Article

Potential geographical distribution of papaya wild cultivated in Mexico

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Abstract

The wild populations of papaya (*Carica papaya* L.) integrate a biological resource for the genetic improvement of the species. The prediction of the geographical distribution of wild and cultivated populations is a useful tool to determine collection sites for their use and conservation. With the objective of estimating the potential distribution of papaya in Mexico, a database with geo-reference information of wild and cultivated papaya individuals was elaborated, then the maximum entropy algorithm (MaxEnt) was applied with 22 bioclimatic variables as predictors. The total area of potential distribution of the wild specimens was 114 546.5 km^2, the high potential areas were located in the Gulf of Mexico (south of Veracruz, Tabasco, Campeche) and on the coast of Chiapas. The cultivated papaya presented a high potential distribution in three zones: south of Veracruz, coast of Chiapas and north of Guerrero, forming 185 396.9 km^2. The variables that contributed most in the model to estimate the potential distribution of wild papaya were: average minimum temperature of the coldest period (33%), average annual temperature (20%) and soil moisture regime (13%), for the distribution of cultivars the most important variables were: average minimum temperature of the coldest period (41%), rainiest semester precipitation (19%) and annual precipitation (11%). The environmental factors temperature and rainfall, were common in the prediction of distribution of both types of papaya in Mexico.

Keywords: maxent, phytogenetic resource, potential distribution.

Reception date: July 2018
Acceptance date: September 2018

Introduction

In Mexico, the family Caricaceae is represented by eight species of the genera *Carica*, *Horovitzia*, *Jacaratia*, *Jarilla* and *Vasconcellea* (Villaseñor, 2016). The species *Carica papaya* L. is a clade confined to Mexico and Guatemala, whose wild populations are strictly dioecious (male and female plants), in contrast, the cultivated ones are trioecious (males, females and hermaphrodites) (Carvalho and Renner, 2012). The morphological differences of varieties and races, with respect to wild ones, are evident mainly in fruit characteristics (Fuentes and Santamaria, 2014; Manshardt, 2014).

Papaya is located east of Mesoamerica, from the Yucatan peninsula (Mexico) to Costa Rica (Scheldeman *et al*., 2011). It is assumed that it was the Spaniards, in the sixteenth century, who expanded their distribution beyond Mesoamerica (Manshardt, 2014). In Mexico, the presence of wild and cultivated papaya has not been documented in seven states of the republic (Baja California, Mexico City, Coahuila, Durango, Guanajuato, Nuevo Leon and Tlaxcala), of the 32 states, in accordance with the Botanical listings published by Villaseñor (2016). Wild populations are regularly found in the lowlands of those states bordering the Gulf of Mexico (Tamaulipas, Veracruz, Tabasco, Campeche), the Peninsula (Campeche, Yucatan and Quintana Roo) and on the border with the Pacific Ocean (Guerrero, Oaxaca and Chiapas) (Chávez and Núñez, 2016), characterized by warm climates.

In order to determine the distribution of wild populations of plant species, computational algorithms have been developed that, based on climatic and edaphic geographic information systems, offer the possibility of characterizing, identifying and representing ecological niches with greater probability of finding them (Phillips *et al*., 2004), in addition, of having multiple applications in the field of conservation, such as the identification of areas and zones for species with conservation problems (Hernandez-Ruiz *et al*., 2016; Qin *et al*., 2017). In this sense, knowing the potential distribution of the species, it is feasible to generate conservation actions, define ecological zones of dispersion or selection of germplasm to be included in genetic improvement programs (Scheldeman and van Zonneveld, 2010), which may be important for economically important species such as *Carica papaya*.

The FloraMap software has been applied to determine distribution zones of species of the genus *Vasconcellea* (Caricaceae), to subsequently collect reproductive material and define patterns of adaptation in certain geographic regions in Venezuela (Rodríguez *et al*., 2005). With a similar objective, for 21 species of this same genus the DIVA-GIS software has been used, including 19 climatic variables and 1 702 georeferenced sites in Central and South America (Scheldeman *et al*., 2007). However, it is considered that with the MaxEnt method it is feasible to model the potential distribution of a species, given that it ignores sampling bias and predicts the potential geographic distribution with plant presence data, supplemented with variable continuous and categorical predictors (Scheldeman and van Zonneveld, 2010; Merow *et al*., 2016).

In this sense, by knowing the geographical distribution of the genetic and morphological diversity of *Carica papaya* L., the foundations are laid for the collection of populations, especially wild, which are a source of useful genes to improve the yield and nutritional quality of the fruits in commercial cultivars (Rodríguez *et al*., 2014). For this reason, in the present work the objective of estimating the potential distribution of cultivars and wild populations of papaya in Mexico was proposed using the MaxEnt prediction computation algorithm.

Materials and methods

Database

A database with geographic locations indicating the presence of *C. papaya* L. in various sites in Mexico was developed in the Excel spreadsheet for Windows (version 10), according to Scheldeman and van Zonneveld (2010). Individuals of wild and cultivated papaya were georeferenced in the states of Guerrero, Oaxaca, Veracruz, Tabasco and Chiapas. The information was collected with field trips in the period from 2013 to 2016, using the Garmin® portable geographic location system, model GPSMAP 64s. The morphological identification of the wild and cultivated papaya was made based on the botanical descriptions of Moreno (1980). Also, 20 georeflection data of papayas present in several states of Mexico were included (Hernández, 2013).

Potential distribution model

The MaxEnt program version 3.3.3 (Phillips *et al*., 2017) was used to develop the analyzes according to the type of papaya: wild and cultivated (races, varieties and hybrids). In total, 390 georeferenced sites with presence of wild populations (208) and cultivars (182) were used in the analyzes. The number of sites analyzed with presence of the species (390) was considered as a sufficient sample size, since Baldwin (2009) indicates that the gain in prediction of geographical distribution is acceptable with a sample size greater than 50 georeferenced sites of the species under study.

The 22 climatic variables were used as predictors (Table 1), of which 19 were spatial resolution bioclimatic of 0.5 arc minutes and were obtained from the WorldClim database (www.worldclim.org). The digital elevation data (DEM, with 90 m resolution) was obtained from the CGIAR-CSI (http://srtm.csi.cgiar.org). The layers in vector format of land use and vegetation were taken from the National Commission for the Knowledge and Use of Biodiversity (CONABIO, 1998), and the soil moisture regime of Maples (1992). The last three variables used were considered because they are important factors of the physical space in which the species lives (Challenger and Caballero, 1998). Agricultural and livestock areas were also discarded in the estimation of potential distribution.

Table 1. Environmental and bioclimatic variables used to determine the potential geographic distribution of *C. papaya* L. in Mexico.

Code	Description of variable	Units
BIO01	Annual average temperature	(°C)
BIO02	Daytime temperature oscillation	(°C)
BIO03	Isothermality	Adimensional
BIO04	Seasonality of temperature	CV
BIO05	Average maximum temperature of the warmest period	(°C)

Code	Description of variable	Units
BIO06	Average minimum temperature of the coldest period	(°C)
BIO07	Annual temperature oscillation	(°C)
BIO08	Average temperature of the rainiest four-month period	(°C)
BIO09	Average temperature of the driest four-month period	(°C)
BIO10	Average temperature of the warmest four-month period	(°C)
BIO11	Average temperature of the coldest four-month period	(°C)
BIO12	Annual rainfall	(mm)
BIO13	Precipitation of the rainiest period	(mm)
BIO14	Precipitation of the driest period	(mm)
BIO15	Seasonality of precipitation	CV
BIO16	Precipitation of the rainiest four-month period	(mm)
BIO17	Precipitation of the driest four-month period	(mm)
BIO18	Precipitation of the warmest four-month period	(mm)
BIO19	Precipitation of the coldest four-month period	(mm)
BIO20	Altitude	(m)
BIO21	Soil moisture regimez*	Types
BIO22	Vegetation	Types

°C= centigrade, CV= coefficient of variation; *= for this data the Thornwaite climatic classification was taken where four soil moisture regimes are recognized in the Mexican territory: Aridic, Xeric, Ustico and Aquic.

Results and discussion

Potential distribution of wild papaya

The wild papaya is distributed in the rainforest of Mexico, and is located mainly in the secondary vegetation of the humid and sub-humid tropical forest (Paz and Vázquez, 1998). In addition to the bioclimatic factors, its distribution in Central and South America has been favored by the abundant amount of seeds produced by the plants and the prolonged viability of the seeds (Paul and Duarte, 2011).

In this analysis, the potential distribution, based on the registry of 208 individuals from wild populations, generated two zones of high probability of finding this type of papayas: 1) The southeast of the Gulf of Mexico, including the state of Veracruz, Tabasco, Campeche and a part to the north of the state of Chiapas, mainly. In these areas the habitat quality for the species is low to moderate (Figure 1). The ecological zone is humid tropical, predominantly humid warm climate, average annual temperature greater than 22 ºC and temperature of the coldest month greater than 18 ºC. The precipitation of the driest month is less than 60 mm, rainfall in summer and percentage of winter rain greater than 10.2% of the annual total, average annual rainfall in a range of 1 500 to 2 000 mm per year; and 2) The Pacific coasts of the state of Chiapas have a moderate to high habitat quality. The ecological zone corresponds to humid tropical, where the climate is warm subhumid with average annual temperature greater than 22 ºC and temperature of the coldest month greater than 18 ºC.

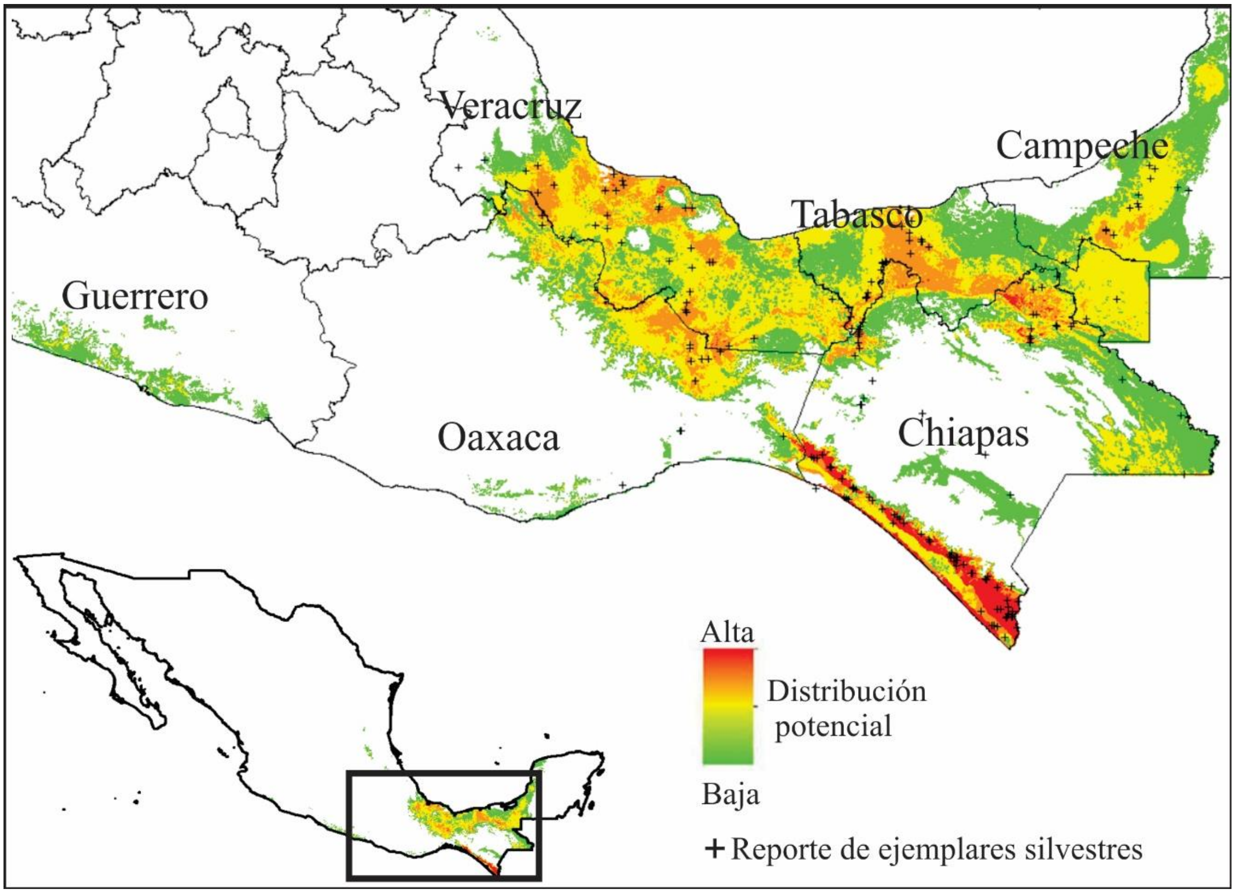

Figure 1. Potential distribution of wild populations of *Carica papaya* L. High distribution areas are indicated in red, with gradual decrease in probability to a low level of green. The white areas indicate non-potential areas.

The analyzes also indicated the existence of potential zones of smaller size on the coast of Oaxaca (15 172.14 km^2); similarly, in the Costa Chica, Costa Grande, Centro, Norte and Tierra Caliente regions of Guerrero, which together comprise 3 171.91 km^2; also in Yucatan (2 487.66 km^2). However, in these areas the habitat quality for the species was classified as low.

Finally, smaller isolated areas were located in San Luis Potosi (954.89 km^2), Tamaulipas (170.22 km^2), Colima (120.03 km^2), and Jalisco (82.16 km^2), where characteristics of the subhumid tropic also prevail.

The total area of potential distribution for wild specimens was 114 546.5 km^2. The largest potential area was located (Table 2) in three states that contributed 69.1%: Chiapas (25%), Veracruz (27.6%) and Campeche (16.5%). In Chiapas, Chavez and Nuñez (2016) report the distribution of wild papaya in the regions bordering Tabasco, and point out the effects caused by agriculture and livestock on the structure of the vegetation where the wild papaya survives.

Table 2. Area (%), by federative entity of the Mexican Republic, of the potential areas for the development of wild and cultivated populations of *C. papaya* L.

State	Wild	Accumulated	State	Cultivars	Accumulated
Veracruz	27.6	27.6	Chiapas	25.7	25.7
Chiapas	25	52.6	Veracruz	17.5	43.2
Campeche	16.5	69.1	Guerrero	16.7	59.9
Oaxaca	13.2	82.3	Oaxaca	14.6	74.5
Tabasco	11.6	93.9	Campeche	9.8	84.3
Guerrero	2.8	96.7	Michoacán	5.6	89.9
Yucatan	2.2	98.9	Tabasco	3.8	93.7
San Luis Potosi	0.8	99.7	Jalisco	2.3	96
Colima	0.1	99.8	San Luis Potosí	1.6	97.6
Jalisco	0.1	99.9	Baja California Sur	1.2	98.8
Tamaulipas	0.1	-	Colima	0.4	99.2
Baja California Sur	0	-	Quintana Roo	0.4	99.6
Michoacan	0	-	Nayarit	0.1	99.7
Nayarit	0	-	Sinaloa	0.1	99.8
Quintana Roo	0	-	Sonora	0.1	99.9
Sinaloa	0	-	Yucatán	0	-
Sonora	0	-	Tamaulipas	0	-
Total	100%			100%	

In wild the total area (100%) was= 114 546.5 km^2; in cultivars the total area (100%) was= 185 396.9 km^2; - = non-contributory state to the distribution.

On the other hand, the zones of high probability of geographical distribution of wild papaya populations, defined in this study, are located partially in the priority regions of biodiversity conservation of Mexico published by Arriaga *et al*. (2000), as with other groups that have been analyzed for potential distribution (Villaseñor and Téllez, 2004), so it is important to validate the potential distributions with observations in the field. In Oaxaca, the areas of potential distribution of wild papaya coincide with priority region number 130 (Sierra del Norte de Oaxaca-Mixe) and 132 (Jungle Zoque-La Sepultura); in Veracruz with the priority regions (RP) 124 (Wetlands of Papaloapan) and 131 (Sierra de los Tuxtlas-Laguna del Ostion); in Chiapas with RP 133 (El Triunfo-La Encrucijada-Palo Blanco) and 135 (Tacana-Boquerón); in Tabasco with RP 142 (El Manzanillal), 143 (Lagunas de Catazaja-Emiliano Zapata) and 144 (Marshes of Centla).

However, there are potential distribution areas, determined in this study, that are not included in any region with conservation priority; for example, in Los Tuxtlas, Veracruz, Chávez *et al*. (2014) highlight that wild papaya populations survive in fragments of vegetation with less genetic diversity than populations present in areas of continuous vegetation; they also report that agricultural and livestock activities cause isolation of populations and put at risk the persistence of natural populations in their ecological niche. For example, in Costa Rica the papaya that develops in areas with disturbance and secondary vegetation, can present a genetic bottleneck (Brown *et al*., 2012). This indicates that the potential distribution areas of wild papaya in Mexico, which are not included in federal protection zones, are exposed to anthropocentric activities that could alter the structure of their genetic reservoir.

Potential distribution of cultivars

It is important to note that the distribution of cultivated papaya has been favored with agricultural management and the economic benefits obtained; In this sense, agronomic technology has focused on increasing the yield of fruit and promoting the best environmental conditions for the development of plants (Guzmán *et al*., 2010). In this way, the varieties of papaya, which have emerged from a process of genetic improvement, are established as a commercial crop in five leading Mexican states: Oaxaca, Chiapas, Colima, Veracruz and Michoacán (SIAP, 2016). In addition to varieties, over time farmers have developed some native varieties that propagate in home gardens or on agricultural land (Paz and Vázquez, 1998). For example, the types known as 'papaya zapote', 'papaya oreja de mico', 'papaya amarilla', 'papaya de monte', are present in home gardens in communities of Yucatán, Campeche and Tabasco, given their food use (Mariaca, 2012). Inclusively, Moo *et al*. (2017) indicate that in Mexico there is a process of substitution of native varieties for varieties arising from genetic improvement; for example, by the Maradol variety.

According to the results of the present study, papaya cultivation has potential in 15 states, but the largest area was located in Chiapas (25.7%), Veracruz (17.5%) and Guerrero (16.7%), which together accounted for almost 60% of the total surface (Figure 2). These zones have distinctive characteristics of a humid tropical ecological zone, with a predominant humid warm climate, an annual average temperature higher than 22 ºC and a temperature of the coldest month higher than 18 ºC. The precipitation of the driest month is less than 60 mm, rainfall in summer, amount of winter rain greater than 10.2% of the annual total and average annual rainfall is in the range of 1 500 to 2 000 mm per year.

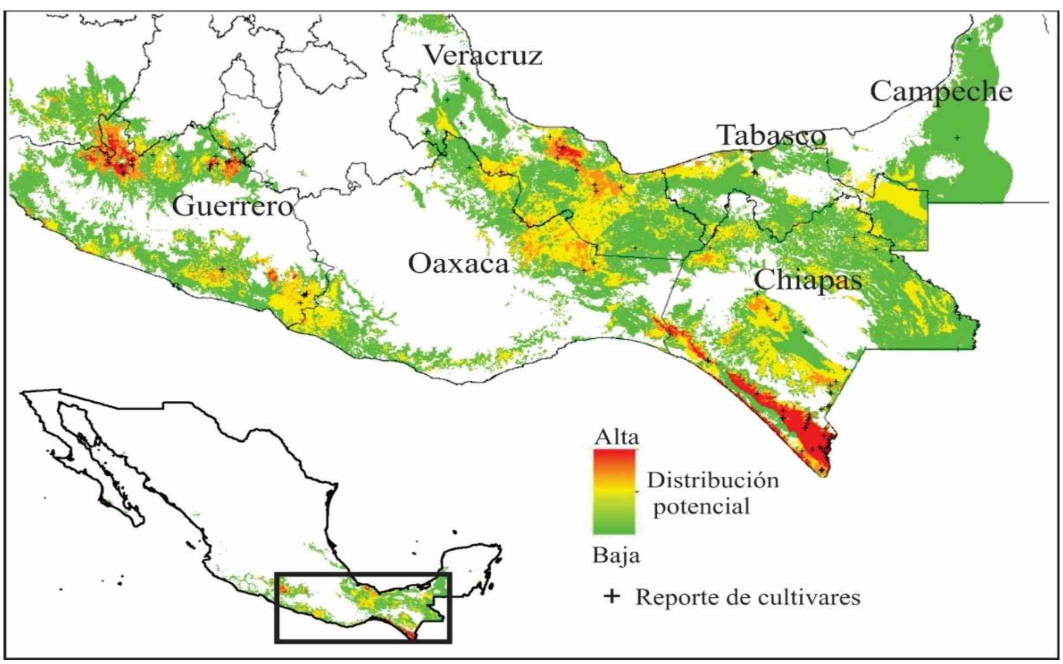

Figure 2. Potential distribution of cultivars of *Carica papaya* L. High distribution areas are indicated in red color, with gradual decrease of the probability to a low level of green color. The white areas indicate non-potential areas. The black dots are the geo-referencing sites.

Other potential areas of the crop, of smaller size and with low ecological quality were located in the states of Baja California, Sonora, Sinaloa, Nayarit, Jalisco, San Luis Potosi and Michoacan (image not presented) as a whole, these areas added 11.8% of the total potential distribution area of papaya cultivars (Table 2).

Climatic variables and potential distribution

Of the 22 climatic and soil variables, used as predictors in the MaxEnt model of geographic distribution of wild populations and cultivars, eight were the most important to explain the distribution of *Carica papaya* in Mexico (Table 3). The variables annual average temperature (BIO01), average minimum temperature of the coldest period (BIO06), annual precipitation (BIO12) and precipitation of the rainiest four-month period (BIO16) were common predictors of the distribution of cultivated and wild papaya. In relation to this, Scheldeman *et al*. (2007) determined that *C. papaya* is better adapted in high temperature niches (24.2 ºC in average) with little seasonal variation, and high rainfall (1 830 mm). On the other hand, Bradie and Leung (2017) establish that temperature and precipitation are environmental variables that contribute the most in the distribution of terrestrial plant species.

Table 3. Contributions (%) of the bioclimatic variables in the MaxEnt model for the distribution of wild and cultivated populations of *Carica papaya* L. in Mexico.

Variable	Contribution for wild (%)	Accumulated (%)	Variable	Contribution for cultivars (%)	Accumulated (%)
BIO06	33	33	BIO06	41.4	41.4
BIO01	20.1	53.1	BIO16	19	60.4
BIO21	13.5	66.6	BIO12	11	71.4
BIO11	10.7	77.3	BIO19	5.1	76.5
BIO16	7.8	85.1	BIO04	4.5	81
BIO12	2.4	87.5	BIO13	2.3	83.3
BIO05	2.2	89.7	BIO01	2.2	85.5
BIO20	2.1	91.8	BIO18	2.2	87.7

In the case of wild papayas, the variables that contributed more than 75% of their distribution were: average annual temperature (BIO01, with 20.1%), average minimum temperature of the coldest month (BIO06, 33%), average temperature of the colder four-month period (Bio11, 10.7%) and humidity regime (BIO21, 13.5%). In general, it is notorious that the distribution of wild papaya is influenced by the low temperature, the soil moisture regime and the level of rainfall.

For papaya cultivars, the variables of greatest importance for their distribution were: average minimum temperature of the coldest month (BIO6, with 41.4%), precipitation of the rainiest four-month period (BIO16, 19%), annual rainfall (BIO12, 11 %) and precipitation of the coldest four-month period (BIO19, 5.1%). This indicates that the distribution of papayas grown in the potential regions will be influenced, in greater magnitude, by the level of rainfall and low temperatures.

In the present study, the average minimum temperature of the coldest period (BIO 6) was the variable that most participated in the definition of potential areas in both wild populations and cultivars. In addition, the climatic variables that contributed substantially to the distribution of the wild were BIO01 (average annual temperature) and BIO21 (soil moisture regime), while for the cultivars were BIO16 (precipitation of the rainiest four-month period) and BIO12 (rainfall annual).

The temperature influences the germination of papaya seeds, when in the soil it oscillates between 29.5 ºC and 29.8 ºC during the summer (Saran *et al*., 2016). The growth of the plant in height and diameter of the stem is adequate with temperatures above 20 ºC (Allan, 2002). Temperatures below 10 °C and above 35 °C are related to fruit and flower development disorders (Workneh *et al*., 2012).

The moisture deficit in the soil triggers the mechanism of osmotic adjustment in the tissue of papaya seedlings and the arrest of growth (Mahouachi *et al*., 2006). Such moisture deficiencies in the soil, in combination with high temperature (> 37 °C), have a negative impact on the photosynthetic process (Liu *et al*., 2014). This affects even the wild types of papaya (Díaz *et al*., 2014).

In addition, it was notorious that rainfall was a relevant bioclimatic variable in the potential distribution of papaya cultivars. For its cultivation the availability of water is important, given that the plants produce 1.8 to 2.8 kg of fresh fruit per cubic meter of water applied (Carr, 2014). However, excess water in the soil, for at least one day, causes problems due to lack of oxygen in the root system (Thani *et al*., 2016).

Conclusions

The analysis of the potential geographic distribution of *Carica papaya* L., using the algorithm Maxent, allowed delimiting two distribution zones of the wild types, with a medium to high probability, the first region in the Gulf of Mexico that included the south of Veracruz, northeast of Oaxaca, center of Tabasco, north of Chiapas and southwest of Campeche; a second one comprised the coast of the state of Chiapas. These five states contributed 93.9% of the potential total area of wild papayas. The algorithm also identifies three areas of potential distribution, with high probability, of papaya cultivars: a first zone in the south of Veracruz, the second in the north of the state of Guerrero and the third on the coast of the state of Chiapas. These three states comprised 59.9% of the potential total area of papaya cultivars. The climatic variables that contributed between 53% and 60% of the prediction capacity of the potential geographic distribution were: average minimum temperature of the coldest period of the year, average annual temperature and precipitation of the rainiest four-month period of the year.

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