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IMPACTO, VULNERABILIDAD Y ADAPTACIÓN DE LAS RAZAS MEXICANAS DE MAÍZ ANTE ESCENARIOS DE CAMBIO CLIMÁTICO

TESIS

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DOCTORA EN CIENCIAS

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COORDINACIÓN

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Presente

Me permito informar a usted que en la reunión del Subcomité por Campo de Conocimiento Ecología y Manejo Integral de Ecosistemas del Posgrado en Ciencias Biológicas, celebrada el día 30 de septiembre de 2013, se aprobó el siguiente jurado para el examen de grado de **DOCTORA EN CIENCIAS** de la alumna **URETA SÁNCHEZ CAROLINA** con número de cuenta **401052279** con la tesis titulada: **"Impacto, vulnerabilidad y adaptación de las razas mexicanas de maíz ante escenarios de cambio climático"**, realizada bajo la dirección del **DR. ENRIQUE MARTÍNEZ MEYER:**

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Sin otro particular, me es grato enviarle un cordial saludo.

ATENTAMENTE
"POR MI RAZA HABLARA EL ESPIRITU"
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Índice

Resumen

El maíz es uno de los cultivos más importantes del mundo en términos de producción y consumo humano. México es centro de origen y diversificación de esta planta agrícola por lo que tenemos una gran responsabilidad de crear las medidas necesarias para preservar su diversidad en el presente y a futuro. La diversidad de maíz mexicano ha sido clasificada en alrededor de 59 razas y constituye uno de los acervos genéticos más relevantes del mundo. En México, el maíz cubre 51% de la superficie sembrada y la mayoría de los productores son microproductores que destinan su cosecha principalmente al autoconsumo. Estos pequeños agricultores son los que facilitan la evolución continua *in situ* de las variedades de maíz, llegando a sembrar hasta 7 poblaciones en una sola parcela. Existen varios factores que ponen en riesgo la diversidad de esta planta agrícola y entre éstos se encuentran los cambios del clima ocasionados por la actividad humana. Reducir los impactos del cambio climático al mismo tiempo que alcanzar la seguridad alimentaria en nuestro país es un gran reto que requiere de un amplio conocimiento para lograr tomar las decisiones más adecuadas. En esta tesis se aborda el tema de los impactos y la vulnerabilidad del maíz mexicano frente a condiciones de cambio climático, tratando de generar conocimiento que permita ir construyendo políticas públicas que faciliten la adaptación en este sector. Los impactos que el cambio climático pudiera tener en el maíz mexicano tienen consecuencias importantes a nivel social, económico, cultural y biológico. Poco a poco se ha ido estudiando el fenómeno del cambio climático sobre el sector agrícola mexicano, pero este trabajo es el primer intento en evaluar el impacto y la vulnerabilidad de cada una de las razas de maíz mexicano, así como el primero en identificar qué otros factores, además de los climáticos, tienen influencia en la distribución del maíz a una escala de país. Finalmente, también se evaluó la posibilidad de obtener información sobre rendimientos a futuro mediante modelación. Información de esta índole facilitarán la planificación temprana para enfrentar las condiciones cambiantes del clima sin necesidad de comprometer la seguridad de nuestra biodiversidad y preservando nuestras tradiciones. Entre los resultados más relevantes encontramos en el primer capítulo que se esperan reducciones significativas en el área de distribución potencial de la mayoría de las razas evaluadas tanto para el 2030 como para el 2050. También encontramos que las zonas de mayor riqueza son menos vulnerables a los cambios en el clima, resultado que resalta la importancia de la conservación de nuestra agrobiodiversidad para lidiar con el cambio climático. En términos de escenarios de emisiones, resulta que el escenario más drástico “A2”

tendrá efectos significativamente más negativos en el maíz mexicano que el escenario “B1”. Por otro lado, la mayoría de las razas evaluadas presentan nuevas áreas de distribución potencial a futuro, sugiriendo que con un manejo apropiado se puede facilitar su preservación. En el segundo capítulo se implementó un método de análisis espacial con minería de datos para encontrar relaciones geográficas entre variables ambientales y sociales con la distribución de las razas de maíz. Los resultados señalan que la altura, factor íntimamente relacionado con el clima, es la variable ambiental que mayor influencia tiene sobre la distribución del maíz mexicano a una escala nacional. Sin embargo, diferentes factores presentan grados distintos de asociación en ciertas razas. Por ejemplo, el grupo étnico fue el factor que mayor influencia espacial tuvo en 12 de 47 razas evaluadas. Lo que es una generalidad, es que entre más variables se utilizan para describir la distribución espacial de una raza, mejora el desempeño del modelo. Para terminar, el tercer capítulo nos ofrece información de una posible manera de proyectar rendimientos bajo condiciones climáticas actuales y condiciones de cambio climático. Recientemente ha habido esfuerzos en combinar la ecología de poblaciones con la ecología geográfica para poder encontrar áreas con mayores abundancias basándose en teoría ecológica; que sugiere que la abundancia está negativamente relacionada con la distancia al centroide del nicho ecológico. Siguiendo este mismo principio, en este tercer capítulo se trató de encontrar las áreas geográficas que posiblemente pudieran tener los mayores rendimientos tanto en el presente como en el futuro de acuerdo a la cercanía ambiental con el centroide o valor óptimo del nicho ecológico. Se estudiaron diez razas, pero sólo se escogieron dos (por razones estadísticas) para proyectar sus rendimientos bajo condiciones actuales y futuras de clima. En las razas Bolita y Celaya se encontraron zonas con el potencial de tener sus máximos rendimientos bajo condiciones de clima actual y bajo condiciones de cambio climático. Asimismo, estas razas fueron divididas en subgrupos (basándonos en un análisis de conglomerados con variables bioclimáticas independientes) para evaluar la posibilidad de la existencia de más de un centroide de nicho o valor óptimo de nicho. En condiciones de cambio climático las zonas de mayor rendimiento se mueven hacia el norte del país tanto a nivel de raza como en los subgrupos. Los resultados provenientes de los tres capítulos son un paso adelante en el entendimiento de la distribución de las razas de maíz en México a una escala nacional y esclarecen las posibles consecuencias del cambio climático en este producto agrícola.

Summary

Maize is one of the most important crops worldwide in terms of production and human consumption. Mexico is its center of origin and diversification, consequently we have a great responsibility in creating the necessary management plans to guarantee its diversity preservation under current and future conditions. Mexican maize diversity has been classified in 59 races that represent one of the most valuable genetic sources of the world. In Mexico, maize covers around 51% of the cultivated land and most maize farmers are smallholders harvesting mainly for self-consumption. These farmers system has prevailed for centuries, promoting *in situ* evolution by growing up to 7 different varieties in the same plot. There are several factors threatening maize diversity, one of which is the anthropogenic climate change. Reducing climate change impacts and simultaneously trying to reach food security is a great challenge that requires deep knowledge to take the most adequate decisions. In this thesis we evaluated the impacts and vulnerability of Mexican maize under climate change conditions, generating knowledge that may help the creating of public politics to facilitate adaptation. Climate change impacts on Mexican maize are expected to have important consequences at social, economic, cultural, and biological levels. Previous efforts exist to assess climate change impacts over the agricultural sector at a national scale. However; this is the first approach evaluating the impacts and vulnerability of each Mexican race under climate change conditions, as well as the first study in identifying which other factors are important on its geographic distribution. Finally, this thesis also explored the capacity of modeling yield under current and future conditions. Information such as the presented in this work is expected to facilitate early planning in the face of climate change without compromising our biodiversity safety and preserving our traditions. Between our most important results we found in the first chapter that significant reductions in the potential distribution areas are expected in 2030 and 2050 for most evaluated races. We also found that areas with higher richness are less vulnerable to climate change, highlighting the importance of agrobiodiversity conservation to deal with changing conditions. In terms of emission scenarios, we showed that under the drastic “A2” scenario impacts on Mexican maize races distribution resulted more severe than under the “B1” scenario. On the other hand, most races presented new potential distribution areas in the future, suggesting that with proper management, agrobiodiversity preservation can be reached. In the second chapter, we searched for geographic relationships between environmental and social factors with Mexican maize races using a data mining method. Results indicate that altitude, a factor that is strongly related to climate, was the factor with greatest influence over Mexican maize distribution at a national scale. However; other factors presented specific degrees of associations among races. For example, the ethinc group had the highest influence in 12 out of 47 races. In general, model performance improved when more variables were used to describe its distribution. Lastly, in the third chapter we modeled maize yields under current and future climatic conditions. Recently, some efforts have combined population ecology with geographic ecology to understand geographic patterns of abundance based on ecological theory, which claims that abundance is negatively related with distance to ecological niche centroid in ecological space. Following the same principle, in this third chapter we modeled spatial pattern of yields under current and future conditions by means of calculating the distance to the ecological centroid or ecological optimum. We assessed ten races choosing only 2 (following statistics criterion) to project their yields under current and future climate. For Bolita and Celaya we found areas with the potential of having their greatest yields under current and future climatic conditions. Furthermore, these races were divided into clusters (using a cluster analysis with independent bioclimatic variables) to evaluate if more than one niche centroid or niche optimum exists within the same race. Under climate change conditions, distributions with the potential of having greater yields will shift to northern states. This thesis represents a first insight to have a better understanding of native maize races distribution under current and future conditions at a national scale. It also shows the possible impacts of climate change in the most important crop in Mexico.

Introducción General

A partir de un importante cúmulo de evidencias arqueológicas, mayores niveles de diversidad genética a nivel mundial, mayor cercanía genética del maíz mexicano con los teocintles (Z*ea spp*.), así como la existencia de poblaciones vivas de este pariente silvestre (Sánchez G. et al. 2011), se ha determinado que México es el centro de origen y diversificación del maíz (MacNeish 1967, Flanery 1986, Harlan 1992, Vavivlov 1994, Kok and Veldkamp 2001, Piperno 2001, Matsuoka et al. 2002, Aragón et al. 2006, Vigouroux et al. 2008, Kato et al. 2009). En nuestro país la diversidad del maíz se ha agrupado en alrededor de 59 razas (Wellhausen et al. 1951, Sánchez Gonzáles and Goodman 1992, Ortega et al. 2000) que han sido creadas a lo largo de aproximadamente 5000 años por selección artificial practicadas por campesinos de acuerdo a sus necesidades (Kato et al. 2009). Esta diversidad genética es de gran importancia biológica e histórica para toda la humanidad, ya que su conservación representa una fuente de genes nuevos y antiguos que asegurarán la evolución continua y darán seguridad en la producción de alimento (Van Etten 2006); al mismo tiempo que se mantiene una herencia cultural milenaria (Aragón et al. 2006) y técnicas agrícolas con racionalidad ecológica (Ortiz Cereceres et al. 2007).

En México, el maíz cubre el 51% de la superficie sembrada y la mayoría de los agricultores de este grano son micro-productores que destinan su cosecha principalmente al autoconsumo, comercializando sus excedentes en mercados locales (Cruz Delgado et al. 2008). Este tipo de agricultores son los que se encargan de sembrar y conservar nuestra diversidad del maíz manteniendo hasta 7 poblaciones diferentes un una sola parcela (Ortega Paczka 2007). Y a pesar de que oficialmente la producción representa sólo alrededor del 12.5% del PIB agropecuario, en realidad el maíz contribuye más mediante la producción destinada al autoconsumo y el valor de los subproductos de la planta que con frecuencia significan altas aportaciones en la estructura de costos para otros sistemas productivos (Polanco and Flores 2008).

Cambio Climático y Agricultura

La agricultura se ha convertido en un sistema amenazado en el mundo, siendo una de las principales amenazas los cambios antropogénicos del clima (Tubiello and Fischer 2007). Esto ha motivado a varias naciones a conocer los impactos potenciales del cambio climático sobre este sector a un nivel regional y global (Easterling 2007). Dichos impactos tendrán influencia en la creación de políticas públicas, tratados internacionales, planeación nacional para la explotación de recursos y en el bienestar de la gente. Aquellos países que cuenten con más estrategias adecuadas serán menos vulnerables a los impactos del cambio climático (Tubiello and Fischer 2007).

La influencia del clima sobre el sector de producción agrícola es innegable, y a pesar de que los especialistas han expresado la dificultad de vincular de manera única y directa los resultados de los estudios sobre cambio climático con la producción agrícola, es un hecho que este fenómeno tendrá un impacto importante. Dado que el clima es incontrolable, para reducir los impactos y aumentar la resiliencia de los sistemas es necesario hacer modificaciones en factores biológicos, sociales y económicos mediante medidas de adaptación y mitigación (Easterling 2007). Reducir los impactos del cambio climático, mantener la seguridad alimenticia, conservar los recursos naturales y mejorar la calidad del ambiente al mismo tiempo, es un reto sumamente difícil por lo que es necesario empezar a generar información lo antes posible.

Cambio Climático y Maíz

Desde hace varios años se ha identificado que el cultivo de maíz es de los más vulnerables al cambio climático dentro del sector agrícola mexicano (Gay et al. 2007). Aproximadamente el 70-80% de los agricultores siembran maíz nativo de temporal y por ende dependen fuertemente de las condiciones climáticas (Conde et al. 1997, Eakin et al. 2006, Gay et al. 2007, Ortega Paczka 2007, Cruz Delgado et al. 2008). Sin embargo, es sabido que en una misma región, el cambio climático puede favorecer a ciertas especies agrícolas y perjudicar a otras (Komatsu et al. 2007). Basándonos en este mismo principio, como las poblaciones de maíz están adaptadas a condiciones climáticas particulares (Aragón et al. 2006, Ruiz-Corral et al. 2013), también se podría suponer que el impacto del cambio climático será diferencial dentro de una especie agrícola que presenta tanta diversidad genética, morfológica, fisiológica y fenológica.

Maíz en un Contexto Social y Económico

Dada la importancia social y económica que tiene el maíz en nuestro país (Esteva and Marielle 2007), se ha sugerido que además de la inevitable influencia que el clima tiene sobre esta planta, existen otros factores que también determinan el que una raza de maíz crezca en cierta región (Brush and Perales 2007). Preferencias alimenticias, tradiciones y rituales son algunos de los fenómenos que tienen influencia sobre lo que le gente quiere sembrar en un lugar (Gutiérrez Serrano 2009). Por lo tanto, es relevante conocer qué otros factores de tipo social y económico están relacionados con la distribución geográfica de las razas de maíz en la actualidad, para tener un mejor entendimiento de cuál sería la situación bajo condiciones de cambio climático.

Planteamiento del Problema

Se ha proyectado que el cambio climático puede tener impactos sumamente negativos en diversos sistemas agrícolas, sobre todo en sistemas de cultivo de temporal por depender directamente del clima (Tubiello and Fischer 2007). En México del 70-80% de los productores de maíz son temporaleros y tienen poco acceso a apoyos económicos y a nuevas tecnologías (Eakin et al. 2006, Ortega Paczka 2007), situación que los convierte en un sector muy vulnerable. Por la importancia que tiene el maíz en México, los impactos pueden tener consecuencias graves desde un punto de vista de conservación, social y económico.

La diversidad genética del maíz se está perdiendo a grandes pasos por el poco apoyo que reciben aquéllos campesinos que mediante la siembra de varias variedades nativas en una milpa, han mantenido la riqueza genética en el campo mexicano. Con la reducción en número de campesinos temporaleros, se pierde también la tecnología agrícola con mayor racionalidad ecológica, que tiene impactos ambientales mucho menos severos en comparación con los ocasionados por los monocultivos tecnificados (Aguilar et al. 2007).

Desde una perspectiva social, el maíz representa para un gran número de agricultores de autoconsumo garantizar la suficiencia y calidad de su alimentación, la posibilidad de mantener su estilo de vida y organización social (Barkin 2007). Por último, desde un punto de vista económico, un país en economía emergente como México, se encuentra en completa desventaja a la globalidad si no produce sus propios alimentos y tiene autosuficiencia. Por tanto, es muy importante disminuir la vulnerabilidad agrícola mexicana ante el cambio climático dando así seguridad alimentaria y soberanía a los mexicanos (Barkin 2007). Todos estos argumentos nos indican que el maíz en la agricultura campesina e indígena debe constituir una prioridad nacional porque es un sector de la sociedad sumamente vulnerable y al mismo tiempo imprescindible para el presente y futuro de la nación (Suárez 2007).

Relevancia del Estudio

Dada la importancia que presenta el maíz en nuestro país, estudios sobre los posibles impactos que el cambio climático pudiera tener sobre esta planta agrícola, así como la generación de información para crear medidas adaptativas son de relevancia social, biológica y económica (Esteva and Marielle 2007). Actualmente, hay muy pocos trabajos sobre la vulnerabilidad, impacto y medidas de adaptación en el sector agrícola mexicano bajo condiciones de cambio climático (Conde et al. 1997, Luers et al. 2003, Gay et al. 2006, Mercer y Perales 2010, Monterroso et al. 2011, Bellon et al. 2011). Este estudio será el primer intento en evaluar el impacto y la vulnerabilidad para cada una de las razas de maíz mexicano, así como el primero en identificar qué otros factores influyen en la distribución geográfica del maíz. Finalmente, también se evaluó la posibilidad de obtener información sobre rendimientos a futuro mediante modelación. Información de esta índole facilitarán la planificación temprana para enfrentar las condiciones cambiantes del clima sin necesidad de comprometer la seguridad de nuestra biodiversidad y preservando nuestras tradiciones.

Estructura del Trabajo

Este trabajo está dividido en tres capítulos:

1- Proyección de los efectos del cambio climático sobre la distribución de las razas de maíz y sus parientes silvestres en México.

"Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico". Artículo publicado en Global Change Biology (2012) 18: 1073-1082.

2- Influencia de Factores Ambientales y Sociales sobre la distribución y Riqueza del Maíz Mexicano: Un Análisis de Minería de Datos.

"Environmental and social factors account for Mexican maize richness and distribution: A data mining approach." Artículo publicado en Agriculture, Ecosystems & Environment (2013) 179: 25.34.

3- Identificación de Áreas con Mayor Potencial de Rendimiento para el Maíz Mexicano bajo Condiciones de Clima Actual y bajo Cambio Climático.

“Finding potential high-yield areas for Mexican maize under current and climate change conditions”. Será enviado a la revista Atmósfera.

El primer capítulo evaluó los posibles impactos que el cambio climático pudiera tener sobre la distribución geográfica de cada una de las razas y sus parientes silvestres, así como sobre sus respectivas zonas de mayor riqueza. En el segundo capítulo se realizó un análisis de minería de datos como el propuesto por Stephens (2009) y González-Salazar et al. (2013) que permitió conocer la importancia del clima en relación a otros factores de distinta naturaleza (tipo de suelo, altitud, pendiente, etnia y nivel socioeconómico), sobre la distribución del maíz. En el tercer capítulo se identificaron las zonas en las que podríamos encontrar los mayores rendimientos de 2 razas nativas en el presente y bajo condiciones de cambio climático.

Hipótesis

A pesar de que el maíz mexicano es una planta de gran importancia social, el clima es de los factores que determinan en mayor medida su distribución y su rendimiento, por lo que el cambio climático es una amenaza importante para su conservación.

Objetivos y Metas

General

Evaluar los impactos que el cambio climático y otros factores de tipo ambiental, social y económico pudieran tener en la distribución y rendimientos del maíz mexicano.

Particulares

- Determinar por medio de modelos de nicho la distribución potencial de 47 razas de maíz mexicano a escala nacional bajo condiciones de clima actual, para 2030 y 2050.

- Crear una base de datos con variables ambientales y sociales para identificar aquéllas con mayor influencia sobre la distribución del maíz.

- Evaluar si existe una relación entre el rendimiento y la distancia al centroide del nicho ambiental de las razas de maíz que permita proyectar bajo condiciones de clima actual y a futuro las áreas con mayores rendimientos.

Capítulo 1

Proyectando los efectos del cambio climático sobre la distribución de las razas de maíz y sus parientes silvestres en México

Global Change Biology

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Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico

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Abstract

Climate change is expected to be a significant threat to biodiversity, including crop diversity at centers of origin and diversification. As a way to avoid food scarcity in the future, it is important to have a better understanding of the possible impacts of climate change on crops. We evaluated these impacts on maize, one of the most important crops worldwide, and its wild relatives *Tripsacum* and Teocintes. Maize is the staple crop in Mexico and Mesoamerica, and there are currently about 59 described races in Mexico, which is considered its center of origin . In this study, we modeled the distribution of maize races and its wild relatives in Mexico for the present and for two time periods in the future (2030 and 2050), to identify the potentially most vulnerable taxa and geographic regions in the face of climate change. Bioclimatic distribution of crops has seldom been modeled, probably because social and cultural factors play an important role on crop suitability. Nonetheless, rainfall and temperature still represent a major influence on crop distribution pattern, particularly in rainfed crop systems under traditional agrotechnology. Such is the case of Mexican maize races and consequently, climate change impacts can be expected. Our findings generally show significant reductions of potential distribution areas by 2030 and 2050 in most cases. However, future projections of each race show contrasting responses to climatic scenarios. Several evaluated races show new potential distribution areas in the future, suggesting that proper management may favor diversity conservation. Modeled distributions of *Tripsacum* species and Teocintes indicate more severe impacts compared with maize races. Our projections lead to *in situ* and *ex situ* conservation recommended actions to guarantee the preservation of the genetic diversity of Mexican maize.

Keywords: center of origin, ecological niche modeling, global warming, impacts, *Zea mays*, *Tripsacum*, Teocinte

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Introduction

Climate change (CC) is expected to be a significant threat to biodiversity, including crops (e.g. Appendini & Liverman, 1994; Conde *et al*., 1997; Gregory *et al*., 2005; Easterling *et al*., 2007; Tubiello & Fischer, 2007; Lobell *et al*., 2008; Walker & Schulze, 2008). To avoid negative consequences to food supply, studies about possible impacts of CC on staple crops should be a top priority worldwide, particularly at their centers of origin and diversification. However, there is a lack of research on the impacts of CC on crops in countries such as Mexico (but see Monterroso *et al*., 2011; Mercer & Perales, 2010), which is the center of origin and/or diversification for about 15% of cultivated plants (CONABIO, 2008).

Undoubtedly, the most important Mexican originated crop is maize (*Zea mays* L. ssp. *mays*) (Kato *et al*., 2009). Maize is the most widely used grain for food around the world (Arlsan, 2011) and Mexican races and wild relatives, *Tripsacum* and Teocintes (*Zea spp*. and *Z. mays spp*.), harbor a genetic diversity that may be critical for breeding programs to meet agricultural crisis and challenges (Ruiz Corral *et al*., 2008; Sánchez González *et al*., 2011). Hence, this genetic resource is of paramount importance for food security worldwide. Overall, 59 races and thousands of varieties have been recognized in Mexico. These races have adapted to different climatic conditions that go from sea level to the highlands, from very dry to very wet climates and they

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are also geared for diverse uses, constituting a key element of Mesoamerican culture (Ortega Paczka *et al*., 1991; LAMP (Proyecto Latinoamericano de Maíz), 1991; Sánchez Gonzáles *et al*., 2000; Wellhausen *et al*., 1951). The race is not commonly used as a unit of analysis and management in cultivated plants, but it has been instrumental to organize and study the great diversity of Mexican maize (Anderson & Cutler, 1942). A maize race can be defined as 'a group of related individuals with enough characteristics in common to permit their recognition as a group' (Anderson & Cutler, 1942).

Mexican maize races are grown and produced by around 85% of maize producers in small-scale farms, mainly using traditional rainfed agrotechnology and commonly at multicropping systems referred to as 'milpas' (Cruz Delgado *et al*., 2008). Mexican races are strongly dependant on weather conditions. It has been reported that meteorological events such as droughts, floods, and wind – which are expected to increase due to CC (IPCC, 2007) – have a negative impact on maize quality and yield at a national scale (Conde *et al*., 1997). We thus postulate that race diversity may be critical to maintain maize production under climatically altered conditions, and that diverse races are likely to respond differently to alternative future scenarios (Mercer & Perales, 2010).

In a first approximation to the problem, Monterroso *et al*. (2011) analyzed suitable areas for growing maize in Mexico under current and future CC conditions, irrespective of race or cultivated type. Geographic areas were classified into four categories: suitable, moderately suitable, limited suitability, and not suitable. In their analyses, suitable areas resulted in the most vulnerable category to CC due to their higher reductions. Although these results provide information on the vulnerability of maize to CC, we do think that finer analyses are needed to better understand CC impacts on Mexican maize. Therefore, we evaluated such potential impacts at race level, to identify the most vulnerable races, the areas with greater agrodiversity in the present and future, and find new suitable areas for race production to propose adaptation strategies under different CC scenarios.

Similar to maize races, its wild relatives, *Tripsacum* species and Teocinte species and subspecies, are expected to respond differently to CC due to different environments in which they currently inhabit (Randolph, 1970; Kato *et al*., 2009). These taxa are key for the long-term conservation of maize, as they constitute an important reservoir of natural genetic variation that may become important to respond to environmental or pest challenges associated to certain CC scenarios (Wellhausen *et al*., 1951; Ruiz Corral *et al*., 2001).

Ecological niche modeling is mainly used to evaluate potential impacts of CC on the distribution of wild species (Peterson *et al*., 2002; Titeux *et al*., 2007; Williams *et al*., 2007) or to identify new suitable areas for their populations (Raxworthy *et al*., 2003), among other topics (Elith & Leathwick, 2009). However, as far as we know, such approach has never been used for cultivated plants or domestic animals. Similar studies by Jarvis *et al*. (2008) and Lira-Saade *et al*. (2009) have focused on crops' wild relatives, but not on the domesticated species. Such a lack of studies might obey the relative independence of domesticated species to climatic conditions due to human intervention. However, it is well known that climate, particularly precipitation and temperature, still play a key role on the geographic distribution of crops (Slingo *et al*., 2005; Gay *et al*., 2006). This dependency is greater in regions where traditional agroecological practices (i.e., no irrigation and reduced use of agrochemicals) is the main production system. At the same time, the quality and detailed information available for cultivated varieties, such as those of maize in Mexico, make traditional agrosystems a valuable target to assess whether species distribution modeling is a good approach to evaluate CC impacts on domesticated plants.

Methods

Maize races, Teocintes and Tripscaum

Maize races, Teocintes and *Tripsacum* taxa were studied at the country level in Mexico. Databases on georeferenced data for successful cultivation of Mexican maize races were obtained from CONABIO (2011). This database incorporates information in 57 of 59 described races of maize (Sánchez Gonzáles *et al*., 2000) with 13 622 records. However, we focused on only 47 races for three main reasons: (a) several races had very small sample sizes (< 18 unique localities) even after 50 years of collecting data and more than 10 000 records in the last 10 years. These races have been so rarely collected that their race status should be reviewed. Consequently, the races Mixeño, Negro Mixteco, Palomero de Chihuahua, Purépecha Quicheño, Nal-tel de Tierra Fría, and Motozinteco were excluded from the study. (b) Chiquito and Nal-tel de Altura are synonym races, as well as Bofo and Elotes Occidentals (Ortega Paczka *et al*., 1991), and thus, we merged them correspondingly. (c) Cubano Amarillo is not of Mexican origin (Ortega Paczka, 1973), and so it was also discarded.

In terms of the wild relatives, the database contained information on fifteen taxa of *Tripsacum* (with 554 records) and five of Teocintes (967 records). Minimum sample sizes for producing reliable niche models at the species level has been discussed (Stockwell & Peterson, 2002; Wisz *et al*., 2008); although nine sample points is still a small sample size, it has been considered sufficient for some modeling methods (e.g., GARP), especially for rare species with few records (Stockwell & Peterson, 2002). Hence, four taxa of *Tripsacum* (*T. anderzonii*, *T. dactyloides floridanum*, *T. jalapense*, and *T. manisuroides*) and one Teocinte (*Z. luxurians*) with less than nine unique records were excluded from the study.

Climatic data

Data on current and future climatic scenarios were obtained from Conde *et al.* (2008), drawn from the Centro de Ciencias de la Atmósfera (CCA), Universidad Nacional Autónoma de México webpage (http://www.atmosfera.unam.mx/cclimat/index.php?option=com_content&view=article&id=44&Itemid=63). The current scenario available in the CCA webpage is a subset corresponding to Mexico of the WorldClim database (Hijmans *et al.*, 2005), which is an interpolation from weather stations data spanning from 1950 to 2000 via the thin-plate smoothing splines method. Future scenarios were regionalized for Mexico from the following general circulation models (GCM): ECHAM5/MPI, UKHADGE/M1, and GDFL CM 2.0, for the A1B, A2, B1, and B2 emission scenarios (Nakicenovic *et al.*, 2000), and for two time periods, 2010–2039 (from here on called 2030) and 2040–2069 (i.e., 2050). The current scenario in the CCA dataset is at 0.09° (around 10 km) grid cell resolution, and future scenarios were downscaled to the same resolution with the MAGICC/SCENGEN 5.3 software (see Conde *et al.*, 2008 for details).With the information available on the webpage, it was possible to create 19 bioclimatic variables (annual mean temperature, mean diurnal range, isothermality, temperature seasonality, maximum temperature of the warmest month, minimum temperature of the coldest month, temperature annual range, mean temperature of the wettest quarter, mean temperature of the driest quarter, mean temperature of the warmest quarter, mean temperature of the coldest quarter, annual precipitation, precipitation of the wettest month, precipitation of the direst month, precipitation seasonality, precipitation of the wettest quarter, precipitation of the driest quarter, precipitation of the warmest quarter, and precipitation of the coldest quarter), which express extreme, seasonal and annual patterns of climate, using the ArcInfo aml script provided in the WorldClim website (http://www.worldclim.org/bioclim) for both current and future scenarios.

Ecological niche modeling

Ecological niche models seek to produce an environmental characterization of species' requirements based on georeferenced point locations and a series of digital environmental layers, and then project such suitable environmental conditions into a geographic scenario producing a map representing the potential distribution of the species (Pearson & Dawson, 2003; Guisan & Thuiller, 2005; Araújo & Rahbek, 2006). Using a parallel series of environmental scenarios at different times, niche model results can be projected for past or future climatic conditions and potential distribution maps produced for such time periods to assess species' geographic responses to changing climates (Peterson *et al.*, 2002; Martínez-Meyer *et al.*, 2004; Thomas *et al.*, 2004; Pearman *et al.*, 2010).

Under such scheme, we used four modeling algorithms implemented in the OpenModeller v1.0.6. (Muñoz *et al.*, 2009) modeling system: BIOCLIM (Nix, 1986), the Genetic Algorithm for Rule-set Production (GARP) with the selection of 'Best subset' models (Stockwell & Peters, 1999; Anderson *et al.*, 2003), Envelope Score (ES; Piñeiro *et al.*, 2007; Nix, 1986), and Support Vector Machine (SVM; Schölkopf *et al.*, 2001).

A total of 100 projections were obtained for each taxon. We produced four projections for the present (one with each of the modeling algorithm) and 96 projections for the future: one with each modeling algorithm for the three GCMs and four emission scenarios at two time periods in the future (2030 and 2050). To integrate the 100 projections into nine final maps per taxon (one under current conditions and eight for future scenarios), we followed a consensus ensemble approach (Araújo & New, 2007). Under this approach, all projections were combined to identify areas where most of them agree in predicting the presence of a species. It is a helpful way to deal with uncertainty that comes from different sources, including point data inaccuracies (Wiens *et al.*, 2009), modeling algorithms (Pearson *et al.*, 2006), GCMs, and the emission scenarios (IPCC, 2007). The ensemble approach helps produce more conservative projections than individual ones by identifying those areas with higher consensus from all individual projections. In addition, it has been evaluated that ensembles produce significantly more robust predictions than single-models, increasing the accuracy of species distribution forecasts (Marmion *et al.*, 2008). Ensembles can be produced in different ways (Araújo & New, 2007). We generated our ensembles with a sequential majority consensus procedure to assure that only those areas with the highest support were identified as suitable for the taxa, hence reducing uncertainty. The procedure was as follows: first, for each taxon, projections obtained from each modeling algorithm for present and CC scenarios (e.g., BIOCLIM-ECHAM-A2-2030, GARP-ECHAM-A2-2030, ES-ECHAM-A2-2030, and SVM-GFDL-A2-2030) were overlaid in a GIS. The map obtained out of this sum was converted into a binary map (i.e., presence-absence) using as a decision criterion, the areas in which the majority of the individual projections coincided in predicting the presence of the taxon. In other words, the areas in which three and four modeling algorithms agreed to predict the presence of the species were considered areas of presence, and the rest were scored as 'absence'. Next, once the modeling algorithms were ensembled, we carried out the consensus for the three GCMs using the same criterion, i.e., the areas where two and three projections coincided in predicting the presence of the species were coded as such, otherwise they were coded as absence. As a result, we obtained nine maps per taxon for each scenario and time: present, 2030 A1B, 2030 A2, 2030 B1, 2030 B2, 2050 A1B, 2050 A2, 2050 B1, and 2050 B2.

Projections from individual algorithms were validated with the area under the curve (AUC) of the receiver-operating characteristic (ROC) plot (Fielding & Bell, 1997). All those taxa with more than 100 unique geo-referenced records were validated with a random 50% set of the original data points, and for those with less than 100 localities, we used a 25% random dataset. The ROC plots were calculated for each algorithm separately. To assess the predictive performance of ensembles, we carried out a Chi-square test taking all those points that were not used to create the projections as validation data (See Appendix S1) (Guisan & Zimmermann, 2000; Peterson, 2001).

Finally, taxa richness maps were obtained by combining final individual projections for the present and for 2030 and 2050 A2 and B1 scenarios. We selected A2 and B1 scenarios because they represent the most pessimistic and optimistic pictures in the future.

Critical bioclimatic thresholds

Bioclimatic thresholds for the 47 maize races and their wild relatives have not yet been fully documented (Ruiz Corral *et al*., 2008) and they are useful to identify similarities among taxa and to know their physiologic tolerances to some climatic factors. Furthermore, the database with which we carried out the analysis has more than three times the number of data that were used in the single piece of information available in this regard Ruiz Corral *et al.* (2008), and thus, a more complete view of tolerance ranges is provided here. Climatic thresholds were extracted by overlaying occurrence records on the 19 bioclimatic variables and by making some basic statistics for all points of the same taxon. The environmental variables extracted were as follows: altitude, mean annual temperature, maximum temperature of the warmest month, minimum temperature of the coldest month, annual precipitation, precipitation of the wettest month, and precipitation of the driest month. In the case of maize races, additional monthly variables were also taken into account: mean temperature and cumulative precipitation between May and October (spring-summer cycle) and between November and April (autumn-winter cycle).

Critical bioclimatic thresholds for each taxon were obtained by extracting the pixel values of their localities using the GIS ArcView 3.2 by overlaying georeferenced data onto bioclimatic maps for Mexico (Téllez *et al*., 2011), and then calculating the minimum, maximum, and average values of the variables mentioned above. The maps used for the bioclimatic thresholds were different from the ones used in the modeling analyses, as they were produced with a much more dense weather station network that covers a larger time span (1898–1995) and final grids are at 1 km resolution (Téllez *et al*., 2011), and thus, they represent climatic patterns more accurately. We were not able to use this climatology for our modeling analyses because their future scenarios counterparts do not exist.

Results

Model validation tests show generally good model performance (AUC > 0.8) for most taxa with the four algorithms. Overall AUC values for maize was 0.924, ranging from 0.795 in Tablilla de Ocho to 0.985 in Serrano Mixe (Appendix S1). For *Tripsacum* and *Teocintes*, AUC scores were also acceptable, with overall performance of 0.894 and 0.857, respectively (Appendix S1). Furthermore, validation tests of ensembles indicated high predictive capacity. Omission values were generally low, with an overall value of 17.84% for maize, 20.02% for *Tripsacum*, and 5.35% for Teocinte. All ensembles had significantly greater predictive values than random expectations ($P < 0.01$; Appendix S1). The consensus assembling followed in this study allowed us to reduce uncertainty by finding the distribution areas with the highest support, producing conservative results.

According to our projections, under current conditions, 77% of the country is suitable to grow at least one race of maize, 36% for at least one taxon of *Tripsacum*, and 18% for at least one Teocinte species or subspecies. Reductions were observed for 2030 and 2050 under different emission scenarios, as shown in Figs 1 and 2. We found significant differences in the potential distribution area loss for maize and *Tripsacum* in 2050 between the pessimistic emission scenario A2 and the optimistic B1 (Mann–Whitney, $P = 0.0021$ and $P = 0.0257$ respectively). In Teocintes, reductions were also observed (Figs 1 and 2), but significances could not be evaluated.

Vulnerability of maize races to climate change

In 2030, in the most pessimistic emission scenario (A2), 43 of 47 races showed a decrease in their potential distribution areas, and four presented an increase, whereas in 2050, 44 reduced their areas, and only three increased them. In the most optimistic scenario (B1) area, increases were detected in six races in 2030 and in four by 2050

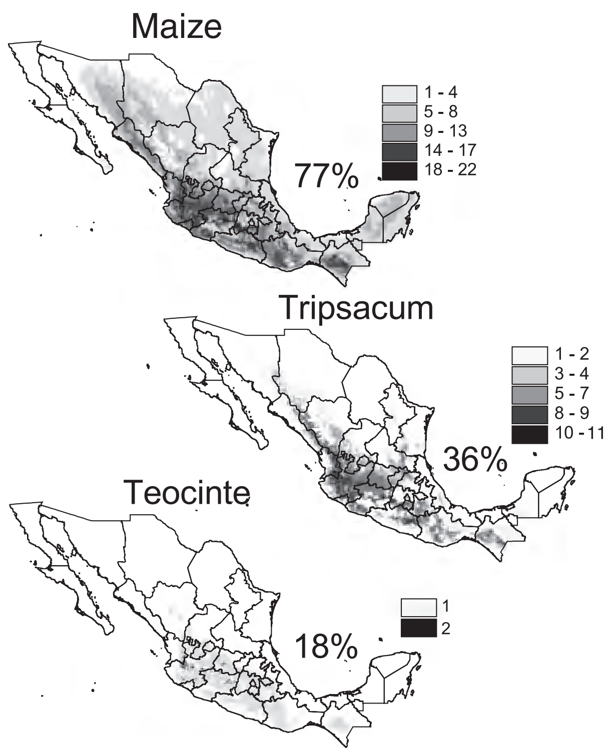

Fig. 1 Richness maps of maize races, *Tripscum* and *Teocinte*, under current climatic conditions. The percentage represents the total suitable or at least one taxon.

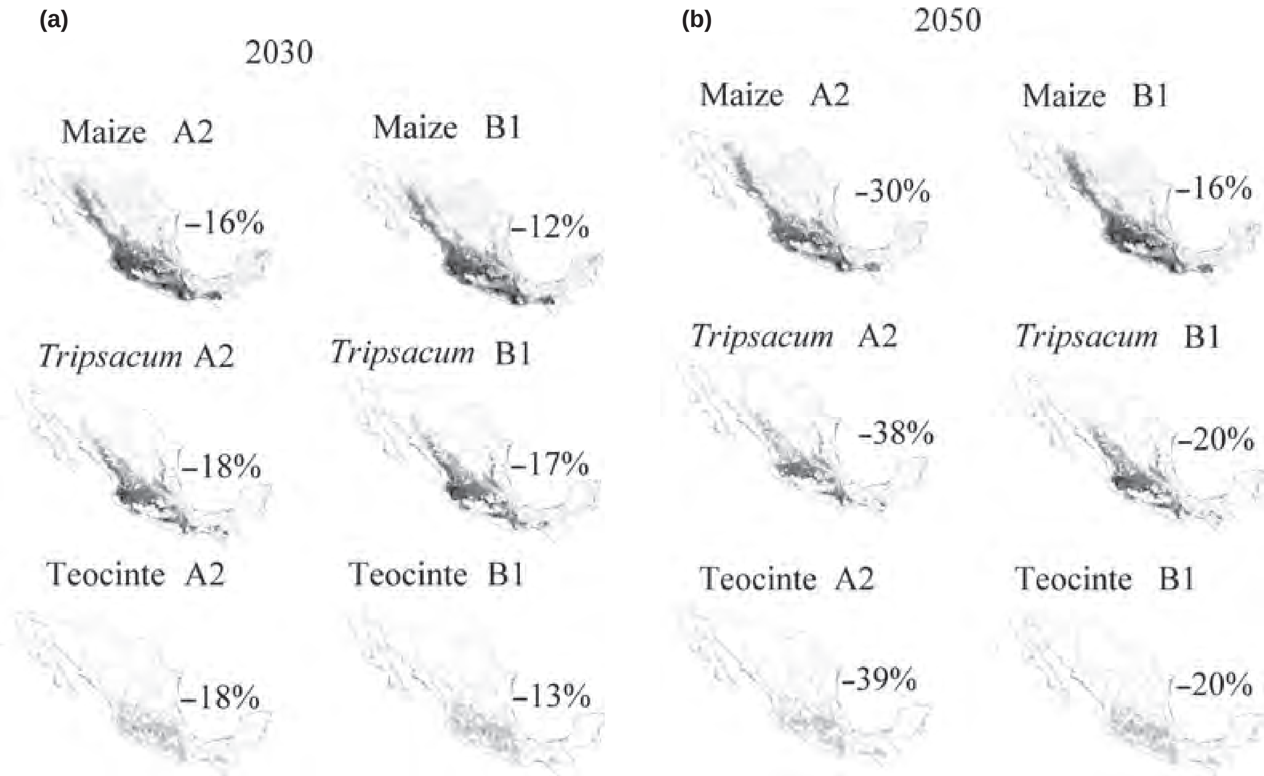

Fig. 2 PDA in 2030 and 2050 under A2 (worst case scenario) and B1 (best case scenario) emission scenarios. The percentage represents the loss of suitable area.

(Appendix S2). The most vulnerable races in terms of area loss either in 2030 or 2050 are presented in Tables 1 and 2. However, even those races that were detected to be among the top five most vulnerable, such as Jala and Coscomatepec, present novel potential suitable areas for the two time periods in the future (Appendix S3). Similarly, 32 other races also presented new suitable areas either in 2030 or 2050 (Appendix S3).

Analysis of bioclimatic thresholds indicated that most vulnerable taxa have some characteristics in common. For example, some races showing the highest decreases (Appendix S2) tend to be distributed in temperate areas with medium annual precipitation (Palomero Toluqueño, Jala and Chapalote), and with restricted distributions (Appendix S3 and S4). Instead, races that were predicted to increase their suitable areas in the future tend to be distributed in hotter and wetter regions that currently inhabit a high number of vegetation and climatic regimes (e.g., Tuxpeño, Vandeño and Conejo; Appendix S3 and S4).

The regions in the country with highest potential race richness under current conditions were in the southern states of Oaxaca and Chiapas, in the western state of Jalisco, in the northern state of Sinaloa, and in central Mexico (Figs 1 and 2). Although in the forthcoming decades these areas of highest richness are not expected to change, our projections show important reductions in race numbers, especially by 2050 (Figs 1 and 2). Most of the potentially suitable areas in the future not inhabited by any race under current conditions were found in the center and south of the country. Ancho, Arrocillo, Conejo, and Serrano Mixe were the only races having novel areas in the north (Appendix S3). Although the northern part of the country does not present great concentration of races (Fig. 1), around 16 races are dispersedly distributed in this region, and between 4 (A1) and 10 (B1), more are expected to find suitable conditions there in the future. Therefore, the entire country plays an important role in preserving the diversity of maize races, both now and in the future.

Vulnerability of wild relatives to climate change

One (A2) and two (B1) taxa of *Tripsacum* were projected to increase their potential distributional areas in 2030 (Tables 1 and 2) and the rest would decrease; however, in 2050, all taxa showed reductions (Appendix S2). Moreover, 4 of 11 taxa presented new suitable areas in A2 scenario and 8 of 13 in B1 scenario (Appendix S3). Species under highest risk is *T. intermedium*, which currently holds the narrowest range of temperature tolerance (Appendix S4) and is expected to lose all of its

Table 1 Major reductions and increases in maize races and wild relative PDAs for 2030 and 2050 under the worst case scenario A2

A2 2030 Maize		*Tripsacum*		Teocinte	
Palomero Toluqueño	−96.82	*T. intermedium*	−96.00	*Z. diploperennis*	−100.00
Coscomatepec	−51.78	*T. latifolium*	−40.14	*Z. perennis*	−100.00
Jala	−50.75	*T. laxum*	−28.65	*Z. mays mexicana*	−23.93
Zapalote Grande	−44.33	*T. dactyloides hispidium*	−22.27	*Z. mays parviglumis*	−9.70
Chapalote	−43.72	*T. maizar*	−21.63		
Maize		*Tripsacum*			
Blando de Sonora	0.61	*T. lanceolatum*	4.09		
Conejo	6.18				
Vandeño	6.20				
Tabloncillo Perla	12.95				

A2 2050 Maize		*Tripsacum*		Teocinte	
Palomero Toluqueño	−99.57	*T. intermedium*	−100.00	*Z. diploperennis*	−100.00
Jala	−98.49	*T. latifolium*	−63.62	*Z. perennis*	−100.00
Apachito	−92.44	*T. laxum*	−55.94	*Z. mays mexicana*	−50.86
Chapalote	−75.99	*T. maizar*	−54.30	*Z. mays parviglumis*	−24.46
Dzit-Bacal	−72.89	*T. dactyloides mexicanum*	−47.15		
Maize					
Conejo	6.41				
Vandeño	10.71				
Tabloncillo Perla	26.45				

suitable area by 2050 (Appendix S3). The richest areas for *Tripsacum* are located in Jalisco, Colima, Guerrero, and in central Mexico. Under climate change, these areas are also projected to decrease (Figs 1 and 2).

The most drastic consequences of CC were aimed at Teocintes, as all its taxa presented reductions in their suitable areas both in 2030 and 2050 (Figs 1 and 2). It must be noticed that our simulations suggest that suitable areas for *Z. diploperennis* and *Z. perennis* may disappear, and important reductions are expected for *Z. mays parviglumis* and *Z. mays mexicana* for all future scenarios (Table 1). Even so, the last two taxa showed new suitable areas in the future, which may be explored now toward conservation purposes. For Teocintes, the richest areas are located in Jalisco and Oaxaca (Fig. 1), but these areas are expected to suffer drastic reductions under all scenarios (Fig. 2).

Discussion

Priority areas for conservation

Areas identified to hold conditions for a great number of races under current climatic conditions are highly concordant with those previously identified areas of origin and greatest diversification of maize derived (Kato *et al.*, 2009), thus providing support to our results. Concordant areas of highest richness were as follows: the southern states of Oaxaca and Chiapas, Central Mexico (both proposed as a centers of origin-domestication), and the western state of Jalisco and surrounding areas (proposed as center of diversification). Kato *et al.* (2009) also proposed the northern state of Chihuahua as an important center of maize diversification. Even though our results did not project high-richness patterns in northern states, experts assure that these areas might have a lot more maize diversity than that reported until now (Acevedo *et al.*, 2011), as suggested by recent explorations throughout the country. Such an effort is a clear necessity, and we firmly encourage its continuation, as a more complete sampling is needed for several races to clarify their status (e.g., Mixeño, Negro Mixteco, Palomero de Chihuahua, Purépecha, Quicheño, Nal-tel de Tierra Fría, and Motozinteco) and also to improve modeling efforts (Stockwell & Peterson, 2002).

For the purpose of preserving maize diversity, we propose a main priority to develop a detailed gap analysis to identify critical areas for maize and its wild relative's diversity conservation that are currently not protected under any formal conservation scheme. High-rich areas of maize resulted quite stable under CC, as no important shifts were detected, and the greatest

Table 2 Major reductions and increases in maize races and wild relative PDAs for 2030 and 2050 under the best case emission scenario B1

B1 2030					
Maize		*Tripsacum*		Teocinte	
Palomero Toluqueño	−99.71	*T. intermedium*	−96.00	*Z. diploperennis*	−100.00
Chapalote	−53.94	*T. laxum*	−23.25	*Z. perennis*	−100.00
Tehua	−52.89	*T. latifolium*	−21.95	*Z. mays mexicana*	−15.83
Coscomatepec	−48.69	*T. dactyloides hispidium*	−19.64	*Z. mays parviglumis*	−8.98
Jala	−46.73	*T. maizar*	−12.33		
Maize		*Tripsacum*			
Conejo	0.86	*T. zopilotense*	2.43		
Reventador	1.36	*T. baravum*	10.63		
Tuxpeño	4.05				
Blando de Sonora	12.10				
Vandeño	13.71				
B1 2050					
Maize		*Tripsacum*		Teocinte	
Palomero Toluqueño	−96.96	*T. intermedium*	−100.00	*Z. diploperennis*	−100.00
Cacahuacintle	−73.60	*T. latifolium*	−36.66	*Z. perennis*	−100.00
Coscomatepec	−64.61	*T. laxum*	−32.09	*Z. mays mexicana*	−32.99
Dzit-Bacal	−62.29	*T. dactyloides hispidium*	−22.68	*Z. mays parviglumis*	−2.89
Jala	−53.27	*T. maizar*	−18.14		
Maize					
Conejo	6.58				
Blando de Sonora	8.22				
Vandeño	8.36				
Tabloncillo Perla	17.75				

decreases were projected in relatively low-rich areas (< 8 races). These results also highlight the strategic importance of preserving the diversity of Mexican races and the role of race diversity in buffering the effects of CC. In high-rich areas, if some races are negatively impacted by climatic changes, there is a higher probability that more resistant races may cover the deficit. Preserving native maize diversity is critical to maintain production under CC. Sufficient provision to satisfy local needs implies fulfilling specific food or cultural needs, as well as avoiding the need to increase transportation and hence, the release of greenhouse gases.

Jalisco and Oaxaca are likely to be very important states for the conservation not only of maize races but also for Teocintes and *Tripsacum*. Similar richness patterns were found for 2030 and 2050, although strong areal reductions were projected (Figs 1 and 2). Conservation efforts should be focused on the most vulnerable taxa of these groups (e.g. *Z. diploperennis*, *Z. perennis*, *T. intermedium*) and *ex situ* and *in situ* programs should be considered; especially with Teocinte taxa, which presented the most potentially and negatively impacted and are the direct maize ancestors (Kato *et al*., 2009).

Vulnerability

We were able to identify three main spatial responses of taxa to CC: (1) suitable area increases, (2) suitable area decreases with prediction of new suitable areas, and (3) decreases of suitable areas without prediction of new suitable areas. From these, taxa in the third category are considered at higher risk. In general, our results indicated significant suitable area reductions for maize and its wild relatives under CC scenarios in 2030 and 2050. A decrease in the area suitable for maize cultivation under CC scenarios was also reported by Monterroso *et al*. (2011). However, this previous study suggested that areas of higher suitability would be more impacted by CC. Instead, our results suggest that the richest areas would be the least impacted. This difference is because the most suitable areas identified by Monterroso *et al*. do not coincide with the agro-richest areas in Mexico. Most of the native races in Mexico are not grown under conditions for very productive maize, but centuries of human selection has produced several races adapted to very different climatic circumstances, fulfilling nutritional needs and a variety of cultural purposes for local populations. Such diversity seems to be critical to resist CC.

Negative impacts varied depending on the emission scenario. Consequently, conservation of domesticated species and their wild relatives at centers of origin should be a priority worldwide and not only regionally. As our results show, actions at a global scale may have consequences at national and local levels, but disruptions at the local level may also affect global food security.

In addition to these generalizations on the geographic behavior of maize races and their wild relatives, some specifications were also detected. For example, vulnerable maize races presented certain patterns in temperature and precipitation requirements, as well as thresholds for growth that could not be found in their wild relatives. They are distributed in areas under relative temperate and dry conditions during the spring–summer cycle. Water availability and seasonality is very important in their ecology and physiology, and thus for their distribution; if spring-summer rainfall decreases or patterns of precipitation gets disrupted, crops are severely affected (Brenes-Arguedas *et al*., 2009; Hlavinka *et al*., 2009), especially when irrigation is not a common practice, as is the case for most Mexican farmers (Bellon *et al*., 2005; Esteva & Marielle, 2007). Consequently, maize production may not afford drier conditions. In terms of temperature, taxa adapted to low temperatures have already been reported as vulnerable to CC (Villers–Ruiz & Trejo–Vázquez); thus, temperature increases to the levels projected by CC scenarios are also expected to affect maize races physiology, ecology, and therefore their geographic distribution. As observed in our results, vulnerable maize races and wild relatives tended to hold more restricted distributions and occupy a lower number of environmental domains than less vulnerable taxa. Races with larger distributions are less prone to the negative effects of climatic changes because novel climates are likely to be occupied by more plastic races. The great genetic diversity and biologic plasticity of maize, both at the intra- and inter-race levels, might play an important role for buffering the negative impacts of CC (Mercer & Perales, 2010).

Races and species whose distributions are expected to decrease severely or even disappear urge special attention. Our analyses suggest that *T. intermedium*, *Z. perennis*, Palomero Toluqueño, Jala, Apachito, Chapalote, and Dzit-Bacal y Zapolote Grande are the most vulnerable taxa in terms of suitable area loss. Risk factors that make these taxa more vulnerable should be reduced. For example, the Apachito and Chapalote races are endemic to the northern part of the country adapted to hot and dry climates. These races may become highly useful in the future, given the tendency of climate to such conditions. Hence, special care to avoid their loss or their modification due to hybridization with improved varieties or transgenic introgression should be made.

Finally, Conde *et al.* (1997) reported that maize might be favored at high altitudes under CC; but even when these areas might become more adequate for additional races or wild relatives, some specific habitats in high altitudes to which other races or wild relatives are adapted will be threatened by CC (Mercer *et al*., 2008). For example, in our study, *T. intermedium* and Palomero Tolqueño grow at high altitudes (Appendix S4) and were recognized as two of the most vulnerable taxa. Also, *Z. perennis* has an extremely restricted distribution, and models projected that suitable climatic conditions for this species are expected to disappear in the forthcoming decades.

Finding new suitable areas

New suitable areas in some cases may represent genuine geographic space that has not been explored yet (Raxworthy *et al*., 2003; Mercer & Perales, 2010), although it should be noted that most seed lots (90%) are obtained within 10 km of a community (Bellon *et al*., 2011). Bellon *et al.* also found that predicted future maize environments were already represented within the 10 km radial zone for 19 of 20 communities studied. In the context of this study, new suitable areas offer the possibility to detect geographic regions with suitable abiotic conditions where vulnerable taxa may be experimentally grown and eventually translocated. Although, most maize races are grown by particular cultural groups and for particular purposes, including a variety of food types and religious ceremonies (Reyes Castañeda, 1990; Esteva & Marielle, 2007), farmers also grow races that are able to grow according to the climatic conditions in a particular moment and place (Seo & Mendelsohn, 2008).

New potential suitable areas under current conditions imply that even when temperature and precipitation have a great influence on the distribution of crops and their wild relatives (Seo & Mendelsohn, 2008), other historic, biotic, and sociocultural factors might be limiting their dispersion (Brush & Perales, 2007). For instance, for *Tripsacum* and Teocinte, biologic interactions, geographic barriers, and dispersal characteristics may be restraining their potential distribution to a smaller area. For maize races, biologic as well as agronomic or cultural factors, such as the ethnic group, pest management, or agrotechnological practices might be playing a fundamental role in restricting their distribution. Niche modeling resulted in a useful first approximation to understand the factors determining distributions of maize races and wild relatives. However, there is still a need of incorporating physiologic, ecological, economic, and cultural information into the models to have a better insight of CC possible consequences on maize (Kearney & Porter, 2009; Stephens *et al.*, 2009).

In conclusion, our results suggest potentially significant reductions of suitable areas for most maize races and its wild relatives under CC, with differential responses among the 47 Mexican races and their wild relatives analyzed here. Also, we were able to identify vulnerable taxa and detect new suitable areas for several taxa in the future. However, although the assembling approach followed in this study produced conservative, reliable models, still several sources of uncertainty can be detected, including scant data for some taxa, and variation among modeling algorithms and among CC models and scenarios; thus, results should be interpreted within the limits of the modeling system.

From our results, some basic recommendation can be drawn to improve our understanding of the possible impacts of CC on maize and to reduce its vulnerability, including: (1) verification of the racial classification; (2) establishment of a monitoring system for the most vulnerable taxa identified; (3) taking into consideration some *in situ* and *ex situ* conservation actions for vulnerable taxa; (4) establishment of formal protection to high-diverse areas and vulnerable taxa; (5) continuation of exploration efforts with the aim of increasing sample sizes and thus improve modeling results; and (6) identification of additional environmental, biologic, and cultural factors that play an important role determining maize and wild relatives' distributions.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. (A) Distribution Modeling Validation. Total Area Under the Curve values of the ROC-test of each algorithm used for each taxa under study. (B) Chi-square test to assess the predictability of the ensemble under current climatic conditions for each taxa under study.
Appendix S2. Vulnerability. Percentage of increases or decreases in the potential distributioin area under climate change scenarios for maize, *Tripscaum* and Teocinte.
Appendix S3. Potential Distribution Areas under 2030, 2050, and current climatic conditions.
Appendix S4. Critic Bioclimatic Thresholds for Mexican races and wild relatives.

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Appendix 1. B. Distribution Modeling Validation. *Chi*-square test to assess the predictability of the ensemble under current climatic conditions for each taxa under study.

	Chi-square	*P*	Omission %
Ancho	197.028	9.2967E-45	15.385
Apachito	167.112	3.1625E-38	16.667
Arrocillo	554.365	1.414E-122	8.333
Azul	158.513	2.3913E-36	16.667
Blando de Sonora	59.082	1.5127E-14	27.273
Bofo	275.615	6.7795E-62	23.377
Bolita	1124.328	1.704E-246	25.962
Cacahuacintle	138.863	4.7185E-32	12.500
Celaya	660.180	1.365E-145	23.276
Chalqueño	851.553	3.342E-187	16.352
Chapolote	812.020	1.315E-178	0.000
Chiquito	1139.634	8.033E-250	25.000
Comiteco	1990.564	0	20.482
Complejo Serrano Jalisco	36.422	1.5892E-09	25.000
Conejo	167.569	2.5126E-38	5.882
Cónico	3370.953	0	14.286
Cónico Norteño	991.188	1.478E-217	21.610
Coscomatepec	501.042	5.641E-111	8.333
Cristalino	587.633	8.198E-130	13.514
Dulce	76.204	2.5588E-18	10.000
Dulcillo del Noroeste	110.654	7.0463E-26	0.000
Dzit-Bacal	1286.376	1.033E-281	20.000
Elotero de Sinaloa	94.557	2.3811E-22	20.000
Elotes Cónicos	832.756	4.078E-183	15.385
Gordo	116.034	4.6717E-27	0.000
Jala	339.596	7.8143E-76	20.000
Mushito	878.146	5.529E-193	17.164
Nal-tel	55.365	1.0012E-13	37.500
Olotillo	1058.666	3.183E-232	20.732
Olotón	1005.272	1.283E-220	31.707
Onaveño	72.948	1.3313E-17	30.769
Palomero Toluqueño	142.802	6.4953E-33	30.000
Pepitilla	315.065	1.7216E-70	5.128
Ratón	107.493	3.4722E-25	25.000
Reventador	227.688	1.9038E-51	21.429
Serrano Mixe	161.320	5.8235E-37	0.000
Tablilla de Ocho	13.724	0.00021172	42.857
Tabloncillo	678.013	1.808E-149	15.789
Tabloncillo Perla	157.176	4.6839E-36	14.286
Tehua	731.668	3.887E-161	16.667
Tepecintle	514.622	6.26E-114	15.702
Tuxpeño	938.753	3.694E-206	18.896
Tuxpeño Norteño	137.993	7.3134E-32	29.333
Vandeño	145.521	1.652E-33	15.152
Zamorano	408.046	9.761E-91	13.514
Zapolote Chico	104.562	1.5233E-24	18.750
Zapolote Grande	288.320	1.1552E-64	12.903
Average			**17.842**

	Chi-square	***P***	**Omission %**
T. baravum	91.059	1.3944E-21	20.000
T. dactyloides dactyloides	89.258	3.466E-21	21.154
T. dactyloides hispidium	84.754	3.3784E-20	7.692
T. dactyloides mexicanum	19.556	9.7689E-06	25.000
T. intermedium	2567.040	0	0.000
T. lanceolatum	138.460	5.7796E-32	28.000
T. latifolium	42.974	5.5486E-11	20.000
T. laxum	60.960	5.8257E-15	0.000
T. maizar	4.410	0.03571927	75.000
T. pilosum	67.014	2.6957E-16	9.091
T. zopilotense	51.494	7.1805E-13	14.286
Average			**20.020**

	Chi-square	***P***	**Omission %**
Z. diploperennis	16059.75	0	0.000
Z. perennis	14276	0	0.000
Z. mays mexicana	1561.37944	0	14.451
Z. mays parviglumis	2997.51294	0	6.944
Average			**5.349**

Appendix 2. Vulnerability. Percentage of increases or decreases in the potential distributioin area under climate change scenarios for maize, *Tripscaum* and Teocinte

2030		2050	
A1		**A1**	
Palomero Toluqueño	-96.38	Palomero Toluqueño	-98.12
Coscomatepec	-52.73	Jala	-88.44
Jala	-49.75	Dzit-Bacal	-82.90
Chapalote	-45.69	Chapalote	-71.92
Zapolote Grande	-42.84	Apachito	-71.51
Tepecintle	-40.95	Cacahuacintle	-70.02
Ratón	-40.69	Coscomatepec	-69.36
Arrocillo	-40.29	Bolita	-58.00
Comiteco	-39.41	Nal-tel	-56.86
Dulce	-38.81	Comiteco	-53.41
Olotillo	-34.91	Tepecintle	-52.94
Dzit-Bacal	-32.05	Cónico Norteño	-51.94
Olotón	-30.28	Serrano Mixe	-51.56
Cónico	-30.26	Zapolote Grande	-51.27
Chiquito	-28.89	Arrocillo	-51.14
Apachito	-28.88	Olotón	-47.84
Nal-tel	-28.51	Cristalino	-47.26
Gordo	-27.54	Olotillo	-46.35
Elotes Cónicos	-27.20	Cónico	-45.43
Chalqueño	-27.06	Gordo	-43.97
Mushito	-25.33	Ratón	-41.88
Onaveño	-24.86	Azul	-41.44
Cacahuacintle	-24.72	Elotes Cónicos	-41.31
Zamorano	-23.69	Onaveño	-41.22
Cónico Norteño	-23.31	Zamorano	-41.00
Cristalino	-21.79	Mushito	-39.46
Azul	-21.55	Dulce	-38.51
Serrano Mixe	-20.70	Tuxpeño Norteño	-32.60
Bofo	-20.58	Chalqueño	-32.08
Tehua	-16.53	Complejo Serrano Jalisco	-29.75
Complejo Serrano Jalisco	-15.00	Tehua	-26.45
Dulcillo del Noroeste	-14.61	Bofo	-25.43
Tuxpeño Norteño	-12.78	Chiquito	-25.00
Bolita	-12.40	Tablilla de Ocho	-23.34
Zapolote Chico	-9.87	Pepitilla	-21.61
Pepitilla	-9.75	Ancho	-20.80
Tablilla de Ocho	-9.52	Zapolote Chico	-19.81
Ancho	-7.08	Elotero de Sinaloa	-14.64
Celaya	-5.76	Tabloncillo	-14.35
Tabloncillo	-5.47	Dulcillo del Noroeste	-14.20
Elotero de Sinaloa	-5.14	Celaya	-13.68
Reventador	-0.72	Reventador	-2.71
Blando de Sonora	0.61	Tuxpeño	-2.68
Tuxpeño	1.18	Conejo	8.07
Conejo	7.21	Blando de Sonora	8.66
Vandeño	9.35	Vandeño	12.25
Tabloncillo Perla	13.64	Tabloncillo Perla	18.68

A2	
Palomero Toluqueño	-96.82
Coscomatepec	-51.78
Jala	-50.75
Zapolote Grande	-44.33
Chapalote	-43.72
Comiteco	-42.17
Tepecintle	-41.64
Ratón	-41.59
Arrocillo	-41.37
Bolita	-39.10
Apachito	-38.57
Dulce	-38.21
Olotillo	-36.55
Olotón	-33.08
Nal-tel	-30.95
Azul	-30.39
Dzit-Bacal	-30.17
Cónico	-30.07
Elotes Cónicos	-26.23
Mushito	-25.90
Gordo	-25.64
Cacahuacintle	-24.92
Onaveño	-24.73
Zamorano	-24.66
Bofo	-23.74
Cónico Norteño	-23.19
Serrano Mixe	-22.14
Cristalino	-18.21
Tehua	-17.36
Chalqueño	-16.46
Chiquito	-14.44
Complejo Serrano Jalisco	-14.33
Dulcillo del Noroeste	-13.78
Tuxpeño Norteño	-12.48
Zapolote Chico	-11.08
Tablilla de Ocho	-11.06
Pepitilla	-10.08
Ancho	-8.53
Elotero de Sinaloa	-6.09
Celaya	-6.09
Tabloncillo	-5.31
Reventador	-2.22
Tuxpeño	-2.00
Blando de Sonora	0.61
Conejo	6.18
Vandeño	6.20
Tabloncillo Perla	12.95

A2	
Palomero Toluqueño	-99.57
Jala	-98.49
Apachito	-92.44
Chapalote	-75.99
Dzit-Bacal	-72.89
Arrocillo	-69.75
Coscomatepec	-69.60
Comiteco	-63.72
Onaveño	-63.22
Zapolote Grande	-62.46
Cacahuacintle	-62.01
Nal-tel	-60.44
Tepecintle	-59.84
Cónico Norteño	-58.04
Olotillo	-56.66
Serrano Mixe	-55.99
Cristalino	-55.26
Olotón	-53.94
Azul	-52.67
Cónico	-47.48
Zamorano	-47.45
Gordo	-46.44
Mushito	-45.04
Elotes Cónicos	-44.98
Chalqueño	-43.22
Ratón	-42.65
Tablilla de Ocho	-42.54
Dulce	-41.94
Tuxpeño Norteño	-37.82
Bolita	-32.40
Pepitilla	-31.87
Ancho	-31.40
Tehua	-30.58
Complejo Serrano Jalisco	-29.67
Chiquito	-26.11
Bofo	-23.89
Zapolote Chico	-23.23
Elotero de Sinaloa	-20.85
Celaya	-19.77
Dulcillo del Noroeste	-18.98
Tabloncillo	-15.55
Tuxpeño	-9.31
Blando de Sonora	-4.11
Reventador	-4.00
Conejo	6.41
Vandeño	10.71
Tabloncillo Perla	26.45

B1	
Palomero Toluqueño	-99.71
Chapalote	-53.94
Tehua	-52.89
Coscomatepec	-48.69
Jala	-46.73
Olotón	-43.26
Zapolote Grande	-42.52
Dulce	-40.69
Ratón	-39.45
Chiquito	-39.44
Arrocillo	-34.67
Tepecintle	-31.72
Apachito	-31.20
Dzit-Bacal	-30.62
Gordo	-29.82
Cónico	-29.34
Nal-tel	-27.27
Comiteco	-26.70
Olotillo	-26.67
Serrano Mixe	-25.26
Onaveño	-25.05
Mushito	-24.67
Azul	-24.31
Cacahuacintle	-23.94
Cónico Norteño	-22.06
Elotes Cónicos	-21.85
Dulcillo del Noroeste	-17.24
Bofo	-17.17
Bolita	-16.20
Zamorano	-14.99
Chalqueño	-14.35
Zapolote Chico	-13.10
Complejo Serrano Jalisco	-11.17
Cristalino	-10.21
Tuxpeño Norteño	-9.69
Pepitilla	-9.56
Tablilla de Ocho	-9.52
Ancho	-6.58
Elotero de Sinaloa	-5.89
Tabloncillo	-5.64
Celaya	-4.92
Conejo	0.86
Reventador	1.36
Tuxpeño	4.05
Blando de Sonora	12.10
Vandeño	13.71
Tabloncillo Perla	13.97

B1	
Palomero Toluqueño	-96.96
Cacahuacintle	-73.60
Coscomatepec	-64.61
Dzit-Bacal	-62.29
Jala	-53.27
Chapalote	-51.48
Tepecintle	-42.95
Zapolote Grande	-40.83
Ratón	-40.58
Nal-tel	-38.02
Apachito	-37.02
Dulce	-36.23
Arrocillo	-36.01
Cónico	-34.90
Olotillo	-34.67
Olotón	-34.35
Bofo	-34.09
Chiquito	-33.89
Serrano Mixe	-32.55
Comiteco	-31.49
Elotes Cónicos	-29.94
Zamorano	-29.61
Gordo	-29.34
Cónico Norteño	-28.43
Mushito	-27.94
Onaveño	-24.92
Cristalino	-24.21
Azul	-24.13
Tuxpeño Norteño	-20.51
Complejo Serrano Jalisco	-20.17
Tehua	-19.01
Chalqueño	-17.31
Zapolote Chico	-11.77
Dulcillo del Noroeste	-11.01
Pepitilla	-10.26
Celaya	-10.11
Ancho	-8.64
Tabloncillo	-8.45
Elotero de Sinaloa	-6.84
Tablilla de Ocho	-5.12
Bolita	-3.40
Tuxpeño	-0.64
Reventador	-0.53
Conejo	6.58
Blando de Sonora	8.22
Vandeño	8.36
Tabloncillo Perla	17.75

	B2
Palomero Toluqueño	-95.08
Coscomatepec	-47.74
Chapalote	-41.26
Ratón	-38.30
Dulce	-36.53
Zapolote Grande	-33.83
Dzit-Bacal	-33.29
Jala	-29.15
Tepecintle	-28.66
Cónico	-26.16
Arrocillo	-25.44
Comiteco	-24.86
Olotillo	-22.92
Gordo	-22.41
Apachito	-21.90
Cristalino	-21.79
Elotes Cónicos	-21.76
Olotón	-21.12
Nal-tel	-20.50
Azul	-19.71
Mushito	-19.19
Cacahuacintle	-18.46
Cónico Norteño	-17.17
Bofo	-17.10
Serrano Mixe	-16.93
Zamorano	-16.19
Onaveño	-15.98
Tehua	-15.70
Complejo Serrano Jalisco	-14.25
Chiquito	-11.67
Dulcillo del Noroeste	-11.43
Chalqueño	-9.79
Tuxpeño Norteño	-9.38
Zapolote Chico	-5.63
Tabloncillo	-5.25
Celaya	-4.47
Pepitilla	-3.39
Tablilla de Ocho	-2.56
Elotero de Sinaloa	-2.28
Ancho	-1.17
Bolita	-1.00
Reventador	3.28
Tuxpeño	5.21
Conejo	6.24
Blando de Sonora	6.50
Vandeño	9.78
Tabloncillo Perla	13.64

	B2
Palomero Toluqueño	-96.96
Cacahuacintle	-70.25
Dzit-Bacal	-69.38
Coscomatepec	-62.47
Chapalote	-62.19
Jala	-59.80
Apachito	-45.74
Zapolote Grande	-44.06
Tepecintle	-43.39
Comiteco	-42.73
Arrocillo	-42.44
Ratón	-39.70
Cónico	-39.54
Nal-tel	-39.00
Serrano Mixe	-38.41
Gordo	-37.51
Olotillo	-36.63
Cónico Norteño	-35.04
Dulce	-33.60
Olotón	-33.59
Elotes Cónicos	-33.08
Cristalino	-32.95
Azul	-30.94
Mushito	-30.45
Onaveño	-29.74
Zamorano	-29.61
Chiquito	-27.22
Chalqueño	-22.37
Tehua	-22.31
Tuxpeño Norteño	-22.14
Complejo Serrano Jalisco	-20.67
Bofo	-18.43
Zapolote Chico	-13.61
Dulcillo del Noroeste	-12.88
Pepitilla	-12.52
Ancho	-9.37
Tablilla de Ocho	-8.38
Celaya	-8.19
Tabloncillo	-7.74
Elotero de Sinaloa	-7.46
Bolita	-6.30
Reventador	0.94
Tuxpeño	5.67
Conejo	8.47
Blando de Sonora	12.33
Vandeño	14.66
Tabloncillo Perla	23.93

2030

A1

T. intermedium	-96.00
T. latifolium	-34.70
T. laxum	-26.65
T. dactyloides hispidium	-20.09
T. maizar	-16.28
T. dactyloides mexicanum	-14.06
T. pilosum	-8.00
T. dactyloides dactyloides	-6.67
T. zopilotense	1.04
T. baravum	1.26
T. lancolatum	3.07

A2

T. intermedium	-96.00
T. latifolium	-40.14
T. laxum	-28.65
T. dactyloides hispidium	-22.27
T. maizar	-21.63
T. dactyloides mexicanum	-17.68
T. pilosum	-12.57
T. dactyloides dactyloides	-7.31
T. baravum	-6.57
T. zopilotense	-1.95
T. lancolatum	4.09

2050

A1

T. intermedium	-100.00
T. latifolium	-51.50
T. laxum	-49.50
T. maizar	-41.05
T. dactyloides mexicanum	-32.85
T. dactyloides hispidium	-27.50
T. baravum	-26.57
T. pilosum	-24.69
T. zopilotense	-16.53
T. dactyloides dactyloides	-16.51
T. lancolatum	-4.78

A2

T. intermedium	-100.00
T. latifolium	-63.62
T. laxum	-55.94
T. maizar	-54.30
T. dactyloides mexicanum	-47.15
T. baravum	-46.43
T. pilosum	-34.89
T. dactyloides hispidium	-32.24
T. zopilotense	-29.37
T. dactyloides dactyloides	-23.18
T. lancolatum	-8.69

B1	
T. intermedium	-96.00
T. laxum	-23.25
T. latifolium	-21.95
T. dactyloides hispidium	-19.64
T. maizar	-12.33
T. dactyloides dactyloides	-9.28
T. pilosum	-7.08
T. dactyloides mexicanum	-3.14
T. lancolatum	-0.92
T. zopilotense	2.43
T. baravum	10.63

B1	
T. intermedium	-100.00
T. latifolium	-36.66
T. laxum	-32.09
T. dactyloides hispidium	-22.68
T. maizar	-18.14
T. zopilotense	-16.53
T. dactyloides mexicanum	-12.61
T. pilosum	-12.16
T. dactyloides dactyloides	-10.02
T. baravum	-1.26
T. lancolatum	-0.87

B2	
T. intermedium	-84.00
T. laxum	-18.86
T. dactyloides hispidium	-16.39
T. latifolium	-11.78
T. maizar	-3.95
T. dactyloides dactyloides	-3.53
T. pilosum	-2.88
T. dactyloides mexicanum	-0.92
T. zopilotense	2.57
T. lancolatum	5.52
T. baravum	16.22

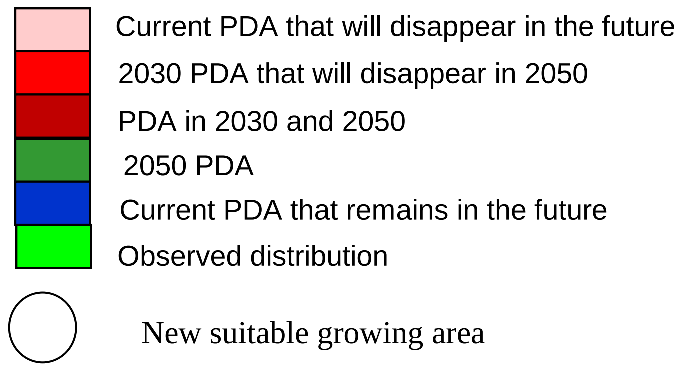
B2	
T. intermedium	-100.00
T. laxum	-39.03
T. latifolium	-34.08
T. zopilotense	-29.37
T. dactyloides hispidium	-22.35
T. maizar	-22.33
T. dactyloides mexicanum	-13.29
T. pilosum	-11.76
T. dactyloides dactyloides	-11.10
T. baravum	-6.43
T. lancolatum	0.07

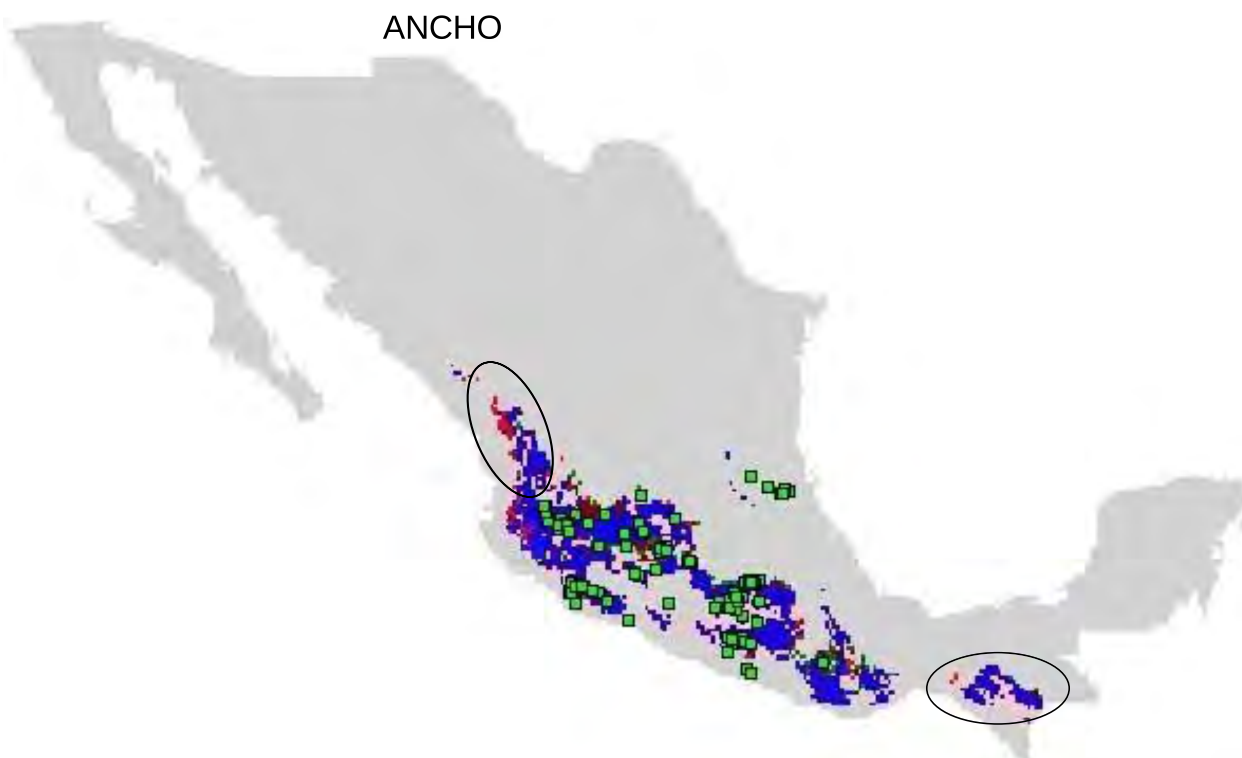
2030	
A1	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-23.93
Z. mays parviglumis	-7.86
A2	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-23.93
Z. mays parviglumis	-9.70
B1	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-15.83
Z. mays parviglumis	-8.98
B2	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-19.34
Z. mays parviglumis	-1.28

2050	
A1	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-47.67
Z. mays parviglumis	-10.99
A2	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-50.86
Z. mays parviglumis	-24.46
B1	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-32.99
Z. mays parviglumis	-2.89
B2	
Z. diploperennis	-100.00
Z. perennis	-100.00
Z. mays mexicana	-33.57
Z. mays parviglumis	-1.36

Appendix 3. Potential Distribution Areas under 2030, 2050 and current climatic conditions

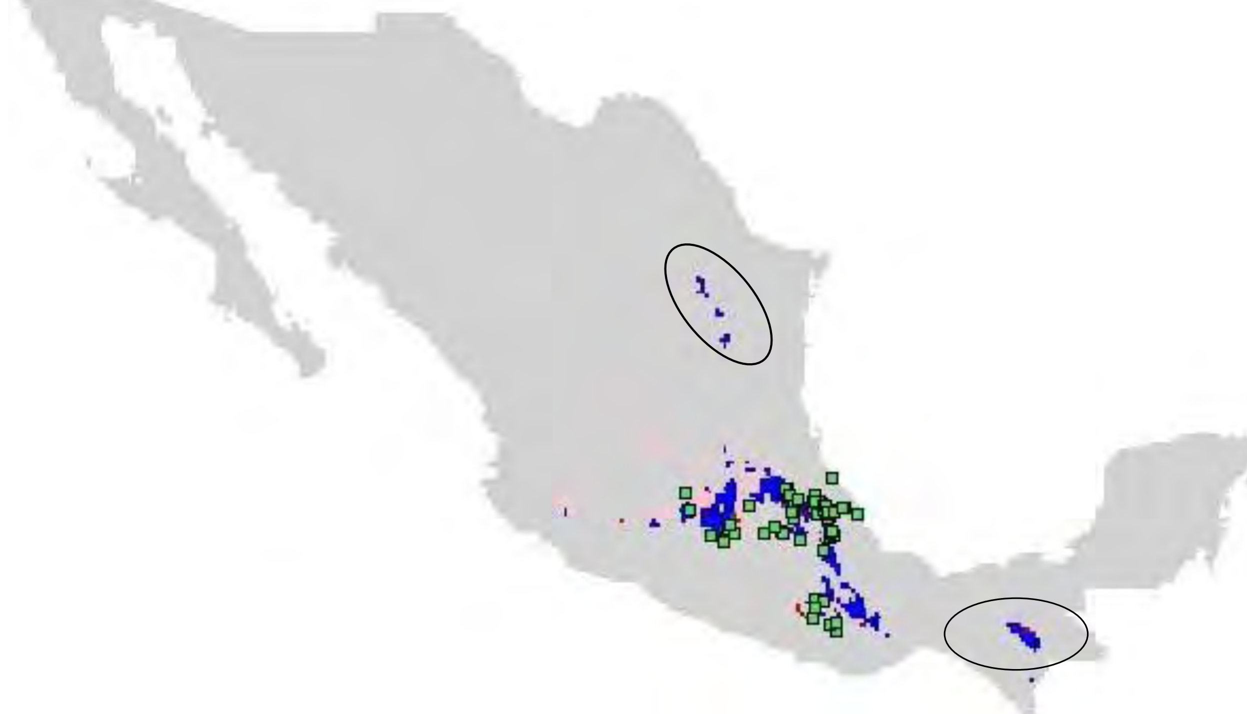
3.1 A2 Worst Case Emission Scenario



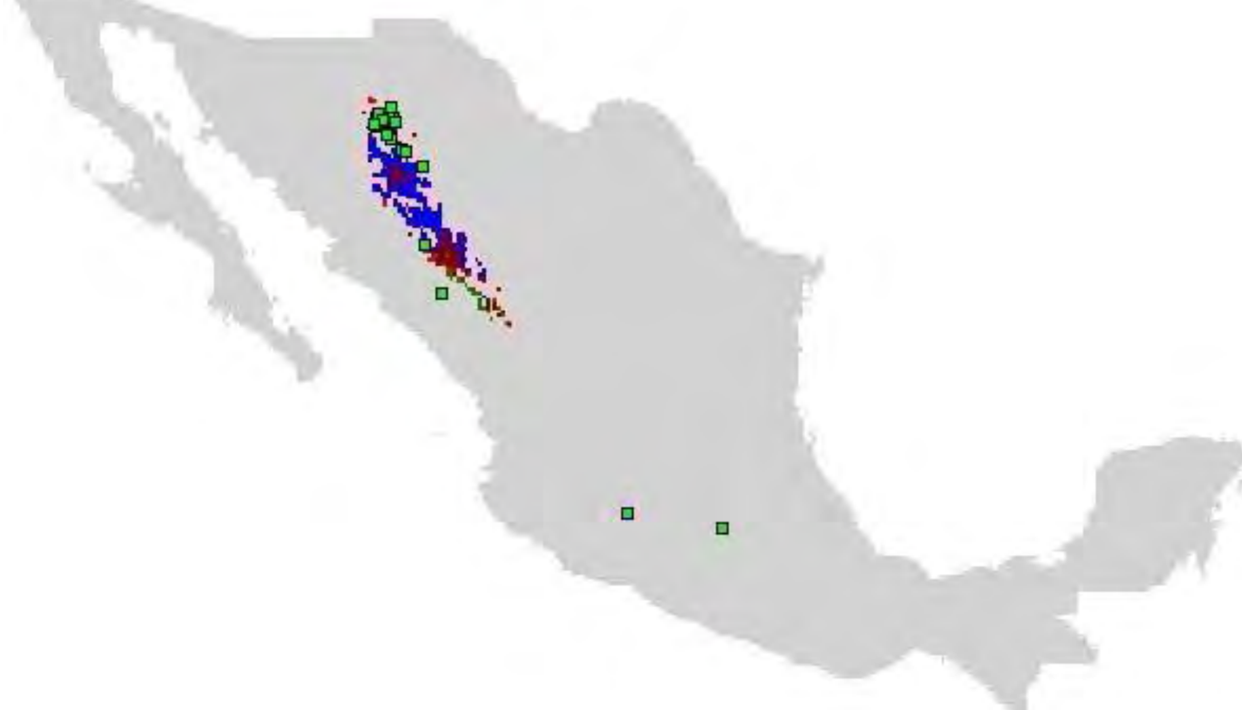

ANCHO


APACHITO

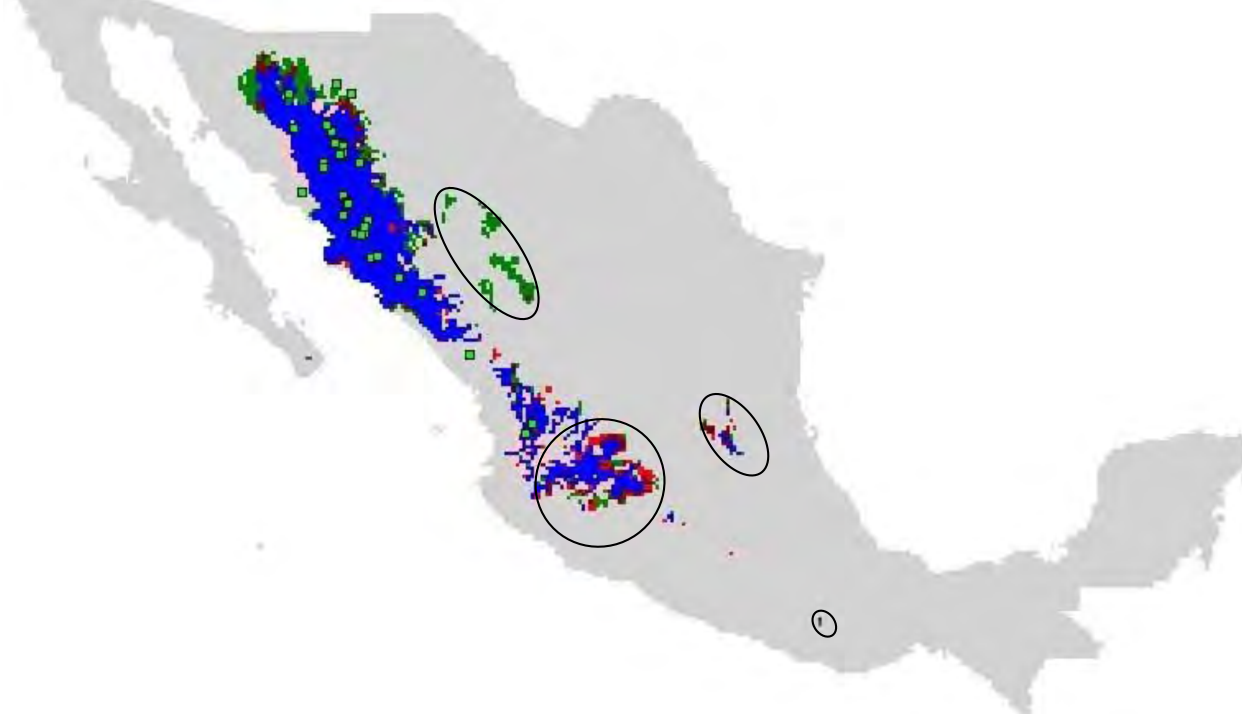
ARROCILLO



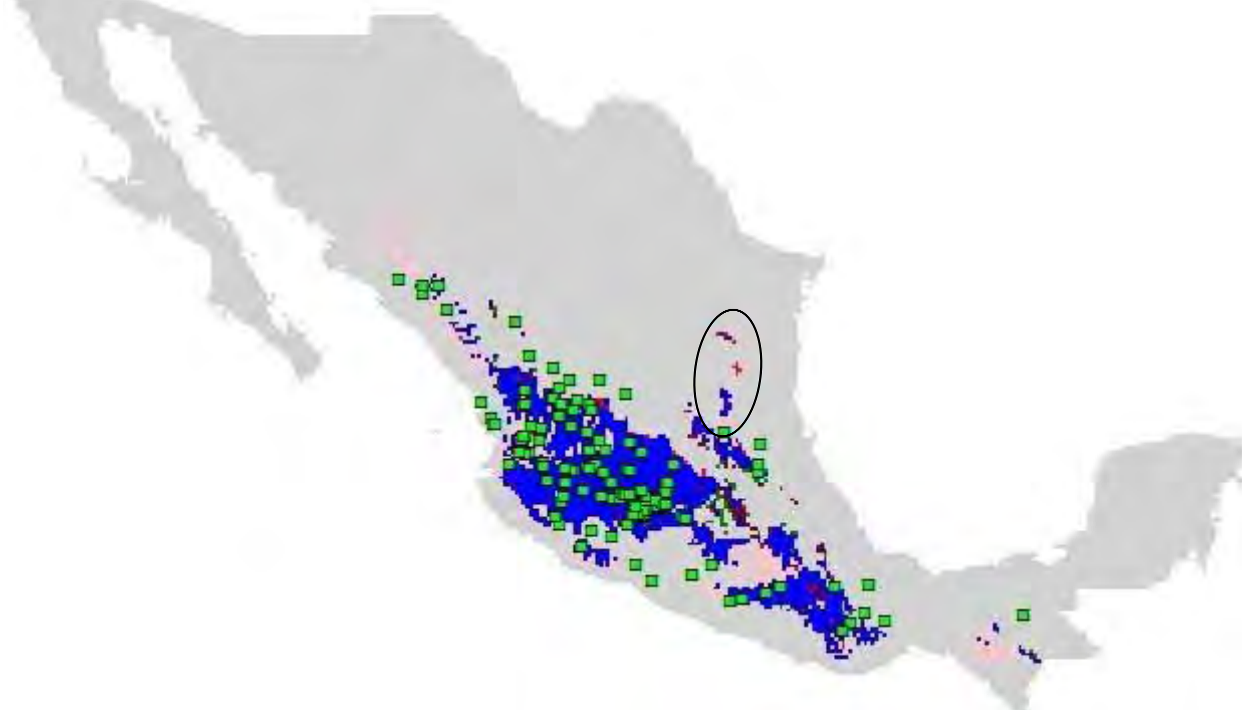
AZUL

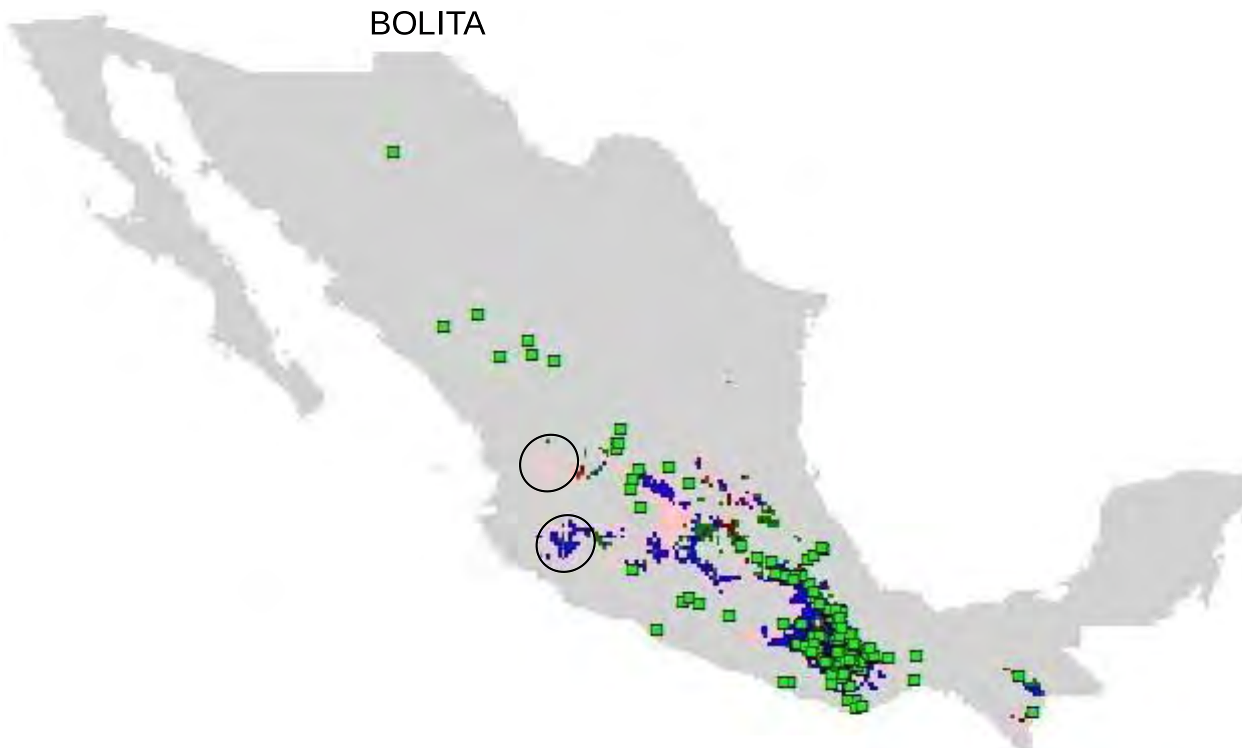


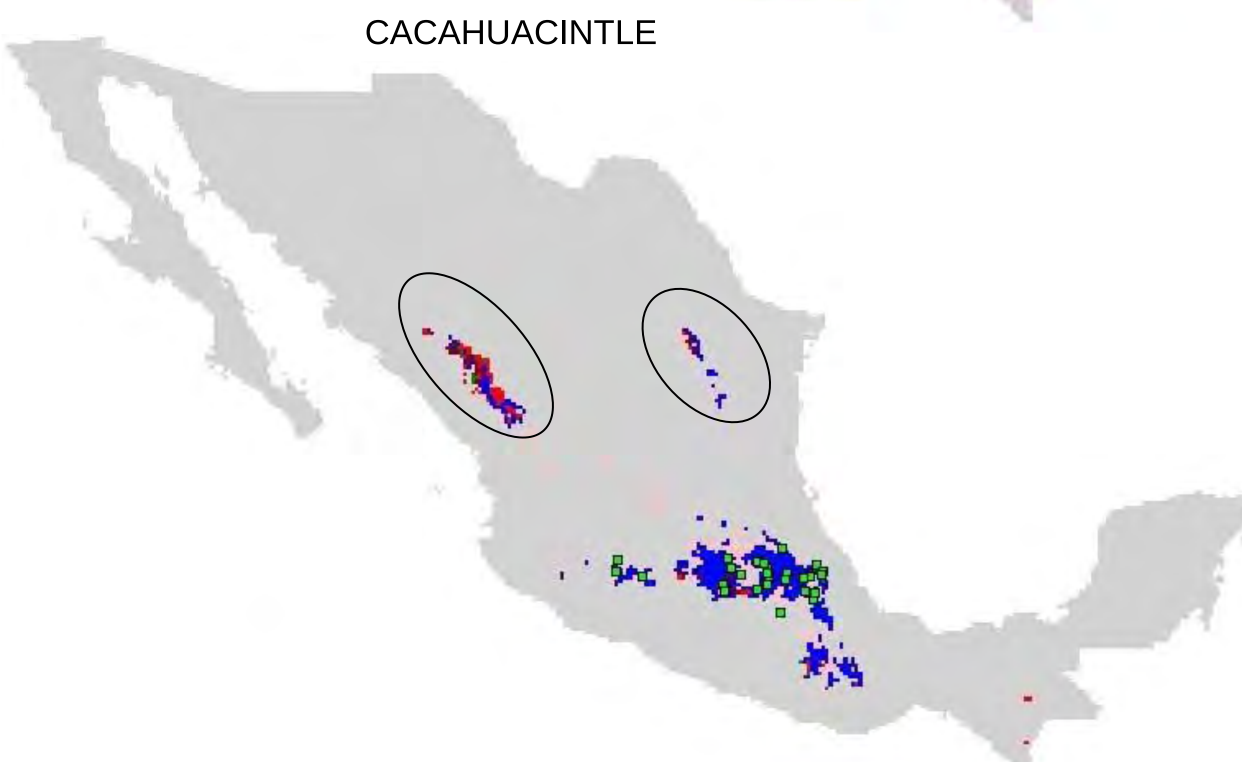
BLANDO DE SONORA



BOFO




BOLITA


CACAHUACINTLE

CELAYA

CHALQUEÑO

CHAPALOTE

CHIQUITO

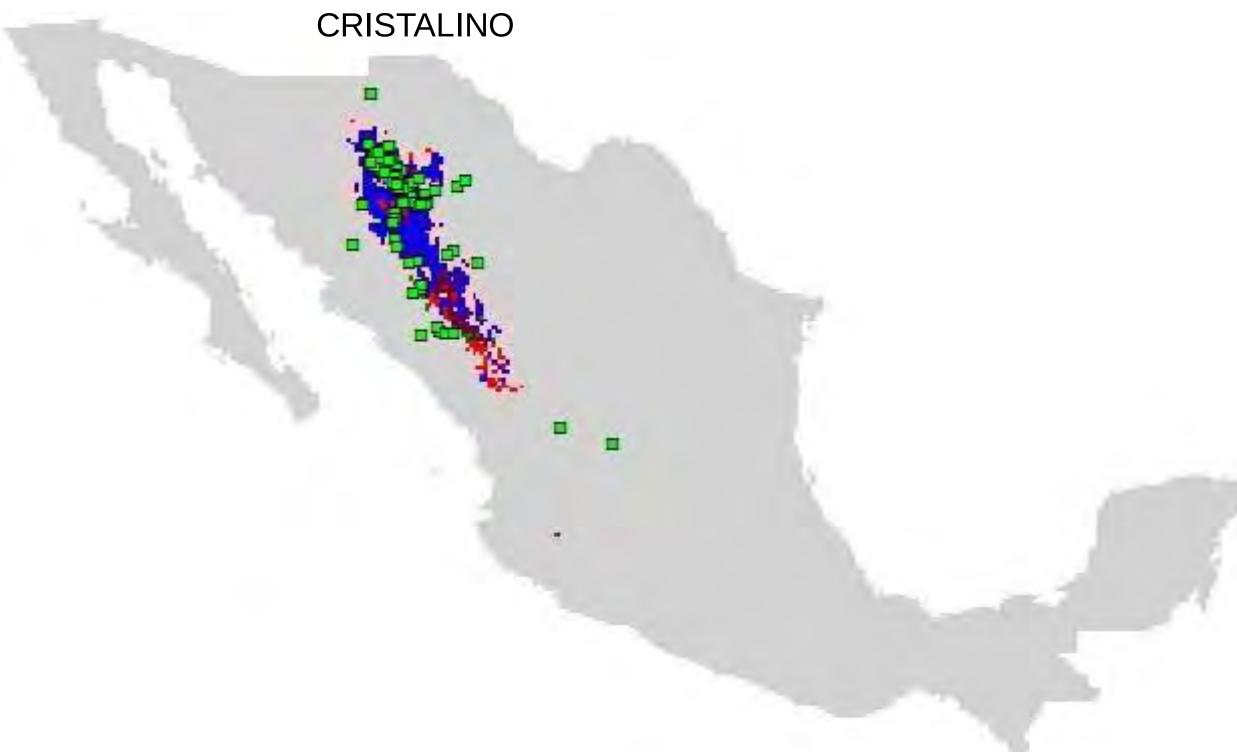
COMITECO

COMPLEJO SERRANO DE JALISCO

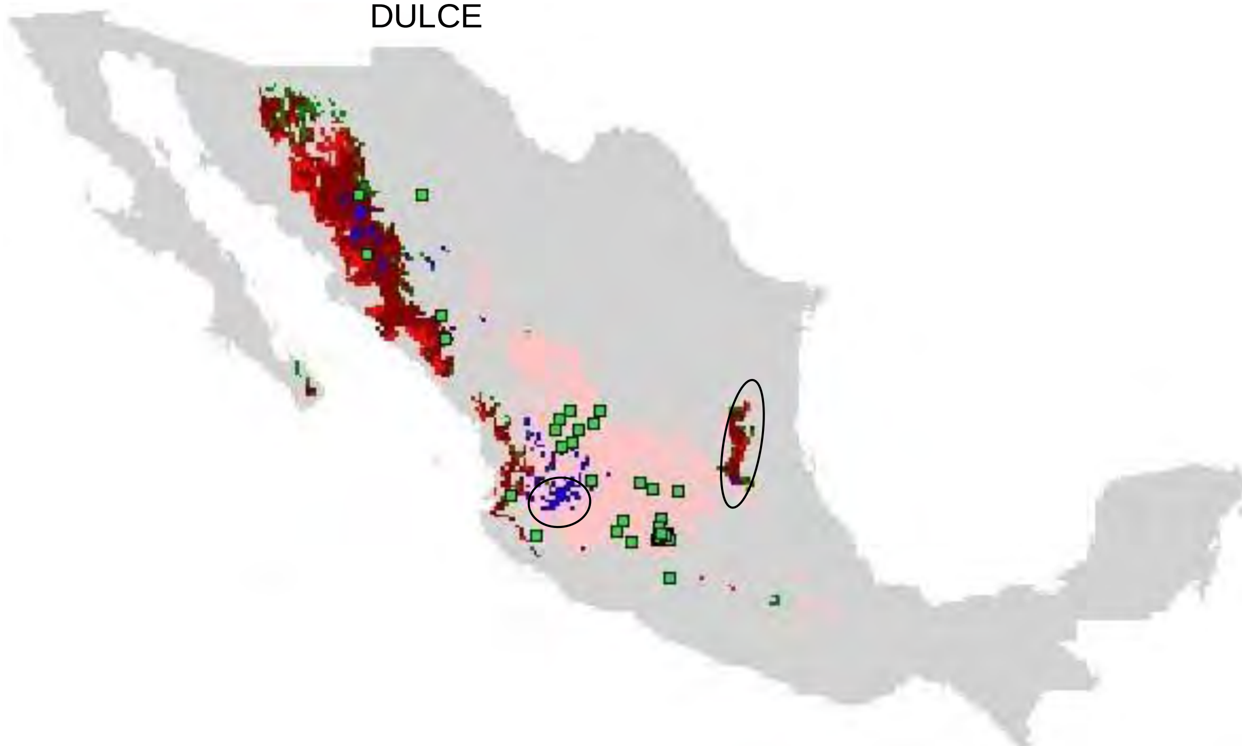
CONEJO

CÓNICO

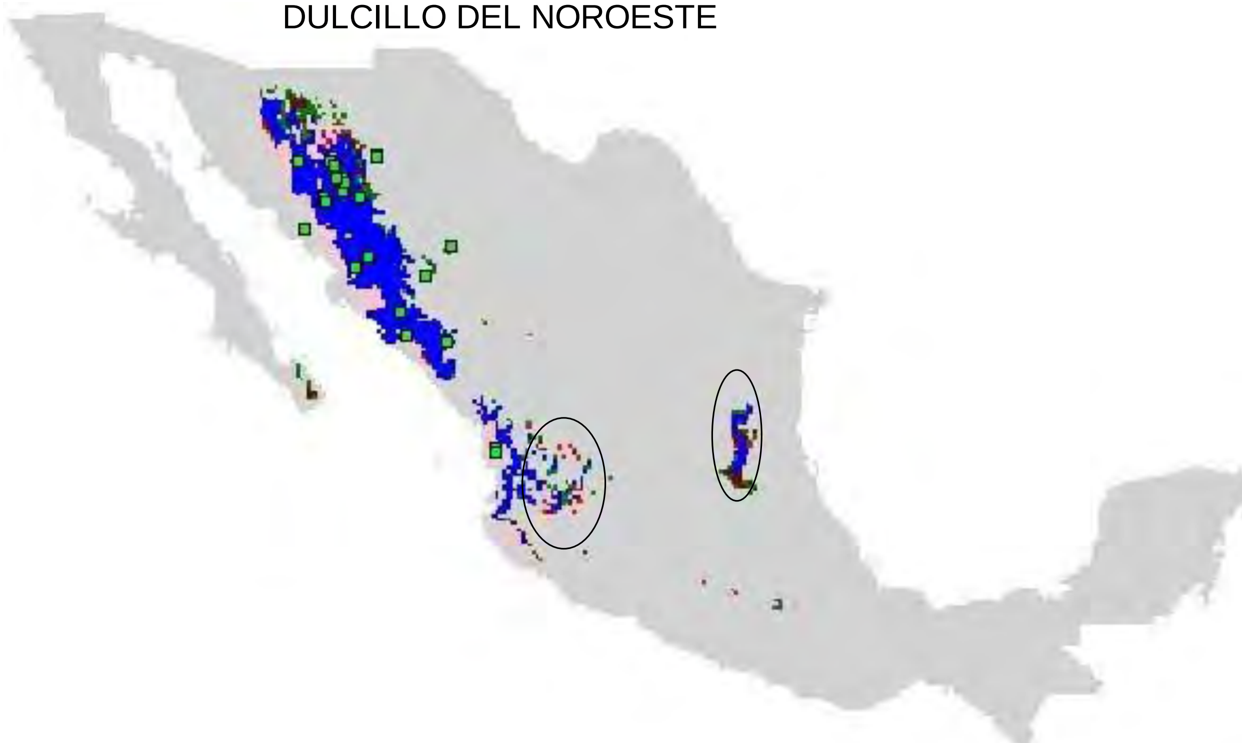

COSCOMATEPEC


CRISTALINO

DULCE



DULCILLO DEL NOROESTE



DZIT-BACAL

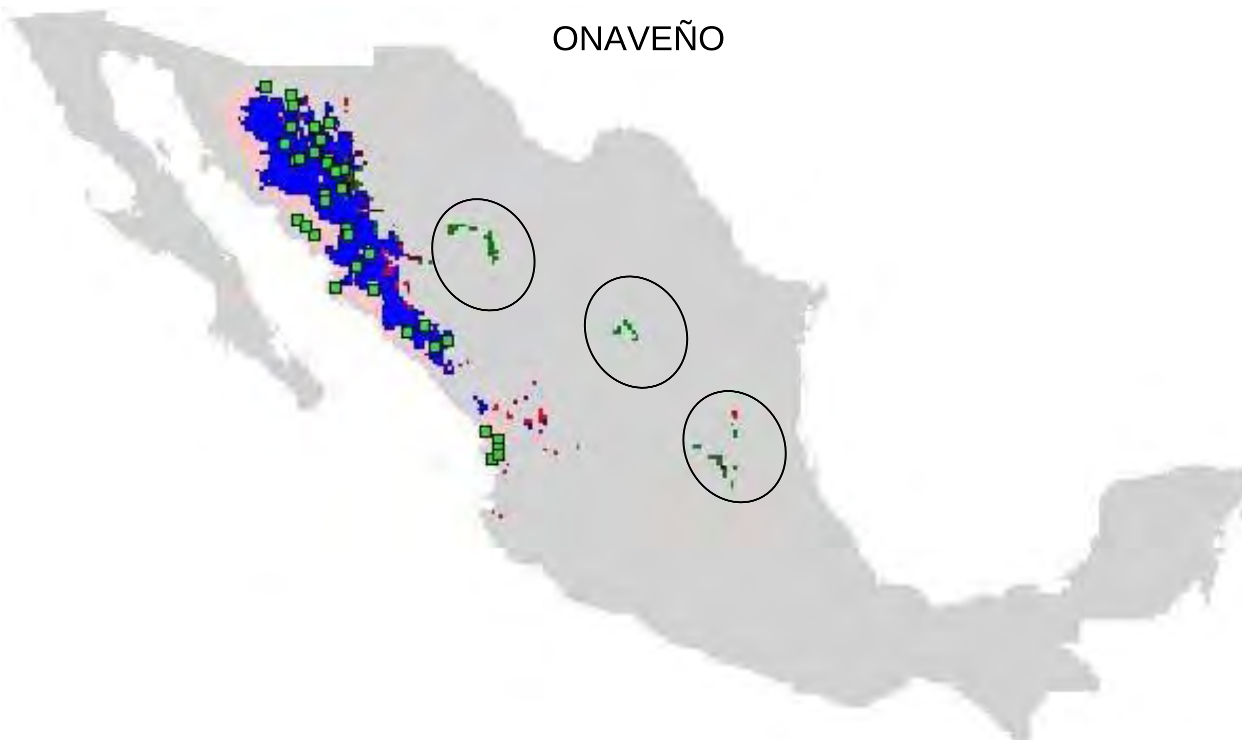
MUSHITO

NAL-TEL

OLOTILLO

OLOTÓN

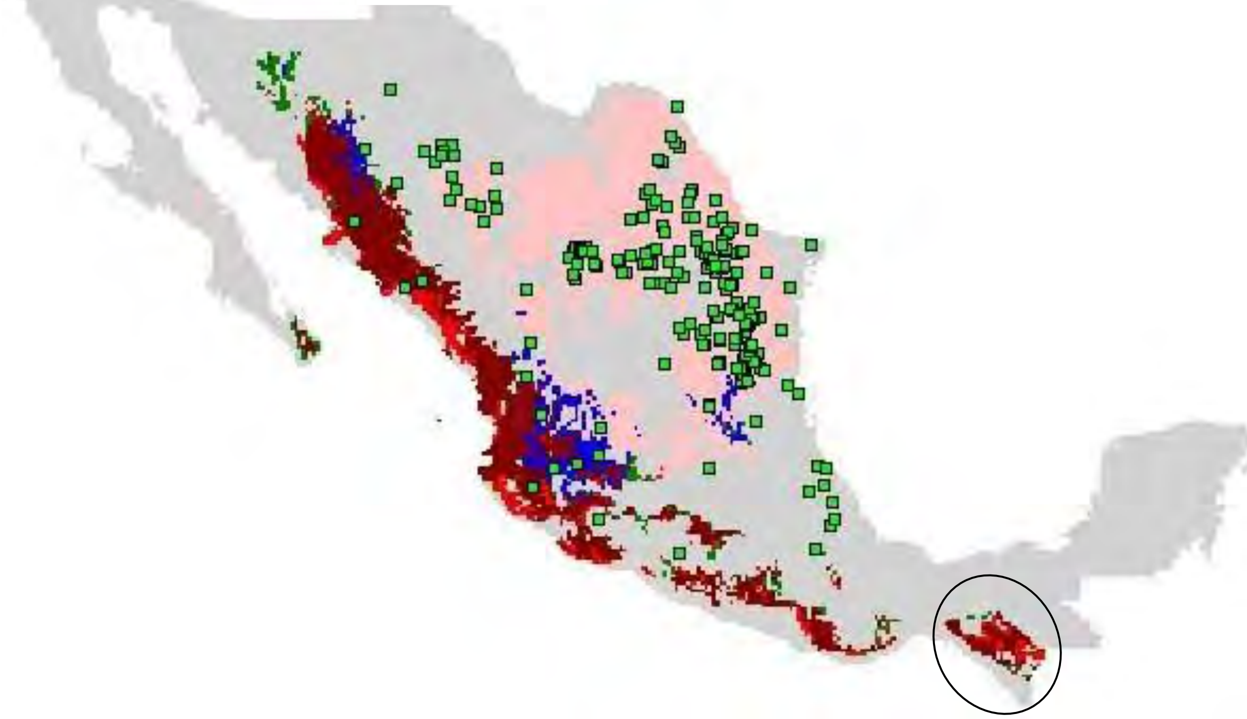
ONAVEÑO



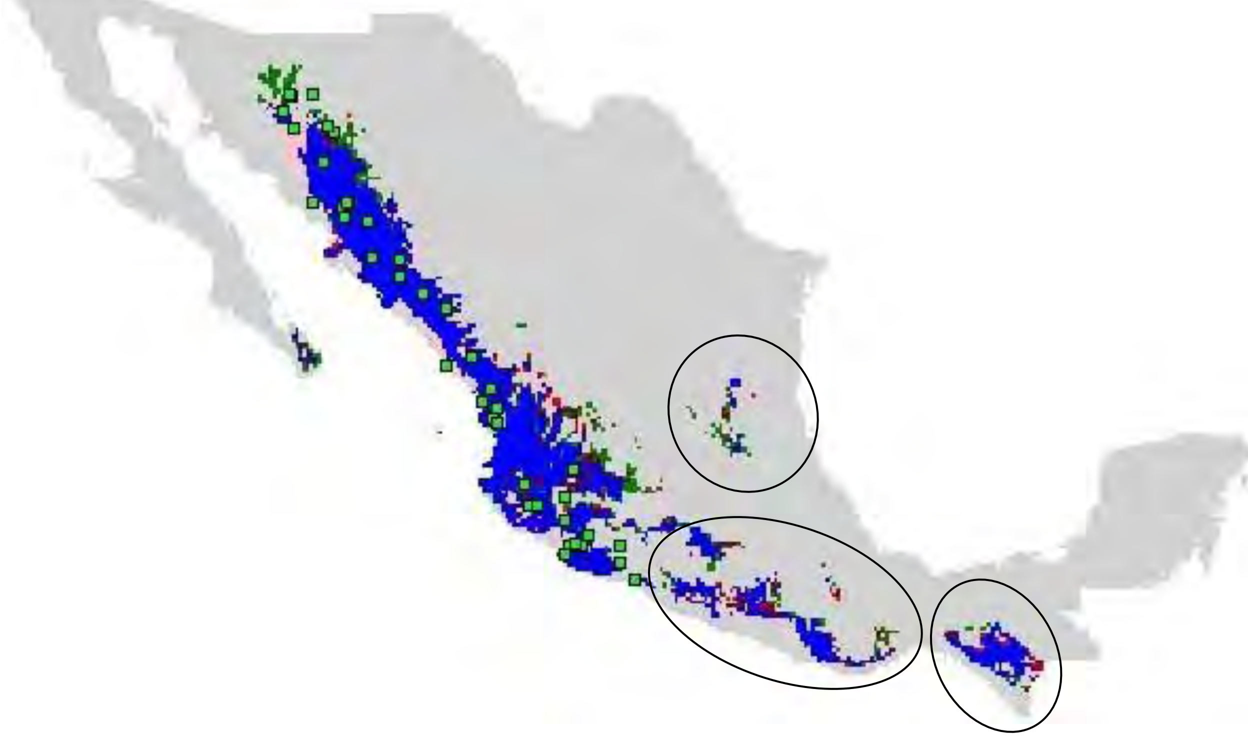
PALOMERO TOLUQUEÑO

PEPITILLA

RATÓN



REVENTADOR



SERRANO MIXE

TABLILLA DE OCHO

TABLONCILLO

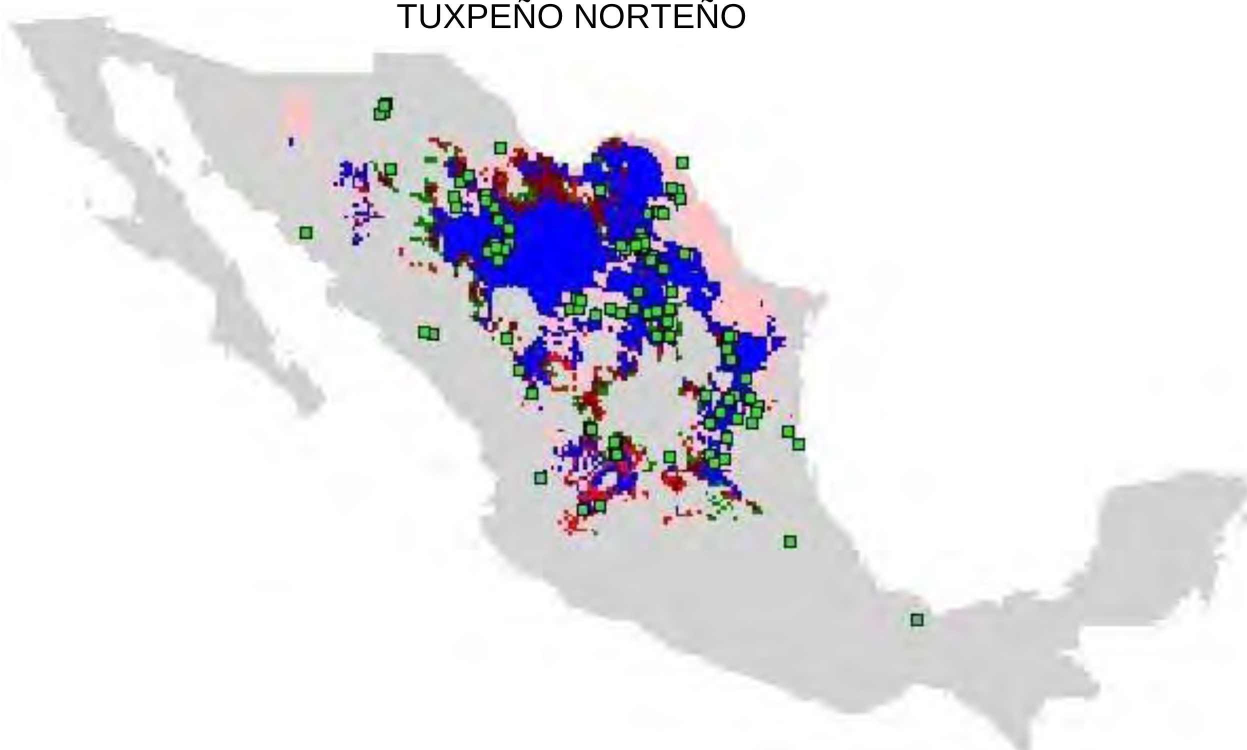
TABLONCILLO PERLA

TEHUA

TEPECINTLE

TUXPEÑO

TUXPEÑO NORTEÑO



VANDEÑO

ZAMORANO

ZAPOLATE CHICO

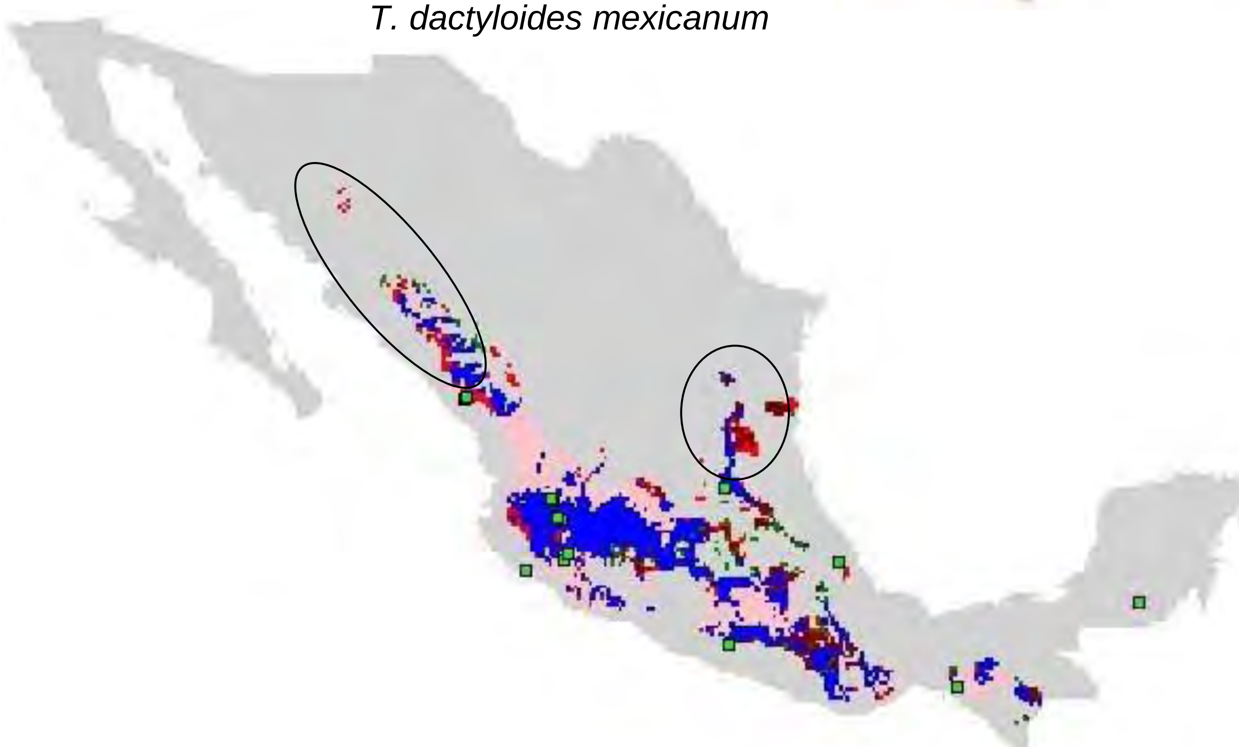
ZAPOLATE GRANDE

T. bravum

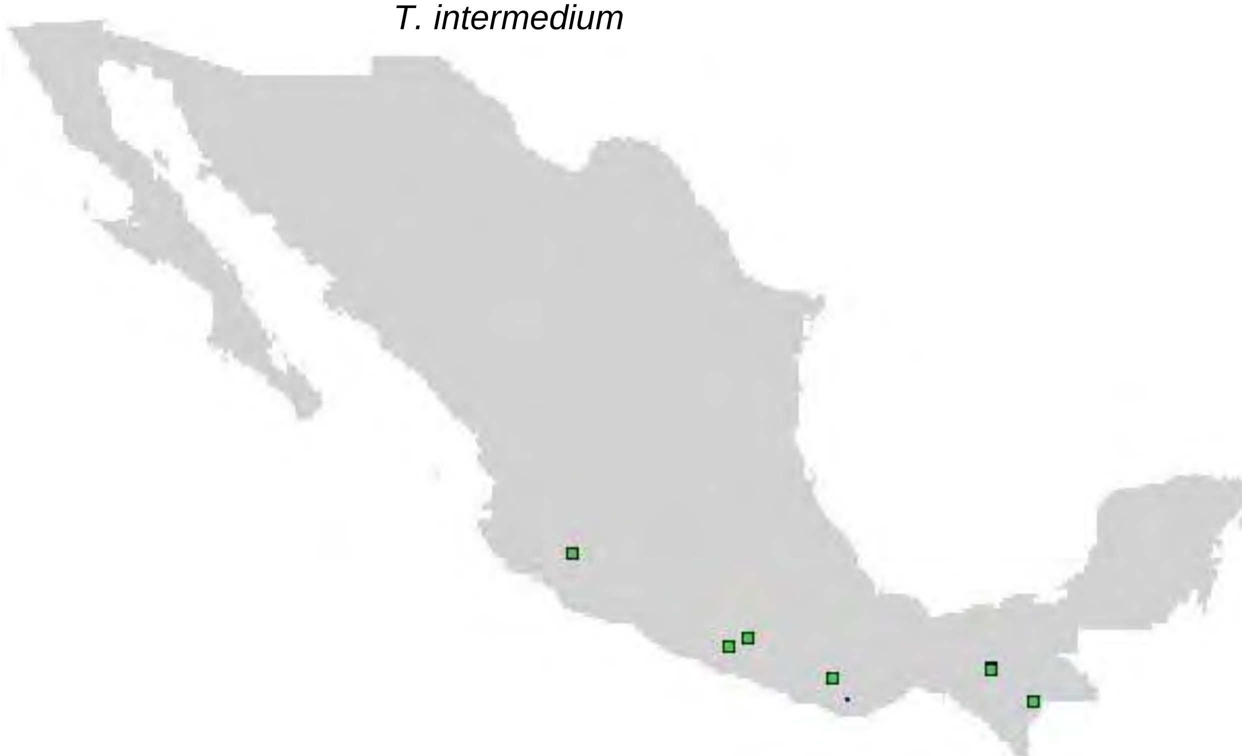
T. dactyloides dactyloides

T. dactyloides hispidium

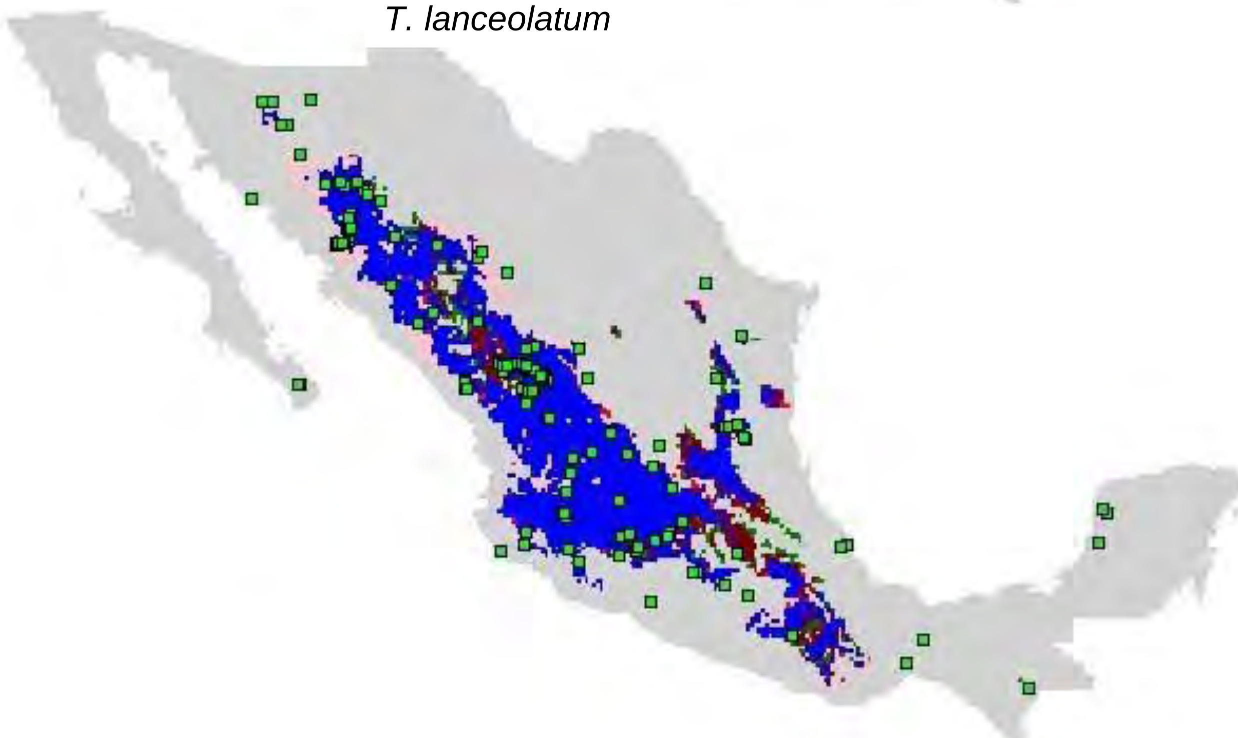
T. dactyloides mexicanum



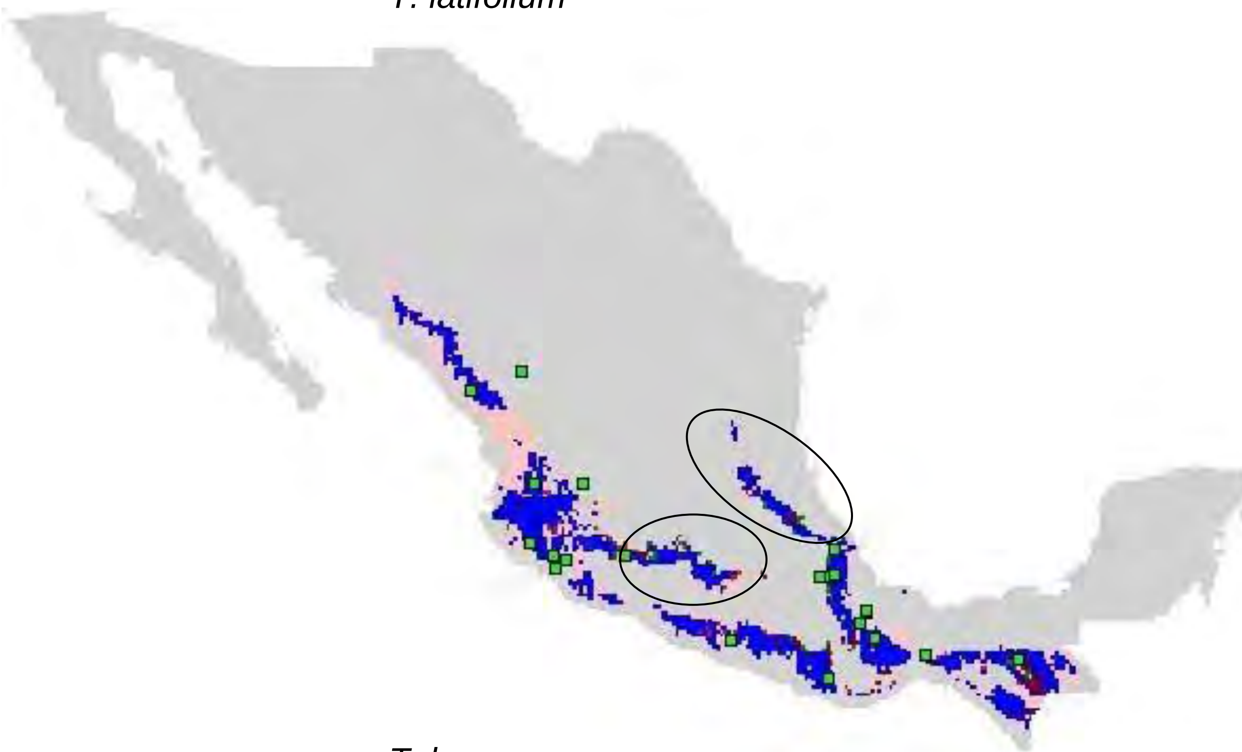
T. intermedium



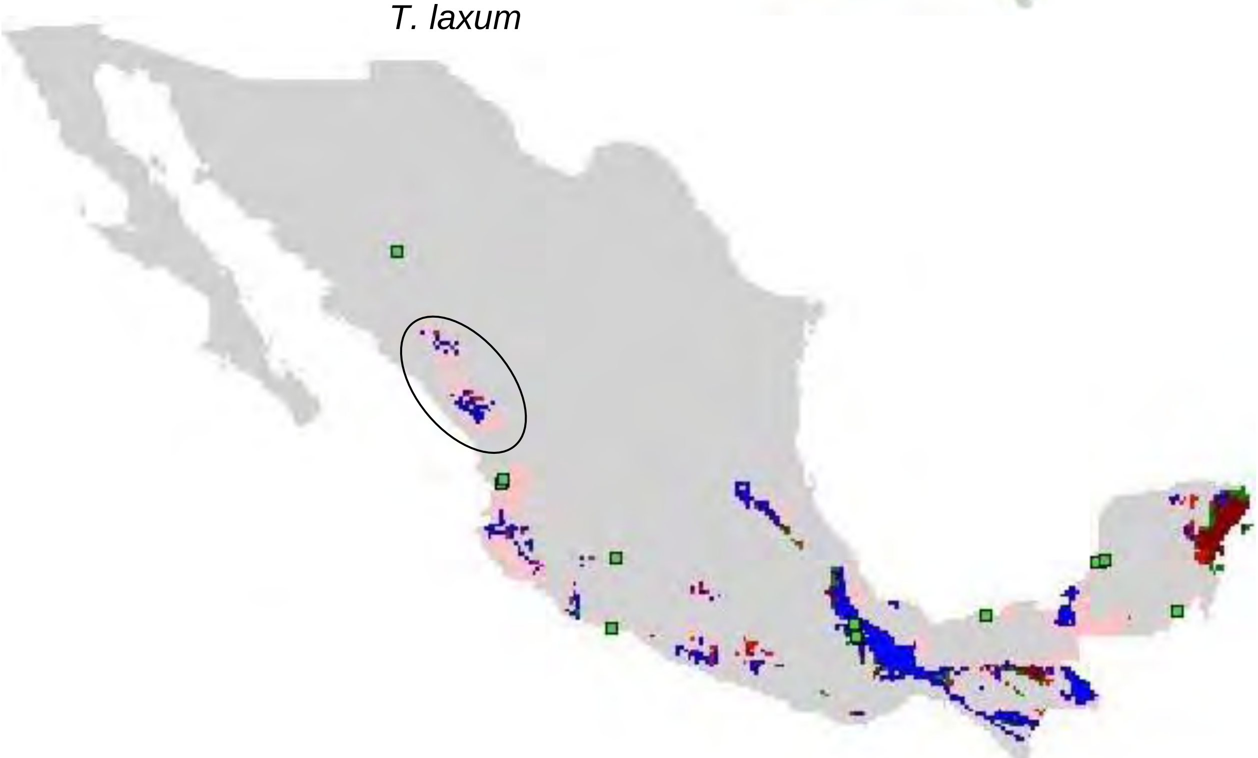
T. lanceolatum



T. latifolium

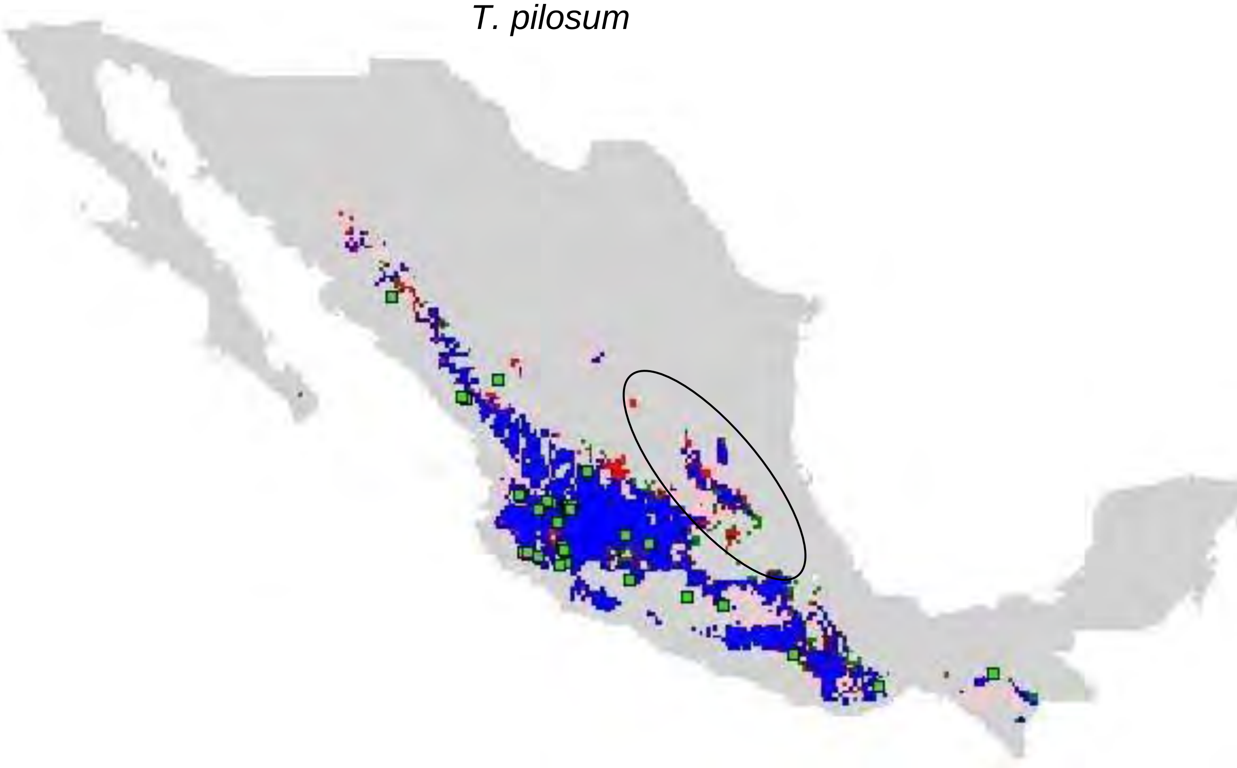


T. laxum



T. maizar

T. pilosum



T. zopilotense

Z. diploperennis

Z. mays maxicana

Z. mays parviglumis

Z. perennis

2.1 B1 Best Case Emission Scenario

Current PDA that will disappear in the future

2030 PDA that will disappear in 2050

PDA in 2030 and 2050

2050 PDA

Current PDA that remains in the future

Observed distribution

New suitable growing area

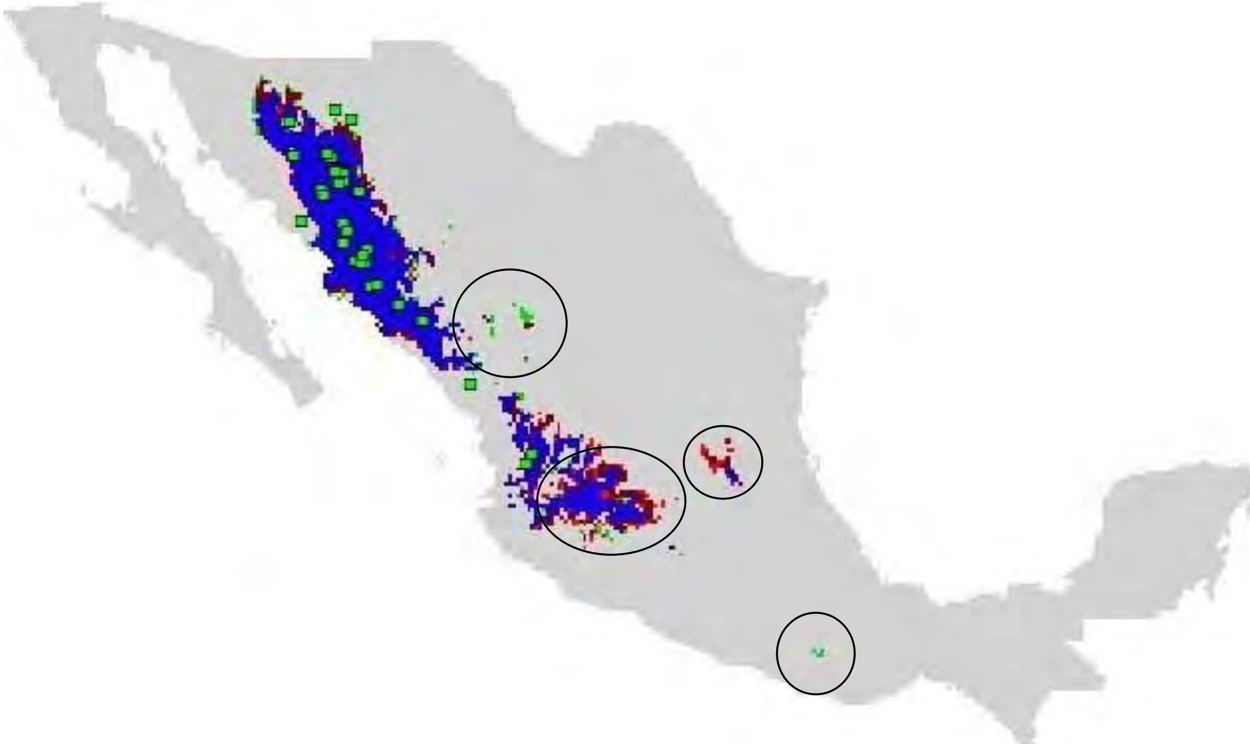
ANCHO

APACHITO

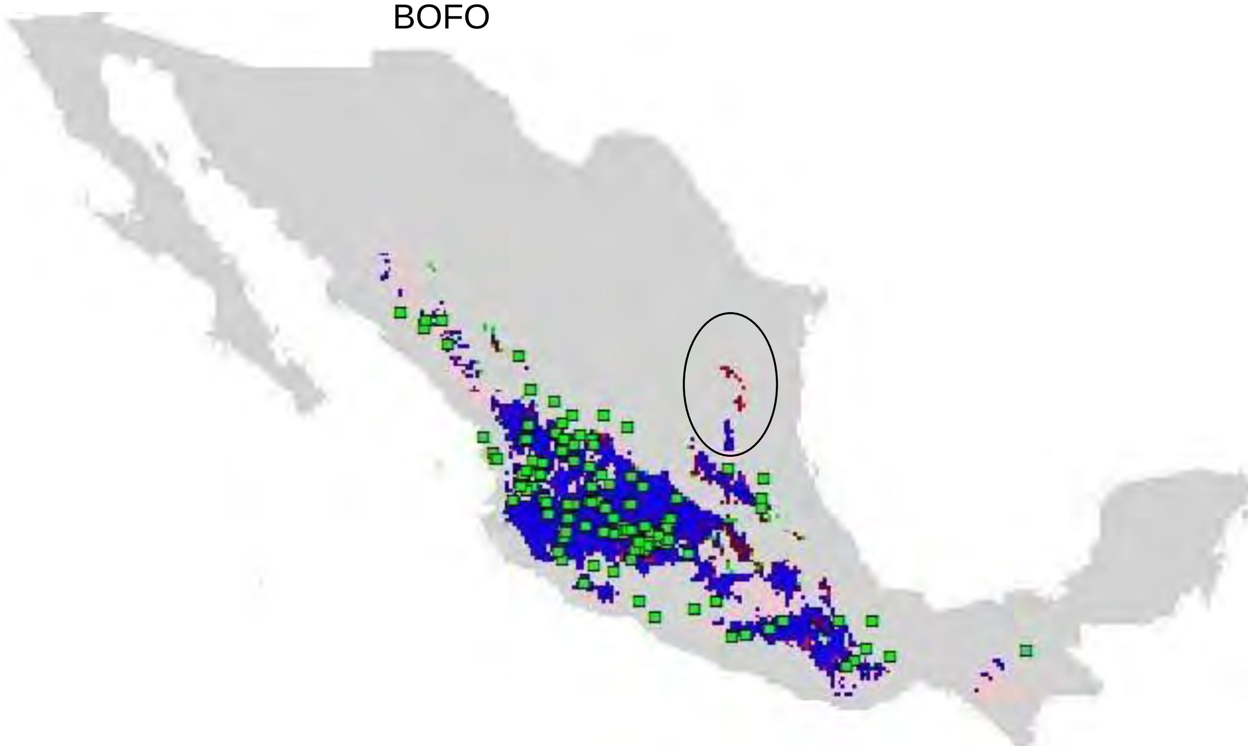
ARROCILLO

AZUL

BLANDO DE SONORA

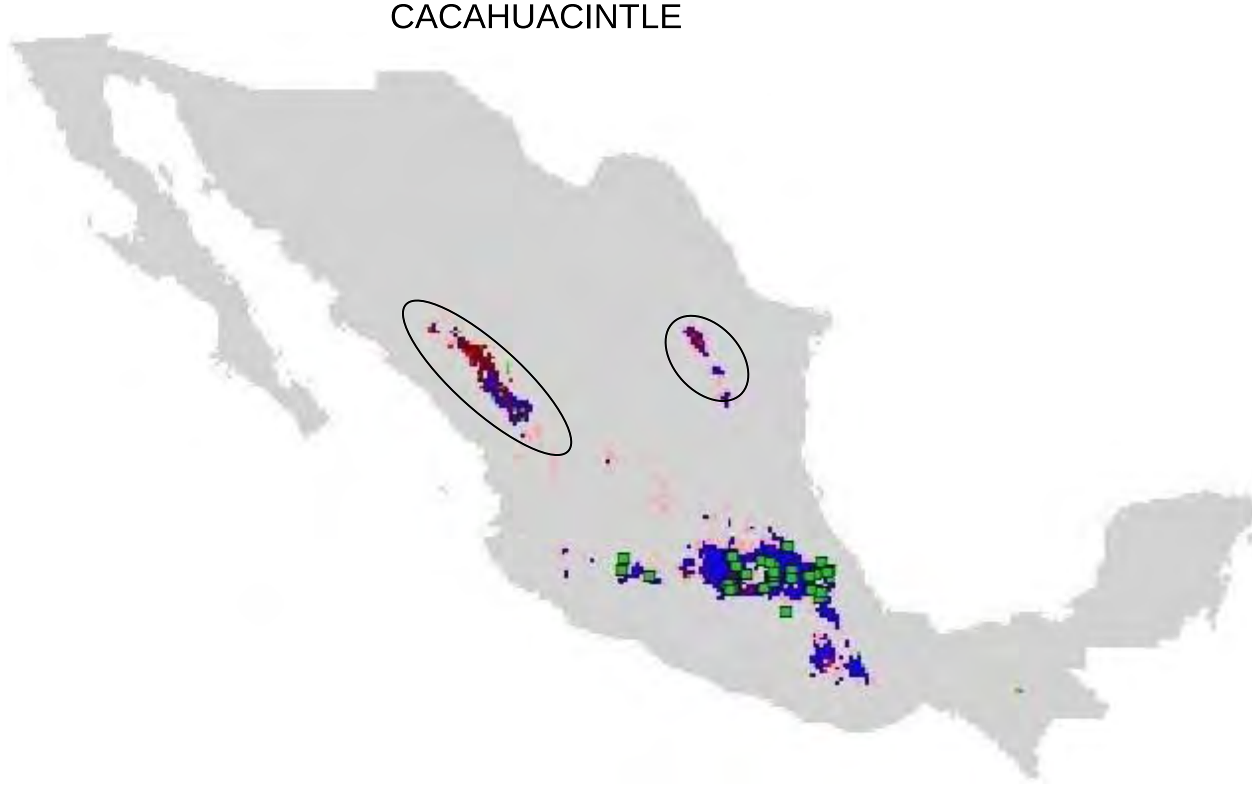


BOFO



BOLITA

CACAHUACINTLE



CELAYA

CHALQUEÑO

CHAPALOTE

CHIQUITO

COMITECO

COMPLEJO SERRANO DE JALISCO

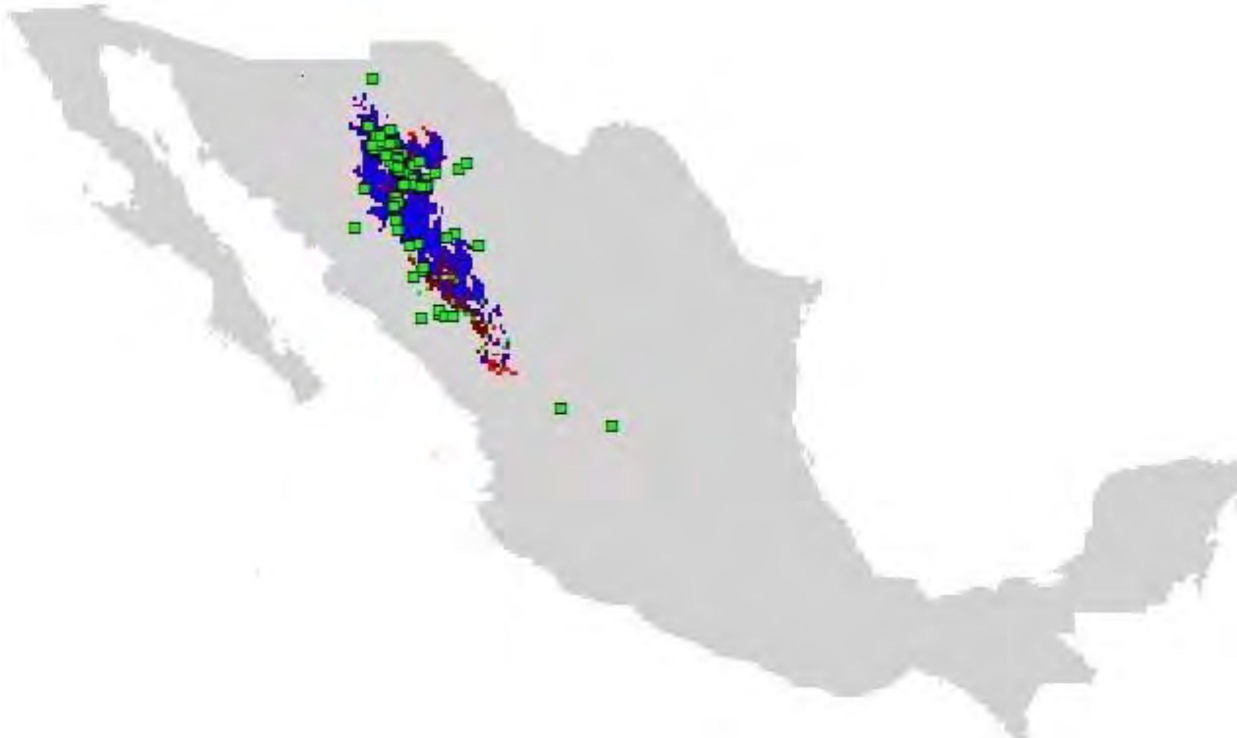
CONEJO

CÓNICO

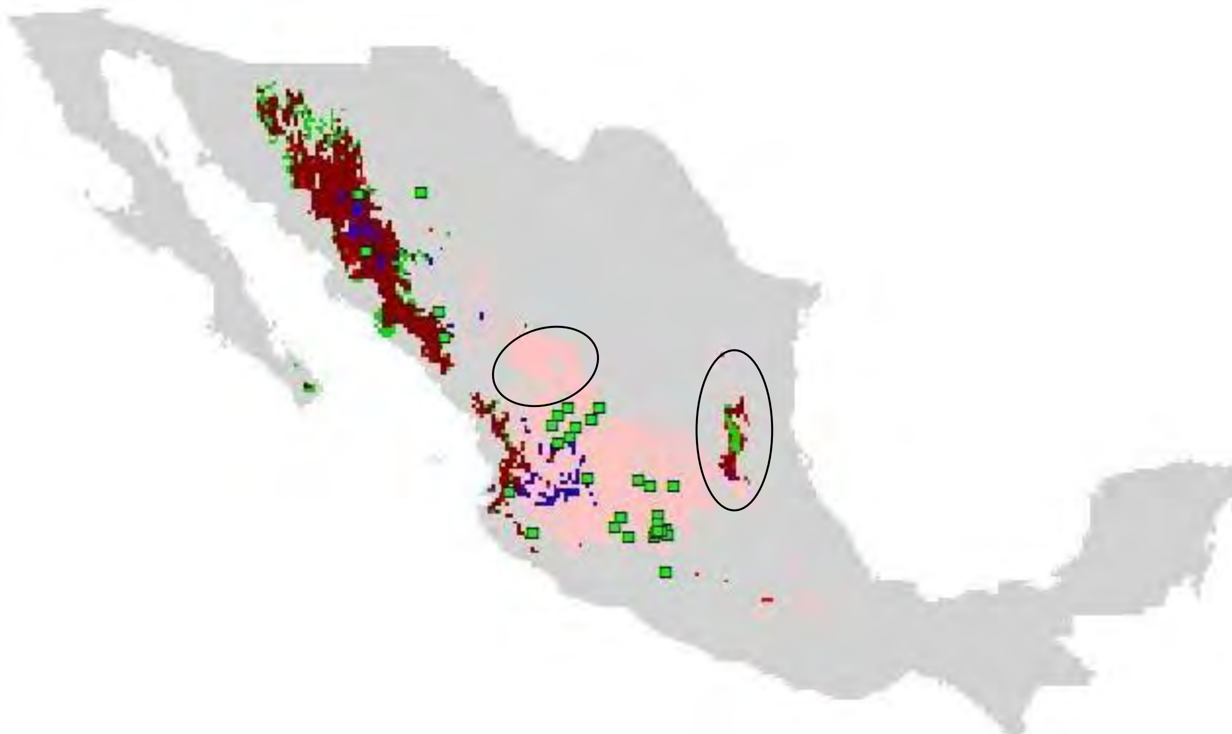
CÓNICO NORTEÑO

COSCOMATEPEC

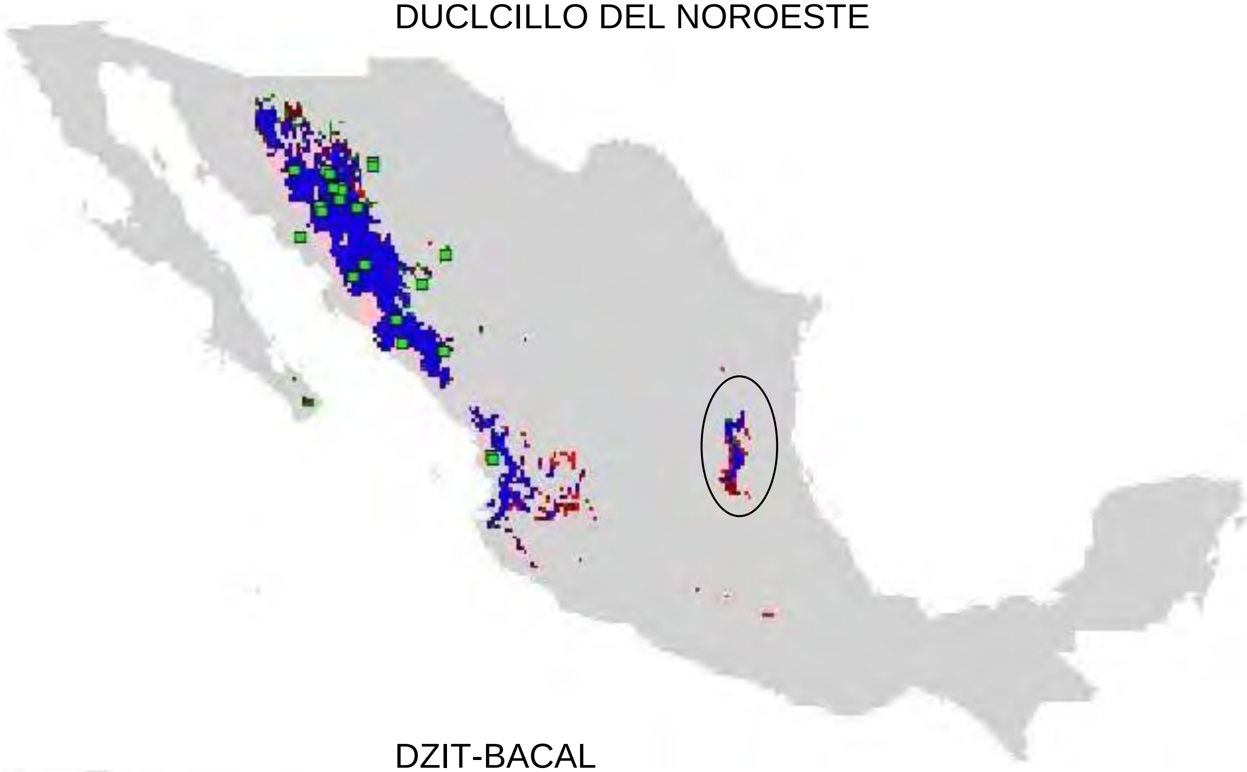
CRISTALINO



DULCE



DUCLCILLO DEL NOROESTE

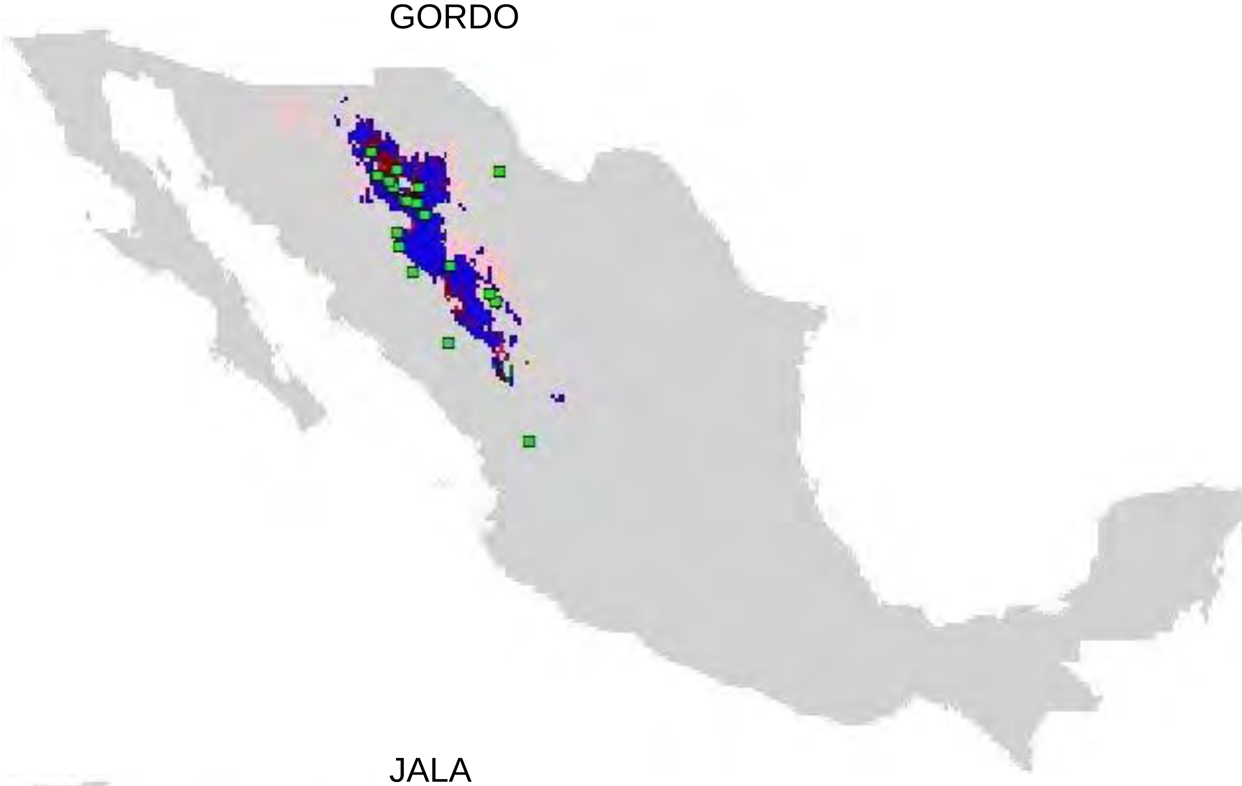


DZIT-BACAL

ELOTERO DE SINALOA

ELOTES CÓNICOS

GORDO



JALA

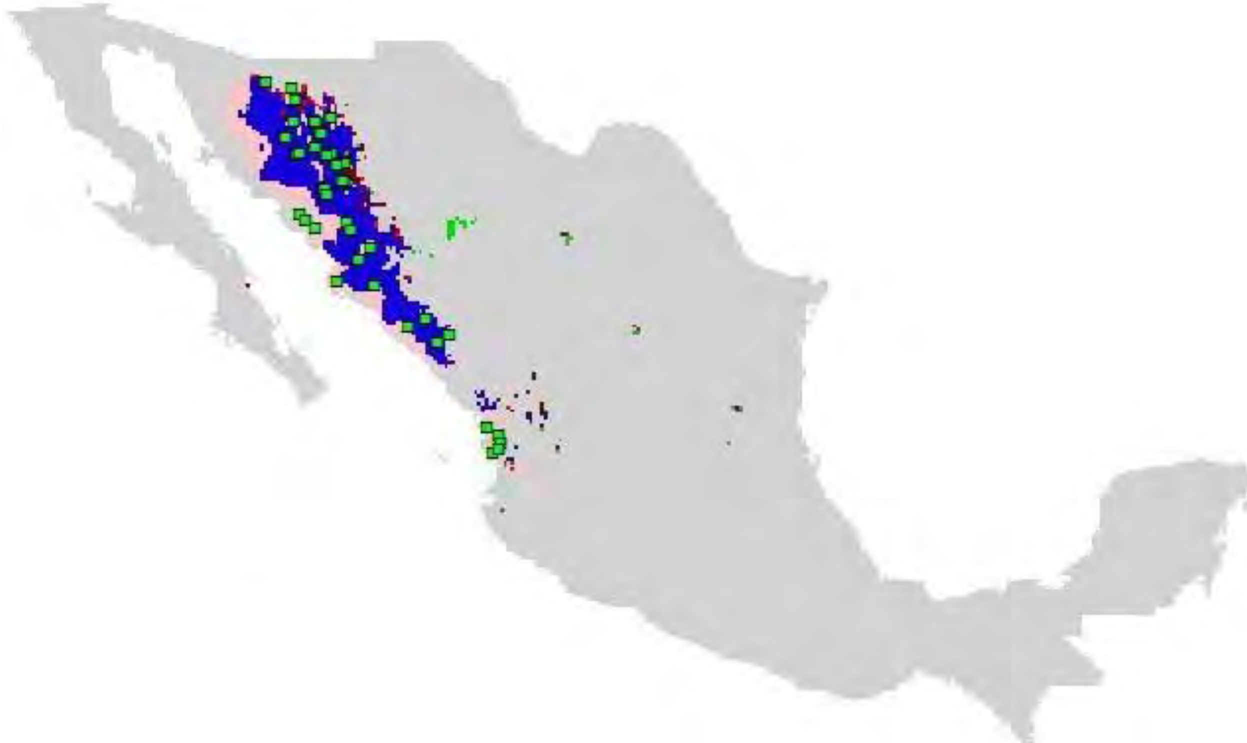
MUSHITO

NAL-TEL

OLOTILLO

OLOTÓN

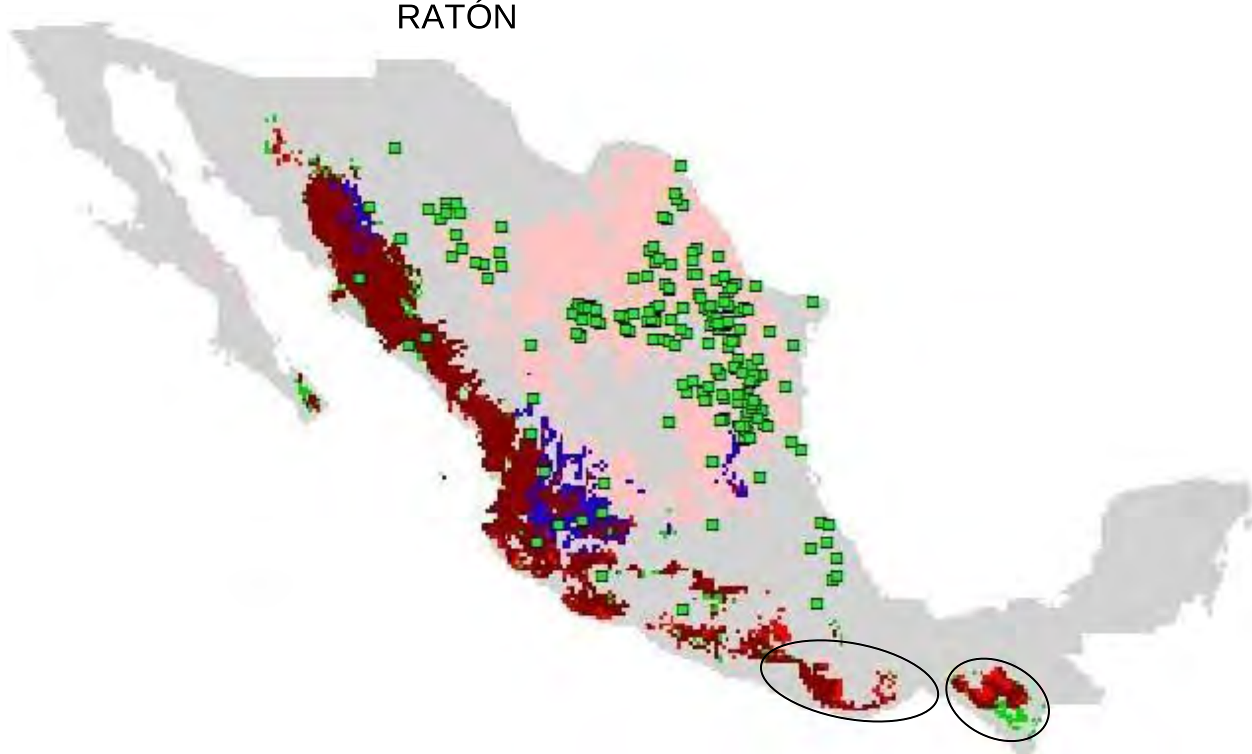
ONAVEÑO



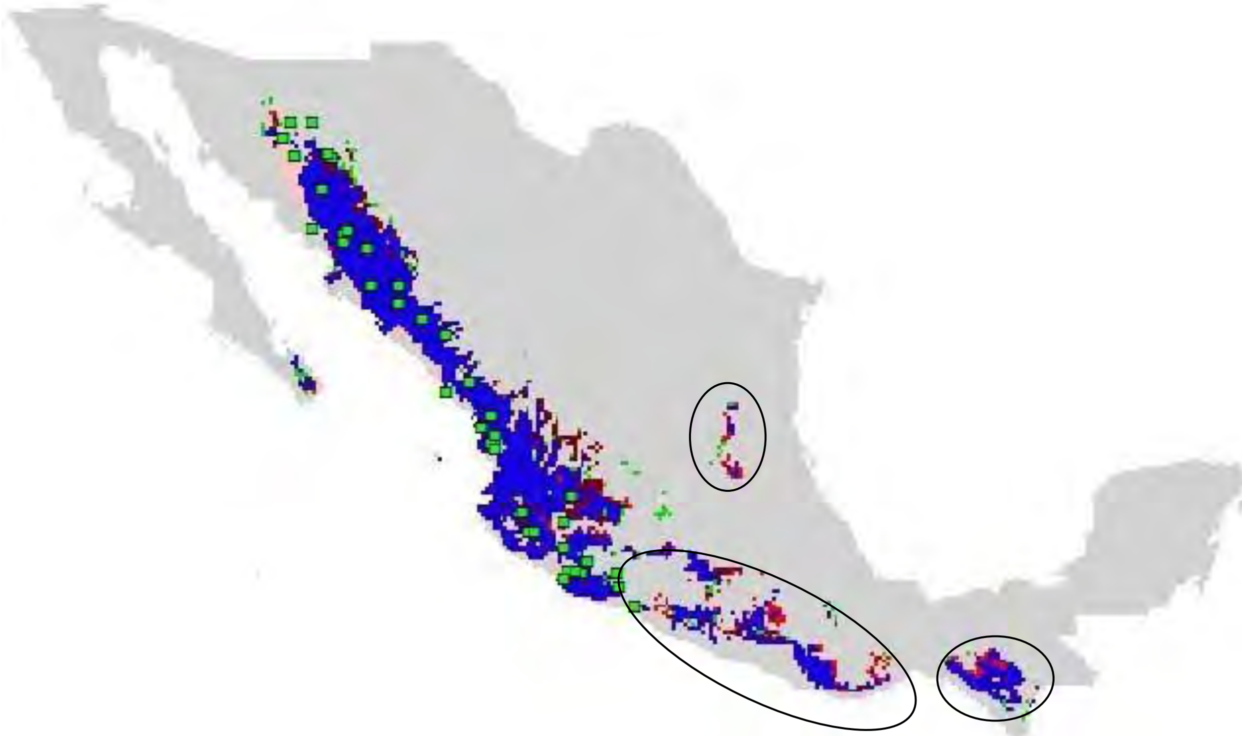
PALOMERO TOLQUEÑO

PEPITILLA

RATÓN



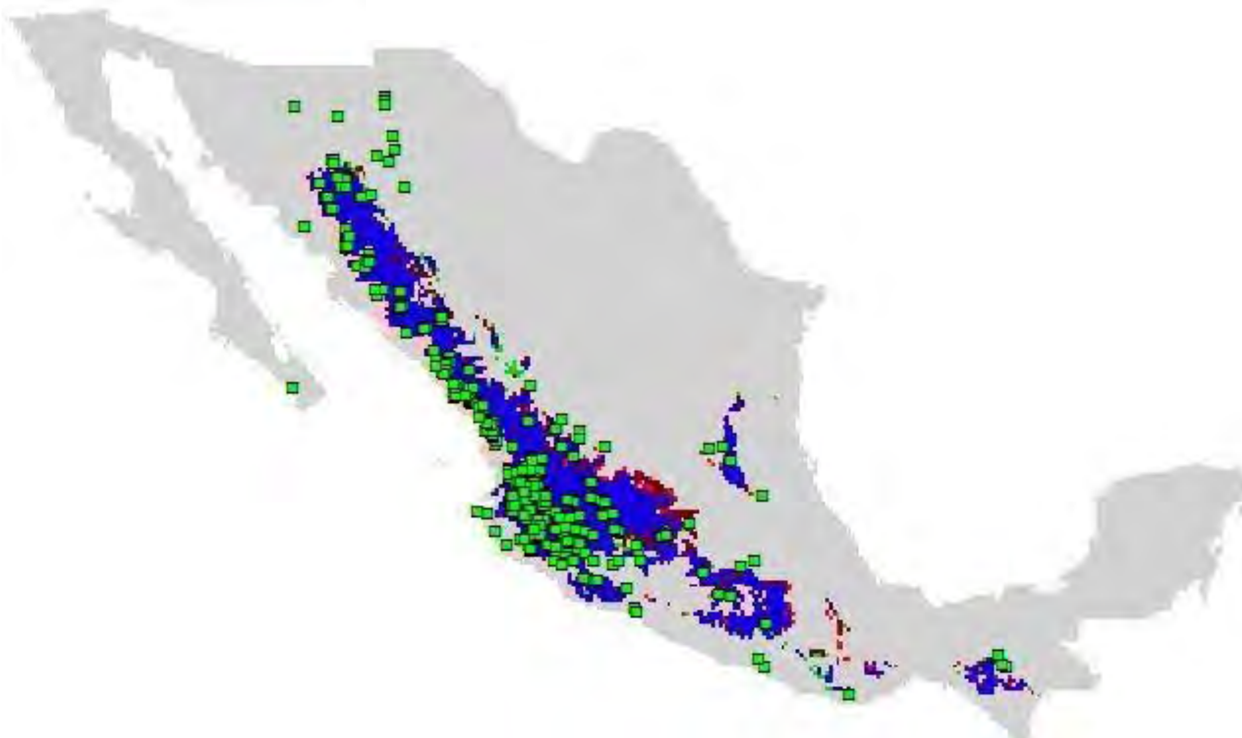
REVENTADOR



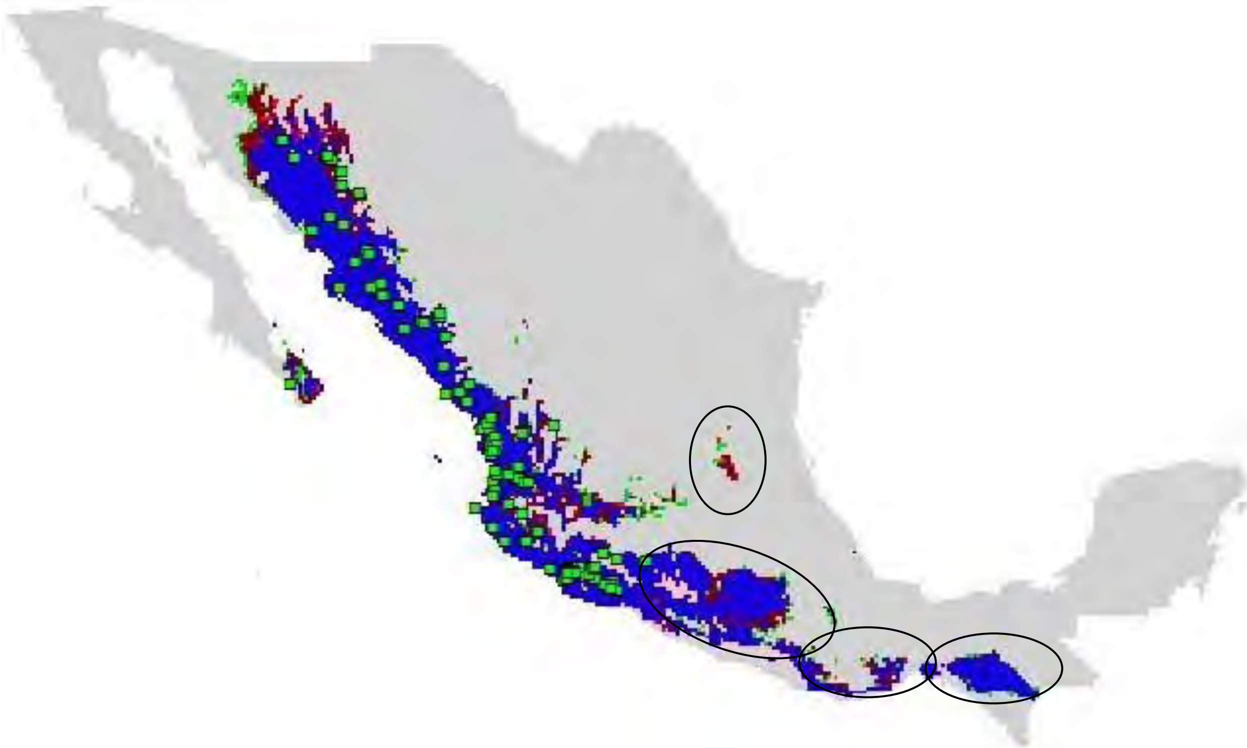
SERRANO MIXE

TABLILLA DE OCHO

TABLONCILLO



TABLONCILLO PERLA

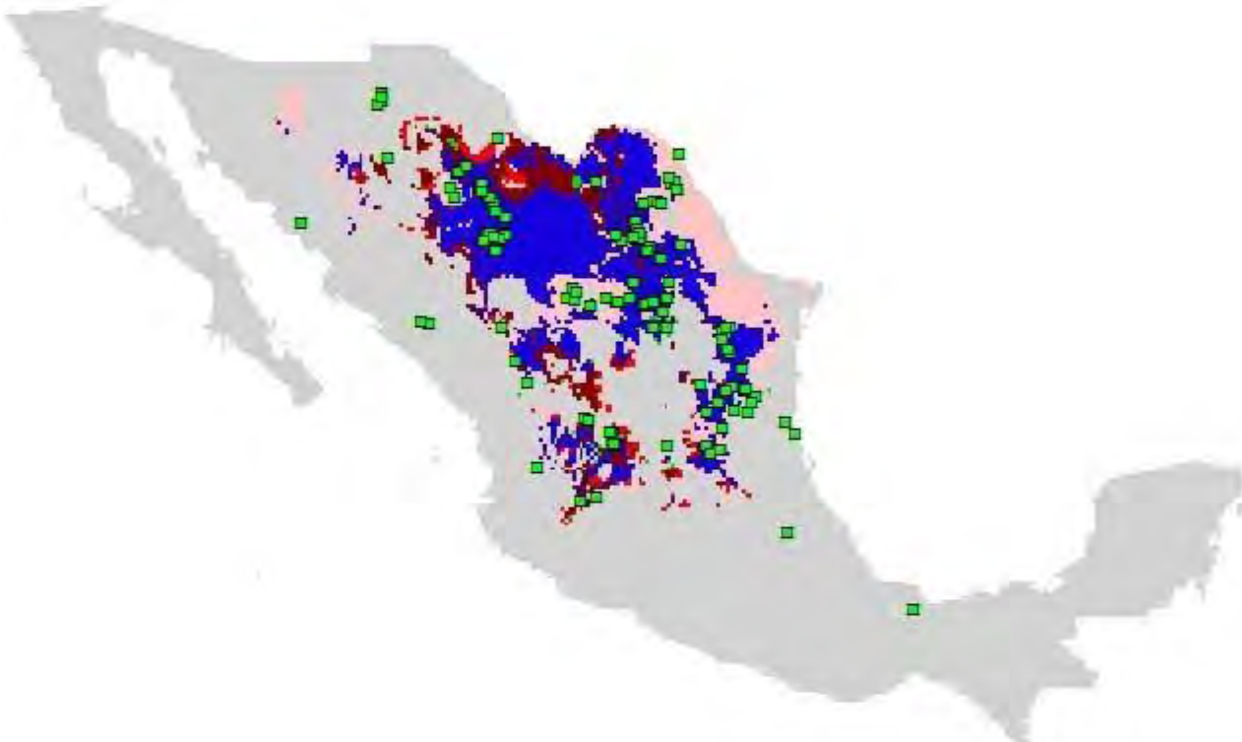


TEHUA

TEPECINTLE

TUXPEÑO

TUXPEÑO NORTEÑO

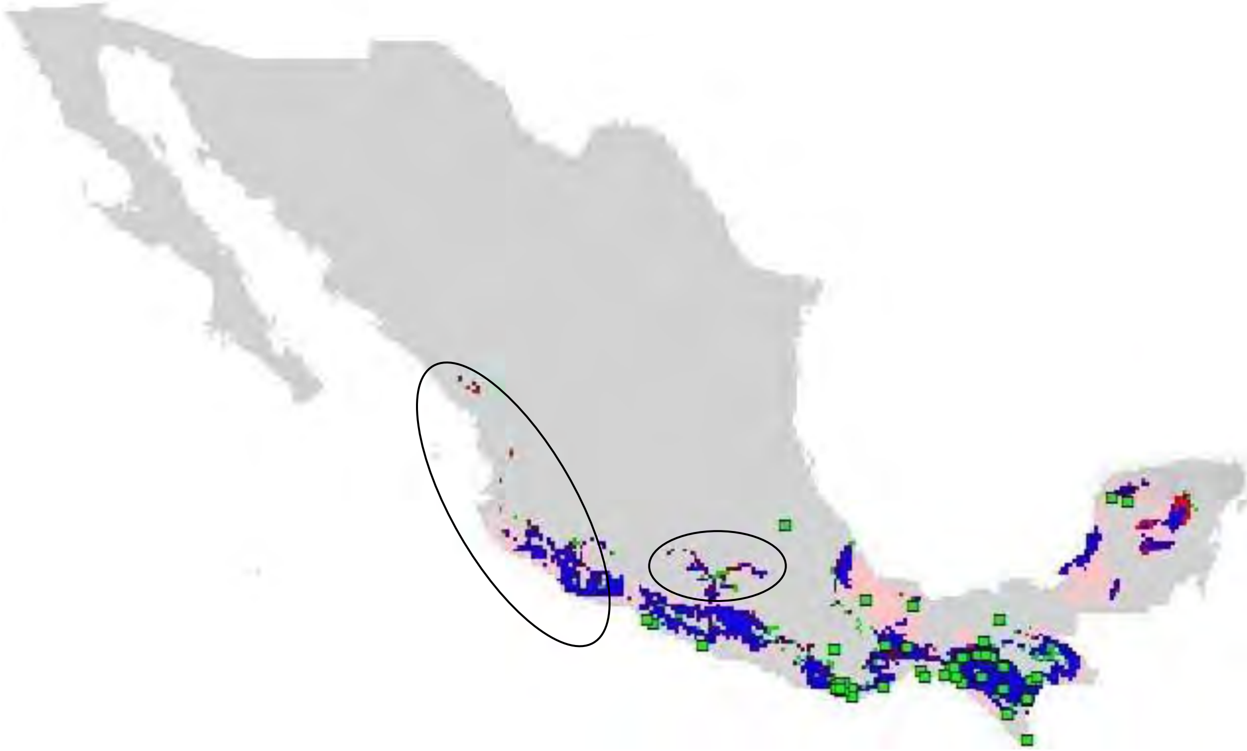


VENDEÑO

ZAMORANO

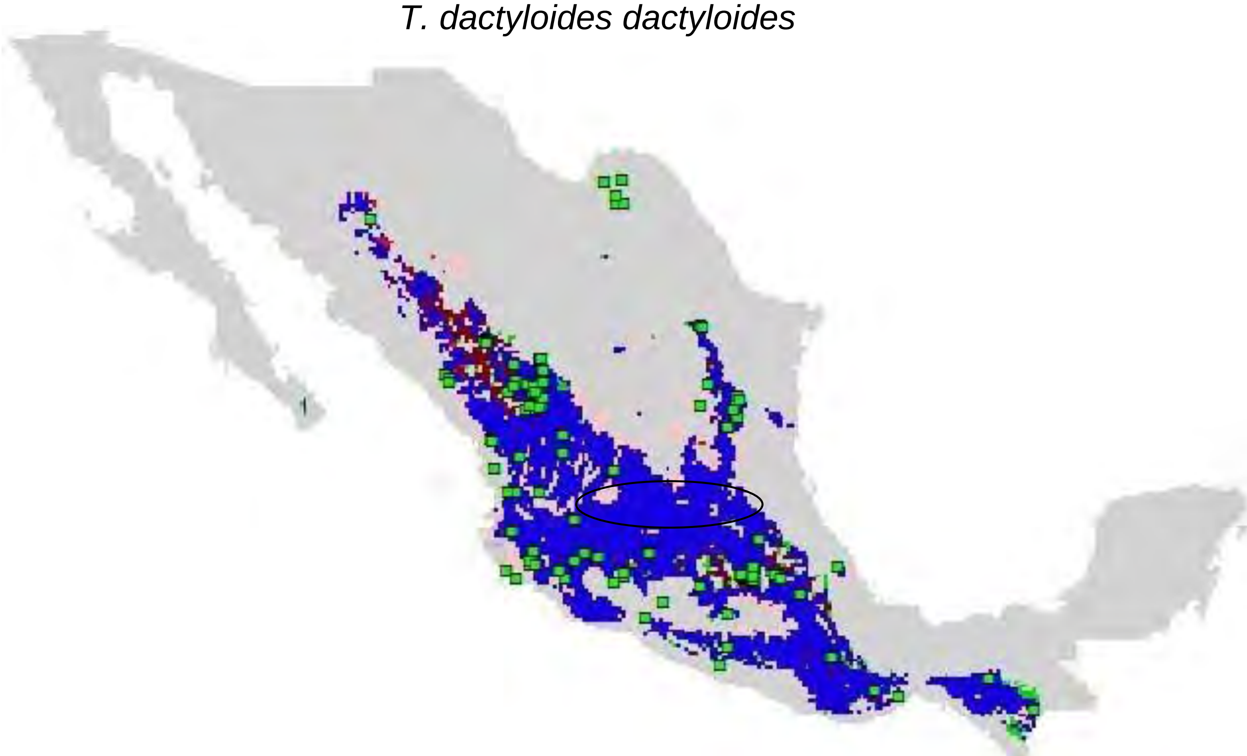
ZAPALOTE CHICO

ZAPALOTE GRANDE

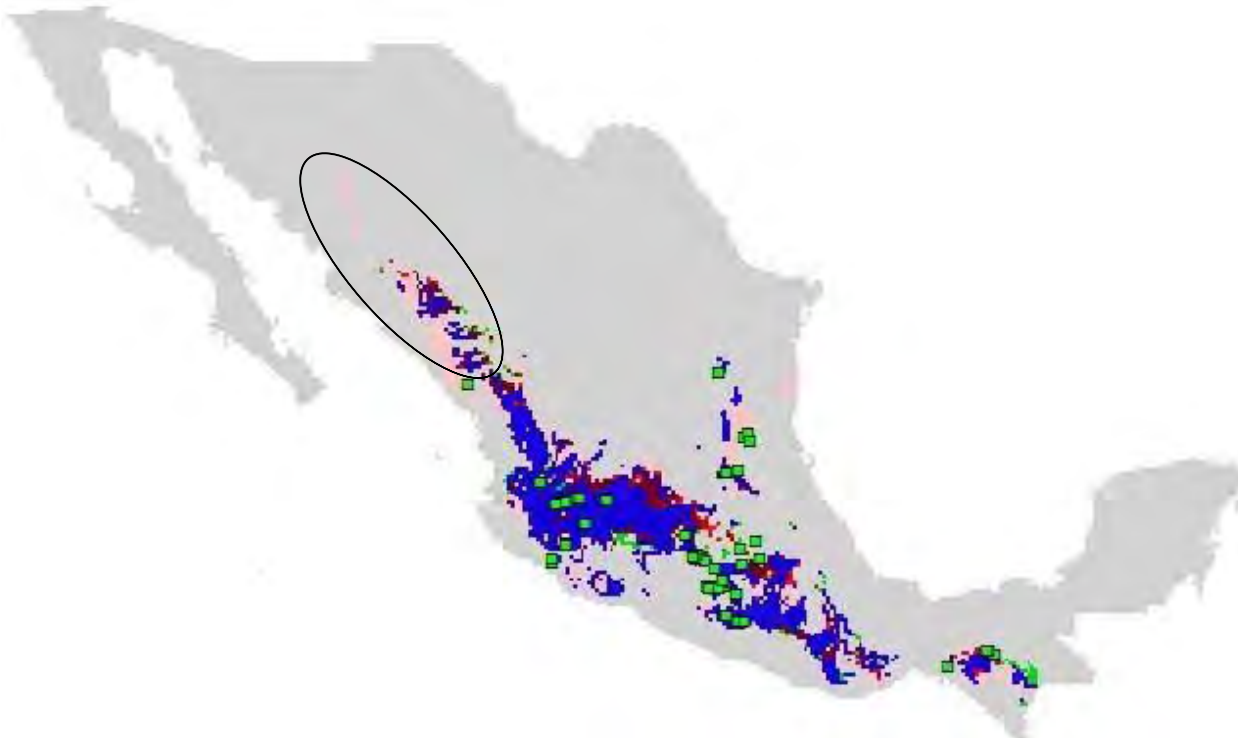


T. bravum

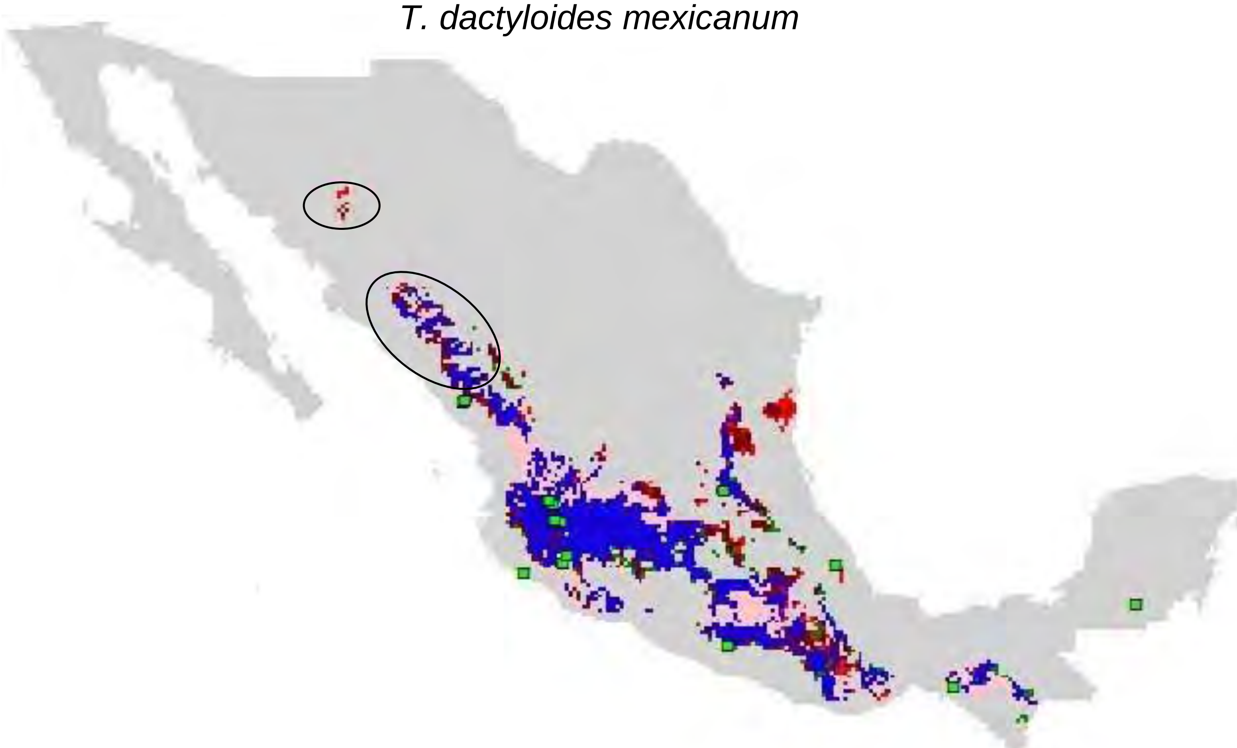
T. dactyloides dactyloides



T. dactyloides hispidium

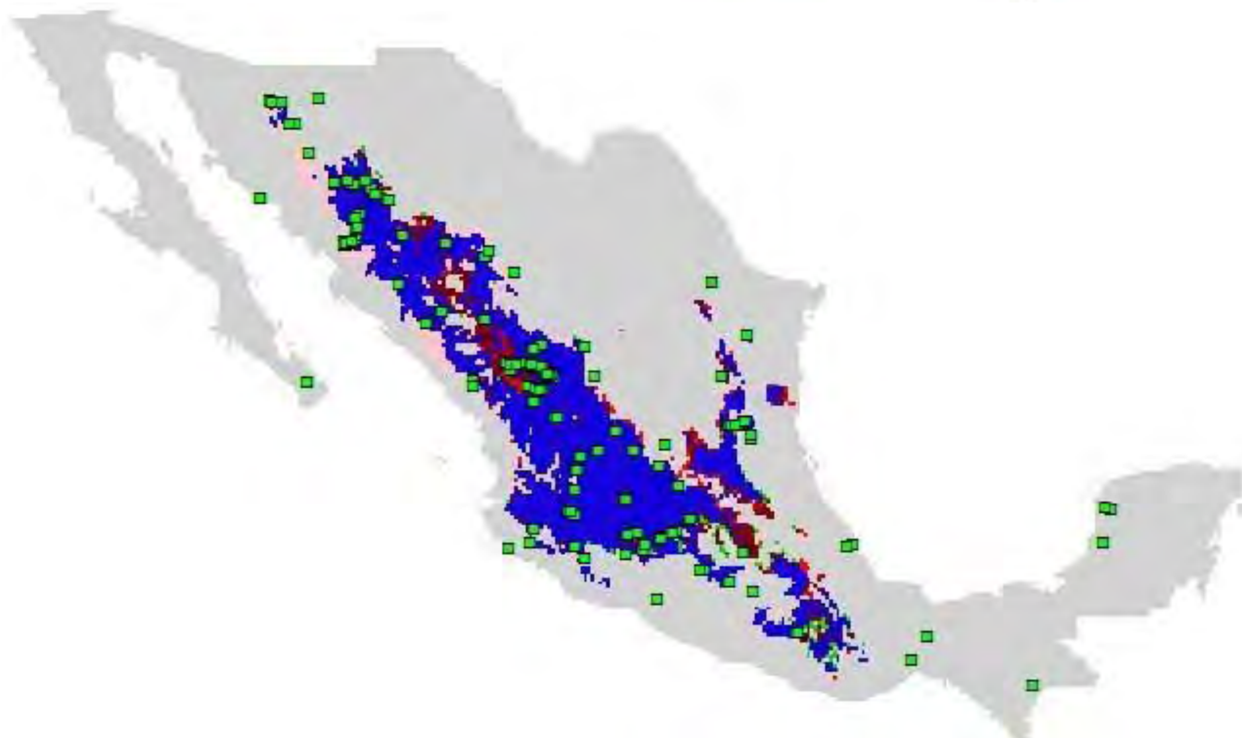


T. dactyloides mexicanum

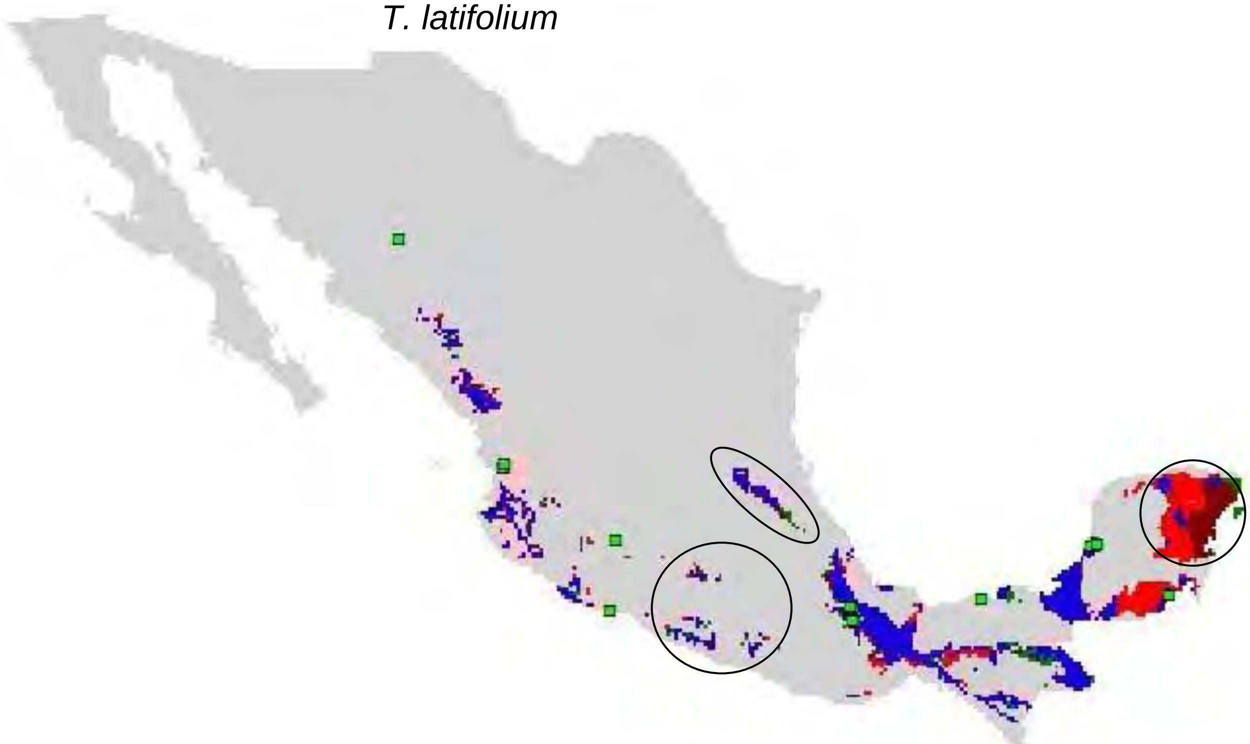


T. intermedium

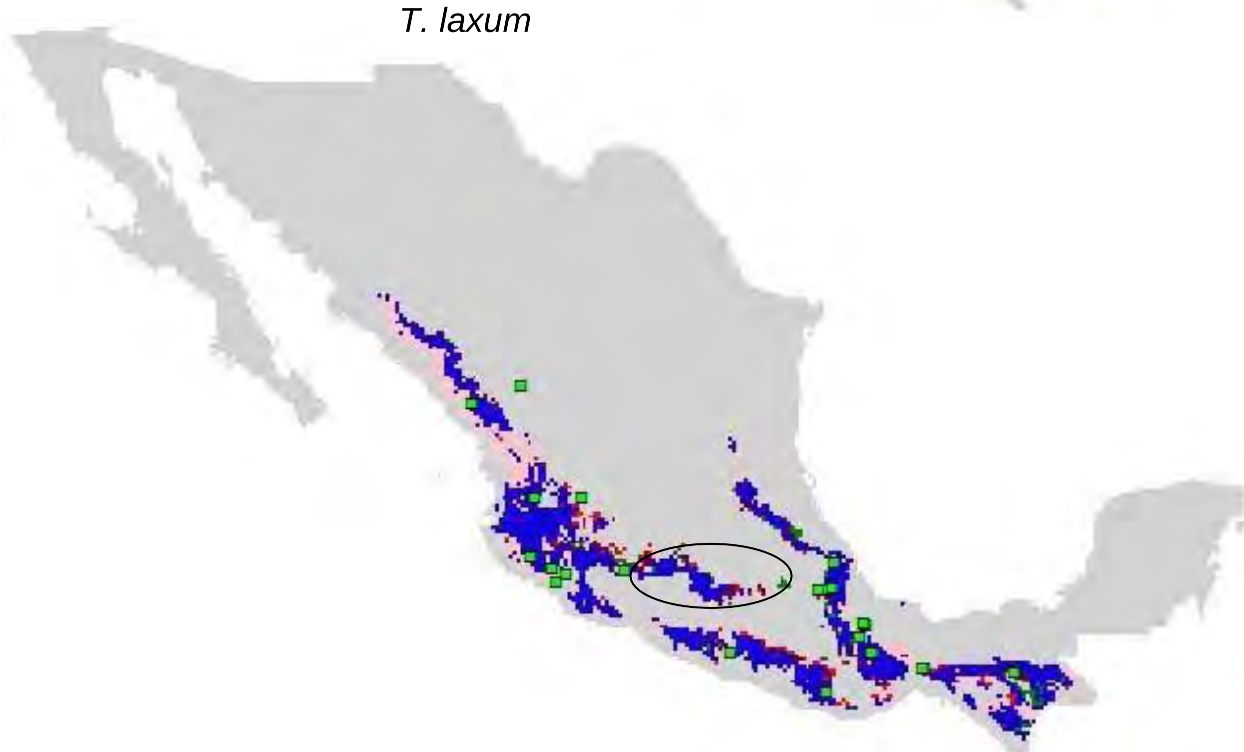
T. lanceolatum



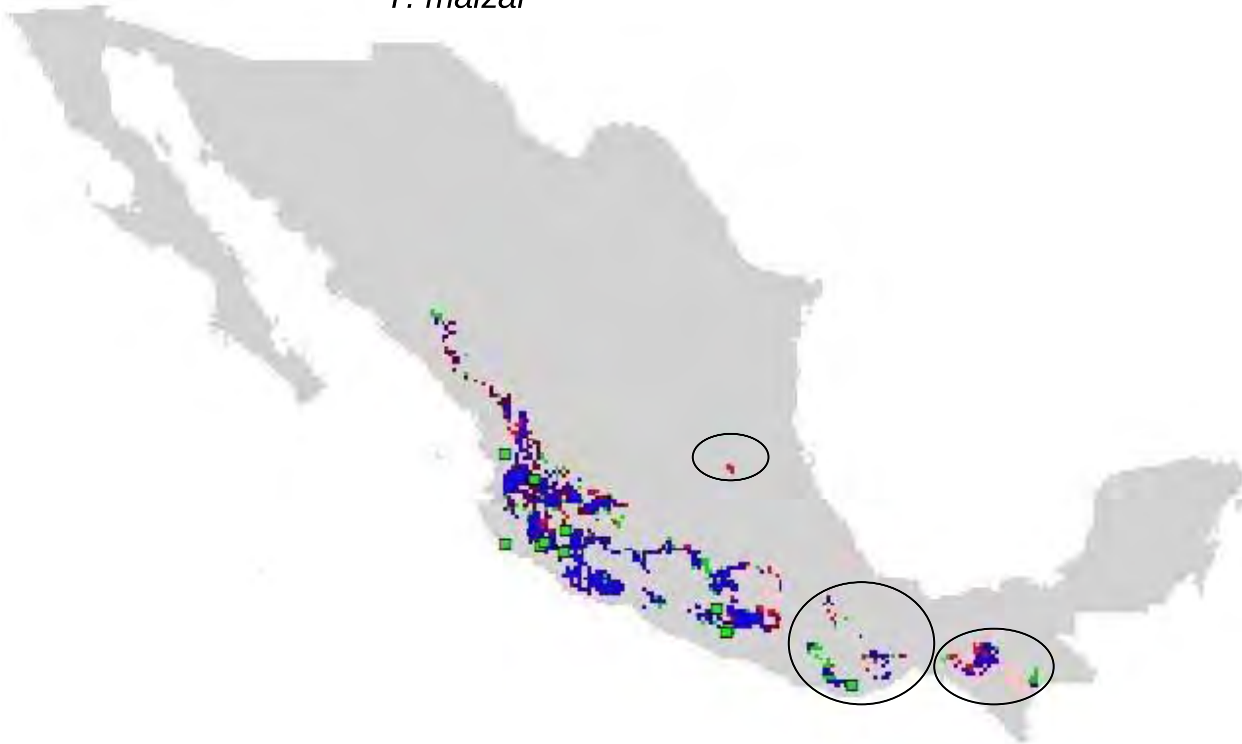
T. latifolium



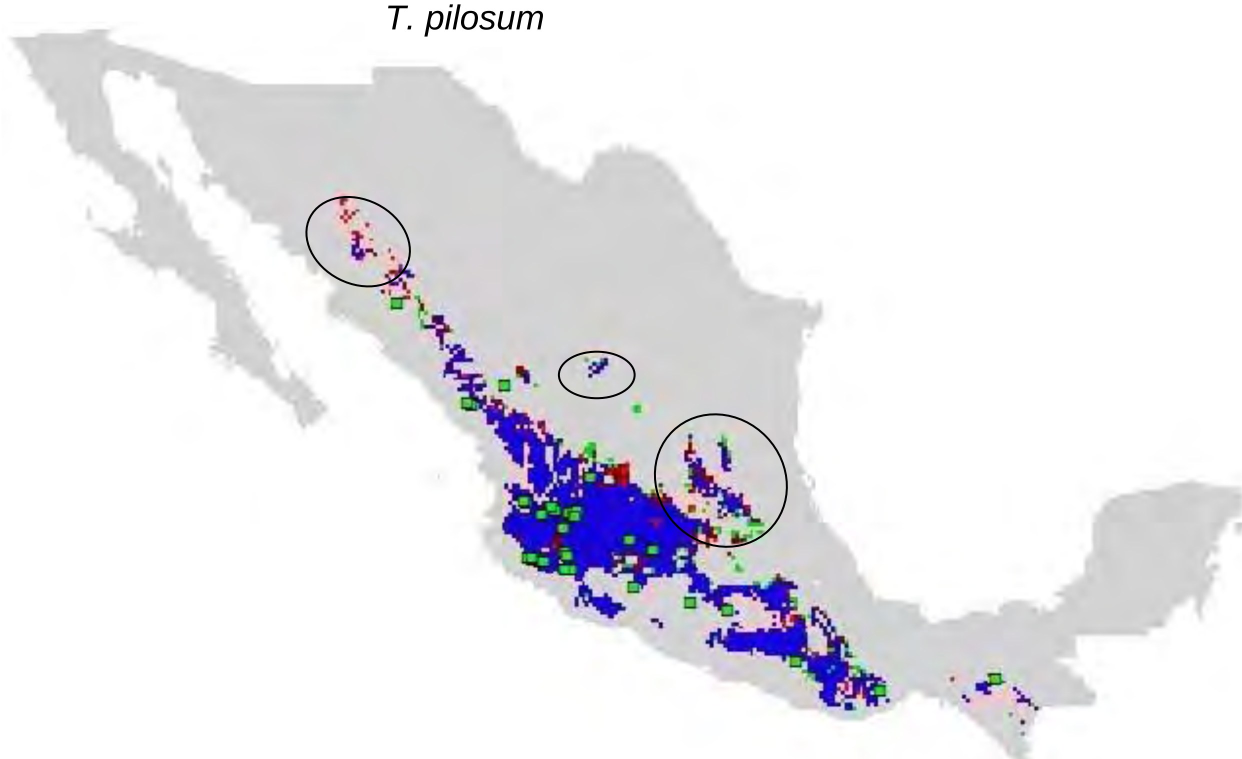
T. laxum



T. maizar



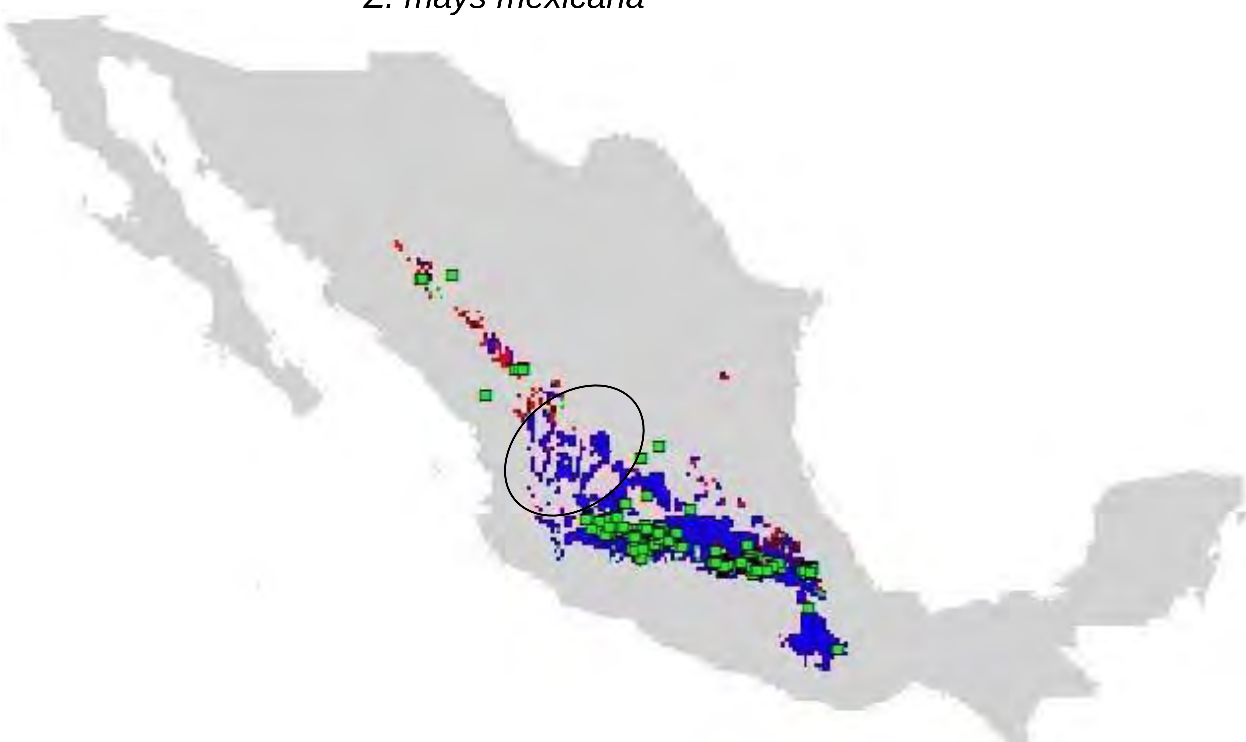
T. pilosum



T. zopilotense

Z. diploperennis

Z. mays mexicana



Z. mays parviglumis

Z. perennis

Appendix 4. Critic Bioclimatic Thresholds for Mexican races and wild relatives

Table 1. Critic Annual Thresholds of Altitude and Temperature

A: Altitude, T max: Maximal temperature of the hottest month, T min: Minimal temperature of the coldest month, T mean annual: Mean Annual Temperature.

Race	A	T max	T min	Mean annual T
ANCHO				
Media	1403.8	32.3	10.1	21.3
Mínima	56.0	26.6	3.6	15.7
Máx	2348.0	40.9	18.5	28.9
APACHITO				
Media	2142.0	29.5	-3.2	12.8
Mínima	1382.0	23.8	-5.3	10.0
Máx	2649.0	35.3	0.8	18.4
ARROCILLO				
Media	2008.7	24.4	5.6	15.1
Mínima	25.0	13.6	0.6	7.2
Máx	3402.0	33.1	15.4	24.7
AZUL				
Media	2145.1	29.0	-4.1	12.2
Mínima	1460.0	23.0	-5.9	9.6
Máx	2679.0	31.9	6.1	17.5
BLANDO DE SONORA				
Media	732.7	37.2	5.8	21.6
Mínima	42.0	26.8	-2.6	12.7
Máx	2088.0	41.0	11.9	25.4
BOFO				
Media	1334.1	33.1	8	21.1
Mínima	5.0	25.6	1.1	14.1
Máx	2523.0	40.0	17.5	28.1
BOLITA				
Media	1632.0	30.1	7.9	19.1
Mínima	19.0	22.1	-5.4	11.9
Máx	2434.0	40.8	19.3	28.2
CACAHUACINTLE				
Media	2426.2	25.4	2.4	14.4
Mínima	1381.0	22.4	0.2	12.5
Máx	2729.0	34.7	12.1	23.3
CELAYA				
Media	1667.9	31.5	6.2	19.1
Mínima	11.0	19.1	-5.1	10.6
Máx	3402.0	41.3	19.6	28.7

Race	A	T max	T min	Mean annual T
CHALQUEÑO				
Media	2239.9	27.4	3.0	15.7
Mínima	1025.0	22.1	-5.2	12.7
Máx	3195.0	36.3	12.3	23.9
CHAPALOTE				
Media	313.7	38.1	7.9	23.6
Mínima	7.0	34.6	3.1	21.0
Máx	631.0	40.1	13.4	25.4
CHIQUITO				
Media	1713.9	27.4	9.1	18.0
Mínima	33.0	22.1	4.7	12.7
Máx	2562.0	35.6	18.2	26.9
COMITECO				
Media	1725.9	26.2	8.5	17.5
Mínima	21.0	21.4	1.3	12.4
Máx	2440.0	36.5	19.1	27.8
COMPLEJO SERRANO DE JALISCO				
Media	1946.2	30.8	7.5	19.0
Mínima	1523.0	26.7	3.1	15.5
Máx	2512.0	33.8	13.4	23.4
CONEJO				
Media	740.8	35.6	15.1	25.3
Mínima	18.0	23.1	4.9	14.6
Máx	2414.0	41.3	21.4	28.4
CONICO				
Media	2339.7	25.8	3.0	14.9
Mínima	169.0	11.8	-0.4	6.0
Máx	3606.0	40.8	16.5	28.1
CONICO NORTEÑO				
Media	2011.6	30.3	2.4	16.7
Mínima	598.0	21.7	-5.9	10.7
Máx	2796.0	36.4	11.0	23.9
COSCOMATEPEC				
Media	1557.4	25.7	8.3	16.9
Mínima	13.0	21.8	2.7	12.3
Máx	2769.0	36.2	17.2	25.9
CRISTALINO DE CHIHUAHUA				
Media	2063.4	29.9	-4.1	12.6
Mínima	257.0	24.0	-5.9	9.6
Máx	2576.0	37.5	10.7	25.0

Race	A	T max	T min	Mean annual T
DULCE				
Media	1733.2	31.5	5.0	18.5
Mínima	254.0	25.9	-3.9	13.3
Máx	2697.0	40.7	15.9	27.9
DULCILLO DEL NOROESTE				
Media	685.8	35.7	5.8	21.2
Mínima	14.0	27.9	-5.1	11.4
Máx	2120.0	40.5	14.5	25.9
DZIT-BACAL				
Media	100.1	35.5	15.2	25.5
Mínima	0.0	30.1	7.2	20.5
Máx	851.0	37.1	18.2	26.6
ELOTERO DE SINALOA				
Media	852.2	35.4	13.0	24.4
Mínima	4.0	26.8	3.3	15.5
Máx	2139.0	41.4	18.8	28.6
ELOTES CONICOS				
Media	2213.7	27.2	3.9	15.9
Mínima	378.0	17.9	-0.4	10.5
Máx	2961.0	40.8	16.5	28.1
GORDO				
Media	1967.8	30.8	-2.6	14.0
Mínima	978.0	26.0	-5.9	10.8
Máx	2576.0	39.2	11.0	25.4
JALA				
Media	1178.2	34.4	9.4	22.2
Mínima	172.0	31.0	6.5	19.4
Máx	1918.0	36.8	13.7	25.5
MUSHITO				
Media	1918.6	28.4	7.1	17.7
Mínima	3.0	20.7	2.2	13.1
Máx	2844.0	40.1	18.9	28.2
NAL-TEL				
Media	461.0	33.6	14.3	24.1
Mínima	6.0	22.1	-2.8	12.2
Máx	2419.0	40.5	19.3	28.0
OLOTILLO				
Media	695.2	32.4	12.6	22.9
Mínima	16.0	22.2	2.4	13.5
Máx	2373.0	40.5	21.3	28.1

Race	**A**	**T max**	**T min**	**Mean annual T**
OLOTON				
Media	2174.5	24.2	6.0	15.5
Mínima	18.0	21.4	1.3	12.4
Máx	2582.0	39.6	17.1	28.2
ONAVEÑO				
Media	535.2	37.2	6.3	21.9
Mínima	6.0	28.8	-2.1	12.6
Máx	2096.0	41.2	14.8	26.0
PALOMERO TOLUQUEÑO				
Media	2374.5	25.8	1.1	13.9
Mínima	14.0	23.0	-5.4	10.8
Máx	2843.0	35.1	14.4	25.9
PEPITILLA				
Media	1291.6	34.0	10.6	22.3
Mínima	45.0	23.4	1.9	14.9
Máx	2527.0	40.5	19.4	28.1
RATON				
Media	828.3	34.5	5.9	21.2
Mínima	2.0	24.1	-4.5	11.6
Máx	2390.0	40.1	17.2	28.2
REVENTADOR				
Media	490.7	36.8	9.8	23.7
Mínima	5.0	26.5	3.1	17.1
Máx	1632.0	40.5	18.2	28.3
SERRANO MIXE				
Media	1951.6	26.6	8.7	17.4
Mínima	733.0	17.9	4.3	10.5
Máx	2961.0	35.2	15.3	25.1
TABLILLA DE OCHO				
Media	1597.8	32.5	5.0	19.0
Mínima	365.0	24.6	-4.6	9.6
Máx	2383.0	39.2	12.9	25.4
TABLONCILLO				
Media	918.4	34.8	9.3	22.5
Mínima	11.0	23.7	-5.8	11.7
Máx	2861.0	41.6	18.2	27.8

Race	**A**	**T max**	**T min**	**Mean annual T**
TABLONCILLO PERLA				
Media	487.0	35.7	11.3	24.2
Mínima	4.0	26.7	-1.4	13.7
Máx	1873.0	41.0	17.4	27.5
TEHUA				
Media	1079.8	30.5	12.3	21.2
Mínima	10.0	26.2	8.4	17.1
Máx	1933.0	36.4	18.2	26.7
TEPECINTLE				
Media	769.6	31.7	13.3	22.6
Mínima	4.0	23.9	6.3	15.0
Máx	2244.0	36.8	19.6	27.7
TUXPEÑO				
Media	548.8	34.0	13.7	24.1
Mínima	0.0	21.6	-0.6	12.1
Máx	2498.0	41.3	21.4	28.7
TUXPEÑO NORTEÑO				
Media	1191.2	34.2	3.3	19.5
Mínima	2.0	25.2	-5.2	13.2
Máx	2325.0	37.6	17.1	25.5
VANDEÑO				
Media	687.9	35.0	13.5	24.3
Mínima	5.0	23.0	2.1	14.4
Máx	2303.0	41.3	21.3	28.5
ZAMORANO AMARILLO				
Media	1776.9	31.0	5.4	18.4
Mínima	49.0	26.4	2.2	15.6
Máx	2338.0	36.3	16.1	26.1
ZAPALOTE CHICO				
Media	177.7	35.4	18.0	26.7
Mínima	4.0	24.6	6.8	15.4
Máx	2256.0	36.5	20.4	28.2
ZAPALOTE GRANDE				
Media	541.9	33.2	15.4	24.4
Mínima	7.0	23.6	3.9	13.9
Máx	2488.0	37.1	19.7	28.2

Table 2. Critic Annual Thresholds of Precipitation.
P+: Maximal Precipitation of the wettest month, P-: Minimal Precipitation of the driest month,
P annual: Annual Precipitation.

Race	**P +**	**P-**	**Anual P**
ANCHO			
Media	56.5	0.1	981.2
Mínima	36.0	0.0	652.0
Máx	110.0	10.0	1949.0
APACHITO			
Media	49.0	0.0	730.9
Mínima	23.0	0.0	360.0
Máx	68.0	0.0	1127.0
ARROCILLO			
Media	70.4	0.5	1299.9
Mínima	24.0	0.0	496.0
Máx	155.0	25.0	3411.0
AZUL			
Media	43.3	0.0	654.7
Mínima	31.0	0.0	453.0
Máx	73.0	0.0	1202.0
BLANDO DE SONORA			
Media	54.7	0.0	731.5
Mínima	23.0	0.0	304.0
Máx	84.0	0.0	1244.0
BOFO			
Media	58.7	6.5	888.2
Mínima	21.0	0.0	390.0
Máx	152.0	12.6	2855.0
BOLITA			
Media	43.4	0.0	776.3
Mínima	18.0	0.0	304.0
Máx	120.0	0.0	2237.0
CACAHUACINTLE			
Media	41.0	0.0	787.0
Mínima	19.0	0.0	397.0
Máx	81.0	0.0	1438.0
CELAYA			
Media	48.0	0.0	788.1
Mínima	11.0	0.0	211.0
Máx	125.0	14.0	2485.0

Race	P +	P-	Anual P
CHALQUEÑO			
Media	41.1	0.0	767.2
Mínima	21.0	0.0	304.0
Máx	97.0	0.0	1687.0
CHAPALOTE			
Media	51.4	0.0	686.6
Mínima	23.0	0.0	304.0
Máx	72.0	0.0	1005.0
CHIQUITO			
Media	72.2	6.4	1393.9
Mínima	33.0	0.0	593.0
Máx	137.0	0.0	2668.0
COMITECO			
Media	69.1	1.5	1510.1
Mínima	49.0	0.0	961.0
Máx	180.0	24.0	4119.0
COMPLEJO SERRANO DE JALISCO			
Media	56.1	0.0	959.8
Mínima	40.0	0.0	667.0
Máx	84.0	0.0	1660.0
CONEJO			
Media	65.2	0.0	1047.3
Mínima	42.0	0.0	692.0
Máx	117.0	0.0	1947.0
CONICO			
Media	40.4	0.0	787.7
Mínima	12.0	0.0	315.0
Máx	126.0	14.0	2712.0
CONICO NORTEÑO			
Media	31.1	0.0	525.7
Mínima	9.0	0.0	184.0
Máx	94.0	0.0	1391.0
COSCOMATEPEC			
Media	75.3	1.9	1549.8
Mínima	45.0	0.0	909.0
Máx	113.0	17.0	2223.0
CRISTALINO DE CHIHUAHUA			
Media	41.1	0.0	602.9
Mínima	19.0	0.0	320.0
Máx	76.0	0.0	1268.0

Race	**P +**	**P-**	**Anual P**
DULCE			
Media	48.0	0.0	755.6
Mínima	21.0	0.0	390.0
Máx	72.0	0.0	1176.0

DULCILLO DEL NOROESTE			
Media	57.0	0.0	775.7
Mínima	23.0	0.0	304.0
Máx	103.0	0.0	1387.0

DZIT-BACAL			
Media	51.6	0.1	1154.6
Mínima	26.0	0.0	563.0
Máx	113.0	10.0	2202.0

ELOTERO DE SINALOA			
Media	62.4	0.0	973.0
Mínima	38.0	0.0	676.0
Máx	103.0	0.0	1379.0

ELOTES CONICOS			
Media	45.5	0.0	844.7
Mínima	18.0	0.0	370.0
Máx	125.0	14.0	2485.0

GORDO			
Media	40.5	0.0	592.5
Mínima	18.0	0.0	299.0
Máx	76.0	0.0	1268.0

JALA			
Media	67.5	0.0	963.9
Mínima	40.0	0.0	667.0
Máx	104.0	0.0	1508.0

MUSHITO			
Media	63.8	0.1	1127.8
Mínima	32.0	0.0	568.0
Máx	125.0	14.0	2485.0

NAL-TEL			
Media	58.5	0.5	1242.2
Mínima	35.0	0.0	609.0
Máx	158.0	24.0	3232.0

OLOTILLO			
Media	72.3	1.6	1334.5
Mínima	9.0	0.0	193.0
Máx	186.0	25.0	3586.0

Race	**P +**	**P-**	**Anual P**
OLOTON			
Media	63.9	0.0	1360.0
Mínima	35.0	0.0	600.0
Máx	161.0	12.0	3307.0

ONAVEÑO			
Media	54.3	0.0	716.5
Mínima	20.0	0.0	266.0
Máx	110.0	0.0	1446.0

PALOMERO TOLUQUEÑO			
Media	46.4	0.2	839.4
Mínima	22.0	0.0	459.0
Máx	103.0	11.0	1502.0

PEPITILLA			
Media	54.1	0.0	935.9
Mínima	23.0	0.0	470.0
Máx	94.0	0.0	1367.0

RATON			
Media	33.9	0.1	632.4
Mínima	8.0	0.0	159.0
Máx	95.0	17.0	2072.0

REVENTADOR			
Media	59.8	0.0	842.2
Mínima	20.0	0.0	312.0
Máx	110.0	0.0	1480.0

SERRANO MIXE			
Media	75.0	0.0	1505.6
Mínima	46.0	0.0	800.0
Máx	91.0	0.0	1868.0

TABLILLA DE OCHO			
Media	50.8	0.0	760.6
Mínima	28.0	0.0	461.0
Máx	103.0	0.0	1523.0

TABLONCILLO			
Media	62.2	0.0	936.4
Mínima	10.0	0.0	141.0
Máx	110.0	0.0	1679.0

Race	P +	P-	Anual P
TABLONCILLO PERLA			
Media	68.7	0.0	994.9
Mínima	10.0	0.0	141.0
Máx	110.0	0.0	1523.0
TEHUA			
Media	84.8	6.1	1838.6
Mínima	63.0	0.0	1088.0
Máx	114.0	15.0	2709.0
TEPECINTLE			
Media	87.7	3.1	1733.1
Mínima	30.0	0.0	546.0
Máx	195.0	28.0	4067.0
TUXPEÑO			
Media	71.7	1.0	1397.9
Mínima	10.0	0.0	219.0
Máx	195.0	28.0	4067.0
TUXPEÑO NORTEÑO			
Media	26.1	0.0	458.9
Mínima	8.0	0.0	159.0
Máx	77.0	0.0	1559.0
VANDEÑO			
Media	69.2	0.5	1179.4
Mínima	13.0	0.0	186.0
Máx	189.0	24.0	3639.0
ZAMORANO AMARILLO			
Media	58.8	0.0	912.7
Mínima	27.0	0.0	523.0
Máx	104.0	0.0	1782.0
ZAPALOTE CHICO			
Media	70.2	0.1	1075.2
Mínima	35.0	0.0	596.0
Máx	150.0	11.0	3070.0
ZAPALOTE GRANDE			
Media	70.2	0.4	1282.7
Mínima	34.0	0.0	609.0
Máx	156.0	24.0	3232.0

Table 3. Critic Thresholds for the Spring-Summer cycle (May-October).
Tmax: Maximal Temperature of the Spring-Summer cycle, Tmin: Minimal Temperature of the Spring-Summer cycle, P: Accumulative Precipitation of the Spring-Summer cycle.

Race	**Tmax**	**Tmin**	**cumulative P**
ANCHO			
Media	28.9	16.0	905.2
Mínima	23.8	10.0	559.9
Máx	35.7	23.3	1684.1
APACHITO			
Media	25.6	8.7	567.4
Mínima	20.5	5.2	312.0
Máx	31.6	14.9	863.9
ARROCILLO			
Media	21.8	11.0	1039.2
Mínima	10.2	2.9	379.0
Máx	31.7	21.9	2598.9
AZUL			
Media	25.2	8.4	517.9
Mínima	19.9	6.0	358.0
Máx	28.7	16.8	1059.5
BLANDO DE SONORA			
Media	33.7	17.8	589.4
Mínima	24.5	8.6	228.8
Máx	37.4	21.9	1058.0
BOFO			
Media	30.2	16.2	798.8
Mínima	21.9	9.4	290.1
Máx	36.2	23.7	2446.2
BOLITA			
Media	26.5	13.6	698.4
Mínima	17.9	6.4	192.4
Máx	35.3	23.6	2047.6
CACAHUACINTLE			
Media	22.5	8.6	684.9
Mínima	19.8	6.9	310.1
Máx	31.4	17.1	1270.3
CELAYA			
Media	27.8	13.8	717.8
Mínima	14.5	4.9	153.9
Máx	37.2	23.7	2153.9

Race	**Tmax**	**Tmin**	**cumulative P**
CHALQUEÑO			
Media	24.3	10.0	684.2
Mínima	17.9	6.3	197.4
Máx	32.8	18.6	1485.8

CHAPALOTE			
Media	35.4	20.1	562.8
Mínima	32.4	17.8	233.3
Máx	37.1	22.4	899.3

CHIQUITO			
Media	24.2	13.5	1219.2
Mínima	17.9	7.8	496.9
Máx	33.0	21.9	2304.4

COMITECO			
Media	24.0	12.7	1249.3
Mínima	19.9	8.4	756.3
Máx	34.1	22.4	3492.9

COMPLEJO SERRANO DE JALISCO			
Media	26.7	14.2	871.1
Mínima	22.7	11.1	575.1
Máx	30.4	18.2	1428.3

CONEJO			
Media	32.0	19.9	998.4
Mínima	20.6	8.8	605.6
Máx	35.8	23.9	1922.9

CONICO			
Media	22.9	9.1	686.2
Mínima	10.2	2.8	181.8
Máx	35.0	22.4	2220.7

CONICO NORTEÑO			
Media	27.1	11.4	458.2
Mínima	18.6	5.6	139.5
Máx	34.8	20.2	1313.8

COSCOMATEPEC			
Media	23.4	13.2	1224.5
Mínima	18.6	6.9	699.4
Máx	33.1	22.7	2094.2

CRISTALINO DE CHIHUAHUA			
Media	25.9	8.8	475.6
Mínima	21.1	6.4	211.9
Máx	35.2	20.8	964.0

Race	**Tmax**	**Tmin**	**cumulative P**
DULCE			
Media	27.9	13.3	680.1
Mínima	23.3	8.6	307.6
Máx	37.0	22.6	1100.1

DULCILLO DEL NOROESTE			
Media	32.7	17.6	637.3
Mínima	24.6	7.6	238.3
Máx	37.1	22.8	1320.1

DZIT-BACAL			
Media	33.3	20.8	922.6
Mínima	27.1	15.7	408.4
Máx	34.4	23.0	1902.8

ELOTERO DE SINALOA			
Media	32.1	19.4	897.9
Mínima	23.7	10.2	467.0
Máx	36.0	23.9	1477.4

ELOTES CONICOS			
Media	24.1	10.1	752.6
Mínima	14.7	5.9	235.7
Máx	34.9	22.4	1972.7

GORDO			
Media	27.0	10.0	487.8
Mínima	23.0	6.4	259.6
Máx	35.2	19.8	958.4

JALA			
Media	31.1	17.5	653.4
Mínima	27.3	14.4	541.7
Máx	34.7	20.7	1597.7

MUSHITO			
Media	25.1	12.4	1025.3
Mínima	18.3	8.3	452.9
Máx	35.7	23.4	2040.8

NAL-TEL			
Media	31.4	19.3	1022.6
Mínima	17.9	7.1	441.4
Máx	35.2	23.0	3065.6

OLOTILLO			
Media	30.3	18.4	1169.4
Mínima	19.9	7.8	148.8
Máx	36.7	23.9	3043.9

Race	Tmax	Tmin	cumulative P
OLOTON			
Media	22.2	10.5	1148.2
Mínima	19.9	7.7	432.1
Máx	35.6	22.6	3042.3
ONAVEÑO			
Media	34.2	18.5	588.5
Mínima	25.0	8.5	182.7
Máx	37.7	23.3	1404.8
PALOMERO TOLUQUEÑO			
Media	22.2	8.8	782.9
Mínima	20.1	5.8	281.5
Máx	33.9	22.7	1562.0
PEPITILLA			
Media	30.1	16.5	881.7
Mínima	20.5	8.2	364.8
Máx	36.0	23.4	1426.4
RATON			
Media	32.0	17.9	517.9
Mínima	21.8	6.7	112.2
Máx	37.4	25.0	1806.1
REVENTADOR			
Media	34.1	19.9	734.8
Mínima	25.0	13.0	212.4
Máx	37.7	23.5	1512.9
SERRANO MIXE			
Media	23.6	13.2	1300.4
Mínima	14.7	6.3	699.5
Máx	32.2	19.0	1632.8
TABLILLA DE OCHO			
Media	29.1	14.1	677.4
Mínima	21.1	6.8	343.5
Máx	34.7	20.4	1482.2
TABLONCILLO			
Media	31.7	17.9	832.1
Mínima	20.8	6.9	93.8
Máx	38.0	23.2	1763.1

Race	**Tmax**	**Tmin**	**cumulative P**
TABLONCILLO PERLA			
Media	33.3	20.2	885.3
Mínima	24.4	9.5	94.0
Máx	37.8	23.5	1590.0
TEHUA			
Media	27.8	16.8	1485.5
Mínima	22.7	12.0	997.9
Máx	33.9	22.6	2174.7
TEPECINTLE			
Media	29.3	18.2	1463.2
Mínima	20.6	10.1	478.3
Máx	34.4	23.2	3494.4
TUXPEÑO			
Media	31.5	19.5	1212.8
Mínima	18.7	7.3	140.4
Máx	37.9	24.1	3604.7
TUXPEÑO NORTEÑO			
Media	31.2	16.1	387.7
Mínima	22.3	7.3	93.6
Máx	36.4	23.0	1410.6
VANDEÑO			
Media	31.8	19.4	1063.5
Mínima	21.1	10.3	136.0
Máx	37.7	24.7	3302.2
ZAMORANO AMARILLO			
Media	27.2	13.1	844.2
Mínima	23.0	9.2	410.1
Máx	34.2	21.9	1716.0
ZAPALOTE CHICO			
Media	33.1	22.1	1024.7
Mínima	22.2	11.7	518.9
Máx	34.7	23.7	2832.1
ZAPALOTE GRANDE			
Media	31.0	19.6	1172.1
Mínima	20.6	8.7	542.7
Máx	34.8	23.4	3012.6

Table 4. Critic Bioclimatic Thresholds for the Autumn- Winter cycle (May-October).
Tmax: Maximal Temperature of the Autumn- Winter cycle, Tmin: Minimal Temperature of the Autumn- Winter cycle, P: Accumulative Precipitation of the Autumn- Winter cycle.

Raza	**Tmax**	**Tmin**	**P acumulada**
ANCHO			
Media	25.6	12.7	76.0
Mínima	20.6	2.9	17.4
Máx	33.9	62.4	374.2
APACHITO			
Media	14.7	27.2	163.4
Mínima	11.4	5.9	35.3
Máx	20.3	45.3	272.0
ARROCILLO			
Media	18.1	43.5	260.8
Mínima	8.4	7.4	44.7
Máx	26.5	136.9	821.2
AZUL			
Media	14.3	22.8	136.8
Mínima	10.7	8.0	48.1
Máx	22.6	58.0	347.9
BLANDO DE SONORA			
Media	28.2	20.2	142.1
Mínima	13.7	10.8	65.0
Máx	42.6	29.6	255.5
BOFO			
Media	25.1	14.9	89.3
Mínima	17.7	1.5	8.9
Máx	33.0	85.7	514.4
BOLITA			
Media	23.8	13.0	77.9
Mínima	13.3	1.1	6.8
Máx	33.4	68.3	410.0
CACAHUACINTLE			
Media	19.1	17.0	102.2
Mínima	16.2	5.8	34.7
Máx	27.9	53.1	318.5
CELAYA			
Media	23.2	11.7	70.3
Mínima	12.1	2.2	12.9
Máx	34.0	91.5	548.9

Raza	Tmax	Tmin	P acumulada
CHALQUEÑO			
Media	20.4	13.8	83.0
Mínima	14.6	1.9	11.6
Máx	29.4	65.1	390.7

CHAPALOTE			
Media	25.6	20.7	123.9
Mínima	21.2	10.6	63.4
Máx	28.5	31.3	187.8

CHIQUITO			
Media	21.7	29.1	174.6
Mínima	16.3	3.3	19.9
Máx	31.1	69.0	414.1

COMITECO			
Media	21.0	43.5	260.7
Mínima	17.3	5.0	30.3
Máx	32.7	211.3	1267.9

COMPLEJO SERRANO DE JALISCO			
Media	22.5	14.8	88.7
Mínima	17.9	7.3	43.7
Máx	27.4	38.8	232.8

CONEJO			
Media	29.7	8.1	48.9
Mínima	17.5	1.9	11.3
Máx	34.1	32.0	192.1

CONICO			
Media	19.5	16.9	101.6
Mínima	8.4	1.9	11.5
Máx	33.3	82.6	495.4

CONICO NORTEÑO			
Media	20.3	11.3	67.5
Mínima	11.9	3.1	18.6
Máx	29.5	44.9	269.2

COSCOMATEPEC			
Media	54.2	19.2	325.3
Mínima	18.6	15.4	111.5
Máx	105.7	27.8	634.2

CRISTALINO DE CHIHUAHUA			
Media	21.2	14.5	127.3
Mínima	5.4	10.7	32.5
Máx	55.7	28.2	334.2

Raza	Tmax	Tmin	P acumulada
DULCE			
Media	22.5	12.6	75.6
Mínima	15.4	4.4	26.4
Máx	33.3	51.6	309.6
DULCILLO DEL NOROESTE			
Media	23.4	23.1	138.5
Mínima	12.9	8.6	51.3
Máx	28.8	37.1	222.7
DZIT-BACAL			
Media	28.4	38.7	231.9
Mínima	23.5	9.7	58.0
Máx	29.8	76.3	458.1
ELOTERO DE SINALOA			
Media	28.5	12.5	75.1
Mínima	19.6	2.7	16.0
Máx	34.0	40.4	242.3
ELOTES CONICOS			
Media	20.5	15.3	92.1
Mínima	13.5	2.1	12.5
Máx	33.3	90.0	539.8
GORDO			
Media	16.3	17.5	104.8
Mínima	11.8	4.8	29.0
Máx	29.4	52.1	312.8
JALA			
Media	26.4	12.6	75.5
Mínima	22.4	7.0	42.3
Máx	29.3	26.3	157.5
MUSHITO			
Media	22.0	17.1	102.4
Mínima	16.6	2.1	12.5
Máx	32.8	91.1	546.5
NAL-TEL			
Media	27.4	36.6	219.5
Mínima	15.2	2.2	13.4
Máx	33.2	194.4	1166.2
OLOTILLO			
Media	26.1	27.5	165.1
Mínima	16.5	1.5	8.8
Máx	33.3	136.9	821.3

Raza	Tmax	Tmin	P acumulada
OLOTON			
Media	19.3	35.3	211.8
Mínima	17.1	3.1	18.7
Máx	32.6	99.5	597.0

ONAVEÑO			
Media	23.6	21.4	128.1
Mínima	14.4	9.5	56.8
Máx	32.6	99.5	597.0

PALOMERO TOLUQUEÑO			
Media	18.6	17.5	105.0
Mínima	11.8	5.5	32.7
Máx	28.5	57.8	346.8

PEPITILLA			
Media	27.3	9.0	54.2
Mínima	18.5	2.2	13.4
Máx	33.3	39.9	239.3

RATON			
Media	22.6	19.1	114.5
Mínima	13.6	2.9	17.3
Máx	33.0	105.7	634.2

REVENTADOR			
Media	26.3	17.9	107.5
Mínima	19.1	6.6	39.6
Máx	32.6	47.3	283.6

SERRANO MIXE			
Media	21.3	34.2	205.1
Mínima	13.8	9.4	56.3
Máx	30.2	53.9	323.4

TABLILLA DE OCHO			
Media	22.8	13.9	83.2
Mínima	10.7	6.1	36.6
Máx	29.7	49.7	298.4

TABLONCILLO			
Media	26.0	17.4	104.2
Mínima	13.0	1.6	9.9
Máx	32.3	66.4	398.3

TABLONCILLO PERLA			
Media	27.0	18.3	109.7
Mínima	15.5	5.3	31.9
Máx	32.1	52.7	316.4

Raza	Tmax	Tmin	P acumulada
TEHUA			
Media	24.2	58.8	353.0
Mínima	20.0	12.5	75.1
Máx	29.2	118.5	710.7
TEPECINTLE			
Media	25.7	45.0	270.0
Mínima	18.5	1.6	9.7
Máx	32.6	252.5	1514.8
TUXPEÑO			
Media	27.5	30.9	185.1
Mínima	15.0	1.1	6.5
Máx	34.1	258.8	1553.0
TUXPEÑO NORTEÑO			
Media	21.2	11.9	71.2
Mínima	15.1	3.7	22.4
Máx	29.4	52.8	317.0
VANDEÑO			
Media	28.0	19.3	115.9
Mínima	18.1	1.3	8.0
Máx	33.9	194.4	1166.2
ZAMORANO AMARILLO			
Media	22.9	11.4	68.4
Mínima	19.2	5.7	33.9
Máx	30.3	44.3	265.7
ZAPALOTE CHICO			
Media	30.2	8.4	50.4
Mínima	20.4	1.3	8.1
Máx	32.8	78.5	471.2
ZAPALOTE GRANDE			
Media	28.2	18.4	110.7
Mínima	17.9	1.5	9.1
Máx	32.8	194.4	1166.2

Table 5. Critic Annual Thresholds of *Tripsacum*'s Altitude and Temperature

A: Altitude, T max: Maximal temperature of the hottest month, T min: Minimal temperature of the coldest month, T mean annual: Mean Annual Temperature.

Taxon	**A**	**T max**	**T min**	**Mean anual T**
Tripsacum bravum				
Mean	1389.2	32.4	10.2	21.1
Min	459.0	29.2	1.3	16.6
Max	1896.0	36.1	14.3	24.8
Tripsacum dactyloides dactyloides				
Mean	1590.8	31.5	6.3	19.4
Min	27.0	25.0	-1.0	14.3
Max	2526.0	41.3	17.8	28.8
Tripsacum dactyloides hispidum				
Mean	1417.9	32.4	10.4	21.4
Min	102.0	17.3	1.5	9.6
Max	3468.0	37.1	16.4	26.2
Tripsacum dactyloides mexicanum				
Mean	1023.0	33.3	11.3	22.6
Min	127.0	29.8	6.1	19.3
Max	1903.0	36.1	15.8	26.0
Tripsacum intermedium				
Mean	1401.2	30.6	11.6	21.2
Min	742.0	25.8	6.8	17.0
Max	2001.0	35.0	14.6	23.7
Tripsacum lanceolatum				
Mean	1578.3	32.1	4.4	18.4
Min	4.0	24.3	-4.1	11.7
Max	2776.0	39.3	17.8	26.5
Tripsacum latifolium				
Mean	494.3	34.3	13.8	24.0
Min	4.0	28.2	-2.9	12.6
Max	2530.0	37.0	18.9	27.0
Tripsacum laxum				
Mean	980.2	32.3	11.7	22.0
Min	51.0	24.0	2.1	13.4
Max	2483.0	37.1	16.4	26.2
Tripsacum maizar				
Mean	1051.0	33.8	12.0	23.2
Min	144.0	28.9	6.5	19.2
Max	2083.0	37.7	15.6	25.9

Tripsacum pilosum				
Mean	1386.3	32.5	8.7	20.8
Min	578.0	24.9	-2.8	12.4
Max	2540.0	39.0	17.1	27.4

Tripsacum zopilotense				
Mean	1335.3	33.0	9.6	21.4
Min	688.0	22.7	-2.8	14.0
Max	2520.0	37.8	16.0	26.9

Table 6. Critic Annual Thresholds of *Tripsacum*'s Precipitation.
P+: Maximal Precipitation of the wettest month, P-: Minimal Precipitation of the driest month, P annual: Annual Precipitation.

Taxon	**P+**	**P-**	**Annual P**
Tripsacum bravum			
Mean	59.3	0.0	1028.8
Min	33.0	0.0	492.0
Max	98.0	0.0	1413.0
Tripsacum dactyloides dactyloides			
Mean	47.8	0.1	790.2
Min	16.0	0.0	304.0
Max	107.0	11.0	1542.0
Tripsacum dactyloides hispidum			
Mean	57.2	0.0	1017.2
Min	31.0	0.0	639.0
Max	91.0	0.0	1352.0
Tripsacum dactyloides mexicanum			
Mean	57.9	0.0	988.1
Min	33.0	0.0	703.0
Max	90.0	0.0	1274.0
Tripsacum intermedium			
Mean	64.1	0.0	1154.4
Min	50.0	0.0	891.0
Max	73.0	0.0	1344.0
Tripsacum lanceolatum			
Mean	48.3	0.1	767.1
Min	17.0	0.0	234.0
Max	145.0	16.0	3604.0
Tripsacum latifolium			
Mean	98.4	3.4	1853.8
Min	53.0	0.0	921.0
Max	177.0	13.0	3618.0
Tripsacum laxum			
Mean	90.6	0.8	1692.3
Min	31.0	0.0	514.0
Max	145.0	11.0	3087.0
Tripsacum maizar			
Mean	66.4	0.0	1065.4
Min	38.0	0.0	662.0
Max	94.0	0.0	1446.0

Tripsacum pilosum			
Mean	65.0	0.0	1014.0
Min	38.0	0.0	660.0
Max	87.0	0.0	1320.0

Tripsacum zopilotense			
Mean	49.0	0.0	840.3
Min	16.0	0.0	351.0
Max	74.0	0.0	1201.0

Table 7. Critic Annual Thresholds of Teocinte's Altitude and Temperature
A: Altitude, T max: Maximal temperature of the hottest month, T min: Minimal temperature of the coldest month, T mean annual: Mean Annual Temperature.

Taxon	A	T max	T min	Mean anual T
Zea diploperennis				
Mean	1801.7	33.6	9.9	22.1
Min	1480.0	30.3	8.8	19.7
Max	2363.0	34.8	10.6	22.9
Zea mays mexicana				
Mean	2132.7	28.2	3.3	16.2
Min	1534.0	22.5	-2.4	12.3
Max	2993.0	33.1	7.4	20.0
Zea mays parviglumis				
Mean	1124.3	34.8	12.7	23.5
Min	176.0	20.2	2.8	11.4
Max	3044.0	41.3	18.2	28.7
Zea perennis				
Mean	1991.7	30.1	7.3	18.5
Min	1541.0	29.1	7.0	17.8
Max	2283.0	32.4	7.6	19.6

Table 8. Critic Annual Thresholds of Taconite's Precipitation.
P+: Maximal Precipitation of the wettest month, P-: Minimal Precipitation of the driest month, P annual: Annual Precipitation.

Taxon	**P+**	**P-**	**Annual P**
Zea diploperennis			
Mean	68.5	0.0	1227.4
Min	63.0	0.0	1199.0
Max	72.0	0.0	1269.0
Zea mays mexicana			
Mean	45.4	0.0	788.3
Min	19.0	0.0	427.0
Max	72.0	0.0	1204.0
Zea mays parviglumis			
Mean	62.1	0.0	1063.6
Min	35.0	0.0	624.0
Max	107.0	0.0	1624.0
Zea perennis			
Mean	46.7	0.0	875.2
Min	40.0	0.0	667.0
Max	50.0	0.0	982.0

Capítulo 2

Influencia de Factores Ambientales y Sociales sobre la distribución y Riqueza del Maíz Mexicano: Un Análisis de Minería de Datos

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Environmental and social factors account for Mexican maize richness and distribution: A data mining approach

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ABSTRACT

Food security is a key topic for human welfare worldwide. In this context, the agrobiodiversity in centers of origin and diversification (COD) for the world's staple crops will be critical for feeding the world under changing environmental and social conditions. Maize is one of the most widely cultivated cereal and is the staple food for African and Latin-American countries, including its COD: Mexico, harboring more than 60% of the world's diversity for this crop. In this study we implemented a data mining approach that allowed us to evaluate spatial relationships of environmental (altitude, climate, slope and soil) and social factors (education and ethnic groups) with the spatial distribution of Mexican races, as well as the areas that can potentially harbor the highest number of races (PRA). In contrast to commonly used species distribution approaches, the data mining method implemented here allowed the integration of contrasting types of variables and their spatial relationships with the focal entity. Our results indicate that altitude, which is related with climate, was the factor with highest predictive power for most races. However, different factors showed different degrees of association with the spatial distribution of particular races. In any case, the performance of the model increased when using all evaluated factors. In our example study case, the highly vulnerable race Palomero Tolqueño was mainly influenced by climate, implying that climate change might threaten its preservation by reducing the areas with favorable conditions for its cultivation. Importantly, however, for this and other eleven races analyzed in detail, is that the ethnic group was the factor with the greatest predictive power. This finding further reinforces the key importance of *in situ* conservation by supporting local indigenous communities who are in charge of preserving, adapting to changing challenges and cultivating local races.

1. Introduction

The preservation of agrobiodiversity at Centers of Crop Origin and Diversification (COD) is critical for global food security (Thrupp, 2000; Esquinas-Alcazar, 2005). Such diversity is dynamically and communally generated at COD and hence, can only be preserved *in situ* (Bardsley and Thomas, 2005; Ortega Paczka, 2007). Therefore, an integrated understating of the role of diverse environmental and social factors on the distribution of individual races and the areas that can potentially harbor the highest number of races (PRA) becomes critical. Yet, such analyses are scarce or have not been conducted for the staple crops of the world (FAO, 2012).

Maize (*Zea mays* L.L.) is one of the most widely cultivated cereals in the world (Nuss and Tanumihardjo, 2010). It is the basic food of many African and Latin-American countries (CIMMYT, 2012), including Mexico, its COD, where around 59 maize races with thousands of varieties comprise 60% of the maize genetic diversity in the world (Ruiz Corral et al., 2008). Although the race unit is not commonly used in cultivated plants, it has been quite useful to systematize maize diversity. Anderson and Cutler (1942) defined a race as "a group of related individuals with enough characteristics in common to permit their recognition as a group".

Such maize diversification has responded to environmental and biotic conditions, but also to social variables since it was

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domesticated around 5000 years ago (Kato et al., 2009). Mexican maize production is highly dependent on environmental factors, but it is also influenced by complex and dynamic socio-cultural processes (Sánchez González and Goodman, 1992; Bellon and Brush, 1993; Brush and Perales, 2007; Kato et al., 2009; Bellon and Hellin, 2011). Indeed, 75–80% of maize cultivation depends on small-hold farmers (mestizos and indigenous peasants) using traditional methods (Brush and Perales, 2007). Consequently, Mexican maize diversity conservation should rely on criteria that incorporate natural and social factors. Despite the acknowledgment, a study providing an integrated analysis of both types of factors is lacking and is critical for future policies concerning the preservation and use of Mexican maize diversity upon a plethora of challenges faced by maize production and diversity conservation. Among such challenges, the alteration of the distribution of adequate regions for maize cultivation due to climate change is outstanding (Ureta et al., 2012). Also of importance is the loss of rare and critical races to maintain production under specific environmental threats, meeting specific cultural or social needs, preserving maize genetic diversity for future breeding programs, and preserving to avoid or diminish farmers' vulnerability under changing environmental, sociopolitical and economic conditions.

Here, we developed such study using a recently published data mining approach (Stephens et al., 2009; González-Salazar et al., 2013). This method allows the incorporation of biotic and abiotic variables and has been used to model the distribution of wild species, leading to more accurate distribution maps in which it is possible to evaluate the relative importance of the different variables considered, and which should be combined to better understand and explain the distribution of any given species. Under the same principle, we integrated the role of environmental and social factors to evaluate and model the spatial distribution of individual races and of the areas that can potentially harbor the highest number of races (PRA). In comparison with traditional species' distribution approaches that have been previously used (Jackson and Robertson, 2011; Loarie, 2008; Prates-Clark et al., 2008), data mining allows variables of contrasting nature and format to be combined and considered.

Specifically, we: (a) identify environmental and social factors associated with races potential distribution (commonly represented by regions with suitable environmental conditions; in this specific study we also incorporated social factors) and PRA (b) evaluate which of these factors have the highest predictive power of the races potential distribution areas, (c) create probability distribution maps of the potential distribution of individual races and PRA. With the aim of presenting the methodological process and determining the factors influencing the races current distribution, we provide a detailed analysis for an exemplar race. For this aim we have selected the vulnerable Palomero Tolqueño (Ureta et al., 2012) and include the results for this race in the main body of this paper. However, the data and analyses for the rest of the 46 evaluated Mexican races are presented in the Appendixes.

2. Methods

2.1. Data sources

We obtained a georeferenced Mexican maize database from the Mexican Commission for Biodiversity CONABIO (2011) (Acevedo et al., 2011). This database contains 50 years of data collection containing 21,848 records, but for the purpose of our analyses, we eliminated spatially duplicated recordsat the cell level (see below) for each race because they do not provide additional useful information, thus remaining 7949 unique records. Also, from the Mexican races identified in the database, only 47 were considered in this study due to existing taxonomic synonyms (Bofo = Elotes Occidentales and Chiquito = Nal-tel de Altura) and because the status of some races is still under debate.

We considered environmental and social factors and evaluated their influence on the distribution of each Mexican race and on the distribution of the areas that can potentially harbor the highest number of races (24–35 races) (PRA). We also identified the socio-environmental drivers of races and richness.

The environmental variables included in this study are: climate, soil type, altitude, and slope. For climate we used 19 bioclimatic variables that provide extreme, seasonal and annual temperature and precipitation patterns (Téllez et al., 2011), whereas altitude and slope came from the Hydro 1 k database (USGS, 2010). Both climatic and topographic variables were originally in raster format at 1 km resolution. We also incorporated 21 soil types countrywide in vector format at a spatial scale of 1: 250,000 (CONABIO, 1995), therefore, in order to analyze our information, categorical data were used in its native format, but continuous variables (climate, altitude and slope) were each discretized into ten categories (Appendix 1).

In terms of social factors, we evaluated the average years of education and ethnic groups. Ethnic groups were established based on the ethnic language spoken (68 different languages were identified) and years of education (INEGI, 2005) were taken as a proxy of overall socioeconomic level, as previously done by the Mexican government (INEGI, 2012). This factor was input as a categorical variable with five categories, ranging from unfinished basic education to bachelors or higher degree (Appendix 1). Ethnic groups were established base on the indigenous language spoken and we worked with 62 out of 68 languages that have been recognized because six of them had just one or two unique georeferenced data points (INALI, 2011), and were insufficient to carry out the analysis.

2.2. Evaluation of factors influencing the distribution of races

We used a recently published non-parametric data mining method (Stephens et al., 2009; González-Salazar et al., 2013) to find significant geographical or spatial associations between particular races and the factors being considered. This method is based on geographical co-occurrences of factors and a target entity: presence of a particular maize race or a unit area with more than 24 races. First, we divided the map of Mexico into a 10 km × 10 km grid (resulting in 20,719 cells); then, we assigned the presence/absence of each race to map cells and the corresponding value for all the associated factors. Such spatial association allowed us to calculate the probability of finding our race under specific conditions using the following formula:

$$P(A_i|I_k) = \frac{N_{Ai\&Ik}}{N_{Ik}} \tag{1}$$

where, $N_{Ai\&Ik}$ is the number of cells in which there is a co-occurrence of the distribution of the Mexican race A_i and factor $\boldsymbol{I}_k$; and $N_{\boldsymbol{I}k}$ is the number of cells in which the factor I_k is distributed.

However, $P(A_i|I_k)$ is a simple probability that does not take into account sample size which is important to determine significance. To incorporate the sample size and avoid bias in our results, we considered the following statistical test:

$$\varepsilon(A_i|I_k) = \left(\frac{N_{Ik}(P(A_i|\boldsymbol{I}_k) - P(A_i))}{N_{\boldsymbol{I}k}P(A_i)(1 - P(A_i))}\right)^{1/2} \tag{2}$$

Where $P(A_i)$ is the probability of finding our entity under study; $P(A_i|\boldsymbol{I}_k)$ the probability of finding the latter when factor I_k is present; and $N_{\boldsymbol{I}k}$ is the number of cells in which the factor I_k is distributed. This method assumes a normal distribution of epsilon values (ε) and uses as a critical value $\varepsilon(A_i|I_k) \geq 2$, which evaluates the statistical dependency between A_i and I_k relative to the null hypothesis that the distribution of A_i is independent of $\boldsymbol{I}_k$ and is randomly distributed over the grid. The critical value of 2 represents 2 standard deviations (95% confidence interval) (Stephens et al., 2009; González-Salazar et al., 2013).

2.3. Calculating score values to create probability maps

We created probability maps for each race by calculating score values $S(A_i|\boldsymbol{I}')$through a Bayes approximation:

$$S(A_i|\boldsymbol{I}\prime) = \sum_{k=1}^{N} S(A_i|I_k) = \sum_{k=1}^{N} \ln\frac{P(I_k/A_i)}{P(I_k/B_i)}, \quad (3)$$

Where A_i is the number of cells in which maize is present; B_i is the number of cells in which maize is absent; I_k is the number of cells in which a factor is present; and $S(A_i|\boldsymbol{I}')$ is a measure of the probability of finding the distribution of A_i when niche profile is $\boldsymbol{I}'$. $P(I_k|A_i)$ is the probability of finding A_i when factor I_k is present; and $P(I_k|B_i)$ is the probability of not finding A_i when factor I_k is present (Stephens et al., 2009; González-Salazar et al., 2013).

We ranked the score values of each cell for all factors together; and divided them in deciles, where the 10th decile represented the highest probability to find a specific race. To demonstrate the different contribution of factors to the distribution of each race, we ranked race's score values for each factor individually.

Finally, we named as the suitable conditions the socio-environmental factors in the 10th decile that presented a spatially significant relationship with the distribution of races' areas.

2.4. Evaluation of factors' influencing race richness

To evaluate factors influencing PRA we firstly had to identify those areas by overlaying the individual probability maps of all races. Individual races maps had to be transformed into binary maps (presence/absence) in order to be added by taking the minimum score value where the race was present as a threshold value. We categorized richness potential distribution areas in 10 classes, with 24–35 races being the richest category (PRA).

Once we recognized PRA, we evaluated $\varepsilon(A_i|I_k)$ and $S(A_i|\boldsymbol{I}')$ to find the suitable socio-environmental conditions that better explained the distribution of such areas. In other words, we identified the factors spatially associated with PRA.

2.5. Validation

To evaluate the predictive capacity of the factors under study, we performed a cross-validation test.This procedure uses part of the original data to fit the model with a specific factor and the rest of the data is used to evaluate its ability to correctly predict them. In our case, we randomly split the occurrence records of maize races into training (70%) and validating (30%) datasets. The training data were used to calculate score values associated to each factor via a Bayes approximation (cross-validation). Each race occurrence was assigned to a cell, and cells were sorted according to their associated score value (that depends on the factor evaluated) and divided into deciles. Good models are expected to have most of their validation points in the higher deciles. Next, we counted how many validation cells were found in the top decile. This procedure was repeated 100 times for each race to obtain the mean of validation cells on each decile and its associated standard deviation. Finally, to determine the importance of factors for model predictability, we carried out a t-test for independent samples between the numbers of occurrences predicted by different factors. This procedure only took place for individual races, because the richness map was constructed only by the addition of these individual maps.

3. Results

3.1. Influence of environmental factors on the distribution of areas that can potentially harbor the highest number of races and of individual races

Areas with the potential of holding 24–35 races were considered the richest (PRA). In these areas we found significant spatial associations with environmental and social factors ($\varepsilon > 2$): altitudes ranging 1000–4952 m.a.s.l., slopes 3.43–30.7°, and 7 different soil types (Regosols, Rankers, Planosol, Gleysol, Chernozem, Cambisol and Acrisol) were identified as the environmental factors with higher influence on PRA distribution (Table 1). The climatic factors significantly associated to the spatial distribution of PRA could be divided into four main groups: (a) annual climatic factors, (b) climatic factors related to spring-summer season, (c) extreme climatic factors and (d) factors representing climatic variability.

Among the annual climatic factors associated with PRA, we found annual mean temperatures between 12.5 and 17.6 °C and annual precipitations between 982 and 1980 mm to be the most important. In terms of seasonal climatic factors, we found that these areas were related to mild-hot temperatures between 9.3 and 24.4 °C and precipitations between 234 and 1222 mm in the warmest and wettest quarter of the year, and precipitation of 19 to 65 mm and temperature of 15.2–21.6 °C during the coldest and driest quarter of the year, respectively. Additionally, precipitation between 201–376 mm (from a range of 9–819 mm) in the wettest month, temperatures not higher than 32.7 °C with a minimum of 12.8 °C in the warmest month, and a minimum temperature between 4.7–12 °C in the coldest month were important extreme climatic factors (Table 1). Finally, factors regarding climatic variability also played an important role, since all of them were significantly associated with the areas that can potentially harbor the highest number of races (Table 1).

Factors that best predicted the presence of individual races varied among races (Table 2). However, Fig. 1b shows that altitude is the environmental factor with highest predictive power for most of the races, followed by slope, soil and climate (see also Table 2). For the race analyzed in detail, Palomero Toluqueño, altitude was the best predictor followed by climate, slope and soil; whereas in other cases, e.g., Elotero de Sinaloa, soil type was the best predictor followed by slope, altitude and climate.

3.2. Influence of social factors on the distribution of areas that can potentially harbor the highest number of racesand of particular races

The level of education was associated with the distribution of PRA, as long as a high-school or lower educational level was being considered. In addition, the presence of 25 different ethnic groups was associated with such areas (see Table 1).

Interestingly, when evaluating the presence and distribution of each race individually, our results show that 12 races (Apachito, Blando, Chiquito, Dulce, Dulcillo, Nal-tel, Olotón, Palomero Toluqueño, Serrano Mixe, Tabloncillo Perla, Zamorano Amarillo, and Zapolote Grande) were better predicted by the presence of a particular ethnic group than by any of the environmental factors (Table 2). For example, the Purepecha was the only ethnic group significantly associated with the presence of Zamorano Amarillo and was also that best explained the distribution pattern of this race.

In terms of individual maize races, we found significant spatial relationships with different levels of education, going from unfinished elementary school to finished high-school. Bachelor or higher degrees of education was not found in the suitable profile of any race (Appendix 2). Additionally, 49 out of the 62 ethnic groups were also significantly associated with particular races (Appendix 2). The ethnic groups more frequently present in suitable profiles of races were Zapoteco, Tojolobal, Otomí, Mixteco, Chatino, Cuicateco, Huave, Mam, Mazateco, Mixe, and Náhuatl. Interestingly, Zapoteco was in the suitable profile of 19 races, being the most frequent ethnic group in the suitable profiles, suggesting that Zapoteco cultures have been involved in the diversification of many races that are still preserved in Mexico.

3.3. Probability maps

Areas supporting high maize richness, as identified by the probability maps, included the southern states of Chiapas, Oaxaca, Guerrero, the western state of Jalisco, and central Mexico. Nevertheless, suitable areas for at least one maize race cover practically the entire Mexican territory (Fig. 2).

Moreover, the probability distribution map of Palomero Tolqueño serves to show the contribution of individual factors to the distribution model (Fig. 3). Occurrences in the highest probability areas of Palomero Toluqueño for each factor map suggest that ethnic group, altitude and climate are the factors with highest predictive power. Additionally, predictive power increases when all factors are used simultaneously; increasing the number of occurrences predicted in the highest decile. Probability maps for each race using all variables are available in Appendix 3.

4. Discussion

There has been a longstanding interest in understanding the effect of various natural and social factors in explaining the

Table 1
Factors significantly associated with Mexican potential maize-rich areas (24–35 races).

Factors	[a]Category	[b]Range	[c]Epsilon	[d]Score
Environmental				
Altitude	1041–4942 m.a.s.l.	0–5500 m.a.s.l.	8.019	2.146
Annual mean temperature	12.5–17.6 °C	7.8–29.1 °C	3.858	0.841
Annual precipitation	982–1980 mm	55–4517 mm	6.388	1.236
Isothermality	65–76	38–85	8.861	1.678
Max temperature of warmest month	13.8–32.7 °C	138–425 °C	6.449	1.519
Mean diurnal range	120–163	60–205	3.768	0.806
Mean temperature of coldest quarter	15.2–21.6 °C	3.2–28.2 °C	5.51	1.113
Mean temperature of driest quarter	16.3–20.2 °C	4.6–29.3 °C	5.704	1.074
Mean temperature of warmest quarter	9.3–24.4 °C	9.3–32.5 °C	5.588	1.263
Min temperature of coldest month	4.7–12 °C	138.425 °C	5.677	1.067
Precipitation of coldest quarter	40–65 mm	1–823 mm	3.519	0.562
Precipitation of driest month	6–12 mm	0–145 mm	4.91	0.765
Precipitation of driest quarter	19–35 mm	0–485 mm	6.423	0.954
Precipitation of warmest quarter	234–556 mm	3–1475 mm	4.528	0.931
Precipitation of wettest month	201–376 mm	9–819 mm	7.676	1.473
Precipitation of wettest quarter	525–1222 mm	21–2187 mm	6.673	1.307
Precipitation seasonality	88–102	29–129 mm	5.985	1.155
Slope	3.43–30.7°	0–34.12°	8.236	1.712
Soil type	Regosol, Ranker, Planosol, Gleysol, Chernozem, Cambisol, Acrisol		3.498	1.381
Temperature annual range	16.7–23.8 °C	12.1–39.4°	7.133	1.254
Temperature seasonality	379–2021	379–9348	11.418	1.885
Social factors				
Ethnic group	Akateko, Cuicateco, Chatino, Chocolteco, Cora, Mixe, Huave Jakalteko, Mam, Mazahua, Mazateco, Mixteco, Náhuatl, Otomí, Purepecha, Qanjobal, Teko, Tlahuica, Tlapaneco, Tojolabal, Triqui de la Baja, Tsetsal, Tsotsil, Zapoteco, Zoque		4.515	2.076
Education	unfinished elementary-finished high school	unfinised elementary-bachelor or higher degree	5.752	0.831

[a] Category = factors' category that presented a significant relationship with the richest areas (24–35 races).
[b] Range = the range of the factor evaluated.
[c] Epsilon = the epsilon value resulted from the spatial interaction between the richest areas (24–35 races) and the factors evaluated.
[d] Score = factors contribution to maize presence.

patterns and extents of distribution of particular races and landraces of maize (Sánchez González and Goodman, 1992; Bellon and Brush, 1993; Brush and Perales, 2007; Kato et al., 2009; Bellon and Hellin, 2011). These studies have suggested that environmental factors are the main driving forces of Mexican maize diversification. Nonetheless, previous studies have also shown the importance of seed selection, landraces yield, market and culture on maize diversity conservation.

However, as far as we know, our study is the first attempt to evaluate the relative importance of social and environmental factors on the distribution of Mexican maize. Despite the fact that we were able to consider many more environmental factors in

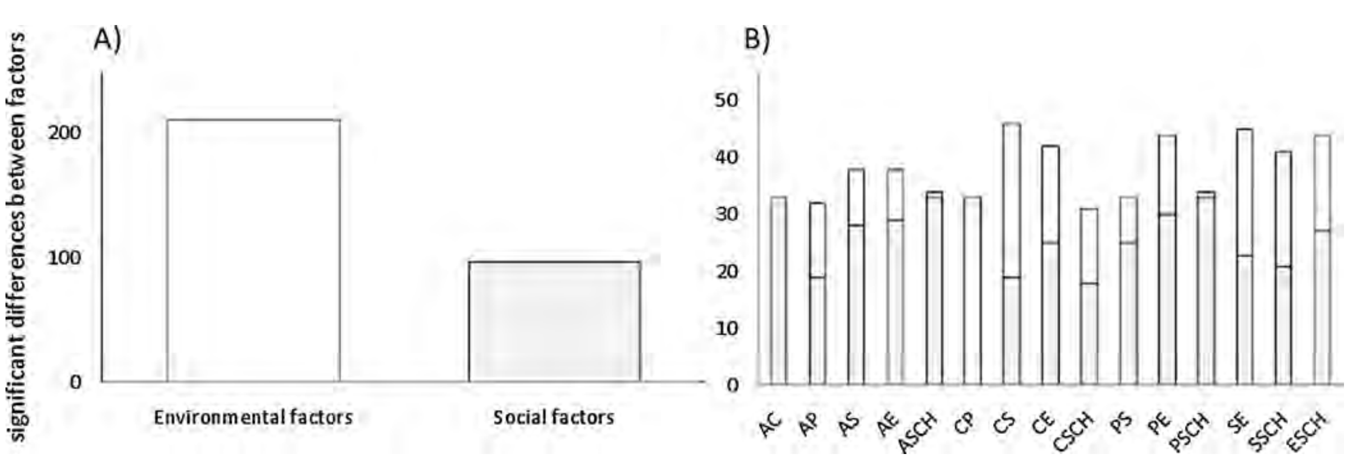

Fig. 1. Significant predictive differences between factors for all Mexican maize races distribution areas. (A) Number of significant differences between all factors evaluated for all races. Environmental factors = number of significant differences in which the environment (altitude, climate, slope and soil) was a better predictor than social factors (ethnic group and education). Social factors = number of significant differences in which the social factors were better predictors. (B) Number of significant differences in all races. Gray = times in which the first factor was significantly better predictor than the second. White = times in which the second factor was a significantly better predictor than the second factor. AC = altitude vs. climate, AP = altitude vs. slope, AS = altitude vs. soil, AE = altitude vs. ethnic group, ASCH = altitude vs. education, CP = climate vs. slope, CS = climate vs. soil, CE = climate vs. ethnic group, CSCH = climate vs. education, PS= slope vs. soil, PE = slope vs. ethnic group, PSCH = slope vs. education, SE = soil vs. ethnic group, SSCH = soil vs. education and ESCH= ethnic group vs. education.

Table 2
T-tests between predictability of variables for all races evaluated.

	A vs. C	A vs. P	A vs. S	A vs. E	A vs. SCH
Ancho	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Apachito	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Arrocillo Amarillo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Azul	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Blando	NS	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS
Bofo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Bolita	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cacahuacintle	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Celaya	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Chalqueño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Chapalote	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	NS
Chiquito	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Comiteco	NS	NS	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)
Conejo	NS	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cónco	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cónico Norteño	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	NS
Coscomatepec	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cristalino	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Dulce	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Dulcillo	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Dzit-bacal	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Elotero de Sinaloa	$P\leq0.05$ (+)	NS	NS	NS	$P\leq0.05$ (+)
Elotes Cónicos	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Gordo	NS	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Jala	NS	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Mushito	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Nal-tel	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Olotillo	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Olotón	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Onaveño	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Palomero Toluqueño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Pepitilla	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	NS
Ratón	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Reventador	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Serrano	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Tablilla de Ocho	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tabloncillo	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS
Tabloncillo Perla	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Tehua	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tepecintle	NS	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tuxpeño	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tuxpeño Norteño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Vandeño	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	NS
Zamorano Amarillo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Zapalote Chico	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Zapalote Grande	NS	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)

	C vs. P	C vs. S	C vs. E	C vs. SCH	P vs. S
Ancho	NS	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Apachito	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Arrocillo Amarillo	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Azul	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Blando	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)
Bofo	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Bolita	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Cacahuacintle	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Celaya	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS
Chalqueño	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Chapalote	NS	$P\leq0.05$ (+)	NS	NS	$P\leq0.05$ (+)
Chiquito	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Comiteco	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Conejo	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cónco	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS
Cónico Norteño	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Coscomatepec	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Cristalino	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Dulce	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	
Dulcillo	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)
Dzit-bacal	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	
Elotero de Sinaloa	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS
Elotes Cónicos	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Gordo	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Jala	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Mushito	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Nal-tel	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	NS
Olotillo	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS	NS
Olotón	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Onaveño	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Palomero Toluqueño	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Pepitilla	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)
Ratón	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS	NS
Reventador	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS
Serrano	NS	$P\leq0.05$ (+)		$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tablilla de Ocho	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tabloncillo	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Tabloncillo Perla	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS
Tehua	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Tepecintle	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tuxpeño	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	NS	NS
Tuxpeño Norteño	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS
Vandeño	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	NS
Zamorano Amarillo	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Zapalote Chico	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS	$P\leq0.05$ (−)
Zapalote Grande	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)

	P vs. E	P vs. SCH	S vs. E	S vs. SCH	E vs. SCH
Ancho	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Apachito	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Arrocillo Amarillo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Azul	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Blando	$P\leq0.05$ (−)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Bofo	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Bolita	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Cacahuacintle	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Celaya	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Chalqueño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Chapalote	NS	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS
Chiquito	$PP\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Comiteco	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Conejo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Cónco	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Cónico Norteño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Coscomatepec	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Cristalino	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Dulce	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Dulcillo	$P\leq0.05$ (−)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Dzit-bacal	$P\leq0.05$ (−)	NS	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Elotero de Sinaloa	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Elotes Cónicos	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Gordo	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	NS
Jala	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Mushito	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Nal-tel	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Olotillo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)(−)
Olotón	NS	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Onaveño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$PP\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Palomero Toluqueño	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Pepitilla	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Ratón	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Reventador	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Serrano	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Tablilla de Ocho	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Tabloncillo	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)
Tabloncillo Perla	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tehua	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tepecintle	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Tuxpeño	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Tuxpeño Norteño	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (−)	$P\leq0.05$ (−)
Vandeño	$P\leq0.05$ (+)	NS	$P\leq0.05$ (+)	NS	$P\leq0.05$ (−)
Zamorano Amarillo	$P\leq0.05$ (−)	NS	$P\leq0.05$ (−)	$P\leq0.05$ (−)	$P\leq0.05$ (+)
Zapalote Chico	$P\leq0.05$ (−)	NS	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)
Zapalote Grande	$P\leq0.05$ (−)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (+)	$P\leq0.05$ (−)

A= altitude, C= climate, P = slope, S= soil, E= ethnic group, SCH= education, (+) =significant difference between the means of the number of predicted validation points; being the mean of the first variable higher than the second variable, (−) = significant difference between the means of the number of predicted validation points; being the mean of the second variable higher than the mean of the first variable, NS= no significant.

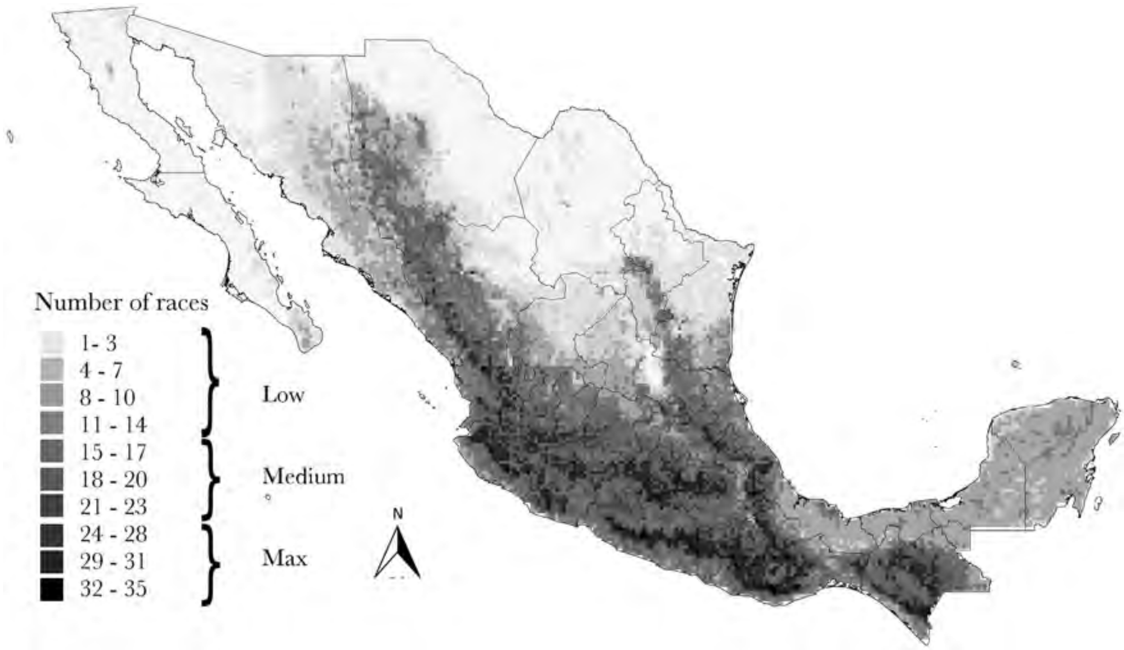

Fig. 2. Maize-rich areas distribution map. Probability map created by adding all Mexican maize race distribution areas. The darker areas in the map represent higher richness.

comparison to social ones, the data mining approach that we have used in this paper has enabled us to identify which are the most informative variables for the distribution of individual races and to gain a better understanding of the factors geographically associated with the areas that can potentially harbor the highest number of races (PRA). However, as in all modeling methods, quality of data does affect the analysis. We are aware that the quality of the data sets for the social factors is inferior to that for the environmental factors, and this likely affected our analyses. Still, the ethnic group factor results to be critical in order to explain the actual distribution of individual maize races, and the potential areas of highest richness in Mexico.

4.1. Methodological issues

Although it is a known fact that scale and resolution of spatial analysis have an influence on the analysis (Peterson et al., 2011), their real impact on results strongly depends on the question to be answer. In our analyses we used a 10 km × 10 km grid to balance between fine-scale social and environmental relationships with maize races, and the coarse-grained countrywide scope of the study. Furthermore, the method implemented in this paper has already been tested with different cell sizes by Stephens et al. (2009) (5, 10, 50, and 100 km) and found that although absolute epsilon values do change as a function of cell size (the number of co-occurrences changes), relative epsilon values remained stable. In other words, the relationship pattern was maintained independently of the cell size. Similarly, Kok and Veldkamp, 2001 evaluated the effects of different spatial resolutions (15 to 75 km) on land use patterns in Central America and found that resolution did not significantly affect the spatial relationship between land use patterns and their determinant factors.

On the other hand, our validation consisted in a cross-validation procedure in which we randomly split our data in a 70:30 proportion, repeating the process 100 times. A cross-validation would ideally use 50% of data to calibrate (fit) the model and 50% to validate it. However, in our case we had races with 18 occurrences, thus carrying out the model with only 9 points implies using a reduced number of degrees of freedom to fit the model. Yet, too few validation data might not let us see how well the model is performing. We considered that the way we split our data represent a good balance between the data used for fitting the model and for validating it. We kept this split ratio throughout the races for the purpose of comparability and because such ration was good enough for analyses with greater amount of data.

Finally, we want to clarify that we created the PRA map, by adding the modeled distributions for individual races, rather than using the actual data for race distribution, thus the resulting map overestimates the number of races per area. For example, we found areas that can potentially hold up to 35 races, when in the field the actual highest number of races found per unit is 22. We decided to add the expected presence of individual races, instead of modeling race richness, because we consider that maize richness is not an entity that responds to environmental or social factors (i.e., it does not have a socio-ecological niche, although it can be spatially related to some social and environmental factors). The latter becomes clear when we compare two equally rich areas that have a contrasting set of races. Consequently, we decided to use the maps for the individual races that have a socio-ecological niche and added such data only to gain a better insight of which factors mostly associated spatially to the areas of highest richness, independently of the races that are found within them. Therefore, for the race-richest areas, ε values represent only geographical associations with factors, and not its niche profile as it was considered for the analysis of each individual race.

4.2. The role of environmental factors on the distribution of areas that can potentially harbor the highest number of races and of particular races

Even though our PRA distribution map is similar to the one presented by Ureta et al. (2012), where only climatic factors were used under an ensemble niche modeling procedure, the present study indicated that climate was not the most important predictor compared to other environmental factors. Nonetheless, altitude, which resulted to be the best predictor in this study, is strongly related to climatic factors, and consequently our maps largely coincide with those modeled with climatic factors only. Altitude is actually an environmental variable that summarizes several climatic factors

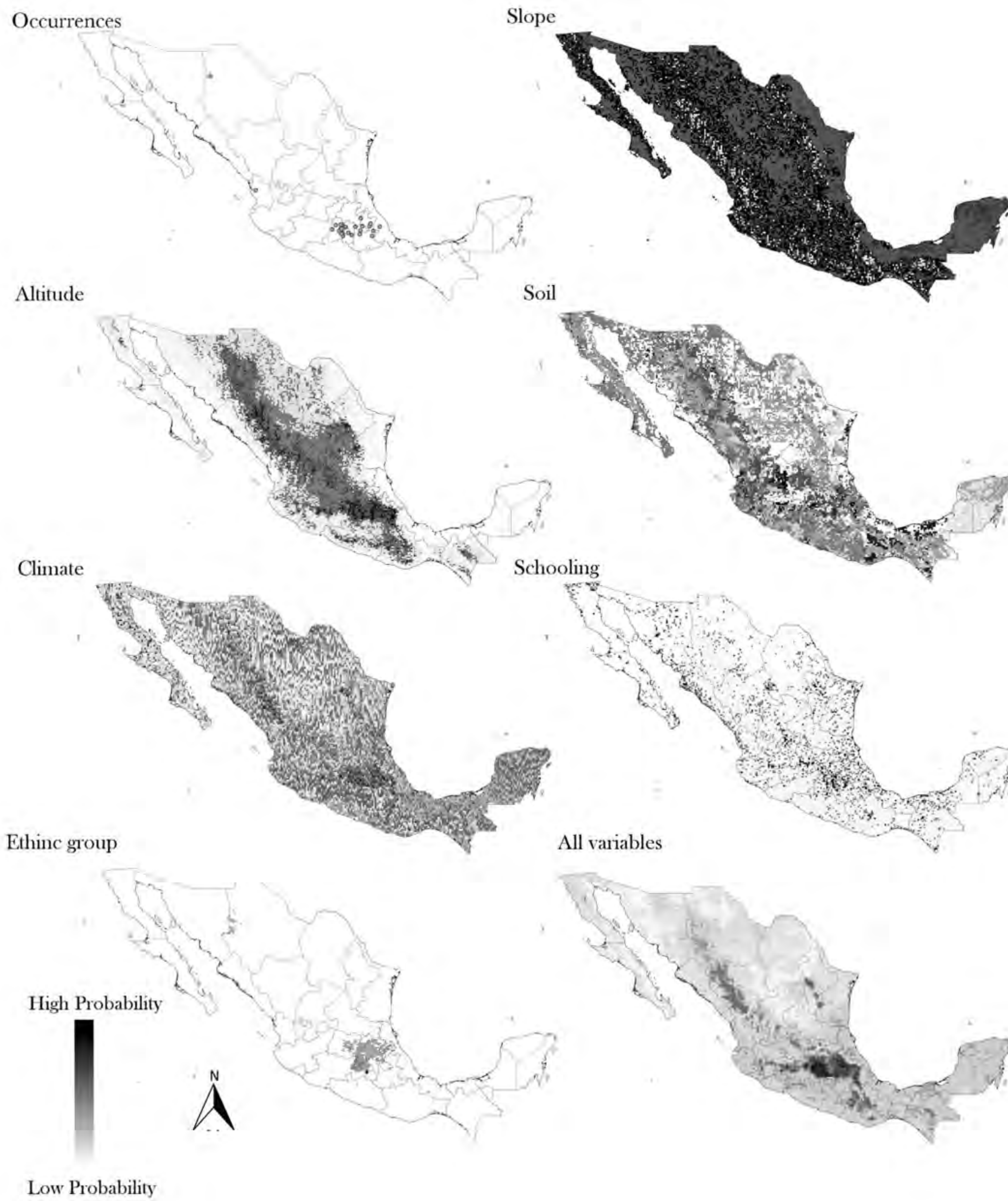

Fig. 3. PalomeroToluqueño's case.Probability maps created by each factor evaluated (altitude, climate, slope, soil, ethnic group; and education) and all together.

acting simultaneously and consequently it might be veiling the important role of climate on the distribution of PRA. Still, the importance of altitude on the distribution of maize is undeniable and has been acknowledge before (Sánchez González and Goodman, 1992; Brush and Perales, 2007).

In terms of climate, we found that PRA is associated with mild temperatures and intermediate precipitation. Such climatic conditions at a given geographical location and their distribution are expected to change in the near future as temperature and rain patterns are altered due to global climate changes (Conde et al., 2008).

When evaluating slopes, such areas were found at 3.43–30.7°. Most Mexican maize-races are distributed along the Mexican mountain ranges. Additionally, Mexican states with highest richness also present very abrupt landscapes. Therefore, adaptation of several races to mid altitudes and slopes can be expected and such areas are among the richest ones for native maize. Finally, the soil types to which PRA is more frequently associated with, include soils of tropical and subtropical areas (Gleysols); dry or very cold areas (Regosols); those that are generally very suitable for agriculture (Cambisols and Chernozems), moderately suitable (Planasols and rankers), or not suitable at all (Acrisols) (FAO, 2012). These results suggest that maize races have diversified in a wide variety of soil types, and have been bred to thrive even in marginal soil conditions.

Compared with more conventionally used distribution modeling methodologies, the data-mining approach used in this study has identified which particular factors and respective categories are significantly associated with the geographic distribution of each one of most Mexican races (Appendix 2). For example, for Palomero Tolqueño it was shown that the environmental factors with highest predictive power are not the same as the best predictors for most races. In this particular case, climate type became the second best predictor instead of the worst. Furthermore, the presence of this race is strongly associated with mild annual temperatures, low annual precipitation, mild temperature during the hottest month, temperatures above 0 °C during the coldest month, low to medium precipitation in the summer-spring season and very low precipitations in the autumn-winter season, as well as with strong isothermality and temperature seasonality (Appendex 3). Its strong association with climatic variables leads to postulate that a temperature increase due to climate change may become an important threat for this race.

Most individual races were better predicted by environmental variables (Fig. 1 and Table 2), however; using social factors to produce the probability maps increased the predictability of distribution maps as shown with Palomero Toluqueño (Fig. 3), for which all factors together gave rise to a more robust predictive distribution map than individual factors. Similar results were shown by González-Salazar et al. (2013) where the addition of biotic variables into abiotic distribution maps increased predictability and reliability of distribution models.

4.3. The role of social factors in the distribution of areas that can potentially harbor the highest number of races and of particular races

For PRA, ε values indicated that four educational level categories and 25 ethnic groups showed significant associations. The only educational level category that was not significantly related with PRA was bachelors or higher degree levels, indicating that most highly educated people are not likely to grow or produce native maize, but farmers with some level of education seem to be more likely involved in crop production, than those who have not received any education. This result is expected because most highly educated persons live in large cities and are not involved in primary production (INEGI, 2012); otherwise, they rather practice large-scale production, (INEGI, 2012).

In contrast, there is a close relationship between the richness of maize races and ethnic groups in Mexico. PRA comprises around 6.9% of the Mexican territory and is associated to areas where more than 40% of the ethnic groups of Mexico live. The results presented here agree with Boege (2010), who also showed that the presence of indigenous communities of diverse ethnic groups are closely associated and have been key for creating and preserving a dynamic diversification of maize races. However, as seen in Brush and Perales (2007), "mestizo" rural communities have also played an important role in the *in situ* generation and conservation of native maize varieties, and they continue to be actively involved in such processes. It is noteworthy, that both types of peasants, indigenous and "mestizo," share the same type of relatively low formal educational level, and generally rely on traditional technological practices, rather than industrialized ones (Bellon et al., 2005). Therefore, the preservation of maize native diversity relies on smallholder farmers, as well as on the cultural diversity associated to different ethnic groups that are strongly associated to specific maize races. Until recent extension programs, modern technology has not reached or aimed at Mexican smallholder farmers needs (Bellon et al., 2005). Exceptions are some studies by Mexican agronomists who have achieved significant increases in yield or other race traits, with various traditional breeding approaches, such as masal selection (Smith et al., 2001).

For the last decade, the Mexican government has supported a few participatory improvement efforts (Aragón-Cuevas et al., 2003; Segura et al., 2011) to collect and evaluate races from different regions of the country. The goal is to be able to collect an important part of the maize race varieties used by local farmers, and promote breeding programs of different sorts. Such programs should effectively support local producers and races in order to further promote and improve their cultivation and production in all the Mexican territory.

Although seed-banks are an alternative tool to preserve agrodiversity in Mexico they have clear drawbacks (lack of representation, sample losses, bad storage conditions, classification problems and inadequate sampling procedures) with respect to *in situ* conservation (Ortega Paczka, 2007); and consequently should not be taken as the only and best way to preserve maize diversity, but rather be considered only as a complementary tool that feedbacks to *in situ* conservation programs that are based on the leaderships of indigenous and campesino communities.

In terms of the distribution of particular maize races, social variables included in our analyses were not as overall good predictors in comparison to environmental data, but they are also important components of the set of factors that seem to be related to the presence of particular races. In fact, twelve races were better predicted by the presence of particular ethnic group, rather than by any environmental variable (Fig. 1, Appendix 2). It is important to consider that the social data set is not as complete as the environmental one, and this could bias the importance of the former. However, epsilon values used in our analyses take into account the bias on the number of factors considered for each type of data and therefore, the suitable profile found for each race helps us identify the key factors mostly associated to the distributions of races, even when they were not good predictors. Future studies should further consider social factors that might be critical for the presence and distribution of other staple crops in developing countries, as well as for determining the location of the richest race areas.

For our case study, Palomero Toluqueño, the ethnic group was the variable with the highest predictive power. The ethnic groups that were related to this race were: Thlahuica, Pima, Otomí, Náhuatl and Mazahua. In this case, associations between most of these ethnic groups and Palomero Tolqueño had already been reported (Romero Contreras et al., 2006; Boege, 2010), except for the case of the Pima. A better understanding of the relationship among ethnic groups and maize race diversification and distribution could help agronomists and biologists identify where endangered races are being grown and how different ethnic groups are actively contributing to the generation and conservation of maize diversity. For instance, Purepecha is the only ethnic group associated with Zamorano Amarillo when the ethnic group was the most important factor in terms of spatial relations and predictive power. Additionally, ethnic groups such as Zapoteco are spatially related to 19 races, meaning that they are playing an important role on the *in situ* preservation of Mexican maize richness. These examples should make clear that preserving maize races implies following the leaderships and supporting the ethnic indigenous communities that are in charge of preserving and further breeding maize races. In other cases, "mestizo" peasants are also key for maize race diversification and preservation. Such *in situ* diversity might be critical to face climate change challenges, as well as to analyze which areas and races are critical to face such novel conditions (see also Ureta et al., 2012).

5. Concluding remarks

Our methodology facilitated the analysis of the complex system of growing maize in Mexico, as it integrates a range of different social and environmental variables, which would be very difficult to combine in a single model, given the most common distribution algorithms that have been proposed. The data-mining methodology used here allowed us to produce maps with predicted distributions of individual races, or of the areas harboring the potential highest richness of races (PRA) by using combined data sets. This contrasts with previous analyses that have only relied on environmental data.

The main results of our study are: (1) Altitude which is strongly related to climate was the factor with highest predictive power for most races. (2) Twelve races potential distribution areas were better predicted by an ethnic group than by any other factor. (3) Predictive power increases when all factors are used simultaneously. (4) Areas supporting high maize richness included Chiapas, Oaxaca, Guerrero, the western state of Jalisco, and central Mexico. Nevertheless, suitable areas for at least one maize race cover practically the entire Mexican territory. (5) PRA comprises around 6.9% of the Mexican territory and are associated to 40% of the ethnic groups of Mexico. (6) Interestingly, Zapoteco cultures have probably been involved in the diversification of many races that are still preserved in Mexico.

It is likely that as data sets for social factors improve and become more complete, this will be more important than suggested by our analyses. Nevertheless, we strongly recommend including current social factors in studies evaluating spatial distributions and associations of other crops. We envision that the presence of ethnic groups will be also critical to explain the distribution of crops associated to traditional agriculture, other than maize, such as native pumpkins (*Cucurbitapepo* L.) and beans (*Phaseoulus vulgaris* L.). The consideration of the leadership of the communities of indigenous communities is thus central to agrobiodiversity conservation at Centers of Crop Origin and/or diversification. On the other hand, additional biological factors such as pests are likely to improve the predicted distribution and impact of possible global climate change or pest crisis on race richness and distribution at Centers of Crop Origin and/or diversification.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2013.06.017.

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Appendix 1. Variables' Categories Environmental Variables

19 Bioclimatic Variables	
Annual Mean Temperature	**Max Temperature of Warmest Month**
7.8-12.5°C	13.8-22.5°C
12.6-14.4°C	22.6-25.0°C
14.5-16.0°C	25.1-27.1°C
16.1-17.5°C	27.2-29.0°C
17.6-19.2°C	29.1-30.8°C
19.3-21.0°C	30.9-32.7°C
21.1-22.8°C	32.8-34.5°C
22.9-24.5°C	34.6-36.2°C
24.6-26.3°C	36.3-38.2°C
26.4-29.1°C	38.3-42.4°C
Mean Diurnal Range	**Min Temperature of Coldest Month**
6.0-9.7°C	-6.1-2.7°C
9.8-10.8°C	-2.6-0.1°C
10.9-11.9°C	0-2.4°C
12.0-13.0°C	2.5-4.6°C
13.1-14.1°C	4.7-6.8°C
14.2-15.2°C	6.9-9.3°C
15.3-16.3°C	9.4-12.0°C
16.4-17.3°C	12.1-14.6°C
17.4-18.3°C	14.7-16.8°C
18.4-20.5°C	16.9-21.3°C
Isothermality	**Temperature Annual Range**
38-44	12.1-16.6°C
45-48	16.7-18.8°C
49-52	18.9-21.3°C
53-56	21.4-23.8°C
57-60	23.9-26.1°C
61-64	26.2-28.3°C
65-68	28.4-30.5°C
69-72	30.6-33.0°C
73-76	33.1-35.9°C
77-85	36.0-39.4°C
Temperature Seasonality	**Mean Temperature of Wettest Quarter**
379-1279	3.8-10.6°C
1280-2021	10.7-14.0°C
2022-2932	14.1-16.5°C
2933-4011	16.6-18.6°C
4012-5050	18.7-20.6°C
5051-6015	20.7-22.7°C
6016-6811	22.8-24.7°C
6812-7487	24.8-26.5°C
7488-8139	26.6-28.5°C
8140-9348	28.6-32.5°C

Mean Temperature of Driest Quarter	Precipitation of Wettest Month
4.6-11.1°C	9-57 mm
11.2-12.8°C	58-103 mm
12.9-14.5°C	104-153 mm
14.6-16.2°C	154-200 mm
16.3-18.1°C	201-247 mm
18.2-20.2°C	248-304 mm
20.3-22.3°C	305-376 mm
22.4-24.3°C	377-461 mm
24.4-26.2°C	462-571 mm
26.3-29.3°C	572-819 mm
Mean temperature of warmest quarter	**Precipitation of Driest Month**
9.3-15.2°C	0-5 mm
15.3-17.3°C	6-12 mm
17.5-19.2°C	13-22 mm
19.3-20.9°C	23-34 mm
21.0-22.7°C	35-45 mm
22-824.4°C	46-57 mm
24.5-26.1°C	58-71 mm
26.1-27.7°C	72-89 mm
27.8-29.3°C	90-111 mm
29.4-32.5°C	112-145 mm
Mean Temperature of Warmest Quarter	**Precipitation Seasonality**
3.2-7.1°C	29-49
7.2-9.3°C	50-55
9.4-11.4°C	56-62
11.5-13.2°C	63-70
13.3-15.1°C	71-79
15.2-17.1°C	80-87
17.2-19.2°C	88-95
19.3-21.6°C	96-102
21.7-24.3°C	103-109
24.4-28.2°C	110-129
Annual Precipitation	**Precipitation of Wettest Quarter**
55-306 mm	21-142 mm
307-516 mm	143-261 mm
517-744 mm	262-397 mm
745-981 mm	398-524 mm
982-1226 mm	525-648 mm
1227-1536 mm	649-800 mm
1537-1980 mm	801-990 mm
1981-2526 mm	991-1222 mm
2527-3194 mm	1223-1501 mm
3195-4517 mm	1502-2187 mm

Precipitation of Driest Quarter	Precipitation of Coldest Quarter
0-18 mm	1-39 mm
19-35 mm	40-65 mm
36-57 mm	66-99 mm
58-85 mm	100-139 mm
86-118 mm	140-195 mm
119-159 mm	196-269 mm
160-208 mm	270-351 mm
209-274 mm	352-451 mm
275-365 mm	452-594 mm
366-485 mm	595-823 mm
Precipitation of Warmest Quarter	
3-87 mm	
88-164 mm	
165-233 mm	
234-305 mm	
306-381 mm	
382-464 mm	
465-556 mm	
557-677 mm	
678-859 mm	
860-1475 mm	

Soil Types
Acrisol
Andosol
Arenosol
Cambisol
Castañozem
Chernozem
Feozem
Fluvisol
Gleysol
Histosol
Luvisol
Nitosol
Planosol
Ranker
Regosol
Rendzina
Solonchak
Solonetz
Vertisol
Xerosol
Yermosol

Altitude		Slope
0-482 m.a.s.l.		1-34.2°
483-1040 m.a.s.l.		34.3-68.3°
1041-1597 m.a.s.l.		68.4-102.4°
1598-2155 m.a.s.l.		102.5-136.5°
2156-2712 m.a.s.l.		136.6-170.6°
2713-3270 m.a.s.l.		170.7-204.7°
3271-3827 m.a.s.l.		204.8-238.8°
3828-4385 m.a.s.l.		238.0-272.9°
4386-4942 m.a.s.l.		273.0-307.0°
4943-5500 m.a.s.l.		207.1-341.2°

Social variables

Ethnic groups	
Akateko	Mayo
Amuzgo	Mazahua
Awakateko	Mazateco
Ayapaneco	Mixe
Chatino	Mixteco
Chichimeco	Nahuatl
Chinanteco	Oluteco
Chocholteco	Otomi
Chol	Paipai
Chontal	Pame
Chuj	Pima
Cora	Popoloca
Cucap	Purepecha
Cuicateco	Qanjobal
Guarijo	Qeqchi
Huasteco	Sayulteco
Huave	Tarahumara
Huichol	Teko
Ixateco	Tepehua
Ixil	Texistepequeño
Jakalteko	Tlahuica
Kaqchikel	Tlapaneco
Kiche	Tojolabal
Kiliwa	Totonaco
Kickapo	Triquidelabaja
Kual	Tsetsal
Kumiai	Tsotsil
Lacandón	Tuzanteco
Mam	Yaqui
Papago	Zapoteco
Maya	Zoque

Education level
unfinished basic education
finished basic education
unfinished highschool
finished highschool
university degree

Appendix 2. Suitable profile for each Mexican maize race. Variable=Environmental and social suitable variables for richness pattern distribution; Category= factors' category that presented a significant relationship with certain race; Range= the range of the factor evaluated; Epsilon= the epsilon value resulted from the spatial interaction between certain race distribution area and the variables evaluated; Score= variables contribution to maize presence.

Ancho

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3827 m.a.s.l.	0-5500 m.a.s.l.	6.876	2.297
Annual mean temperature	17.6-21.0°C	7.8-29.1°C	3.700	0.671
Annual precipitation	745-1226 mm	55-4517 mm	10.625	1.390
Isothermality	61-85	38-85	4.679	1.075
Max temperature of warmest month	29.1-32.7°C	13.8-42.5°C	5.640	0.907
Mean diurnal range	142-163	60-205	6.492	0.989
Mean temperature of coldest quarter	15.2-28.2°C	3.2-28.2°C	4.670	1.016
Mean temperature of driest quarter	16.3-22.3°C	4.6-29.3°C	4.578	0.796
Mean temperature of warmest quarter	19.3-22.7°C	9.3-32.5°C	6.025	0.978
Min temperature of coldest month	4.7-14.6°C	13.8-42.5°C	5.514	1.033
Precipitation of coldest quarter	1-39 mm	1-823 mm	8.873	0.896
Precipitation of driest month	0-5 mm	0-145 mm	4.359	0.485
Precipitation of driest quarter	19-35 mm	0-485 mm	7.736	0.900
Precipitation of warmest quarter	234-381 mm	3-1475 mm	3.609	0.658
Precipitation of wettest month	154-304 mm	9-819 mm	7.156	1.025
Precipitation of wettest quarter	525-800 mm	21-2187 mm	10.783	1.477
Precipitation seasonality	96-109	29-129	9.477	1.324
Slope	0-13.65°	0-34.12°	4.519	1.281
Soil type	Feozem, Vertisol		11.481	1.175
Temperature annual range	18.9-26.1°C	12.1-39.4°C	8.080	1.223
Temperature seasonality	379-2932	379-9348	6.707	1.093

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Mazahua, Náhuatl, Purépecha, Tlahuica, Tlapaneco		7.046	0.985
Education	unfinished elementary-finished high school	unfinished elementary school-bachelor or higher degree	8.101	0.973

Apachito

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	7.292	1.121
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	15.243	2.472
Annual precipitation	517-981 mm	55-4517 mm	5.122	1.124
Isothermality	53-60	38-85	4.244	1.053
Max temperature of warmest month	25.1-30.8°C	13.8-42.5°C	7.400	1.659
Mean diurnal range	174-205	60-205	8.978	1.754
Mean temperature of coldest quarter	3.2-9.3°C	3.2-28.2°C	13.846	2.163
Mean temperature of driest quarter	4.6-12.8°C	4.6-29.3°C	11.586	2.172
Mean temperature of warmest quarter	15.3-20.9°C	9.3-32.5°C	8.032	1.792
Mean temperature of wettest quarter	16.6-20.6°C	3.8-32.5°C	9.518	1.722
Min temperature of coldest month	-6.1-2.6°C	13.8-42.5°C	16.511	2.362
Precipitation of coldest quarter	66-139 mm	1-823 mm	5.390	1.226
Precipitation of driest month	6-22 mm	0-145 mm	5.715	1.141
Precipitation of driest quarter	36-57 mm	0-485 mm	9.831	1.621
Precipitation of warmest quarter	306-464 mm	3-1475 mm	4.600	1.166
Precipitation of wettest month	104-247 mm	9-819 mm	4.041	0.959
Precipitation of wettest quarter	262-524 mm	21-2187 mm	5.225	1.115
Precipitation seasonality	71-87	29-129	3.906	0.971
Slope	3.43-6.83°	0-34.12°	2.747	0.437
Soil type	Feozem, Regosol		5.284	1.115
Temperature annual range	28.4-35.9°C	12.1-39.4°C	4.596	1.144
Temperature seasonality	4012-6015	379-9348	6.086	1.246

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Pima, Tarahumara		23.224	3.856
Education	unfinished elementary-unfinished high- school	unfinished elementary school-bachelor or higher degree	3.478	0.635

Arrocillo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-4385 m.a.s.l.	0-5500 m.a.s.l.	10.856	2.320
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	6.637	1.529
Annual precipitation	745-4517 mm	55-4517 mm	3.369	1.101
Isothermality	65-76	38-85	5.522	1.342
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	12.375	2.309
Mean diurnal range	98-152	60-205	3.504	0.964
Mean temperature of coldest quarter	9.4-15.1°C	3.2-28.2°C	3.781	0.834
Mean temperature of driest quarter	4.6-12.8°C	4.6-29.3°C	5.754	1.350
Mean temperature of warmest quarter	9.3-19.2°C	9.3-32.5°C	12.831	2.402
Mean temperature of wettest quarter	10.7-18.6°C	3.8-32.5°C	9.220	1.874
Min temperature of coldest month	0-9.3°C	13.8-42.5°C	2.796	0.662
Precipitation of coldest quarter	140-351 mm	1-823 mm	3.449	1.273
Precipitation of driest month	6-111 mm	0-145 mm	3.996	1.478
Precipitation of driest quarter	119-365 mm	0-485 mm	4.783	1.791
Precipitation of warmest quarter	234-1475 mm	3-1475 mm	3.318	1.048
Precipitation of wettest month	201-571 mm	9-819 mm	3.703	1.134
Precipitation of wettest quarter	525-990 mm	21-2187 mm	3.856	1.027
Precipitation seasonality	71-95	29-129	5.248	1.050
Slope	3.43-27.29°	0-34.12°	4.760	1.023
Soil type	Acrisol, Gleysol, Plansol, Regosol		6.299	1.826
Temperature annual range	16.7-23.8°C	12.1-39.4°C	6.024	1.203
Temperature seasonality	1280-29.32	379-9348	6.701	1.073

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Mazahua, Mixteco, Náhuatl, Otmoí, Teko, Totonaco, Zapoteco		8.474	2.646
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	8.020	1.208

Azul

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	15.699	1.868
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	20.254	2.638
Annual precipitation	517-981 mm	55-4517 mm	5.356	1.020
Isothermality	53-60	38-85	7.956	1.285
Max temperature of warmest month	25.1-29.0°C	13.8-42.5°C	7.171	1.391
Mean diurnal range	174-205	60-205	11.262	1.771
Mean temperature of coldest quarter	3.2-9.3°C	3.2-28.2°C	18.613	2.181
Mean temperature of driest quarter	4.6-14.5°C	4.6-29.3°C	9.659	1.682
Mean temperature of warmest quarter	15.3-20.9°C	9.3-32.5°C	9.180	1.645
Mean temperature of wettest quarter	16.6-20.6°C	3.8-32.5°C	11.522	1.760
Min temperature of coldest month	-6.1-(-1)°C	13.8-42.5°C	21.894	2.355
Precipitation of coldest quarter	66-139 mm	1-823 mm	4.867	1.025
Precipitation of driest month	6-22 mm	0-145 mm	5.401	0.893
Precipitation of driest quarter	19-57 mm	0-485 mm	5.574	0.919
Precipitation of warmest quarter	234-556 mm	3-1475 mm	3.399	0.806
Precipitation of wettest month	104-247 mm	9-819 mm	4.114	0.825
Precipitation of wettest quarter	262-524 mm	21-2187 mm	6.077	1.071
Precipitation seasonality	80-95	29-129	3.608	0.811
Slope	3.43-6.83°	0-34.12°	6.129	0.962
Soil type	Feozem		3.436	0.441
Temperature annual range	30.6-35.9°C	12.1-39.4°C	9.534	1.576
Temperature seasonality	4012-6015	379-9348	7.687	1.280

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tarahumara, Pima		18.082	3.410
Education	unfinished elementary-unfinished high school	unfinished elementary school-bachelor or higher degree	3.423	0.533

Blando

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1040 m.a.s.l.	0-5500 m.a.s.l.	4.547	0.936
Annual mean temperature	22.9-24.5°C	7.8-29.1°C	6.534	1.631
Annual precipitation	517-981 mm	55-4517 mm	2.320	0.800
Isothermality	57-60	38-85	4.544	1.191
Max temperature of warmest month	36.3-42.5°C	13.8-42.5°C	6.781	1.807
Mean diurnal range	174-183	60-205	4.494	1.325
Mean temperature of coldest quarter	17.2-19.2°C	3.2-28.2°C	5.952	1.618
Mean temperature of driest quarter	22.4-24.3°C	4.6-29.3°C	6.456	1.566
Mean temperature of warmest quarter	27.8-32.5°C	9.3-32.5°C	4.856	1.483
Mean temperature of wettest quarter	26.6-32.5°C	3.8-32.5°C	4.006	1.191
Min temperature of coldest month	6.9-9.3°C	13.8-42.5°C	6.007	1.473
Precipitation of coldest quarter	66-139 mm	1-823 mm	4.825	1.308
Precipitation of driest month	0-5 mm	0-145 mm	2.641	0.583
Precipitation of driest quarter	19-35 mm	0-485 mm	3.739	0.905
Precipitation of warmest quarter	2001-859 mm	3-1475 mm	2.947	1.156
Precipitation seasonality	88-129	29-129	3.004	1.134
Slope	3.43-13.65°	0-34.12°	2.810	0.638
Soil type	Cambisol, Regosol		4.225	1.278
Temperature annual range	28.4-33.0°C	12.1-39.4°C	3.704	1.169
Temperature seasonality	4012-5050	379-9348	5.689	1.451

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Guarijo, Mayo, Pima, Yaqui		7.711	3.256
Education	unfinished elementary-unfinished high-school	unfinished elementary school-bachelor or higher degree	3.337	0.797

Bofo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-2712 m.a.s.l.	0-5500 m.a.s.l.	8.25307	1.4224
Annual mean temperature	16.1-24.5°C	7.8-29.1°C	4.01545	1.25455
Annual precipitation	517-1226 mm	55-4517 mm	8.35842	1.18652
Isothermality	61-72	38-85	8.63789	0.87156
Max temperature of warmest month	27.2-32.7°C	13.8-42.5°C	6.72668	1.01747
Mean diurnal range	142-163	60-205	7.62632	1.00396
Mean temperature of coldest quarter	13.3-19.2°C	3.2-28.2°C	5.83576	0.98153
Mean temperature of driest quarter	16.3-20.2°C	4.6-29.3°C	8.15837	0.97284
Mean temperature of warmest quarter	19.3-22.7°C	9.3-32.5°C	8.06175	0.97621
Mean temperature of wettest quarter	16.6-22.7°C	3.8-32.5°C	8.45903	1.00631
Min temperature of coldest month	4.7-14.6°C	13.8-42.5°C	5.26326	1.23158
Precipitation of coldest quarter	1-39 mm	1-823 mm	9.41795	0.61266
Precipitation of driest month	0-12 mm	0-145 mm	4.53078	0.82193
Precipitation of driest quarter	19-35 mm	0-485 mm	10.0338	0.92237
Precipitation of warmest quarter	165-1475 mm	3-1475 mm	3.15755	1.12428
Precipitation of wettest month	154-304 mm	9-819 mm	7.75738	0.6986
Precipitation of wettest quarter	398-800 mm	21-2187 mm	8.29556	0.73227
Precipitation seasonality	88-129	29-129	6.76037	1.08754
Slope	3.43-20.47°	0-34.12°	5.05804	0.5715
Soil type	Vertisol, Feozem, Castañozem, Cambisol, Chernozem		5.56142	0.48367
Temperature annual range	18.9-26.1°C	12.1-39.4°C	8.86464	0.62043
Temperature seasonality	1280-2932	379-9348	14.6544	0.43374

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Purepecha, Cora, Huave, Otomi, Pame		4.8988	1.14027
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	10.3672	0.83193

Bolita

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-4942 m.a.s.l.	0-5500 m.a.s.l.	6.370	1.565
Annual mean temperature	12.6-19.2°C	7.8-29.1°C	3.854	0.697
Annual precipitation	517-1980 mm	55-4517 mm	4.823	0.806
Isothermality	65-85	38-85	7.365	1.314
Max temperature of warmest month	13.8-30.8°C	13.8-42.5°C	7.209	1.471
Mean diurnal range	142-163	60-205	5.058	0.754
Mean temperature of coldest quarter	11.5-19.2°C	3.2-28.2°C	4.121	0.680
Mean temperature of driest quarter	11.2-20.2°C	4.6-29.3°C	3.704	0.670
Mean temperature of warmest quarter	9.3-22.7°C	9.3-32.5°C	6.873	1.321
Mean temperature of wettest quarter	10.7-22.7°C	3.8-32.5°C	6.177	1.067
Min temperature of coldest month	2.5-9.3°C	13.8-42.5°C	4.453	0.675
Precipitation of coldest quarter	1-39 mm	1-823 mm	7.536	0.722
Precipitation of driest month	6-12 mm	0-145 mm	3.372	0.450
Precipitation of driest quarter	19-35 mm	0-485 mm	4.842	0.579
Precipitation of warmest quarter	165-381 mm	3-1475 mm	4.943	0.709
Precipitation of wettest month	104-247 mm	9-819 mm	5.173	0.758
Precipitation of wettest quarter	262-648 mm	21-2187 mm	5.273	0.769
Precipitation seasonality	80-102	29-129	5.067	0.772
Slope	3.43-20.47°	0-34.12°	4.657	0.559
Soil type	Vertisol, Planosol, Feozem, Chernozem, Castañozem		4.428	1.404
Temperature annual range	18.9-23.8°C	12.1-39.4°C	9.781	1.260
Temperature seasonality	379-2021	379-9348	11.087	1.449

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tlahuica, Otomi, Náhuatl, Mixteco, Mixe, Mazateco, Jakalteko,Cuicateco, Chinanteco, Chichimeco, Chatino		6.285	2.275
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	10.723	1.131

Bofo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	2156-4942 m.a.s.l.	0-5500 m.a.s.l.	12.814	3.249
Annual mean temperature	7.8-16.0°C	7.8-29.1°C	9.325	1.825
Annual precipitation	517-981 mm	55-4517 mm	4.718	1.027
Isothermality	65-72	38-85	7.993	1.456
Max temperature of warmest month	13.8-27.1°C	13.8-42.5°C	15.992	2.986
Mean diurnal range	142-163	60-205	4.001	0.936
Mean temperature of coldest quarter	9.4-13.2°C	3.2-28.2°C	6.796	1.315
Mean temperature of driest quarter	4.6-12.8°C	4.6-29.3°C	12.859	2.251
Mean temperature of warmest quarter	9.3-17.4°C	9.3-32.5°C	24.138	3.374
Mean temperature of wettest quarter	10.7-16.5°C	3.8-32.5°C	15.722	2.598
Min temperature of coldest month	0-4.6°C	13.8-42.5°C	7.239	1.245
Precipitation of coldest quarter	1-39 mm	1-823 mm	3.148	0.578
Precipitation of driest month	6-12 mm	0-145 mm	7.078	1.138
Precipitation of driest quarter	19-57 mm	0-485 mm	4.406	0.902
Precipitation of warmest quarter	234-305 mm	3-1475 mm	7.721	1.338
Precipitation of wettest month	154-247 mm	9-819 mm	2.369	0.674
Precipitation of wettest month	104-153 mm	9-819 mm	3.735	0.880
Precipitation of wettest quarter	262-648 mm	21-2187 mm	3.122	0.817
Precipitation seasonality	71-87	29-129	4.773	1.104
Slope	3.43-10.24°	0-34.12°	3.225	0.513
Soil type	Planosol, Gleysol, Feozem, Cambisol, Acrisol		4.267	1.632
Temperature annual range	18.9-23.8°C	12.1-39.4°C	8.029	1.475
Temperature seasonality	1280-2021	379-9348	13.009	1.832

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Purepecha, Otomí, Mazahua		8.612	2.836
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	8.421	1.323

Bolita

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	14.691	0.890
Annual mean temperature	12.6-19.2°C	7.8-29.1°C	5.540	0.590
Annual precipitation	517-981 mm	55-4517 mm	10.572	0.900
Isothermality	61-68	38-85	11.843	0.925
Max temperature of warmest month	25.1-32.7°C	13.8-42.5°C	8.056	0.818
Mean diurnal range	142-205	60-205	6.355	0.599
Mean temperature of coldest quarter	3.2-17.1°C	3.2-28.2°C	8.309	0.867
Mean temperature of driest quarter	14.6-20.2°C	4.6-29.3°C	8.025	0.765
Mean temperature of warmest quarter	17.5-22.7°C	9.3-32.5°C	11.968	1.100
Mean temperature of wettest quarter	16.6-22.7°C	3.8-32.5°C	12.225	1.090
Min temperature of coldest month	-6.1-9.3°C	13.8-42.5°C	6.522	0.734
Precipitation of coldest quarter	1-39 mm	1-823 mm	12.455	0.724
Precipitation of driest month	6-12 mm	0-145 mm	9.292	0.669
Precipitation of driest month	0-5 mm	0-145 mm	2.967	0.198
Precipitation of driest quarter	19-35 mm	0-485 mm	13.396	0.845
Precipitation of warmest quarter	165-305 mm	3-1475 mm	6.995	0.551
Precipitation of wettest month	104-247 mm	9-819 mm	7.105	0.666
Precipitation of wettest quarter	262-648 mm	21-2187 mm	7.564	0.711
Precipitation seasonality	88-109	29-129	8.139	0.790
Slope	0.01-10.24°	0-34.12°	5.643	0.315
Soil type	Vertisol, Planosol, Feozem, Castañozem		7.804	1.128
Temperature annual range	21.4-26.1°C	12.1-39.4°C	12.688	1.046
Temperature seasonality	1280-2932	379-9348	15.769	1.083

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tarahumara, Purepecha, Popoloca, Otomi, Cuicateco, Chocholteco		4.014	1.593
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	15.538	1.045

Cacahuacintle

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	158-2712 m.a.s.l.	0-5500 m.a.s.l.	15.700	1.715
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	9.654	1.181
Annual precipitation	517-981 mm	55-4517 mm	10.595	1.085
Isothermality	69-76	38-85	1.190	1.190
Max temperature of warmest month	13.8-30.8°C	13.8-42.5°C	12.464	1.643
Mean diurnal range	142-163	60-205	6.237	0.698
Mean temperature of coldest quarter	9.4-13.2°C	3.2-28.2°C	8.171	0.888
Mean temperature of driest quarter	4.6-12.8°C	4.6-29.3°C	7.965	1.017
Mean temperature of warmest quarter	9.3-17.4°C	9.3-32.5°C	16.429	1.913
Mean temperature of wettest quarter	10.7-16.5°C	3.8-32.5°C	1.446	1.446
Min temperature of coldest month	0-4.6°C	13.8-42.5°C	1.126	1.126
Precipitation of coldest quarter	1-65 mm	1-823 mm	0.491	0.491
Precipitation of driest month	6-12 mm	0-145 mm	14.917	1.125
Precipitation of driest quarter	19-35 mm	0-485 mm	12.674	0.990
Precipitation of warmest quarter	165-305 mm	3-1475 mm	9.442	0.930
Precipitation of wettest month	104-247 mm	9-819 mm	6.553	0.749
Precipitation of wettest quarter	262-648 mm	21-2187 mm	6.847	0.789
Precipitation seasonality	71-95	29-129	6.877	0.821
Slope	3.43-10.24°	0-34.12°	5.401	0.411
Soil type	Feozem, Chernozem, Planosol, Acrisol, Castañozem, Fluvisol, Vertisol, Gleysol		4.312	1.193
Temperature annual range	21.4-26.1°C	12.1-39.4°C	13.986	1.280
Temperature seasonality	1280-2932	379-9348	11.882	1.093

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Otomi, Purepecha, Mazahua, Náhuatl, Mixteco, Tlahuica, Cuicateco		9.525	2.428
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	15.439	1.240

Celaya

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1040 m.a.s.l.	0-5500 m.a.s.l.	2.252	0.735
Annual mean temperature	22.9-24.5°C	7.8-29.1°C	3.292	1.365
Annual precipitation	517-744 mm	55-4517 mm	3.877	1.360
Isothermality	57-60	38-85	3.567	1.264
Max temperature of warmest month	36.3-42.5°C	13.8-42.5°C	7.205	2.040
Mean diurnal range	174-205	60-205	3.385	1.470
Mean temperature of coldest quarter	17.2-19.2°C	3.2-28.2°C	5.641	1.857
Mean temperature of driest quarter	20.3-24.3°C	4.6-29.3°C	3.751	1.355
Mean temperature of warmest quarter	27.8-32.5°C	9.3-32.5°C	4.029	1.428
Mean temperature of wettest quarter	28.6-32.5°C	3.8-32.5°C	7.828	2.262
Min temperature of coldest month	6.9-9.3°C	13.8-42.5°C	5.035	1.605
Precipitation of coldest quarter	66-139 mm	1-823 mm	3.470	1.373
Precipitation of driest month	0-5 mm	0-145 mm	2.713	0.765
Precipitation of driest quarter	19-35 mm	0-485 mm	2.643	0.904
Precipitation of warmest quarter	382-464 mm	3-1475 mm	2.550	1.203
Precipitation of wettest month	154-200 mm	9-819 mm	2.420	1.036
Precipitation of wettest quarter	398-524 mm	21-2187 mm	3.441	1.311
Precipitation seasonality	110-129	29-129	2.474	1.582
Soil type	Cambisol		5.107	1.960
Temperature annual range	28.4-39.4°C	12.1-39.4°C	3.296	1.584
Temperature seasonality	4012-5050	379-9348	2.808	1.186

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Yaqui, Mayo		3.508	3.508
Education	unfinished-finished high school	unfinished elementary school-bachelor or higher degree	3.750	1.523

Chalqueño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3270 m.a.s.l.	0-5500 m.a.s.l.	4.695	1.142
Annual mean temperature	12.6-17.5°C	7.8-29.1°C	2.974	1.062
Annual precipitation	982-3194 mm	55-4517 mm	4.063	1.648
Isothermality	65-85	38-85	5.420	1.771
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	6.278	2.093
Mean diurnal range	109-141	60-205	4.057	1.280
Mean temperature of coldest quarter	13.3-17.1°C	3.2-28.2°C	3.615	1.057
Mean temperature of driest quarter	12.9-16.2°C	4.6-29.3°C	3.151	1.008
Mean temperature of warmest quarter	9.3-20.9°C	9.3-32.5°C	4.925	1.735
Mean temperature of wettest quarter	14.1-18.6°C	3.8-32.5°C	6.870	1.858
Min temperature of coldest month	6.9-12°C	13.8-42.5°C	3.504	1.108
Precipitation of coldest quarter	196-269 mm	1-823 mm	5.330	1.902
Precipitation of driest month	13-89 mm	0-145 mm	2.570	1.378
Precipitation of driest quarter	58-365 mm	0-485 mm	3.183	1.559
Precipitation of warmest quarter	306-464 mm	3-1475 mm	4.269	1.265
Precipitation of wettest month	201-571 mm	9-819 mm	4.351	1.538
Precipitation of wettest quarter	649-1501 mm	21-2187 mm	4.679	1.611
Precipitation seasonality	80-87	29-129	4.989	1.341
Slope	3.43-34.12°	0-34.12°	5.373	1.835
Soil type	Gleysol, Castañozem		6.600	2.471
Temperature annual range	16.7-21.3°C	12.1-39.4°C	5.695	1.499
Temperature seasonality	379-2021	379-9348	8.565	1.990

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tsotsil, Tsetsal, Tojolobal, Qanjobal, Nahuatl, Mixteco Mixe, Mazateco, Mam, Jakalteko, Cuicateco, Chuj, Chichimeco, Chatino		8.302	3.052
Education	unfinished elementary-unfinished high-school	unfinished elementary school-bachelor or higher degree	3.707	0.755

Chapalote

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-2712 m.a.s.l.	0-5500 m.a.s.l.	5.544	0.702
Annual mean temperature	14.5-24.5°C	7.8-29.1°C	2.895	0.640
Annual precipitation	982-4517 mm	55-4517 mm	6.720	1.550
Isothermality	69-85	38-85	15.545	2.079
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	7.257	1.772
Mean diurnal range	120-141	60-205	8.575	1.321
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	5.645	1.066
Mean temperature of driest quarter	16.3-22.3°C	4.6-29.3°C	4.140	0.797
Mean temperature of warmest quarter	9.3-26.1°C	9.3-32.5°C	4.031	1.041
Mean temperature of wettest quarter	14.1-24.7°C	3.8-32.5°C	3.704	0.815
Min temperature of coldest month	6.9-14.6°C	13.8-42.5°C	7.338	1.258
Precipitation of coldest quarter	140-351 mm	1-823 mm	4.710	1.414
Precipitation of driest month	13-71 mm	0-145 mm	4.528	1.301
Precipitation of driest quarter	58-274 mm	0-485 mm	4.293	1.277
Precipitation of warmest quarter	306-677 mm	3-1475 mm	5.865	1.099
Precipitation of wettest month	201-819 mm	9-819 mm	5.843	1.452
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	5.900	1.438
Precipitation seasonality	63-87	29-129	2.911	0.635
Slope	0-30.7°	0-34.12°	5.781	1.102
Soil type	Rendzina, Ranker, Nitosol, Luvisol, Gleysol		4.829	1.713
Temperature annual range	16.7-21.3°C	12.1-39.4°C	12.208	1.602
Temperature seasonality	379-2021	379-9348	17.664	2.064

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zoque, Zapoteco, Tuzantecto, Tsotsil, Tsetsal, Tojolobal, Teko, Qanjobal Mixe, Mazateco, Mam, Jakalteko, Cuicateco, Chuj, Chol, Chatino		16.745	3.506
Education	finished elementary-unfinished high-school	unfinished elementary school-bachelor or higher deg	6.445	0.703

Chiquito

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	2.729	1.067
Annual precipitation	745-981 mm	55-4517 mm	4.128	1.653
Isothermality	61-64	38-85	4.420	1.622
Max temperature of warmest month	25.1-30.8°C	13.8-42.5°C	3.588	1.767
Mean diurnal range	131-152	60-205	2.126	1.161
Mean temperature of coldest quarter	15.2-17.1°C	3.2-28.2°C	3.364	1.530
Mean temperature of driest quarter	18.2-20.2°C	4.6-29.3°C	2.363	1.277
Mean temperature of warmest quarter	17.5-22.7°C	9.3-32.5°C	3.101	1.617
Mean temperature of wettest quarter	16.6-22.7°C	3.8-32.5°C	3.392	1.637
Min temperature of coldest month	2.5-4.6°C	13.8-42.5°C	2.266	1.080
Precipitation of coldest quarter	40-65 mm	1-823 mm	3.114	1.199
Precipitation of driest month	6-12 mm	0-145 mm	2.330	1.000
Precipitation of driest quarter	19-35 mm	0-485 mm	2.835	1.102
Precipitation of wettest month	154-200 mm	9-819 mm	4.695	1.705
Precipitation of wettest quarter	398-524 mm	21-2187 mm	4.009	1.614
Precipitation seasonality	80-87	29-129	3.359	1.528
Slope	10.25-13.65°	0-34.12°	2.109	0.912
Soil type	Gleysol, Feozem, Cambisol		4.679	2.175
Temperature annual range	21.4-23.8°C	12.1-39.4°C	5.787	2.010
Temperature seasonality	2022-2932	379-9348	4.094	1.522

Social Factors

Factor	Scale	Range	Epsilon	Score
Education	unfinished elementary-unfinished high-school	unfinished elementary school-bachelor or higher degree	2.766	0.993

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Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1597 m.a.s.l.	0-5500 m.a.s.l.	4.18034	0.60901
Annual mean temperature	21.1-29.1°C	7.8-29.1°C	12.6293	2.36402
Annual precipitation	745-1980 mm	55-4517 mm	2.83217	1.02991
Isothermality	65-85	38-85	11.4026	2.66616
Max temperature of warmest month	38.3-42.5°C	13.8-42.5°C	5.76067	1.58229
Mean diurnal range	131-163	60-205	4.79695	0.91307
Mean temperature of coldest quarter	17.2-28.2°C	3.2-28.2°C	16.4661	2.62515
Mean temperature of driest quarter	18.2-29.3°C	4.6-29.3°C	11.7521	2.16037
Mean temperature of warmest quarter	20.7-24.4°C	9.3-32.5°C	3.31898	0.78774
Min temperature of coldest month	9.4-21.3°C	13.8-42.5°C	4.70866	1.15729
Precipitation of coldest quarter	1-39 mm	1-823 mm	6.80467	0.85596
Precipitation of driest month	0-5 mm	0-145 mm	5.90278	0.70893
Precipitation of driest quarter	0-18 mm	0-485 mm	5.64584	0.76713
Precipitation of warmest quarter	234-381 mm	3-1475 mm	3.63001	0.83482
Precipitation of wettest month	201-376 mm	9-819 mm	4.79791	1.30082
Precipitation of wettest quarter	525-1222 mm	21-2187 mm	2.00086	0.87099
Precipitation seasonality	96-109	29-129	11.0315	1.65945
Slope	3.43-20.47°	0-34.12°	2.16915	0.6451
Soil type	Regosol, Gleysol		5.12743	0.83386
Temperature annual range	12.1-23.8°C	12.1-39.4°C	4.40459	0.95316
Temperature seasonality	379-2021	379-9348	8.60067	1.3248

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Trique de la Baja, Tlapaneco, Mixteco, Chatino		2.84293	1.50811
Education	unfinished elementary-finished high school	unfinished elementary school-bachelor or higher degree	4.80397	1.35323

Complejo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-4942 m.a.s.l.	0-5500 m.a.s.l.	18.423	2.462
Annual mean temperature	7.8-17.5°C	7.8-29.1°C	13.618	1.285
Annual precipitation	517-1226 mm	55-4517 mm	9.745	0.857
Isothermality	65-76	38-85	16.024	1.404
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	24.546	2.344
Mean diurnal range	142-173	60-205	8.034	0.740
Mean temperature of coldest quarter	9.4-15.1°C	3.2-28.2°C	10.172	0.893
Mean temperature of driest quarter	4.6-14.5°C	4.6-29.3°C	15.188	1.427
Mean temperature of warmest quarter	9.3-20.9°C	9.3-32.5°C	24.317	2.061
Mean temperature of wettest quarter	10.7-18.6°C	3.8-32.5°C	22.964	1.958
Min temperature of coldest month	0-6.8°C	13.8-42.5°C	9.992	0.847
Precipitation of coldest quarter	1-65 mm	1-823 mm	6.662	0.489
Precipitation of driest month	6-12 mm	0-145 mm	18.904	1.121
Precipitation of driest quarter	19-57 mm	0-485 mm	10.416	0.782
Precipitation of warmest quarter	165-381 mm	3-1475 mm	8.194	0.717
Precipitation of wettest month	104-247 mm	9-819 mm	8.211	0.765
Precipitation of wettest quarter	262-800 mm	21-2187 mm	7.230	0.735
Precipitation seasonality	71-95	29-129	9.238	0.869
Slope	0.01-13.65°	0-34.12°	6.216	0.385
Soil type	Regosol, Planosol, Gleysol, Feozem, Chernozem, Cambisol, Acrisol		6.134	1.166
Temperature annual range	18.9-26.1°C	12.1-39.4°C	14.042	1.120
Temperature seasonality	379-2932	379-9348	12.193	0.960

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Triqui de la Baja, Tlahuica, Purepecha, Popoloca, Otomí, Náhuatl, Mixteco, Mazahua		12.140	2.547
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	18.762	1.217

Conejo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-3270 m.a.s.l.	0-5500 m.a.s.l.	16.270	0.969
Annual mean temperature	7.8-19.2°C	7.8-29.1°C	9.304	0.952
Annual precipitation	307-744 mm	55-4517 mm	14.830	1.012
Isothermality	53-68	38-85	9.266	0.768
Max temperature of warmest month	27.2-32.7°C	13.8-42.5°C	14.825	1.129
Mean diurnal range	153-205	60-205	9.174	0.859
Mean temperature of coldest quarter	3.2-15.1°C	3.2-28.2°C	9.452	0.916
Mean temperature of driest quarter	4.6-18.1°C	4.6-29.3°C	8.166	0.818
Mean temperature of warmest quarter	17.5-22.7°C	9.3-32.5°C	17.660	1.363
Mean temperature of wettest quarter	16.6-22.7°C	3.8-32.5°C	7.044	0.713
Min temperature of coldest month	-6.1-4.7°C	13.8-42.5°C	10.305	0.997
Precipitation of coldest quarter	1-65 mm	1-823 mm	8.491	0.568
Precipitation of driest month	0-12 mm	0-145 mm	6.799	0.456
Precipitation of driest quarter	0-35 mm	0-485 mm	6.698	0.453
Precipitation of warmest quarter	165-305 mm	3-1475 mm	12.134	0.810
Precipitation of wettest month	58-153 mm	9-819 mm	13.534	0.863
Precipitation of wettest quarter	262-524 mm	21-2187 mm	13.588	0.877
Precipitation seasonality	80-109	29-129	5.682	0.589
Slope	0.01-6.83°	0-34.12°	3.440	0.180
Soil type	Xerosol, Vertisol, Planosol, Feozem, Castañozem		9.746	1.251
Temperature annual range	23.9-35.9°C	12.1-39.4°C	7.282	0.668
Temperature seasonality	2022-6015	379-9348	8.642	0.680

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tarahumara, Otomi, Chinanteco		6.637	1.688
Education	unfinished elementary- finished high-school	unfinished elementary school-bachelor or higher degree	11.534	0.794

Conejo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-4385 m.a.s.l.	0-5500 m.a.s.l.	4.048	1.815
Annual precipitation	1537-3194 mm	55-4517 mm	9.219	2.366
Isothermality	53-60	38-85	2.490	0.842
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	4.536	1.805
Mean diurnal range	60-119	60-205	5.832	1.855
Mean temperature of coldest quarter	15.2-17.1°C	3.2-28.2°C	2.531	0.869
Mean temperature of driest quarter	14.6-16.2°C	4.6-29.3°C	2.460	0.800
Mean temperature of warmest quarter	15.3-20.9°C	9.3-32.5°C	2.687	1.132
Mean temperature of wettest quarter	14.1-20.6°C	3.8-32.5°C	2.579	1.022
Min temperature of coldest month	6.9-12°C	13.8-42.5°C	2.908	0.983
Precipitation of coldest quarter	100-351 mm	1-823 mm	6.018	1.868
Precipitation of driest month	23-111 mm	0-145 mm	6.250	2.335
Precipitation of driest quarter	86-365 mm	0-485 mm	5.839	2.103
Precipitation of warmest quarter	382-859 mm	3-1475 mm	3.767	1.444
Precipitation of wettest month	248-571 mm	9-819 mm	6.921	1.900
Precipitation of wettest quarter	649-1501 mm	21-2187 mm	5.253	1.741
Precipitation seasonality	63-79	29-129	3.925	1.102
Slope	3.43-27.29°	0-34.12°	3.582	1.133
Soil type	Regosol, Planosol, Gleysol		3.846	1.559
Temperature annual range	16.7-21.3°C	12.1-39.4°C	7.136	1.634
Temperature seasonality	1280-2932	379-9348	4.202	1.093

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Totonaco, Tojobal, Texistepequeño, Popoloca, Oluteco, Náhuatl, Mazateco, Mam, Chichimeco		8.417	3.471
Education	unfinished elementary-finished high school	unfinished elementary school-bachelor or higher degree	4.659	1.092

Cónico

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	12.261	1.235
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	21.727	2.522
Annual precipitation	517-981 mm	55-4517 mm	5.709	0.930
Isothermality	53-60	38-85	9.678	1.234
Max temperature of warmest month	25.1-30.8°C	13.8-42.5°C	8.002	1.375
Mean diurnal range	174-205	60-205	12.232	1.680
Mean temperature of coldest quarter	3.2-9.3°C	3.2-28.2°C	20.060	2.009
Mean temperature of driest quarter	4.6-14.5°C	4.6-29.3°C	10.285	1.588
Mean temperature of warmest quarter	15.3-20.9°C	9.3-32.5°C	9.940	1.535
Mean temperature of wettest quarter	16.6-20.6°C	3.8-32.5°C	13.075	1.712
Min temperature of coldest month	-6.1-(-1)°C	13.8-42.5°C	24.014	2.141
Precipitation of coldest quarter	100-139 mm	1-823 mm	4.859	0.869
Precipitation of driest month	6-22 mm	0-145 mm	6.000	0.904
Precipitation of driest quarter	19-57 mm	0-485 mm	5.623	0.812
Precipitation of warmest quarter	234-556 mm	3-1475 mm	4.296	0.814
Precipitation of wettest month	201-247 mm	9-819 mm	4.666	0.746
Precipitation of wettest quarter	398-524 mm	21-2187 mm	7.265	1.007
Precipitation seasonality	103-109	29-129	3.582	0.742
Precipitation seasonality	80-87	29-129	2.871	0.605
Slope	3.43-6.83°	0-34.12°	4.164	0.437
Soil type	Planosol		6.076	1.368
Temperature annual range	33.1-35.9°C	12.1-39.4°C	10.969	1.523
Temperature seasonality	5051-6015	379-9348	8.294	1.161

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tarahumara, Pima		19.706	3.305
Education	unfinished high-school	unfinished elementary school-bachelor or higher degree	3.668	0.472

Cónico Norteño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	4.069	0.867
Annual mean temperature	16.1-19.2°C	7.8-29.1°C	3.749	1.024
Annual precipitation	517-981 mm	55-4517 mm	3.998	1.081
Isothermality	61-68	38-85	4.554	1.100
Max temperature of warmest month	29.1-30.8°C	13.8-42.5°C	6.049	1.439
Mean diurnal range	153-163	60-205	3.542	0.984
Mean temperature of coldest quarter	13.3-15.1°C	3.2-28.2°C	5.356	1.258
Mean temperature of driest quarter	14.6-18.1°C	4.6-29.3°C	3.916	1.073
Mean temperature of warmest quarter	19.3-22.7°C	9.3-32.5°C	6.039	1.468
Mean temperature of wettest quarter	16.6-20.6°C	3.8-32.5°C	4.872	1.372
Min temperature of coldest month	4.7-6.8°C	13.8-42.5°C	5.534	1.332
Precipitation of coldest quarter	1-39 mm	1-823 mm	2.422	0.549
Precipitation of driest month	6-12 mm	0-145 mm	4.872	1.021
Precipitation of driest quarter	19-35 mm	0-485 mm	5.501	1.073
Precipitation of warmest quarter	165-233 mm	3-1475 mm	4.590	1.065
Precipitation of wettest month	154-247 mm	9-819 mm	3.119	0.929
Precipitation of wettest quarter	398-648 mm	21-2187 mm	3.428	1.014
Precipitation seasonality	88-102	29-129	4.511	1.174
Slope	3.43-10.24°	0-34.12°	3.134	0.697
Soil type	Vertisol, Feozem, Castañozem		4.730	1.637
Temperature annual range	21.4-26.1°C	12.1-39.4°C	4.142	1.146
Temperature seasonality	2022-2932	379-9348	5.415	1.205

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Purepecha		11.317	3.579
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	4.974	1.125

Coscomatepec

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Annual mean temperature	22.9-24.5°C	7.8-29.1°C	2.739	1.068
Annual precipitation	517-981 mm	55-4517 mm	2.592	0.942
Isothermality	53-56	38-85	5.944	1.680
Max temperature of warmest month	38.3-42.5°C	13.8-42.5°C	6.800	2.270
Mean diurnal range	174-183	60-205	3.986	1.315
Mean temperature of coldest quarter	17.2-19.2°C	3.2-28.2°C	2.428	1.040
Mean temperature of driest quarter	22.4-24.3°C	4.6-29.3°C	3.654	1.217
Mean temperature of warmest quarter	29.4-32.5°C	9.3-32.5°C	3.377	1.290
Mean temperature of wettest quarter	28.6-32.5°C	3.8-32.5°C	3.997	1.493
Min temperature of coldest month	-6.1-9.3°C	13.8-42.5°C	2.158	1.137
Precipitation of coldest quarter	100-139 mm	1-823 mm	6.258	1.685
Precipitation of driest quarter	36-57 mm	0-485 mm	3.119	1.055
Precipitation of warmest quarter	306-1475 mm	3-1475 mm	3.478	1.622
Precipitation of wettest quarter	398-524 mm	21-2187 mm	2.091	0.831
Precipitation seasonality	88-129	29-129	2.405	1.078
Slope	6.84-10.24°	0-34.12°	2.308	0.716
Soil type	Fluvisol, Cambisol		3.710	1.850
Temperature annual range	28.4-33.0°C	12.1-39.4°C	2.821	1.054
Temperature seasonality	4012-6015	379-9348	3.069	1.039

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Yaqui, Trahumara, Pima, Mayo, Huave, Guarijo, Cora		5.795	2.944
Education	unfinished high-school	unfinished elementary school-bachelor or higher degree	4.683	1.183

Cristalino

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3270 m.a.s.l.	0-5500 m.a.s.l.	6.939	1.171
Annual mean temperature	12.6-16.0°C	7.8-29.1°C	4.774	1.224
Annual precipitation	982-4517 mm	55-4517 mm	4.487	1.447
Isothermality	65-76	38-85	9.351	1.644
Max temperature of warmest month	13.8-29.0°C	13.8-42.5°C	10.163	2.249
Mean diurnal range	120-141	60-205	7.123	1.348
Mean temperature of coldest quarter	11.5-19.2°C	3.2-28.2°C	2.843	0.738
Mean temperature of driest quarter	11.2-18.1°C	4.6-29.3°C	3.061	0.827
Mean temperature of warmest quarter	9.3-20.9°C	9.3-32.5°C	7.356	1.798
Mean temperature of wettest quarter	14.1-20.6°C	3.8-32.5°C	6.481	1.393
Min temperature of coldest month	4.7-9.3°C	13.8-42.5°C	4.956	1.050
Precipitation of coldest quarter	140-351 mm	1-823 mm	4.863	1.563
Precipitation of driest month	6-71 mm	0-145 mm	3.231	1.154
Precipitation of driest quarter	36-208 mm	0-485 mm	3.753	1.197
Precipitation of warmest quarter	382-677 mm	3-1475 mm	5.423	1.333
Precipitation of wettest month	201-819 mm	9-819 mm	4.545	1.504
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	5.266	1.631
Precipitation seasonality	71-87	29-129	4.513	0.994
Slope	3.43-34.12°	0-34.12°	7.350	1.789
Soil type	Ranker, Gleysol, Castañozem		6.703	2.567
Temperature annual range	16.7-21.3°C	12.1-39.4°C	7.866	1.425
Temperature seasonality	379-2021	379-9348	12.669	2.001

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tsotsil, Tsetsal, Triqui de la Baja, Tojolobal, Teko, Qanjobal, Mixteco, Mixe, Mazateco, Mam, Cuicateco, Chuj, Chatino		11.665	3.375
Education	unfinished elementary- unfinished high-school	unfinished elementary school-bachelor or higher degree	5.047	0.744

Dulce

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1597 m.a.s.l.	0-5500 m.a.s.l.	5.005	0.734
Annual mean temperature	21.1-26.3°C	7.8-29.1°C	4.333	0.939
Annual precipitation	745-1536 mm	55-4517 mm	5.527	1.117
Isothermality	61-72	38-85	4.348	0.992
Max temperature of warmest month	30.9-34.5°C	13.8-42.5°C	3.502	0.730
Mean diurnal range	120-152	60-205	5.034	1.102
Mean temperature of coldest quarter	19.3-24.3°C	3.2-28.2°C	8.490	1.477
Mean temperature of driest quarter	20.3-26.2°C	4.6-29.3°C	4.679	1.031
Mean temperature of warmest quarter	22.8-27.7°C	9.3-32.5°C	2.881	0.710
Mean temperature of wettest quarter	22.8-28.5°C	3.8-32.5°C	2.464	0.590
Min temperature of coldest month	9.4-16.8°C	13.8-42.5°C	8.189	1.574
Precipitation of coldest quarter	40-65 mm	1-823 mm	2.016	0.437
Precipitation of driest month	0-5 mm	0-145 mm	5.562	0.742
Precipitation of driest quarter	0-18 mm	0-485 mm	5.323	0.802
Precipitation of warmest quarter	382-1475 mm	3-1475 mm	4.504	1.518
Precipitation of wettest month	201-304 mm	9-819 mm	8.226	1.501
Precipitation of wettest quarter	525-990 mm	21-2187 mm	6.634	1.384
Precipitation seasonality	96-129	29-129	7.015	1.471
Slope	3.42-20.47°	0-34.12°	3.915	0.710
Soil type	Castañozem, Cambisol, Acrisol		2.852	1.434
Temperature annual range	16.7-23.8°C	12.1-39.4°C	4.715	1.038
Temperature seasonality	1280-2932	379-9348	5.946	1.085

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Huave, Cora		9.106	2.939
Education	unfinished elementary- unfinished high-school	unfinished elementary school-bachelor or higher degree	4.208	0.724

Dulcillo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-482 m.a.s.l.	0-5500 m.a.s.l.	6.741	0.806
Annual mean temperature	24.6-26.3°C	7.8-29.1°C	15.764	1.761
Annual precipitation	982-1980 mm	55-4517 mm	7.705	1.360
Isothermality	65-85	38-85	6.406	1.466
Max temperature of warmest month	13.8-36.2°C	13.8-42.5°C	2.939	0.881
Mean diurnal range	109-141	60-205	5.099	1.038
Mean temperature of coldest quarter	21.7-24.3°C	3.2-28.2°C	15.665	1.741
Mean temperature of driest quarter	22.4-29.3°C	4.6-29.3°C	5.588	1.114
Mean temperature of warmest quarter	26.1-27.7°C	9.3-32.5°C	7.214	1.046
Mean temperature of wettest quarter	26.6-28.5°C	3.8-32.5°C	8.742	1.083
Min temperature of coldest month	14.7-21.3°C	13.8-42.5°C	10.280	1.486
Precipitation of coldest quarter	100-195 mm	1-823 mm	8.086	1.414
Precipitation of driest month	23-45 mm	0-145 mm	12.192	1.997
Precipitation of driest quarter	58-159 mm	0-485 mm	9.099	1.597
Precipitation of warmest quarter	234-464 mm	3-1475 mm	5.435	0.948
Precipitation of wettest month	154-819 mm	9-819 mm	5.764	1.344
Precipitation of wettest quarter	398-2187 mm	21-2187 mm	5.758	1.294
Precipitation seasonality	29-62	29-129	3.427	0.902
Slope	0-30.7°	0-34.12°	4.859	1.514
Soil type	Rendzina, Luvisol,Histosol, Gleysol, Chernozem		4.132	1.362
Temperature annual range	12.1-21.3°C	12.1-39.4°C	7.577	1.350
Temperature seasonality	379-2932	379-9348	6.765	1.213

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tojolobal, Mixteco, Mixe, Maya, Chichimeco, Amuzgo		8.160	2.155
Education	unfinished elementary- unfinished high-school	unfinished elementary school-bachelor or higher degree	3.838	0.511

Dzit-Bacal

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-482 m.a.s.l.	0-5500 m.a.s.l.	6.741	0.806
Annual mean temperature	24.6-26.3°C	7.8-29.1°C	15.764	1.761
Annual precipitation	982-1980 mm	55-4517 mm	7.705	1.360
Isothermality	65-85	38-85	6.406	1.466
Max temperature of warmest month	13.8-36.2°C	13.8-42.5°C	2.939	0.881
Mean diurnal range	109-141	60-205	5.099	1.038
Mean temperature of coldest quarter	21.7-24.3°C	3.2-28.2°C	15.665	1.741
Mean temperature of driest quarter	22.4-29.3°C	4.6-29.3°C	5.588	1.114
Mean temperature of warmest quarter	26.1-27.7°C	9.3-32.5°C	7.214	1.046
Mean temperature of wettest quarter	26.6-28.5°C	3.8-32.5°C	8.742	1.083
Min temperature of coldest month	14.7-21.3°C	13.8-42.5°C	10.280	1.486
Precipitation of coldest quarter	100-195 mm	1-823 mm	8.086	1.414
Precipitation of driest month	23-45 mm	0-145 mm	12.192	1.997
Precipitation of driest quarter	58-159 mm	0-485 mm	9.099	1.597
Precipitation of warmest quarter	234-464 mm	3-1475 mm	5.435	0.948
Precipitation of wettest month	154-819 mm	9-819 mm	5.764	1.344
Precipitation of wettest quarter	398-2187 mm	21-2187 mm	5.758	1.294
Precipitation seasonality	29-62	29-129	3.427	0.902
Slope	0-30.7°	0-34.12°	4.859	1.514
Soil type	Rendzina, Luvisol, Histosol, Gleysol, Chernozem		1.362	1.362
Temperature annual range	12.1-21.3°C	12.1-39.4°C	7.577	1.350
Temperature seasonality	379-2932	379-9348	6.765	1.213

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tojolabal, Mixteco, Mixe, Maya, Chichimeca, Amuzgo		8.160	2.155
Education	unfinished elementary-unfinished high-school	unfinished elementary school-bachelor or higher degree	3.838	0.511

Elotero de Sinaloa

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-2155 m.a.s.l.	0-5500 m.a.s.l.	3.266	0.922
Annual mean temperature	19.3-22.8°C	7.8-29.1°C	2.525	1.077
Annual precipitation	745-1226 mm	55-4517 mm	3.316	1.671
Isothermality	61-64	38-85	5.501	1.575
Max temperature of warmest month	29.1-30.8°C	13.8-42.5°C	2.830	1.195
Mean diurnal range	142-163	60-205	3.111	1.198
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	3.440	1.411
Mean temperature of driest quarter	18.2-20.2°C	4.6-29.3°C	3.747	1.412
Mean temperature of warmest quarter	22.8-24.4°C	9.3-32.5°C	3.020	1.266
Mean temperature of wettest quarter	20.7-22.7°C	3.8-32.5°C	2.900	1.221
Min temperature of coldest month	6.9-9.3°C	13.8-42.5°C	3.998	1.397
Precipitation of coldest quarter	40-65 mm	1-823 mm	4.400	1.246
Precipitation of driest month	0-5 mm	0-145 mm	2.439	0.691
Precipitation of driest quarter	19-35 mm	0-485 mm	3.484	1.053
Precipitation of warmest quarter	382-859 mm	3-1475 mm	4.606	2.034
Precipitation of wettest month	201-304 mm	9-819 mm	3.111	1.303
Precipitation of wettest quarter	525-800 mm	21-2187 mm	3.786	1.482
Precipitation seasonality	103-129	29-129	5.220	1.959
Slope	3.43-27.29°	0-34.12°	3.276	1.303
Soil type	Feozem, Cambisol		3.654	1.494
Temperature annual range	21.4-26.1°C	12.1-39.4°C	3.218	1.284
Temperature seasonality	2022-2932	379-9348	6.406	1.657

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Huave		2.932	2.357
Education	finished elementary-unfinished high-school	unfinished elementary school-bachelor or higher degree	3.670	1.018

Elotes Cónicos

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3270 m.a.s.l.	0-5500 m.a.s.l.	8.349	1.018
Annual mean temperature	12.6-17.5°C	7.8-29.1°C	5.954	1.015
Annual precipitation	745-1536 mm	55-4517 mm	7.608	1.131
Isothermality	61-85	38-85	6.342	1.207
Max temperature of warmest month	22.6-30.8°C	13.8-42.5°C	8.565	1.432
Mean diurnal range	142-163	60-205	8.265	1.099
Mean temperature of coldest quarter	11.5-17.1°C	3.2-28.2°C	4.721	0.749
Mean temperature of driest quarter	12.9-18.1°C	4.6-29.3°C	4.841	0.805
Mean temperature of warmest quarter	14.1-22.7°C	9.3-32.5°C	8.092	1.366
Min temperature of coldest month	2.5-6.8°C	13.8-42.5°C	6.356	0.906
Precipitation of coldest quarter	1-65 mm	1-823 mm	4.132	0.526
Precipitation of driest month	6-12 mm	0-145 mm	7.036	0.829
Precipitation of driest quarter	19-35 mm	0-485 mm	7.706	0.858
Precipitation of warmest quarter	165-556 mm	3-1475 mm	2.925	0.574
Precipitation of wettest month	154-304 mm	9-819 mm	7.164	1.023
Precipitation of wettest quarter	525-990 mm	21-2187 mm	7.838	1.136
Precipitation seasonality	88-102	29-129	9.656	1.236
Slope	3.43-20.47°	0-34.12°	6.835	0.799
Soil type	Vertisol, Planosol, Luvisol, Gleysol		4.239	1.075
Temperature annual range	18.9-26.1°C	12.1-39.4°C	7.633	1.039
Temperature seasonality	379-2932	379-9348	8.021	1.210

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Triquie de la Baja, Totonaco, Purepecha, Mixteco, Mazateco, Cuicateco		11.764	2.577
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	4.555	1.127

Gordo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-482 m.a.s.l.	0-5500 m.a.s.l.	6.741	0.806
Annual mean temperature	24.6-26.3°C	7.8-29.1°C	15.764	1.761
Annual precipitation	982-1980 mm	55-4517 mm	7.705	1.360
Isothermality	65-85	38-85	6.406	1.466
Max temperature of warmest month	13.8-36.2°C	13.8-42.5°C	2.939	0.881
Mean diurnal range	109-141	60-205	5.099	1.038
Mean temperature of coldest quarter	21.7-24.3°C	3.2-28.2°C	15.665	1.741
Mean temperature of driest quarter	22.4-29.3°C	4.6-29.3°C	5.501	1.163
Mean temperature of warmest quarter	26.1-27.7°C	9.3-32.5°C	7.214	1.046
Mean temperature of wettest quarter	26.6-28.5°C	3.8-32.5°C	8.742	1.083
Min temperature of coldest month	14.7-21.3°C	13.8-42.5°C	10.280	1.486
Precipitation of coldest quarter	100-195 mm	1-823 mm	8.086	1.414
Precipitation of driest month	23-45 mm	0-145 mm	12.192	1.997
Precipitation of driest quarter	58-159 mm	0-485 mm	9.099	1.597
Precipitation of warmest quarter	234-464 mm	3-1475 mm	5.435	0.948
Precipitation of wettest month	154-819 mm	9-819 mm	5.764	1.344
Precipitation of wettest quarter	398-2187 mm	21-2187 mm	5.758	1.294
Precipitation seasonality	29-62	29-129	3.427	0.902
Slope	0-30.7°	0-34.12°	4.859	1.514
Soil type	Rendzina, Luvisol, Histosol, Gleysol, Chernozem		4.132	1.362
Temperature annual range	12.1-21.3°C	12.1-39.4°C	7.577	1.350
Temperature seasonality	379-2932	379-9348	6.765	1.213

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tojolabal, Mixteco, Mixe, Maya, Chichimeco, Amuzgo		8.160	2.155
Education	unfinished elementary- unfinished high-school	unfinished elementary school-bachelor or higher degree	3.838	0.511

Jala

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-1597 m.a.s.l.	0-5500 m.a.s.l.	5.389	0.435
Annual mean temperature	21.1-29.1°C	7.8-29.1°C	6.080	0.847
Annual precipitation	982-4517 mm	55-4517 mm	8.372	1.317
Isothermality	53-85	38-85	9.963	1.462
Max temperature of warmest month	25.1-34.5°C	13.8-42.5°C	4.012	0.550
Mean diurnal range	60-152	60-205	5.078	0.798
Mean temperature of coldest quarter	17.2-28.2°C	3.2-28.2°C	8.775	1.129
Mean temperature of driest quarter	18.2-29.3°C	4.6-29.3°C	6.515	0.903
Mean temperature of warmest quarter	22.8-27.7°C	9.3-32.5°C	4.443	0.520
Mean temperature of wettest quarter	24.8-26.5°C	3.8-32.5°C	6.825	0.756
Min temperature of coldest month	9.4-21.3°C	13.8-42.5°C	8.535	1.044
Precipitation of coldest quarter	140-351 mm	1-823 mm	7.318	1.267
Precipitation of driest month	35-111 mm	0-145 mm	8.907	1.736
Precipitation of driest quarter	119-365 mm	0-485 mm	9.715	1.685
Precipitation of warmest quarter	306-1475 mm	3-1475 mm	6.847	1.138
Precipitation of wettest month	201-819 mm	9-819 mm	7.830	1.295
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	7.702	1.276
Precipitation seasonality	52-109	29-129	2.951	0.439
Slope	3.43-20.47°	0-34.12°	5.146	0.497
Soil type	Vertisol, Rendzina, Regosol, Ranker, Gleysol, Cambisol		3.876	0.942
Temperature annual range	12.1-23.8°C	12.1-39.4°C	8.910	1.029
Temperature seasonality	379-4011	379-9348	10.590	1.155

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zoque, Zapoteco, Tsotsil, Tsetsal, Totonaco, Tojolobal, Qeqchi, Qanjobal, Popoloca, Otomí, Náhuatl, Mixteco, Mam, Kiche, Kaqchikel, Jakalteko, Huasteco, Chuj, Chol, Chichimeco, Chatino, Amuzgo, Akateko		8.500	2.325
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	10.976	0.924

Olotón

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-3270 m.a.s.l.	0-5500 m.a.s.l.	6.429	0.870
Annual mean temperature	14.5-24.5°C	7.8-29.1°C	6.821	1.194
Annual precipitation	745-4517 mm	55-4517 mm	5.899	1.278
Isothermality	57-76	38-85	7.727	1.151
Max temperature of warmest month	13.8-42.5°C	13.8-42.5°C	7.635	1.536
Mean diurnal range	120-141	60-205	5.362	0.843
Mean temperature of coldest quarter	11.5-21.6°C	3.2-28.2°C	4.988	0.820
Mean temperature of driest quarter	11.2-24.3°C	4.6-29.3°C	4.494	0.764
Mean temperature of warmest quarter	9.3-27.7°C	9.3-32.5°C	5.831	1.244
Mean temperature of wettest quarter	14.1-22.7°C	3.8-32.5°C	5.919	1.093
Min temperature of coldest month	4.7-14.6°C	13.8-42.5°C	6.711	1.000
Precipitation of coldest quarter	140-351 mm	1-823 mm	4.863	1.563
Precipitation of driest month	6-57 mm	0-145 mm	3.231	1.154
Precipitation of driest quarter	36-208 mm	0-485 mm	3.753	1.197
Precipitation of warmest quarter	382-677 mm	3-1475 mm	5.423	1.333
Precipitation of wettest month	201-819 mm	9-819 mm	4.545	1.504
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	5.266	1.631
Precipitation seasonality	71-87	29-129	4.513	0.994
Slope	3.43-34.12°	0-34.12°	7.118	1.357
Soil type	Ranker, Gleysol, Castañozem, Regosol, Feozem, Cambisol, Acrisol		5.900	1.603
Temperature annual range	16.7-26.1°C	12.1-39.4°C	7.740	1.104
Temperature seasonality	379-2932	379-9348	10.297	1.392

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tsotsil, Tsetsal, Triqui de la Baja, Tojolabal, Teko, Qanjobal, Mixteco Mixe, Mazateco, Mam, Cuicateco, Chuj, Chatino, Mayo, Huave, Cora		10.848	3.091
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	7.115	0.754

Onaveño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1040 m.a.s.l.	0-5500 m.a.s.l.	5.290	0.789
Annual mean temperature	21.1-24.5°C	7.8-29.1°C	4.373	1.020
Annual precipitation	517-1980 mm	55-4517 mm	2.756	0.812
Isothermality	53-56	38-85	2.943	0.829
Max temperature of warmest month	36.3-42.5°C	13.8-42.5°C	7.648	1.605
Mean diurnal range	174-183	60-205	2.015	0.600
Mean temperature of coldest quarter	17.2-21.6°C	3.2-28.2°C	4.675	1.167
Mean temperature of driest quarter	20.3-24.3°C	4.6-29.3°C	5.584	1.154
Mean temperature of warmest quarter	26.1-32.5°C	9.3-32.5°C	4.020	0.943
Mean temperature of wettest quarter	26.6-32.5°C	3.8-32.5°C	4.882	1.061
Min temperature of coldest month	6.9-14.6°C	13.8-42.5°C	3.142	0.882
Precipitation of coldest quarter	66-139 mm	1-823 mm	3.203	0.805
Precipitation of driest month	0-5 mm	0-145 mm	4.501	0.640
Precipitation of driest quarter	0-35 mm	0-485 mm	2.770	0.518
Precipitation of warmest quarter	306-1475 mm	3-1475 mm	3.390	1.182
Precipitation of wettest month	201-304 mm	9-819 mm	2.860	0.795
Precipitation of wettest quarter	525-800 mm	21-2187 mm	2.847	0.797
Precipitation seasonality	96-129	29-129	4.329	1.151
Slope	3.43-17.06°	0-34.12°	2.797	0.510
Soil type	Fluvisol, Cambisol		5.457	1.720
Temperature annual range	18.9-21.3°C	12.1-39.4°C	4.038	1.036
Temperature seasonality	1280-6015	379-9348	2.955	0.715

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Yaqui, Mayo, Huave, Guarijo, Cora		5.524	2.446
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	3.847	0.630

Palomero Toluqueño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	2156-3827 m.a.s.l.	0-5500 m.a.s.l.	11.585	11.585
Annual mean temperature	7.8-14.4°C	7.8-29.1°C	10.670	10.670
Annual precipitation	745-1226 mm	55-4517 mm	4.645	4.645
Isothermality	65-72	38-85	6.367	6.367
Max temperature of warmest month	13.8-27.1°C	13.8-42.5°C	13.310	13.310
Mean diurnal range	142-163	60-205	3.623	3.623
Mean temperature of coldest quarter	9.4-11.4°C	3.2-28.2°C	8.905	1.800
Mean temperature of driest quarter	4.6-12.8°C	4.6-29.3°C	10.302	10.302
Mean temperature of warmest quarter	9.3-19.2°C	9.3-32.5°C	13.965	13.965
Mean temperature of wettest quarter	10.7-16.5°C	3.8-32.5°C	11.875	11.875
Min temperature of coldest month	0-4.6°C	13.8-42.5°C	5.333	5.333
Precipitation of driest month	6-89 mm	0-145 mm	3.933	3.933
Precipitation of driest quarter	19-365 mm	0-485 mm	2.954	2.954
Precipitation of warmest quarter	234-305 mm	3-1475 mm	6.265	1.339
Precipitation of wettest month	154-247 mm	9-819 mm	3.925	3.925
Precipitation of wettest quarter	398-648 mm	21-2187 mm	4.065	4.065
Precipitation seasonality	80-95	29-129	3.612	3.612
Slope	3.43-10.24°	0-34.12°	2.237	2.237
Soil type	Planosol, Gleysol, Feozem, Chernozem		5.353	5.353
Temperature annual range	18.9-23.8°C	12.1-39.4°C	5.753	5.753
Temperature seasonality	1280-2021	379-9348	9.785	1.767

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tlahuica, Pima, Otomí, Náhuatl, Mazahua		8.573	8.573
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	7.276	7.276

Pepitilla

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3827 m.a.s.l.	0-5500 m.a.s.l.	5.374	0.977
Annual mean temperature	19.3-24.5°C	7.8-29.1°C	3.397	0.623
Annual precipitation	745-1226 mm	55-4517 mm	11.133	1.360
Isothermality	65-85	38-85	6.744	1.280
Max temperature of warmest month	25.1-32.7°C	13.8-42.5°C	2.407	0.542
Mean diurnal range	142-163	60-205	4.507	0.735
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	6.206	0.965
Mean temperature of driest quarter	18.2-22.3°C	4.6-29.3°C	6.082	0.958
Mean temperature of warmest quarter	19.3-24.4°C	9.3-32.5°C	3.387	0.660
Mean temperature of wettest quarter	16.6-24.7°C	3.8-32.5°C	3.628	0.658
Min temperature of coldest month	9.4-14.6°C	13.8-42.5°C	10.119	1.473
Precipitation of coldest quarter	1-39 mm	1-823 mm	10.104	0.925
Precipitation of driest month	0-5 mm	0-145 mm	5.581	0.551
Precipitation of driest quarter	0-35 mm	0-485 mm	4.338	0.536
Precipitation of warmest quarter	234-381 mm	3-1475 mm	6.364	0.906
Precipitation of wettest month	154-304 mm	9-819 mm	7.661	1.032
Precipitation of wettest quarter	398-800 mm	21-2187 mm	8.085	1.138
Precipitation seasonality	96-109	29-129	9.808	1.263
Slope	3.43-17.06°	0-34.12°	6.047	0.656
Soil type	Vertisol, Regosol, Feozem, Chernozem		3.662	0.880
Temperature annual range	18.9-26.1°C	12.1-39.4°C	7.986	1.148
Temperature seasonality	379-2932	379-9348	7.490	0.998

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tlahuica, Purepecha, Mixteco, Mazahua, Chatino		4.722	2.192
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	8.521	1.014

Ratón

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1040 m.a.s.l.	0-5500 m.a.s.l.	2.175	0.204
Annual mean temperature	19.3-24.5°C	7.8-29.1°C	4.776	0.614
Annual precipitation	307-981 mm	55-4517 mm	3.374	0.442
Isothermality	38-56	38-85	5.698	0.830
Max temperature of warmest month	30.9-38.2°C	13.8-42.5°C	3.116	0.410
Mean diurnal range	60-141	60-205	3.448	0.634
Mean temperature of coldest quarter	13.3-19.2°C	3.2-28.2°C	4.893	0.612
Mean temperature of driest quarter	12.9-20.2°C	4.6-29.3°C	5.183	0.636
Mean temperature of warmest quarter	21-32.5°C	9.3-32.5°C	3.062	0.457
Mean temperature of wettest quarter	20.7-28.5°C	3.8-32.5°C	3.668	0.465
Min temperature of coldest month	4.7-14.6°C	13.8-42.5°C	3.366	0.499
Precipitation of coldest quarter	40-65 mm	1-823 mm	5.905	0.560
Precipitation of driest month	6-22 mm	0-145 mm	7.687	0.792
Precipitation of driest quarter	36-85 mm	0-485 mm	9.094	1.046
Precipitation of warmest quarter	165-305 mm	3-1475 mm	3.883	0.450
Precipitation of wettest month	58-153 mm	9-819 mm	5.281	0.566
Precipitation of wettest quarter	143-397 mm	21-2187 mm	6.119	0.626
Precipitation seasonality	56-129	29-129	5.490	0.792
Soil type	Xerosol, Vertisol, Feozem		5.042	0.670
Temperature annual range	23.9-33.0°C	12.1-39.4°C	3.952	0.534
Temperature seasonality	2933-6015	379-9348	5.292	0.619

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Totonaco, Tarahumara, Náhuatl, Huasteco		2.744	0.971
Education	unfinished elementary-Finished high- school	unfinished elementary school-bachelor or higher degree	8.069	0.752

Reventador

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1597 m.a.s.l.	0-5500 m.a.s.l.	3.952	0.662
Annual mean temperature	22.9-26.3°C	7.8-29.1°C	3.357	0.881
Annual precipitation	745-1226 mm	55-4517 mm	3.573	0.907
Isothermality	65-72	38-85	2.241	0.709
Max temperature of warmest month	30.9-42.5°C	13.8-42.5°C	3.297	1.062
Mean diurnal range	120-130	60-205	5.961	1.384
Mean temperature of coldest quarter	17.2-21.6°C	3.2-28.2°C	3.969	1.076
Mean temperature of driest quarter	18.2-24.3°C	4.6-29.3°C	4.040	0.945
Mean temperature of warmest quarter	26.1-29.3°C	9.3-32.5°C	2.396	0.621
Mean temperature of wettest quarter	26.6-28.5°C	3.8-32.5°C	3.520	0.736
Min temperature of coldest month	6.9-16.8°C	13.8-42.5°C	3.778	1.046
Precipitation of coldest quarter	66-99 mm	1-823 mm	2.535	0.718
Precipitation of driest month	0-5 mm	0-145 mm	4.860	0.719
Precipitation of driest quarter	0-18 mm	0-485 mm	3.596	0.647
Precipitation of warmest quarter	382-1475 mm	3-1475 mm	5.097	1.570
Precipitation of wettest month	201-461 mm	9-819 mm	3.909	1.124
Precipitation of wettest quarter	525-1222 mm	21-2187 mm	3.949	1.173
Precipitation seasonality	96-129	29-129	4.426	1.204
Slope	3.43-20.47°	0-34.12°	3.987	0.800
Soil type	Fluvisol, Cambisol, Acrisol		3.248	1.550
Temperature annual range	16.7-21.3°C	12.1-39.4°C	3.251	0.924
Temperature seasonality	1280-2021	379-9348	5.733	1.185

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Mayo, Huave, Cora		5.445	2.432
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	4.504	0.746

Serrano Mixe

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-3270 m.a.s.l.	0-5500 m.a.s.l.	6.506	1.562
Annual mean temperature	12.6-16.0°C	7.8-29.1°C	5.121	1.819
Annual precipitation	1227-2526 mm	55-4517 mm	4.906	2.009
Isothermality	69-76	38-85	7.934	2.402
Max temperature of warmest month	13.8-27.1°C	13.8-42.5°C	8.858	2.921
Mean diurnal range	109-119	60-205	4.351	1.727
Mean temperature of coldest quarter	13.3-15.1°C	3.2-28.2°C	4.115	1.352
Mean temperature of driest quarter	12.9-16.2°C	4.6-29.3°C	3.737	1.363
Mean temperature of warmest quarter	9.3-19.2°C	9.3-32.5°C	7.497	2.457
Mean temperature of wettest quarter	10.7-16.5°C	3.8-32.5°C	7.503	2.446
Min temperature of coldest month	4.7-9.3°C	13.8-42.5°C	3.823	1.332
Precipitation of coldest quarter	140-269 mm	1-823 mm	5.564	2.226
Precipitation of driest month	13-71 mm	0-145 mm	2.916	1.702
Precipitation of driest quarter	58-159 mm	0-485 mm	3.357	1.627
Precipitation of warmest quarter	306-556 mm	3-1475 mm	2.661	1.208
Precipitation of wettest month	248-461 mm	9-819 mm	3.749	1.701
Precipitation of wettest quarter	801-1222 mm	21-2187 mm	5.254	2.090
Precipitation seasonality	80-87	29-129	5.776	1.712
Slope	3.43-27.29°	0-34.12°	6.014	1.743
Soil type	Gleysol, Chernozem, Castañozem, Acrisol		4.958	2.708
Temperature annual range	16.7-21.3°C	12.1-39.4°C	3.919	1.463
Temperature seasonality	379-2021	379-9348	7.151	2.097

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Triquie de la Baja, Mixteco, Mixe, Cuicateco, Chichimeco		9.618	3.656
Education	finished -finished elementary school	unfinished elementary school-bachelor or higher degree	2.939	0.768

Tablilla de Ocho

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	5.365	1.038
Annual mean temperature	12.6-17.5°C	7.8-29.1°C	3.096	1.051
Annual precipitation	517-981 mm	55-4517 mm	3.482	0.949
Isothermality	53-64	38-85	4.479	1.155
Max temperature of warmest month	29.1-32.7°C	13.8-42.5°C	4.569	1.155
Mean diurnal range	164-183	60-205	3.314	0.945
Mean temperature of coldest quarter	3.2-7.1°C	3.2-28.2°C	2.772	1.297
Mean temperature of driest quarter	4.6-11.1°C	4.6-29.3°C	2.260	1.080
Mean temperature of warmest quarter	19.3-22.7°C	9.3-32.5°C	4.919	1.325
Mean temperature of wettest quarter	18.7-22.7°C	3.8-32.5°C	5.168	1.277
Min temperature of coldest month	-6.1-4.6°C	13.8-42.5°C	2.838	1.120
Precipitation of coldest quarter	40-65 mm	1-823 mm	3.583	0.823
Precipitation of driest month	0-5 mm	0-145 mm	2.310	0.468
Precipitation of warmest quarter	234-305 mm	3-1475 mm	2.794	0.788
Precipitation of wettest month	104-247 mm	9-819 mm	3.026	0.882
Precipitation of wettest quarter	262-648 mm	21-2187 mm	2.911	0.861
Precipitation seasonality	103-109	29-129	4.974	1.338
Slope	3.43-20.47°	0-34.12°	2.720	0.695
Soil type	Feozem, Chernozem, Castañozem, Cambisol		3.960	1.713
Temperature annual range	23.9-33.0°C	12.1-39.4°C	2.779	0.871
Temperature seasonality	2933-4011	379-9348	3.138	0.879

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tarahumara, Pima, Huave, Cora		5.008	2.519
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	3.446	0.846

Tabloncillo

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-2155 m.a.s.l.	0-5500 m.a.s.l.	5.74803	0.46777
Annual mean temperature	22.9-24.5°C	7.8-29.1°C	10.9147	1.1342
Annual precipitation	745-1536 mm	55-4517 mm	8.72433	0.93881
Isothermality	57-68	38-85	6.10397	0.65821
Max temperature of warmest month	29.1-42.5°C	13.8-42.5°C	4.26506	0.5854
Mean diurnal range	131-163	60-205	4.18872	0.50543
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	7.84686	0.92848
Mean temperature of driest quarter	18.2-24.3°C	4.6-29.3°C	5.9273	0.70054
Mean temperature of warmest quarter	19.3-27.7°C	9.3-32.5°C	3.79705	0.50594
Mean temperature of wettest quarter	18.7-22.7°C	3.8-32.5°C	5.07548	0.64237
Min temperature of coldest month	6.9-14.6°C	13.8-42.5°C	7.8807	0.96673
Precipitation of coldest quarter	40-99 mm	1-823 mm	6.02111	0.63743
Precipitation of driest month	0-12 mm	0-145 mm	4.62886	0.38921
Precipitation of driest quarter	19-35 mm	0-485 mm	9.1793	0.74108
Precipitation of warmest quarter	306-1475 mm	3-1475 mm	7.28865	1.24919
Precipitation of wettest month	154-376 mm	9-819 mm	7.77915	0.94343
Precipitation of wettest quarter	398-1222 mm	21-2187 mm	6.77994	0.91972
Precipitation seasonality	88-129	29-129	9.68224	1.10531
Slope	3.43-20.47°	0-34.12°	6.70133	0.57867
Soil type	Regosol, Feozem, Castañozem, Cambisol, Acrisol		5.41838	1.02461
Temperature annual range	18.9-26.1°C	12.1-39.4°C	7.65554	0.88981
Temperature seasonality	1280-2932	379-9348	7.92559	0.78367

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Mayo, Huave, Cora		7.30391	1.8638
Education	unfinished elementary -finished high-school	unfinished elementary school-bachelor or higher degree	8.66673	0.76092

Tabloncillo Perla

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-3827m.a.s.l.	0-5500 m.a.s.l.	5.515	0.786
Annual mean temperature	19.3-24.5°C	7.8-29.1°C	5.276	0.750
Annual precipitation	745-1536 mm	55-4517 mm	8.724	0.939
Isothermality	61-85	38-85	6.470	1.013
Max temperature of warmest month	25.1-42.5°C	13.8-42.5°C	3.469	0.583
Mean diurnal range	131-163	60-205	4.316	0.597
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	7.847	0.928
Mean temperature of driest quarter	18.2-24.3°C	4.6-29.3°C	5.927	0.701
Mean temperature of warmest quarter	19.3-27.7°C	9.3-32.5°C	3.797	0.506
Mean temperature of wettest quarter	18.7-22.7°C	3.8-32.5°C	5.075	0.642
Min temperature of coldest month	6.9-14.6°C	13.8-42.5°C	7.881	0.967
Precipitation of coldest quarter	40-99 mm	1-823 mm	6.021	0.637
Precipitation of driest month	0-12 mm	0-145 mm	4.629	0.389
Precipitation of driest quarter	19-35 mm	0-485 mm	9.179	0.741
Precipitation of warmest quarter	306-1475 mm	3-1475 mm	7.289	1.249
Precipitation of wettest month	154-376 mm	9-819 mm	7.779	0.943
Precipitation of wettest quarter	398-1222 mm	21-2187 mm	6.780	0.920
Precipitation seasonality	88-129	29-129	9.682	1.105
Slope	3.43-20.47°	0-34.12°	6.410	0.613
Soil type	Regosol, Feozem, Castañozem, Cambisol, Acrisol, Vertisol, Regosol,		4.638	0.960
Temperature annual range	18.9-26.1°C	12.1-39.4°C	7.656	0.890
Temperature seasonality	379-2932	379-9348	7.664	0.912

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Mayo, Huave, Cora, Zapoteco, Tlahuica, Purepecha, Mixteco, Mazahua		5.583	2.083
Education	unfinished elementary school-finished highschool	unfinished elementary school-bachelor or higher degree	8.594	0.887

Tehua

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-2155 m.a.s.l.	0-5500 m.a.s.l.	3.349	0.861
Annual precipitation	982-4517 mm	55-4517 mm	3.906	1.760
Isothermality	62-76	38-85	7.904	2.123
Max temperature of warmest month	25.1-29.0°C	13.8-42.5°C	4.798	1.802
Mean diurnal range	120-141	60-205	4.345	1.459
Mean temperature of coldest quarter	15.2-21.6°C	3.2-28.2°C	3.616	1.345
Mean temperature of driest quarter	18.2-22.3°C	4.6-29.3°C	2.188	0.944
Mean temperature of warmest quarter	17.5-22.7°C	9.3-32.5°C	2.335	1.121
Mean temperature of wettest quarter	18.7-22.7°C	3.8-32.5°C	2.642	1.072
Min temperature of coldest month	9.4-14.6°C	13.8-42.5°C	4.669	1.633
Precipitation of coldest quarter	270-594 mm	1-823 mm	2.933	2.144
Precipitation of driest month	46-111 mm	0-145 mm	4.001	2.491
Precipitation of driest quarter	160-365 mm	0-485 mm	3.433	2.230
Precipitation of warmest quarter	306-677 mm	3-1475 mm	3.467	1.439
Precipitation of wettest month	248-461 mm	9-819 mm	4.305	1.741
Precipitation of wettest quarter	649-990 mm	21-2187 mm	5.976	1.891
Slope	6.84-23.88°	0-34.12°	4.773	1.417
Soil type	Luvisol, Gleysol		2.852	1.347
Temperature annual range	16.7-21.3°C	12.1-39.4°C	5.985	1.629
Temperature seasonality	379-2021	379-9348	6.346	1.937

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zoque, Tsotsil, Tsetsal, Tojolobal, Teko, Qanjobal, Mazateco, Mam		11.878	4.014
	Jakalteko, Cuicateco, Chuj, Chol		9.940	3.582
Education	finished elementary school	unfinished elementary school-bachelor or higher degree	3.667	0.840

Tepecintle

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-1597 m.a.s.l.	0-5500 m.a.s.l.	5.938	0.548
Annual mean temperature	22.9-29.1°C	7.8-29.1°C	7.938	1.213
Annual precipitation	982-4517 mm	55-4517 mm	10.516	1.740
Isothermality	65-85	38-85	9.359	1.540
Max temperature of warmest month	25.1-34.5°C	13.8-42.5°C	4.156	0.689
Mean diurnal range	60-152	60-205	5.575	1.003
Mean temperature of coldest quarter	17.2-28.2°C	3.2-28.2°C	8.482	1.261
Mean temperature of driest quarter	18.2-29.3°C	4.6-29.3°C	4.756	0.806
Mean temperature of warmest quarter	24.5-27.7°C	9.3-32.5°C	4.499	0.593
Mean temperature of wettest quarter	22.8-28.5°C	3.8-32.5°C	3.586	0.497
Min temperature of coldest month	9.4-21.3°C	13.8-42.5°C	8.616	1.219
Precipitation of coldest quarter	140-823 mm	1-823 mm	8.641	1.839
Precipitation of driest month	23-145 mm	0-145 mm	8.078	1.892
Precipitation of driest quarter	86-485 mm	0-485 mm	8.188	1.846
Precipitation of warmest quarter	306-859 mm	3-1475 mm	7.786	1.302
Precipitation of wettest month	201-819 mm	9-819 mm	28.734	3.760
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	10.661	1.678
Precipitation seasonality	56-109	29-129	2.725	0.493
Slope	3.43-34.12°	0-34.12°	5.895	1.211
Soil type	Rendzina, Ranker, Gleysol, Cambisol, Acrisol		4.789	1.529
Temperature annual range	12.1-21.3°C	12.1-39.4°C	10.339	1.292
Temperature seasonality	379-2932	379-9348	10.563	1.237

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zoque, Zapoteco, Tuzanteco, Tsotsil, Tsetsal, Triqui de la Baja, Tlapaneco, Tepehua, Teko, Qanjobal, Náhuatl, Mixteco, Mixe, Mazateco, Maya, Mam, Jakalteko, Huasteco, Cuicateco, Chol, Chichimeco, Chatino, Amuzgo		8.204	2.491
Education	unfinished elementary -unfinished high-school	unfinished elementary school-bachelor or higher degree	8.570	0.731

Tuxpeño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-1040 m.a.s.l.	0-5500 m.a.s.l.	11.759	0.547
Annual mean temperature	21.1-29.1°C	7.8-29.1°C	11.856	0.938
Annual precipitation	745-4517 mm	55-4517 mm	10.317	1.128
Isothermality	65-85	38-85	8.848	1.013
Max temperature of warmest month	30.9-36.2°C	13.8-42.5°C	5.934	0.397
Mean diurnal range	60-141	60-205	8.709	0.797
Mean temperature of coldest quarter	15.2-28.2°C	3.2-28.2°C	11.261	0.908
Mean temperature of driest quarter	18.2-26.2°C	4.6-29.3°C	7.351	0.646
Mean temperature of warmest quarter	22.8-29.3°C	9.3-32.5°C	8.250	0.526
Min temperature of coldest month	6.9-21.3°C	13.8-42.5°C	12.230	0.939
Precipitation of coldest quarter	100-823 mm	1-823 mm	4.966	0.839
Precipitation of driest month	13-145 mm	0-145 mm	8.368	1.371
Precipitation of driest quarter	86-159 mm	0-485 mm	8.694	1.335
Precipitation of warmest quarter	234-1475 mm	3-1475 mm	8.595	0.969
Precipitation of wettest month	154-819 mm	9-819 mm	9.713	1.107
Precipitation of wettest quarter	991-1501 mm	21-2187 mm	9.238	1.053
Precipitation seasonality	63-109	29-129	3.837	0.425
Slope	0-10.24°	0-34.12°	4.022	0.258
Soil type	Rendzina, Vertisol, Cambisol, Gleysol, Feozem, Ranker, Andosol, Nitosol, Acrisol		4.907	0.835
Temperature annual range	12.1-23.8°C	12.1-39.4°C	11.620	0.852
Temperature seasonality	379-2021	379-9348	11.486	0.889

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Tsetsal, Tsotsil,Maya, Totonaco, Náhuatl, Mam, Chichimeco, Zoque, Teko, Zapoteco, Huasteco, Chatino, Ayapaneco, Chol, Popoloca, Tojolabal, Pame, Jakalteko, Qanjobal, Mazateco, Huave, Oluteco, Tuzanteco, Amuzgo, Texistepequeño, Otomi		6.402	1.817
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	16.750	0.852

Tuxpeño Norteño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1041-2155 m.a.s.l.	0-5500 m.a.s.l.	4.034	0.442
Annual mean temperature	16.1-21.0°C	7.8-29.1°C	4.162	0.643
Annual precipitation	307-516 mm	55-4517 mm	7.316	2.655
Isothermality	49-56	38-85	4.597	0.741
Max temperature of warmest month	30.9-36.2°C	13.8-42.5°C	2.762	0.436
Mean diurnal range	131-183	60-205	3.556	0.607
Mean temperature of coldest quarter	9.4-15.1°C	3.2-28.2°C	3.884	0.615
Mean temperature of driest quarter	12.9-16.2°C	4.6-29.3°C	7.184	0.988
Mean temperature of warmest quarter	22.8-26.1°C	9.3-32.5°C	4.351	0.689
Mean temperature of wettest quarter	20.7-26.5°C	3.8-32.5°C	4.850	0.731
Min temperature of coldest month	0-6.8°C	13.8-42.5°C	3.473	0.568
Precipitation of coldest quarter	1-65 mm	1-823 mm	4.622	0.528
Precipitation of driest month	6-22 mm	0-145 mm	3.538	0.538
Precipitation of driest quarter	36-57 mm	0-485 mm	5.849	0.820
Precipitation of warmest quarter	88-305 mm	3-1475 mm	3.644	0.512
Precipitation of wettest month	58-153 mm	9-819 mm	6.504	0.814
Precipitation of wettest quarter	143-397 mm	21-2187 mm	6.875	0.828
Precipitation seasonality	63-129	29-129	3.926	0.769
Soil type	Xerosol, Vertisol		8.582	1.086
Temperature annual range	23.9-35.9°C	12.1-39.4°C	3.395	0.592
Temperature seasonality	2933-7487	379-9348	3.737	0.644

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Pame, Kickapo		4.326	2.145
Education	finished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	6.978	0.895

Vandeño

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1597 m.a.s.l.	0-5500 m.a.s.l.	7.538	0.674
Annual mean temperature	21.1-29.1°C	7.8-29.1°C	6.919	1.052
Annual precipitation	745-3194 mm	55-4517 mm	5.749	1.015
Isothermality	65-85	38-85	9.224	1.551
Max temperature of warmest month	32.8-42.5°C	13.8-42.5°C	5.112	0.910
Mean diurnal range	120-163	60-205	3.564	0.563
Mean temperature of coldest quarter	17.2-28.2°C	3.2-28.2°C	9.034	1.297
Mean temperature of driest quarter	20.3-29.3°C	4.6-29.3°C	6.443	0.980
Mean temperature of warmest quarter	22.8-29.3°C	9.3-32.5°C	2.534	0.411
Mean temperature of wettest quarter	20.7-26.5°C	3.8-32.5°C	3.851	0.577
Min temperature of coldest month	9.4-21.3°C	13.8-42.5°C	7.667	1.137
Precipitation of coldest quarter	1-451 mm	1-823 mm	3.965	0.854
Precipitation of driest month	0-111 mm	0-145 mm	3.590	1.034
Precipitation of driest quarter	0-365 mm	0-485 mm	3.897	1.024
Precipitation of warmest quarter	234-1475 mm	3-1475 mm	3.681	0.841
Precipitation of wettest month	201-819 mm	9-819 mm	5.407	1.158
Precipitation of wettest quarter	525-2187 mm	21-2187 mm	5.892	1.192
Precipitation seasonality	96-129	29-129	7.500	1.066
Slope	0-17.06°	0-34.12°	5.074	0.545
Soil type	Regosol, Ranker, Gleysol, Cambisol, Acrisol		3.249	1.136
Temperature annual range	12.1-23.8°C	12.1-39.4°C	6.175	0.917
Temperature seasonality	379-2021	379-9348	13.816	1.643

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tsotsil, Tsetsal, Triqui de la Baja, Tojolabal, Tlapaneco		3.331	1.668
	Teko, Mixe, Huave, Chol, Chichimeco, Chatino, Amuzgo			
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	8.733	0.930

Zamorano

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	1598-2712 m.a.s.l.	0-5500 m.a.s.l.	5.664	0.938
Annual mean temperature	16.1-19.2°C	7.8-29.1°C	5.224	1.101
Annual precipitation	745-1226 mm	55-4517 mm	6.245	1.155
Isothermality	61-64	38-85	11.121	1.612
Max temperature of warmest month	27.2-32.7°C	13.8-42.5°C	4.130	1.001
Mean diurnal range	153-173	60-205	4.597	0.990
Mean temperature of coldest quarter	13.3-15.1°C	3.2-28.2°C	9.122	1.482
Mean temperature of driest quarter	16.3-18.1°C	4.6-29.3°C	8.692	1.506
Mean temperature of warmest quarter	19.3-22.7°C	9.3-32.5°C	6.890	1.413
Mean temperature of wettest quarter	16.6-22.7°C	3.8-32.5°C	4.931	1.126
Min temperature of coldest month	2.5-6.8°C	13.8-42.5°C	5.940	1.129
Precipitation of coldest quarter	1-39 mm	1-823 mm	5.094	0.797
Precipitation of driest month	6-12 mm	0-145 mm	4.534	0.835
Precipitation of driest quarter	19-35 mm	0-485 mm	8.201	1.185
Precipitation of warmest quarter	165-233 mm	3-1475 mm	3.586	0.852
Precipitation of wettest month	201-247 mm	9-819 mm	10.176	1.647
Precipitation of wettest quarter	525-648 mm	21-2187 mm	6.005	1.219
Precipitation seasonality	96-109	29-129	6.778	1.273
Slope	3.43-10.24°	0-34.12°	2.539	0.412
Soil type	Cambisol, Planosol, Vertisol, Feozem		4.677	1.395
Temperature annual range	23.9-26.1°C	12.1-39.4°C	9.978	1.620
Temperature seasonality	2022-2932	379-9348	11.991	1.632

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Purepecha		22.578	4.110
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	5.357	0.962

Zapalote Chico

Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	0-1040 m.a.s.l.	0-5500 m.a.s.l.	4.108	0.720
Annual mean temperature	24.6-29.1°C	7.8-29.1°C	10.720	1.930
Annual precipitation	745-2526 mm	55-4517 mm	4.052	1.335
Isothermality	65-85	38-85	4.774	1.520
Max temperature of warmest month	34.6-36.2°C	13.8-42.5°C	4.993	1.023
Mean diurnal range	60-130	60-205	4.649	1.471
Mean temperature of coldest quarter	19.3-28.2°C	3.2-28.2°C	8.324	1.540
Mean temperature of driest quarter	24.4-29.3°C	4.6-29.3°C	5.959	1.432
Mean temperature of warmest quarter	27.8-29.3°C	9.3-32.5°C	5.574	1.131
Mean temperature of wettest quarter	26.6-28.5°C	3.8-32.5°C	4.785	0.926
Min temperature of coldest month	14.7-21.3°C	13.8-42.5°C	7.929	1.549
Precipitation of coldest quarter	1-39 mm	1-823 mm	4.395	0.749
Precipitation of driest month	0-5 mm	0-145 mm	2.627	0.461
Precipitation of driest quarter	0-18 mm	0-485 mm	4.215	0.742
Precipitation of warmest quarter	234-464 mm	3-1475 mm	4.173	1.012
Precipitation of wettest month	201-461 mm	9-819 mm	3.467	1.177
Precipitation of wettest quarter	398-1222 mm	21-2187 mm	3.274	1.043
Precipitation seasonality	103-129	29-129	7.316	1.737
Slope	6.84-10.24°	0-34.12°	4.608	1.810
Soil type	Ranker, Cambisol		5.064	3.378
Temperature annual range	12.1-21.3°C	12.1-39.4°C	6.663	1.433
Temperature seasonality	379-2021	379-9348	9.260	1.836

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tsetsal, Triqui de la Baja, Qajobal, Mixteco, Mam, Jakalteko		7.659	2.657
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	3.554	0.783

Zapalote Grande

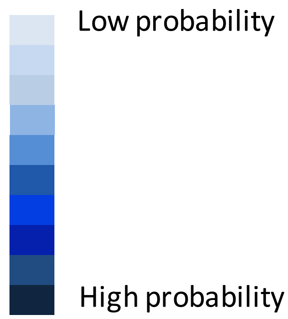
Environmental Factors

Factor	Scale	Range	Epsilon	Score
Altitude	483-1040 m.a.s.l.	0-5500 m.a.s.l.	3.786	0.649
Annual mean temperature	22.9-29.1°C	7.8-29.1°C	5.278	1.363
Annual precipitation	982-4517 mm	55-4517 mm	3.603	1.377
Isothermality	69-85	38-85	8.932	2.174
Max temperature of warmest month	32.8-36.2°C	13.8-42.5°C	2.728	0.627
Mean diurnal range	98-152	60-205	3.114	0.906
Mean temperature of coldest quarter	19.3-28.2°C	3.2-28.2°C	6.313	1.486
Mean temperature of driest quarter	20.3-26.2°C	4.6-29.3°C	4.134	1.153
Mean temperature of warmest quarter	24.5-26.1°C	9.3-32.5°C	2.499	0.658
Mean temperature of wettest quarter	22.8-28.5°C	3.8-32.5°C	2.101	0.533
Min temperature of coldest month	12.1-21.3°C	13.8-42.5°C	5.887	1.421
Precipitation of coldest quarter	1-451 mm	1-823 mm	3.896	1.350
Precipitation of driest month	46-111 mm	0-145 mm	2.399	1.688
Precipitation of driest quarter	0-365 mm	0-485 mm	2.696	1.252
Precipitation of warmest quarter	306-556 mm	3-1475 mm	2.649	0.883
Precipitation of wettest month	248-571 mm	9-819 mm	4.368	1.461
Precipitation of wettest quarter	649-1501 mm	21-2187 mm	4.418	1.462
Precipitation seasonality	96-109	29-129	3.193	0.864
Slope	0-23.88°	0-34.12°	2.515	0.687
Soil type	Cambisol, Ranker, Histosol, Regosol		4.187	1.962
Temperature annual range	12.1-21.3°C	12.1-39.4°C	6.083	1.378
Temperature seasonality	379-2021	379-9348	11.635	1.927

Social Factors

Factor	Scale	Range	Epsilon	Score
Ethnic group	Zapoteco, Tsetsal, Qanjobal, Chuj, Tojolobal, Mam, Sayulteco		7.007	2.863
Education	unfinished elementary-finished high-school	unfinished elementary school-bachelor or higher degree	4.827	0.932

Appendix 3. Probability distribution maps of Mexican races taking into account all variables evaluated: altitude, climate, slope, soil, ethnic group and schooling.



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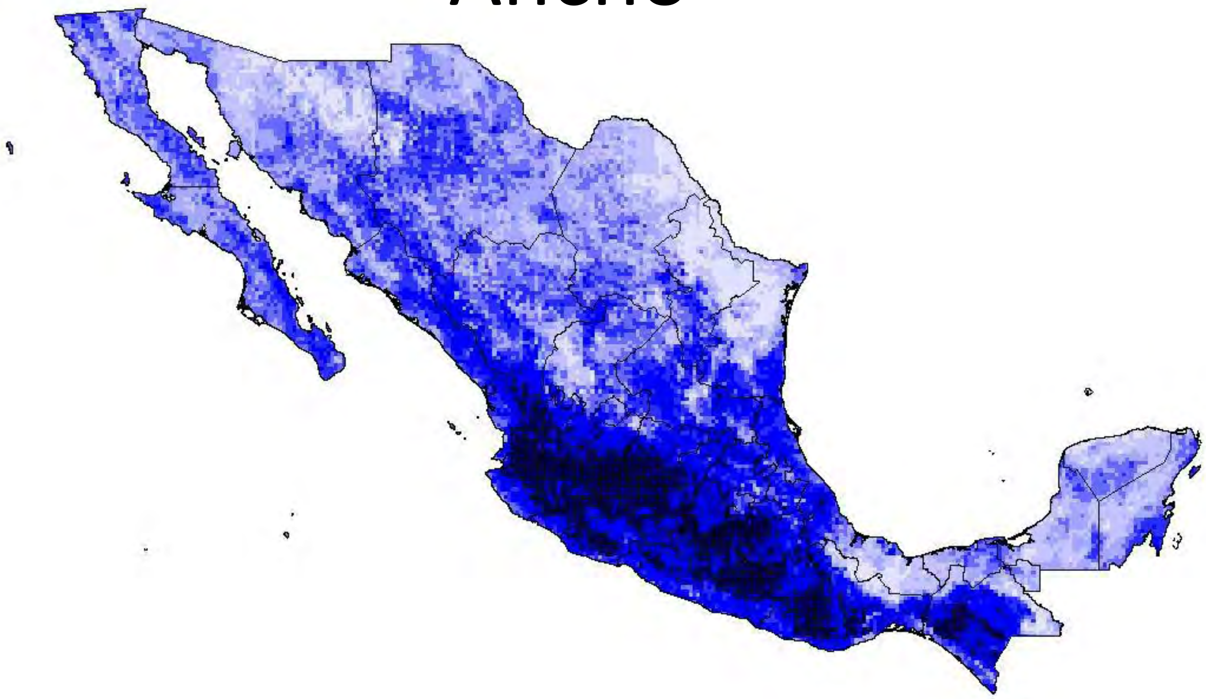

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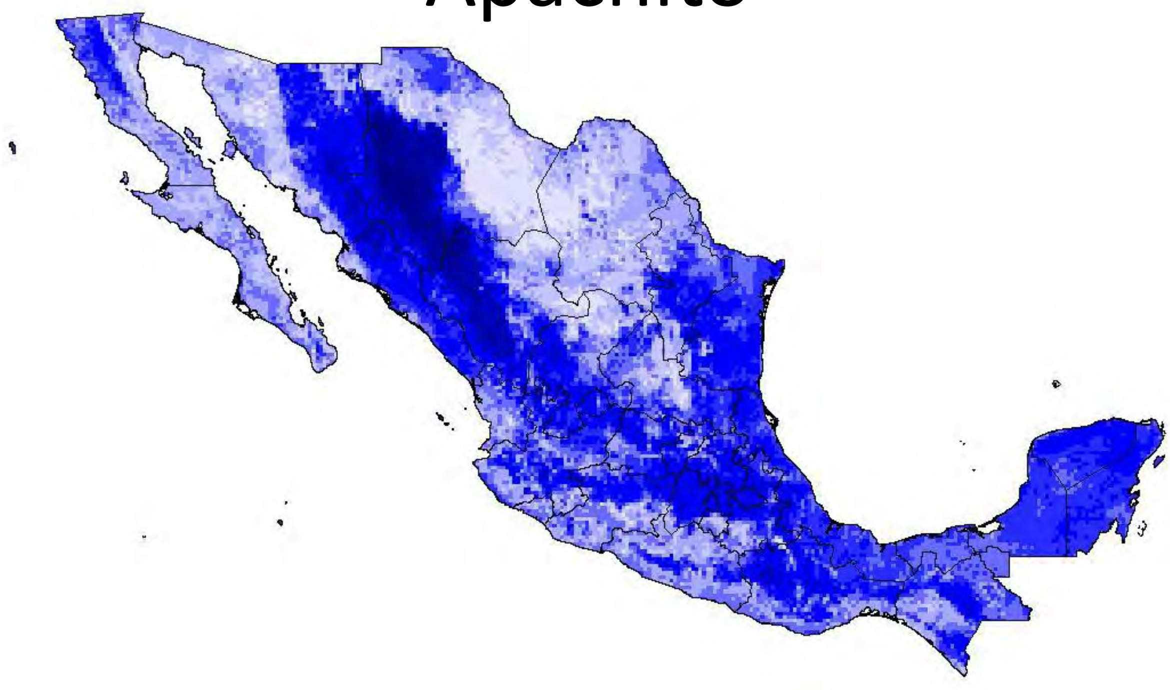

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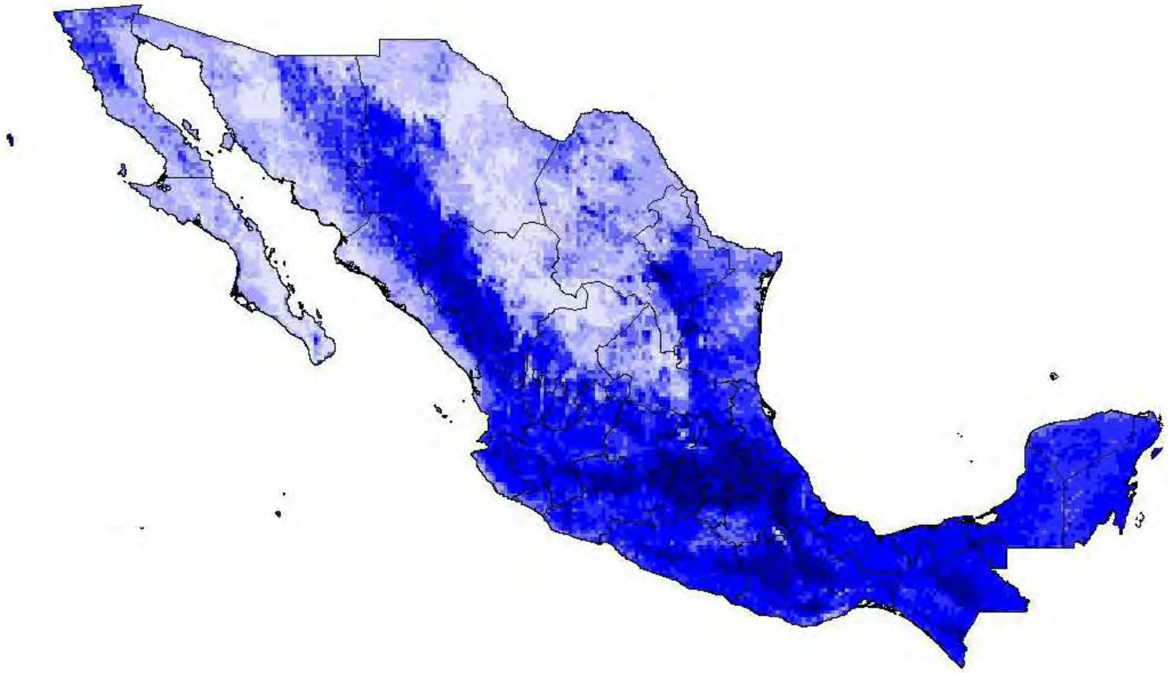

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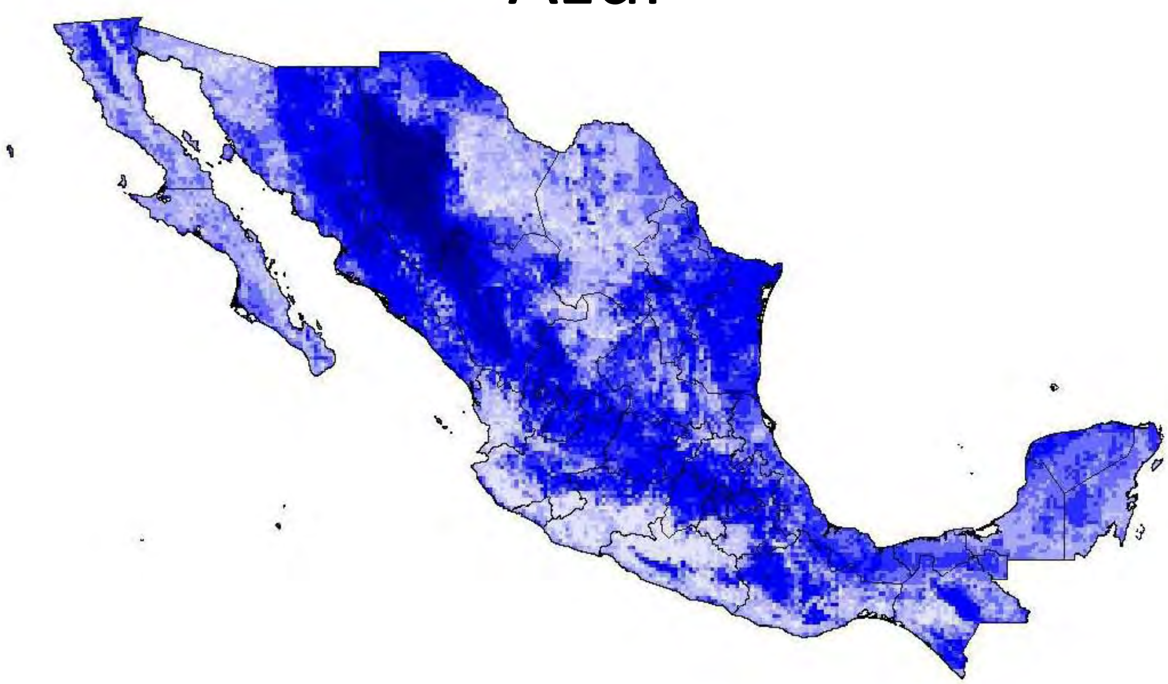
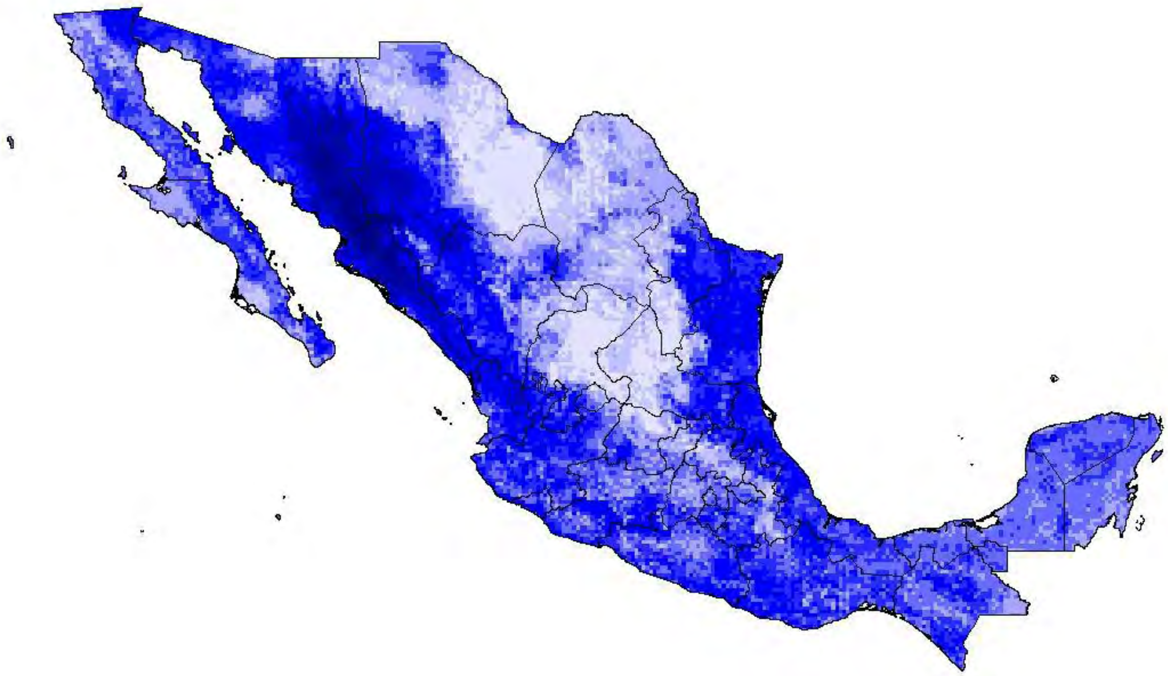
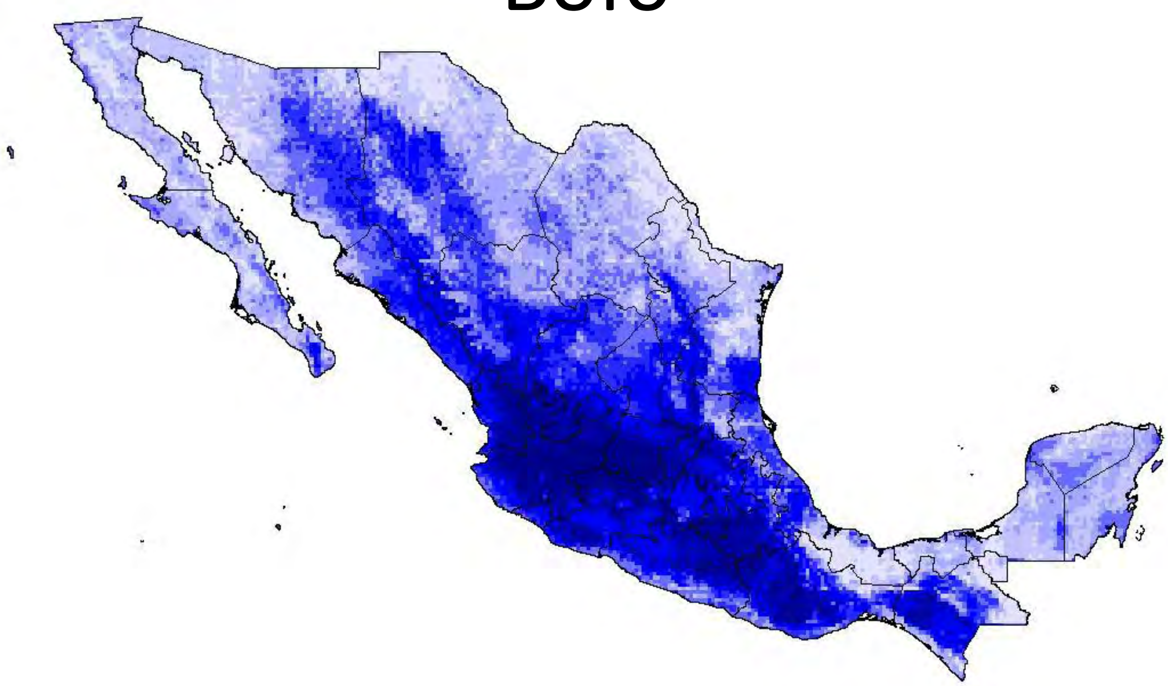


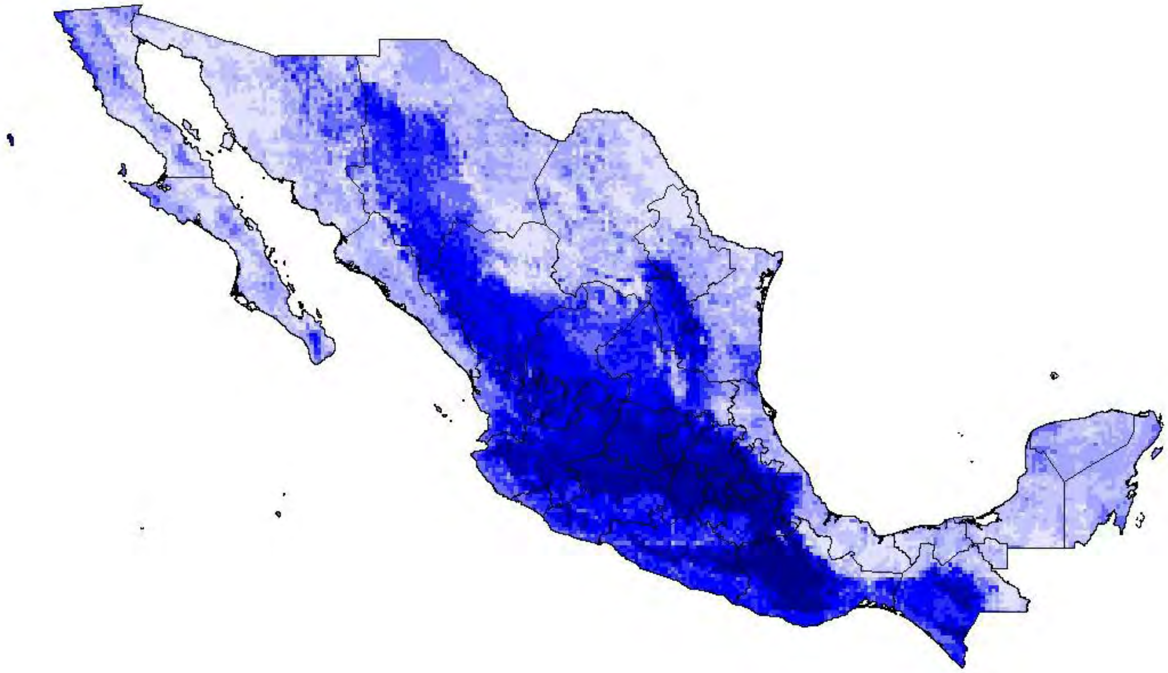
Blando de Sonora



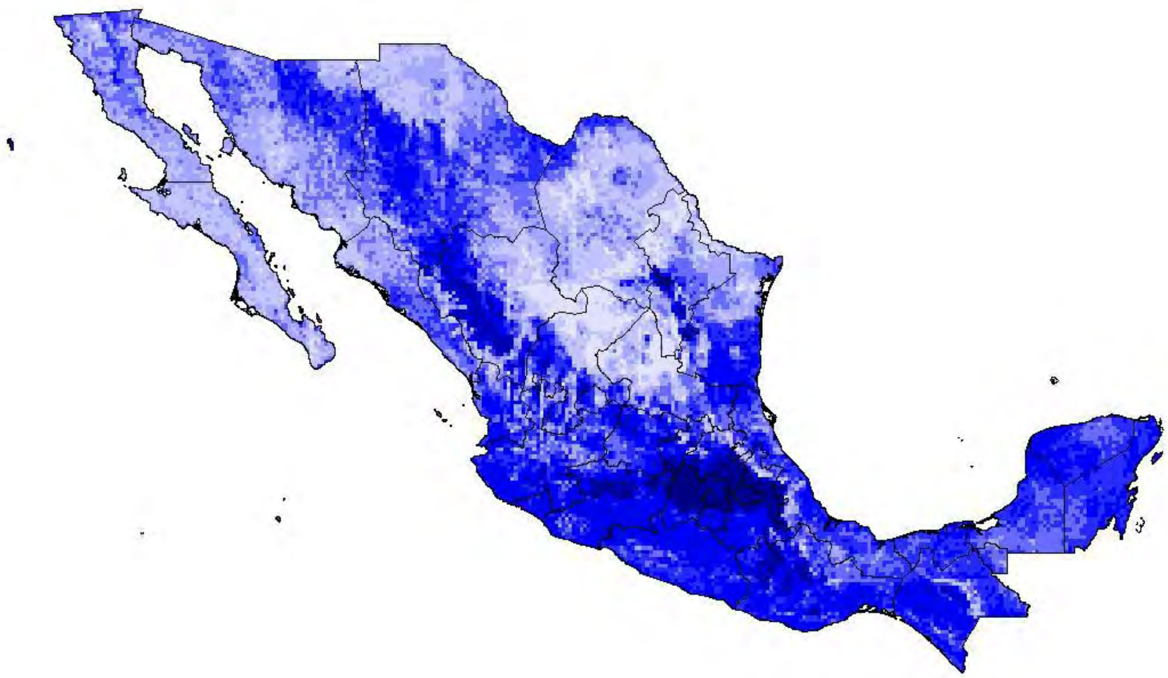
Bofo



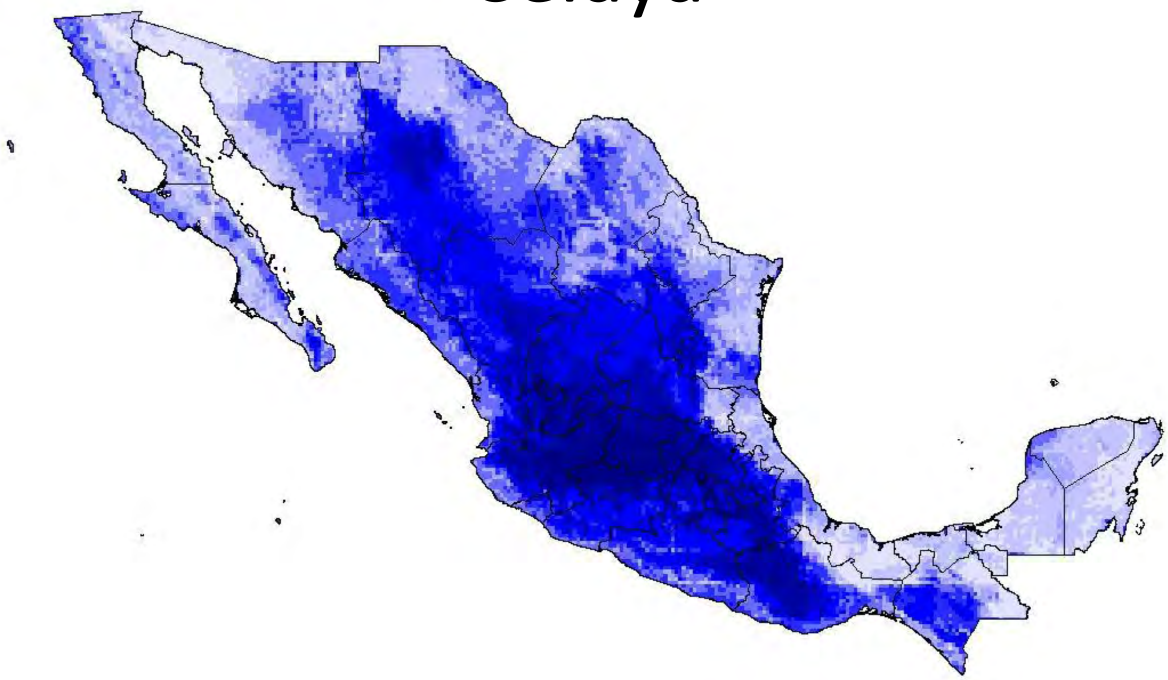
Bolita



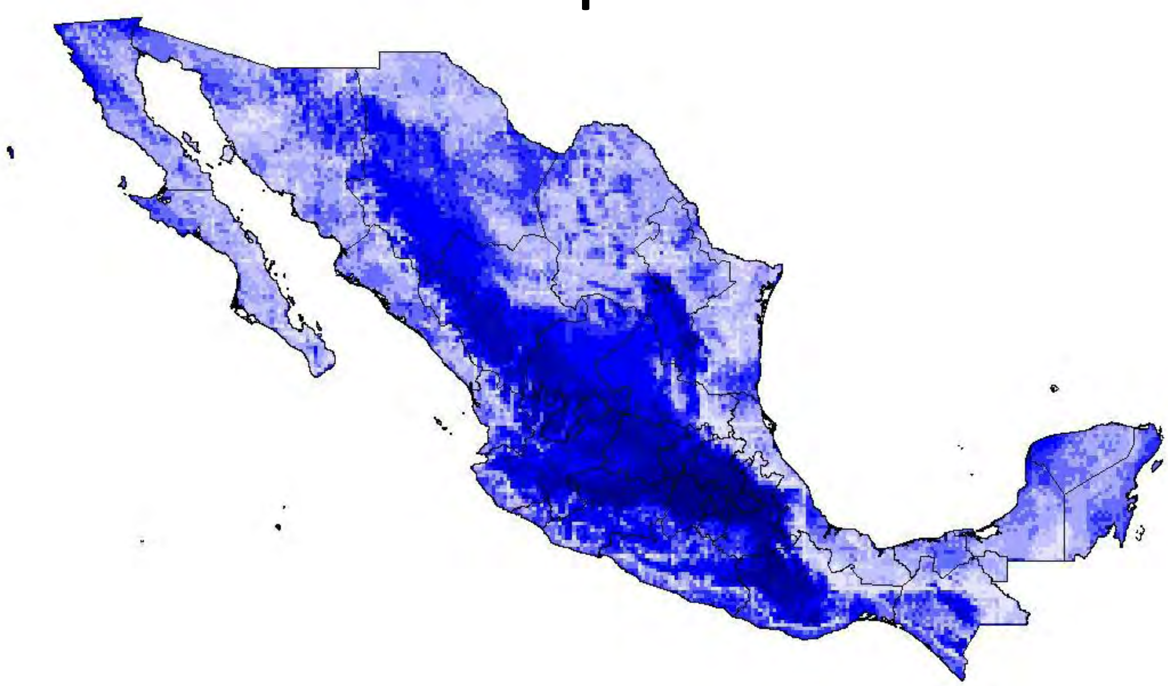
Cacahuacintle



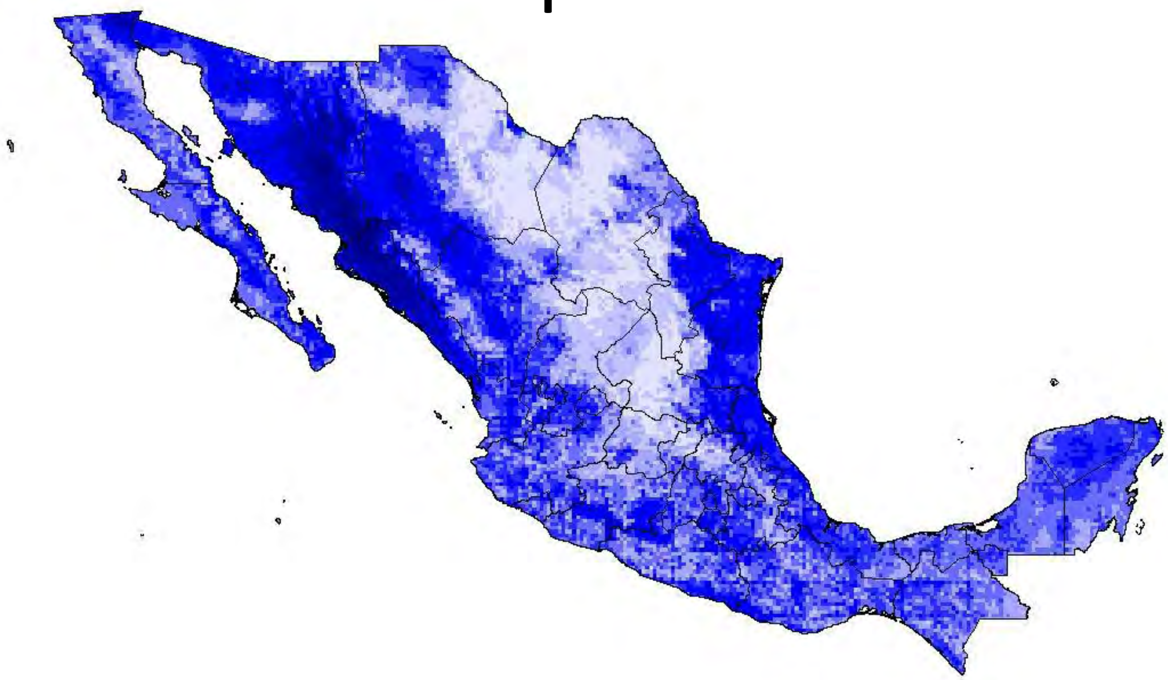
Celaya



Chalqueño



Chapalote



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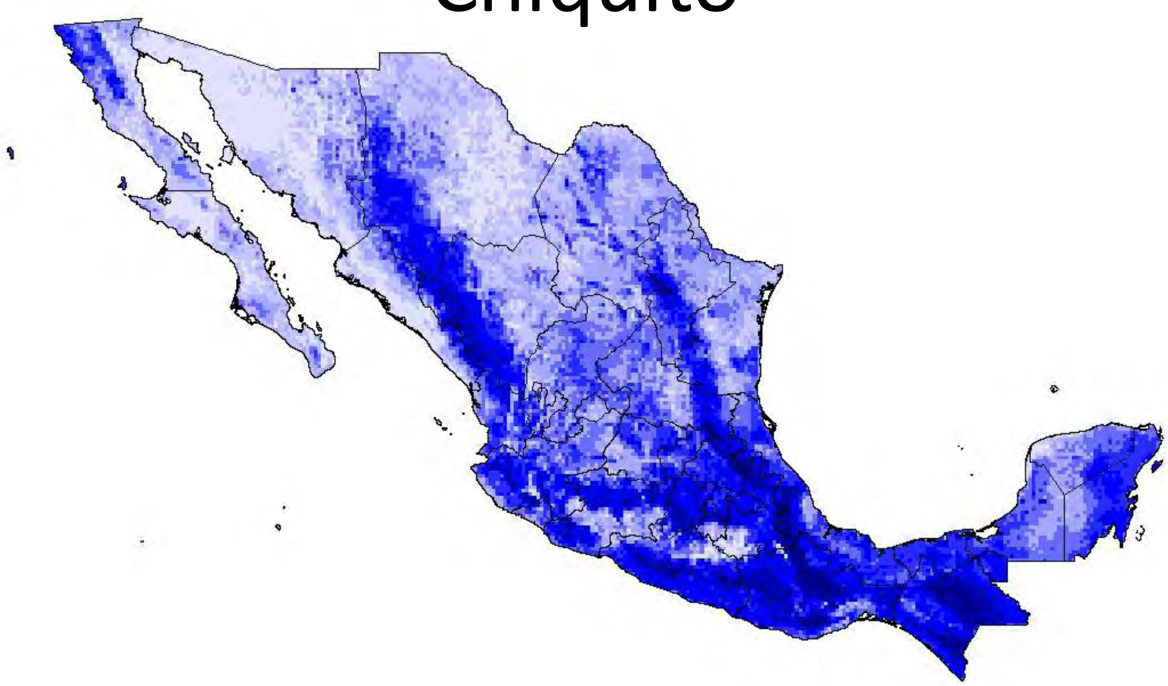
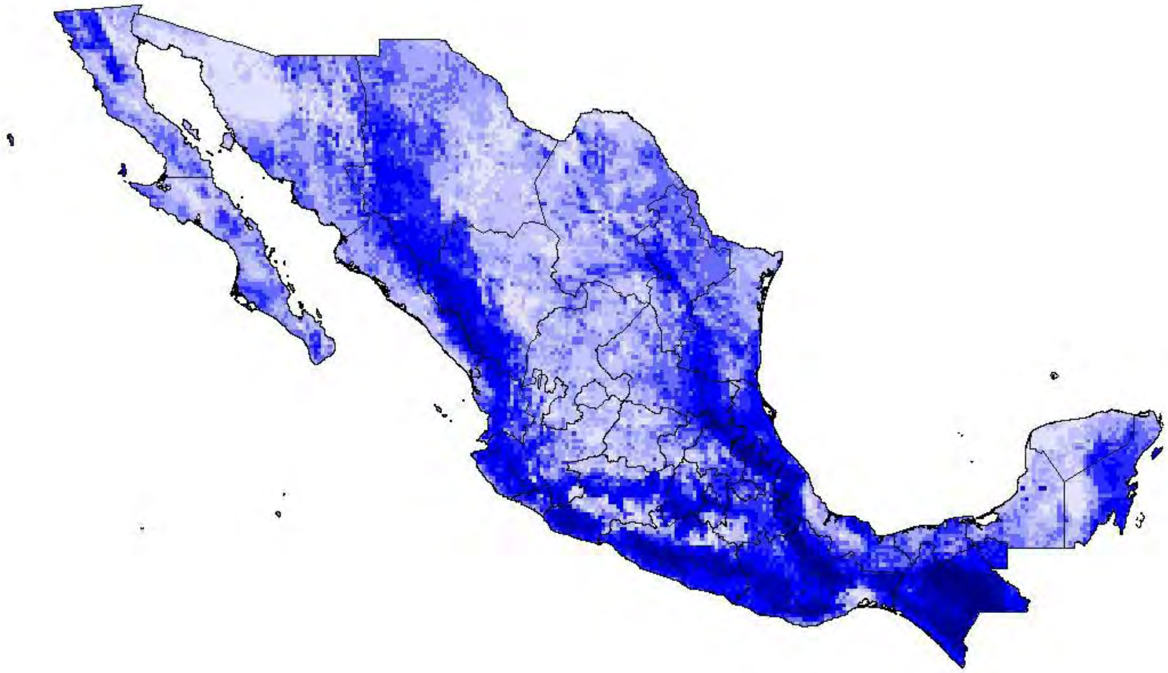
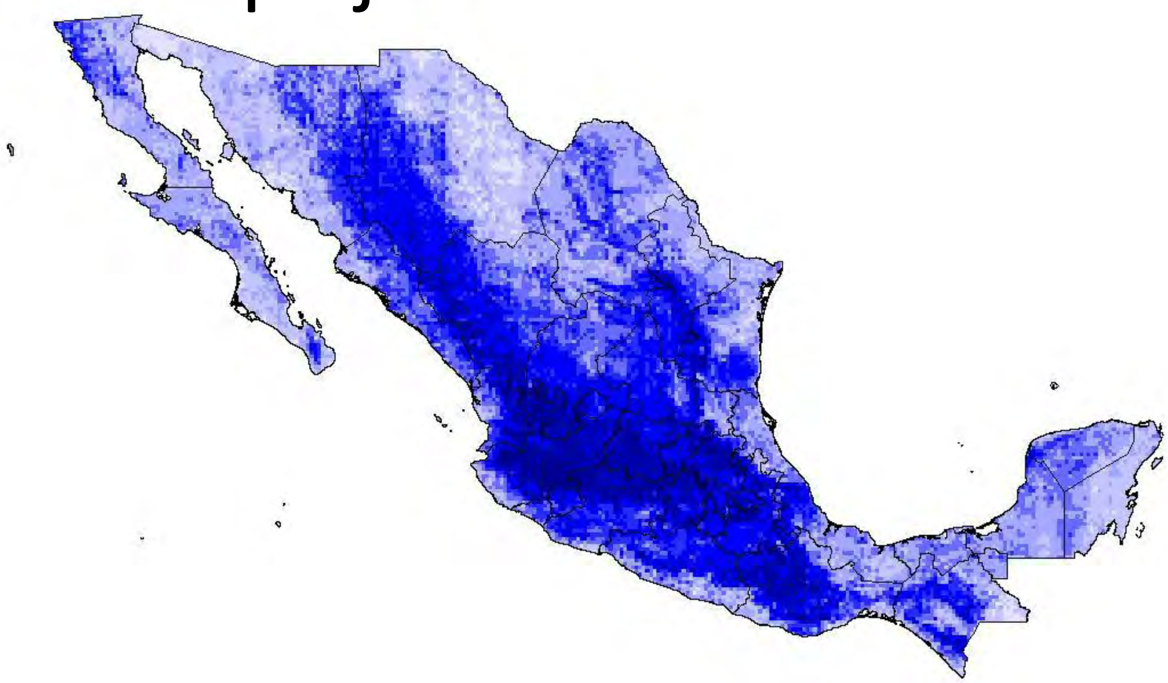


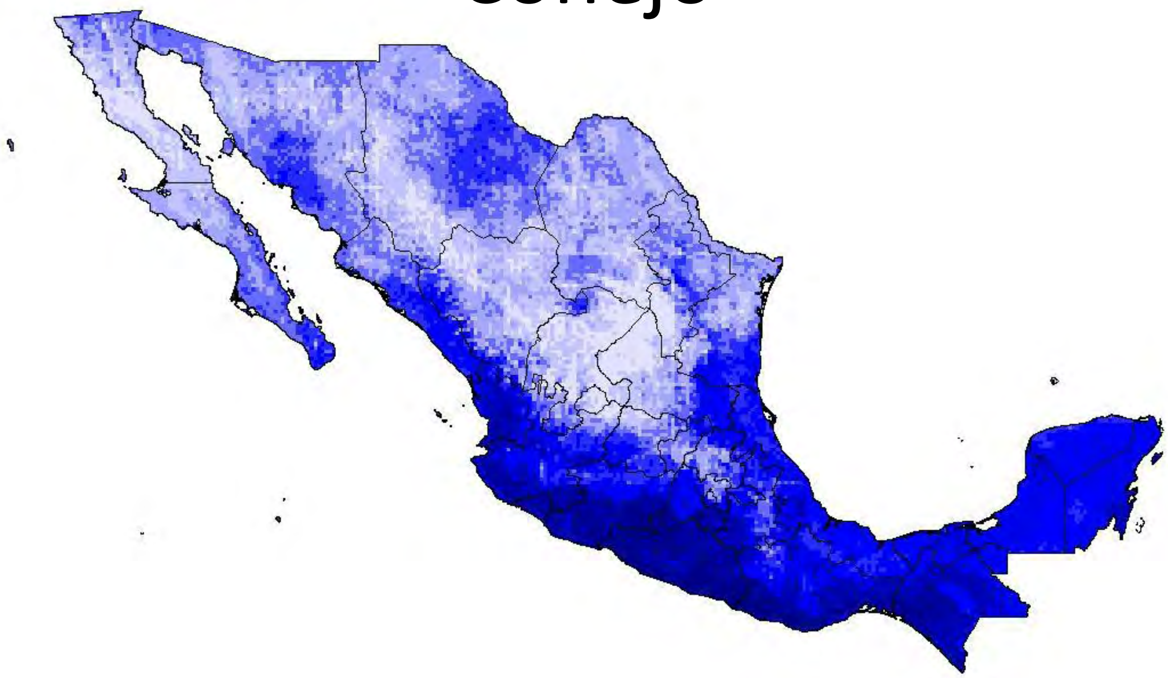
Comiteco



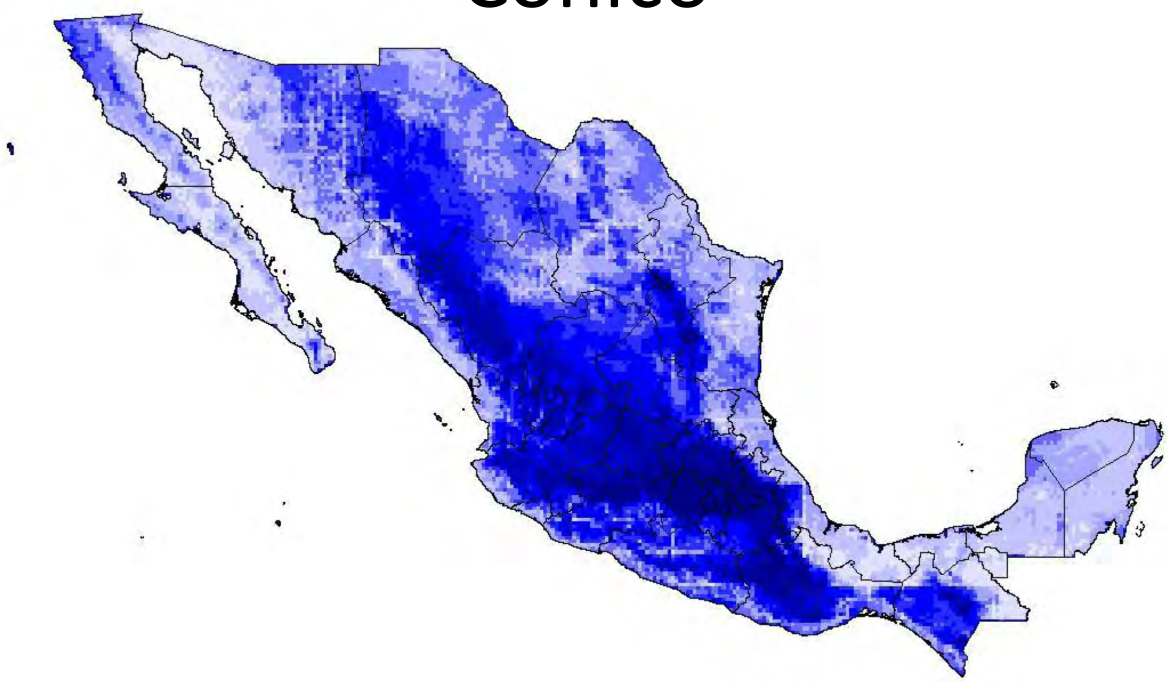
Complejo Serrano de Jalisco



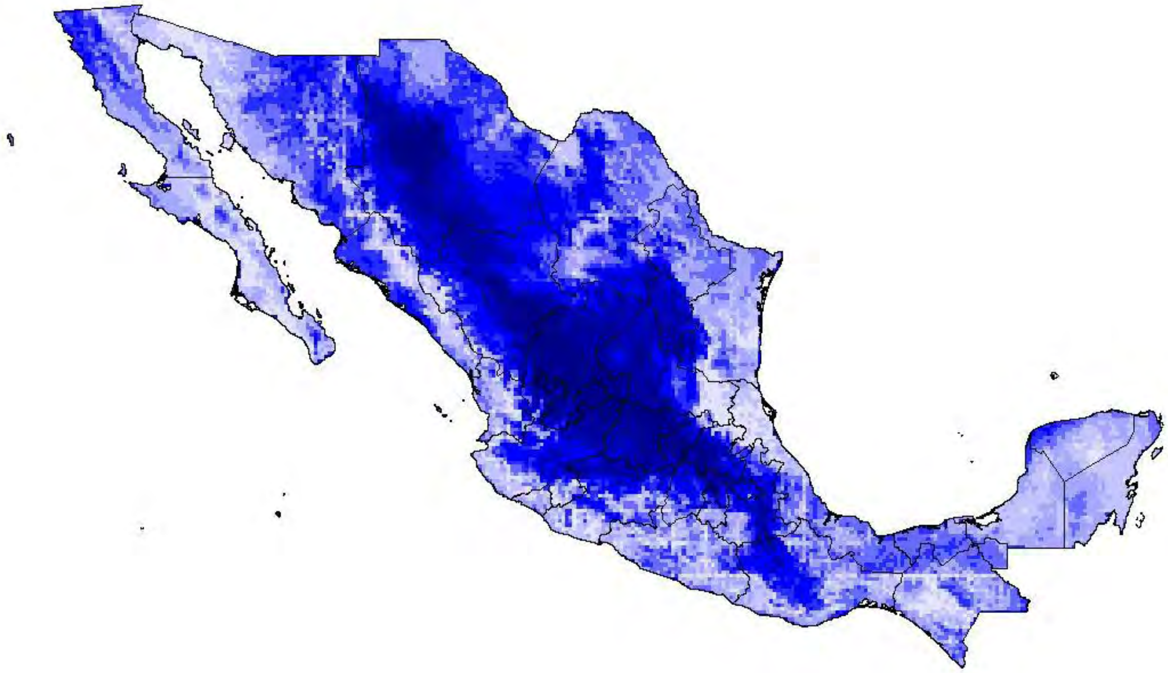
Conejo



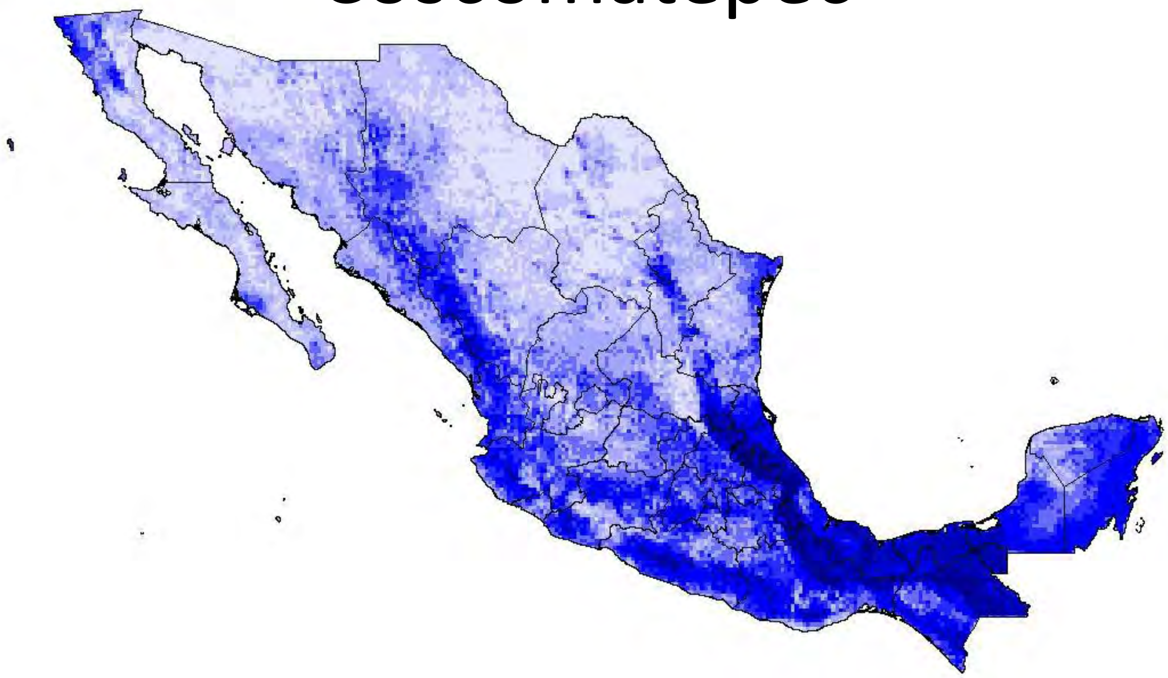
Cónico



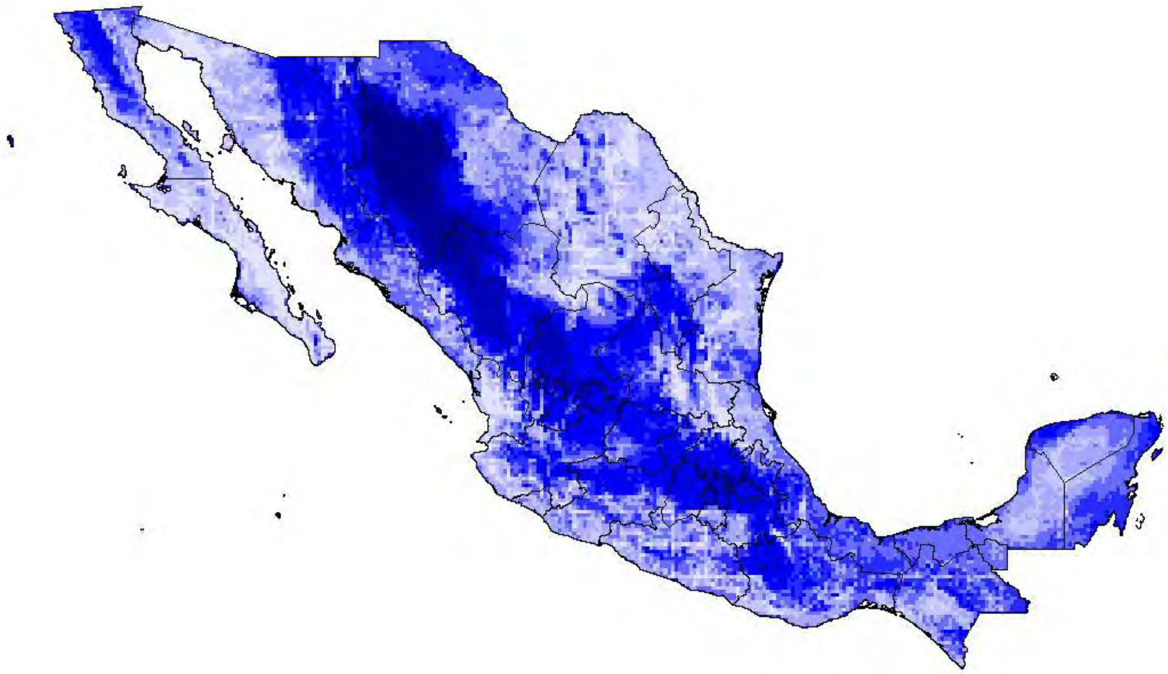
Cónico Norteño



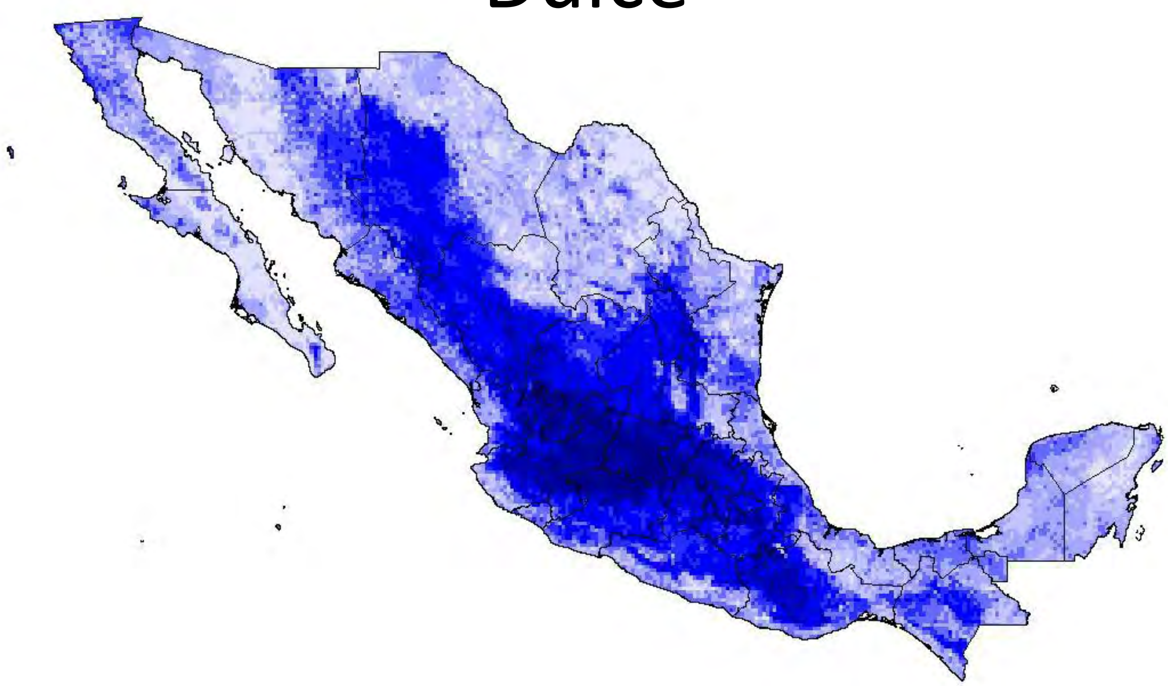
Coscomatepec



Cristalino



Dulce



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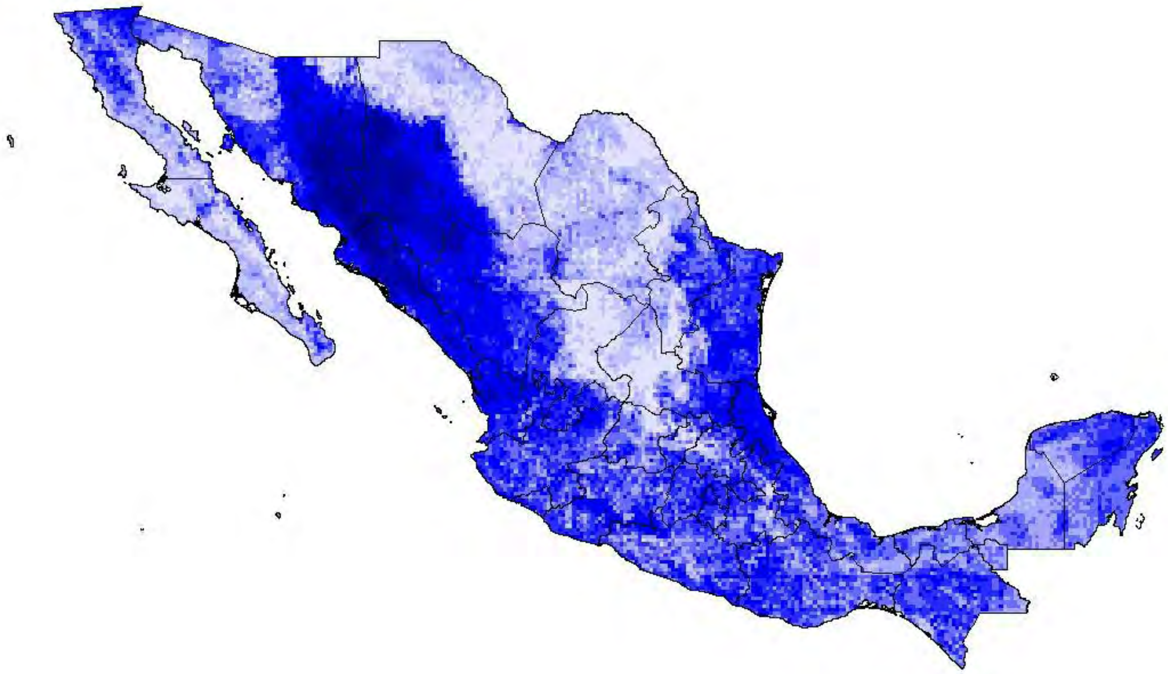
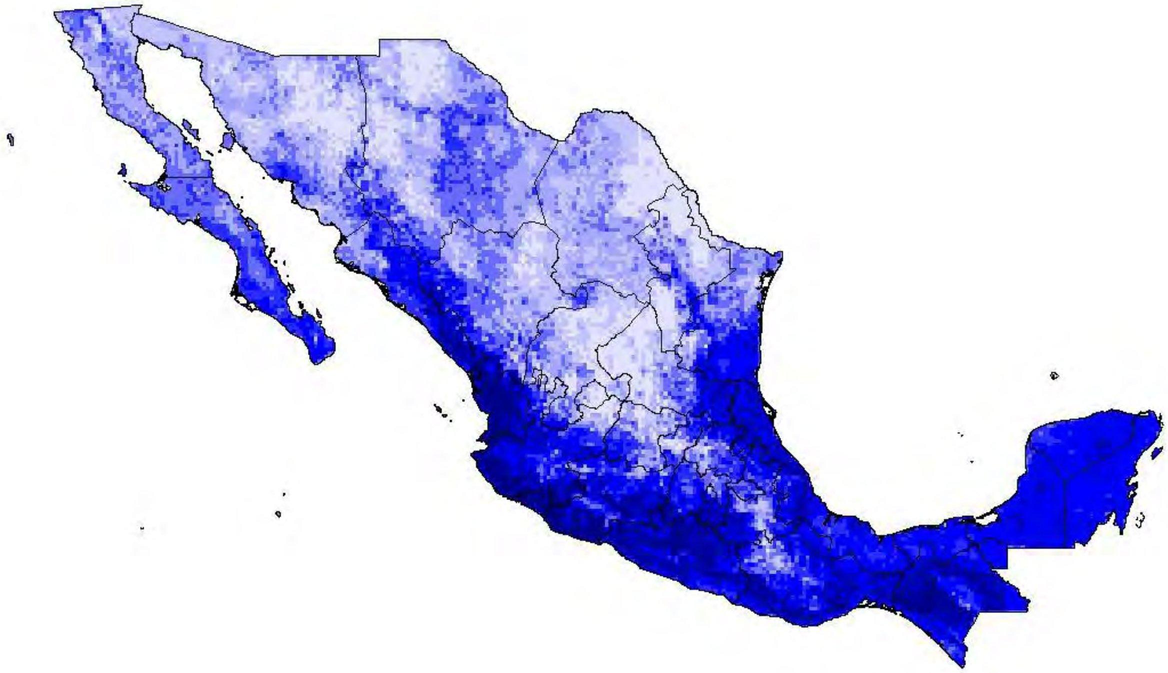
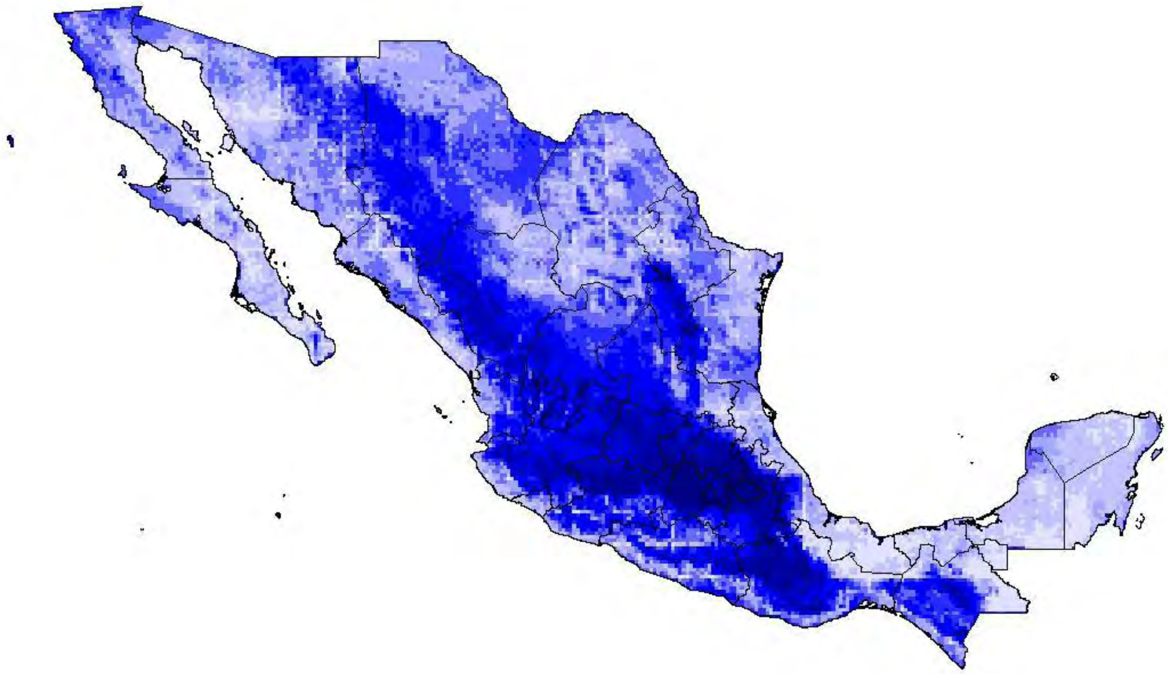


Dzit-Bacal

Elotero de Sinaloa



Elotes Cónicos



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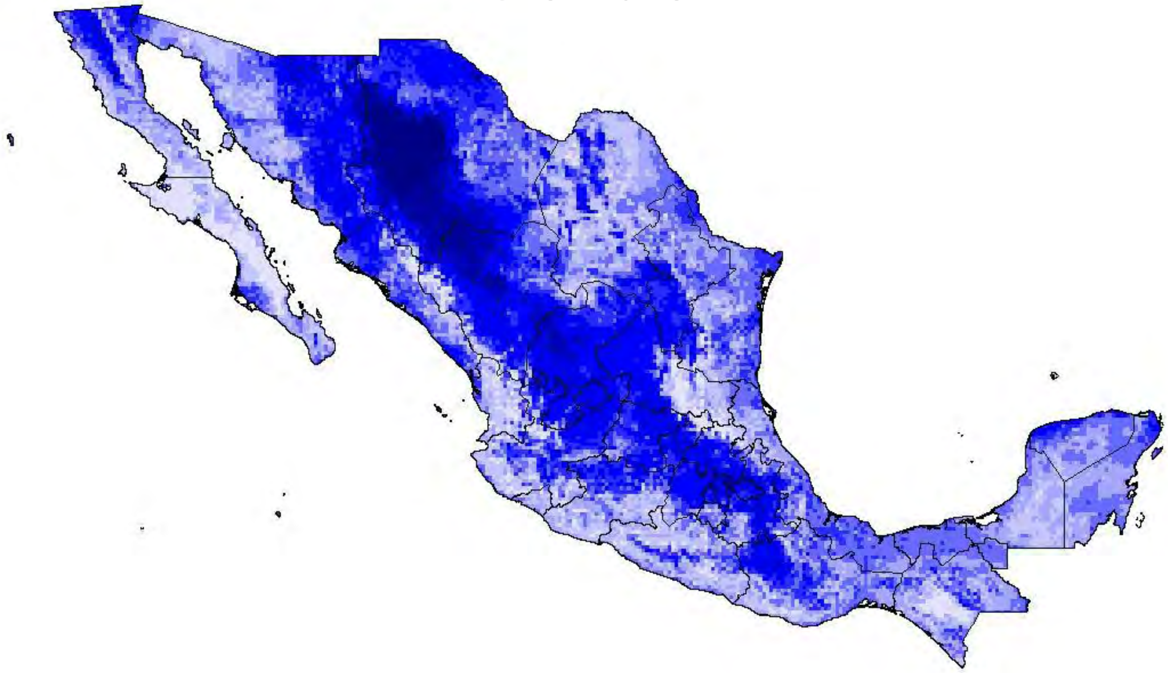
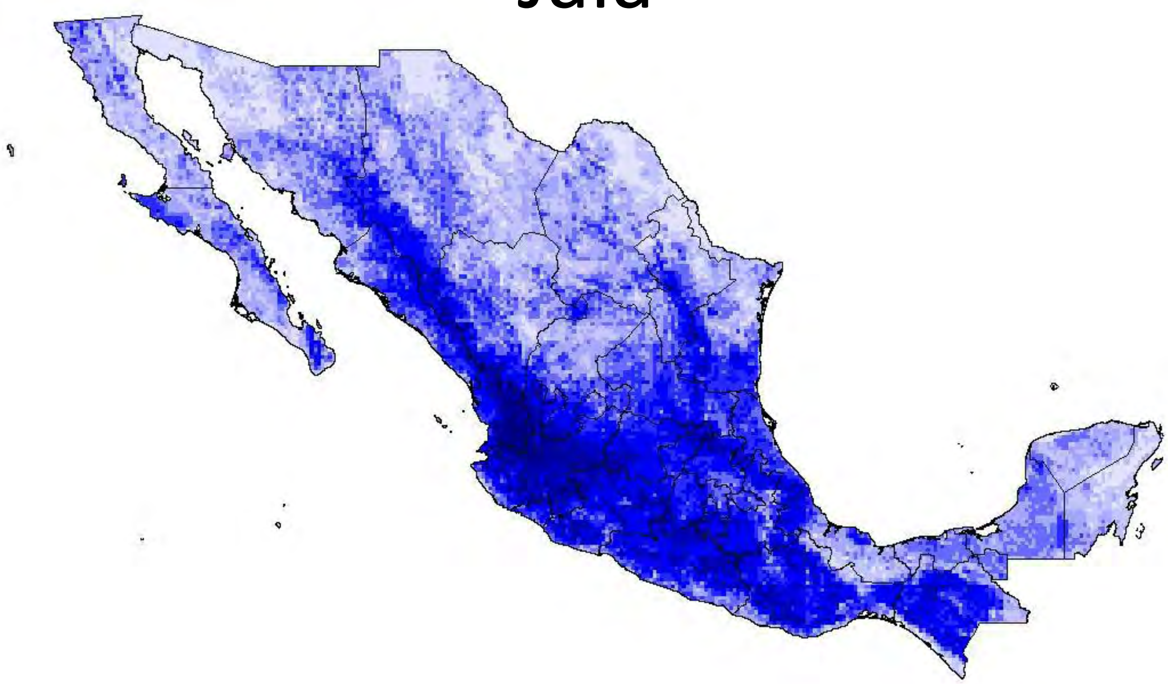
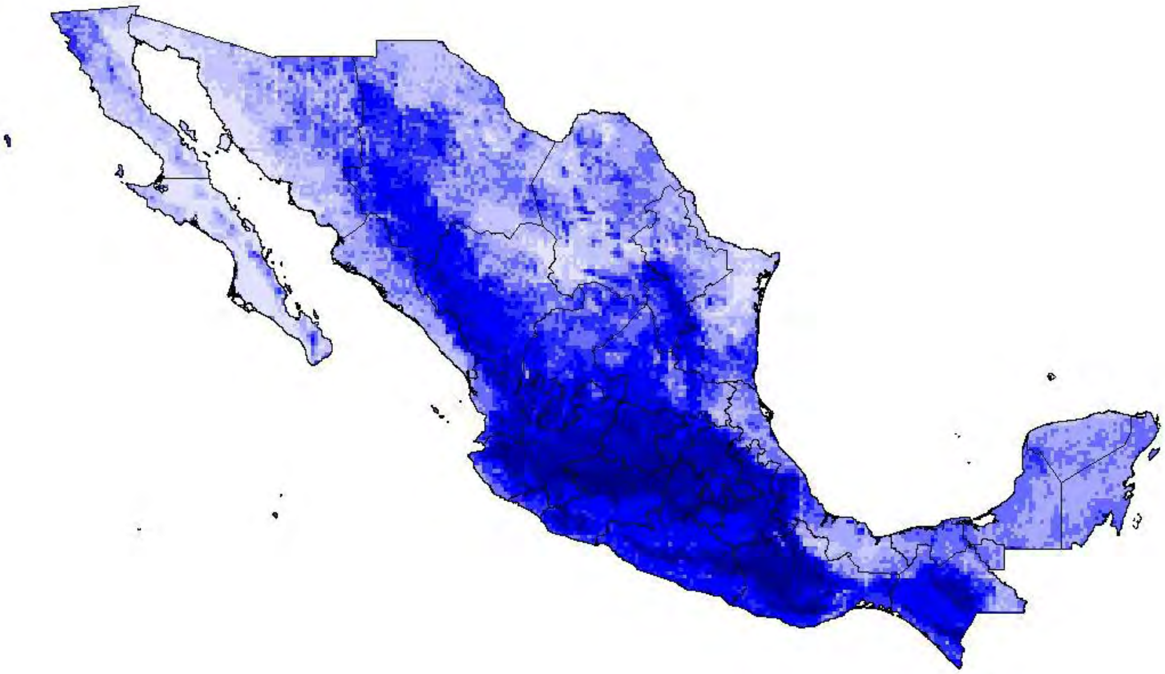


Jala

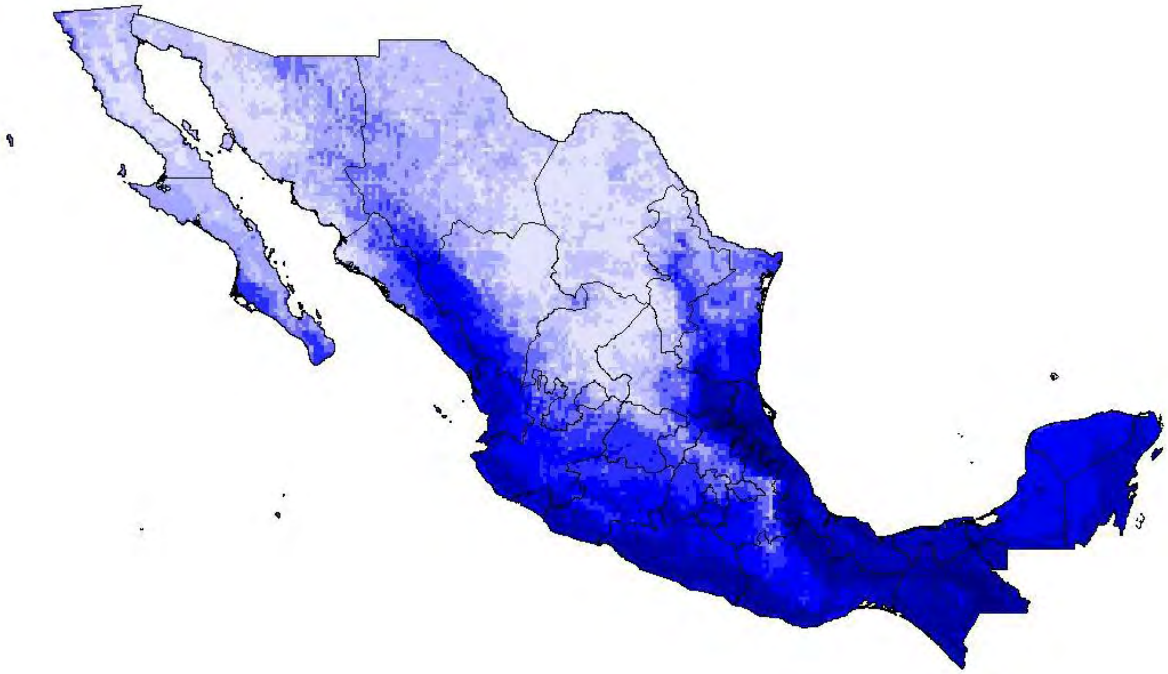


Mushito

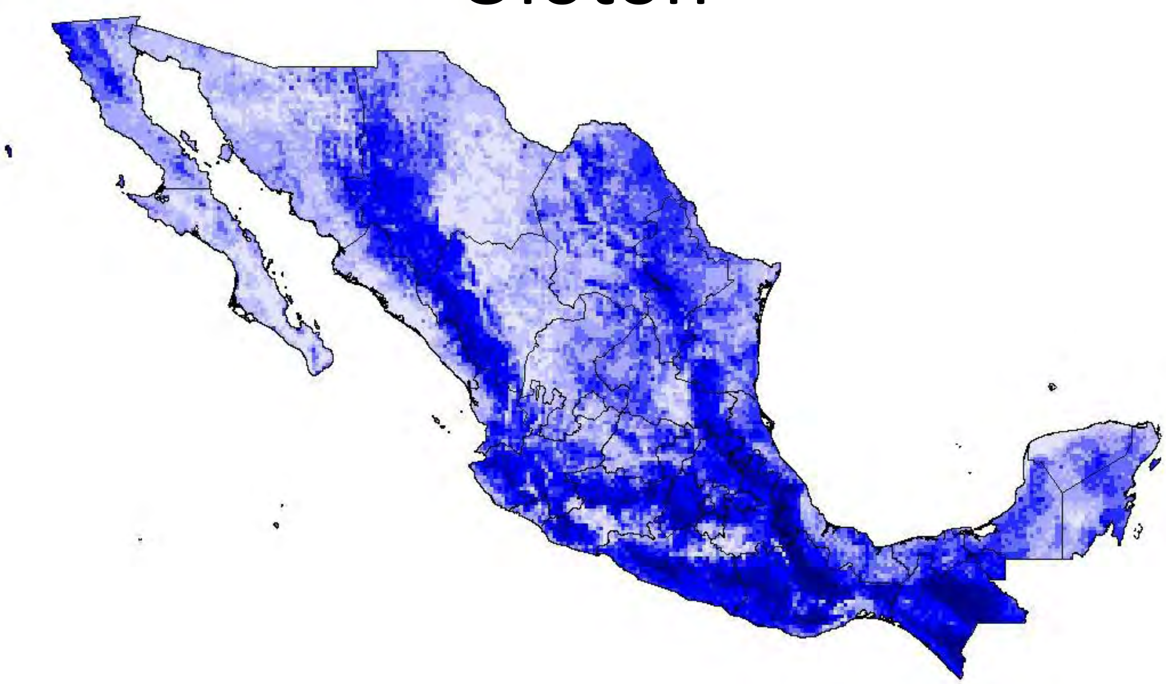


Nal-tel

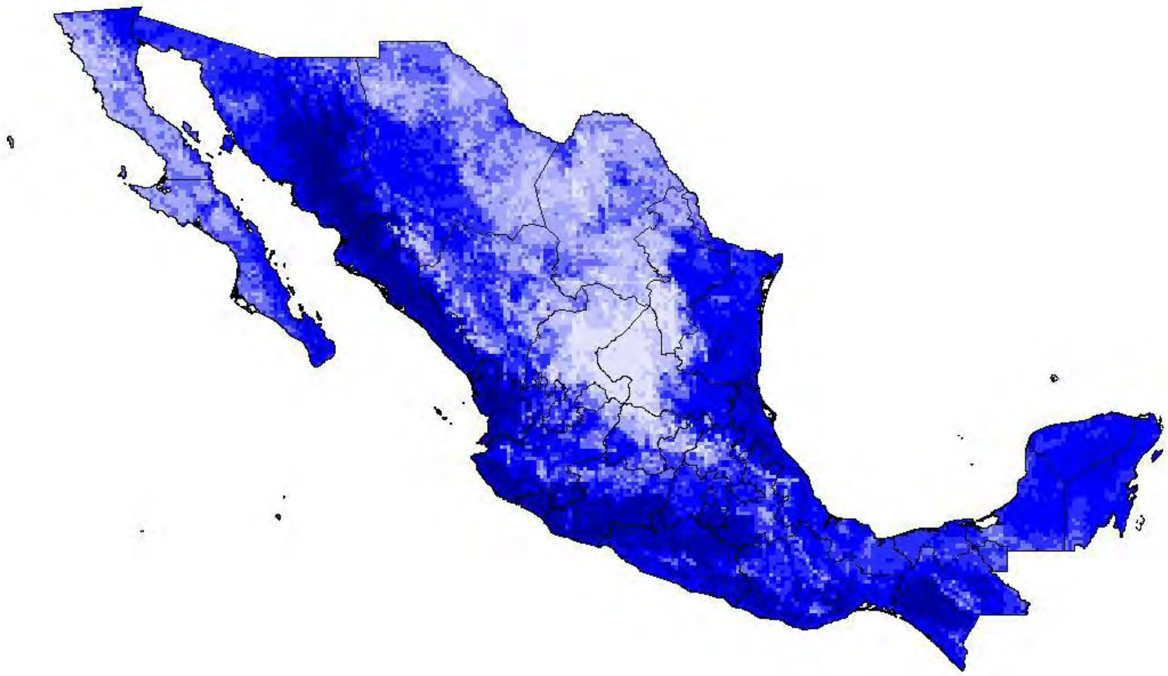
Olotillo



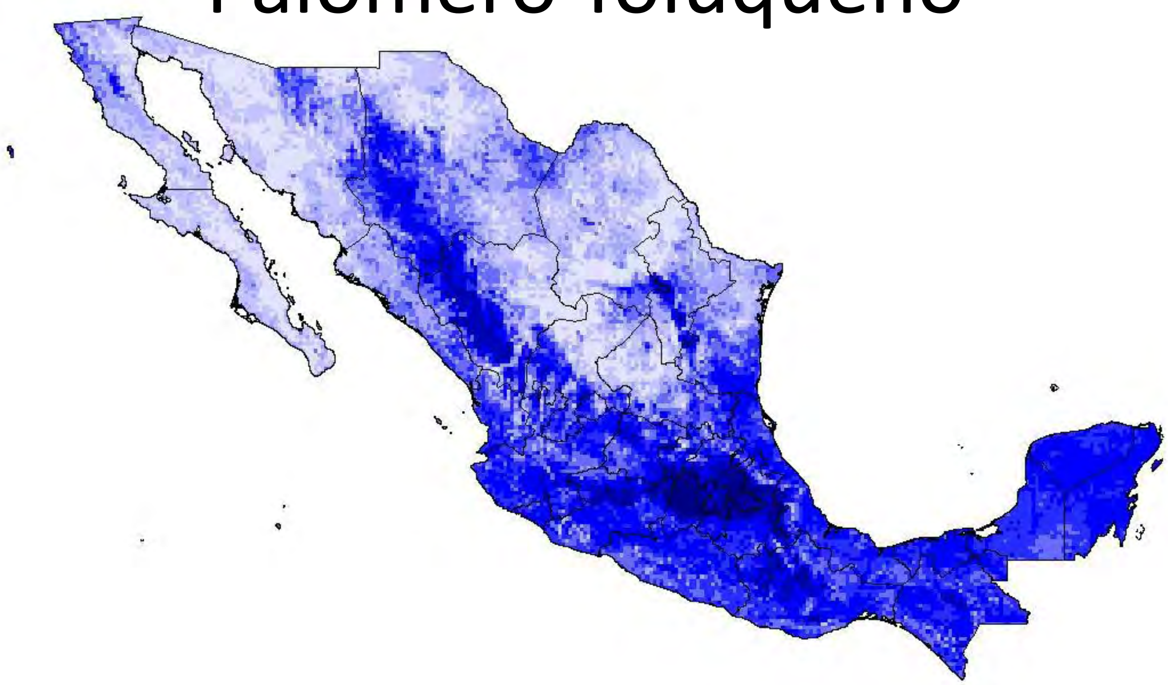
Olotón



Onaveño



Palomero Toluqueño



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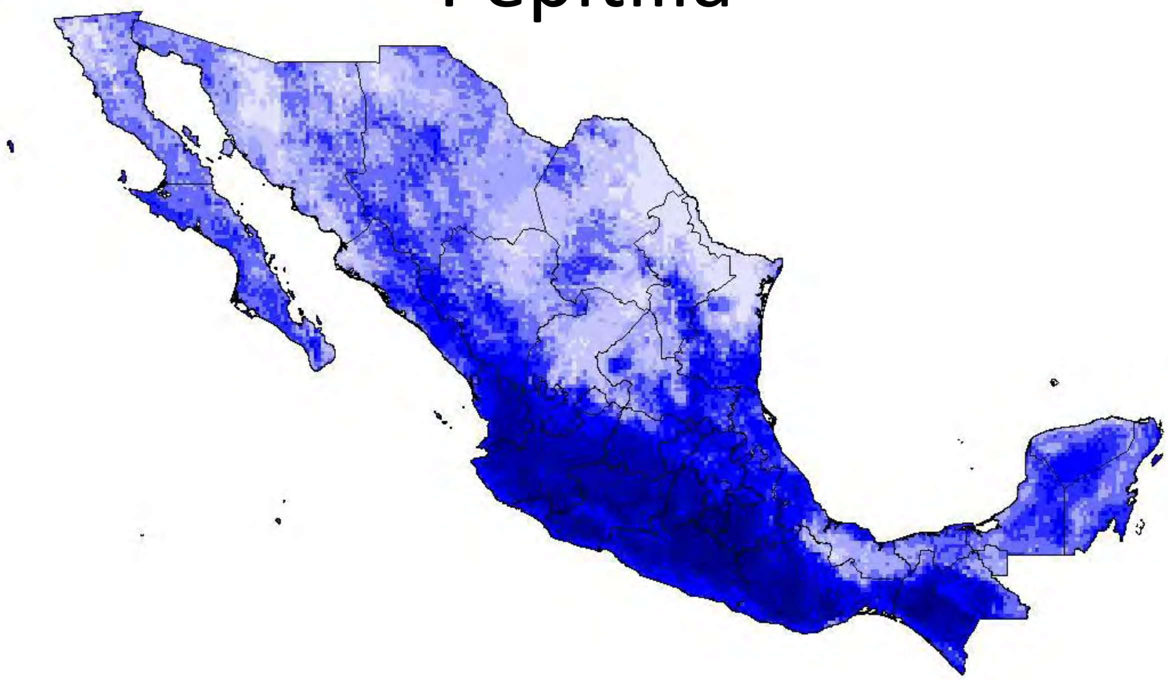
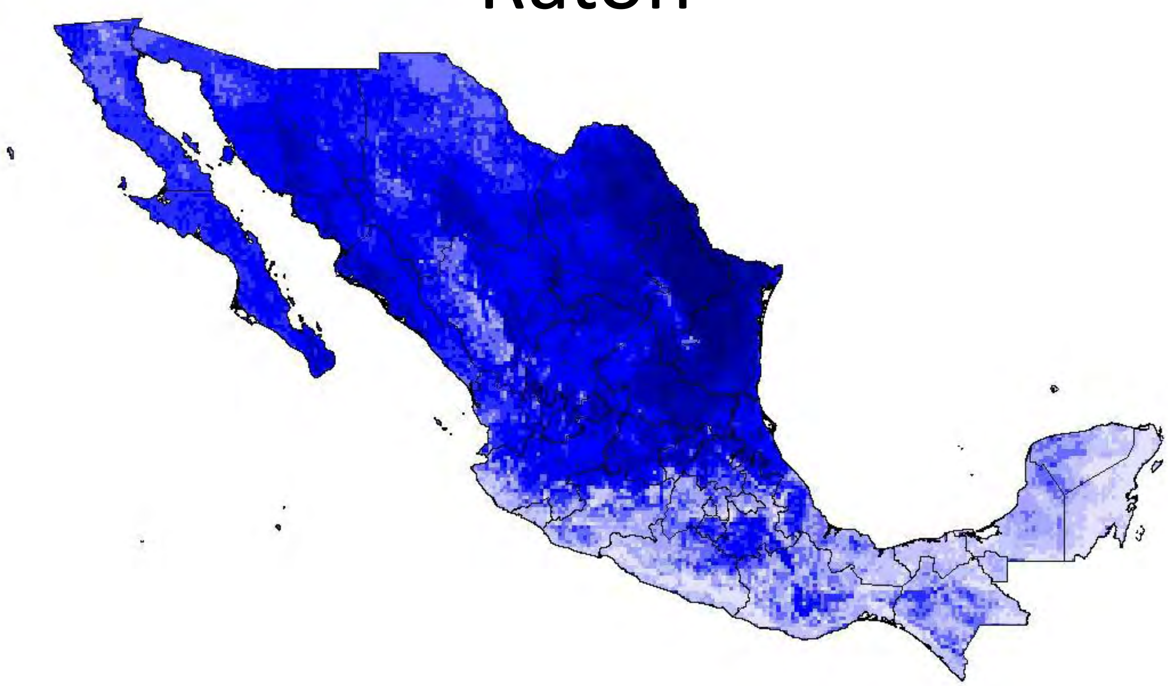
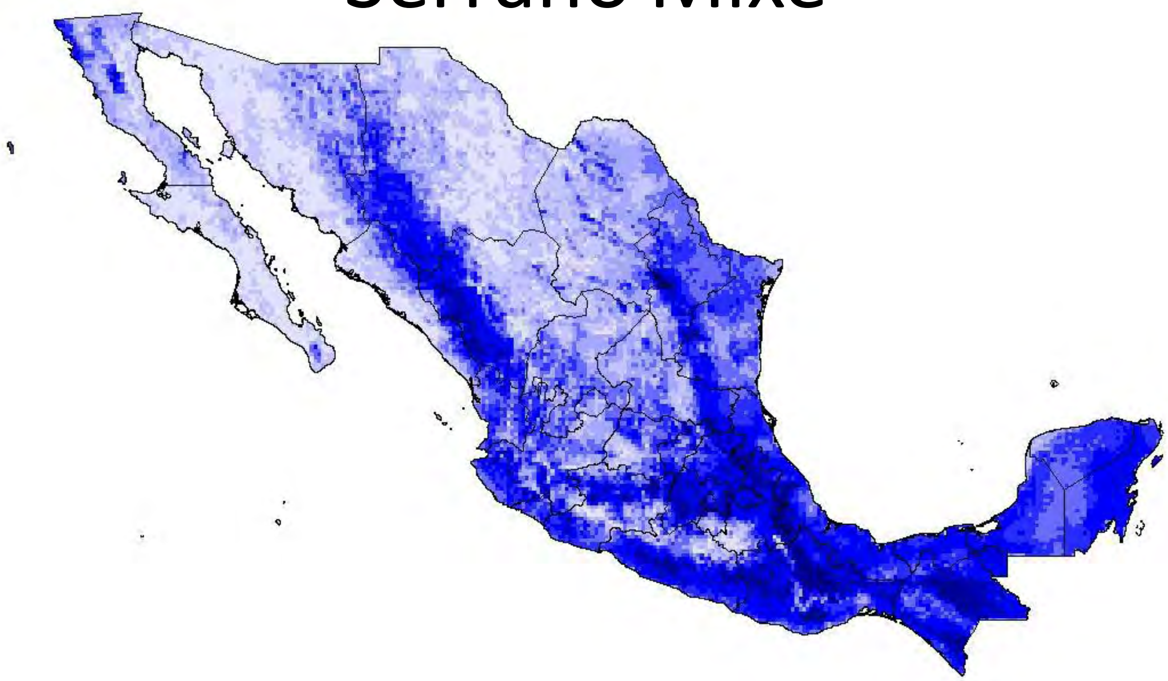


Ratón

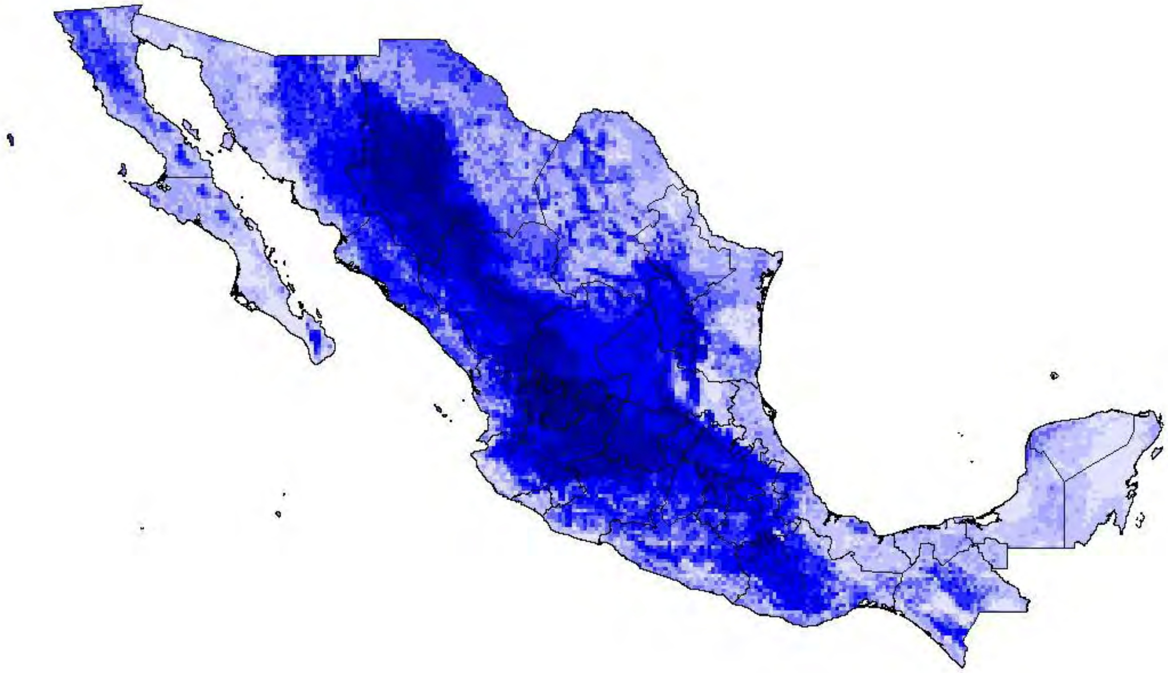


Reventador

Serrano Mixe



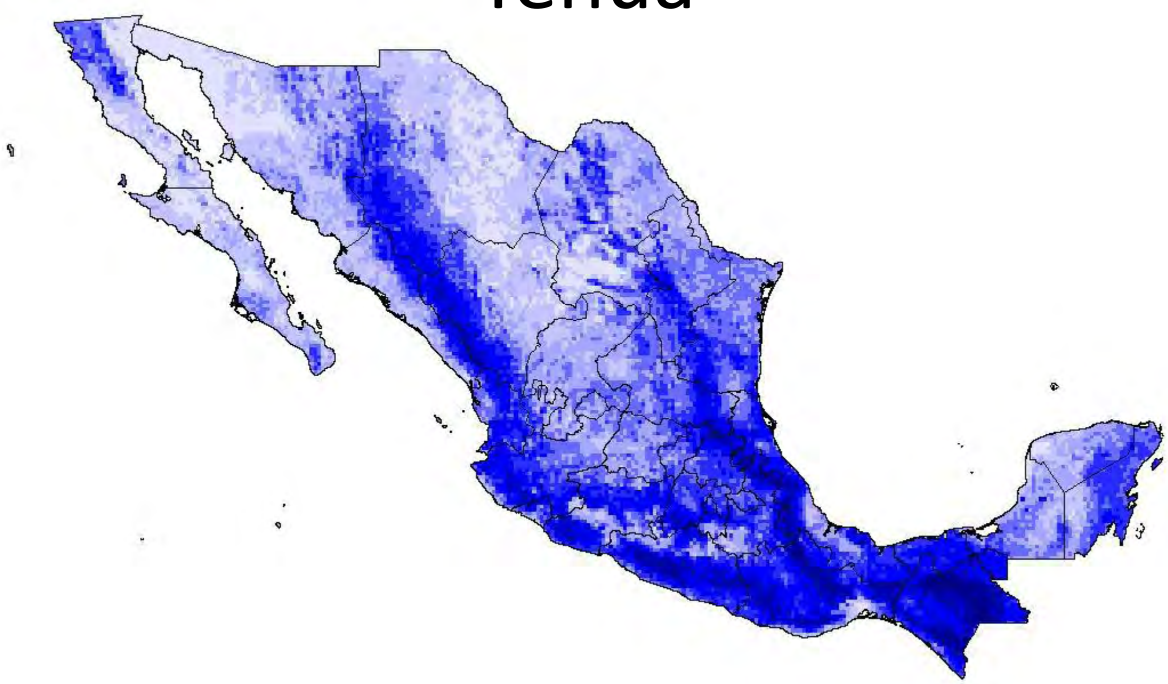
Tablilla de Ocho



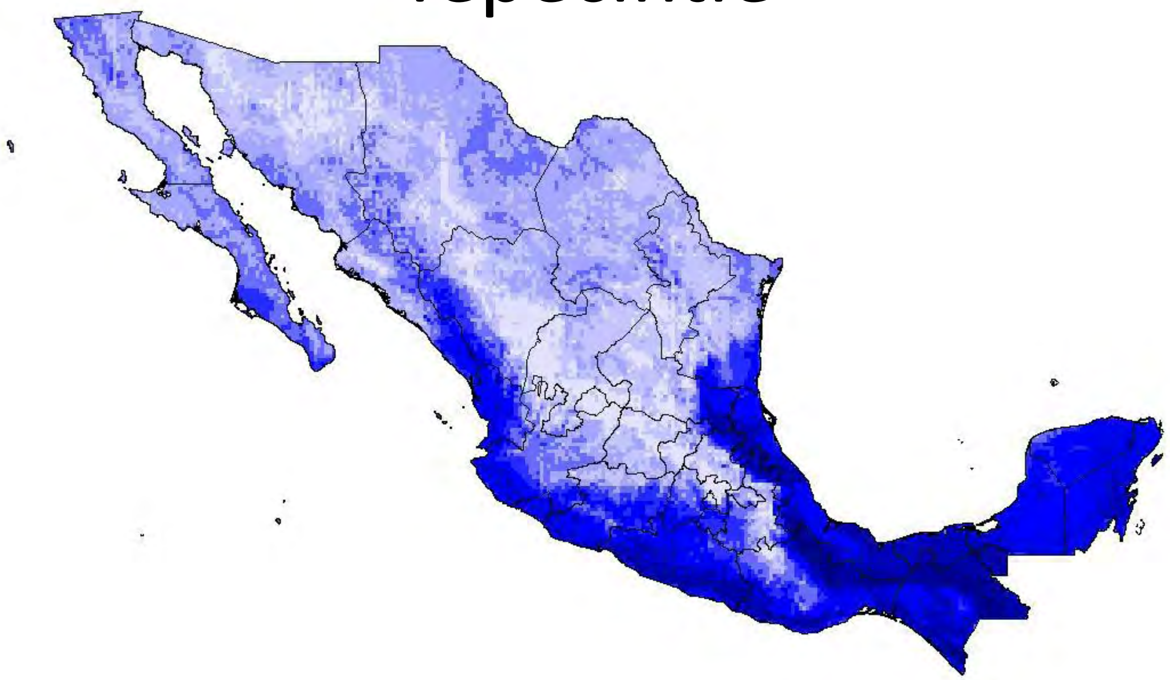
Tabloncillo

Tabloncillo Perla

Tehua

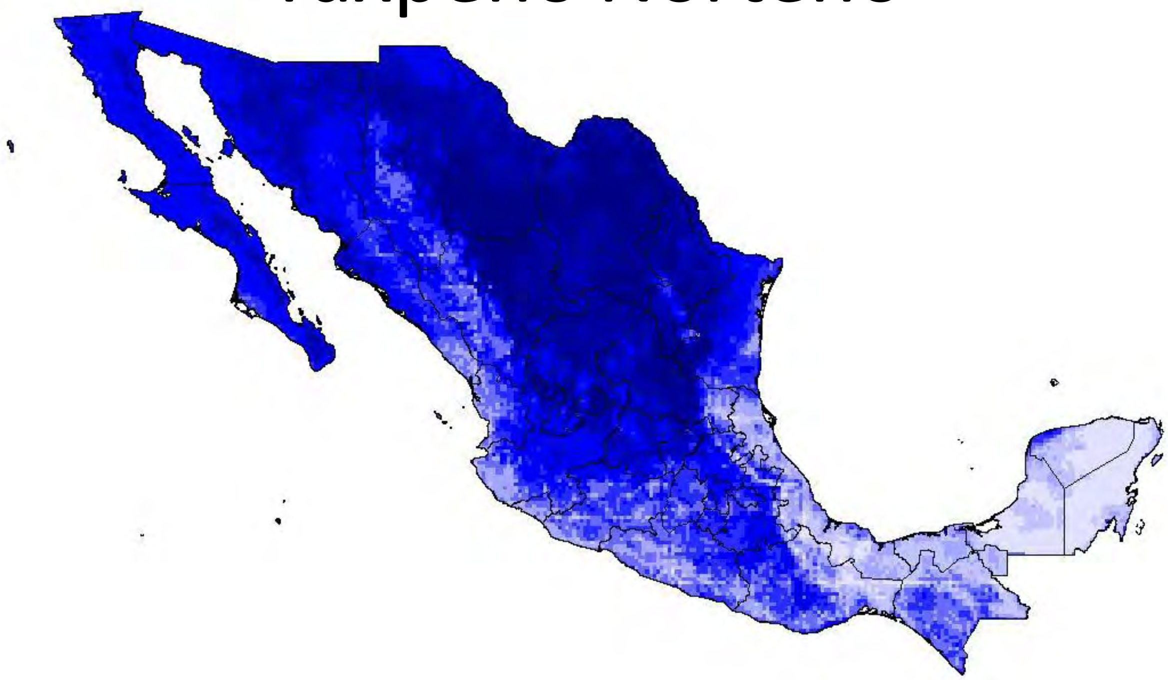


Tepecintle

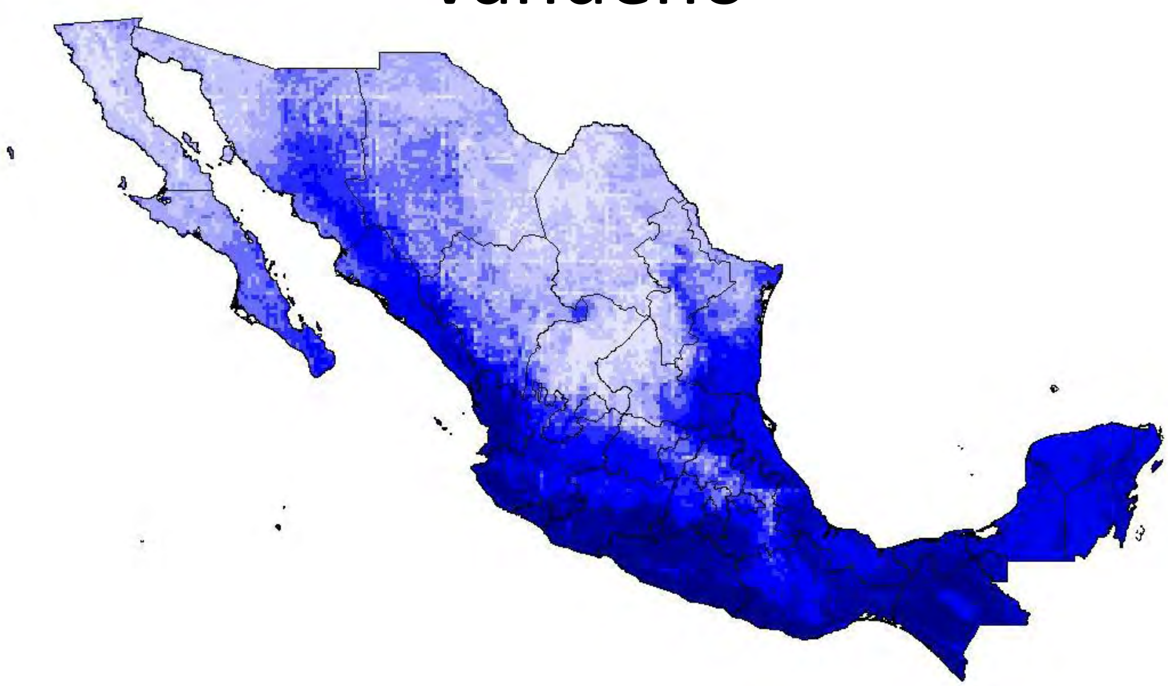


Tuxpeño

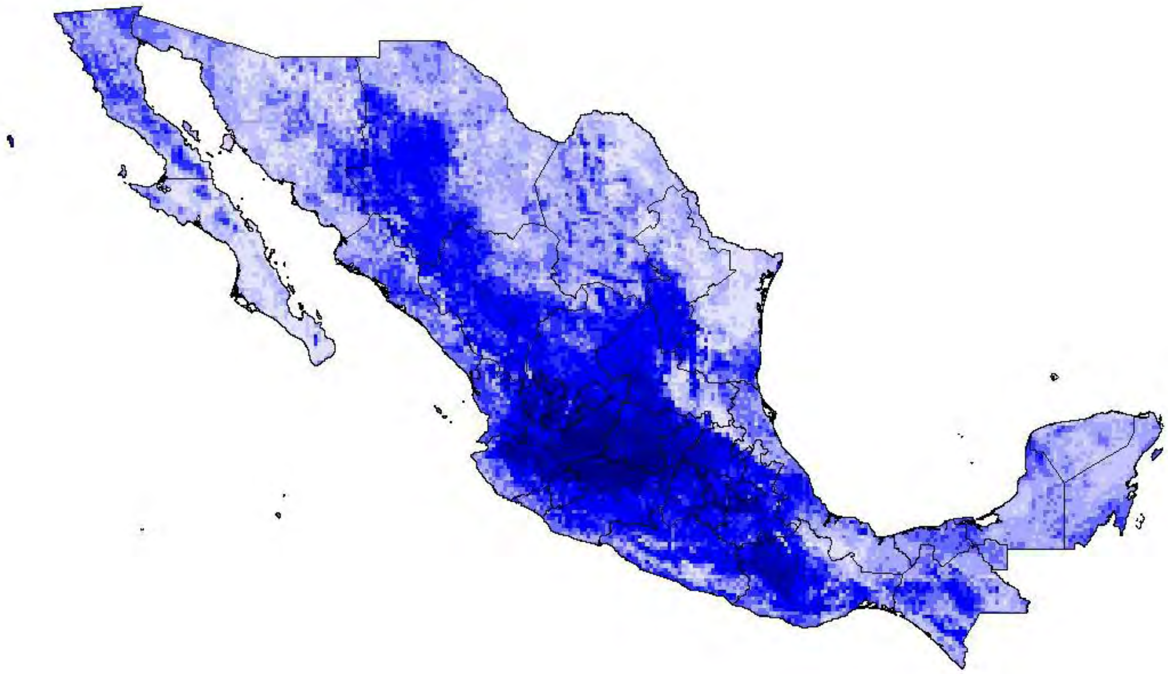
Tuxpeño Norteño



Vandeño

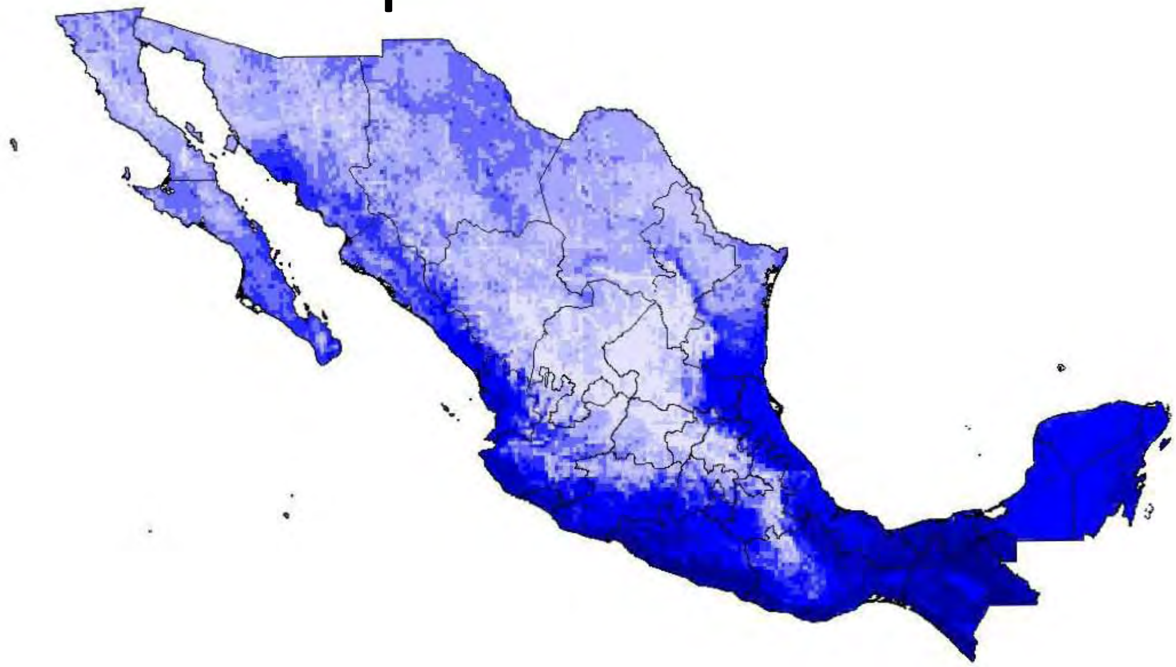


Zamorano



Zapalote Chico

Zapalote Grande



Capítulo 3

Identificación de Áreas con Mayor Potencial de Rendimiento para el Maíz Mexicano bajo Condiciones de Clima Actual y bajo Cambio Climático

Finding potential high-yield areas for Mexican maize under current and climate change conditions

Abstract

Recently, there have been some efforts to combine population and geographic ecology in order to find model geographic patterns of abundance of wild species. Following this idea, in this paper we tried to find geographic areas with higher yields for one of the most important crops worldwide in its center of origin and diversification (Mexico): maize. In Mexico exists one of the key maize genetic reservoirs and consequently, creating management plans might favor not only local people but the entire agricultural industry. Ecological theory suggests that population fitness, and thus abundance, is maximal at and progressively decreases from the centroid of the multidimensional ecological niche. Some recent empirical tests strongly support this idea. Instead of abundance, we used yield to test whether Maguire's theory worked with a domesticated species. We assessed if ten Mexican maize races improved their yield in areas ecologically closer to their ecological niche centroid or niche optima. We introduced the ecological niche optima concept because highly suitable geographic areas may not necessarily coincide with the niche centroid. Even though the quality of yield data at the national scale needs to be improved, we still found five races with significant correlations between yield and distance to the niche centroid or to the niche optima. We projected yields of two races (Bolita and Celaya) under current and future climatic scenarios (2030) to identify higher yield areas, assuming that the correlation found is maintained through time. Furthermore, we created clusters from these two races and carried out the same analyses to evaluate if different niche optima may exist in one single race. Areas with potentially higher yields have a larger presence in northern states under climate change conditions for races and clusters. Celaya was the race presenting a larger area with production

higher than 3000 kg/ha, which will be expanded under climate change. Creating clusters or clusters in taxa with large distributions might be more accurate for projections under current and future climatic conditions. We conclude that the distance to de niche centroid/optima approach is promising in the agroecology field, whenever input data are minimally reliable.

Keywords: *Zea mays*, native races, niche centroid, niche optima, higher yields

Introduction

Small-hold farmers around the world have been the ones actively maintaining agrobiodiversity *in situ* (Thrupp 1998, Bardsley 2003, Ortega Paczka 2007, Ureta et al. 2013) and therefore, in terms of conservation and global food security we need to support them (Kahane et al. 2013). Geographic information about where to find potential high yield areas for the most important crops worldwide in its centers of origin and diversification (COD) might help creating management plans that favor not only local people but the entire crop production industry, by conserving genetic resources.

Maize is one of the three key crops around the globe in terms of production and dietary staple (Nuss and Tanumihardjo 2010). In Mexico its COD (Kato et al. 2009), more than 59 native races have been described representing one of the most valuable genetic reservoirs (Ruiz Corral et al. 2008). Although the taxonomic term "race" is not commonly used in agricultural plants, in the case of maize it has been very useful to classify the species great diversity. A well accepted definition of race goes as follows: "a group of related individuals with enough characteristics in common to permit their recognition as a group" (Anderson and Cutler 1942). In Mexico, around 70% of farmers growing maize are smallholders that grow mostly native races using traditional agrotechnology, with yields depending strongly on environmental conditions (Turrent Fernández

2008). Having information of where higher yields can be produced for individual native races might be an insight to start designing and implementing adaptation plans under current and future climate.

In recent years, some efforts have focused on modeling geographic patterns of abundance from presence-only data for wild species (Van Der Wal et al. 2009, Tôrres et al. 2012, Yañez-Arenas et al. 2012, Martinez-Meyer et al. 2013). In particular, VanDerWal et al. (2009) and Tôrres et al. (2012) tested whether some popular Ecological Niche Modeling (ENM) algorithms produced results that related with the abundance of several species, resulting in marginal success in the best cases. On the other hand, Martínez-Meyer et al. (2013) proposed and tested, and Yañez-Arenas et al. (2012) implemented a novel method to model geographic patterns of abundance based on the ecological niche theory, named the Distance to the Niche Centroid (DNC) approach. According to Maguire (1973), population fitness should be maximal where highest birth rate and lowest death rate coincide in the multidimensional niche space; he proposed that such optimal conditions should occur at or near the centroid of the niche hypervolume. Based on this body of theory, Martínez-Meyer et al. (2013) successfully tested the hypothesis that population abundance of 11 species follow a center-abundant pattern in ecological space, where maximal abundance occurs around the niche centroid and progressively decreases as populations depart from this nucleus. An implementation of this procedure for the White-tailed Deer (*Odocoileus virginianus*) produced robust spatially-explicit models of abundance in two regions of Mexico (Yañez-Arenas et al. 2012). However, it is theoretically feasible that optimal conditions for a given species are not always at or near central values of certain critical ecological variables (i.e., niche centroid); for example, extremophile species are adapted to maximal or minimal values of aridity, salinity, hypoxia, etc.; thus the centroid idea might not apply.

Following this line of thinking, we hypothesize that Mexican maize races will exhibit higher yields in areas ecologically closer to the centroid of their ecological niches (NC) or to a different ecological niche optima (NO). Similar to wild species, in which abundances increase under optima environmental conditions, agricultural plants are expected to increase their grain yields too (Boyer 1982).

The aim of this study is to assess whether it is possible to identify geographic areas where higher yields might be obtain under current and future climatic conditions, using presence data and testing it with available field yield data. We assessed the correlation between yield and distance to the NC and NO for ten different races. Bolita and Celaya were used (due to statistical reasons) to project their yields under current and future conditions (2030 A2). Furthermore, we created clusters from these two races and carried out the same analyses to evaluate if different niche optima may exist in one single race. These results might give a first insight of information to create adaptation plans under climate change conditions for native Mexican maize races and their corresponding bioclimatic clusters.

2. Methods

2.1 Calculating distances to ecological centroids and optima

We used the database compiled by CONABIO (the Mexican Commission for Biodiversity) (Acevedo 2011) and chose the races with occurrence data from 1980 to 2011 that adequately represented their whole distribution range in Mexico country and had yield data covering different areas of its distribution. Yield data were obtained by CONABIO between years 2000 and 2010 through interviews with farmers growing native maize races. These data were not measured or verified with a rigorous method, and consequently we discarded outliers and other dubious data. Even with these drawbacks, these data are the best available for yields of native races at a national scale. Finally, we evaluated 10 races that met the basic characteristics mentioned above to carry out the analysis, namely: Bolita, Celaya, Cónico Norteño, Nal-tel, Olotillo, Ratón, Tabloncillo, Tepecintle, Tuxpeño y Vandeño (Table 1). To characterize the bioclimatic profile of these races we used a 1 km^2 resolution climatology generated for Mexico that goes from 1980 to 2009 (Cuervo-Robayo et al., unpublished data).

For every presence datum, we obtained the value presented for each of the 19 bioclimatic variables evaluated (1-annual mean temperature, 2-mean diurnal range, 3-isothermality, 4-temperature seasonality, 5-maximum temperature of the warmest month, 6-minimum temperature of the coldest month, 7-temperature annual range, 8-mean temperature of the wettest quarter, 9-mean temperature of the driest quarter, 10-mean temperature of the warmest quarter, 11-mean temperature of the coldest quarter, 12-annual precipitation, 13-precipitation of the wettest month, 14-precipitation of the direst month, 15-precipitation seasonality, 16-precipitation of the wettest quarter, 17-precipitation of the driest quarter, 18-precipitation of the warmest quarter and 19-precipitation of the coldest quarter). Although these races are mostly grown in the spring-summer season, we used all the bioclimatic variables because it has been shown that variables dealing with climatic variability, autumn-winter season and extreme climatic events have also an important influence on the distribution of Mexican maize races (Ureta et al., 2013). In this study we only used bioclimatic variables because we wanted to project the effect of climate change in the distribution of future yield. However; we are aware of the importance of other environmental factors (i.e., soil and slope) in the characterization of the niche of a species such as maize (Ureta et al., 2013).

Once we got the bioclimatic variables presented in each record, we normalized them. As it has been done before, the distance of an occurrence datum to the niche centroid (NC) was calculated as the Euclidian distance of all the bioclimatic variables present in the geographic point where the datum was registered, to zero (which corresponds to the standardized mean of the bioclimatic variables). Under current climatic conditions we did not use Ecological niche modeling (ENM) to create potential distribution maps; instead, we used actual presences.

Since optimal conditions may not be at the centroid of the niche for all races, we also measured the Euclidian distance to a multidimensional point what we called the niche optima (NO). To do so, we used the function for building response curves of the presence records of the maize races with respect to each environmental variable which is implemented in the ecological niche modeling program Maxent (Phillips et al. 2006) to identify the value of each environmental variable where the response of the presence of the taxon is more frequent. We used those values to standardize its corresponding variable (rather than the mean) and then calculated the multidimensional Euclidian distance. To run MaxEnt, we used 70% for training the model and the remaining 30% to test it and evaluated the model performance with the area under the receiver-operating characteristics curve (AUC).

2.2 Yield *vs* distance to ecological centroids and optima

Once we got the distance to the NC and NO for every presence datum, we took those occurrences for which yield data were available and correlated yield and distance to the niche centroid/optima. We assessed the fit of two different models through the Akaike Information Criterion (AIC; Akaike 1974):

a) $\text{Yield} = \beta_0 + \beta_1 \times \text{Distance}$,

b) $\text{Yield} = \beta_0 + \beta_1 \times \ln(\text{Distance})$,

With these models we looked for: a) which model was the best to describe the relationship between yield and distance, b) whether there was a difference between the best model and a model of no effect of distance over yield (null model), c) whether differences could be found between models using the distance to the NC and those using the NO, and d) with which model we obtained a higher determination coefficient.

2.3 Potential distribution maps under current and future climatic conditions

To project the occurrences with higher yields under current and future climatic conditions, we chose two races based on their AIC and determination coefficient value: Bolita and Celaya. These two races present a large distribution in Mexico embracing different climates. Consequently, we thought it might be useful to carry out the entire analyzes with clusters within these races and evaluate if correlations between yields and their corresponding NC and NO improve. Clusters were created with the algorithm k-means using 13 independent bioclimatic variables (1, 5, 6, 8, 9, 10, 11, 12, 13, 16, 17, 18 and 19).

For current climate (1980 to 2011) we used the same climatology than above and for the future (2026-2035), hereafter called 2030 the one coming from http://forest.moscowfsl.wsu.edu/climate/. Current climatology was generated for Mexico using the thin-plate spline technique implemented in the ANUCLIM program: http://fennerschool.anu.edu.au at 1 km^2 spatial resolution (Cuervo-Robayo et al., unpublished data). The General Circulation Model (GCM) used were the ones developed by the Geophysical Fluid Dynamics (GFDL) and evaluated by Mexican climatologist as one of the best in representing Mexico's current climate and thus produce reasonable future climatic scenarios (Conde and Gay 2008). We assessed the worst case emission scenario A2 ("business as usual scenario") (IPCC 2007).

To find the future possible regions of higher yields, we firstly modeled the future potential distribution areas running 10 model replicates for each emission scenario with the algorithm Maxent. We converted each replicate probability outputs into a binary map by using the maximal threshold value that minimized the training and test omission rate. Once we got the ten binary maps, we assembled them together into one final map where the presence area was where all models coincided, to reduce uncertainty produced by variations in the replicates ("ensemble forecast" Araújo and New 2006).

We combined the final binary map with the 19 bioclimatic variables obtained for 2030 under the emission scenario A2. We obtained a bioclimatic profile for each pixel of the potential distribution area and calculated the distance to the current NC or NO using the regression equation. In this way, we identified the geographic areas with potentially higher yields in the future for the races Bolita, Celaya and their corresponding clusters found.

3. Results

3.1 Yield *vs* distance to ecological centroids and optima

The niche optima (NO) value was identified via ecological niche modeling and consequently we present results of model performance. Under current climatic conditions, the ecological niche models presented a good performance as indicated by their AUC values that were always above 0.9 (from a range between 0-1) (Appendix 1 to see further details).

We found that correlations between yield and distance to NC and NO were significant in five out of 10 races (Bolita, Celaya, Cónico Norteño, Olotillo and Tabloncillo) (Table 2 and Appendix 2). For Celaya, Tepecintle and Vandeño, R^2 was higher when evaluating the distance to the NO than to the NC, whereas the revers was observed for the rest. In other words, yields of three out of 10 races were more dependent to the distance to the NC than to the NO (Table 2). Nevertheless, the highest significant R^2-value was obtained for Celaya between yield and NO (Table 2).

To identify the geographic areas where higher yields are expected under current climatic conditions we only used those races that got significant determination coefficient values higher than 20% either to the niche centroid or optima, namely Bolita (R^2= 24.7%) and Celaya (R^2= 25.3%) (Table 2), the rest were discarded given their low predictive capacity. Clusters were created within these two races resulting in 5 clusters for Bolita and 7 for Celaya (Table 2). For Bolita only two clusters presented enough yield data to carry out the analysis. In the case of Celaya we could work with 5 out of 7 clusters (Table 2, Appendix 3). From the clusters or clusters obtained, only one in each race had a stronger relationship between yield and NC (Bolita 1, R^2= 41.3%) or NO (Celaya 7, R^2= 77.6%) than the one obtained at a race level. These clusters with a stronger relationship between optima conditions (NC or NO) and yield were also used to project areas with higher yields under current and future climatic conditions.

3.2 Potential distribution maps under current and future climatic conditions

In the case of Bolita, higher yields under current climatic conditions are expected mainly in Oaxaca and Guanajuato (≥3000 kg/ha) (Fig. 1). Under future ones, high yields shift to the north of the country and although we can still find high yields in the northern area of Oaxaca and in Guanajuato, higher yields might also be present in Zacatecas, Michoacán and Jalisco. In the case of the cluster Bolita 1 (which represents 49 out of 102 records), higher yields were observed in Oaxaca and Guanajuato under current climatic conditions. Under future scenario, the areas with the potential of having greater yields shift also north reaching states such as Zacatecas. In compare to the maps at a race level, maps for Bolita 1 under current and future conditions have larger areas with the potential of greater yields.

For the Celaya race, under current climatic conditions higher yields can be found in Guanajuato, Querétaro and Michoacán. In the future, areas with the potential of having greater yields might be expanded up to northern states such as Durango to southern states like Oaxaca; reaching several states in the center of the country. In the cluster Celaya 7, yields ≥ 3000 kg/ha can be found mainly in Michoacán, but also in Zacatecas, San Luis Potosí, Oaxaca and Hidalgo. Under climate change conditions very similar distribution of higher yields can be expected in compare to current conditions, but some potential distribution area projecting high yields might be found further north in Nuevo León and Tamaulipas.

4. Discussion

4.1 Yield *vs* distance to ecological centroids and optima

Both, population and geographic ecology are disciplines that have had a major role in conservation biology (Edwards et al. 1993, Menon and Bawa 1997, Caswell 2001). The intersection between these two areas can help us identifying geographic areas where higher abundances can be found, having significant impacts on ecological management.

Ecological theory has proposed that optima environmental conditions should be closer to the ecological centroid and thus abundance should follow a 'center-abundant' pattern in ecological space (Maguire 1973). Two studies have empirically demonstrated that this relationship does exist (Yañez-Arenas et al. 2012, Martinez-Meyer et al. 2013). Here we observed that 5 out of 10 races presented a significant relationship between yield and the NC or NO. For some races (e.g., Celaya) optimal environmental conditions did not coincide with the niche centroid but with other niche optima. This might be related to the condition of a domesticated species, as several factors other than purely environmental play an important role in its productivity, such as farming technology (Bellon and Brush 1993, Brush and Perales 2007, Ureta et al. 2013). Finally, 5 out of 10 races did not show a relationship between yield and NC or NO.

4.2 Potential distribution maps under current and future climatic conditions

From the 10 races evaluated we only used 2 to create maps to identify areas with higher yields under current climatic conditions because were significantly different from the null model (Table 1) and with the highest significant R^2 value. These races were Bolita and Celaya; which are being produced with considerable success (reaching up to yields ~8000 kg/ha) in central and western Mexico.

Due to the large distribution of our races under study and the strong adaptation of different local populations to their environment, we thought that groups of populations within the race might have their own NC and NO value. That is why we decided to create clusters of the two races that were projected under current and future condition. One of the problems with which we had to deal was the fact that not all the clusters got enough yield data. Nevertheless, we used the clusters with which it was possible to carry out the analysis. Quite stronger relationships between yield and the NC or NO were found in only one cluster for each race. NC and NO values vary between clusters showing the diversity of populations that exist in one single race and that are adapted to different environmental conditions. Our experience shows that with a more complete set of yield data, dividing the races in bioclimatic clusters might help creating more accurate models. Therefore, when looking for higher yields in other cultivated species (or abundances in wild species) with large distribution; we strongly recommend making clusters before carrying out the entire analysis.

Races and clusters were projected under a drastic climate change scenario A2 in 2030, which showed that in the future, areas with the potential of having greater yields will reach northern states in both races and clusters. This pattern of shifting to northern distributions under climate change has been already reported in several species (Chen et al. 2011), however; this is the first time reporting shifts not only in terms of presence but of high yield areas.

Reductions in areas with higher yields were not found in Bolita or Celaya under climate change conditions. On the contrary, Celaya's high yield distribution expanded under future conditions and for both races and clusters northern states will become potentially suitable to grow them successfully. Bolita and Celaya have been classified as native races adapted to hydric stress in at least one part of their life cycle (Ruiz-Corral et al. 2013), consequently they might be able to resist harsher conditions expected in the future for northern states in Mexico. Carrying out this kind of analysis to visualize how our native maize production might be managed under climate change conditions, highlights the importance of having better yield data of these races at a national scale. Native races are expected to have a better success under harsher environmental conditions than improved varieties (Smith et al. 2001), but it is important to know how well will each race perform in different areas of the country to create a national plan of maize production.

4.3 Methodological Issues

The resolution used in our climatology under current and future conditions was of 1km^2. We are aware of the fact that increasing resolution in climate change scenarios increases uncertainty. However; Mexican maize growing takes place in a couple of hectares and consequently we need high resolution maps to evaluate impacts.

Finally, we emphasize that yield data have to be improved in order to produce more reliable models to be able to launch adaptation plans not only for the conservation of races, but to protect small farmers. There are isolated notable efforts taking place to help local smallholders by participatory improvement (Bellon et al. 2003, Pulido and Bocco 2003), but a large scale view would help to identify spots where more attention should be given.

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Table 1. Data of analyzed races and clusters

		Ocurrances	Yield Data
Race	Bolita	102	26
Clusters	Bolia1	49	7
	Bolita2	30	15
	Bolita3	12	0
	Bolita4	8	0
	Bolita5	5	0
Race	Celaya	259	85
Clusters	Celaya1	85	23
	Celaya2	39	8
	Celaya3	37	29
	Celaya4	28	15
	Celaya5	27	0
	Celaya6	10	0
	Celaya7	34	5
Race	Cónico Norteño	511	234
Race	Nal-tel	31	9
Race	Olotillo	475	177
Race	Ratón	237	91
Race	Tabloncillo	273	60
Race	Tepecintle	251	68
Race	Tuxpeño	1265	529
Race	Vandeño	194	78

Table 2. Evaluation of correlation models to describe Yield *vs* Distance to the Ecological Niche Centroid and Optima.
A= Races, B= Clusters, Best models = models that obtained the highest AIC values, AIC (Akaike Information Criterion) = AIC values obtained for the null and chosen model for the centroid and the optima value, R^2 = coefficient of determination obtained for the chosen model, N = number of occurrences with yield data, P= R^2 significance *p*-value.

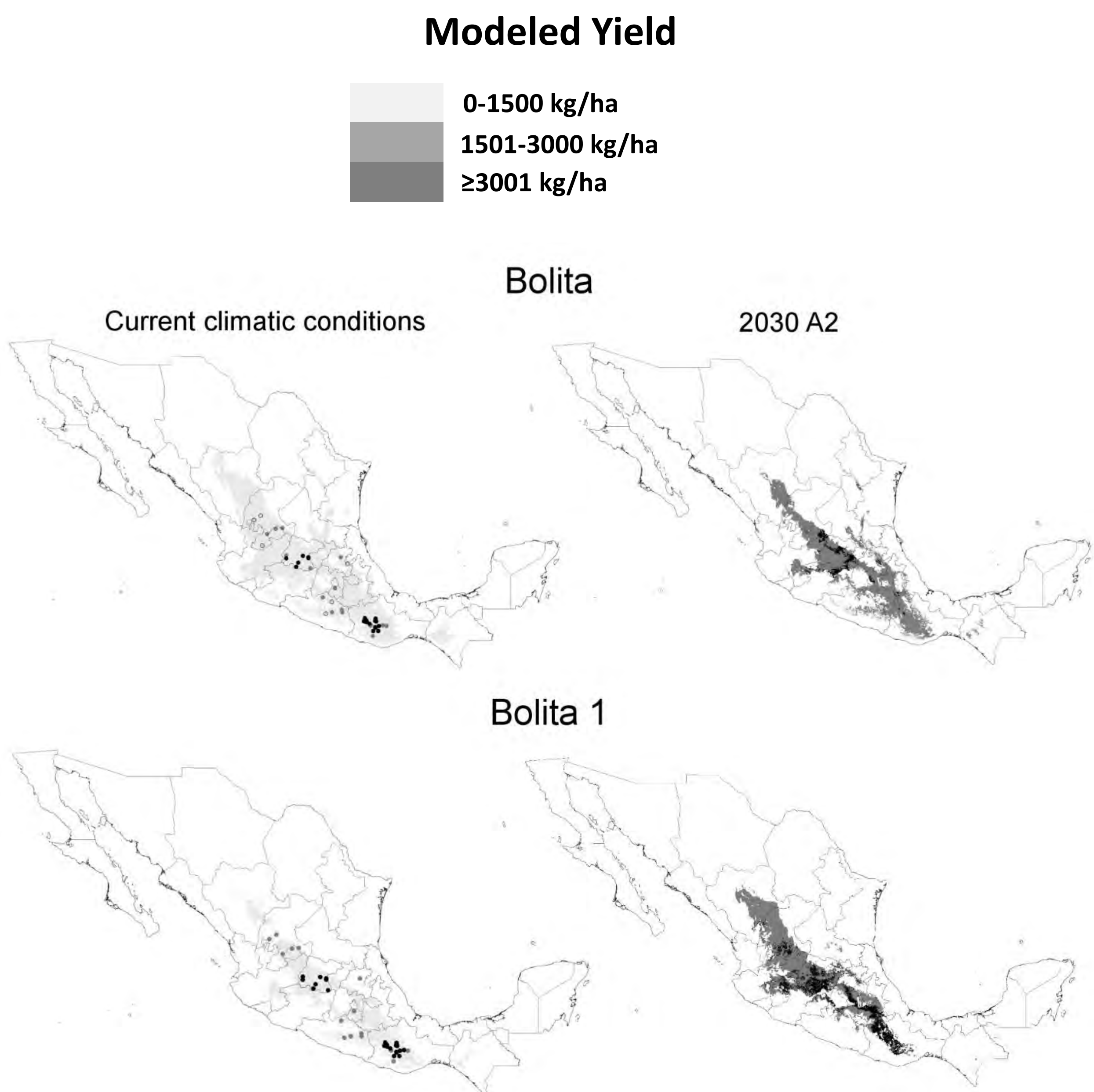
A)

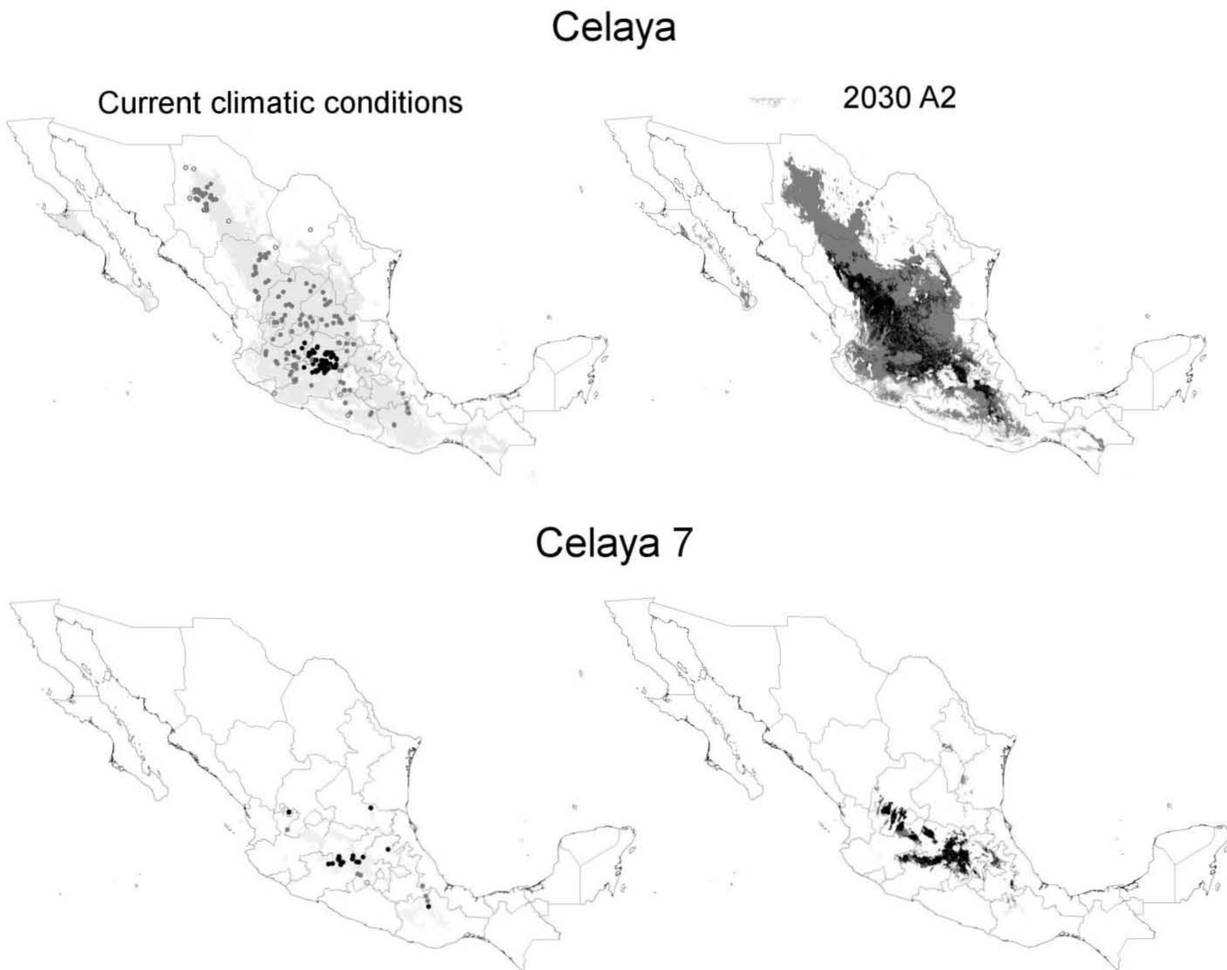
Races	**Best Models**		**AIC**			**R^2**			**P[a]**	
	Centriod	Optimum	Null model	Centriod	Optimum	Centriod	Optimum	N	Centriod	Optimum
Bolita	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times$ Distance	443.076	437.674	439.229	**0.247**	0.200	26	0.0100	0.0210
Celaya	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	1469.329	1453.219	1446.592	0.192	**0.253**	85	≤0.001	≤0.001
Cónico Norteño	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	3922.503	3902.876	3908.679	**0.089**	0.150	234	≤0.001	≤0.001
Nal-tel	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	147.663	146.553	148.491	**0.292**	0.123	9	0.130	0.800
Olotillo	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	2851.283	2827.587	2829.424	**0.132**	0.126	177	≤0.001	≤0.001
Ratón	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	1528.430	1528.057	1528.951	**0.025**	0.016	91	0.1200	0.2300
Tabloncillo	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	1058.425	1051.488	1051.487	**0.194**	0.185	60	0.0030	0.0030
Tepecintle	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	1105.253	1105.617	1104.417	0.024	**0.041**	68	0.2090	0.0980
Tuxpeño	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	8977.315	8975.833	8977.463	**0.007**	0.003	529	0.0620	0.1110
Vandeño	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	1358.328	1359.709	1359.233	0.007	**0.014**	78	0.4388	0.3030

B)

Cluster	Best Models		AIC			R^2			P^a	
	Centriod	Optimum	Null model	Centriod	Optimum	Centriod	Optimum	N Yield	Centriod	Optimum
Bolita1	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	119.474	117.748	120.174	**0.413**	0.170	7	0.009	0.049
Bolita2	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	257.838	257.692	258.215	**0.133**	0.103	15	0.001	0.020
Bolita3								1		
Bolita4								1		
Bolita5								2		
Celaya1	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	389.686	388.327	386.319	0.136	**0.208**	23	0.001	0.003
Celaya2	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	135.182	134.972	134.922	0.241	**0.246**	8	0.007	0.011
Celaya3	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	479.549	476.841	478.206	**0.150**	0.109	29	≤0.001	≤0.001
Celaya4	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ Distance	254.721	255.016	256.420	**0.107**	0.020	15	0.014	0.051
Celaya5								0		
Celaya6								0		
Celaya7	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$	Yield = $\beta_0 + \beta_1 \times$ Distance	92.521	93.926	87.042	0.112	**0.776**	5	0.323	0.036

Fig. 1 Yield prediction under current and future climatic conditions.
For Bolita and Bolita 1, we used the correlation between yield and NC. For Celaya and Celaya 7 we used the correlation between yield and NC. Under current climatic conditions the gray area corresponds to the potential distribution area of the race or the cluster. The circles correspond to records of presence which yield values were modeled. Under 2030 A2 scenario, we present the potential distribution area in the future with its potential yield values.




Celaya
Current climatic conditions
2030 A2
Celaya 7

Appendix. 1. AUC values for current conditions

		Average AUC Values
Races	Clusters	Current
Bolita		0.972 ± 0.007
	Bolita 1	0.947 ± 0.021
	Bolita 2	0.95 ± 0.034
Celaya		0.954 ± 0.005
	Celaya 1	0.989 ± 0.003
	Celaya 2	0.961 ± 0.011
	Celaya 3	0.993 ± 0.003
	Celaya 4	0.978 ± 0.008
	Celaya 7	0.979 ± 0.011
Cónico Norteño		0.961 ± 0.002
Nal-tel		0.983 ± 0.01
Olotillo		0.964 ± 0.011
Ratón		0.936 ± 0.008
Tabloncillo		0.968 ± 0.004
Tepecintle		0.967 ± 0.005
Tuxpeño		0.906 ± 0.004
Vandeño		0.964 ± 0.006

Appendix 2. Correlation models at a race level and clusters for Bolita and Celaya

Race	Null model	Models	
Bolita	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0	0.231	0.248
Optimum R^2	0	0.201	0.188
Centroid AIC	**509.978**	438.243	437.674
Optimum AIC	**509.978**	439.229	439.673
Centroide β_0	2880.357	3973.943	4429.857
Centroide β_1	NA	-393.123	-1533.512
Optimum β_0	2880.357	4628.480	5962.930
Optimum β_1	NA	-420.934	-2170.772

Cluster	Null model	Models	
Bolita 1	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.403	0.413
Optimum R^2	0.000	0.197	0.170
Centroid AIC	119.474	117.859	117.748
Optimum AIC	119.474	119.937	120.174
Centroide β_0	2892.857	5105.161	5416.842
Centroide β_1	NA	-674.463	-2191.692
Optimum β_0	2892.857	4976.774	5751.955
Optimum β_1	NA	-474.003	-1956.024

Cluster	Null model	Models	
Bolita 2	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.129	0.133
Optimum R^2	0.000	0.102	0.103
Centroid AIC	257.838	257.764	257.692
Optimum AIC	257.838	258.232	258.215
Centroide β_0	2066.667	3007.451	3064.673
Centroide β_1	NA	-262.003	-855.179
Optimum β_0	2066.667	3799.993	6102.056
Optimum β_1	NA	-182.861	-1811.182

Race	Null model	Models	
Celaya	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0	0.192	0.171
Optimum R^2	0	0.253	0.250
Centroid AIC	**1516.620**	1453.219	1455.414
Optimum AIC	**1516.620**	1446.592	1446.861
Centroide β_0	2397.965	3715.348	3852.039
Centroide β_1	NA	-338.380	-1168.236
Optimum β_0	2397.965	4192.109	4920.918
Optimum β_1	NA	-371.330	-1685.519

Cluster	Null model	Models	
Celaya 1	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.136	0.103
Optimum R^2	0.000	0.208	0.200
Centroid AIC	389.686	388.327	389.181
Optimum AIC	389.686	386.319	386.550
Centroide β_0	3091.304	4774.317	5002.344
Centroide β_1	NA	-467.546	-1522.323
Optimum β_0	3091.304	6628.427	8830.355
Optimum β_1	NA	-725.635	-3643.191

Cluster	Null model	Models	
Celaya 2	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.241	0.180
Optimum R^2	0.000	0.246	0.192
Centroid AIC	135.182	134.972	135.594
Optimum AIC	135.182	134.922	135.474
Centroide β_0	1975.000	2862.026	3418.063
Centroide β_1	NA	-184.342	-971.474
Optimum β_0	1975.000	3064.764	3914.033
Optimum β_1	NA	-199.649	-1184.778

Cluster	Null model	Models	
Celaya 3	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.150	0.139
Optimum R^2	0.000	0.109	0.097
Centroid AIC	479.549	476.841	477.195
Optimum AIC	479.549	478.206	478.579
Centroide β_0	1546.552	2431.904	2714.862
Centroide β_1	NA	-219.545	-881.577
Optimum β_0	1546.552	2441.921	2958.997
Optimum β_1	NA	-188.448	-933.608

Cluster	Null model	Models	
Celaya 4	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.107	0.115
Optimum R^2	0.000	0.020	0.013
Centroid AIC	254.721	255.016	254.889
Optimum AIC	254.721	256.420	256.527
Centroide β_0	2493.333	4414.280	5148.174
Centroide β_1	NA	-556.728	-2167.674
Optimum β_0	2493.333	3255.590	3373.557
Optimum β_1	NA	-181.203	-620.409

Cluster	Null model	Models	
Celaya 5	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.112	0.082
Optimum R^2	0.000	0.776	0.789
Centroid AIC	92.521	93.926	94.092
Optimum AIC	92.521	87.042	86.731
Centroide β_0	2800.000	5737.816	6111.325
Centroide β_1	NA	-778.498	-2528.494
Optimum β_0	2800.000	23647.993	42304.625
Optimum β_1	NA	-2877.207	-19975.003

Cluster	Null model	Models	
Celaya 7	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0.000	0.112	0.082
Optimum R^2	0.000	0.776	0.789
Centroid AIC	92.521	93.926	94.092
Optimum AIC	92.521	87.042	86.731
Centroide β_0	2800.000	5737.816	6111.325
Centroide β_1	NA	-778.498	-2528.494
Optimum β_0	2800.000	23647.993	42304.625
Optimum β_1	NA	-2877.207	-19975.003

Race	Null model	Models	
Cónco Norteño	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0	0.088	0.065
Optimum R^2	0	0.146	0.150
Centroid AIC	**4021.944**	3902.876	3908.679
Optimum AIC	**4021.944**	3887.609	3886.421
Centroide β_0	1543.830	770.142	827.454
Centroide β_1	NA	200.655	566.069
Optimum β_0	1543.830	-529.293	-2204.004
Optimum β_1	NA	385.764	2254.428

Race	Null model	Models	
Nal-tel	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times \ln(\text{Distance})$
Centroid R^2	0	0.261	0.292
Optimum R^2	0	0.123	0.122
Centroid AIC	**147.663**	146.946	146.553
Optimum AIC	**147.663**	148.478	148.491
Centroide β_0	1022.222	4109.261	3765.258
Centroide β_1	NA	-1317.805	-3248.736
Optimum β_0	1022.222	-673.154	-369.667
Optimum β_1	NA	705.657	1608.956

Race	Null model	Models	
Olotillo	Yield	$Yield = \beta_0 + \beta_1 \times Distance$	$Yield = \beta_0 + \beta_1 \times \ln(Distance)$
Centroid R^2	0	0.107	0.135
Optimum R^2	0	0.117	0.126
Centroid AIC	**2851.283**	2833.203	2827.587
Optimum AIC	**2851.283**	2831.256	2829.424
Centroide β_0	1168.689	607.377	164.069
Centroide β_1	NA	161.556	849.970
Optimum β_0	1168.689	-110.906	-1618.537
Optimum β_1	NA	214.999	1576.736

Race	Null model	Models	
Ratón	Yield	$Yield = \beta_0 + \beta_1 \times Distance$	$Yield = \beta_0 + \beta_1 \times \ln(Distance)$
Centroid R^2	0	0.026	0.020
Optimum R^2	0	0.016	0.015
Centroid AIC	**1528.430**	1528.057	1528.550
Optimum AIC	**1528.430**	1528.951	1529.028
Centroide β_0	1693.956	2251.865	2346.157
Centroide β_1	NA	-144.860	-500.332
Optimum β_0	1693.956	2440.549	3099.079
Optimum β_1	NA	-116.633	-763.016

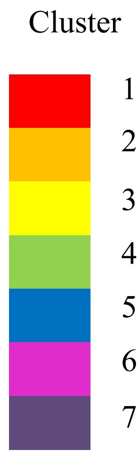
Race	Null model	Models	
Tabloncillo	Yield	$Yield = \beta_0 + \beta_1 \times Distance$	$Yield = \beta_0 + \beta_1 \times \ln(Distance)$
Centroid R^2	0.000	0.138	0.123
Optimum R^2	0.000	0.138	0.115
Centroid AIC	**1058.425**	1051.488	1052.517
Optimum AIC	**1058.425**	1051.487	1053.114
Centroide β_0	3374.167	4511.171	5091.998
Centroide β_1	NA	-277.926	-1314.373
Optimum β_0	3374.167	4771.044	5882.070
Optimum β_1	NA	-233.993	-1463.737

Race	Null model	Models	
Tepecintle	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ ln(Distance)
Centroid R^2	0	0.024	0.022
Optimum R^2	0	0.021	0.041
Centroid AIC	**1165.296**	1105.617	1105.775
Optimum AIC	**1165.296**	1105.841	1104.417
Centroide β_0	1271.290	841.598	614.159
Centroide β_1	NA	88.229	434.982
Optimum β_0	1271.290	2009.259	3698.719
Optimum β_1	NA	-118.903	-1302.185

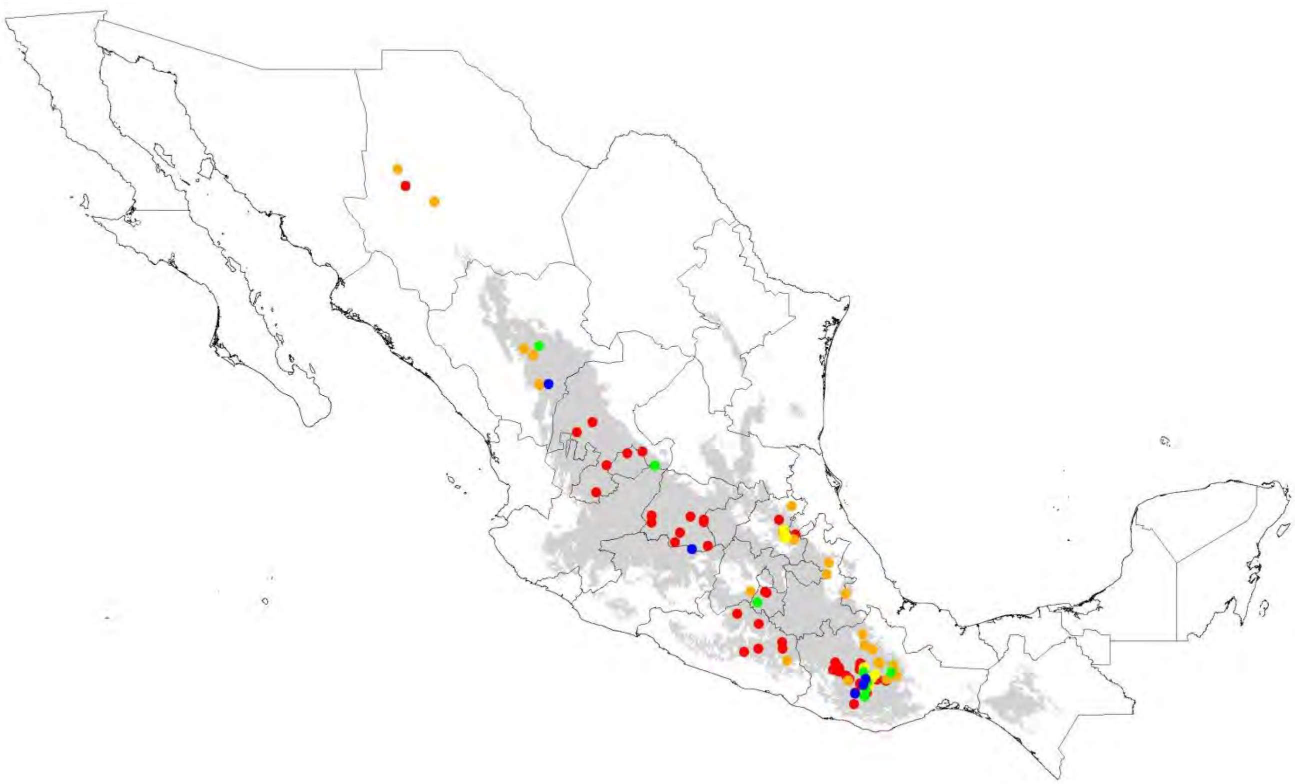
Race	Null model	Models	
Tuxpeño	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ ln(Distance)
Centroid R^2	0	0.020	0.016
Optimum R^2	0	0.023	0.040
Centroid AIC	**9297.127**	1105.867	1106.174
Optimum AIC	**9297.127**	1105.679	1104.465
Centroide β_0	1967.270	604.567	460.769
Centroide β_1	NA	127.178	482.939
Optimum β_0	1967.270	670.104	-77.451
Optimum β_1	NA	48.522	543.195

Race	Null model	Models	
Vandeño	Yield	Yield = $\beta_0 + \beta_1 \times$ Distance	Yield = $\beta_0 + \beta_1 \times$ ln(Distance)
Centroid R^2	0	0.008	0.003
Optimum R^2	0	0.014	0.010
Centroid AIC	**1358.328**	1359.709	1360.131
Optimum AIC	**1358.328**	1359.233	1359.567
Centroide β_0	2234.385	2429.793	2388.751
Centroide β_1	NA	-57.946	-144.295
Optimum β_0	2234.385	2700.755	2972.290
Optimum β_1	NA	-83.204	-442.168

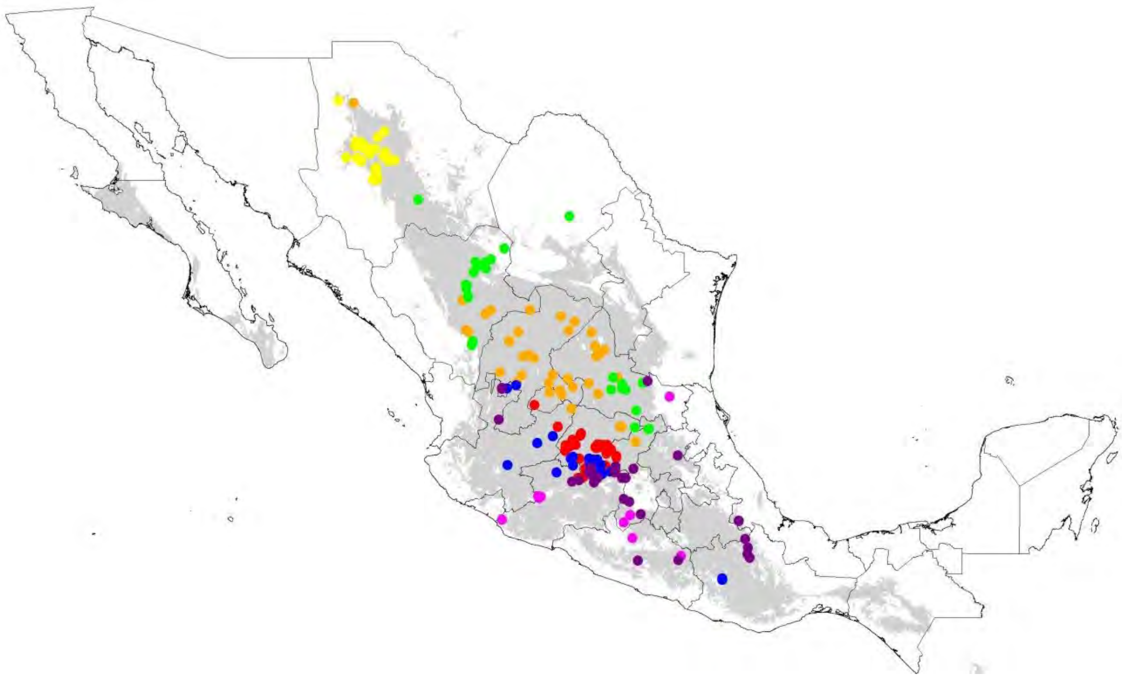
Appendix 3.Potential distribution areas of the races evaluated under current climatic conditions and occurrences of the clusters obtained for each race.



BOLITA



CELAYA



Discusión General

Este trabajo es un primer paso para conocer los impactos y la vulnerabilidad de las razas de maíz mexicano frente a una de sus principales amenazas que es el cambio climático. Nuestros resultados muestran que hay la posibilidad de mantener la seguridad alimentaria sin poner en riesgo nuestra agrobiodiversidad y cultura. Parte de la información contenida en este escrito puede guiar la generación de políticas públicas que estén vinculadas con la adaptación al cambio climático para evitar consecuencias graves a un nivel social, económico, político, cultural y ambiental.

Impactos y Vulnerabilidad del Maíz Mexicano al Cambio Climático

En nuestro primer capítulo se pudo identificar que la mayoría de las razas nativas de maíz tendrán reducciones significativas en su área de distribución potencial para el 2050 y entre escenarios de emisiones A2 (“bussiness as usual”) y B1 (550 ppm) (Conde y Gay 2008), que representan el más pesimista y optimista de los escenarios respectivamente. Estos impactos diferenciales entre escenarios sugieren que las acciones que se tomen a nivel global van a tener consecuencias incluso a un nivel local. En esta primera parte también se localizaron las zonas geográficas en México que tanto en el presente como en el futuro se espera sean las que potencialmente puedan tener la mayor diversidad de razas de maíz de acuerdo a las condiciones bioclimáticas. Estas zonas abarcan los estados de Oaxaca, Chiapas, el centro del país, Jalisco y alrededores y bajo condiciones de cambio climático se espera que no haya cambios importantes en estas áreas. Los estados de mayor riqueza de maíz señalados por el grupo de Kato *et al*. (2009) son muy similares a las nuestros, con la excepción del estado de Chihuahua. La importancia de la parte norte de nuestro país en términos de riqueza se vuelve más evidente en el segundo capítulo de esta tesis, en la que ya se toma en cuenta todos los datos de presencias recabados por CONABIO en los último años (Acevedo 2011). Es también en este segundo capítulo en el que se modeló con todos los registros existentes hasta el momento que se puede demostrar que tenemos la suficiente riqueza de maíz como para poder sembrar al menos una raza en prácticamente cualquier parte del territorio nacional. Este resultado destaca la importancia de proteger todo el país para garantizar la conservación del maíz mexicano.

Los mayores decrementos en áreas de distribución potencial se dieron principalmente en las zonas de menor riqueza (menos de 8 razas). Por lo tanto, se puede concluir que estas zonas de menor riqueza son más vulnerables a los cambios en el clima. En las zonas de mayor riqueza, si ciertas razas son impactadas de manera negativa por condiciones de cambio climático, existe la probabilidad de que otras razas puedan reemplazarlas. Esta situación indica que las zonas de mayor riqueza amortiguan de mejor manera los cambios en el clima, lo que destaca la importancia de la agrobiodiversidad para lidiar con estos cambios. Existe un estudio por Monterroso *et al*. (2011) que sugiere que las áreas con mayor aptitud para sembrar maíz serán las más afectadas por el cambio climático. Esta diferencia en resultado se debe a que las zonas de mayor riqueza de maíz mexicano no coincide con las zonas más aptas, ya que las razas nativas son sembradas muchas veces en condiciones subóptimas gracias a que ha habido una selección natural y artificial que ha permitido que varias razas se adaptan a una variedad grande de condiciones ambientales cubriendo necesidades tanto nutricionales como culturales (Morón 2003, Ruiz Corral et al. 2013). Por ejemplo, Apachito y Chapalote son razas endémicas del norte del país y adaptadas a condiciones de estrés hídrico (Ruiz Corral et al. 2013), por lo que su material genético puede ser muy útil para un futuro mejoramiento. Esta enorme diversidad que puede crecer en condiciones de estrés será muy importante bajo condiciones de cambio climático. La enorme diversidad genética del maíz le confiere una plasticidad biológica a un nivel intra e inter específico que puede estar jugando un papel muy importante en amortiguar los impactos del cambio climático (Mercer and Perales 2010).

Finalmente, razas de las que se espera una vulnerabilidad sobresaliente a las condiciones de cambio climático son aquéllas adaptadas a zonas de mayor altitud, como es el caso de Palomero Toluqueño. Aunque se ha reportado que las zonas de mayor altitud (Conde 1997) posiblemente se vuelvan más aptas para un mayor número de razas (porque la temperatura se verá incrementada), las razas que ya están adaptadas a estas condiciones climáticas se verán amenazadas al no encontrar sus condiciones bioclimáticas óptimas en el futuro.

Maíz en un Contexto Ambiental y Social

Posterior a nuestra evaluación sobre los impactos y vulnerabilidad de las razas de maíz nativo bajo condiciones de cambio climático, nos dimos cuenta que la siembra de maíz en México es una actividad tan compleja que se hacía necesario conocer qué otros factores tanto ambientales como sociales estaban teniendo influencia sobre la distribución de esta planta agrícola y, por lo tanto, en su conservación. Fue por esta razón que mediante un método reciente de minería de datos trabajamos mapas de distribución potencial y evaluamos relaciones entre 47 razas de maíz y factores ambientales (altitud, clima, suelo y pendiente) y sociales (grupo étnico y escolaridad).

El efecto de las variables ambientales y sociales sobre los patrones de distribución de razas nativas es un tema que ha sido de interés desde hace años (Sánchez González and Goodman, 1992; Bellon and Brush, 1993; Brush and Perales, 2007; Kato et al., 2009; Bellon and Hellin, 2011). En estos estudios se ha discutido y reconocido la importancia tanto de factores ambientales como de factores sociales sobre la distribución del maíz. Sin embargo, este artículo fue el primer intento en evaluar de manera comparativa la importancia relativa de factores sociales y ambientales sobre cada una de las razas de maíz mexicano.

En general la altitud resultó ser el factor que más influencia tiene sobre la distribución del mayor número de razas nativas; sin embargo, es claro que la altitud está íntimamente relacionada con las condiciones climáticas, particularmente de temperatura, insolación y concentración de oxígeno, entre otras. La altitud es en realidad, una variable que resume varios factores climáticos interactuando de manera simultánea y por lo tanto pueden estar encubriendo la verdadera importancia de diferentes factores independientes sobre la distribución del maíz. Tanto las condiciones de pendiente como las de suelo con las que las razas de maíz están significativamente relacionadas sugieren que además del clima hay otros factores ambientales muy relevantes y para los cuales el maíz también presenta importante variabilidad.

A pesar de que la mayoría de las razas están geográficamente más determinadas por condiciones ambientales que por factores sociales, usar factores sociales para crear mapas de distribución potencial incrementa el desempeño del modelo. Este hecho significa que factores como el grupo étnico también tienen influencia sobre la distribución del maíz mexicano y que en ocasiones puede llegar a ser el factor más influyente sobre la distribución de una raza en particular. Por lo tanto, al momento de hacer modelación de distribución potencial para alguna otra planta agrícola, es recomendable tomar en cuenta factores sociales, tal como es importante incluir interacciones biológicas en el caso de especies silvestres (Stephens et al. 2009). De las 62 etnias estudiadas incluidas en el análisis, 25 mostraron relación significativa con al menos una razas de maíz y para 12 razas fue el factor que en mayor medida determinaba su distribución geográfica. El factor de grupo étnico muestra también su importancia en las zonas de mayor riqueza de maíz. A pesar de que estas áreas constituyen de manera potencial únicamente cerca del 6.9% del territorio nacional, en este mismo fragmento del país encontramos 40% de los grupos étnicos. Este resultado concuerda con el trabajo de Boege (2010) en el que se presenta que los grupos étnicos han sido clave para crear y preservar la dinámica de la diversificación de las razas de maíz. Sin embargo, también hay que recordar la importancia a los agricultores mestizos en la conservación *in situ* de la diversidad de nuestro maíz nativo (Brush and Perales 2007).

Por otro lado, el nivel socioeconómico fue evaluado indirectamente a partir de la escolaridad, como se ha hecho en estudios de gobierno (INEGI 2012). El único nivel educativo que no presentó relación espacial significativa con ninguna raza, fue el nivel más alto que incluye licenciatura o más estudios. Los agricultores con preparación universitaria están enfocados principalmente a la producción de gran escala y no siembran razas nativas (INEGI 2012). Los agricultores de maíz nativo tienen en general poca educación formal y dependen íntimamente de tecnologías tradicionales para cultivar (Bellon et al. 2005).

Primeros Pasos Hacia la Adaptación

En el primer capítulo obtuvimos que bajo cambio climático podemos encontrar nuevas áreas de distribución potencial para varias razas que puede ser espacio geográfico explorable para siembras. Estas nuevas áreas representan regiones geográficas con condiciones ambientales aptas para que las razas y los taxa de los grupos de teocintle y *Tripsacum* puedan experimentalmente ser sembrados.

En el tercer capítulo se realizó una modelación de rendimientos tanto en condiciones climáticas del presente como en el futuro para conocer en dónde se podrían sembrar las distintas razas y con qué producción. Basándonos en la hipótesis de Maguire (1973) así como lo hecho por otros colegas (Yañez-Arenas et al. 2012, Martinez-Meyer et al. 2013), decidimos poner a prueba si era posible encontrar áreas geográficas con la potencialidad de tener mayores rendimientos en el presente y futuro de acuerdo a su cercanía con el centroide del nicho ecológico. Los mayores rendimientos se esperarían en las condiciones más óptimas (Boyer 1982), así como se observan las mayores abundancias en el caso de especies silvestres.

Nuestros resultados muestran que a pesar de la baja calidad de los datos de rendimiento de las razas nativas a nivel nacional, se pudieron encontrar relaciones significativas entre el rendimiento y la distancia al centroide o al valor óptimo del nicho ecológico en 5 de las 10 razas evaluadas. Se utilizaron 2 razas, Bolita y Celaya (por razones estadísticas) para proyectar su distribución potencial en el presente y futuro. Asimismo, también se llevó a cabo un análisis de conglomerados para obtener subrgupos dentro de estas razas que pudieran tener valores de centroide/óptimo de nicho diferentes.

Las áreas en las que se obtuvieron máximos rendimientos en el presente y futuro se encuentran principalmente en estados del centro y oeste del país. Sin embargo, la distribución de los máximos rendimientos se recorre a algunas zonas de estados en el norte bajo condiciones de cambio climático. Este resultado no es sorprendente ya que muchas especies han tenido que "desplazarse" hacia el norte por cambios en el clima (Chen et al. 2011). A pesar de que se espera que las condiciones en el norte del país se vuelvan más difíciles para la siembra (Conde y Gay 2008), las razas evaluadas están adaptadas a condiciones ambientales de estrés hídrico y térmico por lo que su material genético puede sobrellevar las nuevas condiciones en el norte e incluso servir para mejoramiento (Ruiz Corral et al. 2013).

Conclusiones

- Los modelos de nicho sugieren reducciones importantes en al área de distribución potencial para varias razas de maíz y sus parientes silvestres bajo condiciones de cambio climático.
- Los estados en los que hay más riqueza potencial de maíz son Chiapas, Oaxaca, Guerrero, Jalisco y el centro de México. Sin embargo, todo el territorio Mexicano es apto para crecer al menos una raza nativa de maíz y por lo tanto es importante su protección.
- Las razas de maíz y parientes silvestres más vulnerables a condiciones de cambio climático son: Palomero Toluqueño, Jala, Coscomatepec, Zapalote Grande, Chapalote, Apachito, Dzit-Bacal, *T. intermedium*, *T. laxum*, *T. latifolium*, *T. maizar*, *T. dactyloides hispidium*, *Z. diploperennis*, *Z. perennis*, *Z. mays mexicana* y *Z. parviglumis*.
- La altitud es el factor que más influencia tuvo sobre la mayoría de las 47 razas evaluadas. Sin embargo, la altitud es una variable que resume diversas condiciones climáticas actuando de manera simultánea, por lo que el clima es un factor determinante en la distribución de las razas de maíz mexicano

- Doce razas nativas estuvieron geográficamente mejor explicadas por la distribución de los grupos étnicos que por cualquier otra variable.
- Las áreas de mayor diversidad de maíz coinciden geográficamente con las áreas de mayor riqueza étnica.
- El desempeño del modelo resultado de la minería de datos mejora cuando se usan más variables para explicar la distribución.
- Existe una señal identificable en la relación entre el rendimiento y la distancia al centroide o al óptimo del nicho ecológico. Esta relación nos permite crear modelos espaciales a partir de la correlación y conocer los posibles rendimientos bajo condiciones actuales y bajo condiciones de cambio climático.

Recomendaciones

- Proteger a todo México como centro de origen y diversificación de maíz para garantizar la conservación de su diversidad.

- Establecer sistemas de monitoreo para los taxa que fueron identificados como los más vulnerables.
- Apoyar con más vehemencia el mejoramiento participativo como una forma de conservar *in situ*.
- Incorporar información en bancos de semillas para que sirvan como un mecanismo complementario de conservación.
- Crear un esquema formal de conservación para proteger las razas más vulnerables al cambio climático.
- Incrementar las muestras para las razas que tienen menos registros e incrementar el número y la calidad de los datos de rendimiento.
- Una vez mejorada la calidad de los datos, modelar los rendimientos de todas las razas nativas bajo condiciones de cambio climático para tener más información que permita la generación de planes de manejo.
- Mejorar la calidad de datos sociales existentes como los datos sobre el nivel socioeconómico del agricultor y su grupo étnico, si aplica.

- Mejorar e incrementar la información sobre plagas agrícolas y otros organismos que presentan interacción biológica con el maíz.
- Si se pretende modelar el área de distribución potencial de otras especies agrícolas que están siendo cultivadas por pequeños productores, es recomendable incorporar información de aspectos sociales.
- Utilizar aquellas razas que pueden crecer y obtener rendimientos bajo condiciones de estrés hídrico o térmico para mejoramiento genético.

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