Effects of climate change on nine rainfed *Zea mays* races in Chiapas, Mexico

Efectos del cambio climático sobre nueve razas de temporal de *Zea mays* en Chiapas, México

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Originales: *Recepción:* 30/07/2024 - *Aceptación:* 14/04/2025

Abstract

Maize cultivation (*Zea mays)* is essential for Mexico from a nutritional, cultural and economic perspective. Scientific literature ignores the impact of anthropogenic causes of climate change on rainfed cultivation of *Z. mays* in Chiapas, Mexico, one of the poorest states in the country. Therefore, we modeled the feasibility of rainfed cultivation for nine races of rainfed maize for the years 2060 and 2100. The MaxEnt 4.4.4 algorithm modeled maize cultivation under two scenarios (4.5 and 8.5) for 2060 and 2100. Model inputs were 12 bioclimatic variables, 3 climatic variables, and 1 elevation variable. All layers were obtained from the WorldClim 2.1 project. By 2060, the suitable area for rainfed cultivation of the nine *Z. mays* races would drastically decrease under both modeled scenarios. By 2100, this area will decrease for seven races, and disappear for the Olotillo and Olotón races. To the best of our knowledge, this is the first study providing fundamental information on how climate change will negatively impact the nine *Z. mays* races in Chiapas, Mexico. This enables the development of sustainable management protocols or conservation strategies.

Keywords

bioclimatic variables • climatic variables • elevation • MaxEnt 4.4.4 • rainfed maize races

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Resumen

El cultivo de maíz (*Zea mays*) es de gran importancia para la población de México desde una perspectiva nutricional, cultural y económica. La literatura científica carece de información sobre el impacto del cambio climático antropogénico en el cultivo de temporal de *Z. mays* en Chiapas, México, uno de los estados más pobres del país. Es por ello que modelamos la viabilidad del cultivo de temporal para nueve razas de maíz de temporal para los años 2060 y 2100. Se utilizó el algoritmo MaxEnt 4.4.4 para modelar bajo dos escenarios (4.5 y 8.5) para el 2060 y el 2100. El modelo se alimentó con 12 variables bioclimáticas, 3 variables climáticas y una variable de elevación. Todas las capas se obtuvieron del proyecto WorldClim 2.1. Se proyecta que el área adecuada para el cultivo de temporal de las nueve razas de *Z. mays* disminuirá drásticamente para 2060 bajo los escenarios 4.5 y 8.5. Para el año 2100, bajo los mismos escenarios, la superficie se reducirá para siete razas, mientras que en las razas de maíz Olotillo y Olotón desaparecerá por completo. Por primera vez, se proporciona información fundamental sobre cómo el cambio climático impactará negativamente a las nueve razas de *Z. mays* en Chiapas, México, lo que permitirá desarrollar protocolos de manejo sustentable y/o estrategias de conservación.

Palabras clave
variables bioclimáticas • variables climáticas • elevación • MaxEnt 4.4.4 • razas de maíz de temporal

Introduction

Agriculture is the primary source of global food supply (7). However, this activity is severely threatened by anthropogenic causes of climate change, especially for rainfed crops (21). Increases in environmental temperature, changes in precipitation patterns, and drought events often reduce crop production area (34).

Maize (*Z. mays)* constitutes an essential food in Mexico. It is a highly nutritious source consumed in various presentations, holding particular socio-cultural value for indigenous people and the whole population (24, 32).

Maize production is relevant for national and international markets (44). However, in southeastern Mexico, most rainfed maize areas are being abandoned given social issues, changes in land use, poor technological implementation, and inadequate public policies (55). In Chiapas, farmers are vulnerable to these changes. Aimed at sustaining rainfed maize production, many have resorted to hybrid seeds, declining native varieties and losing ancestral techniques in favor of contemporary ones (31).

Mexico's maize races are cataloged in 7 racial groups based on morphology, adaptation types, and genetic traits (20, 51, 52). Within these groups, the National Commission for Knowledge and Use of Biodiversity (2020) reports a total of 64 races, 59 of which are native. In Chiapas, 11 races have been documented, with 9 having geographical records associated with rainfed agriculture: Zapalote Chico, Cubano Amarillo, Tepecintle, Zapalote Grande, Tuxpeño, Vandeño, Comiteco, Olotón and Olotillo (10), specimens registry of the National Biodiversity Information System (www.snib.mx/).

No study has yet analysed the impact of climate change on cropping areas for these maize races in the state of Chiapas, Mexico. This information is crucial considering approximately 88% of total maize production in Chiapas depends on rain cycles (30). Each race is cultivated in distinct environmental conditions, adapted to specific temperature, precipitation, and elevation (3, 6, 11, 36, 56). Therefore, this study aims to determine whether these races will be differently affected by climate change and provide insights for sustainable management plans (49, 57). This, considering reproductive and adaptation strategies, and cultural practices preventing their disappearance (33).

Materials and methods

Study area

The study area encompassed the entire state of Chiapas, located in southeastern Mexico. It borders the state of Tabasco to the north, Veracruz and Oaxaca to the west, the Pacific Ocean to the south, and Guatemala to the east. It spans 74,415 km^2 (13) and lies between 17°59' to 14°32' N and 90°22' to 94°14' W.

Annual precipitation varies widely across the state, ranging from 800 to 2,500 mm. Variations in the north range from 1,500 to 2,500 mm and between 1,500 and 2,000 mm in the south. In the central part of the state, most areas register annual precipitation between 800 and 1,200 mm, while in the rest of the state, precipitation ranges from 1,200 to 1,500 mm (54).

Chiapas held the first place in harvested maize area from 2010 to 2021. However, now the state ranked 6th in national production volume with 1.3 million tons (45).

Database of spatial records for nine maize races (*Z. mays*) in Chiapas

Georeferenced records for the nine maize races were obtained from scientific databases such as the 2023 Geoinformation Portal from the National Commission for the Knowledge and Use of Biodiversity (2023), the Biodiversity Information Facility (www.gbif.org/es/), COMPADRE (https://compadre-db.org/; COMPADRE Plant Matrix Database 2023), and the Specimen Register of the National System of Information on Biodiversity (www.snib.mx/).

After removing all duplicated records or those with erroneous coordinates (42), we defined 1,215 records for the Comiteco race, 60 for Cubano Amarillo, 209 for Olotillo, 456 for Olotón, 77 for Tepecintle, 1,159 for Tuxpeño, 63 for Vandeño, 13 for Zapalote Chico, and 40 for Zapalote Grande, totaling 3,292 presence records.

Finally, using the "spThin" package in R software and RStudio, the spatial correlation among the presence data for the nine maize races was reduced through 100 iterations (2, 47, 50).

Environmental layers for the nine rainfed maize races

Environmental layers for minimum, maximum, and average monthly temperatures, monthly cumulative rainfall, elevation and 19 bioclimatic variables were obtained to determine suitable environmental conditions for the nine rainfed maize races in Chiapas. These layers correspond to cultivating periods for each race in Chiapas. The cropping season for the Zapalote Chico race occurs from May (planting) to August (harvest) (3, 28, 36). In contrast, Cubano Amarillo, Tepecintle, Vandeño, Tuxpeño, and Zapalote Grande extend from May to October (11), while Comiteco, Olotón, and Olotillo races grow from May to December (3, 11).

All layers were obtained from the WorldClim 2.1 project (18). Each environmental variable consists of a georeferenced raster layer with a spatial resolution of 30 seconds (~1 km^2) (19). Layers were cropped using the georeferenced boundary of the state of Chiapas using R software and its graphical interface, RStudio (47, 50).

Current feasibility of the nine rainfed maize races

To determine current feasibility of the nine maize races, the model was calibrated to the current scenario using the Maxent 4.4.4 algorithm operating on presence data of a particular species to predict its geographical distribution based on maximum entropy (14).

The calibration area was Chiapas, with 75% of presence records used for training and 25% for evaluation. The model was configured with a logistic function and ten cross-validation replicates (41).

A Jackknife test assessed variable contributions, while predictive capacity was evaluated using the area under the curve (AUC) (39). Any replicates under 0.9 were discarded. Then, pixel reclassifications of the resulting raster layer of each replicate (.asc) allowed obtaining a binary map (0 = no feasibility for the nine rainfed maize races, 1 = feasibility for the nine rainfed maize races) using the 10th percentile presence value as cut-off point (27).

Using QGIS version 3.285 (43), the binary map was multiplied for each cross-validation replicate, obtaining a unique raster for each maize race. Binary maps (rasters) were polygonised, and each polygon on the map was dissolved to obtain surface areas in hectares and generate maps of regional feasibility for the nine rainfed maize races.

Feasibility of the nine rainfed maize (*Z. mays*) races under climate change scenarios

Feasibility of the nine rainfed maize races in Chiapas under climate change scenarios (2041-2060 and 2081-2100) was modeled using the same presence records and environmental variables as the current scenario. Similarly, the same parameters were used in MaxEnt.

The HadGEM3-GC31-LL circulation model and the 4.5 and 8.5 greenhouse gas (GHG) concentration pathways were used (46). These scenarios represent different projections of the future (38). The Shared Socioeconomic Pathways (SSP) 245 scenario (GHG concentration pathway 4.5) anticipates a middle-of-the-road pathway where trends continue their historical patterns without significant deviations (38). The SSP 585 scenario (GHG concentration pathway 8.5) assumes low population growth and includes rapid technological change, paired with intensive use of fossil fuels, implying higher levels of greenhouse gas emissions (16).

Results

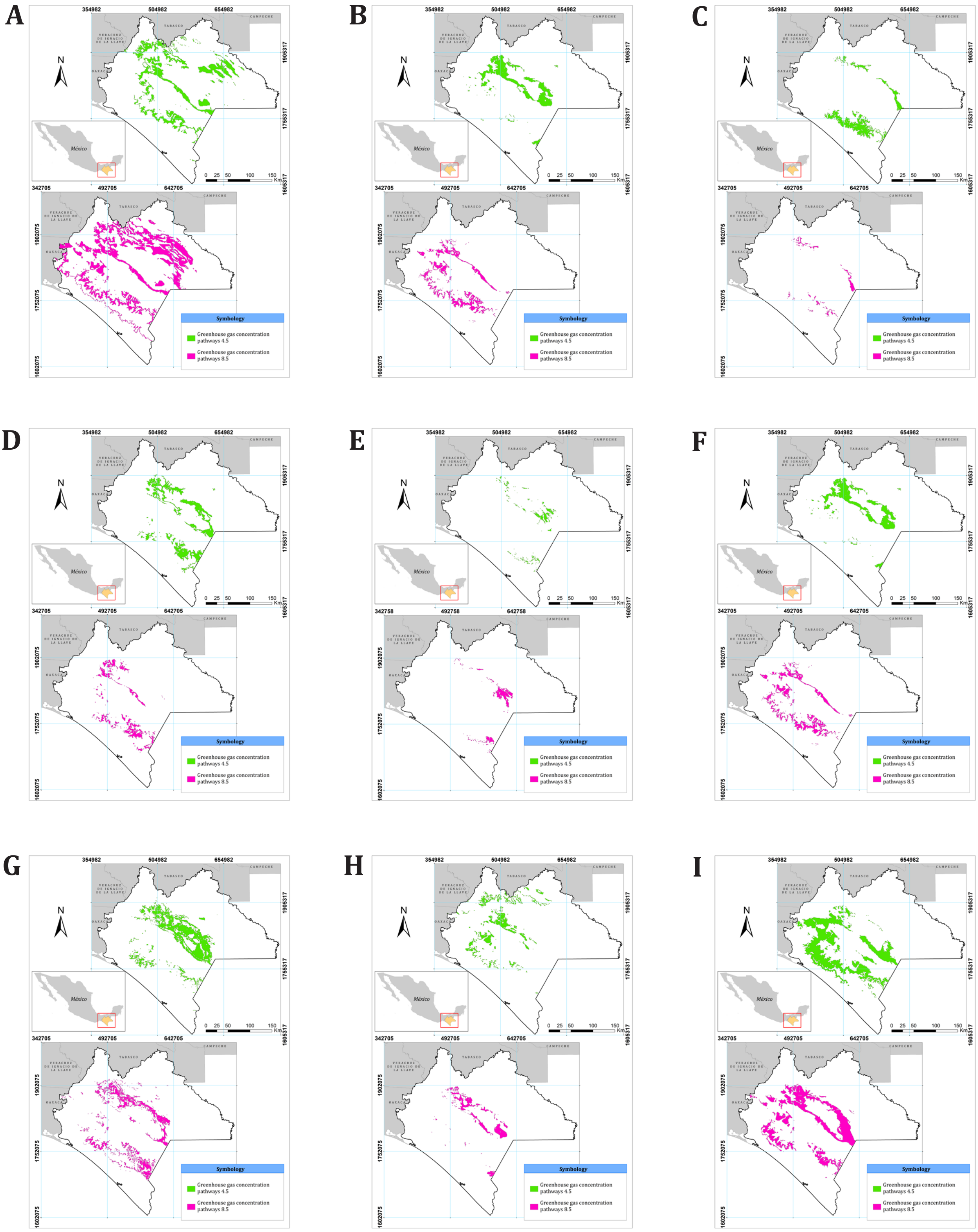
Feasibility of the nine rainfed maize (*Z. mays*) races in Chiapas under climate change scenarios

According to the MaxEnt model, by 2060 under the 4.5 concentration pathway (SSP 245) scenario, the suitable area for rainfed cultivation will shrink for all nine maize races (table 1; figure 1, page XXX). The Olotón race will be most affected, with a projected cultivation area of 6,356 ha, followed by Comiteco, with a projected area of 79,303 ha. Under the 8.5 concentration pathway (SSP 585) scenario, all races will experience similar declines, with Olotón reduced to 990 ha.

Table 1. Feasibility of rainfed cultivation area for nine maize races (*Zea mays*) in 2060 and 2100 under two greenhouse gas concentration pathway scenarios (4.5 and 8.5) in Chiapas, Mexico.

Tabla 1. Superficie de factibilidad de cultivo de temporal de nueve razas de maíz (*Z. mays*) para los escenarios de vía de concentración de 4.5 y 8.5 al año 2060 y 2100, en Chiapas, México.

Race	Feasibility of *Z. mays* rainfed area (Ha)				
	Current scenario	2060 scenario		2100 scenario	
		SSP 245	SSP 585	SSP 245	SSP 585
Comiteco	314,691	79,303	94,946	155,059	6,440
Cubano Amarillo	853,238	439,710	218,085	363,489	19,167
Olotillo	632,659	294,904	61,246	34,086	0
Olotón	286,507	6,356	990	16,425	0
Tepecintle	3,401,913	383,029	319,876	287,384	264,114
Tuxpeño	1,242,256	622,971	454,994	591,708	172,365
Vandeño	1,953,746	305,520	184,916	921,418	164
Zapalote Chico	4,846,495	728,708	1,267,441	368,273	490,703
Zapalote Grande	1,969,184	913,752	760,014	84,283	16,568



A: Zapalote Chico, B: Olotón, C: Olotillo, D: Cubano Amarillo, E: Comiteco, F: Tepecintle, G: Tuxpeño, H: Vandeño, I: Zapalote Grande.

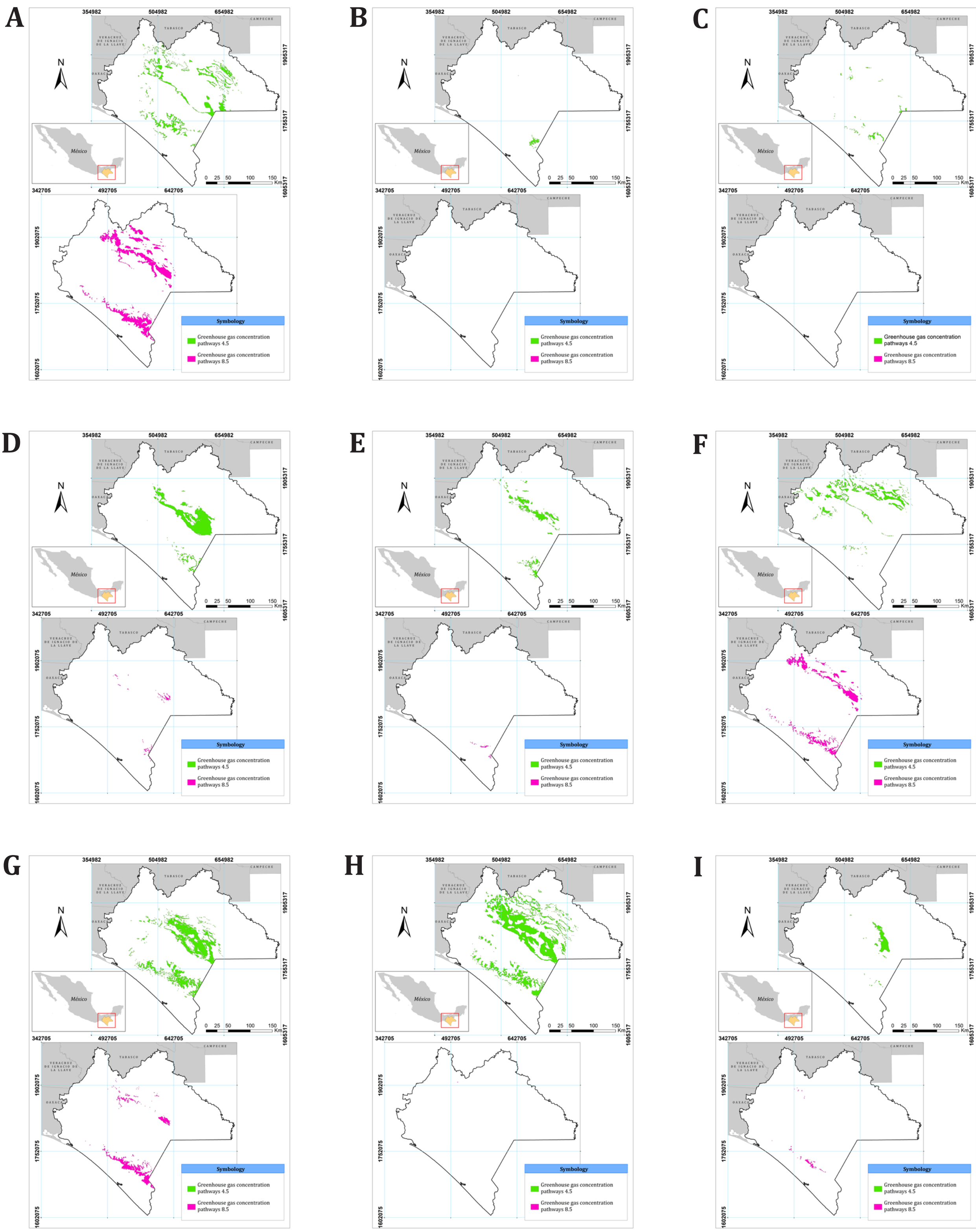
Figure 1. Feasibility of rainfed areas for nine maize (*Zea mays*) races in 2060 under two greenhouse gas concentration pathway scenarios (4.5 and 8.5) in Chiapas, Mexico.

Figura 1. Factibilidad de la superficie de temporal para las nueve razas de maíz estudiadas (*Z. mays*) para el año 2060, bajo dos escenarios de trayectorias de concentración de gases de efecto invernadero (4.5 y 8.5), en Chiapas, México.

The variables that contributed the most to the 2060 model under the 4.5 concentration pathway scenario were: “maximum temperature of the warmest month” (Bio 5), explaining 74% of modeling results for the Zapalote Chico race; “mean diurnal range” (Bio 2), contributing 22.8%, 26.6%, 30.2%, and 16.4% for the Cubano Amarillo, Tuxpeño, Vandeño, and Comiteco races, respectively; “average precipitation for December” with 20.4% and 21.6% for the Tepecintle and Zapalote Grande races, respectively; “precipitation seasonality” (Bio 15) contributing 22.2% for the Olotillo race; and finally, “average minimum temperature for June”, contributing 39.3% for the Olotón race. Under the 5.8 concentration pathways, the most influential variables were: “maximum temperature of the warmest month” (Bio 5), contributing 92.6% for the Zapalote Chico race; “mean diurnal range” (Bio 2), with 27%, 34.5%, 31.3%, and 15.4% for Cubano Amarillo, Tuxpeño, Vandeño, and Comiteco, respectively; “average precipitation for December” with 19.2% and 21.8% for Tepecintle and Zapalote Grande, respectively; “precipitation seasonality” (Bio 15), contributing with 21.5% for the Olotillo race; and finally, “average minimum temperature for June” contributing 40.1% for the Olotón race.

According to the MaxEnt model in the concentration pathway scenario 4.5 (SSP 245), similarly to the 2060 scenario, in the 2100 scenario, all nine maize races will experience a rainfed area reduction (table 1, page XXX; figure 2, page XXX). The Olotón race will drastically reduce its area to 16,425 ha. In the concentration pathway scenario 8.5 (SSP 585), the rainfed area of nine maize races will be significantly reduced, with the Olotillo and Olotón races disappearing by the year 2100.

The variables that most contributed to the 2100 model, in the concentration pathway scenario 4.5, were “maximum temperature of the warmest month” (Bio 5) with 59.3% contribution for the Zapalote Chico race, “mean diurnal range” (Bio 2) with 22.2%, 34.7%, 34.9%, 16.9%, and 23% for the Cubano Amarillo, Tuxpeño, Vandeño, Comiteco, and Olotillo races respectively, “average precipitation for October” with 21.5% for the Zapalote Grande race, “average precipitation for December” with 21.7% for the Tepecintle race, and finally, “average minimum temperature for June” with 40.8% for the Olotón race. For the concentration pathways 5.8 were “maximum temperature of the warmest month” (Bio 5) with 89.1% contribution for the Zapalote Chico race, “mean diurnal range” (Bio 2) with 25.9%, 31.5%, 31.3%, 17.2%, and 19.8% for the Cubano Amarillo, Tuxpeño, Vandeño, Comiteco, and Olotillo races respectively, “average precipitation for October” with 23.4% for the Zapalote Grande race, “average precipitation for December” with 13.4% for the Tepecintle race, and finally, “average minimum temperature for June” with 36.9% for the Olotón race.



A: Zapalote Chico, B: Olotón, C: Olotillo, D: Cubano Amarillo, E: Comiteco, F: Tepecintle, G: Tuxpeño, H: Vandeño, I: Zapalote Grande.

Figure 2. Feasibility of rainfed area for nine maize (*Z. mays*) races in 2100, under two greenhouse gas concentration pathway scenarios (4.5 and 8.5), in Chiapas, Mexico.

Figura 2. Factibilidad de la superficie de temporal para las nueve razas de maíz estudiadas (*Z. mays*) para el año 2100 bajo dos escenarios de trayectorias de concentración de gases de efecto invernadero (4.5 y 8.5), en Chiapas, México.

Discussion

Chiapas has the largest maize cultivation area in all of Mexico (approximately 900,000 hectares), ranking fourth in national production, with 294,468 maize producers. Rainfed maize accounts for 98% of this area (33). However, climate change may reduce rainfed areas, limiting production and threatening food security for Chiapas' rural population (1). As a result, communities may lose physical, social and economic access to many maize races, reducing the availability of safe and nutritious food (19).

According to the MaxEnt model, climate change will significantly impact feasibility of cultivation areas for the 9 maize races in Chiapas, as suggested for other regions of Mexico (22, 30, 55) and other countries (4, 9, 17). For example, the feasible rainfed area for the Zapalote Chico race decreases drastically under climate change scenarios, dropping from 4,846,495 ha to 728,708 ha by 2060 and to 368,273 ha by 2100 with the 4.5 concentration pathway (figure 3 and figure 4, page XXX), due to increased maximum temperatures of the warmest month (Bio 5) and decreased precipitation of the warmest quarter (Bio 18). Additionally, the feasible rainfed area for Olotón and Olotillo also decreases drastically under climate change scenarios. Olotón rainfed area decreases from 286,507 ha to 6,356 ha by 2060 and to 16,425 ha by 2100 with the 4.5 concentration pathway, while the Olotillo rainfed area decreases from 632,659 ha to 294,904 ha by 2060 and to 34,086 ha by 2100 with the 4.5 concentration pathway. But, by 2100, under the 8.5 concentration pathway, these two maize races will disappear from Chiapas after the influence of mean diurnal range and the increasing average minimum temperature for June, as for Zapalote Chico.

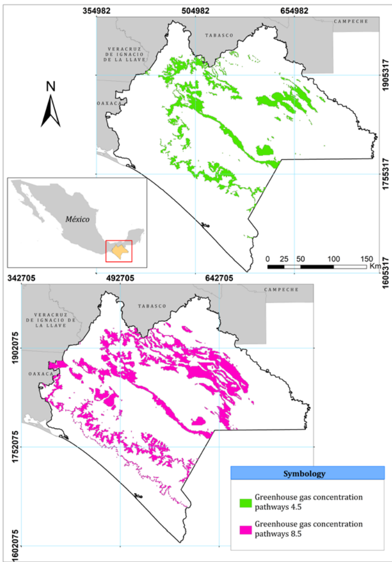


Figure 3. Feasibility of rainfed areas for the Zapalote Chico maize race (*Z. mays*) by 2060 under two greenhouse gas concentration pathway scenarios (4.5 and 8.5), in Chiapas, Mexico.

Figura 3. Factibilidad de la superficie de temporal para la raza de maíz Zapalote Chico (*Z. mays*) para el año 2060 bajo dos escenarios de trayectorias de concentración de gases de efecto invernadero (4.5 y 8.5), en Chiapas, México.

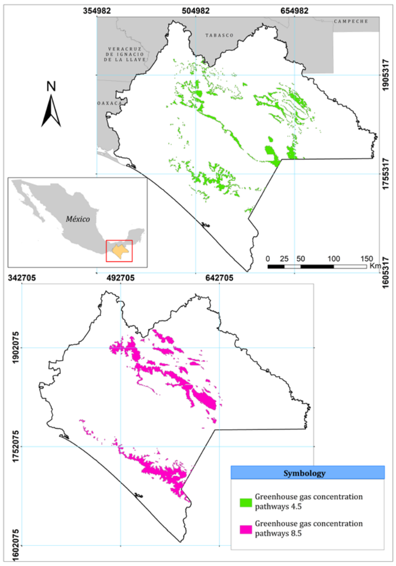


Figure 4. Feasibility of rainfed areas for the Zapalote Chico maze race (*Z. mays*) by 2100 under two greenhouse gas concentration pathway scenarios (4.5 and 8.5) in Chiapas, Mexico.

Figura 4. Factibilidad de la superficie de temporal para la raza de maíz Zapalote Chico (*Z. mays*) para el año 2100 bajo dos escenarios de trayectorias de concentración de gases de efecto invernadero (4.5 y 8.5), en Chiapas, México.

Suitable environmental conditions in Chiapas, derived from the MaxEnt model, under the current scenario for rainfed Zapalote Chico race are temperatures ranging from 8.2°C to 29.1°C, accumulated precipitation from 80.3 mm to 2,092 mm, and an elevation ranging from -2 to 2,155 m.a.s.l (3, 6, 36). Suitable environmental conditions in Chiapas, derived from the Maxent model for the current scenario and rainfed cultivation of Olotón race, are temperatures ranging from 4.4°C to 21.1°C, accumulated precipitation from 282.2 mm to 1,630 mm, and an elevation ranging from 384 to 2,732 m.a.s.l., while for Olotillo race, suitable conditions include ambient temperatures from 4.7°C to 26.1°C, accumulated precipitation from 196.1 mm to 1,695 mm, and elevations from 112.7 meters to 2,302 m a. s. l. (3, 6, 36).

Currently, the geographic areas of Chiapas meet these environmental conditions, allowing optimal development of all 9 races (6, 11), preventing both water and thermal stress (42). However, the increase in temperature due to climate change will shorten the cultivation period by accelerating growth rates (25). Exposure to high temperatures causes severe damage and cellular collapse (8), leading to pollination failure, fruit abortion and reduced load, promoting vegetative growth (15). This ultimately results in significant losses of aerial biomass, poor seed production, and reduced grain yield expressed as fewer grains per cob, and therefore, lower overall yields (26, 48).

High temperatures and less rainfall will negatively impact rainfed cultivation of these races in Chiapas. Water is essential for plant growth (5), and a limiting resource in rainfed cultivation. Reduced precipitation causes water stress and plant death when transpiration exceeds cavitation thresholds (29). Transpiration is closely associated with CO_2 exchange for photosynthesis and is essential for plant growth and development (53). On the other hand, reduced precipitation further delays stigma exposure (pollen release), leading to reduced crop productivity (58).

Rainfed maize cultivation is fundamental for food security in Chiapas and Latin America, contributing to local and regional economic growth (7). Beyond its economic importance, maize holds deep cultural significance for various ethnic groups, playing an integral role in their worldview, ranging from traditional cuisine to its use in sacred rituals (6). Nutritionally, maize is closely associated with nixtamalization, a process that involves treating it with lime. This technique enhances calcium bioavailability and improves protein assimilation, allowing for the preparation of tortillas, an essential and highly nutritious staple (40).

This study shows how climate change will negatively impact nine rainfed maize races in Chiapas, offering key insight for future sustainable management protocols and/or conservation actions (23). However, a more comprehensive long-term cohort study should also consider social, economic, and cultural factors. Recognizing the importance of the social context in such research will value both subjective experiences and the understanding of sociocultural realities (35).

Conclusions

Our results suggest that the nine maize (*Z. mays*) races currently grown in Chiapas, Mexico, will experience a dramatic decrease in their rainfed cultivation area under climate change scenarios for the years 2060 and 2100.

Supplemmentary material

https://docs.google.com/document/d/14UogbVdf2wcb2ZcKhiJ0GMOhjxBhTUN9/edit?usp=sharing&ouid=111310786017351827239&rtpof=true&sd=true

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