



Environmentally suitable area of four C₄ forage grasses in Western Mexico*

Área ambientalmente adecuada de cuatro gramíneas forrajeras C₄ del Occidente de México

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Abstract

Introduction. Grasslands are habitats for numerous species, provide various ecosystem services, and can contribute to carbon sequestration to mitigate climate change. **Objective.** To analyze the future environmentally suitable area for four C₄ forage grasses in the dry tropics of Western Mexico under different scenarios. **Materials and methods.** Study sites include the dry tropics of the states of Colima, Jalisco, and Nayarit, located in Western Mexico. Fifteen bioclimatic variables were used and processed with the Idrisi Selva software. Reference climate data corresponding to the period 1970-2000 and future climate scenarios with the representative concentration pathways (RCP4.5 and RCP8.5) for the 2041-2060 and 2061-2080 periods were employed. The MaxEnt model was used to analyze the environmentally suitable area (ESA) of *Bouteloua curtipendula*, *Brachiaria fasciculata*, *Sorghastrum nutans*, and *Tripsacum dactyloides*. **Results.** The MaxEnt model showed that under future scenarios, precipitation will increase in Sierra Madre Occidental, the Trans-Mexican Volcanic Belt, and the Pacific Ocean watershed, while the state of Jalisco will experience a reduction; the mean annual temperature in the study region will increase between 1.7 °C and 2.6 °C in the future scenarios compared to the reference climate. In addition, climate zones such as the sub-humid tropical, and the semi-arid tropical will increase in extent, while sub-tropical semi-arid zones will decrease. The models for the years 2060 and 2080 suggest that the environmentally suitable area for *B. curtipendula*, *B. fasciculata*, *S. nutans*, and *T. dactyloides* will decrease in RCP4.5 and RCP8.5; however, only *B. curtipendula* will increase in the period 2041-2060 (RCP4.5). **Conclusions.** Temperature and precipitation changes throughout the region will modify the duration and timing of seasonal heat and alter climatic zones, thereby reducing the environmentally suitable area of the grasses analyzed in Western Mexico.

Keywords: climate change, grasslands, modelling, simulation, representative concentration pathways.



Resumen

Introducción. Los pastizales son hábitats para numerosas especies, proporcionan diversos servicios ecosistémicos y pueden contribuir al secuestro de carbono para mitigar el cambio climático. **Objetivo.** Analizar el área ambientalmente adecuada (AAA) futura para cuatro gramíneas forrajeras C₄ en el trópico seco del occidente de México bajo diferentes escenarios. **Materiales y métodos.** Los sitios de estudio incluyeron el trópico seco de los estados de Colima, Jalisco y Nayarit, ubicados en el occidente de México. Se utilizaron quince variables bioclimáticas procesadas con el software Idrisi Selva. Se emplearon datos climáticos de referencia correspondientes al período 1970-2000 y escenarios climáticos futuros con las trayectorias de concentración representativas (RCP4.5 y RCP8.5) para los períodos 2041-2060 y 2061-2080. Se utilizó el modelo MaxEnt para analizar el área ambientalmente adecuada de *Bouteloua curtipendula*, *Brachiaria fasciculata*, *Sorghastrum nutans* y *Tripsacum dactyloides*. **Resultados.** El modelo MaxEnt mostró que, bajo escenarios futuros, la precipitación aumentará en la Sierra Madre Occidental, el Eje Volcánico Transmexicano y la vertiente del Océano Pacífico, mientras que el estado de Jalisco presentará una reducción; la temperatura media anual en la región de estudio aumentará entre 1,7 °C y 2,6 °C en los escenarios futuros en comparación con el clima de referencia. Además, zonas climáticas como el trópico subhúmedo y el trópico semiárido aumentarán su extensión, mientras que las zonas semiáridas subtropicales disminuirán. Los modelos para los años 2060 y 2080 sugieren que el área ambientalmente adecuada para *B. curtipendula*, *B. fasciculata*, *S. nutans* y *T. dactyloides* disminuirá en RCP4.5 y RCP8.5; sin embargo, solo *B. curtipendula* aumentará en el período 2041-2060 (RCP4.5). **Conclusiones.** Los cambios en temperatura y precipitación en toda la región modificarán la duración y el momento de las estaciones cálidas, así como las zonas climáticas, lo que reducirá el área ambientalmente adecuada de las gramíneas analizadas en el occidente de México.

Palabras clave: cambio climático, pastizales, modelado, simulación, trayectorias de concentración representativas.

Introduction

Grasslands are habitats for numerous species and provide a range of ecosystem services (Richter et al., 2021); however, these habitats are particularly vulnerable to environmental changes and human activities (Guo et al., 2023). Grasslands can also help mitigate climate change by reducing atmospheric CO₂ levels and increasing carbon sequestration. Soil organic carbon (SOC) can be sequestered at levels of 64.2 and 122.1 Gg per year in the soil layers from 0-10 cm and 0-30 cm, respectively, in semi-arid grasslands (Li et al., 2017).

Soil coverage in native grasslands is mainly occupied by species of the Poaceae family, which comprises approximately 215 genera and 1,312 species in Mexico (Sánchez-Ken, 2019). Previous studies conducted in Mexico indicate that climate change will increase temperatures and decrease precipitation relative to the current climate (Cavazos & Arriaga-Ramírez, 2012; García-Cueto et al., 2014; Liverman & O'Brien, 1991). It has also been reported that potential evaporation will increase while soil moisture will decrease, with these climatic variables having direct and indirect impacts on agricultural and livestock production.

Warm-season (C₄) grasses are widely distributed and abundant in tropical and subtropical regions between 30° N and 30° S latitude, and most of the grasses in these regions are C₄ (Vendramini et al., 2023). C₄ grasses dominate in tropical regions due to their more efficient carbon fixation pathway under high temperature and radiation conditions, as well as their more efficient use of water and nitrogen compared to cool-season (C₃) plants (Majeran et al., 2010). These differences are largely attributable to Ribulose-1,5-bisphosphate carbox-ylase/oxygenase (Rubisco), the key enzyme of photosynthetic carbon fixation, which is central to differentiating the metabolic efficiency of C₃ and C₄ plants (Wang et al., 2012).

In C₃ plants, carbon fixation occurs exclusively through the Calvin cycle, where Rubisco catalyzes the CO₂ fixation in mesophyll cells; in contrast, C₄ species exhibit a spatial separation of photosynthetic processes between mesophyll and bundle sheath cells (Erb & Zarzycki, 2018). The evolutionary drivers that led to C₄ photosynthesis include a low atmospheric CO₂ concentration during the Oligocene Epoch, rising atmospheric O₂ levels (almost 21 %), and the anatomical changes such as the presence of dimorphic chloroplasts, spatially separated enzymes, closely arranged mesophyll, bundle sheath cells, and the re-routing of Krebs' cycle enzymes (Mukundan et al., 2024). These adaptations confer a significant advantage to C₄ grasses under current and projected global warming scenarios characterized by higher temperatures and high light availability (Luo et al., 2024).

The grass species analyzed in this study are of ecological and economic importance in grasslands and forage systems in Mexico. These C₄ grasses include *Bouteloua curtipendula* (Michx.) Torr., *Brachiaria fasciculata* (Sw.) Parodi, *Sorghastrum nutans* (L.) Nash and *Tripsacum dactyloides* L. These species are characterized by their high forage quality, drought tolerance, and favorable adaptive and productive traits under challenging environmental conditions (Álvarez-Holguín et al., 2021; Oquendo et al., 2013; Swift et al., 2025; United States Department of Agriculture, 2021).

The livestock sector plays a fundamental role in global food security, providing about 15 % of total calories and 31 % of protein consumed worldwide. Nearly one-third of global ruminant meat and a significant share of milk production originate from grazing-based systems (Godde et al., 2021). Within these systems, native C₄ grasses are essential forage sources because they are highly adapted to local climates, drought-tolerant, capable of producing abundant biomass, and require minimal inputs for their establishment and maintenance (Ramírez et al., 2009). Beyond feeding livestock, grasslands offer essential ecosystem services by regulating water cycles, reducing soil erosion, sequestering greenhouse gases, and promoting soil health and biodiversity (Lemaire et al., 2014; Rao et al., 2015).

Since the mid-20th century, General Circulation Models (GCM) have been central to climate and weather prediction (Bauer et al., 2015). In Mexico, GCMs such as ECHAM5, MIROC, UKMO_HADCM3, and GFDL-CM3 have been applied to assess climate change impacts on crops like *Salvia hispanica* L., *Gossypium hirsutum* L., and *Leucaena leucocephala* (Lam.) de Wit (Durán Puga et al., 2020; Orozco de Rosas et al., 2014; Ramírez-Ojeda et al., 2014). These studies estimated the environmentally suitable area (ESA) for different climate change scenarios, which represent geographic models comprising environmental variables favorable for the development of certain species (Durán Puga et al., 2020; Martínez Sifuentes et al., 2020a), calculated using an algorithm such as MaxEnt.

The MaxEnt model predicts species distributions by integrating environmental variables with presence-only data, allowing the identification of potentially environmentally suitable areas with high accuracy even when data availability is limited (Liu et al., 2024). This model combines machine learning and maximum entropy principles and is one of the most widely used algorithms for conservation, biogeography, and evolutionary studies (Li et al., 2020). In contrast to other distribution models such as the Genetic Algorithm for Rule Set Production (GARP) and logistic regression, the MaxEnt model relies solely on presence-only data rather than both presence and absence data (Ghahremanian et al., 2025).

Currently, biodiversity distribution throughout the use of the MaxEnt model has become an important tool for predicting the current and future potential distribution of plants and animal species. To understand the effect of climate impact on C₄ grasses of Mexico, the present study aims to analyze the future environmentally suitable area for four C₄ forage grasses in the dry tropics of Western Mexico under different scenarios.

Materials and methods

Study area

The dry tropics of the states of Colima, Jalisco, and Nayarit, located in Western Mexico, were selected as the study area. The vegetation type in this region is considered dry forest, dry tropical forest, dry selva, low deciduous forest, sub-deciduous forest, and others. The classification of climatic zones was carried out following the methodology of Medina García et al. (1998). The experimental period was from November 2021 to November 2022.

Climatic requirements of the evaluated species

Bouteloua curtipendula is widely distributed in Mexico, where it occurs in various dry and semi-dry forests, low deciduous forests in grasslands, and dry forests (Rosales-Serna et al., 2025). However, the species also thrives in the natural grasslands of arid and semi-arid areas (Beltrán-López et al., 2013). In addition, it can increase its abundance by up to 57.9 % in response to an increase in precipitation in the grassland ecosystem (Chaves & Smith, 2021).

Brachiaria fasciculata is widely distributed from the southern United States and Mexico to South America (Morrone & Zuloaga, 1993). Its distribution includes tropical and subtropical zones, and it is widely sown as forage crop to feed ruminants in the American and African tropics, particularly in areas with marginal soils (Higgins et al., 2022).

Sorghastrum nutans is found in natural grassland areas with annual precipitation between 600 and 1200 mm (Anderson, 2006). This grass responds to water stress by producing more abscisic acid, and its metabolism responds quickly during stress, conferring an advantage in tolerating the extreme heat expected in the future (Hoffman et al., 2018). Moreover, this species recovers quickly after water stress (Swemmer et al., 2006).

Tripsacum dactyloides is adapted to a wide variety of tropical and subtropical environments and can grow in prairies, coastal plains, semi-arid regions, clearings in forested areas, moist grasslands, and around the edges of marshes. It thrives in climates with annual precipitation between 900 and 1,500 mm, and prefers moist, moderately well-drained, slightly acidic to neutral, and fertile soils (Rojas-Sandoval, 2017).

Bioclimatic variables

Fifteen bioclimatic variables were used to analyze the ESA under both reference climate (RC) and future climate (FC) scenarios (Table 1). The bioclimatic variables were extracted from WorldClim (Fick & Hijmans, 2017) and the remaining variables were processed using the Idrisi Selva software, where the humidity index (HI) is the precipitation/evapotranspiration ratio (ETP). ETP was calculated using the formula of Hargreaves and Allen (2003), which incorporates mean temperature and solar radiation. The period from June to October represents the growing season of most native grasses, and the December to March period was included to evaluate the relationship between precipitation and moisture deficit during months with low precipitation and low temperatures.

Each environmental variable was processed with the Idrisi Selva application in raster-type maps with a resolution of 30 s (squares of ca. 1 km²). This resolution is necessary due to the changing surface land in the Western Mexico region. The maps were transformed into ASCII code for analysis with the Maximum Entropy Species Distribution Modeling v 3.4.4 program (American Museum of Natural History, 2021), known as MaxEnt, to analyze the change in areas with an environmental suitability for each species in FC scenarios relative to the RC.

Table 1. The bioclimatic variables used for reference and future climate. Tepatitlan de Morelos, Mexico. 2021.

Cuadro 1. Variables bioclimáticas empleadas para el clima de referencia y futuro. Tepatitlán de Morelos, México. 2021.

| Number | Variable description |
|--------|--|
| 1 | Maximum temperature from June to October |
| 2 | Maximum temperature from December to March |
| 3 | Average temperature from June to October |
| 4 | Average temperature from December to March |
| 5 | Minimum temperature from June to October |
| 6 | Minimum temperature from December to March |
| 7 | Isothermality* |
| 8 | Temperature seasonality* |
| 9 | Thermal oscillation from June to October |
| 10 | Thermal oscillation from December to March |
| 11 | Precipitation from June to October |
| 12 | Precipitation from December to March |
| 13 | Precipitation seasonality* |
| 14 | Humidity index from June to October |
| 15 | Humidity index from December to March |

* Bioclimatic variables extracted directly from WorldClim. / * Variables bioclimáticas extraídas directamente de WorldClim.

Climate data analysis

The WorldClim data was processed using ArcGIS v. 10.2.2 (Environmental Systems Research Institute, US) to extract the environmental information corresponding to the states of Colima, Jalisco, and Nayarit, which was exported to Idrisi Selva v. 17.0 (Clark Labs, Clark University, US) to generate raster maps of these variables; then translated to ASCII format to enable their use with the MaxEnt model. RC data corresponding to the period 1970-2000 were used, and FC data were obtained with the representative concentration pathways (RCP) 4.5 and 8.5, based on the concentration of CO₂ in the atmosphere (4.5 ~650 ppm CO₂ eq by 2100 and 8.5 ~1370 ppm CO₂ eq by 2100) (Van Buuren et al., 2011) for the GFDL model (Donner et al., 2011) in the periods 2041-2060 and 2061-2080.

RCP scenarios were used because climate projections based on the Shared Socioeconomic Pathways (SSP) were not available at 30 s resolution on the WorldClim website at the time the research commenced in November 2021. This data limitation made it necessary to use the RCP-based datasets. However, according to some researchers, there is an equivalence between RCP4.5 and RCP8.5 with SSP2 and SSP5, respectively (Kebede et al., 2018; Meinshausen et al., 2020).

Species evaluated

Scientific articles and floristic studies were consulted to identify grass species reported in Western Mexico (Enríquez Quiroz et al., 2011; Ramírez-Delgadillo & Cupul-Magaña, 1999; Sánchez-Ken, 2011; Vigosa-Mercado & Fonseca, 2017; Villanueva-Avalos et al., 2021), and select those with the highest forage value and frequency of occurrence in dry, semi-dry, and sub-humid tropical areas (Allred, 2005; Garduño Velázquez et al., 2015; Leithead et al., 1971; Quero Carrillo et al., 2017; Ramírez et al., 2009). Moreover, the Global Biodiversity Information Facility (2021a, 2021b, 2021c, 2021d) database was used to estimate the frequency of occurrence of each species,

resulting in the selection of four species: *Bouteloua curtipendula* (Michx.) Torr., *Brachiaria fasciculata* (Sw.) Parodi, *Sorghastrum nutans* (L.) Nash, and *Tripsacum dactyloides* (L.).

Analysis of environmentally suitable area

The MaxEnt model employed cross-validation (10 replicates), jackknife curves, 30 % of the data for model training, 2500 iterations, response curves, which produce a logistic output, using a fixed cumulative value of 10 threshold as the criterion for defining the ESA. These settings have provided satisfactory results in prior studies on native and cultivated grasses (Durán Puga et al., 2020; Instituto Nacional de Estadística y Geografía [INEGI], 2009; Morales & Fernández, 2020). Finally, the Idrisi Selva software was used to quantify the ESA in the RC and the FC scenarios; final maps excluded water bodies and urban areas using INEGI (2016), and the Servicio Meteorológico Nacional (2022) data.

A relative comparison approach was used to assess changes in the environmentally suitable area between the RC and FC scenarios, with the reference climate serving as the baseline condition (100 %). This approach allowed identification of directional trends in spatial suitability, as changes were expressed as percentage changes across scenarios.

Results

Climate change analysis in Western Mexico

The analysis of climate data across the four FC scenarios indicates that the mean annual precipitation will increase by 12.7 % and 17.1 % in the Sierra Madre Occidental, Trans-Mexican Volcanic Belt, and the Pacific Ocean watershed relative to RC, respectively. Conversely, precipitation is expected to decrease in the central, northern, and highland areas of Jalisco. The precipitation from June to October during the RC accounted for 79.8 % of the annual mean in Western Mexico; in the FC scenarios, this proportion increased slightly, ranging between 81.8 % and 83.1 % for the same period.

Regarding temperature, the mean annual temperature in the study region will increase between 1.7 °C and 2.6 °C across the four FC scenarios compared to the RC, with greater increases in the semi-arid zones of the northeast and north of Jalisco, and smaller changes along the Pacific coast and the western slope of the mountainous areas near the coast. The hottest period under the RC occurred from May to July; however, in the four FC scenarios, this period shifts to April-June. Similarly, while the warmest month in the RC is June, the results indicate that May will be the warmest month under the FC scenarios.

The sub-humid tropical zone will increase in extent by approximately 124.1 % in the period 2041-2060, with smaller increases of 50.3 %, 39.3 %, and 3.4 % relative to the RC surface area; the semi-arid tropical zones will also expand by 25.4 %-57.9 %. In contrast, the zones with a subtropical semiarid climate will contract from 31.6 % of the RC area to 5.8 % under the most severe climate change scenario (supplementary material).

Environmentally suitable area (EAA) for *B. curtipendula*

The environmentally suitable area is characterized by a diurnal temperature range between 14 °C and 16 °C, a mean annual temperature between 27 °C and 32 °C, and precipitation between June and October between 400 mm and 1100 mm, in tropical, semi-arid and arid sub-tropical climatic zones (Figure 1). FC scenarios showed that *B. curtipendula* will show a slight increase (+0.5 %) in its ESA in FC45-50 scenario but will decrease in all other

FC scenarios, where FC85-70 will represent the most severe climate change scenario (-2.6%) (Table 2). This expanded area will encompass areas that are currently classified as sub-humid tropics and will become sub-humid sub-tropics in that period mainly on the eastern slope of the Sierra Madre Occidental.

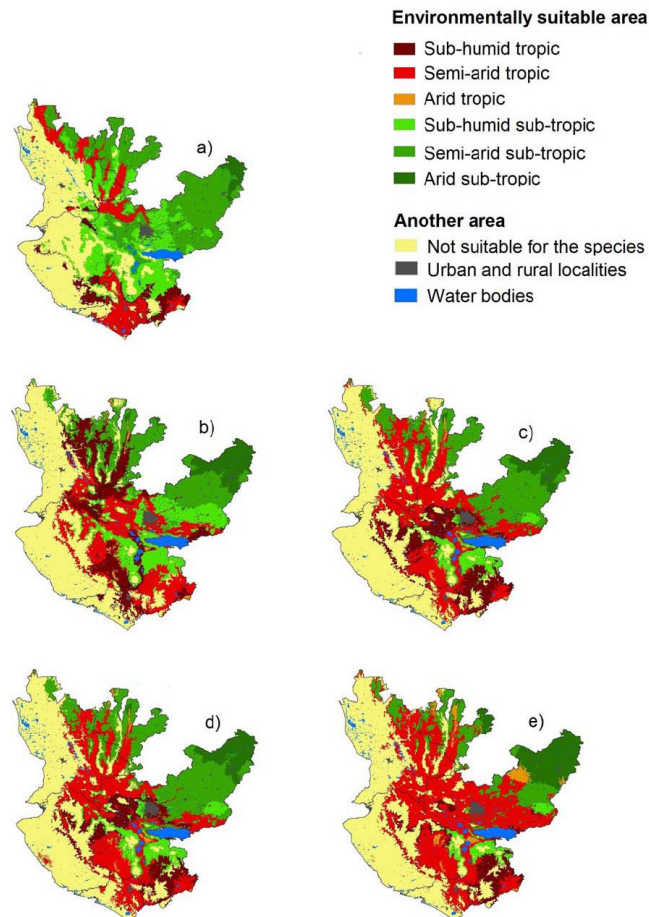


Figure 1. The environmentally suitable area for *B. curtipendula* in Western Mexico. **a)** Reference climate. **b)** FC45-50: Future climate with RCP4.5 in the period 2041-2060. **c)** FC45-70: Future climate with RCP4.5 in the period 2061-2080. **d)** FC85-50: Future climate with RCP8.5 in the period 2041-2060. **e)** FC85-70: Future climate with RCP8.5 in the period 2061-2080. Tepatitlan de Morelos, Mexico, 2021.

Figura 1. Área ambientalmente adecuada para *B. curtipendula* en el Occidente de México. **a)** Clima de referencia. **b)** FC45-50: Clima futuro con RCP4.5 en el periodo 2041-2060. **c)** FC45-70: Clima futuro con RCP4.5 en el periodo 2061-2080. **d)** FC85-50: Clima futuro con RCP8.5 en el periodo 2041-2060. **e)** FC85-70: Clima futuro con RCP8.5 en el periodo 2061-2080. Tepatitlán de Morelos, México, 2021.

Environmentally suitable area for *B. fasciculata*

This species is distributed in warm and rainy areas under RC, corresponding to the sub-humid tropical climate (Figure 2). Results showed that this species will experience a decline in its ESA across all the FC scenarios; FC45-70 scenario will have the least impact (-0.7%) among all FC scenarios, while FC85-70 will have the greatest impact (-4.8%) (Table 2). Additionally, the results suggest that this species will remain in the same geographical

Table 2. The environmentally suitable area for four C₄ grasses in Western Mexico. Tepatitlan de Morelos, Mexico. 2021.**Cuadro 2.** Área ambientalmente adecuada de cuatro gramíneas forrajeras C₄ en el Occidente de México. Tepatitlán de Morelos, México. 2021.

| Species | RC (km ²) | FC45-50 (%) | FC45-70 (%) | FC85-50 (%) | FC85-70 (%) |
|------------------------|-----------------------|-------------|-------------|-------------|-------------|
| <i>B. curtipendula</i> | 72 789.4 | 100.5 | 98.8 | 99.8 | 97.4 |
| <i>B. fasciculata</i> | 37 191.7 | 99.1 | 99.3 | 97.2 | 95.2 |
| <i>S. nutans</i> | 75 129.0 | 99.0 | 98.0 | 96.6 | 98.2 |
| <i>T. dactyloides</i> | 84 612.2 | 97.4 | 98.1 | 96.5 | 97.4 |

RC: Reference climate represents 100 %. **FC45-50:** Future climate with RCP4.5 in the period 2041-2060. **FC45-70:** Future climate with RCP4.5 in the period 2061-2080. **FC85-50:** Future climate with RCP8.5 in the period 2041-2060. **FC85-70:** Future climate with RCP8.5 in the period 2061-2080. / **RC:** Clima de referencia representa el 100 %. **FC45-50:** Clima futuro con RCP4.5 en el periodo 2041-2060. **FC45-70:** Clima futuro con RCP4.5 en el periodo 2061-2080. **FC85-50:** Clima futuro con RCP8.5 en el periodo 2041-2060. **FC85-70:** Clima futuro con RCP8.5 en el periodo 2061-2080.

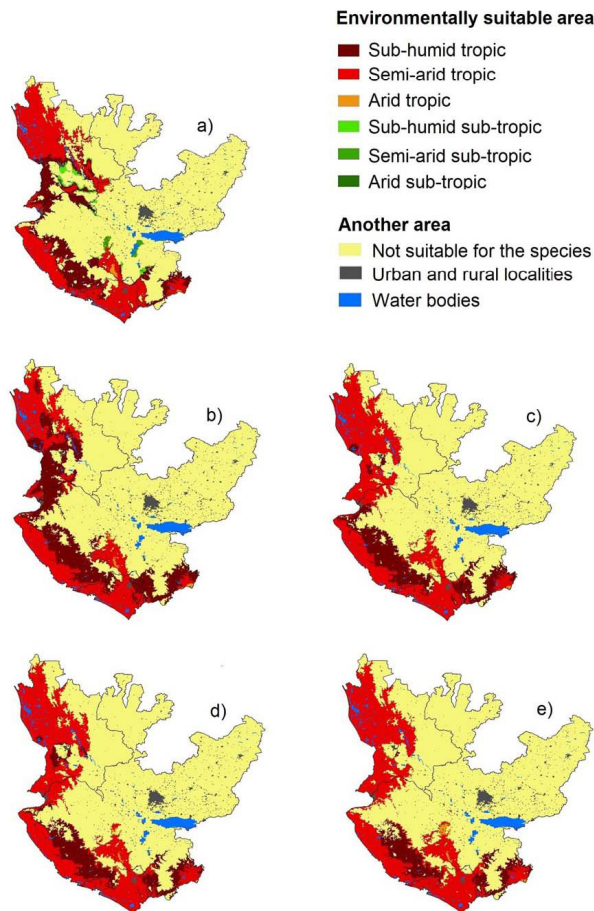
**Figure 2.** The environmentally suitable area for *B. fasciculata* in Western Mexico. **a)** Reference climate. **b)** FC45-50: Future climate with RCP4.5 in the period 2041-2060. **c)** FC45-70: Future climate with RCP4.5 in the period 2061-2080. **d)** FC85-50: Future climate with RCP8.5 in the period 2041-2060. **e)** FC85-70: Future climate with RCP8.5 in the period 2061-2080. Tepatitlan de Morelos, Mexico. 2021.

Figura 2. Área ambientalmente adecuada para *B. fasciculata* en el Occidente de México. **a)** Clima de referencia. **b)** FC45-50: Clima futuro con RCP4.5 en el periodo 2041-2060. **c)** FC45-70: Clima futuro con RCP4.5 en el periodo 2061-2080. **d)** FC85-50: Clima futuro con RCP8.5 en el periodo 2041-2060. **e)** FC85-70: Clima futuro con RCP8.5 en el periodo 2061-2080. Tepatitlán de Morelos, México. 2021.

area regardless of the transition in the climatic zone from semi-arid tropical to sub-humid tropical due to increased precipitation; moreover, the species is expected to find favorable conditions in areas near the Pacific Ocean coast of Colima, Jalisco, and Nayarit.

Environmentally suitable area for *S. nutans*

This species showed the second widest distribution in the study area, with its presence in climates ranging from the humid sub-tropics on the Pacific Ocean coast to the arid sub-tropics of the northeastern analyzed area (Figure 3). The ESA will decrease between FC45-50 (−1.0 %) and FC85-50 (−3.4 %), accompanied by changes in the geographical distribution of climatic zones due to climate change (Table 2).

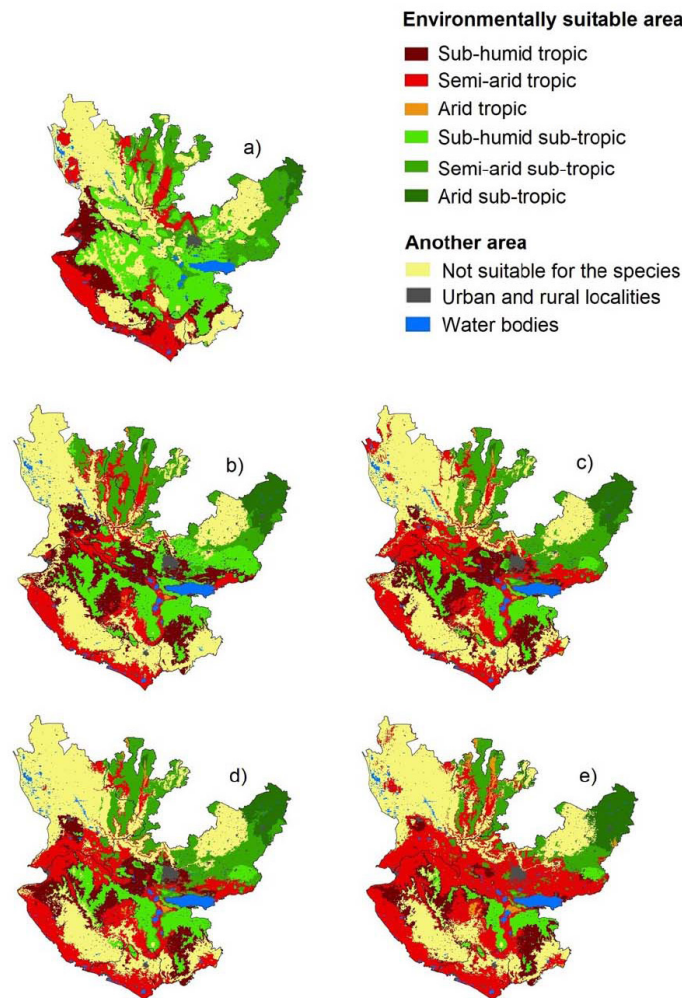


Figure 3. The environmentally suitable area for *S. nutans* in Western Mexico. **a)** Reference climate. **b)** FC45-50: Future climate with RCP4.5 in the period 2041-2060. **c)** FC45-70: Future climate with RCP4.5 in the period 2061-2080. **d)** FC85-50: Future climate with RCP8.5 in the period 2041-2060. **e)** FC85-70: Future climate with RCP8.5 in the period 2061-2080. Tepatitlán de Morelos, Mexico. 2021.

Figura 3. Área ambientalmente adecuada para *S. nutans* en el Occidente de México. **a)** Clima de referencia. **b)** FC45-50: Clima futuro con RCP4.5 en el periodo 2041-2060. **c)** FC45-70: Clima futuro con RCP4.5 en el periodo 2061-2080. **d)** FC85-50: Clima futuro con RCP8.5 en el periodo 2041-2060. **e)** FC85-70: Clima futuro con RCP8.5 en el periodo 2061-2080. Tepatitlán de Morelos, México. 2021.

Environmentally suitable area for *T. dactyloides*

The ESA for this species is the largest among the analyzed species and is distributed over a geographical area larger than the rest of analyzed species, mainly in the sub-humid tropics, arid tropics, sub-humid sub-tropics, and semi-arid sub-tropics, as well as small areas with arid climates (Figure 4). ESA will decrease across all FC scenarios, where FC85-50 will have the greatest reduction (−3.5 %) and FC45-50 will have the smallest impact (−1.9 %) (Table 2).

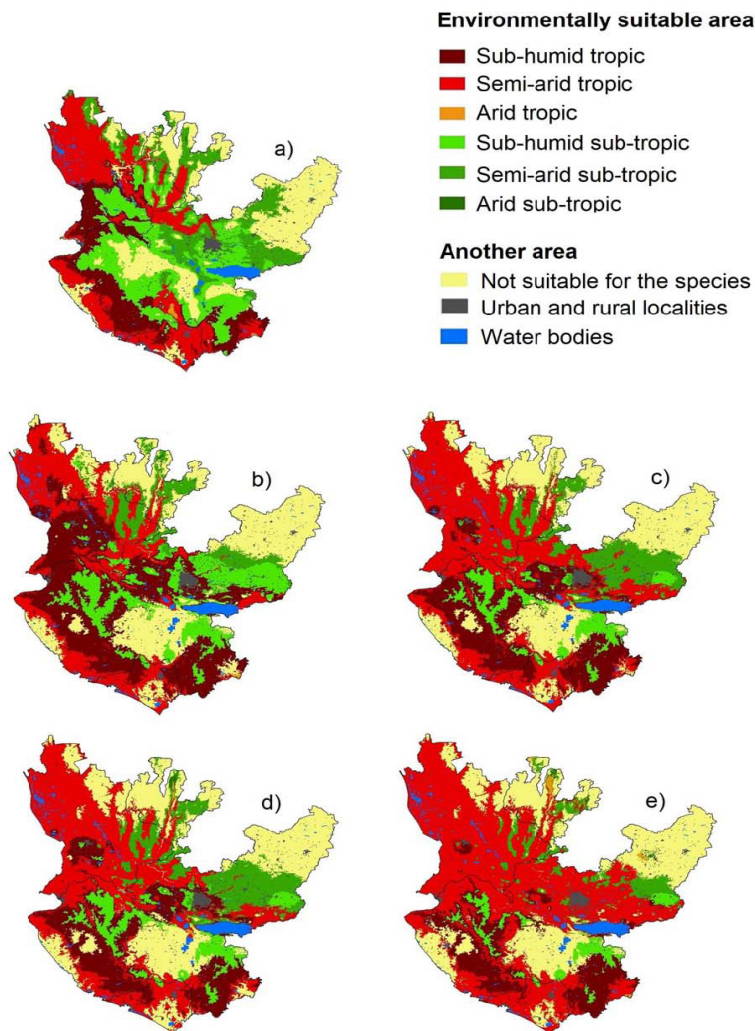


Figure 4. The environmentally suitable area for *T. dactyloides* in Western Mexico. **a)** Reference climate. **b)** FC45-50: Future climate with RCP4.5 in the period 2041-2060. **c)** FC45-70: Future climate with RCP4.5 in the period 2061-2080. **d)** FC85-50: Future climate with RCP8.5 in the period 2041-2060. **e)** FC85-70: Future climate with RCP8.5 in the period 2061-2080. Tepatitlán de Morelos, Mexico. 2021.

Figura 4. Área ambientalmente adecuada para *T. dactyloides* en el Occidente de México. **a)** Clima de referencia. **b)** FC45-50: Clima futuro con RCP4.5 en el periodo 2041-2060. **c)** FC45-70: Clima futuro con RCP4.5 en el periodo 2061-2080. **d)** FC85-50: Clima futuro con RCP8.5 en el periodo 2041-2060. **e)** FC85-70: Clima futuro con RCP8.5 en el periodo 2061-2080. Tepatitlán de Morelos, México. 2021.

Discussion

Changes in ESA are related to the ecological and productive climatic requirements of the evaluated C₄ grasses, particularly temperature regimes, precipitation, and precipitation seasonality during the growing season. Thermal conditions and water availability are known to exert a major impact on C₄ grasses' physiological performance, biomass production, and spatial distribution (Lattanzi, 2010; Von Fischer et al., 2008). The anticipated variations in suitability across future scenarios are interpreted as responses to changes in climatic conditions relative to the tolerance ranges that define favorable environments for each species.

In tropical regions, climate change will affect crops due to temperature fluctuations, altered precipitation patterns, and rising CO₂ levels (Mariappan et al., 2023). This study showed regional variations in precipitation across Western Mexico relative to RC; these results are consistent with Manzanilla-Quiñones et al. (2019), who reported that temperature will increase between 0.7 and 2.1 °C and precipitation will decrease between 2.8 and 3.8 % during the 2041-2060 period under RCP4.5 and RCP8.5 in the Trans-Mexican Volcanic Belt, which includes parts of this study. These variations are caused by the country's complex topography, and Mexico's position between two adjacent oceans generates a variety of climates and processes that not all GCMs can accurately reproduce (Romero Centeno et al., 2016).

One indicator of the impacts of climate change is the shift in climate classification. The climate zone transitions observed in this study revealed an expansion of sub-humid tropical and semi-arid tropical zones, while sub-tropical and semi-arid zones are expected to contract under the most severe FC scenario. This scenario has also been observed in past periods (1901-2011) (Zhang & Yang, 2014); however, considering projected increases in CO₂ concentration under FC85-70, along with increases in temperature and changes in precipitation such as those reported here, the distribution of climate zones will shift as described previously by Zhang et al. (2017).

Furthermore, results showed that under the most severe climate change scenarios, high seasonal temperatures will occur earlier, in April. This shift has been attributed to greenhouse warming and has been reported previously by researchers who have documented that heat extremes represent a threat to agriculture, ecology, and health (Christidis et al., 2020; Perkins-Kirkpatrick & Lewis, 2020; Tamm et al., 2023; Wang et al., 2021). These seasonal changes will modify the duration and an early onset of seasons; if this trend continues, a longer summer and shorter winter will become the norm by the 21st century (Wang et al., 2021).

Climate change is expected to affect grasslands; according to projected changes in future climatic conditions, the ESA of the assessed C₄ grasses will decrease across all FC scenarios except FC45-50 for *B. curtipendula*. This suggests that this species may be capable of adapting by modifying its ecology, physiology, and behavior over ecological timescales (Yurkonis & Harris, 2019). Similar projections for *B. curtipendula* using GFDL-CM3 and HadGEM-ES GCMs reported a slight decrease in ESA by 2050 under the RCP4.5 and RCP8.5 scenarios; however, the area is projected to recover by 2070 in the RCP8.5 (Martínez Sifuentes et al., 2020b).

The decrease in ESA for the studied species, together with changes in temperature and precipitation under FC scenarios, and transitions in climate zones, could trigger a regime shift, including the transition from grasslands to desert (Kayler et al., 2015). Such geographic distribution changes will depend on the species ability to tolerate environmental stresses, respond to biological interactions, and overcome dispersal constraints (Abbass et al., 2022). When individuals of one species cannot colonize new niches or lack the physiological tolerance to respond to climate change, they will be prone to extinction (Becerra-López et al., 2017).

The evaluation of potential changes in environmental suitability is based on comparative analyses between reference and predicted climatic scenarios, a method commonly used in species distribution modeling, rather than traditional statistical significance testing (Guillera-Aroita et al., 2015; Morales et al., 2017). Model uncertainty was addressed by internal validation methods in MaxEnt, including cross-validation replicates, jackknife analysis of variable contribution, and verification of response curve consistency across scenarios (Anderson & Gonzalez,

2011; Li et al., 2020). These methods support a cautious interpretation of climate-driven trends, acknowledging the inherent limitations of correlative modeling.

Known drawbacks associated with the use of the MaxEnt model have been identified; one key aspect to consider is its relatively coarse spatial resolution (thousands of km²) for assessing regional or local changes, and the model does not account for certain surface processes such as topography or spatial heterogeneities of the Earth's surface (Akobé et al., 2024; Turco et al., 2017). The possibility of modeling outputs based on oversimplified models must be considered, as they may lead to an overestimated potential distribution of the assessed species, or overfitting of modeling output to the input data (Morales et al., 2017). Another important limitation of MaxEnt model concerns the decision-making process due to variation caused by the parameters used for modeling (Anderson & Gonzalez, 2011).

The potential effects of climate change on C₄ grasslands could be interpreted more ecologically accurately by combining modelled changes in environmentally suitable area with species-specific climatic requirements. This approach facilitated an understanding of how temperature increases, precipitation redistribution, and seasonal shifts may affect future ecological patterns under various scenarios, while also helping to identify relative differences in climatic sensitivity among species (Martínez Sifuentes et al., 2020b).

Conclusions

Changes in the environmentally suitable area of the assessed C₄ grasses are related to variations in temperature, precipitation, and seasonal timing, according to projected climate change scenarios for Western Mexico. While *Bouteloua curtipendula* demonstrated relatively greater tolerance under intermediate scenarios, most species are projected to experience reductions in suitable areas under future conditions. Changes in seasonal heat patterns and the distribution of climate zones suggest potential shifts in the distribution of grasslands throughout the study area with potential implications for ecological sites and farming operations in Western Mexico.

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Conflict of interests

The authors declare that there is no conflict of interest.

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