for our data and the value of the common k was >1 . This result indicated that *S. singularis* populations were strongly

aggregated on cacao trees. Taylor (1971) suggested “that b may reflect the behavioral interaction between organism and environment.” The causes of aggregation may have been due to the interaction between *S. singularis*, the management regime, the action of natural enemies (i.e., parasitoids and predators), and abiotic factors (mainly rainfall). Also, we noted that the slope coefficients (b) did not significantly differ from year to year, confirming that aggregation in this mirid species may be more related to the heterogeneity of the environment (such as microclimate, plant parts preferred, or natural enemies) (Southwood 1978) or oviposition habits (number of oviposition sites per female and number of eggs per site) than to active aggregation behavior by *S. singularis*. Previous studies (Decazy 1979, Bruneau De Miré 1985, Coulibaly 1988) have shown that *S. singularis* populations may aggregate in “pockets” on the trees where conditions are particularly favorable (e.g., openings in the shade canopy).

Although no studies on the dispersion of *S. singularis* are currently available for direct comparison, the observed values for β and b are similar to those of insect species with moderate aggregation behavior (Taylor 1961, 1971). Changes in the density of an insect often result in changes in the dispersion (Southwood 1978). However, we did not detect apparent density-dependent distribution changes in the *S. singularis* populations (Fig. 4).

We found that 74% of the sample observations in year 1 and 67% in year 2 were >0 , indicating that the populations of *S. singularis* were usually aggregated on cacao trees. These observations further support the results obtained using Taylor’s power law and Iwao’s models. However, the Taylor power law provided the best fit for our data and gives the most reliable parameters for different habitats, sampling methods, and mirid bug densities (Taylor 1984).

We found that sample sizes increased dramatically when the precision required increased. Sample sizes were small at the 0.25 and higher at the 0.10 level. In practice, estimates of *S. singularis* population densities with 0.25 levels of precision can be accomplished with relatively little sampling effort. The level of precision needed is a choice made according to the purpose of a sampling plan. Estimates of population densities with precision levels of 0.10 are recommended for ecological or applied research studies, and those of 0.25 are recommended for pest management decision making (Southwood 1978). The economic threshold for phytosanitary intervention is fixed at 0.7 *S. singularis* per tree in Cameroon (Decazy and Essono 1979) and 0.6 *S. singularis* per tree in Ghana (Padi and Owusu 1998). Therefore, to obtain estimates of *S. singularis* densities in cacao with 0.10 or 0.25 precision, we recommend visually inspecting 170 or 27 cacao trees, respectively. This sample number will provide the desired precision averaged over many sampling bouts across the range of observed *S. singularis* densities. In other words, for a specific sampling bout, the average precision might be better (i.e., lower sampling error) than desired if densities are high, or worse (i.e., greater sampling

Table 2. Comparison of model parameters for years 1 and 2

Model and parameter	Year	
	1	2
Iwao’s ($m^* = \alpha + \beta m$)		
N	50	60
$\alpha \pm SE$	-0.18 ± 0.041	0.41 ± 0.070
$\beta \pm SE$	1.73 ± 0.010	2.45 ± 0.025
R^2	0.87**	0.63**
Taylor’s ($S^2 = am^b$)		
N	50	60
$a \pm SE$	1.10 ± 0.04	1.11 ± 0.04
$b \pm SE$	1.50 ± 0.07	1.50 ± 0.10
r^2	0.90**	0.80**
Nachman’s ($P = 1 - \exp(-fm^c)$)		
N	50	60
$f \pm SE$	-0.15 ± 0.07	-0.25 ± 0.05
$G \pm SE$	0.50 ± 0.07	0.39 ± 0.06
r^2	0.60**	0.44**
k for the NBD ($k = c + dm$)		
N	37	40
$c \pm SE$	3.06 ± 0.64	2.35 ± 0.41
$d \pm SE$	0.05 ± 0.10	0.06 ± 0.06
r^2	0.007 ns	0.020 ns

** : Significant at $P < 0.0001$; ns: not significant.

error) than desired if densities are low. To obtain a sample number of 27 trees for a precision level of 0.25 required a reasonable amount of cost (≈ 2 person hours); however, if a precision level of 0.10 is necessary, the cost (≈ 12.6 person hours) to inspect 170 cacao trees may be prohibitively high in some circumstances and also high for smallholder cacao farmers.

Sequential sampling allows economizing sampling while retaining a high level of confidence in decisions made. A person sampling *S. singularis* can use Fig. 6 by plotting T_n (accumulated number of *S. singularis* at 75%, $\ln T_n = 5.7358 - \ln[n]$) and n (number of trees) after each sample is taken. When the plot falls above the stop line, sampling is stopped and the mean number of *S. singularis* per tree (m) is within 75% of $m = T_n/n$. The stop line is a straight line if T_n is graphed against n on \ln -graph paper. The line will be horizontal for the Poisson distribution ($b = 1$), and will have a negative slope for $1 < b < 2$ (Green 1970).

Our results show that parameters estimated by Taylor's model remained constant during the two periods sampled. Our results also show that Taylor's estimates are reliable for pest management decision making. Sampling *S. singularis* is operationally difficult and often time-consuming. In this paper we have developed a sequential sampling plan that is based on counts of *S. singularis*. This sequential sampling should be based on Taylor's model parameter estimates with precision levels of 75% (with a coefficient of variation of 0.25) for pest management decision-making. In addition, this work provides a research tool for monitoring *S. singularis* populations in cacao plantations. Furthermore, these sampling plans could be used to estimate *S. singularis* densities as part of a decision-making program, in which the relationship between pest density and plant damage is used to estimate thresholds for *S. singularis* in cacao, or in conjunction with possible natural enemies to make management decisions (Nyrop and van der Werf 1994).

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