Cacao (Theobroma cacao L.) represents one of the most important agricultural crops of the humid Mexican tropics. In the last 10 yr, approximately 23,000 t of this grain were no longer produced per cycle. The objective of this study was to identify characteristics and factors that restrict production in the states of Tabasco and Chiapas. A survey was applied to obtain information about 184 producers and their plantations by two-stage sampling. Descriptive statistics were calculated and multilevel models were adjusted to analyze the information. Results show that there are differences (P < 0.05) in cacao yield between municipalities (380 kg ha⁻¹ + μoj is the estimated residual for each municipality). Crop productivity levels are higher in the state of Tabasco than in Chiapas (644 and 344 kg ha⁻¹, respectively). Incidence of frosty pod rot of cacao, also known as moniliasis, induced by Moniliophthora roreri [(Cif) H.C. Evans, Stalpers, Samson & Benny 1978] is significantly greater (P < 0.05) in the state of Chiapas (60%) than in Tabasco (48%). Producers who carry out more crop management practices increase yields and decrease the pathogen’s impact on their plantations. Results suggest the need to apply differentiated public policies to promote production within each region or municipality.

Key words: Cocoa production, Moniliophthora roreri, multilevel analysis, Theobroma cacao.
MATERIALS AND METHODS

Information was obtained by applying a survey to producers in Tabasco and Chiapas; sampling was carried out in two stages from the cacao producer census. To calculate sample size, the population was divided into groups; in the first stage, primary units, municipalities, were selected by simple random sampling, and the second stage consisted in sampling each municipality with the following formula:

\[ n = Z^2 \cdot q \cdot \text{DEFF} / r^2 \cdot p(1 - trn) \cdot \text{PS} \]  

where \( n \) is sample size, \( Z \) is the value of the normal distribution, \( p \) is the proportion of interest (maximum variance), \( q = 1 - \) proportion of interest, \( \text{DEFF} \) is the design effect defined as the loss or gain in design efficiency by grouping elements of the population to form units, \( r \) is the maximum expected relative error, \( trn \) is the rate of expected non-maximum response, and \( \text{PS} = N/N_i \) is the municipal proportion of rural production units recorded in the producer census where \( N \) is the total number of secondary units in the population (30 000) producers and \( N_i \) is the number of secondary units in the selected municipality. Sample size was 184 producers (136 in Tabasco and 48 in Chiapas). A questionnaire consisting of three sections was applied: a) information related to general producer attributes (age, education, land ownership), b) characteristics of cacao plantations (yield, crop association, area, age of plantation), and c) cultivation and marketing practices (plague and disease control, pruning, input purchase, cacao sales).

Statistical analysis of producer data was performed with multilevel models which adjust models of hierarchical or nested data. According to Hox (2002), analyzing variables that have different levels as if they had only one level is not adequate for two reasons: a) the first is of a statistical nature because they lose information and power; and b) the second is conceptual since data are analyzed at one level and sometimes conclusions are formulated at a different level. For theoretical discussion and development, see De Leeuw and Meijer (2008) and Snijders (2011). In the present study, a two-level model was applied; producers generated the first level and municipalities the second (Figure 1).

Regarding data analysis, statistics were calculated and a multilevel regression analysis was performed with the R statistical package. Multilevel analysis is a step-by-step process (Steele, 2008) that stems from a simple null model [2].

\[ y_{ij} = \beta_0 + e_{ij} \]  

In the two-level model the residual is divided into two components, which correspond to each level in the data structure (3). The multilevel null model is expressed in Equation [3].

\[ y_{ij} = \beta_0 + \mu_{oj} + e_{ij} \]  

where \( y_{ij} \) is the cacao yield of producer \( i \) in municipality \( j \). \( \beta_0 \) is the overall yield mean in the municipalities (all groups), \( \mu_{oj} \) is the effect of municipality \( j \) on yield, and \( e_{ij} \) is each producer’s residual (difference between the \( y \)-value for the \( i \)th individual and that individual’s group mean). The variance between municipalities \( \sigma^2_u \) (level 2) and the variance between producers \( \sigma^2_e \) (level 1) were obtained by equation [3]. The variance partition coefficient (VPC) was calculated to measure the proportion of total variance that is explained by differences between groups, expressed in Equation [4].

\[ \text{VPC} = \frac{\sigma^2_u}{\sigma^2_u + \sigma^2_e} \]  

To compare groups in level 2, estimators were obtained for \( \mu_j \) for each municipality with the Equation [5a]:

\[ \mu_j = w \cdot \bar{e}_j \]  

where \( \bar{e}_j \) is the mean residual for each group \( j \), expressed in Equation [5b]:

\[ \bar{e}_j = \bar{y}_j - \hat{\beta}_0 \]  

The estimator \( w \) expresses the shrunk residuals or Empirical Bayes Estimates in Equation [5c]:

\[ w = \frac{\sigma^2_u}{\sigma^2_u + \sigma^2_e/n_j} \]  

Residues at the producer \( e_{ij} \) level are the predictions and they were obtained as expressed in Equation [5d]:

\[ \hat{e}_{ij} = e_{ij} - u_j - y_{ij} - \hat{\beta}_0 - \hat{\mu}_j \]  

To test the null hypothesis that there are no group differences (\( Ho: \sigma^2_u = 0 \)) by comparing the null [2] and multilevel [3] models in a likelihood ratio test, a comparison test was performed by the following equation

\[ LR = -2 \log L_1 - (-2 \log L_2) \]  

where \( L_1 \) and \( L_2 \) are likelihood values of the single and multilevel models and \( \log \) is the natural logarithm. Rejection of \( Ho \) implies that there are real group differences.

In the second phase, a multilevel random intercept model was adjusted to identify the variables that affect cacao yield. When adding a \( X_{ij} \) covariable to Equation [3] at the cacao producer level, the model was specified according to Equation [7]:

\[ y_{ij} = \beta_0 + \beta_1 X_{ij} + \mu_j + e_{ij} \]  

The overall relationship between \( y \) and \( X \) in this model is represented by a straight line with \( \beta_0 \) intercept and \( \beta_1 \) slope; however, the intercept for a given group \( j \) is \( \beta_0 + \mu_j \). A multilevel model of this type consists of two components, a fixed part that specifies the relationships between the mean of \( y \) and the explanatory variables and a random part that contains the residuals at levels 1 (\( e_{ij} \)) and 2 (\( \mu_j \)). In Equation [7], the fixed component is \( \beta_0 + \beta_1 X_{ij} \) and the random component is \( \mu_j + e_{ij} \). The overall relationship between \( y \) and \( X \) in this model is represented by a straight line with \( \beta_0 \) intercept and \( \beta_1 \) slope; however, the intercept for a given group \( j \) is \( \beta_0 + \mu_j \). A multilevel model of this type consists of two components, a fixed part that specifies the relationships between the mean of \( y \) and the explanatory variables and a random part that contains the residuals at levels 1 (\( e_{ij} \)) and 2 (\( \mu_j \)). In Equation [7], the fixed component is \( \beta_0 + \beta_1 X_{ij} \) and the random component is \( \mu_j + e_{ij} \).
The descriptive statistics obtained show that cacao plantations are small (< 2 ha) due to the phenomenon of property fragmentation in Mexico (Díaz-José et al., 2011). This restricts the development of the activity since there is a need for efficient organizational schemes to encourage activities promoting cacao production (access to credit, marketing, transaction costs related to inputs and products, and legal disease control) (Nyemek et al., 2007; Eastwood et al., 2009).

Schemes that outweigh the restrictions and costs related to small-scale management should be suggested when they arise from producer and plantation characteristics. Collective action could be a determining factor without external rules affecting the ability of producers to solve their problems. Collective action, rather than producer organizations, is mentioned because the formal organization is required to gain access to credit and subsidies, and structural variables are even more disrupted because of trust and reciprocity issues (Ostrom, 2010).

Differences in cacao yield

The VPC value (0.1786) indicates that approximately 18% of the variance in cacao yield in Chiapas and Tabasco could be attributed to differences between municipalities. This suggests that the variance between yields in each one of the observations is high.

Results from the comparison test of the null models of the level 1 and multilevel null model (LR = 24.71) show that there are differences in cacao yields between municipalities. Ho is rejected when 5% (α = 0.05) of distribution χ² with 1 df = 3.84; there is therefore evidence that the municipality variable affects cacao yield. This indicates that a multilevel model is preferable to a simple regression model to analyze this type of data. The joint mean of cacao yield was estimated as 380 kg ha⁻¹; therefore, the estimated mean for any municipality j was 380 kg ha⁻¹ + μj, which is the estimated residual for municipality j (Table 2). This coincides with results reported by OEIDRUS (2013) for the differences between

| Variable | Mean | Minimum | Maximum | SD |
|----------|------|---------|---------|----|
| Age      | 57.50| 29.0    | 94.0    | 14.2|
| Education| 4.80 | 0.0     | 19.0    | 3.5 |
| Experience| 31.30| 2.0     | 73.0    | 13.4|
| Age of plantation, yr | 33.20| 5.0     | 70.0    | 12.1|
| Area of plantation, ha | 1.75 | 0.3     | 9.0     | 1.4 |

SD: standard deviation.
yields at a municipal level. Tendencies in yield levels in the municipalities of Tabasco coincide with the results of this study, but statistics for the state of Chiapas present different results.

Data shown in Table 2 indicate two important findings: i) municipalities present differences in yield, which reflect the diversity of factors (climate, management practices, incidence of MO) that can affect cacao production; and ii) municipalities in Tabasco have higher estimated mean yields than those in Chiapas. This result concurs with Díaz-José et al. (2013a), who used an econometric model to find that the decrease in cacao yield per unit area in Chiapas is greater than in Tabasco.

Cacao yield alteration

Table 3 shows the results of the fixed multilevel model for variables that affect cacao yield. The sample mean of alteration caused by MO in Mexico is 39%. In the multilevel fixed model, \( \beta_0 \) can be interpreted as the predicted yield index for producers who have that degree of alteration. For any of the municipalities, increasing MO incidence will reduce cacao yields (\( \beta_2 \)). These results support Krauss et al. (2010) with regard to yield levels affected by MO.

Relative humidity is directly related to the amount of water available in the soil. Results show that yield increases with high relative humidity (\( \beta_2 \)). This concurs with Balasimha et al. (1991), who mention that prolonged dry periods can affect the physiological process which reduces cacao production. In the same way, Rada et al. (2005) mention that micro-climatic characteristics, such as relative humidity and air temperature, significantly affect stomatal conductance that conditions yield. However, when interpreting relative humidity and yield relationships, precautions should be taken because high levels of relative humidity induce diseases caused by fungi.

A higher index of crop management practices (\( \beta_3 \)) increases yield. Practices such as weed control, drain maintenance, fertilization, pesticide application to control plagues and diseases improve plantation conditions and permit higher production. In this regard, Díaz-José et al. (2013b) found that low yields are associated with a low rate of good farming practices. It is therefore necessary to intensify farming practices to improve cacao production.

The variable related to plantation age (\( \beta_4 \)) was not significant; this can be attributed to the fact that yield performance behaves as a normal curve with respect to tree age. Finally, for any municipality, increasing area by 1 ha would reduce the predicted yield (\( \beta_5 \)). Given that the current management of MO in Mexico is carried out through cultural practices and since cacao prices are low, increasing plantation area requires adequate management, which entails increased costs and losses for the producer. These results coincide with Fowler et al. (1956), who found a highly significant negative correlation between yield and cacao plantation area and attributed this behavior to the fact that growth rate management in smaller cacao plantations is better. In addition, Phillips-Mora et al. (2007) mention that the frequency and costs of cultural practices are the main factors that restrict the adequate management of cacao plantations.

When calculating confidence intervals from the standard deviation between municipalities, it was found that producers who reside in municipalities with the lowest yields obtain up to 111 kg ha\(^{-1}\), while those who are in the municipalities with the highest yields obtain production greater than 680 kg ha\(^{-1}\) (this interval was estimated as \( \beta_0 \pm [1.96 \times \sqrt{\sigma^2_{p0}}] = [111.99, 680.17] \)).

Results suggest that intervention strategies to promote cacao production should consider two important scenarios: i) zones where there is an abandonment of the activity, as evidenced by the productive level of plantations, and where there is a need for rescue strategies of the activity; and ii) zones with productive potential and good yield where an increase in productivity should be promoted, as well as improving the quality of grains obtained. These points show the need to apply differentiated strategies based on the characteristics of each production region.

**Incidence of moniliasis and maintenance practices in plantations**

Results indicate that MO disease has a higher occurrence in Chiapas (60%) than in Tabasco (48%) (Table 4).
an important number of management practices have a significant incidence of the pathogen; iii) municipalities with a low index of maintenance practices that have high MO incidence; and iv) municipalities that perform few management practices and have low incidence of the disease. It is interesting that the latter are concentrated in the northern region of the state of Chiapas.

The first group of municipalities has a behavior that corresponds to studies reporting that the best strategy for MO control is based on intensifying crop management practices (Porras et al., 1990; Leach et al., 2002; Evans, 2007; Torres de la Cruz et al., 2011). In the second group, it is evident that plantation management has not been effective although efforts have been made to counteract the disease; this can be the result of poorly applying the practices, scarcity of information about the biological effects of the pathogen, or agro-climatic variables that promote the development of the disease.

The third group shows that the abandonment of plantations increases MO incidence. According to Krauss et al. (2010), after MO appears it can reduce yield up to 80% in only a few years. The fourth group has a different behavior from what is logical for this analysis; in the case of two municipalities in Chiapas (Pichucalco and Ostuacan), low incidence can be attributed to the geographic location and different climatic conditions, while Villa Comaltitán exhibits the general mean of MO incidence obtained in this study.

Leach et al. (2002) mention that cacao cultivation is economically viable in spite of the presence of MO; however, it is necessary to provide plantation maintenance by removing diseased fruits to prevent dispersion and accumulation of the disease in the plots.

**CONCLUSIONS**

Cacao cultivation in Mexico exhibits structural characteristics (plantation area, age of producers, plantation age, and moniliasis incidence) that condition production and yield. There are marked differences in yields between the states of Tabasco and Chiapas, as well as between their municipalities. Alteration caused by moniliasis is also differentially reproduced and is approximately 40% in the cacao plantations, which largely reduces yields; however, a higher number of management practices can increase plantation yields and reduce the effect of moniliasis. Moniliasis has become a negative externality of cacao production in Mexico since a plot without maintenance disperses the disease to other plantations, which is why sanitation regulatory instruments are required. This suggests the need to apply policies to promote cacao production that take into account technical and social aspects, that is, equipment and training for pruning and management, strategies for plantation renewal, information systems for decision making, and political instruments that promote collective
action. These strategies should be differentiated according to local producer conditions. Future research should include other variables, such as geographic and soil references, to determine conditions that foster moniliasis development.

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