*Artículo Científico*

Rev. Fitotec. Mex. Vol. 43 (4): 389 - 397, 2020

# ECOLOGICAL NICHE OF SEMIDOMESTICATED POPULATIONS OF *Capsicum pubescens* RUIZ & PAV. BASED ON ACCESSIONS FROM VERACRUZ, MEXICO

# NICHO ECOLÓGICO DE POBLACIONES SEMIDOMESTICADAS DE *Capsicum pubescens* RUIZ & PAV. CON BASE EN ACCESIONES DE VERACRUZ, MÉXICO

**Ricardo Serna-Lagunes[1], Pablo Andrés-Meza[1]*, Otto R. Leyva-Ovalle[1], José L. Del Rosario-Arellano[1], Miguel Merino-Valdes[1], Joaquín Murguía-González[1], Ma. Elena Galindo-Tovar[1], Jaime Mejía-Carranza[2], Mauro Sierra-Macías[3], Alejandro Espinosa-Calderón[4], Margarita Tadeo-Robledo[5] y Juan Del Rosario-Arellano[1]**

[1]Universidad Veracruzana, Facultad de Ciencias Biológicas y Agropecuarias, Amatlán de los Reyes, Veracruz, México. [2]Universidad Autónoma del Estado de México, Centro universitario Tenancingo, Tenancingo, Estado de México, México. [3]Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (INIFAP), Campo Experimental Cotaxtla, Medellín de Bravo, Veracruz, México. [4]INIFAP, Campo Experimental Valle de México, Texcoco, Estado de México, México. [5]Universidad Nacional Autónoma de México, Facultad de Estudios Superiores Cuautitlán, Cuautitlán Izcalli, Estado de México, México.

**Autor de correspondencia* (pandres@uv.mx)

## SUMMARY

To be able to cultivate a wild species it is necessary to modify the genetic scheme resulting from natural selection processes to one adapted to human-managed conditions, it implies to detect geographic areas similar to those where the species originated. This study analyzes a model of potential geographic areas for *Capsicum pubescens* Ruiz & Pav adaptation, aiming to detect the appropriate ecological niche conditions in Mexico, and to describe the relationships between the environment and the morphological characteristics of the fruit. The recent maximum entropy modeling algorithm (MaxEnt) was used to model the niche of *C. pubescens* within an important region in Central Veracruz, Mexico. A total of 44 sites of presence and four bioclimatic variables were used to detect adequate niches for the species; also, a partial least squares regression analysis was performed by combining presence sites, bioclimatic variables and morphological characteristics of the fruit. A final suitability map was built identifying the areas suitable for *C. pubescens* growth. The contributions of the predictor variables to the model were annual rainfall (Bio12) 43.9 %, potassium layer (K) 23 %, altitude (DEM) 22.3 % and mean annual temperature (Bio1) 10.7 %, with a value of area under the curve of 99.7 %. The partial minimum squares corroborated the importance of covariables, which intervene in the expression of morphological characteristics of the fruit, helping to better understand the relationships between species and the environment. Areas not yet explored had occurrence values over 90 %, mainly in the mountainous regions of Chihuahua, Tamaulipas, Nuevo Leon, and the Santa Martha Sierra in southern Veracruz. A group of outstanding accessions was identified that could serve as the basis to initiate a breeding program for this species.

Index words: *Capsicum pubescens*, bioclimatic gradients, deductive approach, maximum entropy, plant species management, species distribution models.

## RESUMEN

Para cultivar una especie silvestre es necesario modificar el esquema genético resultante de los procesos de selección natural a uno adaptado a las condiciones manejadas por el hombre, e implica detectar áreas geográficas similares a aquellas donde se originó la especie. En este estudio se analiza un modelo de áreas geográficas potenciales para la adaptación de *Capsicum pubescens* Ruiz & Pav. con el objetivo de detectar las condiciones de nicho ecológico apropiado, determinar zonas potenciales en México y describir las relaciones entre el medio ambiente y las características morfológicas del fruto. Se utilizó el algoritmo reciente de máxima entropía (MaxEnt) para modelar el nicho de *C. pubescens* dentro de una región de importancia en el centro de Veracruz, México. Se utilizó un total de 44 sitios de presencia y cuatro variables bioclimáticas para detectar nichos adecuados para la especie; así mismo, se realizó un análisis de regresión por mínimos cuadrados parciales (PLS) combinando los sitios de presencia, variables bioclimáticas y características morfológicas del fruto. Se construyó un mapa final de idoneidad identificando las áreas adecuadas para el crecimiento de *C. pubescens.* Las contribuciones de las variables predictoras al modelo fueron preipitación anual (Bio12) 43.9 %, capa de potasio (K) 23 %, altitud (DEM) 22.3 % y temperatura media anual (Bio1) 10.7 %, con valor del área bajo la curva de 99.7 %. Los mínimos cuadrados parciales corroboraron la importancia de las covariables, que intervienen en la expresión de características morfológicas del fruto, ayudando a entender mejor las relaciones entre especies y el medio ambiente. Áreas aún no exploradas arrojaron probabilidades de ocurrencia mayores a 90 %, principalmente en las zonas montañosas de Chihuahua, Tamaulipas, Nuevo León y la Sierra de Santa Martha al sur del estado de Veracruz. Se identificó un grupo de accesiones sobresalientes que podrían servir como base para iniciar un programa de mejoramiento genético en esta especie.

Palabras clave: *Capsicum pubescens*, enfoque deductivo, gradientes bioclimáticos, manejo de especies de plantas, máxima entropía, modelos de distribución de especies.

## INTRODUCTION

Genetic resources of wild species related to cultivated plants constitute a gene pool that can help to solve agricultural problems (Hernández-Verdugo *et al*., 1998). To be able to cultivate a wild species it is necessary to modify the genetic scheme resulting from natural selection processes to one adapted to human-managed conditions (Hernández, 1985). Such manipulation allows man to adapt biological diversity to the needs of human society (Casas and Caballero, 1995) and is carried out through artificial selection, which in parallel also results in the evolutionary

**Recibido:** 15 de Agosto de 2019
**Aceptado:** 19 de Agosto de 2020

process of domestication (Mastretta-Yanes *et al.*, 2019). For Gepts and Papa (2003), domestication is a continuous genetic selection process exercised by humans during the adaptation of plants and animals; this process generated morphological, physiological and genetic changes known as domestication syndrome (Gepts, 2005; Pickersgill, 2007).

Crops vary within and between species in their degrees of domestication. All known accessions of *Capsicum pubescens* have large fruits that have lost their dispersal mechanism, and this species occurs only in cultivation. The four other species of domesticated chili pepper each includes a range of variation from wild peppers, through cultivated peppers with somewhat larger fruits that are still capable of natural dispersal, to fully domesticated peppers with large fruits that remain firmly attached to the parent plant after maturity. Clement (1999) proposed two intermediate categories, incipiently domesticated and semidomesticated, to cover the spectrum of changes resulting from human interactions with species of tree fruits in Amazonia. Semidomesticated also fits the situation described by Casas *et al*. (1998) for *Stenocereus stellatus*, a giant cactus exploited and cultivated for its fruit in the Tehuacan Valley of Mexico. Casas (1998) considered that such changes in allele frequencies resulting from human selection constitute at least incipient domestication.

The *Capsicum* genus includes around 25 species belonging to the Solanaceae family (Meckelmann *et al*., 2015); of these, five species have been domesticated in at least two geographical regions of the new world (*C. annuum* and *C. frutescens* in Mesoamerica; *C. baccatum*, *C. pubescens*, and *C. chinense* in South America) (Loaiza-Figueroa *et al*., 1989; Pickersgill, 2007). Of the five domesticated species, *C. pubescens* Ruiz & Pav. is one of the main native species cultivated in the Andes (DeWitt and Bosland, 2009). Recent studies indicate that its cultivation and domestication began approximately 6000 years BC in the mid and high regions of Peru and Bolivia, at altitudes ranging from 1300 to 3000 masl (Ruiz and Pavon, 1799). *C. pubescens* is commonly known as "Rocoto" in Peru and "Locoto" in Bolivia (Meckelmann *et al*., 2015), and as "Manzano" and "Cera" in Mexico (Pérez-Grajales *et al*., 2004), due to its shape and appearance.

In Mexico, *C. pubescens* is distributed throughout the temperate areas of the states of Puebla, Michoacan, Mexico, Oaxaca and Veracruz. It is generally grown in production systems associated with fruit trees such as coffee (*Coffea arabica* L.), banana (*Musa* spp. L.), apple (*Malus domestica* Borkh.), peach (*Prunus persica* (L.) Batsch.), avocado (*Persea americana* Mill.), as well as some lumber species like cedar (*Cedrus* spp.) and ilite (*Alnus acuminata* Kunth.), among others. *Capsicum pubescens* is a perennial plant with purple flowers and hard-headed black seeds (Leyva-Ovalle *et al*., 2018). Its growth habit can be determined or undetermined, with trichomes in stems and leaves (Pérez-Grajales *et al*., 2004). Fruits vary greatly in size, shape and color (DeWitt and Bosland, 2009; Leyva-Ovalle *et al*., 2018; Rick, 1950; Yamamoto *et al*., 2013).

The fruits are rich in vitamins (A, C and B6), β-carotene, flavonoids, capsanthin, among others (Liu *et al*., 2013); also, the antioxidant properties of carotenoids protect against diverse heart diseases and cancer (Rodríguez-Burruezo *et al*., 2009). Likewise, the fruits can be dehydrated and used as a condiment in different dishes (Oboh *et al*., 2007). Because of this, the consumption of this fruit has grown in recent years as a consequence of increasing Latin American populations in the United States of America and Europe, as well as the increasing interest in functional foodstuffs (Pérez and Castro, 2008; Rodríguez-Burruezo *et al*., 2009).

There are few papers on the cultivation and distribution of *C. pubescens*, especially in Central America, where it has diversified. The influence of environmental, geographical, and soil conditions associated with its ecological niche is unknown; therefore, this study was carried out to elucidate the ecological niche conditions, to determine potential growing zones in Mexico, and to describe the possible relationships between the environment and the morphological characteristics of the fruit, as revealed by its current distribution.

## MATERIALS AND METHODS

### Study sites and data collection

The field work was carried out from October 2016 to March 2017 in 13 municipalities of the central region of the state of Veracruz, Mexico (Table 1, Figure 1). A total of 44 accessions of *C. pubescens* were obtained; the geographical coordinates of each site were registered to be used as occurrences to build the model.

### Characterization of *C. pubescens* fruits

Fifteen fruits at harvest maturity stage were collected from each site. Each of the fruits was morphologically characterized based on descriptors of the International Plant Genetic Resources Institute (IPGRI, 1995). Traits registered were length fruit (Lenfru) in cm, width fruit (Widfru) in cm, weight fruit (Wefru) in g, pedicel length (Lenped) in mm, wall thickness (Thfru) in mm, placental length (Lenpla) in cm, and number of seeds (Numsed).

A multivariate technique of partial least squares

**Table 1. Accessions evaluated in this study.**

| Id | Accesion | Municipality | Origin | Farmer name | Altitude | Latitude | Longitude |
|---|---|---|---|---|---|---|---|
| 1 | MEXUVDC1 | Coscomatepec | Dos caminos | Miguel Milian Ramos | 1454 | 19.04419 | -97.03058 |
| 2 | MEXUVCAL1 | Calcahualco | Calcahualco | Roberto Reyes M | 1762 | 19.12128 | -97.08269 |
| 3 | MEXUVCAL2 | Calcahualco | Calcahualco | Marcelino Espinoza de la Cruz | 1680 | 19.12000 | -97.07697 |
| 4 | MEXUVCAL3 | Calcahualco | Calcahualco | Marcelino Espinoza de la Cruz | 1708 | 19.11708 | -97.07697 |
| 5 | MEXUVCV1 | Calcahualco | Cruz Verde | Estanislao García | 1927 | 19.13417 | -97.10750 |
| 6 | MEXUVCV2 | Calcahualco | Cruz Verde | Remigia Ortiz Hernández | 1923 | 19.13306 | -97.10556 |
| 7 | MEXUVTE1 | Alpatlahuac | Teacalco | Manuela Martínez | 2570 | 19.11417 | -97.16556 |
| 8 | MEXUVCO1 | Alpatlahuac | Cocalcingo | Amalia Martínez | 1990 | 19.09272 | -97.10944 |
| 9 | MEUVTL1 | Alpatlahuac | Tlatelpa | David Dorantes | 1799 | 19.11667 | -97.08528 |
| 10 | MEXUVTEPE1 | Zongolica | Tepetitlanapa | José Ismael Vallejo Chimalgua | 1523 | 18.64172 | -97.01292 |
| 11 | MEXUVTEX1 | Texhuacan | Texhuacan | Matilde Tepole Xalamihua | 2019 | 18.62193 | -97.04673 |
| 12 | MEXUVBP1 | Mixtla de Altamirano | Barrio Primero | Evaristo Mayahua Flores | 1678 | 18.60077 | -96.99268 |
| 13 | MEXUVLA1 | Texhuacan | La Aposteca | Félix Cano Hernández | 1431 | 18.61490 | -97.00960 |
| 14 | MEXUVCG1 | Chocamán | Colonia la Garita | Anonymous | 1332 | 19.00816 | -97.02664 |
| 15 | MEXUVBJ1 | Coscomatepec | Barranca de Jamapa | María Antonia Tentle Morales | 1365 | 19.09937 | -97.03216 |
| 16 | MEXUVTEP1 | Huatusco | Tepampa | Francisco Huerta Ballona | 1716 | 19.13524 | -97.02220 |
| 17 | MEXUVTEP2 | Huatusco | Tepampa | Lázaro Huerta Rodríguez | 1743 | 19.14219 | -97.02421 |
| 18 | MEXUVTEN1 | Huatusco | Tenejapa | Anonymous | 1404 | 19.13699 | -97.00624 |
| 19 | MEXUVTEN2 | Huatusco | Tenejapa | María Luisa Sánchez Marinero | 1373 | 19.13587 | -97.00200 |
| 20 | MEXUVTZ1 | Tehuipango | Tzacoala Primero | Agustina Calihua Panzo | 2090 | 18.53895 | -97.07902 |
| 21 | MEXUVTLA1 | Tehuipango | Tlalchichilco | Pascuala Panso Chipahua | 2369 | 18.54041 | -97.05128 |
| 22 | MEXUVTLA2 | Tehuipango | Tlalchichilco | Pascuala Panso Chipahua | 2369 | 18.54041 | -97.05128 |
| 23 | MEXUVTE2 | Alpatlahuac | Teacalco | Alejandro Gómez | 1825 | 19.10950 | -97.09961 |
| 24 | MEXUVTL2 | Alpatlahuac | Tlatelpa | David Dorantes | 1803 | 19.11697 | -97.08578 |
| 25 | MEXUVCO2 | Alpatlahuac | Cocaltzingo | María Martínez | 1968 | 19.09156 | -97.10953 |
| 26 | MEXUVBV1 | Tepatlaxco | Buena Vista | Roberto Sánchez Hernández | 1457 | 19.04153 | -96.87311 |
| 27 | MEXUVTE3 | Alpatlahuac | Teacalco | Gerardo Torres | 1825 | 19.10983 | -97.09953 |
| 28 | MEXUVCV3 | Calcahualco | Cruz Verde | Anonymous | 1934 | 19.13447 | -97.10783 |
| 29 | MEXUVCV4 | Calcahualco | Cruz Verde | Vicente Espejel | 1939 | 19.13614 | -97.10978 |
| 30 | MEXUVTER1 | Calcahualco | Terrero | Rosalino | 1913 | 19.13192 | -97.10344 |
| 31 | MEXUVCV5 | Calcahualco | Cruz Verde | Remigia | 1940 | 19.13611 | -97.10975 |
| 32 | MEXUVTER2 | Calcahualco | Terrero | Diocleciana | 1914 | 19.13194 | -97.10333 |
| 33 | MEXUVTER3 | Calcahualco | Terrero | Serafina | 1914 | 19.13192 | -97.10339 |
| 34 | MEXUVTET1 | Coscomatepec | Tetlaxco | Cirilo Roque | 1678 | 19.03711 | -97.06344 |
| 35 | MEXUVTET2 | Coscomatepec | Tetlaxco | Juan Alejo Rosales | 1683 | 19.03692 | -97.06258 |
| 36 | MEXUVHU1 | Soledad Atzompa | Huixtitla | Leticia López Flores | 2514 | 18.71276 | -97.16385 |

**Table 1. Continues.**

| Id | Accesion | Municipality | Origin | Farmer name | Altitude | Latitude | Longitude |
|---|---|---|---|---|---|---|---|
| 37 | MEXUVNE1 | Camerino Z. Mendoza | Necoxtla | Margarita Pérez Flores | 2045 | 18.77791 | -97.15361 |
| 38 | MEXUVCU1 | Tehuipango | Cuauyolotitla | Gines Panzo Panzo | 2387 | 18.51914 | -97.06378 |
| 39 | MEXUVCU2 | Tehuipango | Cuauyolotitla | Gines Panzo Panzo | 2408 | 18.51906 | -97.06331 |
| 40 | MEXUVTZ2 | Tehuipango | Tzacoala Primero | Anonymous | 2108 | 18.53874 | -97.08197 |
| 41 | MEXUVTEH1 | Tehuipango | Tehuipango | Anonymous | 2393 | 18.51947 | -97.05444 |
| 42 | MEXUVVH1 | Tlaquilpa | Vista Hermosa | Lucía Clemente Sandoval | 2592 | 18.59497 | -97.12811 |
| 43 | MEXUVCA1 | Tlaquilpa | Capillatixtla | Jerónima Rosales | 2410 | 18.61050 | -97.11708 |
| 44 | MEXUVDA1 | Tlaquilpa | Desviación Atempa | Félix | 2226 | 18.60092 | -97.10422 |

regression (PLSR) was applied, which allows describing the populations considering several morphological characteristics simultaneously, without failing to consider the relationship existing between them. This analysis is useful to predict a set of dependent variables (morphological characteristics) from a set of predictor variables (bioclimatic layers) (Gaviria *et al*., 2016).

### Species distribution model

The species distribution model (SDM) was used to predict suitable areas for *C. pubescens* in places where it occurs. In this model, the locations of the current known distribution of *C. pubescens* are grouped. Four climatic prediction variables were selected: mean annual temperature (Bio1), annual rainfall (Bio12), altitude (DEM), and a potassium (K) layer as soil property (Bugarín-Montoya *et al*., 2002; Cruz-Cárdenas *et al*., 2014). These variables were taken from the spatial databases from http://www.worldclim.org (Hijmans *et al*., 2005). The estimation of the ecological niche was carried out through the maximum entropy algorithm, MaxEnt® Ver. 3.3 (Phillips *et al*., 2006). Once the potential distribution map was obtained, it was exported to the ArcMap® Versión 10.5.1 software (ESRI, 2017) for contextualization and image manipulation. The quality of the model was evaluated with > 0.9 values of the area under the curve (AUC), which characterizes the performance of the model. The result is a graph output that shows the discrimination capacity of a given presence (sensitivity) versus the discrimination capacity of a given absence (specificity) (Phillips *et al*., 2004).

## RESULTS AND DISCUSSION

### *C. pubescens* presence sites

Forty-four sites were identified with the presence of *C. pubescens* in the studied area. Using the coordinates, a distribution map was generated and two regions, A and B, were identified (Figure 1). Region A included the municipalities of Zongolica, Tlaquilpa, Texhuacan, Mixtla de Altamirano, Camerino Z. Mendoza, Soledad Atzompa and Tehuipango; region B included the municipalities of Calcahualco, Alpatlahuac, Chocamán, Coscomatepec, Huatusco and Tepatlaxco.

Region A has a *Cf* type climate, temperate humid with rains throughout the year, exceeding 2200 mm per year (> 18 % of winter rain), with little thermal oscillation (5 to 7 °C). Region B posesses a *Cw* type climate, temperate sub-humid with rains in the Summer, with more than 800 mm per year (< 10.2 % of winter rain), with isothermal oscillation range (< 5 °C) (Díaz *et al*., 2006; García, 2004). Both regions have altitudes ranging from 1300 to 2700 masl, places where the maximum rainfall arises as a result of the discharge of water by warm air masses from the sea (Krasilnikov *et al*., 2013). They also have an average annual temperature between 5 to 18 °C, while in the coldest month between -3 to 18 °C (García, 2004; SEMARNAT, 2006).

### Ecological niche model for *C. pubescens*

The efficiency of the model reached an AUC value over 0.997, indicating that the ability of the model to classify presences was consistent in the prediction of the ecological niche (Baldwin, 2009; Phillips and Dudík, 2008). The results of the test data (P = 0.5) revealed that the model obtained is better than a randomized model, since the curves are located at the upper left corner (Figure 2) and indicate that there is no error of omission (100 % sensibility) and no error of commission (100 % specificity) (Cruz-Cárdenas *et al*., 2014). These results indicate that the samples were viably taken from the population and that they are truly representative, as there is no ambiguity in the prediction of the ecological niche for *C. pubescens*. In biological terms, the model reflects reliability, providing useful information

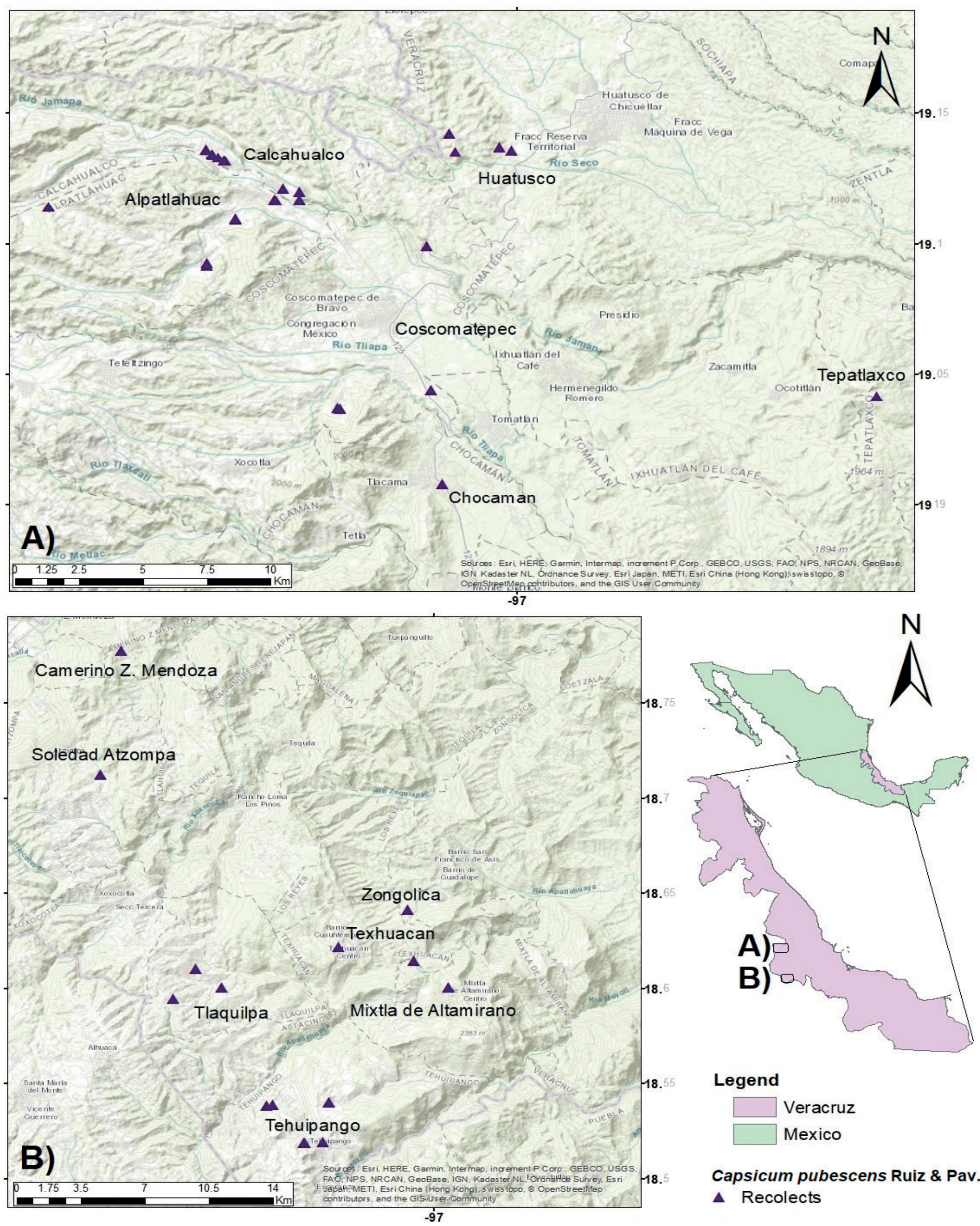


**Figure 1. Geographical distribution of 44 *C. pubescens* accessions from the central region of the state of Veracruz, Mexico in two contrasting zones, A and B.**

for a breeding program. In this regard, Pearson *et al.* (2007) mentioned that few presences can give enough information for the MaxEnt model to produce acceptable predictions for the distribution of a certain species.

To this regard, the potential distribution of *C. pubescens* shown in the map of Figure 3, reveals that the best conditions of occurrence are found in the mountainous regions of Chiapas, Oaxaca, Puebla, and Hidalgo, Mexico (Figure 3B); however, a new registry was found in southern Veracruz, at the San Martin Sierra and the Santa Martha Sierra in the Tuxtlas region, at an altitude of 1500 masl (Figure 3B). From an ecological standpoint, *C. pubescens* is distributed in temperate regions, which coincide with areas of dense vegetation and subtropical forests. This is consistent with the reports on its distribution and habitat (Yamamoto *et al.*, 2013).

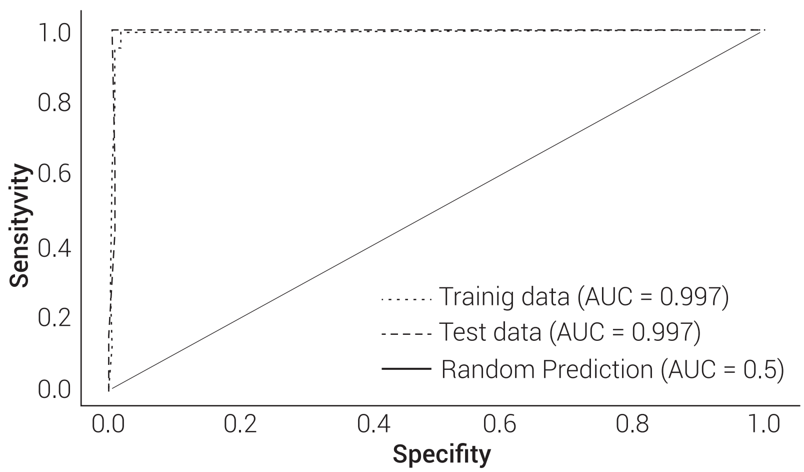


**Figure 2. Goodness of fit of the model to estimate the potential distribution of *C. pubescens.***

The model revealed other areas where the presence of *C. pubescens* is unknown (Leyva-Ovalle *et al*., 2018). These areas showed a restricted habitat potential, like the Sierra Madre Oriental and Sierra Madre Occidental in the states of Tamaulipas, Nuevo Leon and Chihuahua, Mexico, at an altitude gradient between 2200 and 2700 masl (Figure 3A).

According to the analysis of the contribution of each variable provided by the MaxEnt model, it was found that the variables with larger contribution to the model when they are used separately were annual rainfall (Bio12) with 43.9 %, potassium layer (K) with 23 %, altitude (DEM) with 22.3 %, and mean annual temperature (Bio1) with 10.7 %. This suggests that *C. pubescens* achieves good growth and development in temperate zones with high rainfall; however, the presence of low temperatures and frost at higher altitudes may limit its distribution (Soto and Geissert, 2011). Furthermore, the species grows on pyroclastic sediments, in acidic volcanic ash, which explains the high content of K, an element that is highly resistant to weathering (Krasilnikov *et al*., 2013). On the other hand, the humid conditions in areas where the species grows promote the acidity of the soil (pH = 4.2), and together with their mountainous relief, they cause erosion and loss of nutrients (Krasilnikov *et al*., 2013; Medina *et al*., 2010; SEMARNAT, 2006), demonstrating their adaptation even under these conditions; in this sense, the use of ecological niche models contributes to a better understanding of the relationships between species and the environment (Parolo *et al*., 2008).

### Partial least square regression in *C. pubescens*

The least square regression is a technique that generalizes and combines the principal component analysis and the linear regression analysis. It is ideal to predict a set of dependent variables (*e.g.* morphological) from a set of predictor variables (*e.g.* climatological). The covariable with the highest inertia and positively linked to the first axis was mean annual rainfall (Bio12), while negatively it was the availability of potassium (K) in the soil. The covariable positively linked to the second axis was altitude (DEM), while negatively was mean annual temperature (Bio1).

Accessions MEXUVCAL1, MEXUVCAL3, MEXUVTL2, MEXUVBV1, MEXUVCV5 and MEXUVTER3 showed the best values in number of seeds, fruit thickness and peduncle length; also, their expression is better in more humid environments (Figure 4). These accessions were collected in Calcahualco, Alpatlahuac, and Tepatlaxco, Veracruz, Mexico, whose altitude ranges from 1400 to 1800 masl and have a mean annual rainfall between 1800 and 2300 mm.

Meanwhile, accessions MEXUVCO1, MEXUVTEX1, MEXUVTZ1, MEXUVTLA2, MEXUVCO2, MEXUVCU2, MEXUVTZ2, MEXUVTEH1 and MEXUVDA1 were segregated, mainly due to the variables altitude (DEM) and potassium (K) as a soil property (Figure 4), they showed high values for fruit weight and width, which agrees with the locations of provenance, as Tehuipango and Alpatlahuac, Veracruz, Mexico, located at 2500 masl. The interactions detected in this dataset are mainly attributed to these two traits, from the ecological standpoint. This clarifies various ecological hypotheses that can contribute to better understand the relationships between environments and genotypes.

The presence of potassium (K) is closely linked to fruit weight, width and length, its presence is related to fruit quality. It is important to mention that the extraction of large amounts of this element is greatly due to the formation and development of fruits, which are the most

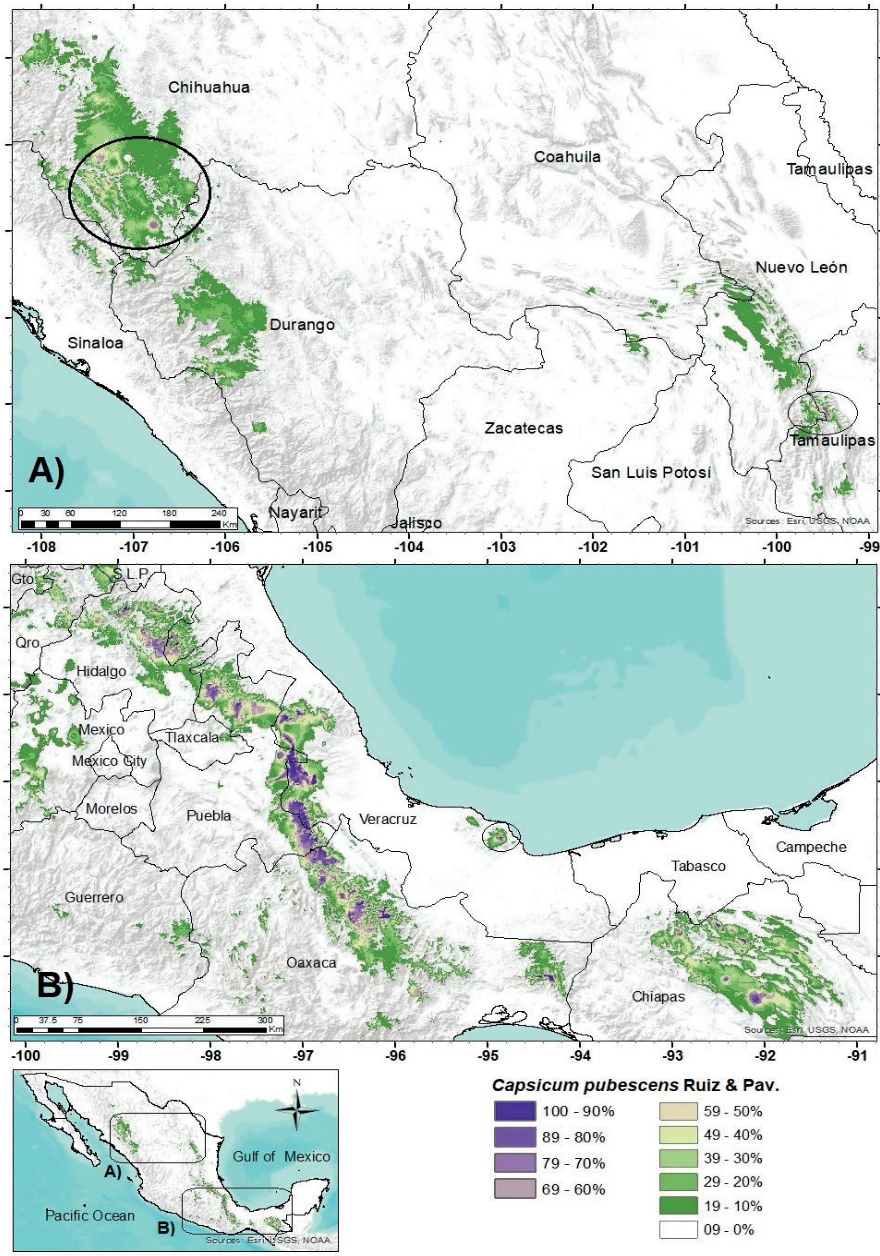


**Figure 3. Potential distribution area of *C. pubescens* in Mexico, as predicted by the maximum entropy model (MaxEnt).**

demanding organ in *Capsicum*, with values from 70 to 80 % of the total amount extracted from each plant (Bugarín-Montoya *et al*., 2002).

The opposing projection of the covariables altitude (DEM) and mean annual temperature (Bio1) suggests that the latter changes differentially from one location to another, directly affecting some fruit characteristics. Accessions MEXUVBJ1, MEXUVTEP1, MEXUVTEN2 and MEXUVTET2 showed the lowest values in relation to the length of the placenta, which indicates that this characteristic was significantly affected by Bio1. According to the mean values of Bio1 registered in the locations where these accessions were collected, the values are above the optimum limits for *C. pubescens* (18 and 25 ºC). Pérez and Castro (2008) reported an optimum range from 15 to 22 ºC for proper development of *C. pubescens*; moreover, they mentioned that temperatures below 7 ºC halt the physiological-metabolic processes in the plant, while temperatures above 32 ºC during the critical stage of the crop stimulate abortion of flowers.

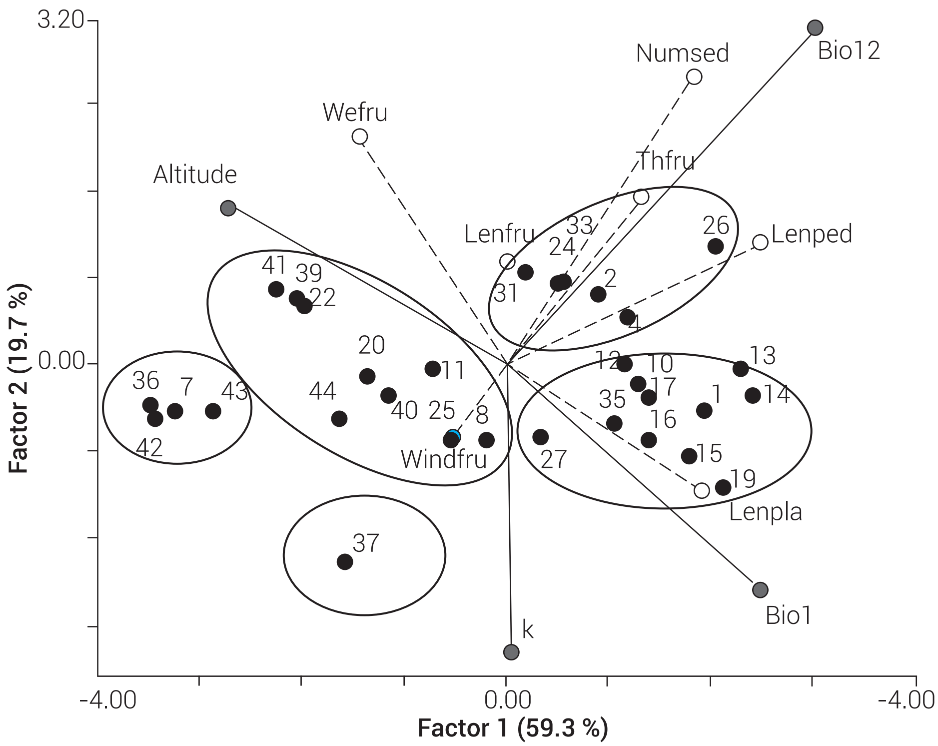


**Figure 4. Interaction of 44 accessions of *C. pubescens* and four environmental variables, against a matrix of seven morphological variables of the fruit.**

## CONCLUSIONS

The distribution model MaxEnt produced probability values > 70 % for the presence of the species. These areas are located in the states of Tamaulipas, Nuevo Leon, Chihuahua and the Santa Martha Sierra in southern Veracruz; nevertheless, it is necessary to carry out exploratory trips to corroborate the presence of the species where it was predicted. Mean annual rainfall (Bio12), mean annual temperature (Bio1), potassium (K), and altitude (DEM) were the most importat bioclimatic variables to define specific environments for *C. pubescens*, and they significantly influence the expression of morphological characteristics of the fruit.

## ACKNOWLEDGMENTS

The authors would like to thank the Universidad Veracruzana for the Grant "Programa para el Desarrollo Profesional Docente (PRODEP) 511-6/18-9245/PTC-874".

## BIBLIOGRAPHY

Baldwin R. A. (2009) Use of maximum entropy modeling in wildlife research. *Entropy* 11:854-866, https://doi.org/10.3390/e11040854

Bugarín-Montoya R., A. Galvis-Spinola, P. Sánchez-García and D. García-Paredes (2002) Demanda de potasio del tomate tipo saladette. *Terra Latinoamericana* 20:391-399.

Casas A. (1998) Domesticación de plantas y recursos genéticos de México. *Boletín de la Sociedad Botánica de México* 62:73-76, https://doi.org/10.17129/botsci.1552

Casas A. and J. Caballero (1995) Domesticación de plantas y el origen de la agricultura en Mesoamérica. *Ciencias* 40:36-45.

Clement C. R. (1999) 1492 and the loss of Amazonian crop genetic resources. II. Crop biogeography at contact. *Economic Botany* 53:203-216, https://doi.org/10.1007/BF02866499

Cruz-Cárdenas G., L. López-Mata, C. A. Ortiz-Solorio, J. L. Villaseñor, E. Ortiz, J. T. Silva and F. Estrada-Godoy (2014) Interpolation of Mexican soil properties at a scale of 1: 1,000,000. *Geoderma* 213:29-35, https://doi.org/10.1016/j.geoderma.2013.07.014

DeWitt D. and P. W. Bosland (2009) The Complete Chile Pepper Book: A Gardener's Guide to Choosing, Growing, Preserving, and Cooking. Timber Press. Portland, Oregon, USA. 336 p.

Díaz P. G., J. A. Ruíz C., M. Á. Cano G., V. Serrano A. y G. Medina G. (2006) Estadísticas Climatológicas Básicas del Estado de Veracruz (Período 1961-2003). Libro Técnico Núm. 13. Campo Experimental Cotaxtla. INIFAP. Medellín de Bravo Veracruz, México. 292 p.

ESRI, Environmental Systems Research Institute (2017) ArcMap. Version 10.5.1. Redlands. Environmental Systems Research Institute, Inc. California. USA.

García E. (2004) Modificaciones a la Clasificación Climática de Köppen. Instituto de Geografía, UNAM. México, D. F. 90 p.

Gaviria P. C. A., R. Pérez A. and M. E. Puerta Y. (2016) Regresión por mínimos cuadrados parciales PLS con datos de intervalo. *Revista de la Facultad de Ciencias (Colombia)* 5:148-159, https://doi.org/10.15446/rev.fac.cienc.v5n1.54616

Gepts P. (2005) Plant and animal domestication as human-made evolution. *In*: Evolutionary Science and Society: Educating a New Generation. J. Cracraft and R.W. Bybee (eds.). Biological Sciences Curriculum Study and the American Institute of Biological Sciences. Colorado Springs, CO, USA. pp:180-186.

Gepts P. and R. Papa (2003) Evolution during domestication. *In*:

Encyclopedia of Life Sciences. Macmillan Publisher Ltd. New York. pp:1-7, https://doi.org/10.1038/npg.els.0003071
Hernández X. E. (1985) Biología Agrícola. CECSA. México, D. F. 62 p.
Hernández-Verdugo S., R. G. Guevara-González, R. F. Rivera-Bustamante, C. Vázquez-Yanes y K. Oyama (1998) Los parientes silvestres del chile (*Capsicum* spp.) como recursos genéticos. *Boletín de la Sociedad Botánica de México* 62:171-181, https://doi.org/10.17129/botsci.1559
Hijmans R. J., S. E. Cameron, J. L. Parra, P. G. Jones and A. Jarvis (2005) Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25:1965-1978, https://doi.org/10.1002/joc.1276
IPGRI, International Plant Genetic Resources Institute (1995) Descriptors for *Capsicum* (*Capsicum* spp.). International Plant Genetic Resources Institute, Rome, Italy; The Asian Vegetable Research and Development Center, Taipei, Taiwan, and Centro Agronómico Tropical de Investigación y Enseñanza, Turrialba, Costa Rica. 51 p.
Krasilnikov P., M. C. Gutiérrez-Castorena, R. J. Ahrens, C. O. Cruz-Gaistardo, S. Sedov and E. Solleiro-Rebolledo (2013) The Soil of Mexico. Springer. Heidelberg, The Netherlands, 187 p.
Leyva-Ovalle O. R., P. Andrés-Meza, D. Del Valle-Hernández, I. Meneses-Márquez, J. Murguía-González, M. E. Galindo-Tovar, … y A. Espinosa-Calderón (2018) Caracterización morfológica de poblaciones de chile manzano (*Capsicum pubescens* Ruiz & Pav.) en la región centro del estado de Veracruz, México. *Revista Bio Ciencias* 5:e388, https://doi.org/10.15741/revbio.05.01.20
Liu S., W. Li, Y. Wu, C. Chen and J. Lei (2013) *De novo* transcriptome assembly in chili pepper (*Capsicum frutescens*) to identify genes involved in the biosynthesis of capsaicinoids. *PLoS ONE* 8:e48156, https://doi.org/10.1371/journal.pone.0048156
Loaiza-Figueroa F., K. Ritland, J. A. Laborde C. and S. D. Tanksley (1989) Patterns of genetic variation of the genus *Capsicum* (Solanaceae) in Mexico. *Plant Systematics and Evolution* 165:159-188, https://doi.org/10.1007/BF00936000
Mastretta-Yanes A., M. R. Bellon, F. Acevedo, C. Burgeff, D. Piñero y J. Sarukhán (2019) Un programa para México de conservación y uso de la diversidad genética de las plantas domesticadas y sus parientes silvestres. *Revista Fitotecnia Mexicana* 42:321-334, https://doi.org/10.35196/rfm.2019.4.321-334
Meckelmann S. W., C. Jansen, D. W. Riegel, M. van Zonneveld, L. Ríos, K. Peña, … and M. Petz (2015) Phytochemicals in native Peruvian *Capsicum pubescens* (Rocoto). *European Food Research and Technology* 241:817-825, https://doi.org/10.1007/s00217-015-2506-y
Medina C. A., T. E. Salazar C. y J. L. Álvarez P. (2010) Fisiografía y suelos. *In*: Atlas del Patrimonio Natural, Histórico y Cultural de Veracruz. J. Ortíz y E. Florescano (eds.). Universidad Veracruzana. Gobierno del Estado de Veracruz. Xalapa, Veracruz. pp:29-41.
Oboh G., R. L. Puntel and J. B. T. Rocha (2007) Hot pepper (*Capsicum annuum*, tepin and *Capsicum chinese*, Habanero) prevents $Fe^{2+}$-induced lipid peroxidation in brain – *in vitro*. *Food Chemistry* 102:178-185, https://doi.org/10.1016/j.foodchem.2006.05.048
Parolo G., G. Rossi and A. Ferrarini (2008) Toward improved species niche modelling: *Arnica montana* in the Alps as a case study. *Journal of Applied Ecology* 45:1410-1418, https://doi.org/10.1111/j.1365-2664.2008.01516.x
Pearson R. G., C. J. Raxworthy, M. Nakamura and A. Townsend P. (2007) Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *Journal of Biogeography* 34:102-117, https://doi.org/10.1111/j.1365-2699.2006.01594.x
Pérez-Grajales M., V. A. González-Hernández, M. C. Mendoza-Castillo, C. Peña-Valdivia, A. Peña-Lomelí and J. Sahagún-Castellanos (2004) Physiological characterization of manzano hot pepper (*Capsicum pubescens* R & P) landraces. *Journal of the American Society for Horticultural Science* 129:88-92, https://doi.org/10.21273/JASHS.129.1.0088
Pérez G. M. y R. Castro B. (2008) El Chile Manzano. Universidad Autónoma Chapingo. Chapingo, Estado de México. 128 p.
Phillips S. J. and M. Dudík (2008) Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 31:161-175, https://doi.org/10.1111/j.0906-7590.2008.5203.x
Phillips S. J., M. Dudík and R. E. Schapire (2004) A maximum entropy approach to species distribution modeling. *In*: Proceedings of the 21st International Conference on Machine Learning. ACM Press. New York, USA. pp:655-662.
Phillips S. J., R. P. Anderson and R. E. Schapire (2006) Maximum entropy modeling of species geographic distributions. *Ecological Modelling* 190:231-259, https://doi.org/10.1016/j.ecolmodel.2005.03.026
Pickersgill B. (2007) Domestication of plants in the Americas: insights from Mendelian and molecular genetics. *Annals of Botany* 100:925-940, https://doi.org/10.1093/aob/mcm193
Rick C. M. (1950) *Capsicum pubescens*: a little-known pungent pepper from Latin America. *Missouri Botanical Garden Bulletin* 38:36-42.
Rodríguez-Burruezo A., J. Prohens, M. D. Raigón and F. Nuez (2009) Variation for bioactive compounds in ají (*Capsicum baccatum* L.) and rocoto (*C. pubescens R.* & *P.*) and implications for breeding. *Euphytica* 170:169-181, https://doi.org/10.1007/s10681-009-9916-5
Ruiz H. and J. Pavon (1799) Flora Peruviana, *et* Chilensis, Sive Descriptiones, *et* Icones *Plantarum Peruvianarum*, *et Chilensium*, Secundum Systema Linnaeanum Digestae, Cum Characteribus Plurium Generum Evulgatorum Reformatis. Tomus II. Typis Gabrielis de Sancha. Madrid. 76 p.
SEMARNAT, Secretaría de Medio Ambiente y Recursos Naturales (2006) Atlas Geográfico del Medio Ambiente y Recursos Naturales. Secretaría de Medio Ambiente y Recursos Naturales. México, D.F. 78 p.
Soto E. M. y D. Geissert K. (2011) Geografía. *In*: La Biodiversidad en Veracruz: Estudio de Estado. Vol. I. Contexto Actual del Estado y Perspectivas de Conservación de su Biodiversidad. A. Cruz A. (ed.). Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Gobierno del Estado de Veracruz, Universidad Veracruzana, Instituto de Ecología, A.C. México, D. F. pp:31-34.
Yamamoto S., T. Djarwaningsih and H. Wiriadinata (2013) *Capsicum pubescens* (Solanaceae) in Indonesia: its history, taxonomy, and distribution. *Economic Botany* 67:161-170, https://doi.org/10.1007/s12231-013-9230-y