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Impact of removing diseased pods on cocoa black pod caused by *Phytophthora megakarya* and on cocoa production in Cameroon

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Abstract

Black pod rot, caused by *Phytophthora megakarya*, is the main cause of cocoa harvest losses in Cameroon. Field experiments were carried out over two successive years in two smallholders' plots of cocoa trees, in order to assess the impact of diseased pod removal (phytosanitary pod removal) on disease progress, total production and final harvest. The generalized linear mixed model proved to be the most appropriate for comparing the two treatments (without and with pod removal) set up in a randomized complete block design. Removing diseased pods helped to reduce the black pod rate by 22% and 31% in the two sites in the first year, and by 9% and 11% in the second year, compared to a plot in which no preventive control measures were taken. The rate of cherelle (very young pod) appearance was also higher when pod removal was carried out. Total production was higher in the plots with pod removal, but the difference between the two treatments was not significant. This study allowed an evaluation of the respective roles of primary and secondary inoculum in the spread of the disease. The cultural practice of phytosanitary pod removal was found to be a potentially efficient control method. However, it would need to be associated with other control methods to establish an integrated management system for cocoa farmers.

Keywords: Epidemiology; Generalized linear mixed model; *Phytophthora megakarya*; Phytosanitary pod removal; *Theobroma cacao*

1. Introduction

Black pod rot is the most serious disease affecting cocoa production in Cameroon. Beans from pods attacked by the disease are not suitable for processing and must be discarded. Losses can reach 100% of annual production if no control measures are taken. The disease is caused worldwide by various species of *Phytophthora*. The species *Phytophthora megakarya* Brasier and Griffin predominate in Cameroon (Nyasse, 1992), but strains of *P. palmivora* Butler seem to be present too (Ducamp, pers. comm.).

The methods available for controlling cocoa black pod rot are fungicide application, use of resistant cultivars and other appropriate cultural practices. An increase in the effectiveness of control can be expected when these methods are combined (Berry and Cilas, 1994).

Among the aforementioned methods, appropriate cultural practices seem to be the simplest to apply, in both terms of costs and environmental conservation. These practices should create conditions unfavorable for pathogen development and inoculum production. Phytosanitary pod removal, which is a preventive method, consists in cleaning trees at the beginning of the season by removing mummified fruits left from the previous season, which are a potential source of primary inoculum, and then regularly removing diseased pods, which are a potential source of secondary inoculum.

In Cameroon, Muller (1974) showed that weekly removal of diseased pods from the plots varied considerably in efficiency, not only from one year to another but also from one plot to the next, most of the variation being driven by macro- and micro-climate. The purpose of those trials was to study the effects of preventive methods on *P. palmivora* dissemination.

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However, later studies by Nyasse (1992) revealed that *P. megakarya* is the species predominating in cocoa plots in Cameroon. Therefore, identity of the pathogen in Muller's trial is not clear and his results might not be relevant in the current context. Partiot et al. (1984) confirmed that the impact of phytosanitary pod removal was highly dependent upon climatic factors. Its main action was to slow down the spread of the epidemic on fruits located on branches. However, no quantitative evaluation of the effect of pod removal on disease was attempted in that study. Tondje et al. (1993) tested several combinations of cultural practices in a regularly weeded experimental plot containing a single hybrid. The best disease control was achieved with pruning and removal of mummified pods at the beginning of the season, followed by weekly phytosanitary removals. However, the study was only conducted for 1 year, on an experimental station. None of the trials described above was realized under conditions reflecting routine smallholder practices, and very few, if any, replicates in time and space, were available. In Peru, Soberanis et al. (1999) conducted a study on farmers' fields, the purpose of which was to make recommendations for disease control, based on the frequency of phytosanitary removal (at weekly or fortnightly intervals). The authors showed that weekly phytosanitary removal relatively reduced cocoa black pod rot incidence by between 35% and 66%.

In Nigeria, between 1975 and 1978, experiments were carried out at Gambari (experimental station) to look at the epidemic in various situations: under the 'ultimate hygiene' treatment with daily removal of black pods; in a 'normal' situation with removal of black pods every 3 weeks; and with basal pod suppression in conjunction with 3-weekly harvests of black pods (Griffin et al., 1981). The results showed that the removal of 'initiators' before they sporulate prevents the development of infection sequences; in areas where the black pods were allowed to sporulate within the 3-weekly harvest regime, rain-splash infections from already sporulating pods outnumbered those from other source; plots with pods and flowers removed below 0.8 m had only two-thirds as many black pods as the untreated plots.

The aim of the present study was to assess in a smallholder's plot the effect of phytosanitary pod removal on black pod incidence and cocoa production. The study was conducted over two consecutive years and in experimental conditions which were chosen to be representative of the typical cocoa production conditions in Cameroon. The results gave indirect clues on the respective role of primary and secondary inoculum in the dynamics of the disease. It was hoped that the conclusions of the study could be the basis of practical recommendations for disease control. The data were analyzed with a new model based on the generalized linear mixed model.

2. Material and methods

2.1. Experimental design

The study was conducted in smallholders' plots over two consecutive years (1998 and 1999), at two sites. Both sites were located in agro-ecological zone V, which covers the Centre, South and East provinces of Cameroon (Fig. 1). The sites were thought to be representative of the agro-ecological conditions suitable for optimal cocoa production.

On both sites, many farmers were prepared to allow experiments in their cocoa fields. Experimental plots were selected on the basis of accessibility, size and maintenance of the farm. Two experimental plots of 800 and 1000 cocoa trees were finally selected at Elale and Ngoulessaman, respectively. The spacing between trees within a plot varied from $2.5 \times 2.5\,\text{m}^2$ to $3 \times 3\,\text{m}^2$, giving densities of 1111–1600 trees/ha. As dead trees were not systematically replaced, there were numerous 'gaps' in the different plots, thereby reducing the density. Small numbers of other trees such as coconut palms, mangoes, plums and avocado pear trees could also be found in the plots.

The experimental design used randomized complete blocks. It included eight blocks at Elale and 10 blocks at Ngoulessaman. Each block contained two treatments: treatment 1 (T1) without pod removal, and treatment 2 (T2) with pod removal. Each elementary plot contained 25 trees, and the plots were separated from each other by two border rows, made up of cocoa trees. There were therefore 500 and 400 useful trees at Ngoulessaman and Elale, respectively.

2.2. Climatic measurements

Rainfall total, as well as minimum and maximum temperatures were recorded on a daily basis. On each site, a rain gauge and a thermometer were installed out of the field, while another thermometer was placed under the cocoa tree canopy. The two thermometers installed on each site were appropriately screened. The climatic variables were recorded only in 1999 (Fig. 2).

Recorded climatic data were analyzed on a weekly basis. The mean minimum and maximum temperatures are the means of the daily minimum and maximum temperatures recorded during a week, respectively. The mean temperature is the mean of the minimum and maximum temperatures recorded during a week. Rainfall total was expressed as the weekly sum of daily precipitations.

2.3. Disease assessment and phytosanitary removal

Rotten pods (i.e. young and adult pods more than 4 cm in length affected by black pod), wilted pods (early

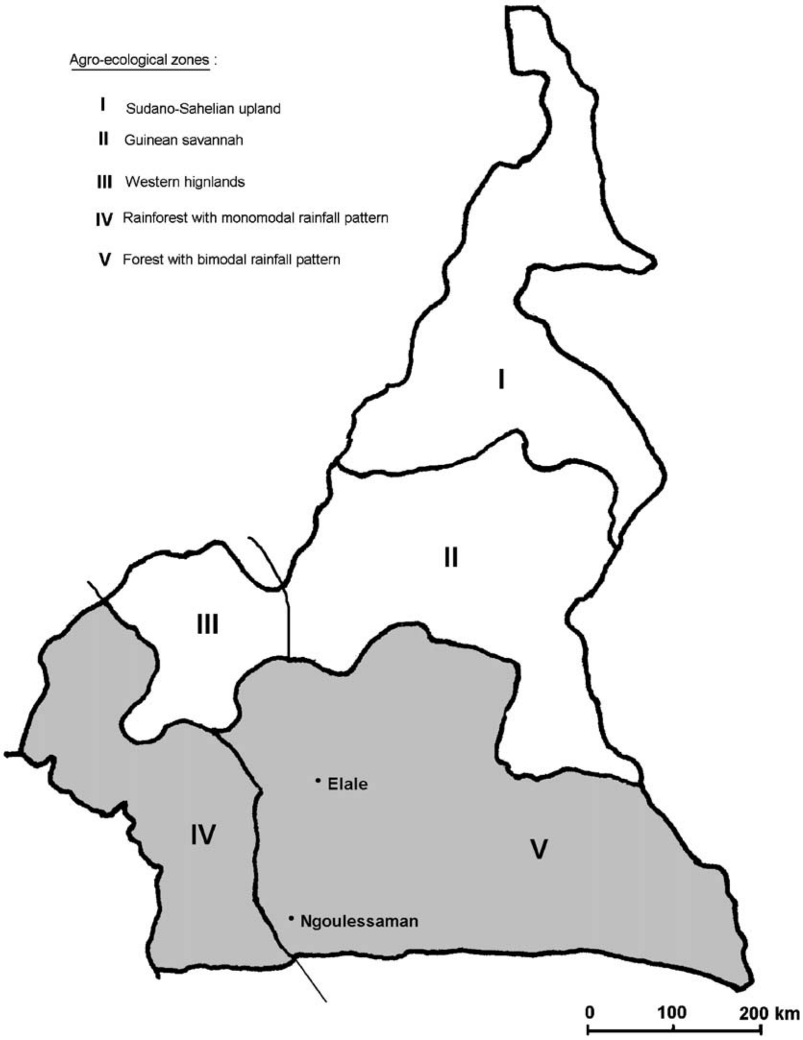

Fig. 1. Map of Cameroon showing the five agro-ecological zones defined by IRAD and the location of the two experimental sites of this study. The gray areas represent the cocoa production zones.

drying out of a physiological nature), rodent-damaged pods, pods affected by diseases other than black pod rot, cherelles (fruits having reached 4 cm in length), young pods (pods having exceeded the cherelle stage, but not having reached adult size), healthy adult pods (fruits having reached adult size but not ripe), and ripe-healthy (HR) pods were counted weekly on all trees. Total production was expressed as the number of rotten pods added to the number of young, adult and HR pods. The rate at which cherelles appeared was evaluated on five trees taken at random in each elementary plot.

Observations began each year as soon as the first pods appeared (April–May) and continued up to the end of the cultural season (November–December). There were no pods between December and April. There were therefore around 30 weeks of observations per site. Ripe pods were harvested every week from the two treatments. Diseased pods were not removed from the non-sanitized plots till the end of the cocoa season.

The phytosanitary removal primarily consisted in removing every week rotten pods from the trees. It was completed with sucker removal at the beginning of the observation period. Rotten pods were not removed by hand, as the observer could have become a source of contamination for the other fruits. Either a machete was used, or a cocoa pole for fruits high up. Removed pods were immediately taken out of the experimental plot.

2.4. Data analysis

Pod rot rate was calculated according to Berry and Cilas (1994) and De Jesus (1992). Losses due to rot were estimated in relation to diseased pods plus available pods (i.e. young, adult and HR pods, excluding wilted

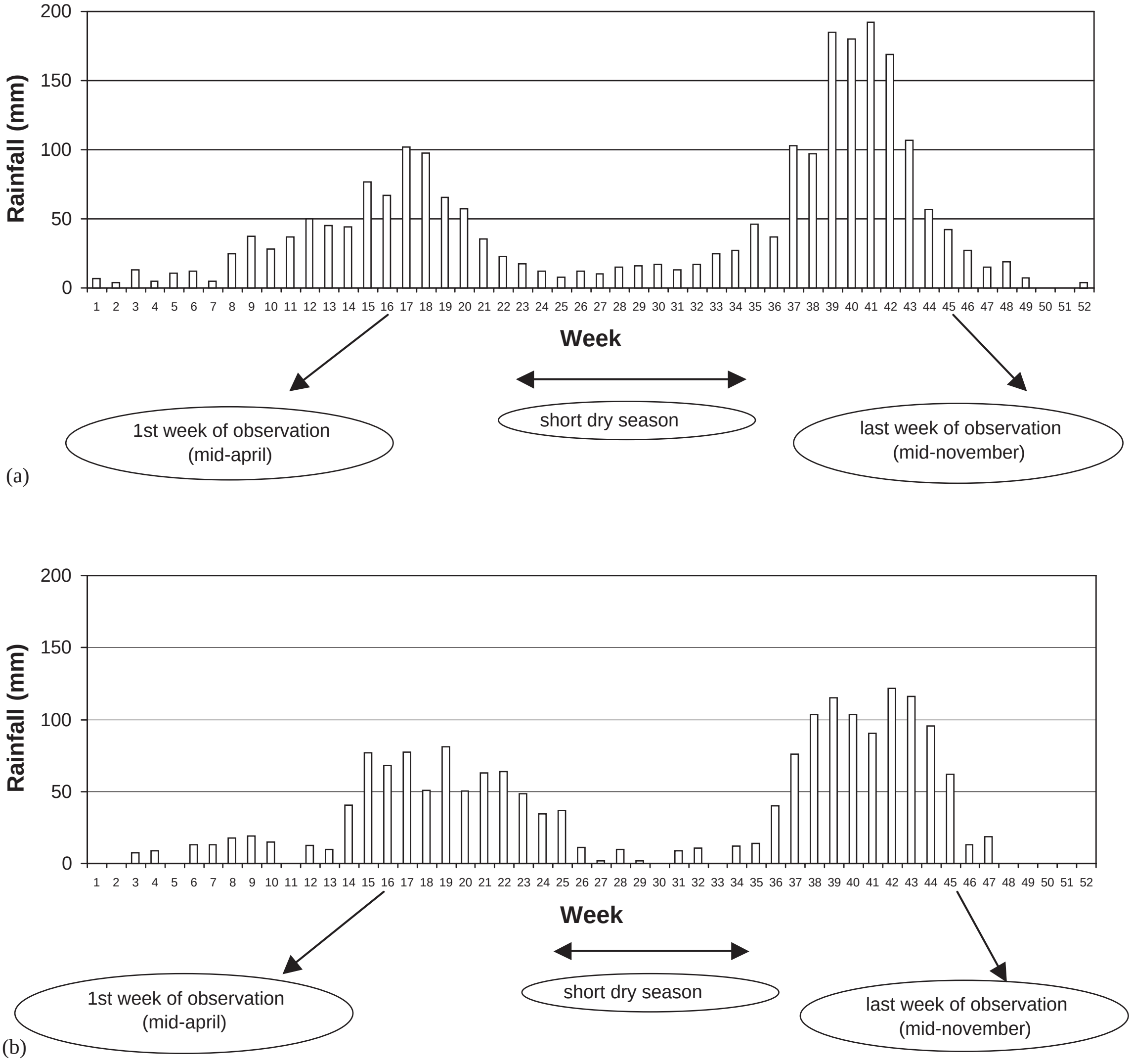

Fig. 2. Rainfall distribution in Ngoulessaman (a) and Elale (b) in 1999.

and rodent-damaged pods as well as those affected by other diseases).

Weekly rot rate (WRR) was calculated each week (i), according to

$$\mathrm{WRR}_i = \frac{\mathrm{ROT}_i{*}100}{(\mathrm{ROT}_i + \mathrm{YP}_i + \mathrm{HG}_i + \mathrm{HR}_i)}, \tag{1}$$

where ROT_i is the number of rotten pods in week i, YP_i is the number of young pods in week i, HG_i is the number of healthy adult pods in week i and HR_i is the number of healthy ripe pods in week i.

Cumulated rot rate (CRR) was calculated according to

$$\mathrm{CRR}_i = \frac{\sum_{i=1}^{i=N} \mathrm{ROT}i{*}100}{(\mathrm{YP}_N + \mathrm{HG}_N) + \sum_{i=1}^{i=N}(\mathrm{ROT}_i + \mathrm{HR}_i)}, \tag{2}$$

where i is the observation week number, N is the total number of observations, ROT_i is the number of rotten pods in week i, YP_N is the number of young pods in the final week of observations, HG_N is the number of healthy adult pods in the final week of observations and HR_i is the number of healthy ripe pods in week i.

Disease progress curves were drawn in order to analyze the effect of the treatments on disease development over time.

Analyses were carried out using three different models:

1. The *general linear model* with the SAS GLM procedure, according to

   $$y_{ij} = \mu + \alpha_i + \beta_j + e_{ij}, \tag{3}$$

   where i stands for block and varies from 1 to 10, j stands for treatment and varies from 1 to 2, y_{ij} is the final number of pods in each phytosanitary class (rotten, wilted, etc.) in the ijth block-treatment combination, μ is the overall mean, α_i is the block effect, β_j is the treatment effect and e_{ij} is the random error. μ, α_i, β_j are fixed parameters. The link function was an identity and the residuals were assumed to follow a normal distribution.

2. The *generalized linear model* with the SAS GENMOD procedure according to Eq. (4).

   Percentage data:

   $$\mathrm{Ln}[p_{ij}/(1-p_{ij})] = \mu + \alpha_i + \beta_j + e_{ij}. \tag{4}$$

   Count data:

   $$\mathrm{Ln}(y_{ij}) = \mu + \alpha_i + \beta_j + e_{ij}, \tag{5}$$

   where p_{ij} is the rot rate (number of diseased pods over the total number of pods in the block i and treatment j) and μ, α_i, β_j are fixed parameters. The link function is logit for percentage data and logarithm for count data. The residuals of percentage data were assumed to follow a binomial distribution, while those of count data were assumed to follow a Poisson distribution.

3. The *generalized linear mixed model* with the SAS GLIMMIX macro (Littell et al., 1996).

   Percentage data:

   $$\mathrm{Ln}[p_{ijk}/(1-p_{ijk})] = \mu + \alpha_i + \beta_j + \alpha_i\beta_j + c_{ijk} + e_{ijk}. \tag{6}$$

   Count data:

   $$\mathrm{Ln}(y_{ijk}) = \mu + \alpha_i + \beta_j + \alpha_i\beta_j + c_{ijk} + e_{ijk}, \tag{7}$$

   where k stands for tree and varies from 1 to 25, p_{ijk} is the rot rate, y_{ijk} is a count variable, p_{ijk} is rot rate or the number of pods of a given count variable in the ijkth block-treatment-tree combination, $\alpha_i\beta_j$ is the elementary plot effect and c_{ijk} is the tree effect. μ, β_j, α_i are fixed parameters and c_{ijk} is the random parameter. The link function was logit for percentage data and logarithm for count data. The residuals of percentage data were assumed to follow a binomial distribution, while those of count data were assumed to follow a Poisson distribution.

For the generalized linear model and the generalized linear mixed model, which are extensions of fixed-effect linear models to cases where standard linear model assumptions are violated, parameters were estimated using maximum likelihood based on the distribution of the data. The deviance (the generalization of error sum of squares in analysis of variance and the likelihood ratio χ^2 in contingency tables) was used to test model goodness of fit. It followed a χ^2 distribution with (n–p) degrees of freedom, where n was the total number of observations (500 at Ngoulessaman and 400 at Elale) and p the number of independent modalities of the treatment factor (i.e. 1). The degrees of freedom (df) were therefore 499 and 399 at Ngoulessaman and Elale, respectively. As the theoretical χ^2 values could not be read directly off conventional statistical tables (since df $\gg$ 100), the following approximation was used (Saporta, 1990):

$$\left[\left(\frac{\chi_v^2}{v}\right)^{1/3} + \frac{2}{9v} - 1\right]\left(\frac{9v}{2}\right)^{1/2} \approx U, \tag{8}$$

where χ_v^2/v is the critical deviance threshold, $U = 1.96$ and v is the number of degrees of freedom.

The statistical analyses were carried out per variable, per site and per year. The data for both years were then pooled, to obtain more precise results.

Data were analyzed using SAS version 8.2 (SAS, 2001) and Statistica version 5.1 (Statistica, 1998) software packages.

3. Results

Final disease incidence in both sites and years of study is shown in Table 1. On both sites and each year, the rot incidence was significantly higher ($P<0.05$) in the plot with no pod removal than in the plot with pod removal. In 1998, the average differences between the rot incidence in the two treatments were 22% and 31% at the two sites, whereas in 1999, the differences were 9% and 11%. The difference in rot incidence between treatments was greater when disease pressure was lower.

The change in cumulated rot incidence followed the same trend each year and on both sites for a given treatment (phytosanitary pod removal vs. no removal). When diseased pods were stripped (Fig. 3, squares), the

Table 1
Disease incidence (final rot) measured on the two experimental sites

Site	Year	Treatment		Relative reduction (%)
		No pod removal (%)	With pod removal (%)	
Elale	1998	67 (64; 69) a	52 (49; 54) b	22
	1999	75 (72; 77) a	68 (65; 70) b	9
Ngoulessaman	1998	59 (56; 61) a	41 (38; 43) b	31
	1999	78 (75; 80) a	69 (66; 71) b	11

Note: Values in brackets are the confidence intervals at 5% significance level; for a given year at the same site, values followed by the same letter are not significantly different at $\alpha = 0.05$.

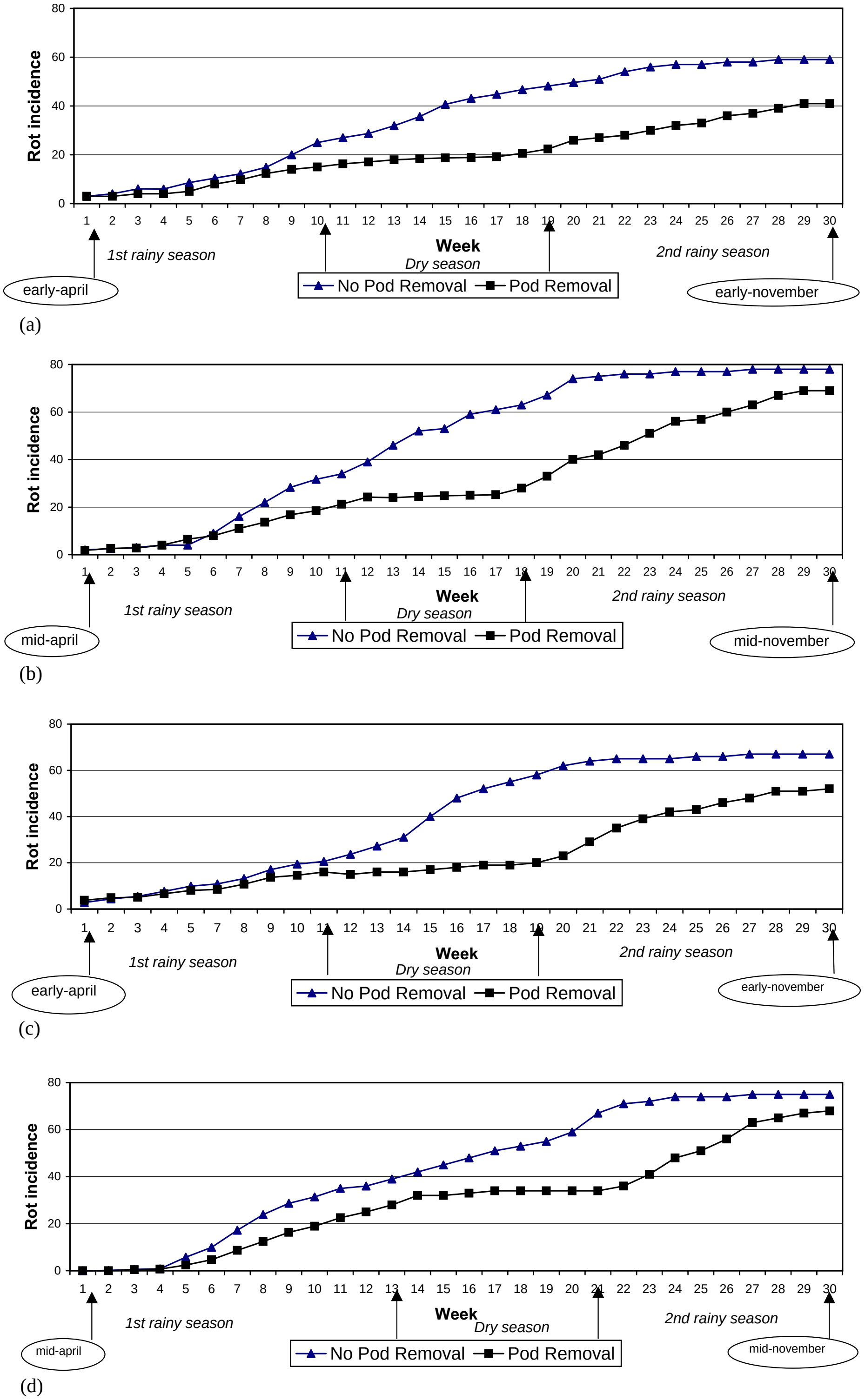

Fig. 3. Cumulated curves of cocoa black pod incidence observed in Ngoulessaman (1998 (a); 1999 (b)) and Elale (1998 (c); 1999 (d)) with (square symbols) or without (triangle symbols) phytosanitary pod removal.

disease progress curve showed a double-S pattern. The first plateau roughly coincided with the short dry season on each site. The disease then resumed with the beginning of the second rainy season. Conversely, when diseased pods were not removed (Fig. 3, triangles), the disease progress curve showed a simple S pattern. The disease progress was not slowed down during the short dry season. In the absence of removal, the asymptote

Table 2
Climatic variables measured on the two experimental sites in 1999

Variables	Sites	
	Elale	Ngoulessaman
Rainfall (mm)	1835	2304
Minimum 'ambient' temperature (°C)	22 (20.5; 23.5) a	21 (19.5; 22.5) a
Maximum 'ambient' temperature (°C)	33 (31.5; 34.5) a	30 (28.5; 31.5) b
Mean 'ambient' temperature (°C)	27.5 (26; 28) a	25.5 (24; 27) a
Minimum 'under-cocoa' temperature (°C)	20 (18.5; 21.5) a	19 (17.5; 20.5) a
Maximum 'under-cocoa' temperature (°C)	26 (24.5; 27.5) a	24 (22.5; 25.5) a
Mean 'under-cocoa' temperature (°C)	23 (21.5; 24.5) a	21.5 (20; 23) a

Note: Values in brackets are the confidence intervals at 5% significance level; for a given variable, values followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 3
Goodness of fit of the three models fitted to the experimental data

Site	Variables	GLM		GENMOD		GLIMMIX	
		R^{2}[a]	CV (%)[b]	Deviance per df[c]	Theoretical χ^2	Deviance per df	Theoretical χ^2
Ngoulessaman	Ripe-healthy	0.14	164.54	8.84	1.26	1.19	1.26
	Cherelles	0.21	53.12	6.95	1.26	1.11	1.26
	Total production	0.11	101.55	20.16	1.26	1.35	1.26
	Final rot rate	0.06	49.65	7.72	1.26	0.94	1.25
Elale	Ripe-healthy	0.11	119.84	5.57	1.27	1.23	1.27
	Cherelles	0.17	51.38	4.72	1.27	1.17	1.27
	Total production	0.04	81.44	18.09	1.27	1.21	1.27
	Final rot rate	0.09	39.91	6.45	1.27	0.98	1.25

Note: GLM, general linear model; GENMOD, generalized linear model; GLIMIX, generalized linear mixed model.
[a] R^2, coefficient of determination.
[b] CV, coefficient of variation.
[c] df, degrees of freedom.

corresponding to the final disease level was reached 5–7 weeks earlier than in the phytosanitary pod removal treatment.

Climatic data for 1999 are summarized in Table 2. It rained more at Ngoulessaman than at Elale. However, the disease progress curves in 1999 at both sites were quite similar (Fig. 3b and d). Overall, temperatures were not significantly different between both sites. On both sites, the 'ambient' temperatures were significantly greater than the 'under-cocoa' temperatures ($P < 0.05$).

Initial analysis carried out with the general linear model yielded a very poor fit. Table 3 shows very low coefficients of determination and very high coefficients of variation. The graphs of the residues also showed non-homogeneity of variance and non-normality of the residuals. Therefore, there was a strong violation of the assumptions underlying the validity of the general linear model. Arcsine transformation (for the percentage variables) and Naperian logarithm (Ln) transformation (for the count variables) did not significantly improve model goodness of fit. Coefficients of variation dropped but the coefficients of determination remained very low, thereby indicating the low percentage of variability explained by the model. Likewise, the transformations improved the normality of the residuals but heteroscedasticity persisted, therefore making use of the general linear model inadequate for analysis of these data.

Results obtained with the generalized linear model using the GENMOD procedure were better than those obtained with the GLM procedure, as GENMOD took into account either the binomial or the Poisson distribution, as followed by percentage data and count data residuals, respectively. However, for all variables, the ratio of deviance to degrees of freedom remained very high ($\gg 1$), well over the theoretical χ^2 (Table 3), which was indicator of excessive data scatter. The generalized linear model was therefore not adequate to analyze these data.

Finally, the generalized linear mixed model was used to analyze these data which had non-normal distribution, and to take into account the existence of fixed and random effect factors. Table 3 shows that the values of the deviance degrees of freedom ratio are all close to 1

Table 4
Tests for fixed effects on three variables (WRR: weekly rot rate; HR: ripe healthy and TP: total production) at Elale

Year	1998				1999			
Variable	Effect	df[a]	F value	$Pr > F$	Effect	df[a]	F value	$Pr > F$
WRR	Bloc	7/374	7.37	<0.0001	Bloc	7/372	5.13	<0.0001
	Treatment	1/374	28.37	<0.0001	Treatment	1/372	103.21	<0.0001
	Bloc∗ treatment	7/374	2.07	0.0462	Bloc∗ treatment	7/372	2.02	0.0473
HR	Bloc	7/374	4.02	0.0003	Bloc	7/372	5.34	<0.0001
	Treatment	1/374	44.50	<0.0001	Treatment	1/372	79.57	<0.0001
	Bloc∗ treatment	7/374	2.98	0.0382	Bloc∗ treatment	7/372	2.11	0.0426
TP	Bloc	7/374	5.01	<0.0001	Bloc	7/372	1.74	0.0982
	Treatment	1/374	0.03	0.8522	Treatment	1/372	0.63	0.4291
	Bloc∗ treatment	7/374	1.27	0.2624	Bloc∗ treatment	7/372	2.00	0.0538

[a] df, degrees of freedom (numerator df/denominator df).

Table 5
Tests for fixed effects on three variables (WRR: weekly rot rate; HR: ripe healthy and TP: total production) at Ngoulessaman

Year	1998				1999			
Variable	Effect	df[a]	F value	$Pr > F$	Effect	df[a]	F value	$Pr > F$
WRR	Bloc	9/437	4.93	<0.0001	Bloc	9/449	5.30	<0.0001
	Treatment	1/437	25.55	<0.0001	Treatment	1/449	130.78	<0.0001
	Bloc∗ treatment	9/437	1.62	0.1074	Bloc∗ treatment	9/449	1.24	0.0487
HR	Bloc	9/437	48.92	<0.0001	Bloc	9/449	4.46	<0.0001
	Treatment	1/437	7.01	0.0084	Treatment	1/449	4.64	0.0317
	Bloc∗ treatment	9/437	3.12	0.0361	Bloc∗ treatment	9/449	1.36	0.2048
TP	Bloc	9/437	5.80	<0.0001	Bloc	9/449	9.90	0.0982
	Treatment	1/437	2.75	0.0982	Treatment	1/449	0.94	0.4291
	Bloc∗ treatment	9/437	1.08	0.3755	Bloc∗ treatment	9/449	1.54	0.0538

[a] df, degrees of freedom (numerator df/denominator df).

and below the theoretical χ^2, which indicates that the model was satisfactory.

Tests for fixed effects of some variables are shown in Tables 4 and 5. Overall, treatment effect was highly significant for WRR and HR, whereas there was no significant difference for potential production (PP) between the two treatments.

Means of count variables, estimated by the maximum likelihood method, are shown in Table 6. On both sites, the number of wilted pods per tree was very high. In 1998, the number of wilted pods was significantly higher in treatment with pod removal in Ngoulessaman only. In 1999, however, the effect of pod removal on the number of wilted pods was observed in Elale only.

In all cases, the number of rodent-damaged and other diseased pods per tree was very low, compared to the number of wilted and rotten pods.

Appearance of new pods was assessed by the number of cherelles. Table 4 shows that the rate of cherelle appearance was significantly different ($P < 0.05$) between the two treatments in the four situations considered. Phytosanitary removal caused an increase in the number of set pods and therefore attainable yield. In terms of PP, this study did not yield any significant difference between the two treatments, though the total number of pods was higher in the plots with pod removal than in those without it.

Each year on both sites, the number of HR pods was quite low and significantly higher in the treatment

Table 6
Average number of pods per tree in the different phytosanitary classes

Year	Variable	Site			
		Ngoulessaman		Elale	
		No pod removal	Pod removal	No pod removal	Pod removal
1998	Rotten	13.6 (11.9; 15.1) a	9.7 (8.0; 11.2) b	17.9 (16.2; 19.4) a	13.9 (12.2; 15.4) b
	Wilted	30.6 (28.3; 32.5) a	37.2 (34.9; 39.1) b	33.4 (31.1; 35.3) a	32.2 (29.9; 34.1) a
	R.-damaged	0.39 (0.36; 0.41) a	0.56 (0.53; 0.58) b	0.43 (0.40; 0.45) a	0.72 (0.69; 0.74) b
	Other diseases	0.31 (0.28; 0.33) a	0.47 (0.44; 0.49) b	0.18 (0.15; 0.20) a	0.22 (0.19; 0.24) a
	Cherelles	15.1 (13.2; 16.8) a	19.2 (17.3; 20.9) b	14.9 (13.0; 16.6) a	20.4 (18.5; 22.1) b
	TP	23.1 (20.3; 25.4) a	24.5 (21.7; 25.1) a	26.7 (24.9; 28.3) a	27.0 (25.2; 28.6) a
	Ripe-healthy	2.8 (1.5; 3.9) a	6.1 (4.8; 7.1) b	3.8 (2.9; 4.5) a	5.8 (4.7; 7.2) b
1999	Rotten	33.2 (31.1; 35.0) a	27.6 (25.5; 29.4) b	34.6 (32.5; 36.4) a	30.2 (28.1; 32.0) b
	Wilted	48.1 (45.5; 50.4) a	44.3 (41.7; 46.6) a	38.2 (35.0; 40.5) a	51.2 (48.6; 53.5) b
	R. damaged	0.63 (0.59; 0.66) a	1.73 (1.69; 1.76) b	0.89 (0.85; 0.92) a	0.95 (0.91; 0.98) a
	Other diseases	0.44 (0.40; 0.47) a	0.69 (0.65; 0.72) b	0.53 (0.49; 0.56) a	0.72 (0.68; 0.75) b
	Cherelles	18.5 (16.4; 20.3) a	23.2 (21.1; 25.0) b	20.6 (18.5; 21.4) a	27.0 (24.9; 28.8) b
	TP	42.1 (39.8; 43.9) a	40.2 (37.9; 42.1) a	45.3 (43.1; 47.2) a	44.1 (41.8; 45.9) a
	Ripe-healthy	1.9 (1.6; 2.1) a	6.5 (4.9; 7.4) b	3.3 (3.2; 4.2) a	5.6 (3.6; 6.8) b

Note: *R*.-damaged, rodent damaged; TP, total production. For a given variable at the same site, figures followed by the same letter are not significantly different at $\alpha = 0.05$; Values in brackets are the confidence intervals of the mean.

with pod removal than in the one without pod removal.

4. Discussion

This work enabled us to quantify the impact of pod removal on black pod rot incidence. The practice effectively reduced the black pod incidence by 9–11% to 22–31%, depending on the year. The differences in disease incidence between both treatments (phytosanitary pod removal vs. no removal) can be related to the differences in the dynamics of secondary inoculum. Progress of infection, which takes place within a tree both downwards and upwards can be caused by several mechanisms: direct contact between neighboring healthy and diseased pods, spread of pathogen zoospores by rain drops dripping downwards from diseased pods onto healthy ones, upwards splashing of zoospores onto healthy pods through the impact of rain drops on diseased pods or on the ground, which may act as a reservoir of the parasite (Muller, 1974; Gregory et al., 1984; Ristaino and Gumpertz, 2000). Obviously, water-mediated disease dispersal mostly occurs during the rainy season, but dispersal events can also occur during the short dry season, when scarce rain events promote moderate expansion of disease, provided secondary inoculum is available. Infection can also progress sideways in a tree, both by splash in trajectory droplets and occasionally by wind blown droplets (Maddison and Griffin, 1981).

Phytosanitary pod removal suppressed most sources of secondary inoculum, thus explaining the first plateau observed in the disease curves (Fig. 3, squares). However, a resumption of disease progress was observed in both treatments when the second rainy season began. Other inoculum not originating from the pods and requiring a certain quantity of free water must be necessary for the resumption of the epidemics. Some sites for survival of the parasite as primary sources of infection may be the soil, flower cushions, bark of cocoa and shade trees, mosses and other epiphytes covering the bark (Muller, 1974).

Our results did not completely agree with those obtained in Peru by Soberanis et al. (1999), who found a reduction in black pod incidence of 35–66% following weekly phytosanitary pod removal. The difference in efficiency of the control measure observed between Peru and Cameroon might be due in part to different pathogens existing in the two countries. In Peru, the pathogen is *P. palmivora*, which is less aggressive than *P. megakarya* (Brasier and Griffin, 1979), the species widespread in Cameroon.

In this study, the rate at which pods appeared was greater in plots where phytosanitary pod removal was carried out. Diseased pods can be considered as nutriment consumers and their removal would have made more resources available for the production of new fruits. However, no significant difference ($P > 0.05$) in PP was found between both treatments, although a higher number of total pods was found in plots with pod removal. This can be explained by the higher rate of physiological wilting which occurs when young pods are especially numerous.

Among the methods of statistical analysis which were tested in this study, the generalized linear mixed model proved to be the most appropriate. This new model, using the GLIMMIX macro (Littell et al., 1996) took into account both the fixed (phytosanitary treatments) and random (blocks and trees) effects of factors, as well as the distribution of the residues of random variables. Combinations of fixed and random factors are very common in experimental designs used in field research. Our model, which gave much better results than the GLM and GENMOD procedures commonly used in such cases, could be useful for assessing a large array of experimental studies.

The pod removal carried out during this study was not strictly identical to smallholders' practices. A cocoa farmer does not carry out pod removal systematically every week. Moreover, the mummified pods removed are not always discarded from the plot. If the observed drop in pod rot rate and the relative increase in production are to be realized, the farmer needs to ensure stricter pod removal than that currently practised. Asking a farmer to do so entails him in additional work. An economic study is therefore required to find out whether the benefits generated by a careful pod stripping are substantial when compared to the additional costs incurred. A model for the field dynamics of *P. megakarya* similar to the one developed for *Moniliophthora roreri* (Leach et al., 2002), another cocoa tree disease, would allow the evaluation of net returns from various management strategies for farmers in Cameroon.

5. Conclusion

Earlier studies showed that losses due to cocoa black pod rot in Cameroon are around 50–60% (Despréaux, 1988; Despréaux et al., 1989). Although removing diseased pods from trees significantly reduced the rate of pod rot, this measure was not sufficient alone to solve the problem, probably because of the uncontrolled sources of inoculum mentioned above. This practice could be used in addition to other control methods, such as planting more resistant material and the rational use of fungicides, as a means to establish an integrated control system against the disease.

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