NUTRITIONAL CHARACTERIZATION OF COCOA SOILS IN MEXICO †

[CARACTERIZACIÓN NUTRIMENTAL DE SUELOS CACAOTEROS DE MÉXICO]

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SUMMARY

Background: Cocoa in Mexico is produced mainly in the states of Tabasco and Chiapas, where among other factors, agroecological characteristics of the region allow its cultivation. The limitation in the production of this crop is often due to the low fertility of the soil. However, only a few studies have characterized the physical and chemical properties of the soils where cocoa is produced. **Objective:** To characterize the physicochemical properties of the soil under cocoa plantations in Chiapas and Tabasco, Mexico. **Methodology:** One hundred and seven (107) soil samples distributed in different municipalities of the states of Chiapas and Tabasco were collected for the analysis of their physical and chemical properties. A multivariate analysis was performed to observe the distribution of the samples. Finally, they were grouped using a hierarchical cluster analysis to compare the grouping based on their physical and chemical properties. **Results:** The grouping of the soil samples was presented based on their origin rather than due to altitude or nutrient content. According to the hierarchical cluster analysis, three groups and eight subgroups were obtained. The pH between the subgroups ranged between 5.3 and 7.3. The IIIc subgroup of Tuxtla Chico and Cacahoatán (Chiapas) presented the most significant amount of organic matter. **Implications:** It was a challenge to explain the physical and chemical characteristics of 107 different soils; achieving correlations required a lot of statistical analysis. **Conclusion:** From the soils studied, it was possible to identify the nutritional ranges and group them according to location, finding that it is variable between the subgroups, however, despite the variability they managed to meet the nutrient requirements for cocoa cultivation.
Key words: Fertility; cocoa; soil physical-chemistry.

RESUMEN

Antecedentes: El cacao en México se produce principalmente en los estados de Tabasco y Chiapas, donde las características geográficas de la región permiten su cultivo. Muchas veces la limitación en producción de este cultivo es debido a la baja fertilidad del suelo, sin embargo, existen pocos estudios que abarquen los análisis físico químicos de los suelos donde se produce el cacao. **Objetivo**: Realizar la caracterización nutrimental de los suelos cacaoteros de Chiapas y Tabasco, México. **Metodología**: Se realizó un muestreo de 107 suelos de cacao distribuidos en diferentes municipios de los estados de Chiapas y Tabasco, para posteriormente realizar la caracterización físico química de estas muestras. Se realizó un análisis multivariado, para observar la distribución de las muestras y finalmente se agruparon mediante un análisis de conglomerado jerárquico, para comparar la agrupación en función de sus características físico químicas. **Resultados**: La agrupación de las muestras de suelo se presentó con una tendencia al origen de estas, más que por la altitud o el contenido de los nutrimentos. Según los análisis de conglomerados jerárquicos, se lograron destacar tres grupos y a su vez ocho

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subgrupos. El pH entre los subgrupos oscilo entre 5.3 y 7.3; referente a la materia orgánica el subgrupo IIIc perteneciente a Tuxtla chico y Cacahoatán (Chiapas), presento mayor cantidad. **Implicaciones**: Fue un reto explicar las características físico químicas de 107 suelos diferentes, lograr las correlaciones demando mucho poder estadístico y análisis. **Conclusión**: A partir de los suelos estudiados se lograron identificar los rangos nutrimentales y agruparlos en función de ubicación, encontrando que es variable entre los subgrupos, sin embargo, y a pesar de la variabilidad estos lograron cumplir los requerimientos de nutrientes para el cultivo del cacao.
Palabras clave: Fertilidad; cacao; físico-química de suelos.

INTRODUCTION

Financial benefits derived from cocoa cultivation provide a good alternative for developing tropical and subtropical areas of Mexico and the world. In 2021, 52,993.9 ha of cocoa were cultivated in Mexico, with the states of Tabasco and Chiapas being the most important due to their area and production (SIAP, 2022). It is estimated that more than 5,000 producers are growing the crop, with an average yield of 540 kg/ha and a production value of 1,176,811 pesos (SIAP, 2022). However, in the last fifteen years, production has decreased due to different factors, such as pests and diseases, nutrition, quality, and conventional soil management. Cocoa production in Mexico is carried out in different types of soils, such as Cambisols, Luvisols, Nitosols, and Andosols (Suárez-Venero *et al*., 2021).

Bautista *et al.* (2004) established that the indicators of good quality soil should allow (a) an analysis of the current situation and identify critical points concerning sustainable development, (b) an analysis of possible impacts before an intervention, (c) monitoring of the impact of anthropogenic interventions; and (d) help determine whether the use of the resource is sustainable.

The cocoa agroecosystem in Mexico, as in all cocoa-producing areas in the world, presents problems in its production because it is unknown if the plantations were established on ideal soils and if the right varieties were used. Among several deficiencies in the management of the cocoa production system, constant soil nutrient removal throughout the harvest stands out (Villason and Olguera, 2020). It has been observed that, although this is a closed system where initially the crop was planted in fertile soils previously occupied by forest the soil has become impoverished and is currently not able to supply enough nutrients to the crop to achieve good yields (Hartemink, 2005). Regarding its yield and mineral fertilization, there are still doubts since, in some cases, fertilization has shown little effect; but this is because it is necessary to know about the specific nutritional requirements of the tree, as well as the availability of nutrients in the soil (Rodríguez, 1992). These nutrient deficiencies can be resolved through rational crop fertilization (Rodríguez *et al*., 2001) once the nutritional removal standards of the cocoa tree are known (Alonso et al., 2020). Moreover, for a specific site, the chemical analysis of the soil will allow the formulation of a rational mineral fertilization dose (González, *et al*., 2018). It is therefore imperative to know the factors that affect its growth and performance, one of them is mineral fertilization depending on the type of soil and its fertility status. Regarding the above, evaluating and understanding the soil's properties is necessary based on the cocoa agroecosystem's nutritional condition and requirements (Villason and Olguera, 2020).

Soil fertility is considered the most significant indicator for the sustainable production of agroecosystems this is fundamentally derived from its physical, chemical, and biological properties that reveal the current and future condition of its productivity (Hanks and Ritchie, 1991; Wibawa et al., 1993). For the chemical properties of the soil in the cocoa agroecosystem and its relationship with the values determined in the entities of Chiapas and Tabasco, this vital information should lead to determining the relationship of these characteristics between the types of soil present in the cocoa agroecosystem and also inferring its fertility condition (Wadt, 2005). Therefore, the soil data series allows for inferring ideal soil conditions in this agroecosystem (Bockheim, 2008). On the other hand, multivariate analysis allows us to reduce the number of variables to understand the variation of soils due to their nutritional status (Du et al., 2008). For this reason, this work aimed to characterize the soils under cocoa plantation in Chiapas and Tabasco, Mexico.

MATERIALS AND METHODS

Site selection

The study was carried out in different cocoa-growing municipalities of Chiapas and Tabasco, Mexico. The properties were located where the representative cocoa plots over fifteen years old were selected, with a surface area of 1 hectare and this was the reason for selecting the soils.

Sampling of cocoa soils

Within the plots, at each sampling site, the soil surface was cleaned of leaves and other residues, and using a straight shovel 15 cm wide by 30 cm long with a sharp tip, a 30 cm x 30 cm stump was opened. x 30 cm deep, in each vine and from the walls facing the sun, the samples were collected from top to bottom and packaged in 30 cm x 40 cm plastic bags (Thong and Ng, 1978; de Oliveira and Valle, 1990; Wood and Lass, 2008). Each sample was identified by numerical order, locality, entity, and georeferenced (Njukeng and Baligar, 2016) (Supplementary 1).

Physical-chemical characterization of soils

Once in the laboratory, the samples were dried for eight days in outdoors, under the shade. Subsequently, the dried samples were sieved with a 2 mm mesh, and 800 g of each were weighed; their chemical and physical characteristics were determined (Okoffo et al., 2016). Phosphorus oxide (P_2O_5) and Potassium (K) were determined by atomic absorption; Nitrogen (N) and Nitric Oxide (NO) by visible light spectrophotometry with a colorimeter, pH by a potentiometer and Organic Matter (OM) by the method of Walkley and Black (1934). Other determinations: Calcium (Ca) and Magnesium (Mg) (by complexometry), Iron (Fe), Manganese (Mn), Zinc (Zn), Copper (Cu) (by Atomic Absorption), Sulfur (S) (turbidimetry) and Boron (B) (Colorimetric Method and Oxalic Acid). Toxic elements such as Chlorine (Cl) (turbidimetry or potentiometry), Bicarbonate (HCO3) (ICP), Carbonate (CO3) (by combustion) and Cationic Exchange Capacity (CIC) (Ammonium Acetate). The texture was determined by Bouyoucos's method (1962).

Statistical analysis

Multivariate analysis was used to analyze the data: principal component analysis (PCA) was carried out using the PRINCOMP procedure of SAS (2020), where the eigenvalues and eigenvectors were considered. The principal components 1, 2, and 3 were plotted on a Cartesian plane to observe the distribution of the samples. In addition, hierarchical cluster analysis was used, and through the squared Euclidean distance and the semipartial correlation coefficient, the groups of the different ecotypes were separated. The groups were compared using the Tukey test of means with an alpha=0.05.

RESULTS AND DISCUSSION

Principal component analysis

According to the principal components analysis, 70.9% of the variation in cocoa soils in Mexico was explained with the first three components and 96% with the first five components (Table 1).

The variables that contributed the most to the variation within each principal component were for CP1 pH, NO3, Ca, Mg, Fe, and B; for CP2, the MO, N, Zn, Mn, and Cu; and CP3, the P_2O_5, K, and S. (Table 2).

The variables that contributed the most to the distribution of the cocoa soils of Chiapas and Tabasco were MO, N, NO, pH, Mg, and Ca (Figure 1A) and P_2O_5, S, Fe, and B (Figure 1B).

The nutritional content of Chiapas and Tabasco, Mexico's cocoa soils, shows a wide dispersion. The grouping tendency is mainly due to nutrient concentration rather than origin. In quadrant I, samples from Chiapas are mainly grouped, and their dispersion is due to the content of OM and N (Figure 2, Figure 1A). In quadrant II, the content of B and Fe groups them; in quadrant III, the content of P and Cu; and finally, in quadrant IV, the grouping is by pH, Mg, Ca, and NO (Figure 2, Figure 1A).

Figure 3 shows how the samples tend to concentrate in the center, resulting in little dispersion. In quadrant I, five samples are characterized by their higher content of Ca and Mg (Figure 3, Figure 1B). In quadrant II, two samples stand out for their P and S content (Figure 3, Figure 1B).

Hierarchical cluster analysis (HCJ)

According to the ACJ, three large groups and eight subgroups were formed (Figure 4).

The grouping of the soil samples was presented with a tendency to their origin rather than due to altitude or nutrient content. The general altitude of all samples ranged from 5 m to 516 m and, on average, 151.4 m.

Table 1. Eigenvalues of the principal components (CP) analysis, using the correlation matrix. Eigenvalues and proportion of the total variance explained by principal component, based on soil chemical analyses.

	Eigenvalues of the correlation matrix			
CP	**Eigenvalues**	**Difference**	**Proportion**	**Accumulated**
1	3.37	1.27	0.24	0.24
2	2.11	0.50	0.15	0.39
3	1.61	0.31	0.11	0.51
4	1.30	0.08	0.09	0.60
5	1.23	0.18	0.09	0.69

Table 2. Eigenvectors and Pearson correlation of the original variables with the principal components.

Variable	Principal Component			Pearson's correlation		
	CP1	**CP2**	**CP3**	**CP1**	**CP2**	**CP3**
pH	0.41	-0.19	0.03	0.75**	-0.28	0.04
MO	0.18	0.63	0.06	0.33	0.91**	0.07
NO_3	0.38	-0.08	0.01	0.71**	-0.11	0.01
N	0.18	0.63	0.06	0.34	0.91**	0.07
P_2O_5	-0.15	-0.12	0.48	-0.27	-0.18	0.61**
K	0.09	0.03	0.47	0.17	0.04	0.59**
Ca	0.44	-0.12	0.25	0.81**	-0.18	0.32
Mg	0.41	-0.15	0.20	0.76**	-0.22	0.25
S	-0.09	0.05	0.51	-0.17	0.08	0.64**
Fe	-0.32	0.04	0.25	-0.59**	0.06	0.32
Zn	0.00	0.19	0.21	0.00	0.27**	0.26
Mn	-0.08	0.14	0.03	-0.15	0.20*	0.04
Cu	-0.13	-0.22	0.24	-0.24	-0.32**	0.30
B	-0.30	0.09	0.13	-0.54**	0.12	0.17

**High correlation

Group I presented two subgroups. G Ia was characterized by grouping 36 samples, predominantly from the state of Tabasco, with an average altitude of 7 m to 465 m and, on average, 93.4 m. On average the pH of this subgroup was 6.3; MO 2.59%; NO 13.41 ppm; N 90.55 kg/ha; P 40.52 kg/ha; K 191.53 kg/ha; Ca 1979.9 ppm; Mg 397.6 ppm; S 33.05 ppm; Fe 56.78 ppm; Zn 1.49 ppm; Mn 12.33 ppm; Cu 7.06 ppm and B 0.1 ppm. For its part, G Ib grouped 12 samples from Tabasco and Chiapas, the altitude ranged between 5 m and 180 m and on average 61 m; pH 6.5; MO 0.74%; NO 7.28 ppm; N 26.38 kg/ha; P 27.85 kg/ha; K 241.63 kg/ha; Ca 1113.6 ppm; Mg 238.3 ppm; S 31.82 ppm; Fe 27.6 ppm; Zn 0.7 ppm; Mn 7.77 ppm; Cu 2.4 ppm; and B 0.1 ppm.

In group II, three subgroups were formed. The G IIa were two samples from Chiapas; the altitude ranged between 17 m and 84 m and on average 50.5 m; pH 5.3; MO 2.8%; NO 0.15 ppm; N 98 kg/ha; P 207.5 kg/ha; K 810 kg/ha; Ca 5.8 ppm; Mg 1.3 ppm; S 328.49 ppm; Fe 81.45 ppm; Zn 0.9 ppm; Mn 11.25 ppm; Cu 8.20 ppm; and B 0.1 ppm. The G IIb, were 12 samples where Chiapas predominated, the altitude ranged between 7 m and 516 m and on average 190.6 m; pH 6.3; MO 3.14%; NO 9.71 ppm; N 110.15 kg/ha; P 100.29 kg/ha; K 277.58 kg/ha; Ca 1686.9 ppm; Mg 285 ppm; S 27.96 ppm; Fe 82.08 ppm; Zn 4.97 ppm; Mn 12.49 ppm; Cu 11.34 ppm; and B 0.12 ppm. The G IIc, there were 19 samples where Chiapas predominated and only five were from Tabasco, the altitude ranged between 6 m and 398 m and on average 63.6 m; pH 5.7; MO 2.88%; NO 0.15 ppm; N 100.84 kg/ha; P 24.33 kg/ha; K 283.81 kg/ha; Ca 8.7 ppm; Mg 106.3 ppm; S 39.04 ppm; Fe 104.02 ppm; Zn 1.9 ppm; Mn 20.01 ppm; Cu 5.47 ppm; and B 0.15 ppm.

In group III, three subgroups were formed. G IIIa, were 4 samples from Chiapas, the altitude ranged between 230 m and 516 m and on average 381 m; pH 7.3; MO 4.85%; NO 25.83 ppm; N 169.95 kg/ha; P 10.68 kg/ha; K 519.45 kg/ha; Ca 6671.5 ppm; Mg 2409.3 ppm; S 43.03 ppm; Fe 27.08 ppm; Zn 0.7 ppm; Mn 3.38 ppm; Cu 3.13 ppm; and B 0.1 ppm. G IIIb, were 14 samples from Chiapas, the altitude ranged between 84 m and 492 m and on average 284.1 m; pH 6.5; MO 4.42%; NO 10.93 ppm; N 155.26 kg/ha; P 19.45 kg/ha; K 475.77 kg/ha; Ca 3934.6 ppm; Mg 584.4 ppm; S 16.91 ppm; Fe 52.51 ppm; Zn 2.16 ppm; Mn 28.18 ppm; Cu 4.34 ppm; and B 0.1 ppm. Finally, G IIIc were 8 samples from Chiapas, the altitude ranged between 83 m and 500 m and on average 376.5 m; pH 6.2; MO 9.11%; NO 10.12 ppm; N 318.79 kg/ha; P 5.46 kg/ha; K 221.33 kg/ha; Ca 922.9 ppm; Mg 112.8 ppm; S 40.94 ppm; Fe 38.4 ppm; Zn 2.30 ppm; Mn 8.22 ppm; Cu 1.56 ppm; and B 0.11 ppm.

The pH is one of the main variables that indicate the general state of the soil; in this work, this parameter ranges between a pH of 5.3 to 7.3. When comparing the groups and subgroups, subgroup IIIa, where all samples come from Maravilla Tenejapa, Chiapas, presented the highest pH (7.3) and NO (25.83), above what is recommended for cocoa and subgroup IIa from Escuintla and Huehuetán, Chiapas had the lowest pH (5.3) below the recommended ranges for cocoa. Which could limit the availability, absorption, concentration of nutrients, and yield in cocoa cultivation (Rosas-Patiño et al., 2021). On the other hand, pH values between 7 and 7.5 are related to high Cationic Exchange Capacity and, therefore, greater nutrient intake (González-Gordon et al., 2018; Argüello et al., 2019). The other subgroups are within the recommended pH range for cocoa (Table 3).

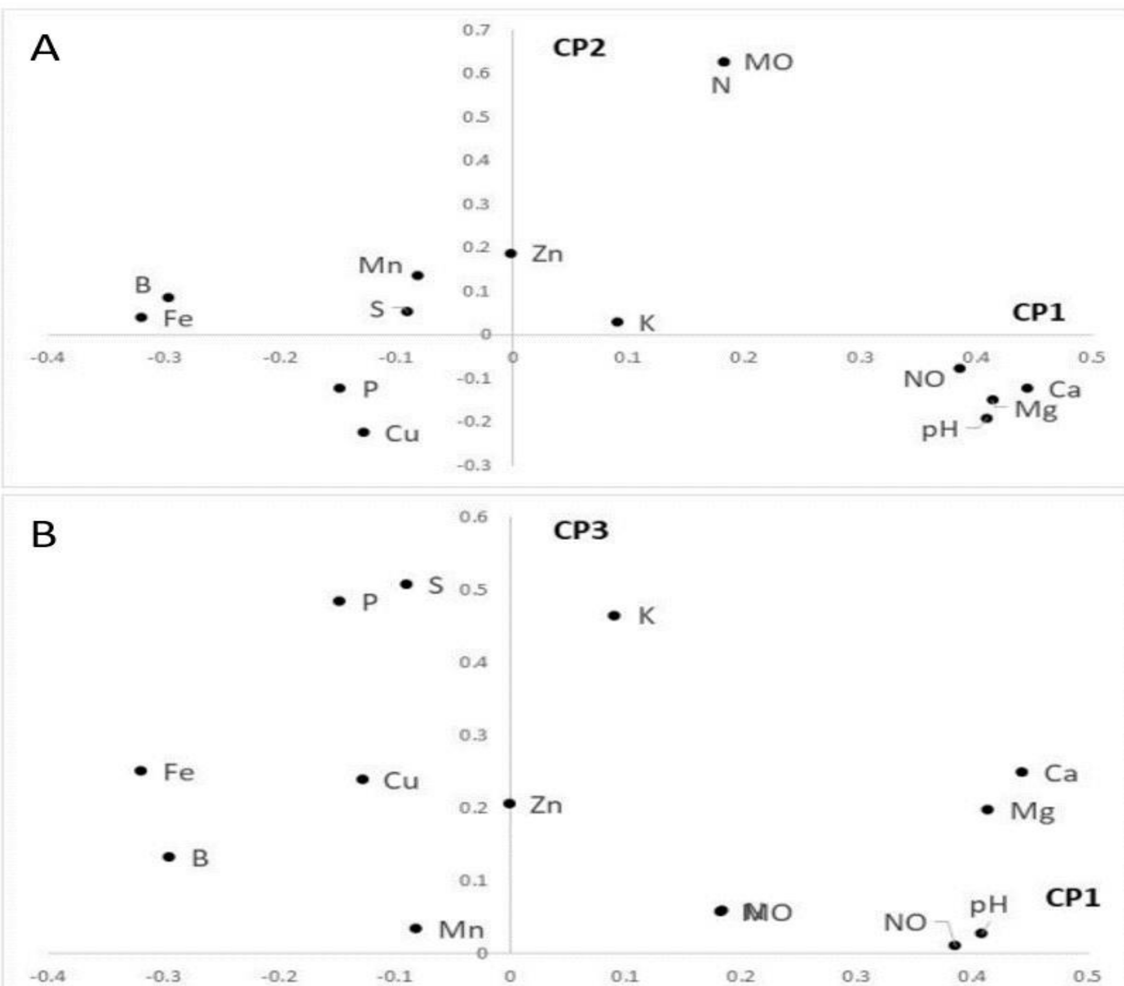

Figure 1. A: Contribution of the variables for CP1 and CP2; B: Contribution for CP1 and CP3.

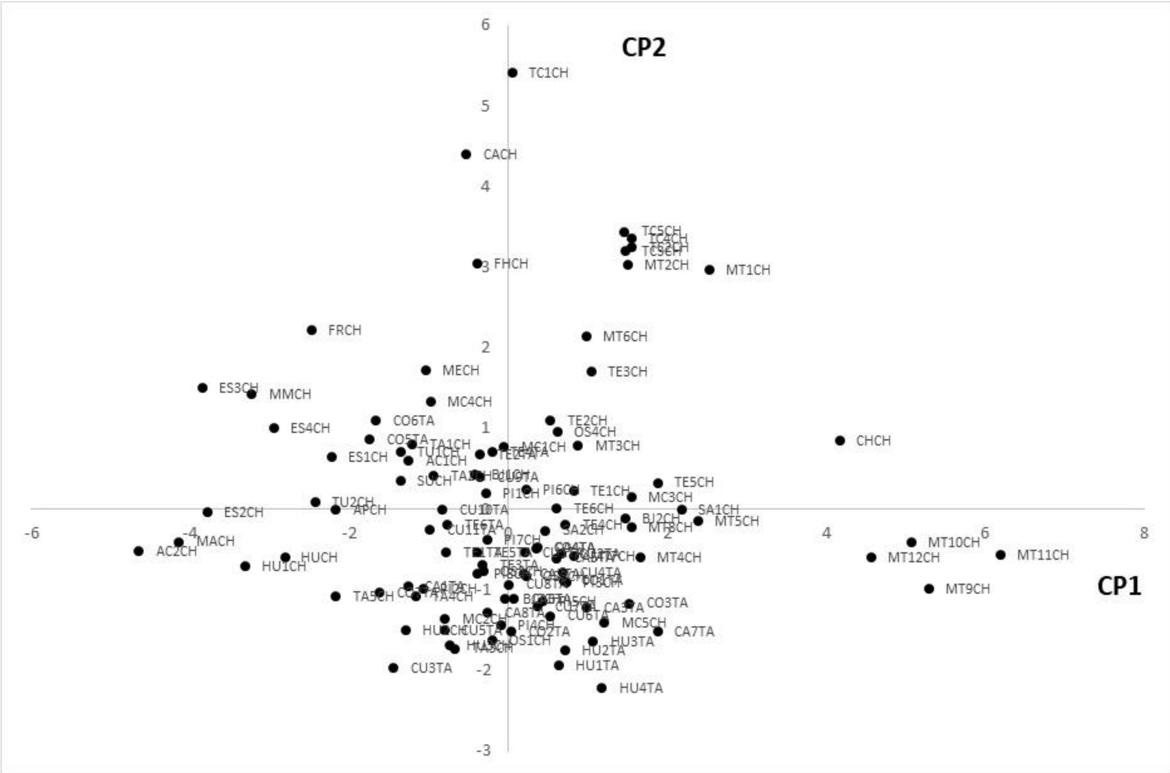

Figure 2. Dispersion of the 107 soil samples according to components CP1 and CP2.

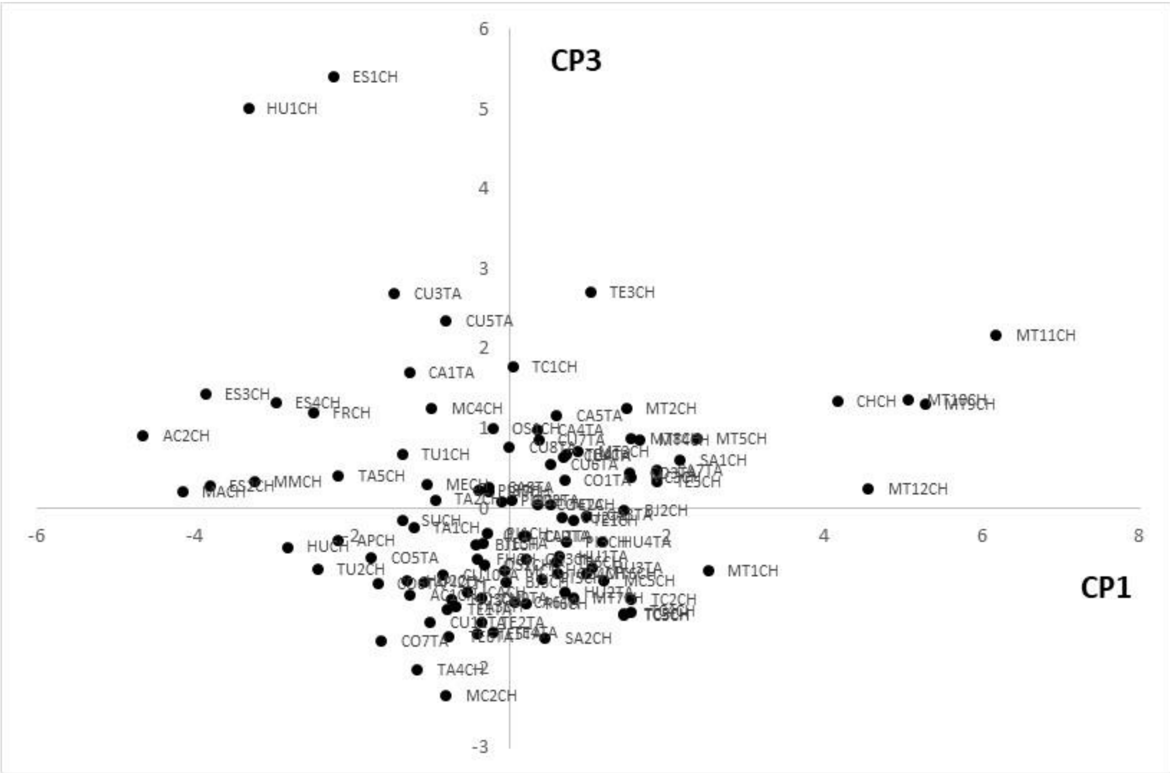

Figure 3. Dispersion of the 107 soil samples according to components CP1 and CP3.

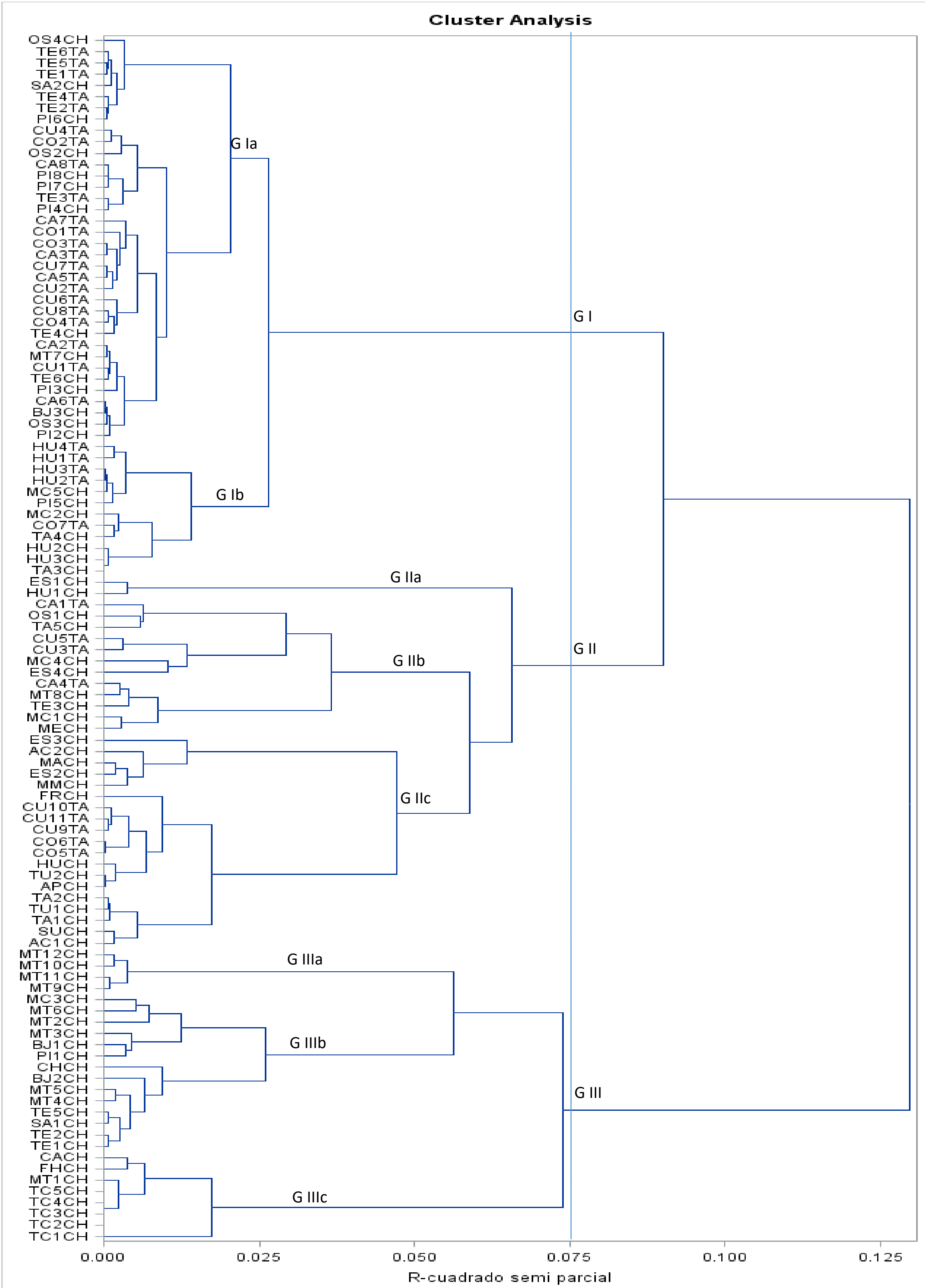

Figure 4. Dendrogram with complete data matrix. Note: Termination TA=Tabasco, CH=Chiapas

Table 3. Comparison of means of 15 variables in 107 soil samples from Chiapas and Tabasco, México.

Variables	Subgroups							
	Ia	**Ib**	**IIa**	**IIb**	**IIc**	**IIIa**	**IIIb**	**IIIc**
pH	6.3b c	6.5 b	5.3 d	6.3 bc	5.7 cd	7.3 a	6.5 b	6.2 bc
MO	2.59 c	0.74 c	2.80 c	3.14 c	2.88 c	4.85 b	4.42 b	9.11 a
NO	13.41 b	7.28 b	0.15 c	9.71 b	0.14 c	25.83 a	10.93 b	10.12b
N	90.55 c	26.38 d	98 c	110 c	100.8 c	170 b	155.2 b	318.7 a
P	40.5 c	27.9 c	207.5 a	100.3 b	24.3 c	10.6 c	19.4 c	5.46 c
K	191.5 d	241.6 d	810 a	277.5 cd	283.8 cd	519.4 b	475.7 bc	221.3 d
Ca	1979.9 c	1113.6 cd	5.8 d	1686.9 c	8.7 d	6671.5 a	3934.6 b	922.9 cd
Mg	397.6 bc	238.3 cde	1.3 e	285 cd	106.3 de	2409.3 a	584.4 b	112.8 de
S	33.05 b	31.82 b	328.4 a	27.96 b	39.04 b	43.03 b	16.91 b	40.94 b
Fe	56.78 bc	27.6 c	81.45 ab	82.08 ab	104.02 a	27.08 c	52.5 bc	38.4 c
Zn	1.49 bc	0.70 c	0.90 bc	4.97 a	1.90 bc	0.70 c	2.16 b	2.30 b
Mn	12.3 bc	7.77 bc	11.2 bc	12.5 bc	20.01 ab	3.38 c	28.18 a	8.22 bc
Cu	7.06 abc	2.40 c	8.20 ab	11.34 a	5.47 bc	3.13 bc	4.34 bc	1.56 c
B	0.10 b	0.10 b	0.1 b	0.12 ab	0.15 a	0.1 b	0.10 b	0.11 b
Altitude	93.4 c	61 c	50.5 c	190.6 bc	63.6 c	381 a	284.1 ab	376.5 a

The high production of cocoa leaves constitutes a reforestation system since it provides a large amount of organic matter through the leaf litter. OM is a natural nitrogen source from plant and animal remains (Schalatter et al., 2006). The OM is an edaphic variable that allows defining soil fertility since it favors physical fertility, reduces apparent density, and increases the infiltration rate, as well as the availability of nutrients (Cantú-Silva and Yáñez-Díaz, 2018), the IIIc subgroup with the majority of samples from Tuxtla chico and Cacahoatán, Chiapas, presented the highest values of MO (9.11) and N (318.79), which allows us to observe the correlation between the OM and the N present (Ramírez-Huila et al., 2016). On the other hand, subgroup Ib presented the lowest value of MO (0.74), and N (26.38) below what is recommended for cocoa, and the samples come from Comalcalco, Huimanguillo, Tabasco; Huehuetan, Marquez de Comillas, Pichucalco and Tapachula, Chiapas; the other subgroups are in the recommended OM range for cocoa (Table 3).

The most significant sources of P come from the mineralization of phosphate rocks, which, when weathered, decompose and release phosphates. These are absorbed by plants, subsequently by animals through ingestion, and finally return to the soil to be transformed into orthophosphates, through the microorganisms present (Ruttenberg, 2003). K, for its part, is one of the elements most in demand in cocoa (Reetz, 2016). Subgroup IIa presented the highest values of P and K (207.5 and 810 kg/ha, respectively). The samples come from Escuintla and Huehuetán, Chiapas, and subgroup IIIc with the lowest values of P (5.46 kg/ha) with samples mainly from Tuxtla chico, Chiapas and subgroup Ia for K (191.53 kg/ha), with samples from Tabasco (Conduacán, Teapa and Cárdenas) and Chiapas (Pichucalco and Tecpatán) (Table 4). The husk is the part that has a high requirement in K; this could be one of the reasons why these soils have had a lower presence of this element. The husk is usually discarded due to its potential to cause fungal diseases (Pascual-Cordova et al., 2017; Castillo et al., 2018).

Subgroup IIIa, where all samples are from Maravilla Tenejapa, Chiapas, presented the highest values of Ca (6671.5 ppm) and Mg (2409.3 ppm), and subgroup IIa the lowest values of Ca (5.8 ppm) and Mg (1.3 ppm); two samples from Escuintla and Huehuetán, Chiapas (Table 4). *Ca* is an element usually found in high concentrations in cocoa plantations. This is usually a nutrient that is little required by the cocoa plant, so it is found in high quantities in certain regions (Pascual-Cordova et al., 2017; Singh et al., 2019). Mg is also usually found in high concentrations due to the contribution of this element, which is made by tree litter (Furcal-Beriguete, 2017).

When analyzing the S concentration, subgroup IIa presented the highest values (328.49 ppm) and IIIb the lowest (16.91 ppm), the latter with samples from Chiapas (Maravilla Tenejapa, Marquéz de Comillas, Pichucalco, Tecpatán and Salto de Water) (Table 4). Regarding Fe, subgroup IIc, with samples from Chiapas, presented the highest value (104.02 ppm) IIIa and c, and Ib the lowest value (Table 6). Subgroup IIb, with samples from Tabasco and Chiapas, presented the highest value of Zn (4.97 ppm), and subgroups IIIa and Ib with the lowest value (0.7 ppm). The highest Mn value (28.18 ppm) was for subgroup IIIb and the lowest (3.38) for subgroup IIIa (Table 4).

Concerning Cu, the highest value (11.34 ppm) is located in subgroup IIb with samples from Tabasco and Chiapas, and the lowest value (1.56 ppm) in subgroup IIIc with samples mainly from Tuxtla, Chico, Chiapas (Table 7). Finally, B is an element used to promote flowering and reduce the effect of some viral and fungal diseases in cocoa plants (Krauss and Soberanis, 2002). It has been reported that the foliar application of this element during the flowering of the cocoa plant favors tolerance to the cocoa swollen shoot virus disease (Kouadio et al., 2017) was highest in the IIc subgroup and lowest in IIIa with samples from Maravilla Tenejapa, Chiapas (Table 4). The highest altitude of the plots was for subgroup IIIa of Maravilla Tenejapa, Chiapas, and the lowest for Escuintla and Huehuetán (Table 4).

The characterization of the groups carried out using this methodology on the chemical properties and nutritional concentration of the soils of Chiapas and Tabasco, referenced with the standards reported in the specialized literature for the sustainable production of the cocoa agroecosystem in the world, confirm that its chemical characteristics of pH and MO, the reference standards show the following ideal values for this production system: pH (5.5-7.0) and MO (2.93-5.52). Likewise, concerning the macronutrients (N, P, K, Ca, Mg and S) determined in these soils, they are located within the ideal reference standards for the sustainable production of cocoa in these entities: N (105- 280 kg/ha), P (32-48 kg/ha), K (234-938 kg/ka), Ca (800-3600 ppm), Mg (110-488 ppm) and S (>50 ppm), (Wessel, 1971; Ritung et al., 2007; Njukeng and Baligar (2016); PBI, 2015; McDonald, 1934). Also, these references indicate that the concentrations of micronutrients are ideal in the cocoa agroecosystem of Chiapas and Tabasco: Fe (19-45 ppm), Zn (3-12 ppm), Cu (0.4-1.80 ppm), Mn (0.5-2.20 ppm), B (0.16-0.90 ppm) and Al (9-133 ppm). Based on the results, except for some values on the chemical properties (pH and MO), as well as the macronutrients and micronutrients, of the soils in this agroecosystem, supported by this classification system within the framework of their pedological properties, and compared with reference standards, both systems confirm that the cocoa agroecosystem in Mexico maintains ideal conditions for its sustainable production.

CONCLUSIONS

The cocoa soils of Mexico present nutritional ranges primarily according to the requirements of cocoa. Likewise, the nutrients that systematically differentiate the cocoa soils of Mexico are pH, NO, Ca, Mg, Fe, B, MO, NI, Zn, Mn, Cu, P, K, and S.

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Competing interests. The authors declare no competing interests.

Compliance with ethical standards. This work does not require approval by a bioethical committee.

Data availability. Data is available with the corresponding author upon reasonable request.

Author contribution statement (CRediT). CH Avendaño-Arrazate: Writing – original draft and Visualization; **M. Alonso-Báez, PA Ruíz-Cruz and LJ Gómez-Godínez:** Writing – review & editing; **CH Avendaño-Arrazate, M. Alonso-Báez, PA Ruíz-Cruz and LJ Gómez-Godínez:** Data curation, Formal Analysis, Investigation.

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Supplement 1. Location of soil samples used in the study.

Acronym	State	Municipality	X	Y	Altitude
TC1CH	Chiapas	Tuxtla Chico	590658.5	1655363	433
TC2CH	Chiapas	Tuxtla Chico	590658.5	1655363	433
TC3CH	Chiapas	Tuxtla Chico	590658.5	1655363	433
TC4CH	Chiapas	Tuxtla Chico	590658.5	1655363	433
TC5CH	Chiapas	Tuxtla Chico	590658.5	1655363	433
AC1CH	Chiapas	Acacaoyagua	536672	1701221	398
SUCH	Chiapas	Suchiate	582086	1618980	19
TA1CH	Chiapas	Tapachula	571924	1643444	60
APCH	Chiapas	Acapetahua	530773	1692492	34
FHCH	Chiapas	Frontera Hidalgo	587577	1635447	83
HU1CH	Chiapas	Huehuetan	559941	1657255	17
ES1CH	Chiapas	Escuintla	528280.3	1944550.5	84
FRCH	Chiapas	Frontera	587577	1635447	83
CACH	Chiapas	Cacahoatan	586167	1658130	500
MMCH	Chiapas	Mariano Matamoros	519563.8	1945615.8	154
ES2CH	Chiapas	Escuintla	525848.9	1944393.6	54
ES3CH	Chiapas	Escuintla	528280.3	1944550.5	84
TU1CH	Chiapas	Tuzantan	558966	1669483	33
TU2CH	Chiapas	Tuzantan	558966	1669483	33
HUCH	Chiapas	Huixtla	554524	1666228	19
MECH	Chiapas	Metapa	586045	1637418	91
MACH	Chiapas	Papastepec	514271	1700423	29
ES4CH	Chiapas	Escuintla	536672	1701221	398
AC2CH	Chiapas	Acacoyagua	530773	1692492	34
TA2CH	Chiapas	Tapachula	571924	1643444	65
TA3CH	Chiapas	Tapachula	571924	1643444	48
TA4CH	Chiapas	Tapachula	571924	1643444	78
HU2CH	Chiapas	Huehuetan	559941	1657255	28
HU3CH	Chiapas	Huehuetan	559941	1657255	32
TA5CH	Chiapas	Tapachula	571924	1643444	84
TE1CH	Chiapas	Tecpatan	532465.9	1896245.1	310
MT1CH	Chiapas	Maravilla Tenejapa	319477.2	1794758.1	264
TE2CH	Chiapas	Tecpatan	534483.8	1896180.7	480
PI1CH	Chiapas	Pichucalco	483362	1938473	155
PI2CH	Chiapas	Pichucalco	487607	1939430	78
MT2CH	Chiapas	Maravilla Tenejapa	314009.1	1784889.8	492
MT3CH	Chiapas	Maravilla Tenejapa	318352.5	1793433.2	318
PI3CH	Chiapas	Pichucalco	506594.3	1941679.9	38
PI4CH	Chiapas	Pichucalco	513181	1935079.1	121
PI5CH	Chiapas	Pichucalco	514174.6	1939480.4	60
PI6CH	Chiapas	Pichucalco	516702	1938554.3	164
TE3CH	Chiapas	Tecpatan	534902.9	1896482.6	509
MT4CH	Chiapas	Maravilla Tenejapa	307664.4	1796663.1	226
TE4CH	Chiapas	Tecpatan	532709.3	1893608.8	465
OS1CH	Chiapas	Ostuacan	536442	1926423	268
SA1CH	Chiapas	Salto De Agua	402206.6	1917580.5	150
TE5CH	Chiapas	Tecpatan	535165.2	1896854.9	480
TE6CH	Chiapas	Tecpatan	532573.9	1897022.7	334
MT5CH	Chiapas	Maravilla Tenejapa	322245	1791452.4	283
SA2CH	Chiapas	Salto De Agua (Huim)	402206.6	1917580.5	150
OS2CH	Chiapas	Ostuacan	535976.4	1926145.6	153
OS3CH	Chiapas	Ostuacan	535976.4	1926145.6	153
MT6CH	Chiapas	Maravilla Tenejapa	316925.3	1787911.8	459
MT7CH	Chiapas	Maravilla Tenejapa	680817	1790973	230

Acronym	State	Municipality	X	Y	Altitude
MC1CH	Chiapas	Marquéz De Comillas	275150.8	1787133.8	173
MT8CH	Chiapas	Maravilla Tenejapa	686826	1785025	516
MC2CH	Chiapas	Márquez De Comillas	278127.1	1783158.8	162
OS4CH	Chiapas	Ostuacán	542119.2	1930115.6	244
PI7CH	Chiapas	Pichucalco	534079.3	1938502.4	60
PI8CH	Chiapas	Pichucalco	513181	1935079.1	121
MC3CH	Chiapas	Márquez De Comillas	271480.2	1798490.1	145
BJ1CH	Chiapas	Benito Juárez	528280.3	1944550.5	84
MC4CH	Chiapas	Marquéz De Comillas	270860.5	1788075.9	161
MC5CH	Chiapas	Marquéz De Comillas	268836.1	1797881.4	180
BJ2CH	Chiapas	Benito Juárez	519563.8	1945615.8	154
CHCH	Chiapas	Chilón	399656.5	1906184.4	242
BJ3CH	Chiapas	Benito Juárez	525848.9	1944393.6	54
MT9CH	Chiapas	Maravilla Tenejapa	680817	1790973	230
MT10CH	Chiapas	Maravilla Tenejapa	686826	1785025	516
MT11CH	Chiapas	Maravilla Tenejapa	668386	1787333	460
MT12CH	Chiapas	Maravilla Tenejapa	318352.5	1793433.2	318
CU1TA	Tabasco	Cunduacán	536094.5	2007174.2	9
CU2TA	Tabasco	Cunduacán	531840.7	2004957	19
CO1TA	Tabasco	Comacalco	539475.7	1997260	18
CU3TA	Tabasco	Cunduacán	520897.2	2005719.7	7
CA1TA	Tabasco	Cardenas	538118.9	1984506.2	30
CO2TA	Tabasco	Comalcalco	462347	2012860	8
CA2TA	Tabasco	Cardenas	538467.7	1994138.6	19
CU4TA	Tabasco	Cunduacán	535413.6	2006767.2	7
CA3TA	Tabasco	Cárdenas	537085	1994609.2	21
CA4TA	Tabasco	Cárdenas	539024.7	1986060	32
CO3TA	Tabasco	Comalcalco	521200.4	2015969.5	11
CU5TA	Tabasco	Cunduacán	531840.7	2004957	19
CO4TA	Tabasco	Comalcalco	521371.7	2009764.7	13
CA5TA	Tabasco	Cárdenas	537747	1994337	18
CA6TA	Tabasco	Cárdenas	538631.2	1999188.4	28
CA7TA	Tabasco	Cárdenas	537747	1994337	16
CA8TA	Tabasco	Cárdenas	538631.2	1999188.4	28
HU1TA	Tabasco	Huimanguillo	459038	1974972	25
TE1TA	Tabasco	Teapa	491095	1935817.4	96
HU2TA	Tabasco	Huimanguillo	541933.1	1973868.2	53
CU6TA	Tabasco	Cunduacán	519610.6	2002402.3	12
TE2TA	Tabasco	Teapa	490399.1	1935654.8	100
HU3TA	Tabasco	Huimanguillo	459038	1974972	25
CU7TA	Tabasco	Cunduacán	535462.8	2000712.9	20
TE3TA	Tabasco	Teapa	486131.5	1934501.8	235
CU8TA	Tabasco	Cunduacán	535706.5	2000842.4	20
TE4TA	Tabasco	Teapa	489938.3	1939988.1	90
TE5TA	Tabasco	Teapa	498558.5	1941045.8	94
TE6TA	Tabasco	Teapa	491095	1935817.4	116
HU4TA	Tabasco	Huimanguillo	540962.6	1974926.5	36
CO5TA	Tabasco	Comalcalco	462042	2012627	6
CO6TA	Tabasco	Comalcalco	462347	2012860	8
CO7TA	Tabasco	Comalcalco	475089	1999388	5
CU9TA	Tabasco	Cunduacán	475164	1999907	18
CU10TA	Tabasco	Cunduacán	465200	2006740	59
CU11TA	Tabasco	Cunduacán	464966	2007286	19