



Scientia Agropecuaria

Web page: <http://revistas.unitru.edu.pe/index.php/scientiaagrop>

Facultad de Ciencias
Agropecuarias

Universidad Nacional de
Trujillo

RESEARCH ARTICLE



Agroecological zoning of mezcal and tequila agaves in Mexico through MaxEnt ecological niche modeling: Sustainability and climate resilience implications

Christian Michel-Cuello^{1*} ; Noé Aguilar-Rivera² ; Cristian López-Palacios¹

¹ Universidad Autónoma de San Luis Potosí, Facultad de Estudios Profesionales Zona Media. Rioverde, San Luis Potosí, México.

² Universidad Veracruzana, Facultad de Ciencias Biológicas y Agropecuarias, Orizaba, Veracruz, México.

* Corresponding author: christian.michel@uaslp.mx (C. Michel-Cuello).

Received: 4 February 2026. Accepted: 27 September 2026. Published: 10 October 2026.

Abstract

Agave-based distilled-beverage production in Mexico, particularly mezcal and tequila, is facing intensifying sustainability challenges driven by climate change, monocropping expansion, and degradation of socio-ecological systems. In this context, agroecological zoning represents a strategic tool for improving territorial planning and strengthening climate resilience. This study aimed to identify agroecologically suitable areas for mezcal (*Agave angustifolia*) and tequila (*Agave tequilana*) agaves across Mexico, while minimising biodiversity impacts and supporting sustainable land-use decision-making. We combined bibliometric analysis with ecological niche modelling using the maximum entropy algorithm (MaxEnt), integrating georeferenced occurrence data from major producing municipalities with climatic, topographic, and edaphic variables for the 2020 - 2025 period. The resulting models showed high predictive performance, with area under the curve (AUC) values of 0.941 for *A. angustifolia* and 0.978 for *A. tequilana*. Species-specific vulnerability patterns were identified: *A. angustifolia* displayed greater sensitivity to topographic and soil-chemical factors, whereas *A. tequilana* was predominantly constrained by climatic variables, particularly temperature and precipitation, increasing its exposure to climate change. Threshold analyses delineated a statistically robust core area of approximately 4,578 km² with guaranteed agroecological suitability, representing zones of long term productive stability. Expanding cultivation beyond these core areas was associated with decreasing statistical confidence and higher agronomic risk. Overall, the findings demonstrate that agroecological zoning can support climate resilient and regenerative agave production pathways in Mexico. These findings underscore the need for differentiated public policies that promote polyculture systems, genetic diversity conservation, and circular management of agave by products to ensure the long term sustainability of mezcal and tequila producing landscapes.

Keywords: agroecological zoning; climate resilience; ecological niche modeling; MaxEnt; sustainable agave production; land-use planning.

DOI: <https://doi.org/10.17268/sci.agropecu.2026.55>

Cite this article:

Michel-Cuello, C., Aguilar-Rivera, N., & López-Palacios, C. (2026). Agroecological zoning of mezcal and tequila agaves in Mexico through MaxEnt ecological niche modeling: Sustainability and climate resilience implications. *Scientia Agropecuaria*, 17(3), 815-827.

1. Introduction

Agaves (*Agave* spp.) are widely distributed perennial plants that play a fundamental role in agroecosystems of arid and semi-arid regions, particularly in Mexico. From a plant-biology and agroecological perspective, agaves are characterised by high water-use efficiency, physiological adaptations to climatic stress, and strong interactions with soil and topographic conditions, making them a model system for evaluating plant-environment relationships under conditions of increasing climatic variability. Furthermore, the crassulacean acid metabolism (CAM) characteristic of *Agave* species confers

exceptionally high water-use efficiency by enabling nocturnal carbon fixation, thereby enhancing drought tolerance and positioning agaves as particularly resilient crops under scenarios of increasing aridity and global warming (Davis et al., 2021; Davis & Ortiz-Cano, 2023). Their integration within diversified agricultural systems has historically contributed to soil stability, landscape heterogeneity, and the conservation of plant biodiversity. As such, agaves represent a crop group of broad relevance for sustainable agriculture and the development of resilient horticultural systems, in line with current priorities in plant science and agronomy.

With the arrival of European colonisers, agave-based production underwent substantial diversification, most prominently within the sector of high-alcohol beverages, following the introduction of the alembic and distillation technologies. This transition gave rise to several distilled spirits (such as raicilla, bacanora, sotol, and tobalá) and, most notably, mezcal and tequila. These beverages are now consumed internationally, protected under denomination-of-origin frameworks, and recognised as emblematic of Mexico's folklore, traditions, and cultural, historical, and gastronomic heritage (Santiago-Martínez et al., 2023).

Given the substantial regional economic importance of agave-based distilled beverages, academic literature has, for several decades, addressed multiple dimensions aimed at improving productivity, sustainability, and overall system performance. Research efforts have focused on the botanical and ecological characterisation of agave species, including morphological traits, physiological adaptations, and habitat requirements (Ortiz-Cano et al., 2023; Cuéllar-Martínez et al., 2026), as well as on the documentation of traditional uses of leaves, fibres, and associated by-products that highlight their cultural significance and functional applications within Indigenous and rural communities (Molina et al., 2023; Tripathi et al., 2023). Parallel to this, recent studies have explored biorefinery approaches for mezcal and tequila by-products, particularly vinasas and bagasse, emphasizing waste valorisation and circular bioeconomy strategies (De Anda-Rodríguez et al., 2025; Suárez-Sánchez et al., 2025), alongside the development of high-value bioproducts derived from agave, such as inulin and maguey syrup, with attention to their technological, nutritional, and commercial potential (Saraiva et al., 2022; Noriega-Juárez et al., 2025).

In addition, the literature has examined economic indicators and market dynamics related to mezcal and tequila production, including competitiveness, value chains, and trade performance (López-Santiago et al., 2024; Lozano, 2024), while also addressing significant socio-economic and environmental challenges. These include deforestation and the conversion of native forests or tropical dry forest ecosystems driven largely by denomination-of-origin frameworks and large-scale export demand (Tetreault et al., 2021; Valiente-Banuet & Arizmendi, 2023), soil degradation processes such as erosion associated with intensive agave cultivation practices (Guevara-Gutiérrez et al., 2024; Queiroz et al., 2024), and the displacement of wild agave populations coupled with the genetic vulnerability of monocultivars, which represent critical

biological risks to long-term system resilience (Tetreault et al., 2021; Valiente-Banuet & Arizmendi, 2023). Emerging research has increasingly highlighted the need for agroecological and regenerative production models supported by public policies that promote food security, local labour use, and reduced dependence on agrochemicals (Giller et al., 2021; Rieger, 2025), as well as the preservation of ancestral knowledge systems and management practices that sustain agroecological balance and cultural continuity (Santiago-Martínez et al., 2023; Rieger, 2025). Furthermore, climate change impacts, including reduced resilience and accelerating soil erosion in agave plantations, have become a central concern (Guevara-Gutiérrez, 2024; Queiroz et al., 2024), reinforcing proposals for the reintroduction of polyculture systems (such as intercropping agave with maize, beans, and endemic tree species). Traditional management of *Agave angustifolia* in mezcal-producing regions has historically relied on diversified agroecosystems, where agaves are commonly established as living fences, integrated into agroforestry systems, or cultivated in association with maize and beans within the traditional milpa system. These practices contribute to soil conservation, landscape heterogeneity, pollinator protection, and the maintenance of agrobiodiversity, while reducing dependence on external inputs (Valiente-Banuet & Arizmendi, 2023; Castañeda-Hidalgo et al., 2025). The adoption and strengthening of these traditional management strategies, together with reduced tillage practices, may enhance soil health, ecosystem functionality, and climate resilience in agave-producing landscapes (Ávila-Reyes et al., 2025; Márquez-Rangel et al., 2025; Terán-Bustamante et al., 2025).

Despite the breadth of research addressing biological, technological, economic, and socio-cultural dimensions of agave-based production systems, much of the existing literature remains fragmented and frequently focused on isolated components of the value chain. This compartmentalised approach has limited the capacity to fully capture the complex interactions between agave cultivation, landscape transformation, resource use, and environmental feedback at broader spatial and temporal scales. As a result, critical vulnerabilities associated with land-use change, ecosystem degradation, and the intensification of production systems have become increasingly evident, underscoring the need for integrated assessments that explicitly address the long-term sustainability of mezcal and tequila socio-ecological systems.

Nevertheless, one of the most critical challenges confronting agave-based socio-ecological systems

associated with mezcal and tequila production is their long-term sustainability. These systems are increasingly threatened by deforestation, the burning of natural areas, and the conversion of tropical dry forests into intensively managed monoculture plantations that rely heavily on water extraction and agrochemical inputs. Additional pressures arise from the harvesting of endemic species (an expression of agro-extractivism) and the overexploitation of wild agave populations, both of which contribute to biodiversity loss in response to growing global market demand. Furthermore, the intensive environmental contamination generated by production by-products, particularly agave bagasse and vinasses, exacerbates ecosystem degradation and places further constraints on the ecological viability of these production systems (Queiroz et al., 2024) (Figure 1).

A bibliometric analysis revealed distinct thematic clusters underpinning the sustainability of agave-based socio-ecological systems. The red cluster encompasses species biodiversity and traditional uses. The blue cluster highlights the central role of agave in the production of Mexico's emblematic distilled spirits (tequila and mezcal) driven by organoleptic attributes, alongside the need to optimise fermentation and position sustainability as a core market asset. The green and yellow clusters reflect the synergy with traditional markets, including the revitalisation of pulque and the development of food additives, superfoods, and bioproducts. A second blue cluster underscores the urgent requirement for waste treatment and the conversion of residues into new value chains (Figure 2).

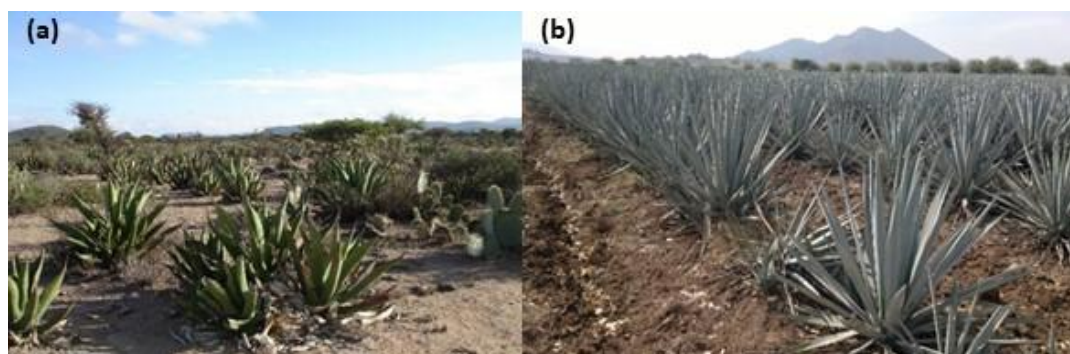


Figure 1. Agave plants for distilled-spirit production in Mexico: (a) *Agave angustifolia* plantation in Charcas, San Luis Potosí; (b) *Agave tequilana* plantation in Tequila, Jalisco.

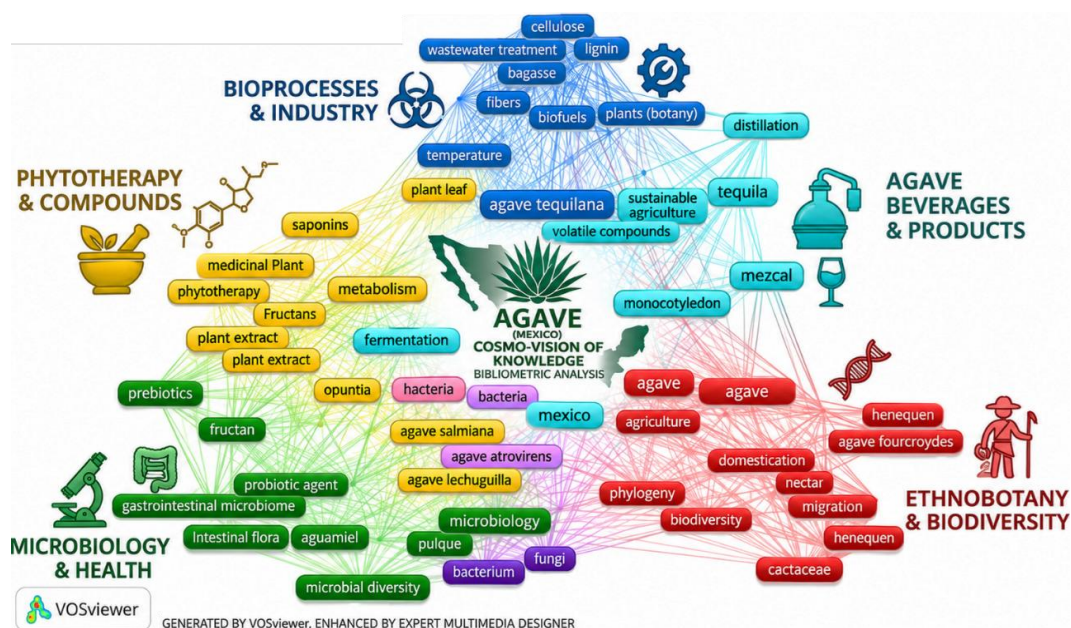


Figure 2. High-resolution bibliometric network of global agave research generated using VOSviewer from keyword co-occurrence analysis of the scientific literature. Node size is proportional to keyword frequency, connecting lines represent co-occurrence relationships, and colors identify major thematic clusters within agave research.

In this context, the present study aims to identify agroecologically suitable areas for mezcal (*Agave angustifolia*) and tequila (*Agave tequilana*) agaves in Mexico through ecological niche modelling. By integrating climatic, topographic, and edaphic variables within a maximum-entropy framework, the study seeks to contribute to a broader understanding of species-specific environmental requirements in perennial crops. The results provide an agroecological basis for sustainable land-use planning, biodiversity conservation, and climate-resilient management of agave cultivation systems, offering insights that are transferable to other horticultural and agricultural contexts subject to environmental constraints.

2. Methodology

2.1 Geographical data and presence records for ecological niche modeling

Geographical coordinates were compiled for municipalities with the highest production of maguey for mezcal and tequila in Mexico, derived from the Mexican National Geostatistical Framework (INEGI, 2025).

Mezcal: The coordinates examined correspond to the following municipalities Chiapas: Comitán de Domínguez and Siltepec; Durango: Durango and Mezquital; Guanajuato: San Felipe and San Luis de la Paz; Guerrero: Ahuacutzingo, Chilapa de Álvarez, Mártir de Cuilápan, and Tixtla de Guerrero; Jalisco: Tolimán, Tonaya, and Zapotitlán de Vadillo; Oaxaca: Santo Domingo Teojomulco, San Pablo Villa de Mitla, San Pedro Apóstol, Santa Cruz Xitla, Santa María del Tule, Teotitlán del Valle, Villa Sola de Vega, and Zimatlán de Álvarez; Puebla: Acajete, Amozoc, Izúcar de Matamoros, Libres, and Quecholac; San Luis Potosí: Ahualulco, Charcas, and Villa de Guadalupe; Sonora: Bacanora (georeferenced at the municipal level); Tamaulipas: Burgos, Bustamante, Miquihuana, and San Carlos; Zacatecas: Jalpa, Pinos, Teúl de González Ortega, and Villa Hidalgo. In total, these records represent 38 presence points (Table 1).

Table 1
Occurrences of mezcal maguey cultivation in Mexico (38 reference points)

State	Absolute frequency	Percentage frequency (%)
Chiapas	2	5.26
Durango	2	5.26
Guanajuato	2	5.26
Guerrero	4	10.53
Jalisco	3	7.89
Oaxaca	8	21.05
Puebla	5	13.16
San Luis Potosí	3	7.89
Sonora	1	2.63
Tamaulipas	4	10.53
Zacatecas	4	10.53

Tequila: The georeferenced municipalities are Guanajuato: Huanímaro and Pénjamo; Jalisco: Amatitán, Arandas, Atotonilco el Alto, Tequila, and Zapopan; Michoacán: Maravatío and Sahuayo; Nayarit: Ixtlán del Río; Tamaulipas: González. These records correspond to 11 presence points (Table 2).

Table 2
Occurrences of tequilero maguey cultivation in Mexico (11 reference points)

State	Absolute frequency	Percentage frequency (%)
Guanajuato	5	45.45
Jalisco	1	9.09
Michoacán	2	18.18
Nayarit	1	9.09
Tamaulipas	2	18.18

2.2 Agroecological zoning modelling

For the agroecological zoning, we employed 19 climatic layers and one topographic layer at a spatial resolution of 30 arc-seconds ($\approx 1\text{ km}^2$ at the equator) (Hijmans et al., 2005; Hernández et al., 2024). The information contained in each grid cell of every layer represents environmental values interpolated from observations for the period 2020 - 2025. All layers were clipped to the following geographic extent to ensure full coverage of the Mexican territory: Northern limit 33°, Southern limit 14°, Eastern limit -86°, and Western limit -119°. In addition, we incorporated nine layers describing soil properties of Mexico at a 1:1,000,000 scale (Cruz-Cárdenas et al., 2014a,b).

2.3 Ecological niche modelling and model evaluation

Ecological niche modelling was conducted using MaxEnt (Phillips & Dudík, 2008; Amici et al., 2017; Phillips et al., 2017; Sillero & Barbosa, 2021; Ortiz-Cano et al., 2023), which is grounded in the maximum entropy framework. Mathematically, the approach identifies the environmental predictors intersecting at each georeferenced occurrence of the crop (Townsend-Peterson et al., 1999) and, from these, estimates the average probability associated with each environmental variable across all occurrence coordinates included in the analysis (Phillips et al., 2004; Phillips et al., 2017).

A preliminary run was performed to select the climatic variables of greatest relevance to the biological development of both crops. Specifically, an initial run incorporated 29 environmental and edaphic predictors; a subsequent run excluded non-informative variables to improve interpretability of the agroecological model (Soberon & Townsend-Peterson, 2005; Elith et al., 2011). The selection of environmental predictors was based on their contribution to model performance during preliminary MaxEnt runs and subsequent evaluation of variable

importance through Jackknife tests. Although a prior collinearity screening based on pairwise correlation coefficients was not applied, MaxEnt has been reported to be relatively robust to correlated predictors, particularly when variable selection is subsequently guided by permutation importance, percent contribution, and Jackknife diagnostics (Elith et al., 2011; Merow et al., 2013; Phillips et al., 2017). Previous studies have shown that predictor collinearity may have a stronger effect on parameter interpretation than on predictive performance in machine-learning algorithms such as MaxEnt, especially when ecologically meaningful variables are retained and non-informative predictors are excluded during model refinement (De Marco Júnior & Nóbrega, 2018; Tong et al., 2023; Vasconcelos et al., 2024). Therefore, non-informative variables were excluded according to their contribution to model performance and ecological interpretability rather than solely on correlation thresholds. The resulting agroecological zoning model was evaluated using the area under the receiver operating characteristic curve (AUC), with values > 0.9 indicating robust performance of the agroecological gradient as a function of crop presence (Phillips et al., 2006; Phillips et al., 2017). The output corresponds to a map that depicts the trade-off between sensitivity (discrimination of presences) and specificity (discrimination of absences). The colour scale represents the probability of environmental suitability for crop development: lighter tones indicate the most favourable agroecological conditions, whereas progressively darker tones denote decreasing probability of suitable conditions (Rodríguez-Merino et al., 2020; Arslan & Örcü, 2021). Model parametrisation prioritised the selection of the most influential environmental variables, with results reported in a logistic output format (Merow et al., 2013; Zurell et al., 2020). In addition, a Jackknife procedure implemented in MaxEnt was applied to quantify the relative importance of each predictor, thereby evidencing the variables of greatest agroecological relevance (Phillips et al., 2006; Bradie & Leung, 2017; Fois et al., 2018). Finally, we computed the fraction of the predicted area within the study extent supported by occurrence data using a binomial omission test and its associated statistical significance (Elith et al., 2011; Ortiz-Cano et al., 2023).

Although the number of occurrence records used in this study was relatively limited (38 records for *Agave angustifolia* and 11 records for *Agave tequilana*), previous studies have demonstrated that MaxEnt performs reliably with small sample sizes and often outperforms alternative species distribution modeling approaches under presence-only

conditions. Pearson et al. (2007) reported successful predictions using as few as 5–10 occurrence records, while Wisz et al. (2008) showed that MaxEnt maintains acceptable predictive performance even with restricted datasets when occurrences capture a representative environmental gradient. Furthermore, the high AUC values obtained in the present study (0.941 for *A. angustifolia* and 0.978 for *A. tequilana*) indicate strong discriminatory power and support the adequacy of the available occurrence records for characterizing the ecological niche of both species.

Ecological niche models were developed using the default parameter settings implemented in MaxEnt, without modifying the regularization multiplier or feature classes. These settings have been widely validated for species distribution modeling and have demonstrated reliable performance across a broad range of sample sizes and environmental conditions (Phillips & Dudík, 2008; Merow et al., 2013; Phillips et al., 2017). To minimize the potential effects of overfitting, model interpretation was based on a refined set of informative environmental variables selected through preliminary model runs, while model performance was evaluated using AUC values, omission tests, and Jackknife analyses of variable importance.

3. Results and discussion

3.1 Spatial patterns of suitability and model performance

Figures 3 and 4 present the agroecological zoning of mezcal agave (*Agave angustifolia*) and tequila agave (*Agave tequilana*) in Mexico, delineating areas with varying levels of suitability for crop development. Within each polygon, warmer and more intense color tones denote zones of high suitability (probability > 70%), where the combined effects of climatic, edaphic, and topographic conditions favor crop establishment and growth; conversely, the gradient toward blue tones indicate lower suitability (probability < 70%), classifying regions that do not meet minimum agroecological requirements (Figures 3 and 4).

Model evaluation using the area under the curve (AUC) revealed high discriminatory performance for both species, with AUC = 0.941 for *A. angustifolia* (Figure 5) and AUC = 0.978 for *A. tequilana* (Figure 6). These results are consistent with the demonstrated robustness of MaxEnt under presence-only modeling scenarios and support its applicability for guiding territorial planning of perennial crops under conditions of climatic variability (Phillips et al., 2006, 2017; Elith et al., 2011; Merow et al., 2013; Zurell et al., 2020).

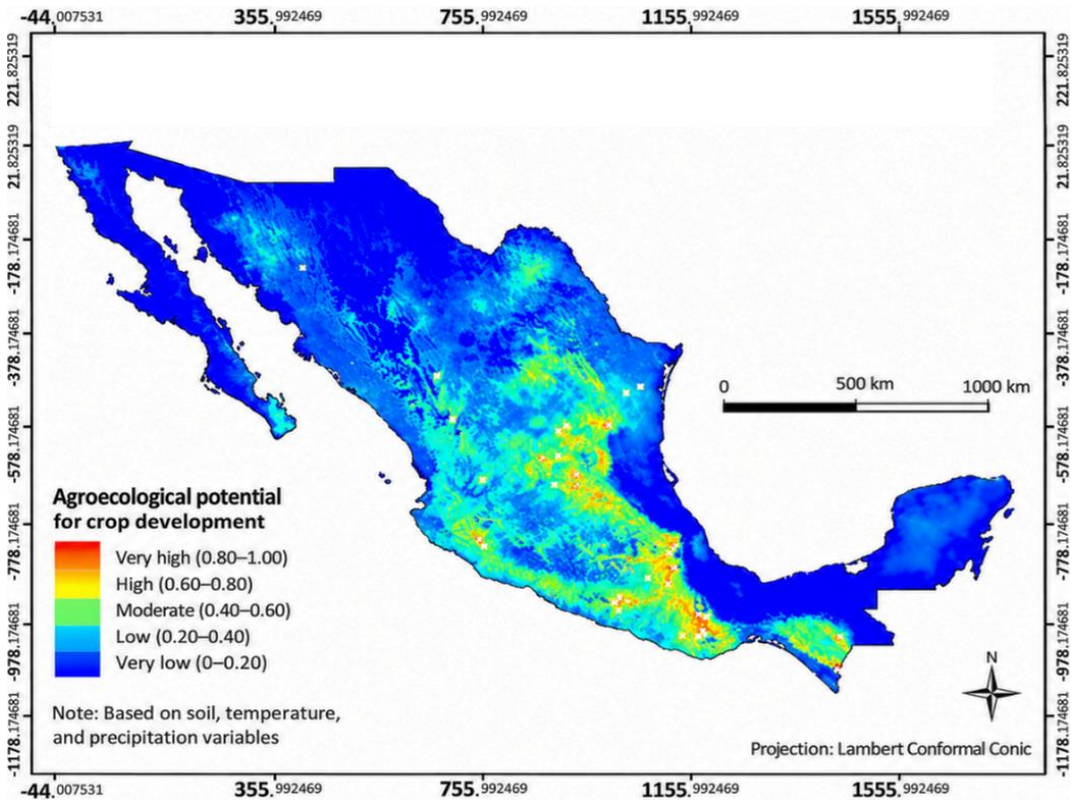


Figure 3. Agroecological zoning of *Agave angustifolia* for **mezcal** production in Mexico, using maximum entropy theory.

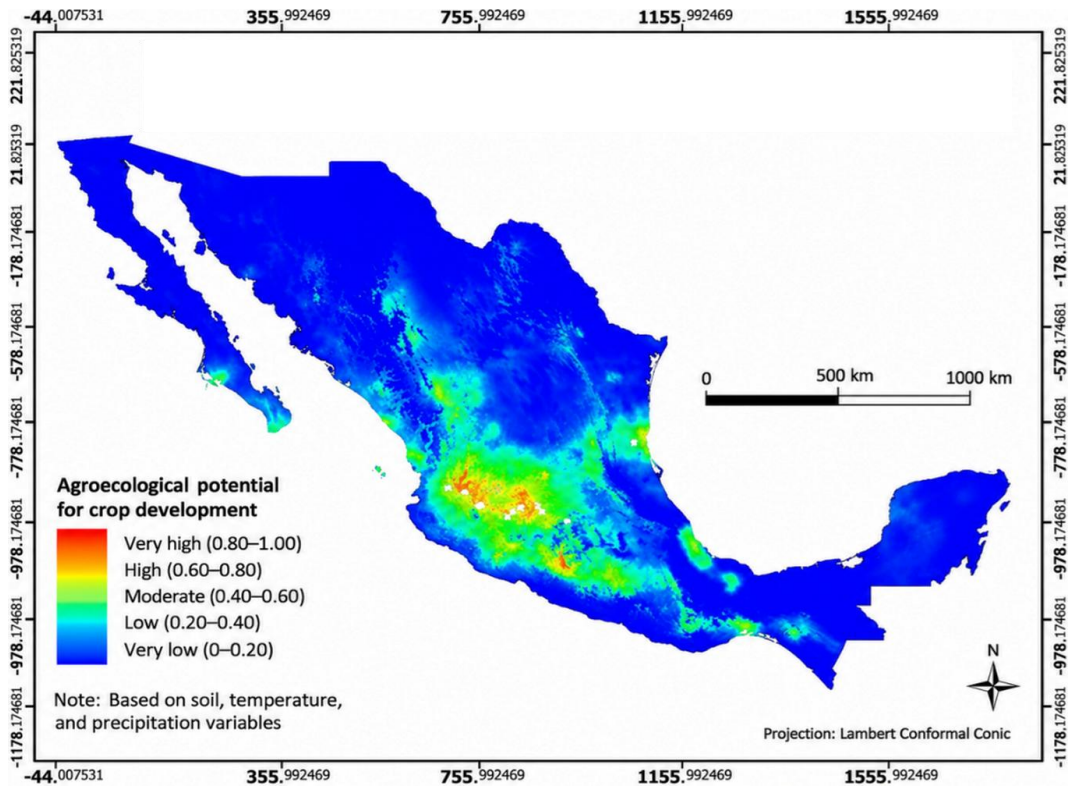


Figure 4. Agroecological zoning of *Agave tequilana* for **tequila** production in Mexico, using maximum entropy theory.

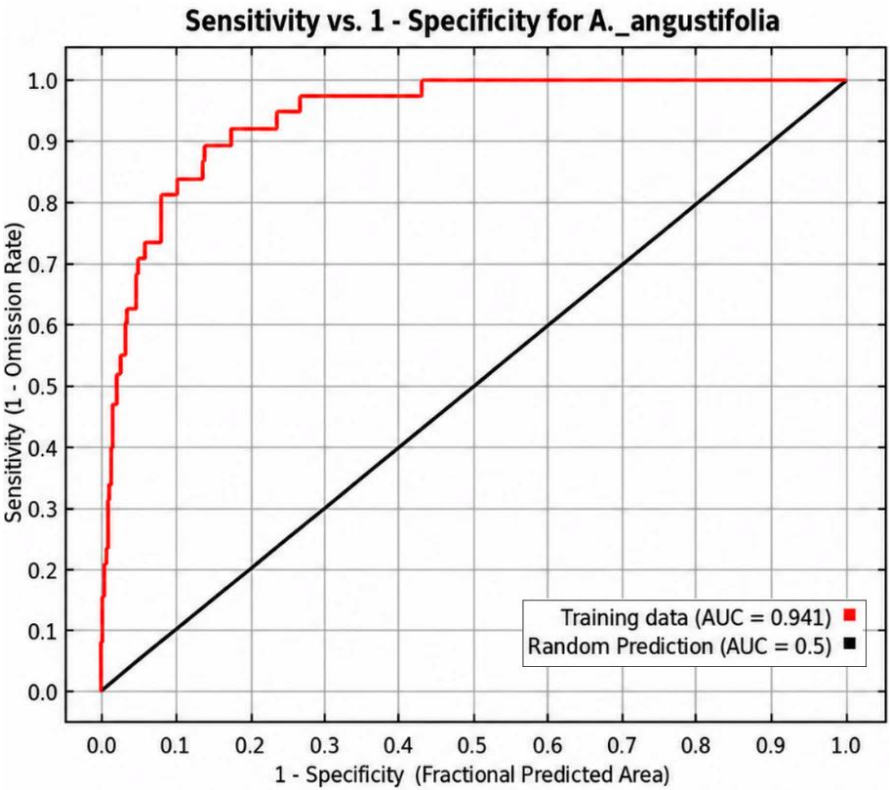


Figure 5. Model evaluation curve for the agroecological zoning of *Agave angustifolia* for mezcal production in Mexico.

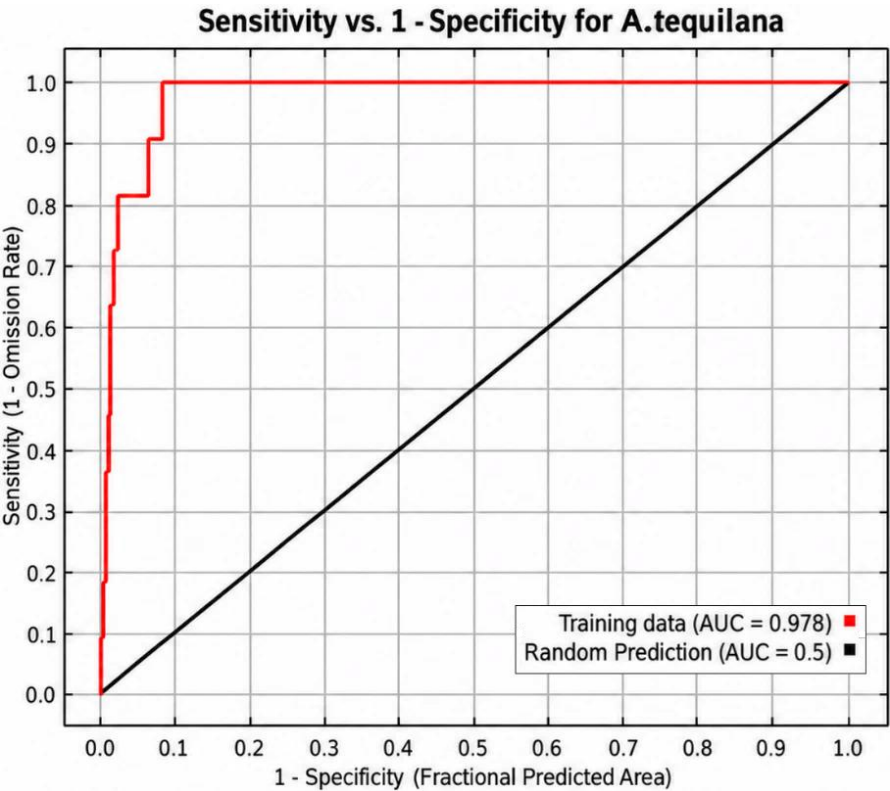


Figure 6. Model evaluation curve for the agroecological zoning of *Agave tequilana* in Mexico.

3.2 Species-specific environmental controls

Of the 29 variables initially evaluated, 18 contributed to the model for *A. angustifolia* and 16 to that for *A. tequilana* (Tables 3 and 4). For mezcal agave, temperature seasonality (Bio4), elevation (DEM20), and precipitation during the wettest and coldest quarters (Bio16, Bio19) emerged as dominant predictors, together with non-trivial edaphic effects of Na, Mg, and EC. This pattern is consistent with the historical association of mezcal production with heterogeneous mountainous landscapes and underscores the importance of topo-edaphic mosaics for yield stability and resilience (Rodríguez-Merino et al., 2020; Hernández et al., 2024). In contrast, *A. tequilana* exhibited a predominantly climatic dependence [temperature seasonality (Bio4) and precipitation seasonality (Bio15)] with marginal edaphic/topographic influence, suggesting a narrower climatic niche and greater vulnerability to warming and shifts in rainfall regimes (Ortiz-Cano et al., 2023; Queiroz et al., 2024). An additional factor contributing to the vulnerability of *Agave tequilana* is its reduced genetic diversity resulting from long-term clonal propagation. The tequila industry has largely relied on the cultivation of a single domesticated variety (*A. tequilana* Weber var. azul), propagated vegetatively through offshoots and managed under highly ho-

mogeneous production systems. Recent genomic studies have shown that modern tequila agave populations exhibit low genetic differentiation and substantial genetic uniformity compared with traditional landraces and wild relatives, reflecting an advanced process of genetic and biocultural erosion (Martínez-Lona et al., 2026). This reduction in genetic diversity may limit adaptive capacity to emerging environmental stresses, pests, diseases, and climate change, thereby increasing production risks in monoculture systems. In contrast, traditional agave management practices that maintain greater genetic variability and promote gene flow have been recognized as important mechanisms for enhancing resilience and long-term sustainability in agave-based agroecosystems (Ortiz-Cano et al., 2023; Guevara-Gutiérrez et al., 2024; Martínez-Lona et al., 2026; Martínez-Velasco et al., 2026). In addition to its climatic dependence, physiological studies suggest that *Agave tequilana* exhibits a relatively narrow thermal tolerance compared with other agave species. Experimental evidence indicates that this species has limited tolerance to low temperatures and reduced capacity for cold acclimation, which has historically constrained its cultivation to regions with favorable thermal regimes (Nobel et al., 1998).

Table 3
Key agroecological variables influencing the cultivation of *Agave angustifolia* in Mexico

Temperature	Importance (%)	Precipitation	Importance (%)	Soil	Importance (%)	Topographic	Importance (%)
Bio4	27.6	Bio16	8.7	Na	3.9	DEM20	22.6
Bio6	12.8	Bio19	8.5	Mg	1.2		
Bio2	2.1	Bio12	5.3	ce	0.4		
Bio9	1.0	Bio18	3.5	K	0.2		
		Bio14	0.7	pH	0.2		
		Bio13	0.4				
Bio8	0.9						
Bio10	0.5						
Bio3	0.2						
Total	45.1		27.10		5.9		22.6

Table 4
Key agroecological variables influencing the cultivation of *Agave tequilana* in Mexico

Temperature	Importance (%)	Precipitation	Importance (%)	Soil	Importance (%)	Topographic	Importance (%)
Bio4	32.0	Bio15	28.3	pH	0.6	DEM	2.4
Bio3	15.5	Bio19	5.2	K	0.3		
Bio6	6.0	Bio12	3.1	ce	0.3		
Bio7	3.1	Bio18	0.1				
		Bio13	0.3				
		Bio17	0.2				
		Bio14	0.2				
		Bio16	0.1				
Total	57.0		37.5		1.2		2.4

The abbreviations used are defined as follows: Bio1: Annual mean temperature (°C); Bio2: Diurnal temperature range (°C); Bio3: Isothermality (°C); Bio4: Temperature seasonality (°C); Bio5: Mean maximum temperature of the warmest period (°C); Bio6: Mean minimum temperature of the coldest period (°C); Bio7: Annual temperature range (°C); Bio8: Mean temperature of the wettest quarter (°C); Bio9: Mean temperature of the driest quarter (°C); Bio10: Mean temperature of the warmest quarter (°C); Bio11: Mean temperature of the coldest quarter (°C); Bio12: Annual precipitation (mm); Bio13: Precipitation of the wettest period (mm); Bio14: Precipitation of the driest period (mm); Bio15: Precipitation seasonality (mm); Bio16: Precipitation of the wettest quarter (mm); Bio17: Precipitation of the driest quarter (mm); Bio18: Precipitation of the warmest quarter (mm); Bio19: Precipitation of the coldest quarter (mm); DEM20: Digital elevation model; Na: sodium; Mg: magnesium; EC: electrical conductivity; K: potassium; pH: potential of hydrogen.

Furthermore, as a CAM species, its carbon assimilation is strongly dependent on nocturnal CO₂ uptake, with maximum nocturnal acid accumulation and carbon gain occurring under moderate night time temperatures. Both excessively low and excessively high temperatures can substantially reduce net carbon assimilation and overall productivity (Nobel & Valenzuela, 1987; Pimienta-Barrios *et al.*, 2001). These physiological characteristics provide a mechanistic explanation for the high contribution of temperature seasonality (Bio4) in the present model, as seasonal fluctuations in temperature directly influence nocturnal carbon fixation, growth performance, and the long term agroecological suitability of *A. tequilana*. Jackknife profiles confirmed the differential contribution of predictors when excluded, evaluated independently, or assessed simultaneously (Figures 7a and 7b).

3.3 Thresholds, statistical precision, and limits to expansion

Threshold-based analysis (Table 5) identified a core suitability area of 4,577.72 km² (cumulative threshold = 3.32) with maximum statistical significance (p = 0), consolidating this zone as the most stable and favorable for the analyzed species. As the predicted agricultural frontier expands, model reliability decreases when the area increases to 11,274.28 km², the P-value rises to 0.079, exceeding the conventional significance criterion (p < 0.05). In practical terms, relaxing thresholds increases agronomic risk in marginal lands (due to suboptimal soils, climatic instability, or both) thereby challenging narratives of unconstrained expansion driven by global demand (Elith *et al.*, 2011; Zurell *et al.*, 2020; Tetreault *et al.*, 2021; Valiente-Banuet & Arizmendi, 2023).

Consequently, the area with “guaranteed” suitability represents approximately 43.1% of the optimally predicted area, underscoring clear spatial constraints on the sector’s sustainable growth.

Table 5
Area (km²) of land characterised by different threshold levels with agroecological suitability for distilled-beverage production in Mexico. *Non-significant

Cumulative threshold	Logistic threshold	Predicted area fraction	P-value	Area (km ²)
1.000	0.022	58.6	0.000	3,366.89420
3.320	0.054	43.1	0.000	4,577.72622
5.000	0.077	37.1	0.026	5,318.05930
10.000	0.149	27.2	0.026	7,253.67647
11.796	0.169	24.8	0.053*	7,955.64516
19.535	0.252	17.5	0.079*	11,274.28570
25.201	0.310	13.9	0.105*	14,194.24460
25.547	0.314	13.7	0.132*	14,401.45990

3.4 Management and public policy implications

Given the differentiated sensitivities, identified species-specific strategies are required. For *A. angustifolia*, landscape designs should capitalize on topographic heterogeneity and restore soil function through polyculture systems, reduced tillage, and regenerative practices, in alignment with agroecological principles and local knowledge (Ávila-Reyes *et al.*, 2025). For *A. tequilana*, climate resilience is the primary priority, including the diversification of planting zones, conservation of genetic resources, and the adoption of water-efficient, seasonality-aware management practices (Ortiz-Cano *et al.*, 2023; Queiroz *et al.*, 2024). Transversally, regenerative agriculture provides a coherent framework to reverse degradation, reduce dependence on agrochemicals, and enhance long-term agroecosystem health (Giller *et al.*, 2021; Rieger, 2025).

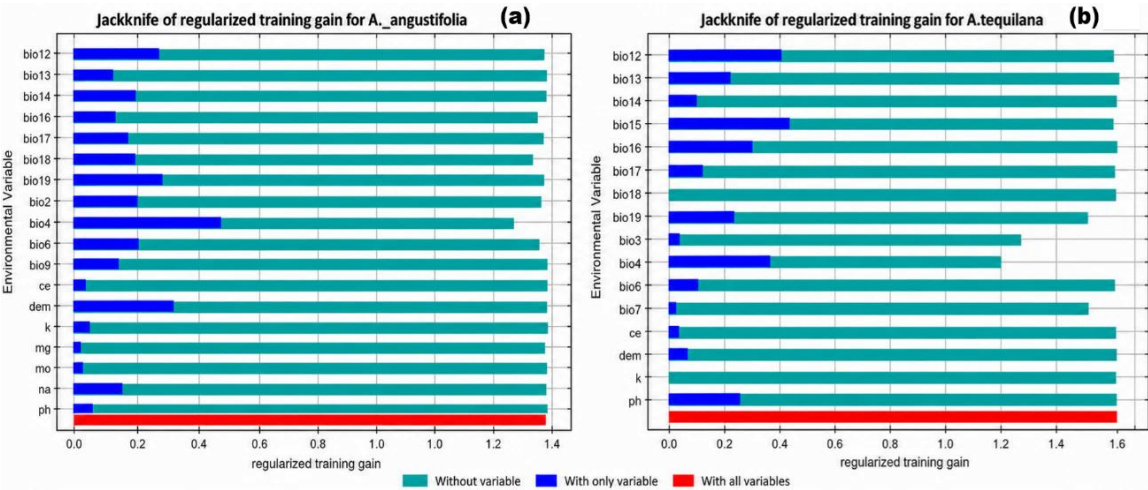


Figure 7. Relative importance of each variable according to the Jackknife test, expressed as gain values, when the variable is used in isolation, when the model is built using only that variable, and when all variables are included; 7(a) for *Agave angustifolia* and 7(b) for *Agave tequilana*.

More specifically, the implementation of agroecological practices already documented in traditional agave production systems could strengthen the regenerative transition of the sector. Evidence from the Index of Agroecological Practices in *Agave tequilana* (IPAAT) indicates that traditional polyculture systems consistently incorporate a greater number of sustainable management practices than conventional monocultures, including intercropping, crop rotation, contour planting, soil and water conservation measures, age staggering of agave plants, incorporation of organic matter, and reduced herbicide use. These practices contribute to improved soil conservation, greater landscape heterogeneity, enhanced biodiversity, and reduced environmental vulnerability, thereby supporting the long-term sustainability and resilience of agave-producing agroecosystems (Herrera-Pérez et al., 2017). Furthermore, several of these management strategies are consistent with contemporary principles of regenerative agriculture, highlighting the value of integrating traditional ecological knowledge into future agave production policies and sustainability certification schemes.

Beyond the conservation of agave genetic resources, the sustainability of mezcal and tequila producing landscapes also depends on the preservation of associated fauna, particularly nectar-feeding bats of the genus *Leptonycteris*, which are among the most important pollinators of agaves in Mexico. These bats play a critical ecological role by promoting gene flow among wild and cultivated agave populations through long-distance pollen transfer, thereby contributing to the maintenance of genetic diversity and ecosystem resilience (Trejo-Salazar et al., 2023; Trejo-Salazar et al., 2025). The expansion of intensive monocultures, combined with the widespread practice of harvesting agaves before flowering, reduces the availability of floral resources and disrupts ecological interactions between agaves and their pollinators, negatively affecting both bat populations and the natural regeneration of agaves (Trejo-Salazar et al., 2016; Zapata-Morán et al., 2024). In this context, initiatives such as the Bat Friendly™ program encourage producers to allow a proportion of agave plants to flower, facilitating bat pollination and enhancing genetic diversity in cultivated populations. Integrating pollinator conservation into agroecological zoning and sustainability policies could therefore generate synergies among biodiversity conservation, genetic-resource management, and the long-term resilience of agave production systems. In addition to their importance for mezcal and tequila production, agaves represent a versatile

biological resource with significant potential for economic diversification and sustainable rural development. Recent studies highlight the growing importance of agave-derived products such as syrup, inulin, fibers, animal feed, biofuels, and other biobased products within emerging circular bioeconomy frameworks. Agave syrup, for example, has gained international relevance as a natural sweetener with applications in the food industry, while agave biomass and processing residues can be valorized for the production of livestock feed, renewable energy, and bioproducts, reducing waste generation and enhancing resource-use efficiency (Saraiva et al., 2022; Pérez-Pimienta et al., 2024). Furthermore, the high water-use efficiency associated with CAM metabolism and the capacity of agaves to thrive in semi-arid environments position these species as promising feedstocks for sustainable bioenergy production and climate-change adaptation strategies in marginal lands (Honorato-Salazar et al., 2021; Davis & Ortiz-Cano, 2023). Consequently, agroecological zoning may contribute not only to the sustainability of distilled-beverage production but also to the development of diversified agave-based value chains that strengthen rural livelihoods and promote a circular, climate-resilient bioeconomy.

Given the limited extent of the core suitability area, shifting industrial growth beyond these zones increases the risk of erosion, biodiversity loss, and socio-ecological fragility (Tetreault et al., 2021; Guevara-Gutiérrez et al., 2024).

3.5 Methodological considerations and reproducibility

The variable-selection workflow (comprising preliminary runs including all predictors followed by the exclusion of non-informative variables) enhances model interpretability and is consistent with best practices in MaxEnt modeling (Soberon & Townsend-Peterson, 2005; Elith et al., 2011). Jack-knife diagnostics help prevent misattribution of variable importance (Phillips et al., 2006; Bradie & Leung, 2017; Fois et al., 2018), while the use of logistic outputs and omission-based significance testing supports transparent reporting and reproducibility (Merow et al., 2013; Zurell et al., 2020).

In summary, agroecological zoning supported by niche modeling provides a spatially explicit framework for identifying both opportunities and constraints of agave-based systems in Mexico, revealing species-specific vulnerabilities and trade-offs between statistical precision and exploitable land area. These findings underpin the need to transition from uniform production models toward

differentiated, territorially grounded strategies that align productivity with soil conservation, biodiversity protection, and socio-ecological resilience. On this basis, the Conclusions section synthesizes operational and policy implications (including the adoption of regenerative agriculture, the promotion of genetic diversity, and the design of “Sustainability of Origin” instruments) aimed at ensuring the long-term viability of mezcal and tequila systems under climate change (Tetreault et al., 2021; Valiente-Banuet & Arizmendi, 2023; Rieger, 2025).

4. Conclusions

Sustainable agave based distilled beverage production is attainable; however, it requires a structural transition towards agroecological models supported by technological innovation and spatially explicit planning. Climate change resilience and the conservation of genetic diversity depend on the effective alignment of public policy instruments with stakeholder participation across production systems. Species specific vulnerability patterns were consistently identified: *Agave angustifolia* exhibits greater sensitivity to topographic and soil chemical variables, whereas *Agave tequilana* is predominantly constrained by climatic factors, increasing its exposure to global warming. Within this context, regenerative agriculture emerges as a viable response to degradation driven by monoculture and agro extractivism, enabling soil restoration, reduced agro-chemical dependence, and long term socio ecological system recovery. Accordingly, differentiated public policies are required, prioritising multi species propagation strategies, targeted support for artisanal production systems, and the development of “Sustainability of Origin” certification schemes that incentivise verified regenerative practices and the conservation of agrobiodiversity.

From a policy perspective, the results of this study highlight the need to incorporate biodiversity conservation, genetic diversity, pollinator protection, and agroecological management criteria into agave production systems. Regulatory institutions such as the Consejo Regulador del Tequila and analogous organizations associated with mezcal production could play a strategic role in promoting sustainability indicators that recognize polyculture systems, conservation of flowering agaves, restoration of pollinator habitats, and regenerative agricultural practices. Likewise, future revisions of Denominations of Origin could incorporate biodiversity-based criteria that encourage traditional management systems and strengthen the long-term resilience of agave-producing landscapes.

Building upon the agroecological zoning framework developed in this study, future research should focus on improving the spatial and environmental resolution of agroecological suitability assessments through the integration of higher-resolution environmental datasets, broader occurrence records, and climate change projections to evaluate potential shifts in suitable areas for agave cultivation. Particular attention should be given to incorporating indicators of genetic diversity, pollinator distribution, ecosystem services, and land-use dynamics in order to improve the understanding of long-term socio-ecological resilience. Although the present study achieved high predictive performance, the occurrence records may reflect geographic concentration within major production areas, and the spatial resolution of approximately 1 km² may not fully capture local microclimatic variability. The results presented here provide a valuable baseline for territorial planning, biodiversity conservation, sustainability certification schemes, and the development of public policies that promote climate-resilient and regenerative agave production systems in Mexico.

Acknowledgements

This research received support from the National System of Researchers (SNI), under the Secretariat of Science, Humanities, Technology and Innovation (SECIHTI) of Mexico.

Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

Authors' Contributions

C. Michel-Cuello: Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Methodology, Project administration, Visualization, Writing–review & editing. **N. Aguilar-Rivera:** Conceptualization, Data curation Investigation, Software, Methodology, Validation, Writing–review & editing. **C. López-Palacios:** Investigation, Visualization, Writing–original draft.

ORCID

C. Michel-Cuello  <https://orcid.org/0000-0001-9966-084X>

N. Aguilar-Rivera  <https://orcid.org/0000-0002-7833-6749>

C. López-Palacios  <https://orcid.org/0000-0002-7823-4902>

References

- Amici, V., Marcantonio, M., La Porta, N., & Rocchini, D. (2017). A multi-temporal approach in MaxEnt modelling: A new frontier for land use/land cover change detection. *Ecological Informatics*, 40, 40–49. <https://doi.org/10.1016/j.ecoinf.2017.04.005>
- Arslan, E. S., & Örüçü, Ö. K. (2021). MaxEnt modelling of the potential distribution areas of cultural ecosystem services using social media data and GIS. *Environment, Development and Sustainability*, 23(2), 2655–2667. <https://doi.org/10.1007/s10668-020-00692-3>
- Ávila-Reyes, S. V., Jiménez-Aparicio, A. R., Melgar-Lalanne, G., Fajardo-Espinoza, F. S., & Hernández-Sánchez, H. (2025). Mezcal: A review of chemistry, processing, and potential health

- benefits. *Foods*, 14(8), 1408. <https://doi.org/10.3390/foods14081408>
- Bradie, J., & Leung, B. (2017). A quantitative synthesis of the importance of variables used in MaxEnt species distribution models. *Journal of Biogeography*, 44(6), 1344–1361. <https://doi.org/10.1111/jbi.12894>
- Castañeda Hidalgo, E., Aquino López, R., Santiago Martínez, G. M., Lozano Trejo, S., & Jerez Salas, M. P. (2025). Evolution and dynamics of Agave cultivation in Oaxaca: A trend analysis. *Textual*, 85. <https://doi.org/10.5154/r.textual/2024.85.09>
- Cruz-Cárdenas, G., López-Mata, L., Ortiz-Solorio, C. A., Villaseñor, J. L., Ortiz, E., Silva, J. T., & Estrada-Godoy, F. (2014a). Interpolation of Mexican soil properties at a scale of 1:1,000,000. *Geoderma*, 273, 29–35. <https://doi.org/10.1016/j.geoderma.2013.07.014>
- Cruz-Cárdenas, G., Villaseñor, J. L., López-Mata, L., Martínez-Meyer, E., & Ortiz, E. (2014b). Selección de predictores ambientales para el modelado de la distribución de especies en MaxEnt. *Chapingo Journal. Series: Forest and Environmental Sciences*, 20(2), 187–201. <https://doi.org/10.5154/r.rchscfa.2013.09.034>
- Cuéllar-Martínez, M., Moreno-Letelier, A., MacSwiney-González, M. C., & Galindo-González, J. (2026). Pollination biology and genetic neighborhood size in Agave obscura Schiede: Insights into the reproductive biology of a population from central Veracruz. *Botanical Sciences*, 104(1), 114–133. <https://doi.org/10.17129/botsci.3766>
- Davis, S. C., Abatzoglou, J. T., & LeBauer, D. S. (2021). Expanded potential growing region and yield increase for Agave americana with future climate. *Agronomy*, 11(11), 2109. <https://doi.org/10.3390/agronomy11112109>
- Davis, S. C., & Ortiz-Cano, H. G. (2023). Lessons from the history of Agave: Ecological and cultural context for valuation of CAM. *Annals of Botany*, 132(4), 819–833. <https://doi.org/10.1093/aob/mcad072>
- De Anda-Rodríguez, F. A., Corona-Ramírez, M. R., Patiño-Arévalo, C. D., Zárate-Navarro, M. A., Zárate-Guzmán, A. I., & Romero-Cano, L. A. (2025). Mycomaterials from agave bagasse: A valorization strategy for sustainable tequila packaging. *Fermentation*, 11(9), 500. <https://doi.org/10.3390/fermentation11090500>
- De Marco Júnior, P., & Nóbrega, C. C. (2018). Evaluating collinearity effects on species distribution models: An approach based on virtual species simulation. *PLoS ONE*, 13(9), e0202403. <https://doi.org/10.1371/journal.pone.0202403>
- Elith, J., Phillips, S. J., Hastie, T., Dudík, M., Chee, Y. E., & Yates, C. J. (2011). A statistical explanation of MaxEnt for ecologists. *Diversity and Distributions*, 17(1), 43–57. <https://doi.org/10.1111/j.1472-4642.2010.00725.x>
- Fois, M., Cuenca-Lombrana, A., Fenu, G., & Bacchetta, G. (2018). Using species distribution models at local scale to guide the search of poorly known species: Review, methodological issues and future directions. *Ecological Modelling*, 385, 124–132. <https://doi.org/10.1016/j.ecolmodel.2018.07.018>
- Giller, K. E., Hijbeek, R., Andersson, J. A., & Sumberg, J. (2021). Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture*, 50(1), 13–25. <https://doi.org/10.1177/003027027021998063>
- Guevara-Gutiérrez, R. D., Palomera-García, C., Olguín-López, J. L., Mancilla-Villa, O. R., Rosales-Almendra, M. P., & Barreto-García, O. A. (2024). Effect of blue agave (Agave tequilana Weber) management on soil erosion. *Air, Soil and Water Research*, 17, 1–10. <https://doi.org/10.1177/11786221241236632>
- Hernández, C. E., Huerta-Zavala, J., Espinosa-Rodríguez, M., Sarmiento-Villagrana, A., Ochoa-Miranda, R., & Segura-Pacheco, H. R. (2024). Areas with agroecological potential for *Agave cupreata* (Trel. & Berger) plantations in Guerrero, Mexico. *Agro Productividad*, 17(12). <https://doi.org/10.32854/agrop.v17i12.2920>
- Herrera-Pérez, L., Valtierra-Pacheco, E., Ocampo-Fletes, I., Tórono-Campante, M. A., Hernández-Plascencia, J. A., & Rodríguez-Macias, R. (2017). Ecological practices in Agave tequilana Weber under two agricultural systems in Tequila, Jalisco. *Revista Mexicana de Ciencias Agrícolas, Número Especial 18*, 3713–3726. <https://doi.org/10.29312/remexca.v8i18.216>
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology*, 25, 1965–1978. <https://doi.org/10.1002/joc.1276>
- Honorato-Salazar, J. A., Aburto, J., & Amezcua-Allieri, M. A. (2021). Agave and Opuntia species as sustainable feedstocks for bioenergy and byproducts. *Sustainability*, 13(21), 12263. <https://doi.org/10.3390/su132112263>
- López-Santiago, M. A., Sánchez-Toledano, B. I., Valdivia-Alcalá, R., Hernández-Ortiz, J., García-Vázquez, R., & Vásquez-Maya, I. I. (2024). Analysis of the normalized revealed comparative advantage index for mezcal, tequila and rum in Mexico. *Journal Bio Ciencias*, 10, e1414. <https://doi.org/10.15741/revbio.10.e1414>
- Lozano-Arias, C. J. (2024). El tequila como fuente económica en México. *Revista de Investigación Académica Sin Frontera*, 6(41). <https://doi.org/10.46589/riasf.vi41.661>
- Márquez-Rangel, I., Cruz, M., Ruiz, H. A., Rodríguez-Jasso, R. M., Loredó-Treviño, A., & Belmares, R. (2025). Evaluation of Agave salmiana by-products as a functional ingredient for the development of sustainable foods. *Journal of the Science of Food and Agriculture*, 105(8), 4349–4358. <https://doi.org/10.1002/jsfa.14167>
- Martínez-Lona, D. I., Mendoza-Galindo, E., Herrera-Estrella, A., Simpson, J., & Hernández-Hernández, T. (2026). Clonal domestication and biocultural erosion in tequila agave (Agave tequilana Weber var. azul). *Annals of Botany*. mcag208. <https://doi.org/10.1093/aob/mcag208>
- Martínez-Velasco, I., Gasca-Pineda, J., Mastretta-Yanes, A., Gargiulo, R., Klimova, A., Aguirre-Planter, E., Valiente-Banuet, A., Lira, R., & Eguarte, L. E. (2026). Clonality, management and geography shape genetic structure in a perennial species with restricted distribution. *Annals of Botany*. mcag132. <https://doi.org/10.1093/aob/mcag132>
- Merow, C., Smith, M. J., & Silander, J. A. (2013). A practical guide to MaxEnt for modeling species distributions: What it does, and why inputs and settings matter. *Ecography*, 36(10), 1058–1069. <https://doi.org/10.1111/j.1600-0587.2013.07872.x>
- Molina, A., Kothari, A., Odundo, A., & Prakash, M. (2023). Agave sisalana: Towards distributed manufacturing of absorbent media for menstrual pads in semi-arid regions. *Communications Engineering*, 2, 130. <https://doi.org/10.1038/s44172-023-00130-y>
- National Institute of Statistics, Geography and Informatics (INEGI). (2025). Geostatistical framework 2025. México.
- Noriega-Juárez, A. D., Meza-Espinoza, L., García-Magaña, M. L., Ortiz-Basurto, R. I., Chacón-López, M. A., Anaya-Esparza, L. M., & Montalvo-González, E. (2025). Agamiel, a traditional Mexican beverage: A review of its nutritional composition, health effects and conservation. *Foods*, 14(1), 134. <https://doi.org/10.3390/foods14010134>
- Nobel, P. S., & Valenzuela, A. G. (1987). Environmental responses and productivity of the CAM plant, Agave tequilana. *Agricultural and Forest Meteorology*, 39, 319–334. [https://doi.org/10.1016/0168-1923\(87\)90024-4](https://doi.org/10.1016/0168-1923(87)90024-4)
- Nobel, P. S., Castañeda, M., North, G., Pimienta-Barrios, E., & Ruiz, A. (1998). Temperature influences on leaf CO₂ exchange, cell viability and cultivation range for Agave tequilana. *Journal of Arid Environments*, 39(1), 1–9. <https://doi.org/10.1006/jare.1998.0374>
- Ortiz-Cano, H. G., Hadfield, R., Gómez, T., Hultine, K., Mata-González, R., Petersen, S. L., ... Stewart, J. R. (2023). Ecological niche modeling reveals current opportunities for agave dryland farming in Sonora, Mexico and Arizona, USA. *PLOS ONE*, 18(1), e0279877. <https://doi.org/10.1371/journal.pone.0279877>
- Pearson, R. G., Raxworthy, C. J., Nakamura, M., & Townsend Peterson, A. (2007). Predicting species distributions from small numbers of occurrence records: A test case using cryptic geckos

- in Madagascar. *Journal of Biogeography*, 34(1), 102-117. <https://doi.org/10.1111/j.1365-2699.2006.01594.x>
- Perez-Pimienta, J. A., Méndez-Acosta, H. O., Davis, S. C., & Tan, D. K. Y. (2024). Editorial: The role of agave as feedstock within a sustainable circular bioeconomy. *Frontiers in Chemical Engineering*, 5, 1343629. <https://doi.org/10.3389/fceng.2023.1343629>
- Phillips, S. J., Anderson, R. P., Dudík, M., Schapire, R. E., & Blair, M. E. (2017). Opening the black box: An open-source release of MaxEnt. *Ecography*, 40(7), 887-893. <https://doi.org/10.1111/ecog.03049>
- Phillips, S. J., Anderson, R. P., & Schapire, R. E. (2006). Maximum entropy modeling of species geographic distributions. *Ecological Modelling*, 190(3), 231-259. <https://doi.org/10.1016/j.ecolmodel.2005.03.026>
- Phillips, S. J., & Dudík, M. (2008). Modeling of species distributions with MaxEnt: New extensions and a comprehensive evaluation. *Ecography*, 31(2), 161-175. <https://doi.org/10.1111/j.0906-7590.2008.05203.x>
- Phillips, S. J., Dudík, M., & Schapire, R. E. (2004). A maximum entropy approach to species distribution modeling. In Proceedings of the twenty-first international conference on Machine learning (ICML '04). Association for Computing Machinery, New York, NY, USA, 83. <https://doi.org/10.1145/1015330.1015412>
- Pimienta-Barrios, E., Robles-Murguía, C., & Nobel, P. S. (2001). Net CO₂ uptake for Agave tequilana in a warm and a temperate environment. *Biotropica*, 33(2), 312-318. <https://doi.org/10.1111/j.1744-7429.2001.tb00181.x>
- Queiroz, H. M., Ferreira, T. O., Cerrí, C. E., Pereira, G. A., & Cherubin, M. R. (2024). Advancing the agave-soil nexus approach: A systematic review. *Biofuels, Bioproducts and Biorefining*, 18(5), 1306-1320. <https://doi.org/10.1002/bbb.2625>
- Rieger, I. A. (2025). Rewilding the mezcal market: Cultural practices and the conservation of agaves in Oaxaca, Mexico. *Wild*, 2(2), 20. <https://doi.org/10.3390/wild2020020>
- Rodríguez-Merino, A., García-Murillo, P., & Fernández-Zamudio, R. (2020). Combining multicriteria decision analysis and GIS to assess vulnerability within a protected area: An objective methodology for managing complex and fragile systems. *Ecological Indicators*, 108, 105738. <https://doi.org/10.1016/j.ecolind.2019.105738>
- Santiago-Martínez, A., Pérez-Herrera, A., Martínez-Gutiérrez, G. A., & Meneses, M. E. (2023). Contributions of agaves to human health and nutrition. *Food Bioscience*, 53, 102753. <https://doi.org/10.1016/j.fbio.2023.102753>
- Saraiva, A., Carrascosa, C., Ramos, F., Raheem, D., & Raposo, A. (2022). Agave syrup: Chemical analysis and nutritional profile, applications in the food industry and health impacts. *International Journal of Environmental Research and Public Health*, 19(12), 7022. <https://doi.org/10.3390/ijerph19127022>
- Sillero, N., & Barbosa, A. M. (2021). Common mistakes in ecological niche models. *International Journal of Geographical Information Science*, 35(2), 213-226. <https://doi.org/10.1080/13658816.2020.1798968>
- Soberón, J., & Townsend-Peterson, A. (2005). Interpretation of models of fundamental ecological niches and species distributional areas. *Biodiversity Informatics*, 2, 1-10. <https://doi.org/10.17161/bi.v2i0.4>
- Suárez-Sánchez, M., Merritt, H., Oyoque-Salcedo, G., Estrella-Santiago, D. P., Oregel-Zamudio, E., & Arias-Martínez, S. (2025). Sustainable valorization of tequila industry vinasse: A patent review on bioeconomy-driven technologies. *Agronomy*, 15(7), 1567. <https://doi.org/10.3390/agronomy15071567>
- Terán-Bustamante, A., Martínez-Velasco, A., & Leyva-Hernández, S. N. (2025). Management of scientific and ancestral knowledge: A decision-making model in mezcal industry in Mexico. *Frontiers in Artificial Intelligence*, 8, 1570617. <https://doi.org/10.3389/frai.2025.1570617>
- Tetreault, D., McCulligh, C., & Lucio, C. (2021). Distilling agro-extractivism: Agave and tequila production in Mexico. *Journal of Agrarian Change*, 27(2), 219-241. <https://doi.org/10.1111/joac.12402>
- Tong, R., Yesson, C., Yu, J., Luo, Y., & Zhang, L. (2023). Key factors for species distribution modeling in benthic marine environments. *Frontiers in Marine Science*, 10, 1222382. <https://doi.org/10.3389/fmars.2023.1222382>
- Townsend-Peterson, A., Soberón, J., & Sánchez-Cordero, V. (1999). Conservatism of ecological niches in evolutionary time. *Science*, 285(5431), 1265-1267. <https://doi.org/10.1126/science.285.5431.1265>
- Trejo-Salazar, R.-E., Eguarte, L. E., Suro-Piñera, D., & Medellín, R. A. (2016). Save our bats, save our tequila: Industry and science join forces to help bats and agaves. *Natural Areas Journal*, 36(4), 523-530. <https://doi.org/10.3375/043.036.0418>
- Trejo-Salazar, R.-E., Gámez, N., Escalona-Prado, E., Scheinvar, E., Medellín, R. A., Moreno-Letelier, A., Aguirre-Planter, E., & Eguarte, L. E. (2023). Historical, temporal, and geographic dynamism of the interaction between Agave and Leptonycteris nectar-feeding bats. *American Journal of Botany*, 110(10), e16222. <https://doi.org/10.1002/ajb2.16222>
- Trejo-Salazar, R.-E., Gasca-Pineda, J., Hernández-Bolaños, K., Hernández-Rosales, D.-C., Tapia-López, R., Aguirre-Planter, E., Medellín, R. A., León-Paniagua, L., & Eguarte, L. E. (2025). High genetic variation, low differentiation, and Pleistocene expansions of the migratory and endangered long-nosed tequila bat (*Leptonycteris nivalis*) inferred using both maternal and paternal genetic markers. *PLOS ONE*, 20(1), e0316530. <https://doi.org/10.1371/journal.pone.0316530>
- Tripathi, A. H., Kumari, A., Chand, G., Kumar, R., Durgapal, A., Mahajan, L., ... Upadhyay, S. K. (2023). An overview of phytomedicinal, ethnobotanical applications and phytochemical constituents of four major Agave species. *Indian Journal of Natural Products and Resources*, 14(2), 148-161. <https://doi.org/10.56042/ijnpr.v14i2.4199>
- Valiente-Banuet, A., & Arizmendi, M. C. (2023). Mezcal boom and extinction debts. In R. W. Jones, C. P. Omelas-García, R. Pineda-López, & F. Álvarez (Eds.), *Mexican fauna in the Anthropocene* (pp. 303-318). Springer, Cham. https://doi.org/10.1007/978-3-031-17277-9_14
- Vasconcelos, R. N., Cantillo-Pérez, T., Franca Rocha, W. J. S., Aguiar, W. M., Mendes, D. T., de Jesus, T. B., de Santana, C. O., de Santana, M. M. M., & Oliveira, R. P. (2024). Advances and Challenges in Species Ecological Niche Modeling: A Mixed Review. *Earth*, 5(4), 963-989. <https://doi.org/10.3390/earth5040050>
- Wis, M. S., Hijmans, R. J., Li, J., Peterson, A. T., Graham, C. H., Guisan, A., & NCEAS Predicting Species Distributions Working Group. (2008). Effects of sample size on the performance of species distribution models. *Diversity and Distributions*, 14(5), 763-773. <https://doi.org/10.1111/j.1472-4642.2008.00482.x>
- Zapata-Morán, I., Lopez-Feldman, A., & Bejarano, H. (2024). Tequila, bats, and agave farmers: Towards an understanding of the right incentives to protect genetic diversity. *Environmental Research Communications*, 6(1), 011002. <https://doi.org/10.1088/2515-7620/ad19f4>
- Zurell, D., Franklin, J., König, C., Bouchet, P. J., Dormann, C. F., Elith, J., ... Merow, C. (2020). A standard protocol for reporting species distribution models. *Ecography*, 43(9), 1261-1277. <https://doi.org/10.1111/ecog.04960>