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Agro-climatic suitability of *Opuntia ficus-indica* under future climate scenarios (SSP2 and SSP5) in north-central Mexico

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Abstract. The impact of climate change on food production systems affects agri-food safety and, consequently, national food sovereignty. Thus, food systems must adopt new practices, including the modification of crop selection. Within this context, agro-climatic suitability studies for species adapted to warmer temperatures and drought are crucial. *Opuntia ficus-indica* is a tolerant crop, notable for its nutritional and cultural significance. For that reason, the objective of this study was to determine its agro-climatic suitability using annual precipitation, mean temperature, and minimum temperature for the current scenario (1990-2020) and the 2040–2070 period, defined by the Shared Socioeconomic Pathways (SSP) 2 and 5. The results showed a general decrease in the proportion of highly suitable territory, with the notable exception of Zacatecas. This state, known as a major national producer of this crop, exhibited a 17% increase in the proportion of suitable territory in the 2040-2070 scenarios for both SSPs compared to the current scenario. The model's validity was confirmed via Chi-square (χ^2) and Frequency Ratio (FR) analysis for current scenario. Overall, this research indicates a reduction in optimal agro-climatic conditions for *O. ficus-indica* cultivation in the north-central states of Mexico.

Keywords: *agro-ecological zoning, climate change, food production systems*

Introduction

The impact of climate change on agri-food security and national sovereignty is the central topic driving the nationalization of production systems, particularly given the instability and uncertainty of globalized capitalism (Daramola and Xu, 2022). This problem is multi-disciplinary, but from a fundamental view, governments must ensure the well-being of their citizens. For that reason, national demand should be met by internal production to reduce dependency on other countries, which are subject to climate events and socioeconomic conflicts (Sloat *et al.,* 2022).

A knowledge gap exists regarding how existing and alternative crops that satisfy consumer demand will react to future climate conditions.

This underscores the necessity of agro-climatic suitability studies, which serve to determine areas for specific priority crop production (Trnka *et al.,* 2021). Furthermore, C4 and CAM photosynthesis species are gaining relevance due to their tolerance to drought and, in some cases, salinity stress (Falasca *et al.,* 2011; Hussain *et al.,* 2021). Although these species may not currently hold the same dietary significance as staple crops like tomato, chili, and potato, their resilience makes them increasingly important for adaptation strategies (Willett *et al.,* 2019).

Internationally, interest in *Opuntia ficus-indica* is increasing; agro-climatic suitability studies for this species have been performed in arid and semiarid zones in Argentina and Chile (Falasca *et al.,* 2011; Homer *et al.,* 2020). Additionally, Medina-García *et al.* (2021) conducted research to define the impact of climate change on the thermal requirements of this species in the central states of Mexico. In this context, *O. ficus-indica* was selected for assessment in this study because it utilizes CAM photosynthesis, and arid zones are increasing in north-central Mexico (Correa-Islas *et al.,* 2023). Moreover, its nutraceutical quality is highly relevant for public health, and it is native to the central highlands of Mexico between the Sierra Madre Oriental and Occidental, where the study area is located (Lugo-Palacios *et al.,* 2024; Medina-García *et al.,* 2021). Nonetheless, the commercial cultivation of the crop is not yet significant in this zone, accounting for 7% of the national surface destined for tender cladode production, and 27% for prickly pear fruit, with Zacatecas contributing 26% and 2.3% respectively (SIAP, 2025).

Agro-climatic zoning methodologies principally use temperature and precipitation (SIAP, 2019). Temperature has been highlighted as the most important factor for agro-climatic zoning, explaining 75% of the variance in a study in Iran. In contrast, annual rainfall contributed 23.2% to fig suitability in Mexico (Sharafi *et al.,* 2022; Martinez-Macias *et al.,* 2022). For the study conducted in Argentina, Falasca *et al.* (2012) used precipitation, annual mean temperature, and frost intensity; additionally, the same variables were considered by Homer *et al.* (2020) to identify suitable areas for this crop in Chile.

Based on the previous considerations, the aim of this study was to develop agro-climatic suitability maps for *O. ficus-indica* in the north-central states of Mexico based on temperature and precipitation data. The current scenario (1990-2020) information developed by Wang *et al.* (2016) was considered, as well as SSP2 and SSP5 for the 2040-2070 period using General Circulation Models (GCMs) built by Mahony *et al.* (2022). All data were obtained from the ClimateNA geodatabase version v7.41.

Material and Methods

Study area

The study area encompasses the north-central states of Mexico; these constitute an administrative region defined by the North-Central Regional Research Center (CIRNOC, by its Spanish acronym) of the National Institute of Forestry, Agricultural and Livestock Research. This area includes the States of Aguascalientes, Chihuahua, Durango, and Zacatecas, plus the “Comarca Lagunera” region of Coahuila de Zaragoza. For the purpose of this study, the entire State of Coahuila de Zaragoza was included to provide a complete geographic context.

This administrative region is highly important for agri-food security and national sovereignty. From the perspective of national cultivated area, it stands out with 60% of bean crops, 80% of pecan and apple, and 45% of green chili, among other crops like aji (43%). It is also crucial for forage production,

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contributing 50% of maize, 96% of sorghum, and 61% of oats, in addition to its relevance for livestock (SIAP, 2025).

Opuntia ficus indica agro-climatic requirements

The agro-climatic requirements for *O. ficus-indica* were compiled from bibliographic information based on the following parameters, annual mean temperature, average minimum temperature, and annual precipitation. These parameters were classified into highly, moderately suitable, slightly suitable and non-suitable ranges according to the literature (Table 1).

Table 1. *Opuntia ficus-indica* clases for the north-central Mexico.

Parameters	Classification				Sources
	Highly suitable	Moderately suitable	Slightly suitable	Non suitable	
Mean annual temperature (°C)	14 - 19	13 - 14 19 - 21	> 21 < 13	-	Medina-García *et al.,* 2021
Average minimum temperature (°C)	> 10	≥ - 2	≤ - 7	-	Nobel and De la Barrera, 2003 Homer *et al.,* 2020)
Precipitation (mm)	400 - 600	200 - 400	< 200	> 600	Alam-Eldein *et al.,* 2021

Climatic data

The climatic data were obtained from the ClimateNA geodatabase with a spatial resolution of 4 km: annual mean temperature, average minimum temperature, and precipitation. Then, INEGI (2019) vector maps were used for data extraction within the study area (Wang *et al.,* 2016). Data included climatic parameters under the current scenario (1990-2020), as well as projections for 2040–2070 considering the SSP2 and SSP5 scenarios. These were derived from an 8-GCM ensemble composed of the following models: ACCESS-ESM1.5, CNRM-ESM2-1, EC-Earth3, GFDL-ESM4, GISS-E2-1-G, MIROC6, MPI-ESM1.2-HR, and MRI-ESM2.0 (Mahony *et al.,* 2022).

Determination of agro-climatic suitability

This study was performed following SIAP (2019) and Falasca *et al.* (2011) methodologies to determine the agro-climatic suitability of *O. ficus-indica*. After raster extraction, raster reclassification was performed for the climatic parameters mentioned above. This process assigned a preliminary suitability score (PSS) to each cell as stated in Table 1: highly suitable = 3, moderately suitable = 2, slightly suitable = 1, and non-suitable = 0.

The final agro-climatic classification (ACC) was obtained by applying Equation 1:

$$ACC = \frac{[PSS\ for\ precipitation\ x\ (PSS\ for\ mean\ temperature\ +\ PSS\ for\ minimum\ temperature)]}{3} \quad [1]$$

This multiplicative algorithm prioritizes the PSS for precipitation as the primary limiting factor. The resulting ACC scores were then categorized into the final agro-climatic suitability classes (Table 2). Subsequently, maps were developed for each parameter and agro-climatic suitability scenario using QGIS 3.34: the current scenario and 2040-2070 projections for SSP2 and SSP5.

Table 2. Agro-climatic suitability classes obtained within study region.

Class	Selected ACC values	Details
Highly suitable	6	All agro-climatic requirements are fully satisfied.
Moderately suitable	3.3 - 5	Crop requirements are mostly met; however, slight deficits in thermal or hydric (water) conditions may occur, leading to minor limitations on production.
Slightly suitable	1 - 3	Crop requirements are significantly limited by strong deficits in thermal or hydric conditions, resulting in major constraints on growth and potential yield.
Non suitable	0	Conditions are unsuitable for cultivation. This is primarily due to excessive precipitation leading to harmful or damaging conditions (e.g., waterlogging, fungal growth) for *O. ficus-indica*.

Statistical analysis

The statistical analysis was conducted to characterize suitability classes under the current scenario, and the 2040-2070 scenarios according to SSP2 and SSP5. The analysis consisted of descriptive statistics extraction per State; this was carried out using the raster layer statistics function in QGIS 3.34. These statistics include measures of central tendency (e.g., mean) and dispersion (i.e., range, standard deviation) for the suitability scores. The change in suitable area from ACC maps was calculated as a percentage (%), based on the difference between the SSP2/SSP5 scenarios and the current scenario.

Validation

The occurrence points of *O. ficus-indica* were obtained from GBIF (2025) with detailed specifications available at https://doi.org/10.15468/dl.exgfdb. Then, the extraction of points within the study area was carried out using INEGI (2019) vector maps.

A Chi-square (χ^2) was performed to address randomness in the current scenario for model validation of the proposed agro-climatic suitability zoning. For this analysis, the points observed per class and expected occurrence points of this species were considered (Hernández-Sampieri *et al.,* 1991). Then, Cramer's V test was calculated to determine the strength of the correlation between these variables. Subsequently, a frequency ratio (FR) analysis was performed to evaluate the probability of *O. ficus-indica* presence per class and the corresponding occurrence points found (Khan *et al.,* 2019).

Results and Discussion

Mean annual temperature and O. ficus-indica agro-climatic suitability

The increase in mean annual temperature appears to affect the agro-climatic suitability of *O. ficus-indica* within the study area (Table 3). The changes in surface proportion were observed for all north-central states of Mexico, principally in the highly suitable classification. Although *O. ficus-indica* is tolerant of warmer zones, its optimal annual mean temperature range is 14-19 °C (Medina-García *et al.,* 2021).

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Table 3. Mean temperature suitability classification change (%) for north-central Mexico: current scenario vs. SSP2 and SSP5 (2040-2070 period).

States	Actual scenario (1990-2020)			SSP2 scenario (2040-2070)			SSP5 scenario (2040-2070)		
	Annual mean temperature class								
	SS	MS	HS	SS	MS	HS	SS	MS	HS
Aguascalientes	0.00	5.26	94.74	3.86	55.44	-59.30	5.96	68.42	-74.39
Durango	28.83	29.73	41.44	8.38	-5.80	-2.58	13.11	-7.00	-6.11
Zacatecas	5.19	15.83	78.98	12.44	21.85	-34.29	20.03	33.01	-53.04
Coahuila de Zaragoza	53.41	38.66	7.93	27.07	-21.98	-5.10	35.22	-29.17	-6.05
Chihuahua	9.09	26.43	64.48	3.24	19.58	-22.83	14.01	16.62	-30.63

SS: Slightly suitable; MS: Moderately suitable; HS: Highly suitable.

In the current scenario (1990-2020), the mean temperature across the study area ranges from 10.7 to 25.40 °C. Coahuila of Zaragoza State has the highest mean annual temperature at 21.14 °C, while Chihuahua present the lowest at 17.28 °C (Wang *et al.,* 2016). All States exhibit a standard deviation < 1.7 °C, suggesting thermal homogeneity, except for Durango and Chihuahua States, which recorded 3.11 °C and 2.35 °C, respectively (Figure 1).

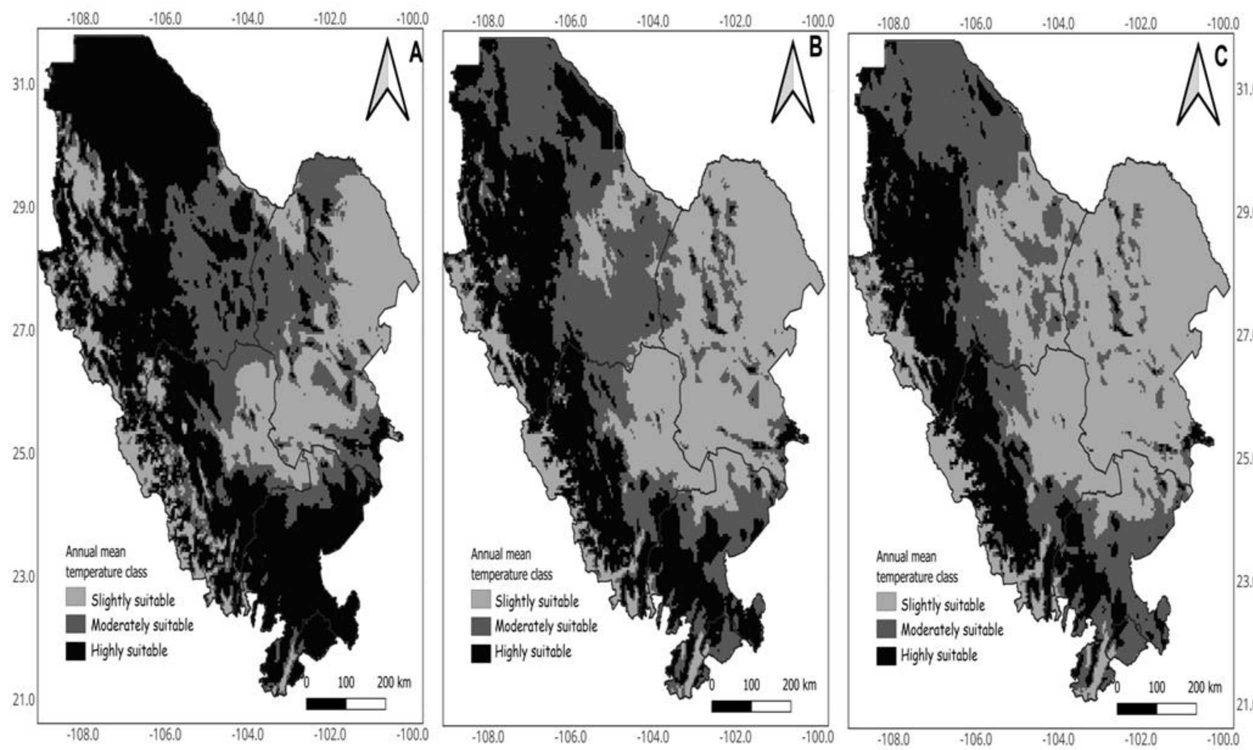

Figure 1. Suitability classification of *O. ficus-indica* for annual mean temperature of North central Mexico states, under actual scenario (1990-2020) (A), SSP2 for 2040-2070 (B) and SSP5 for 2040-2070 (C).

Regarding the SSP2 and SSP5 scenarios (2040-2070), the study area is projected to experience a mean temperature increase of 1.48 and 2.05 °C, respectively (Mahony *et al.,* 2022). Similarly, Correa-

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Islas *et al.* (2022) found an expansion in aridity index zones in Economic Region II of Mexico, where this study area is located; this is driven by the increase in annual mean temperature and potential evapotranspiration (Daramola and Xu, 2022). Table 3 shows a progressive contraction of the highly suitable zone and a concurrent expansion of the moderately and slightly suitable classes. This pattern suggests that, when considering mean temperature in isolation, warming trends may diminish the geographical range for optimal *O. ficus-indica* cultivation because temperatures exceed the upper limit of its ideal range.

Impact of average minimum temperature on O. ficus-indica suitability

Figure 2 highlights a consistent geographic pattern across all three scenarios. The moderately suitable areas are predominantly located in the northernmost part of the mapped region, along with scattered patches near the Sierra Madre Occidental in Chihuahua and Durango, across all three scenarios. The highly suitable regions are located in the rest of the mapped area. This species is best suited to warmer zones, while colder areas, particularly towards the northwest of the study area, are less suitable for *O. ficus-indica* cultivation (Nobel and De la Barrera, 2003; Homer *et al.,* 2020). This is due to cooler temperatures observed in Chihuahua and Durango, with 8.9 and 12.2 °C respectively, while the rest of the state's range between 12.5 and 12.8 °C in the current scenario (Wang *et al.,* 2016).

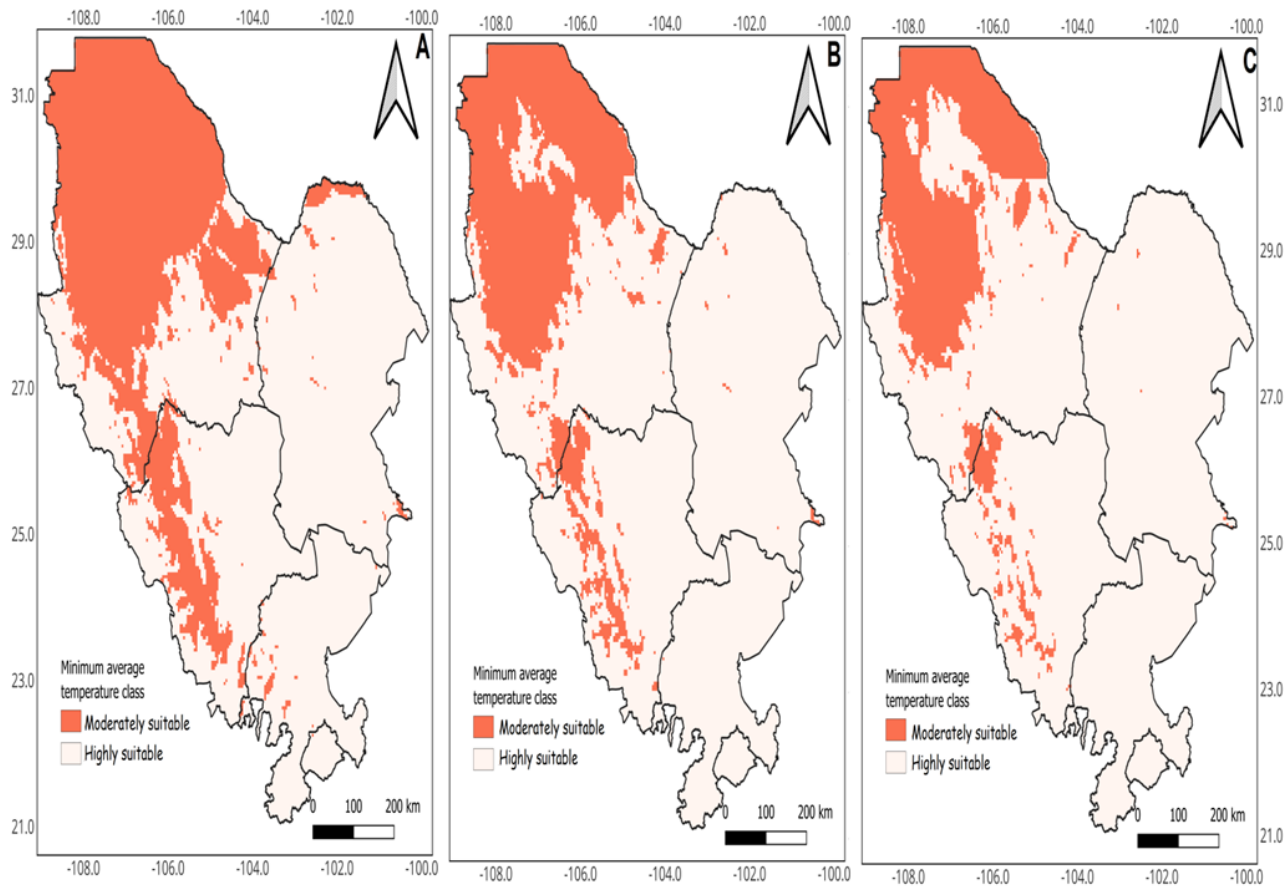

Figure 2. Suitability classification of *O. ficus-indica* for annual minimum average temperature of North central Mexico states, under actual scenario (1990-2020) (A), SSP2 for 2040-2070 (B) and SSP5 for 2040-2070 (C).

For the 2040-2070 projections considering both SSP2 and SSP5 scenarios, there is a mean increase in minimum temperature of 1.3-1.7 °C for the north-central states of Mexico. This facilitates better conditions for *O. ficus-indica* cultivation according to this parameter (Table 4) (Mahony *et al.,* 2022). This finding agrees with Hadi *et al.* (2024), who estimated that the mean minimum temperature in Iraq will increase within the range of 1.4-1.7 °C when comparing the 2021-2040 period to SSP2 and SSP5 scenarios for the 2041-2060 interval.

Table 4. Minimum average temperature suitability classification change (%) for north-central Mexico along actual scenario vs. SSP2 and SSP5, both for 2040-2070 period.

States	**Actual scenario (1990-2020)**		**SSP2 scenario (2040-2070)**		**SSP5 scenario (2040-2070)**	
	Annual minimum average temperature suitability class					
	MS	**HS**	**MS**	**HS**	**MS**	**HS**
Aguascalientes	0.4	99.6	-0.4	0.4	-0.4	0.4
Durango	24.1	75.9	-10.6	10.6	-15.3	15.3
Zacatecas	2.2	97.8	-2.1	2.1	-2.2	2.2
Coahuila de Zaragoza	3.2	96.8	-2.7	2.7	-3.0	3.0
Chihuahua	69.5	30.5	-18.8	18.8	-27.3	27.3

MS: Moderately suitable; HS: Highly suitable.

Annual accumulated precipitation and O. ficus-indica agro-climatic suitability

Regarding annual accumulated precipitation in north-central Mexico, an expansion in the proportion of highly suitable territory occurs in both scenarios (SSP2 and SSP5), ranging from 7 to 27% depending on the State (Table 5). This is primarily due to a mean increase in precipitation of 87 and 76 mm, respectively, compared to the current scenario. Nonetheless, variability increased in both future scenarios, indicated by larger standard deviations (around 155-158 mm) compared to the current scenario (124 mm) (Mahony *et al.,* 2022).

Table 5. Precipitation suitability classification change (%) for north-central Mexico along actual scenario vs. SSP2 and SSP5, both for 2040-2070 period.

States	Actual scenario (1990-2020)				SSP2 scenario (2040-2070)				SSP5 scenario (2040-2070)			
	Accumulated annual precipitation suitability classification											
	NS	SS	MS	HS	NS	SS	MS	HS	NS	SS	MS	HS
Aguascalientes	15.27	0.00	69.08	15.65	5.94	0.00	-13.22	7.28	5.70	0.00	-12.75	7.05
Durango	0.00	10.38	73.97	15.65	0.09	-7.18	-8.52	15.61	0.05	-6.54	-7.76	14.25
Zacatecas	0.00	0.00	41.75	58.25	23.86	0.00	-41.75	17.89	14.04	0.00	-41.75	27.72
Coahuila de Zaragoza	2.74	0.00	75.78	21.49	7.43	0.00	-34.52	27.09	5.68	0.00	-27.77	22.09
Chihuahua	31.13	1.34	43.94	23.59	12.68	-1.34	-15.11	3.77	11.93	-1.32	-14.35	3.75

NS: Non-suitable; SS: Slightly suitable; MS: Moderately suitable; HS: Highly suitable.

With respect to the highly suitable class, corresponding to annual accumulated precipitation between 400 and 600 mm (Table 1), this area is currently concentrated on the eastern side of the Sierra Madre Occidental and in the northeast of the study area (Figure 3) (Wang *et al.,* 2016). Coincidentally, *O.*

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ficus-indica is native to this part of Mexico, within the Sierra Madre Oriental and Occidental (Correa-Islas *et al.,* 2022; Medina-García *et al.,* 2021).

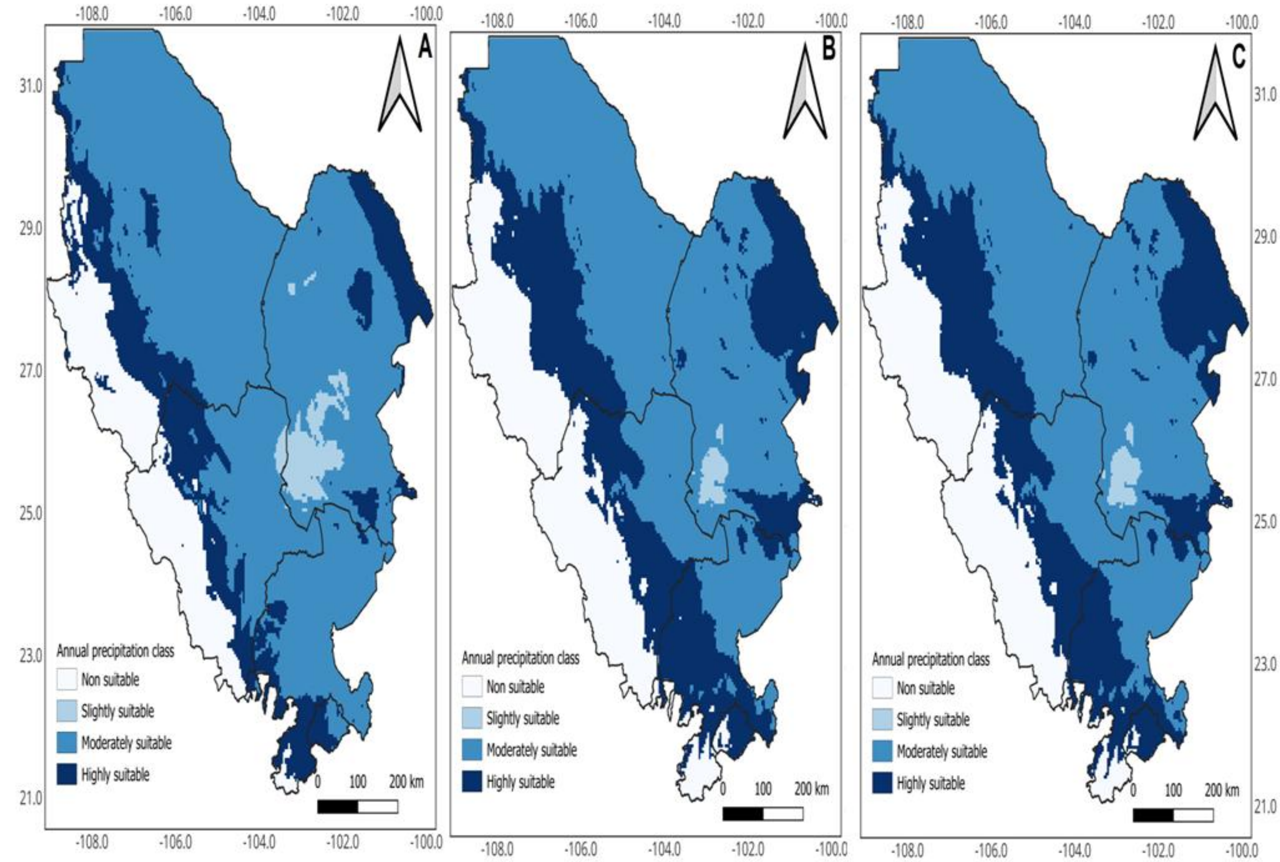

Figure 3. Suitability classification of *O. ficus-indica* for annual accumulated precipitation of North central Mexico states, under actual scenario (1990-2020) (A), SSP2 for 2040-2070 (B) and SSP5 for 2040-2070 (C).

Agro-climatic suitability

The area with highly suitable conditions is concentrated in the central and southern parts of the study area. A large, non-contiguous area in the northern and western parts is classified as non-suitable, mainly due to excessive rainfall along the Sierra Madre Occidental western slopes (> 600 mm), which could damage *O. ficus-indica* growth (Alam-Eldein *et al.,* 2021; Wang *et al.,* 2016).

It is estimated that the non-suitable zones will increase by 6-24% and 6-14% under SSP2 and SSP5, respectively. This is driven by an increase in precipitation in the zones mentioned in previous paragraphs. On the other hand, the highly suitable class remains relatively stable regionally, except for Aguascalientes and Zacatecas States. The former is projected to lose 32.63% of its highly suitable territory, while the latter is projected to expand by 16.58%. This is particularly significant because Zacatecas is the second-highest producer of prickly pear fruit in Mexico and ranks tenth for tender cladodes (SIAP, 2025). Consequently, the estimated expansion of highly suitable zones supports strategies to diminish the climate change impact on food production by enabling shifts in cultivation dates or the introduction of resilient crops like *O. ficus-indica* (Medina-García *et al.,* 2021).

At the same time, the moderately and slightly suitable classes experienced notable shifts. The moderately suitable class is estimated to decrease, while the slightly suitable class is predicted to increase. In other words, this study area faces a reduction in appropriate conditions for this crop, which implies that *O. ficus-indica* could face drought and/or thermal stress (Hadi *et al.,* 2024). Similar findings were reported in the Czech Republic, where changing precipitation patterns and increased temperature resulted in notable agro-climatic zone shifts. The authors attributed that change to increased potential evapotranspiration, which is affected by both climatic parameters mentioned (Figure 4) (Trnka *et al.,* 2021).

Regarding suitability studies for this crop, Falasca *et al.* (2011) determined the agro-climatic suitability of *O. ficus-indica* in the entire territory of Argentina. They found that around 50% of the territory fell within the optimal class, which is similar to the highly suitable class of the present study. Additionally, those authors included a marginal category defined by water deficit, similar to the moderately and slightly suitable classes of the present study.

On the other hand, in the analysis of the present sutdy, the current scenario, suitable territory (comprising slightly, moderately, and highly suitable classes) ranges from 69 to 100% depending on the State. In contrast, the SSP2 and SSP5 scenarios for the 2040-2070 period range between 56 and 100%. These findings reinforce the probable necessity of changing agricultural land use per specific state, or even per agricultural region, due to different climatic conditions (Table 6).

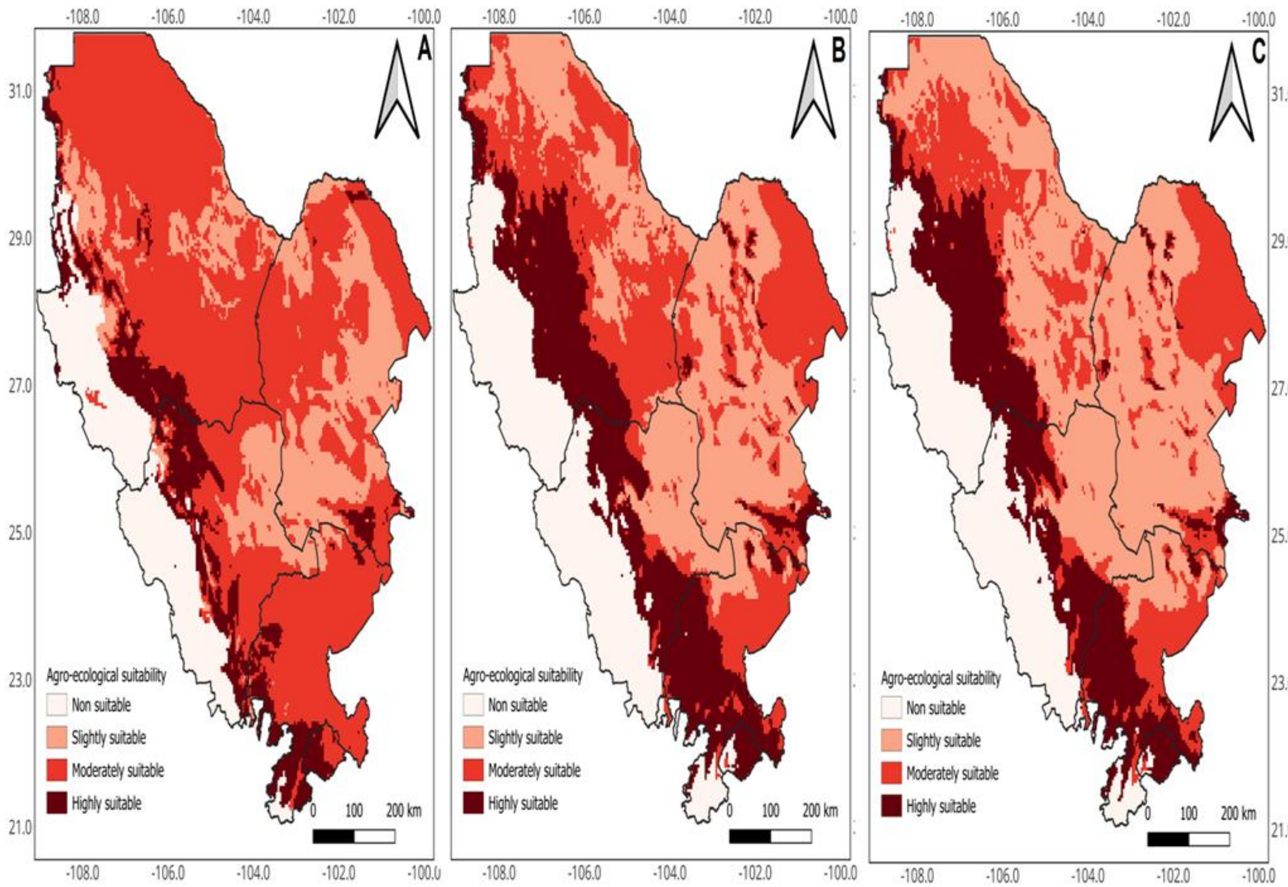

Figure 4. Agro-climatic suitability of *O. ficus-indica* for North central Mexico states, under actual scenario (1990 – 2020) (A), SSP2 for 2040 – 2070 (B) and SSP5 for 2040 – 2070 (C).

Table 6. Agro-climatic suitability change (%) for north-central Mexico along actual scenario vs. SSP2 and SSP5, both for 2040-2070 period.

States	**Actual scenario (1990-2020)**				**SSP2 scenario (2040-2070)**				**SSP5 scenario (2040-2070)**			
	Suitability classification											
	NS	**SS**	**MS**	**HS**	**NS**	**SS**	**MS**	**HS**	**NS**	**SS**	**MS**	**HS**
Chihuahua	15.27	11.99	69.94	2.80	5.94	11.04	-16.84	-0.14	5.70	22.24	-27.51	-0.43
Coahuila	0.00	43.00	55.86	1.14	0.09	11.51	-12.49	0.89	0.05	20.12	-20.67	0.50
Aguascalientes	0.00	0.00	47.02	52.98	23.86	0.00	8.77	-32.63	14.04	0.00	24.56	-38.60
Zacatecas	2.74	3.47	77.52	16.27	7.43	8.14	-32.15	16.58	5.68	14.63	-25.79	5.48
Durango	31.13	17.66	39.78	11.42	12.68	7.74	-19.73	-0.69	11.93	10.10	-18.20	-3.83

NS: Non-suitable; SS: Slightly suitable; MS: Moderately suitable; HS: Highly suitable.

Agro-climatic suitability validation

The statistical validity of the agro-climatic zoning was confirmed through the Chi-square (χ^2). The calculated value of χ^2 (9.15) exceeds the critical χ^2 value of 7.815 (for 3 degrees of freedom and α=0.05) (Table 7). Consequently, the null hypothesis is rejected, establishing that the observed (O) and expected (E) occurrence points of *O. ficus-indica* are statistically associated (Hernández-Sampieri *et al.,* 1991). This indicates that the zoning model, considering the determined classes, is a medium reliable predictor of the species' spatial patterns in north-central Mexico according to Cramer's V value of 0.24 (for 3 degrees of freedom) (Iečko and Bradac-Hojnik*,* 2024).

Table 7. Agro-climatic suitability validation according to χ^2 and frequency ratio for north-central Mexico for actual scenario.

Suitability class	Parcial χ^2	FR
Non-suitable	2.74	0.58
Slightly suitable	1.51	0.75
Moderately suitable	3.68	1.2
Highly suitable	1.22	0.78
Total	9.15	

Regarding the intensity of each class, the FR illustrates the distribution preference patterns of *O. ficus-indica*. FR values < 1 suggest a lower probability of occurrence for this species than that determined by the suitability classes, while higher values (FR > 1) indicate a higher probability of presence (Khan et al., 2019). As can be observed, the FR for the non-suitable class is 42% less than expected, while the most favorable class is moderately suitable, with a 20% higher chance of finding *O. ficus-indica*.

Conversely, the highly suitable class exhibited species avoidance (lower than expected occurrence). From an agronomic perspective, this discrepancy likely occurs because highly suitable lands are prioritized for intensive cash crops (e.g., beans, cotton) or forages (e.g., maize, oats, sorghum, alfalfa), thereby displacing *O. ficus-indica* to marginal or moderate lands (SIAP, 2025; Soberón, 2007).

Conclusions

The agro-climatic suitability analysis demonstrates that future climate scenarios (SSP2 and SSP5) will induce significant shifts in the proportion of suitable territory for *Opuntia ficus-indica* across the north-central States of Mexico. *Opuntia ficus-indica* suitability is projected to see a region-wide increase in the slightly suitable class. This suggests that maintaining productivity under the new climatic regime will require the crop to demand more water to satisfy its needs, potentially necessitating supplemental irrigation in marginal zones. Conversely, Aguascalientes is projected to lose highly suitable territory, while Zacatecas, a nationally important producer of tender cladodes and prickly pear fruit, will see the territory occupied by this classification increase.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

Not applicable

AUTHOR CONTRIBUTIONS

Conceptualization, A.D.L.-P.; methodology, A.D.L.-P and R.E.L.-P.; software, A.D.L.-P.; validation, S.Y.M.-G.; and M.G.R.-A.; formal analysis, R.E.L.-P., A.D.L.-P, and S.Y.M.-G.; investigation, A.D.L.-P and R.E.L.-P.; resources, R.E.L.-P., A.D.L.-P. and M.G.R.-A.; data curation, R.E.L.-P., and A.D.L.-P.; writing—original draft preparation, A.D.L.-P. and R.E.L.-P.; writing—review and editing, E.C.-L.; and E.M.G.-C.; visualization, E.C.-L.; supervision, E.M.G.-C.; ; project administration, E.C.-L. and E.M.G.-C.

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