Article

Edaphoclimatic zoning of cacao cultivation in the state of Chiapas

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Abstract

The state of Chiapas is the second largest cacao producer in Mexico; however, agricultural yields are low, and in many regions, there are limits related to edaphoclimatic factors. Therefore, the research aimed to identify edaphoclimatic areas that meet the requirements of cacao, based on achieving a higher yield in the state of Chiapas. The methodology used was founded and designed as a simplified form of the general methodology of FAO and based on methodological proposals made in coffee and cacao cultivation in other countries, with specific adaptations to the specific conditions and existing information of Chiapas. The edaphoclimatic conditions characterizing four categories of zoning (optimal, medium optimal, acceptable and unsuitable), represented on maps at 1:100 000 scale, were determined. A total area of 1 549 804.4 ha with different productive potentials was identified, representing 20.08% of the total area of the state and distributed in 59 municipalities. Of these, 34 have no history of cultivation, indicating the possibilities of exploring new areas for it. Extreme temperatures (low and high) and the physical properties of the soil were the main limiting factors for cacao development and occupy the largest unsuitable area of the state. From a practical point of view, the results are a tool for making decisions on a wide scale for the establishment of cacao cultivation in Chiapas.

Keywords: *Theobroma cacao* L., areas, climate, municipalities, soils.

Reception date: March 2021
Acceptance date: June 2021

Introduction

Cacao (*Theobroma cacao* L.) is a plant grown in several countries around the world for its food and medicinal qualities (Mcfadden, 2008). However, despite this importance, production levels do not yet satisfy the demands of the product. In Mexico, a decreasing trend in production has been observed in the last 10 years. It is concentrated in the states of Tabasco, Oaxaca and Chiapas. The latter ranks second in production after Tabasco, with an average of 9 707 t and a yield of 0.47 t ha^{-1} (SIAP, 2018).

Environmental, technological, economic and social factors have influenced these results and they are aggravated by phytosanitary problems such as diseases that destroy entire plantations (Hernández-Gómez *et al*., 2015). From an environmental point of view, changes that occur with climate patterns and transformations in soil properties make it possible for many areas to lose conditions for cacao development in correspondence with their edaphoclimatic requirements. The foregoing brings with it a lack of compatibility between edaphoclimatic conditions and cacao requirements, as a result of improper use of the soil. Such a situation constitutes a problem to be consider in the design of research to increase current cacao yields (Suárez *et al*., 2015).

Particularly in Chiapas, the traditional regions in the development of cultivation are in the North, Central, Soconusco and Northern-Jungle zones. These plantations have been developed with criteria of the traditional culture and without criteria of zoning studies that scientifically validate the conditions of these areas and that allow the proper planning of the land. Therefore, it is currently possible to find areas with aptitudes for the development of cultivation that are not exploited, or areas where cultivation has been developing for a long time with loss of its aptitudes. The latter condition means less possibilities of obtaining the potential yield according to the characteristics of agrosystems.

To solve these problems, different studies have been carried out for land use planning through agroecological zoning (AEZ) and edaphoclimatic zoning (ECZ) of crops (FAO, 1997). In these topics, the most significant works that have been carried out in Mexico are those of Puebla *et al*. (1991); Villa *et al*. (2001); Pérez and Geissert (2006); Martínez *et al*. (2007); Rivera *et al*. (2012); Hernández *et al*. (2014); González *et al*. (2015); Espinosa-García *et al*. (2015). The objective of this research was to identify edaphoclimatic zones that meet the requirements of cacao cultivation, in order to achieve higher yields and achieving a process of more effective decision-making in the state of Chiapas.

Materials and methods

Location and selection of the study area

The research was carried out in the state of Chiapas, Mexico (Figure 1). It is in southeastern Mexico; it adjoins the state of Tabasco to the north, Veracruz and Oaxaca to the west, the Pacific Ocean to the south, and the Republic of Guatemala to the east. To the north 17° 59’, to the south 14° 32’ north latitude; to the east 90° 22’, to the west 94° 14’ west longitude. It has a total area of 77 148.263 km^2, which represents 3.8% of the national territory (Gobierno de Chiapas, 2019).

Figure 1. Location of the state of Chiapas.

Methodological design

The general research scheme was developed as a simplified form of FAO's general methodology (1997) and based on the methodological proposals made by Soto *et al*. (2001) for the cultivation of coffee and Suárez *et al*. (2015) for cacao cultivation, specifically adapted to the specific conditions of the state of Chiapas, level of information and scale of work.

To do this, annual rainfall (mm), average annual temperature (°C) and groups of soils with their natural properties were considered. In this context, the basis for edaphoclimatic zoning for cacao according to Suárez *et al*. (2013) were considered, which was determined by the expert criterion, for which the Delphi methodology described by Linstone and Turrof (1975) was applied.

According to the methodological scheme used, an edaphoclimatic characterization of the state was performed and the representation of climate and soil characteristics with different aptitudes for the development of cacao cultivation was obtained. From the combinations of the thematic maps, the map resulting from the edaphoclimatic zoning of cacao for the state of Chiapas was developed at 1: 100 000 scale, according to the criteria of the bases of zoning in four categories: optimal, medium optimal, acceptable and unsuitable.

The delimitation of these zones was generated with the use of ArcGIS 9.3 as a geographic information system (GIS) that facilitated the manipulation and overlaying of layers of thematic information of relief, climate and soil.

Edaphoclimatic database

For the specific case of the climate, existing annual rainfall information and minimum and maximum temperatures of 30 years (1986-2016) were collected from the CONAGUA database (2018). It was digitized and represented according to the criteria defined in the bases of zoning for cultivation.

The soil information base used was that existing in the state's National Institute of Statistics and Geography (INEGI). This contains geospatial information that shows the distribution of the main soil groups in the national territory, as well as physical, chemical and limiting attributes, according to the world reference base for soil resources of FAO (IUSS, WRB, 2015). From this same source, basic relief information was also obtained using topographic information from a digital elevation model (DEM) that served to delimit the altitude levels of the territory.

Results and discussion

Climatic characterization of the state of Chiapas according to the edaphoclimatic zoning of cacao to evaluate the availability or climatic limitations of a given region, it is essential to characterize in quantitative terms the behavior of the different elements of the climate. According to Köppen's classification modified by García (1973), the predominant climate in the Chiapas region is of type Af (tropical wet with rain all year long) and Am (tropical wet with rain in summer).

Rainfall

The northern region of the state presents rains all year long, in the rest of the state rains abound in summer. The total annual rainfall varies, depending on the region, between 1 200 and 4 000 mm, as well as large extensions with a rainy season (May-October) and a dry (November-April) perfectly defined (Figure 2).

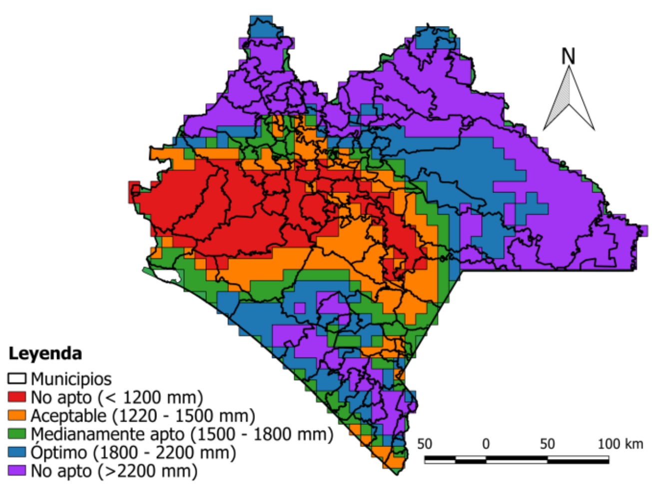

Figure 2. Map representing the average annual precipitation according to aptitude criteria for cacao cultivation in the state of Chiapas, Mexico.

Rainfall ranging from 1 800 mm to more than 2200 mm occurred in 21.56% of the territory, with an annual average of 2 100 mm, extreme precipitation values suitable for cacao growth and development. However, in most of the total state area (56.87%) a compatible rainfall level for the normal growth and development of cacao was recorded (González, 2008).

In the northern part coinciding with the Central American mountain range and areas of the range of Chiapas and Guatemala, maximum extreme rainfalls were recorded with values between 3 000 and 4 000 mm, which makes possible an excess of moisture and a rainfall regime that do not meet the requirements for the normal development of cultivation. The above is related to altitude levels above 750 m. The opposite was recorded in the southern coastal plain where the average annual rainfalls do not exceed 800 mm, creating moisture deficit conditions for cultivation.

Temperature

The average annual temperature also varies depending on the region, from 18 ºC in the Highlands of Chiapas, to 28 ºC in the Coastal Plain, with the highest average temperature of 30 ºC and the minimum of 17.5 ºC (Figure 3).

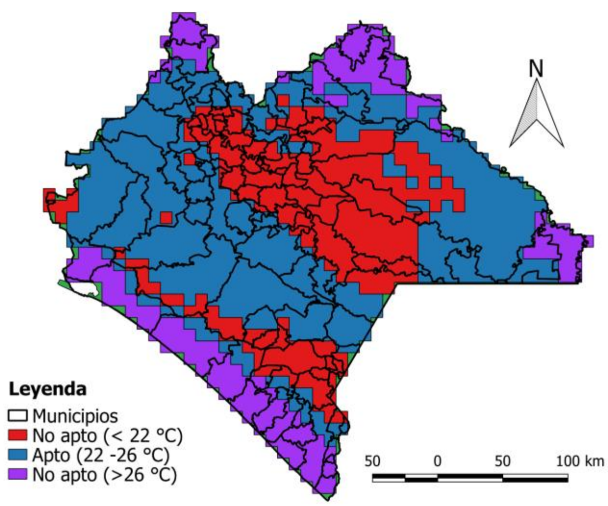

Figure 3. Map representing the average temperature according to aptitude criteria for cacao cultivation in the state of Chiapas, Mexico.

It has hot zones with average temperatures above 23 ºC and without large thermal oscillations and semi-hot areas at an altitude between 800 and 1 550 m above sea level, with constant temperatures of 20 ºC. There are also temperate areas popularly called cold, located above 1 500 masl, in which the temperature oscillates between 12 and 15 ºC and the summit of the Tacaná volcano that has a cold climate, as it is above 4 000 meters above sea level.

In 45.2% of the total area of the territory, temperatures between 22 ºC and 26 ºC, with an annual average of 24.8 ºC, were recorded. These values correspond to the behavior of this variable in the main cacao production areas in the world. Therefore, on this area this climatic variable meets the requirements of the crop since it requires an optimal average monthly temperature of 25 ºC.

In this regard, Gómez and Azócar (2002) reported that the overall monthly average temperature range for cacao cultivation ranges from 15 ºC to 30 ºC, with an average value of 25.5 ºC. Alvim (1984) reported that cacao flowering occurs from 21 ºC, with an optimum of 25.5 ºC. On the other hand, Ramos and Gómez (2004); Batista (2009) agree that these temperature values are optimal to ensure regular growth of the tree, with abundant formation of flowers and fruits, adequate distribution of bud sprouting and new leaves during the year.

However, despite what was explained above, in most of the territory (54.8%), extreme temperature values for the crop were recorded, either below 22°C coincident with altitudes above 850 m or above 28°C in the lower areas of the north and south of the territory, becoming a limiting factor for cacao production in the state.

Soil characterization of the state of Chiapas depending on the zoning of cacao cultivation

To perform the soil characterization in this territory according to the edaphoclimatic zoning of cacao, it is important to recognize the soil requirements of the crop. In cacao, as it is perennial crop, soil selection is the greatest responsibility at the stage of its establishment and is essential to obtain high productivity.

Espinal *et al*. (2005) reported that cacao requires soils with two opposite characteristics in the same group: moisture retention in a low rainy period, and at the same time good drainage in rainy season, in addition to being deep soils. These characteristics are determined by the nature of these, mainly by their physical characteristics. Consequently, the selection of soil groups that meet these requirements is of vital importance for the determination of zones for cacao development.

Of the 15 soil groups classified by the IUSS, Working Group WRB (2015), nine groups predominate in the state of Chiapas and of them only four satisfy the soil requirements of cacao (Figure 4). This is related to climatic characteristics and the relief, as they determine the pedogenetic process of soils (Zavala-Cruz *et al*., 2014).

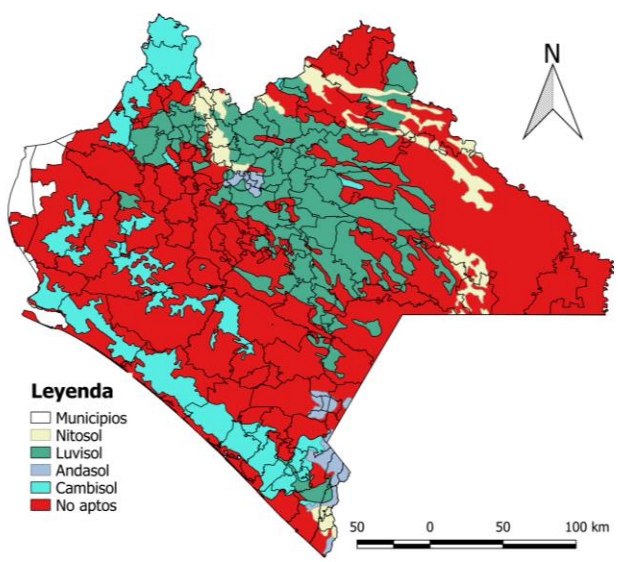

Figure 4. Map representing the distribution of soils according to cacao cultivation requirements in the state of Chiapas, Mexico.

The existing soil groups in Chiapas compatible with the requirements of cacao are: Cambisol, Luvisol, Nitosol and Andosol (Figure 4). Their main characteristics according to the requirements of the crop are described below.

Cambisol: it includes an area of 953 037 ha that represents 12.35% of the total state area. Due to their pedogenesis, they have good structure and depth, essential requirements for cacao cultivation. Besides, washing of important nutrients does not happen, since given their youth and thickness they treasure many alterable minerals that detach from their mother rock with the processes of weathering.

Luvisol: it consists of an area of 1 525 695 ha which means 19.77% of the total state area. It is the fifth most important group of soils for its territorial extension in Mexico and the first group of soils in Chiapas (INEGI, 2017).

Most Luvisols are referred to as fertile soils and generally have a high degree of base saturation. A good part of the Luvisols in Mexico is red (38.1%), poor in calcium and magnesium (24.8%) but with high organic carbon content (more than 1% in the first 50 cm deep). In this soil predominates the presence of sand, characteristic that provides rapid drainage, beneficial characteristic for cacao cultivation. Research developed by Gómez-González *et al*. (2018) for the cultivation of coffee in Chiapas characterized this type of soil with an argic B horizon, CIC greater than 24 $cmol^+ kg^{-1}$ of clay and a saturation of bases greater than 50%.

Nitisol: it encompasses an area of 367 891.9 ha which means 4.76% of the total state area. They have high structural stability and are considered fertile soils despite their low content of assimilable phosphorus and their low saturation in bases. They are deep, stable and with favorable physical properties for cacao cultivation (Working Group WRB, 2015).

Andosol: it covers an area of 118 751.6 ha which means 1.53% of the total state area. They have adequate effective depth for the development of the cacao root system. They are generally fertile soils, particularly Andosols that develop on intermediate or basic volcanic ash and not exposed to excessive washing of their nutrients. Their main limitation is the high capacity to fix phosphates caused by active aluminium; however, this effect can be minimized with the application of organic matter and phosphate fertilizer (Working Group WRB, 2015).

Each of these soil units has associations of morphodynamic processes, determined by the effects of physical and chemical weathering of the climate that has effects on the primary pedogenetic processes (Working Group WRB, 2015). Therefore, in the territory under study, these soils comply with different regularities in their geographical distribution, which determines the area they occupy.

According to the vertical geographical zonality scheme of the soils in this territory, these are located at different altitudes with predominances of different climate conditions that, together with the relief, vegetation, time and material of origin as soil forming agents, may have influenced this distribution (Hernández *et al*., 2006).

However, at the same time these can constitute the limiting factors of the environment that limit productivity in many agro-systems, limiting factors that are observed reflected in those groups of soils not selected for the development of cultivation.

Existing soil groups in the state that were not selected for cacao (Acrisol, Leptosol, Regosol, Solonchak, Vertisol) cover an area of 4 749 451.4 ha, which means 61.5% of the total state area and have the major limiting factors of agroproductivity that affect the normal development of cultivation in the state, compared to those that were selected.

In the particular case of the Acrisols, the main limitations for cultivation are their strong acidity and low saturation of bases caused by their strong alteration. Mineral nutrient poverty, aluminum toxicity, strong phosphate adsorption and high susceptibility to erosion are the main restrictions on their use.

Regarding the toxicity of aluminum, Hernández *et al*. (2006) indicated that when the amount of this element in the soil solution reaches concentrations greater than 1 $cmol^{+}$ kg^{-1}, the direct implications for plant growth due to intoxication are noticeable. Moreover, Vera *et al*. (2000) stated that this cation may limit the successful development of cacao due to its effects on mineral nutrition and root growth of the plant. The roots become thicker and have dead spots. If it accumulates in the roots, it prevents the absorption and transfer of calcium and phosphorus to the aerial part, causing deficiencies of these elements in the plant.

Leptosols are a type of soil that predominates in escarpments and rocky outcrops. Its thickness is less than 10 cm and supports a low vegetation, therefore, its shallow depth and high stoniness limit the development of cacao. In Regosols, the evolution of the profile is minimal as a result of their youth. Therefore, its poor evolution gives it negative characteristics to be used in the cultivation of cacao due to physical and chemical limitations.

Solonchaks soils have as their main limiting their saline character. They are found in arid or semi-arid regions. They have a very low usability, only for plants tolerant of salt, an aspect not compatible with the requirements of the crop. The Vertisol type has a high content of expansive and heavy clay minerals, among them many montmorillonites, which form deep cracks in dry seasons. These become very hard in the dry season and very plastic in the wet season. Therefore, although its natural fertility is high, its heavy textural composition makes possible its incompatibility with the demands of cacao.

Edaphoclimatic zoning for cacao in the state of Chiapas, Mexico

The results of the combination between the climatic and soil zones appropriate to the requirements of cultivation, considering the bases of the defined zoning for cacao, originated the edaphoclimatic zones which are represented in Figure 5 and their distribution in the municipalities in Table 1.

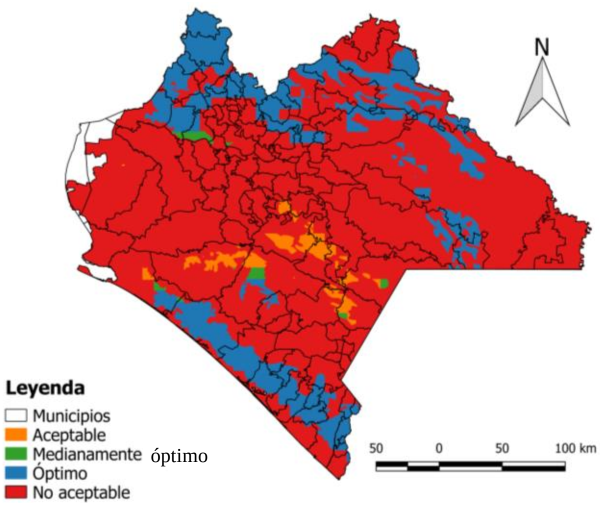

Figure 5. Map representing the edaphoclimatic zoning for cacao cultivation in the state of Chiapas, Mexico.

Table 1. Municipalities with areas represented by some category of edaphoclimatic zoning for cacao in the state of Chiapas, Mexico.

Number of municipalities by category with aptitudes for cacao development	Municipalities
Optimal zones (48)	A. Albino Corzo, Acacoyagua*, Acapetagua*, Amatán, Cacahoatán*, Chalchihuitán, Chapultenango, Chenalhó, Chilón, Escuintla*, F. de León*, F. Hidalgo*, Huehuetán*, Huitiupán, Huixtla*, Ixtapangajoya*, Ixtacomitán*, Juárez*, La Concordia, La Libertad, La Margaritas*, M. Tenejapa, Mapastepec*, Metapa*, Motozintla, Ocosingo, Ostuacán*, Palenque*, Pantheló, Pichucalco*, Pijijiapan, Reforma, Sabanilla, Salto de agua*, Simojovel, Sitalá, Solosuchiapa, Suchiate*, Tapachula*, Técpatan*, Teopatán, Tila, Tonalá, Tumbalá, Tuxtla Chico*, Tuzantán*, Unión Juárez and V. Comatitlán*.
Medium-optimal zones (7)	Coatilla, Copainalá, Chicomuselo, F. Comalá, La Trinitaria, Técpatan* and Tonalá*
Acceptable zones (11)	Chicomuselo, F. Comalá, La Concordia, La Trinitaria y La Rosa, Socoltenango, Tzimol, Tonalá, Totolapa, V. Carranza and Villa Corzo

*= municipalities with a history in cacao production in the state of Chiapas, Mexico.

Optimal zone: it comprises an area of 1 349 461.4 ha in the state, representing 17.50% of the total area in Chiapas. Of the 118 municipalities that constitute the state, this category is represented in 35 municipalities, being Tuxtla Chico, Metapa, Tuzantán, Yajalón, Iztapangajoya, Reforma and Juárez the municipalities with 100% of their surfaces represented in this category. Cacao plantations that develop on these areas can achieve a yield greater than 2 t ha^{-1} if the technological factor is not a limitation for production.

On the other hand, all municipalities that currently grow cacao are represented in this category, which corroborates the appropriate edaphoclimatic conditions for cultivation in these municipalities and validates the results obtained in this research.

Medium optimal zone: it encompasses an area of 40 343 ha in the state, representing 0.52% of the total area in Chiapas. Areas belonging to seven municipalities are represented, of which Técpatan is the only one with a history in the development of cacao cultivation. Cacao plantations that develop on these areas can yield between 1 and 0.99 t ha^{-1} if an adequate level in crop management is maintained.

Acceptable zone: it covers an area of 160 000 ha in the state, representing 2.07% of the total area in Chiapas. Areas belonging to eleven municipalities are represented, none of which has a history in the development of cacao cultivation. Within this category, the municipalities Chicomuselo, Frontera Comalá, La Trinitaria and Tonalá share it with one or another identified category. Potentially, cacao plantations that develop on these areas can achieve a yield between 0.5 and 0.99 t ha^{-1} with adequate technological management.

Unsuitable zone: it encompasses an area of 6 165 021.9 ha in the state, which represents 69.91% of the total area in Chiapas. Of the 118 municipalities that constitute the state, this category is represented in 59 municipalities, none of which has a history in the development of cacao cultivation. The main limitations of this zone that restrict the development of cultivation are the extreme temperatures (high or low) motivated by the altitude above sea level and the physical properties of the soil. These limiting conditions occupy the largest area in the state (Figure 3 and 4), so the potential yield for this area is very low, whose values are planned below the limits to make a plantation economically profitable.

In general, in the state of Chiapas there are 1 549 804.4 ha with climate and soil characteristics suitable for the development of cacao cultivation, which means 20.08% of the state territory with different yields and potentialities. The results described differ from those obtained by Espinosa-García *et al*. (2015), who determined a total of 3 691 000 ha with potential to produce cacao in the state using the SWAT program as a hydrological model that is applied at the basin level in nine states of the South-southeast of Mexico.

Cacao is currently grown in 25 municipalities in the state, with the largest area and municipalities in the Soconusco region which, because of its tropical climate, is one of the regions where cacao has been cultivated since ancient times. However, the results of this research made it possible to distinguish edaphoclimatic potentialities for cacao establishment in 59 municipalities with different productive potential. This indicates the existence of new areas with aptitudes for cultivation that are in 34 municipalities with no history in its production. Only the municipalities of Mazatan and Sunuapa with a history of cultivation are not represented in edaphoclimatic areas with some category of aptitude.

From a practical point of view, the results make available to producers and decision-makers a useful tool in the location of cacao in appropriate edaphoclimatic zones to increase current yields. Nevertheless, as the scale of work used is broad, these do not allow decision-makers to take measures for the establishment of cultivation at the local level, but it contributes to planning actions and work programs at the municipal and state level for the redistribution of planting areas.

The location of cacao in areas with adequate climate and soil conditions constitutes one of the agricultural strategies to promote precision agriculture and helps to face the challenges of the changes that currently occur in some global climate patterns and affect agriculture (Valdés and Vargas, 2011). In this context, cacao plantations are sites with high capacity to capture carbon dioxide (CO_2) and release oxygen (O_2) due to the large amount of biomass it produces and its habit of growth. Therefore, the establishment of cultivation in places where growth and development are more efficient will contribute to confronting the effects of climate change.

The methodology used in this research has enabled the identification of zones with different aptitudes for cacao cultivation in the state of Chiapas to collaborate with the decision-making process on a broad scale on their establishment and support for development plans for cultivation. Through it, the methodological foundations used by FAO (1997) and methodologies used in this and other regions in the country have been simplified.

In this regard, most authors have used the edaphoclimatic criteria for studies of agroecological zoning of crops, among them the research carried out in agroforestry systems in Mexico by Pérez and Geissert (2006); Rivera *et al*. (2012) in the cultivation of cassava (*Manihot sculpted* Crantz) in the state of Tabasco, Mexico, stand out. However, not all soil and climatic variables have the same weight when defining the appropriate zones for locating a crop, due to the relationship between themselves and between them with the applied technologies.

It is recommended that these results be used to facilitate the design of public policies that consider increasing new plantations or reordering cacao areas. Likewise, in the decision-making process this information must be superimposed with the current use of land to delimit risk zones, matching zones and zones that have infrastructure uses.

Conclusions

An area of 1 549 804.4 ha with different productive potential for the development of cacao cultivation was identified, which represents 20.08% of the total territory of the state of Chiapas and located in areas of 59 municipalities, of which 34 have no history with cultivation. Extreme temperatures (low and high) related to the relief and physical properties of the soil were the main limiting factors for the development of cacao cultivation in Chiapas and occupy the largest area with the unsuitable category in the state.

From a practical point of view, the results are a tool to collaborate with the broad-scale decision-making process on the establishment of cacao cultivation as a crop of economic importance for the state of Chiapas.

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