Geospatial Health

Geospatial Health 2026; 21:1468
doi:10.4081/gh.2026.1468

Snakebite epidemiology in the State of Mexico, Mexico 2003-2024

Aldo Gómez-Benitez,[1,2] Erika Adriana Reyes-Velázquez,[2,3] Edgar Oviedo-Hernández,[2,3] Laura Sonia Arzate-Garay,[2,4] Justin Lloyd Rheubert,[5] Oswaldo Hernández-Gallegos[3]

[1] Escuela Normal Superior del Estado de México, Secretaría de Educación, Ciencia, Tecnología e Innovación, Toluca de Lerdo, Estado de México, México; [2]Red de Investigación y Divulgación de Anfibios y Reptiles MX, Toluca, Estado de México, México; [3]Laboratorio de Herpetología, Facultad de Ciencias, Universidad Autónoma del Estado de México, Toluca de Lerdo, Estado de México, México; [4]Laboratorio de Ecofisiología Animal, Facultad de Ciencias, Universidad Autónoma del Estado de México, Toluca de Lerdo, Estado de México, México; [5]Department of Biology, University of Findlay, Findlay, Ohio 45840, USA

Abstract

In the State of Mexico, several venomous snakes have low median lethal doses, which therefore pose serious health risks. We analysed the epidemiology of snakebites from 2003 to 2024 and examined their relationship with demographic, socioeconomic, and biological factors. Incidence rates and demographic characteristics were calculated, and Getis-Ord Gi* statistics were used to identify snakebite hotspots. We also applied Non-Metric Multi-Dimensional Scaling (NMDS) to explore associations between hotspot categories and socioeconomic conditions. The potential distribution of 14 venomous snake species was modelled to estimate venomous snake diversity across municipalities. A total of 3,972 cases were reported, with an increasing trend over time. Most bites occurred in summer, affecting mainly males aged 25-44. Hotspot analysis identified 27 municipalities as hotspots, 50 as not significant and 48 as coldspots. Southern municipalities showed higher snakebite incidence. Coldspot areas had higher educational attainment and greater employment in services and tertiary sectors, despite similar snake diversity to hotspots. These findings can guide public health strategies, particularly regarding the allocation of antivenoms in regional hospitals.

Key words: biological factors; Mexico; neglected tropical disease; snakebite; socioeconomic factors.

Correspondence: Aldo Gómez-Benitez, Escuela Normal Superior del Estado de México, Secretaría de Educación, Ciencia, Tecnología e Innovación, Toluca de Lerdo, Mexico. Tel.: +52.7223988334. E-mail: gobeal940814@gmail.comm

Introduction

Snakebites that result in envenomation, *i.e.* injection of venom through specialized grooved fangs found in specific snake families, are globally recognized as expressions of neglected tropical disease and they remain a significant cause of human morbidity and mortality (Gutiérrez *et al.*, 2017; World Health Organization, 2019; Palci *et al.*, 2021). Each year, snakebites affect approximately 2.7 million people worldwide, predominantly in rural tropical regions, making Africa, Southeast Asia and Latin America the most affected areas (Kasturiratne et al., 2008; Longbottom *et al.*, 2018). Global mortality estimates range from 81,000 to 138,000 deaths annually (World Health Organization, 2019); and many survivors suffer permanent disabilities such as amputations or loss of motor function (Siria-Hernández & Arellano-Bravo, 2009; Gutiérrez *et al.*, 2017). Recent studies in Mexico suggest that snakebite risk emerges from the combined influence of socioeconomic conditions and the spatial distribution of venomous snake species, highlighting the multifactorial nature of this public health problem (Rangel-Camacho *et al.*, 2025). At the state level, biological context has also been recognized as relevant for snakebite risk, a recent study in Zacatecas highlights that higher venomous snake species richness may increase encounter probability and require special epidemiological attention (Lara-Galván *et al.*, 2025).

In Mexico, 2,311 snakebite cases were reported in 2024, with 1,634 involving men and 677 women. In 2024, the State of Mexico ranked sixth nationally in snakebite incidence, with 132 cases, representing 8.1% of the country's total (Dirección General de Epidemiología, 2024). The state is home to 15 venomous snake species: 12 viperids: Such as *Agkistrodon bilineatus*, *Crotalus intermedius*, *C. ravus* and *C. scutulatus* and three elapids: *Micrurus browni*, *M. laticollaris* and *M. tener* (Lemos-Espinal & Smith, 2020; Monroy-Vilchis *et al.*, 2024; Monter-Pozos *et al.*, 2025). However, the presence of *C. atrox* in the State of Mexico is disputed (Castoe *et al.*, 2007; Schield *et al.*, 2015). Notably, three species (*C. scutulatus*, *M. browni*, and *M. laticollaris*) have a median lethal dose (LD50) below 1 µg/g, making its bite a special medical threat (Carbajal-Saucedo *et al.*, 2013; Bénard-Valle *et al.*, 2014; Borja *et al.*, 2018; Neri-Castro *et al.*, 2020).

Luna-Trejo (2018) conducted a preliminary epidemiological study on venomous animals in the State of Mexico, including snakes, from 2004 to 2016, highlighting the Tenancingo health jurisdiction as the most affected and reporting a higher incidence among males. However, the relationships between snakebite envenomation and socioeconomic or biological variables remain unstudied in the State of Mexico. Spatial analyses of snakebite epidemiology have commonly relied on incidence mapping and global measures of spatial autocorrelation, which describe overall spatial patterns but do not explicitly account for neighbourhood effects among administrative units (Auchincloss *et al.*, 2012; Da Costa *et al.*, 2019). This limitation is particularly relevant in Mexico where snakebite cases are recorded in the municipality where medical care is provided, rather than where envenomation occurs, potentially biasing municipality-level estimates. Local hotspot analysis (Getis & Ord, 1992) allows identification of clusters of high incidence while incorporating spatial context, thereby highlighting municipalities that may be epidemiologically relevant despite reporting few or no cases.

This cross-sectional study aims to assess snakebite epidemiology, understood as the spatial and temporal distribution of cases and their associated determinants, in the State of Mexico over a 22-year period (2003–2024), with particular emphasis on identifying spatial patterns and clusters of snakebite risk at the municipal level, by integrating multiple epidemiological proxies and explanatory factors. Following previous studies in Mexico, socioeconomic and biological variables were included to explore potential drivers of snakebite occurrence (Rangel-Camacho *et al.*, 2025), although using alternative proxies adapted to a municipal-scale analysis. Biological factors were represented by venomous snake species richness, used as a spatial proxy of potential human-snake interaction risk. In addition, three complementary approaches were employed to characterize snakebite patterns: raw case counts, population-adjusted incidence, and hotspot analysis. Together, these metrics allow evaluation of different epidemiological scenarios, accounting for statistical rigor, spatial dependence, and the potential bias introduced by recording cases in the municipality of medical attention rather than occurrence.

Materials and Methods

Study area

The State of Mexico comprises 125 municipalities, with elevation ranging from 326 to 5,381 meters above sea level. It encompasses highly variable topography and belongs to two major physiographic provinces: the Trans-Mexican Volcanic Belt (Faja Volcánica Transmexicana) and the Sierra Madre del Sur (Cervantes-Zamora *et al*., 1990; Lemos-Espinal & Smith, 2020). The region exhibits diverse climates, ranging from cold to hot and from semi-arid to subhumid, with summer precipitation patterns according to the García's (2004) modification of the Köppen climate classification. The public health system is organized into 19 health jurisdictions distributed strategically across municipalities, serving nearby localities through disease prevention and health promotion programs (Contreras-Landgrave & Tetelboin-Henrion, 2011). We obtained data on annual snakebite cases by municipality, including the month of occurrence, age, and sex of the affected individuals, for a continuous period lasting 2003–2024. These records were compiled by the Instituto de Salud del Estado de México (ISEM) through the Secretaría de Salud, Instituto Mexicano del Seguro Social (IMSS), Instituto de Seguridad y Servicios Sociales de los Trabajadores del Estado (ISSSTE), Sistema Nacional para el Desarrollo Integral de la Familia (DIF), and Secretaría de la Defensa Nacional (SEDENA). The workflow can be seen in Figure 1.

Snakebite incidence

We calculated municipality-specific snakebite incidence rates following approaches previously applied to contemporary epidemiological problems (Pacheco-Barrios *et al.*, 2020) and to snakebite epidemiology in other Mexican states (Yáñez-Arenas, 2014; Yáñez-Arenas *et al.*, 2016), by dividing the total number of reported cases by the respective municipal population and multiplying the result by 100,000 for the entire study period, this scaling factor was selected to ensure comparability with prior research conducted in Mexico (Rangel-Camacho *et al.*, 2025). To address the known instability of small-area rates when case counts are low (Waller & Gotway, 2004), municipality-level incidence estimates were accompanied by exact Poisson 95% confidence intervals (Lawson, 2013), and raw case counts were also reported. Annual incidence rates were also calculated by dividing the number of cases reported each year by the total population of the State of Mexico in that year obtained from the Instituto Nacional de Estadística y Geografía (INEGI, 2021), and then multiplying by 100,000 (Yáñez-Arenas, 2014; Yáñez-Arenas *et al.*, 2016).

Hotspots analysis and descriptive demography

Hotspot analysis, using Getis-Ord Gi* statistic in the spdep package in R (Pebesma & Bivand, 2023), was employed to account for spatial dependence among neighbouring municipalities and to reduce the potential bias arising from administrative assignment of snakebite cases to the municipality of medical attention rather than occurrence. We aimed to identify clusters of significantly high (hotspot) or low (coldspot) snakebite incidence. In this study, a municipality was classified as a hotspot when it was embedded within a statistically significant cluster of high snakebite incidence values, defined by its own incidence and that of spatially neighbouring municipalities within the specified distance band (see below), coldspots were defined analogously as clusters of significantly low incidence values. The analysis was based on a vector layer with polygonal geometry representing the 125 municipalities of the State of Mexico (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, 2021) using incidence values as the input field. The fixed distance band, used to define neighbouring municipalities, was determined using the Incremental Spatial Autocorrelation tool in ArcGIS 10.8.1, which evaluates clustering strength at increasing distances to identify the most spatially autocorrelated scale. The optimal distance band identified was 53,690 meters, and the distance method applied was Euclidean. The fixed distance band ensures a consistent spatial scale across municipalities and defines spatial relationships based on geographic proximity rather than administrative contiguity.

The statistic was calculated following the equation proposed by Getis and Ord (1992) and Ord and Getis (1995):

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - X \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[\sum_{j=1}^{n} w_{i,j} - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}$$

where X_j is the attribute value for feature j and,$W_{i,j}$ a binary spatial weight indicating whether features i and j are within the specified distance threshold of each other.

To examine temporal trends in snakebite incidence, we performed a Pearson correlation between annual incidence rates and year. Seasonal patterns (spring: April–June; summer: July–September; autumn: October–December; winter: January–March) were evaluated using descriptive statistics. Demographic characteristics of snakebite cases, including victim sex and age, were summarized using histograms. Differences in incidence between sexes were evaluated using a Chi-square test comparing observed versus expected frequencies under the assumption of equal risk.

Socioeconomic factors

To evaluate the relationship between education levels, economic activity sectors, and occupational divisions and snakebite incidence, we performed a non-metric multidimensional scaling (NMDS) analysis based on Bray-Curtis distance. NMDS was used as an exploratory ordination method to summarize multivariate socioeconomic patterns without assuming linear relationships (Zar, 1999). Bray–Curtis dissimilarity was applied because it is appropriate for non-negative, continuous variables expressed as proportions (Legendre & Legendre, 2012). Socioeconomic data were obtained from the most recent (2020) Population and Housing Census conducted by the Instituto Nacional de Estadística y Geografía (INEGI, 2020). Variables included the percentage of the population with different levels of education (no schooling, preschool, basic, technical, secondary, undergraduate, and postgraduate), percentage of engagement in the three main economic sectors (primary, secondary, tertiary), and percentage of participation in specific occupational divisions: i) officials, professionals, technicians, administrators; ii) agricultural workers; iii) industrial workers; iv) merchants and service workers. The first two NMDS axes, representing the main dimensions of dissimilarity in multivariate socioeconomic composition among municipalities, were compared across municipalities categorized by hotspot analysis results (hotspots, non-significant, coldspots) using Analysis Of Variance (ANOVA). The Kolmogorov-Smirnov test confirmed normal distribution of NMDS scores. A post hoc Tukey test was subsequently applied to identify significant pair-wise differences among the hotspot categories.

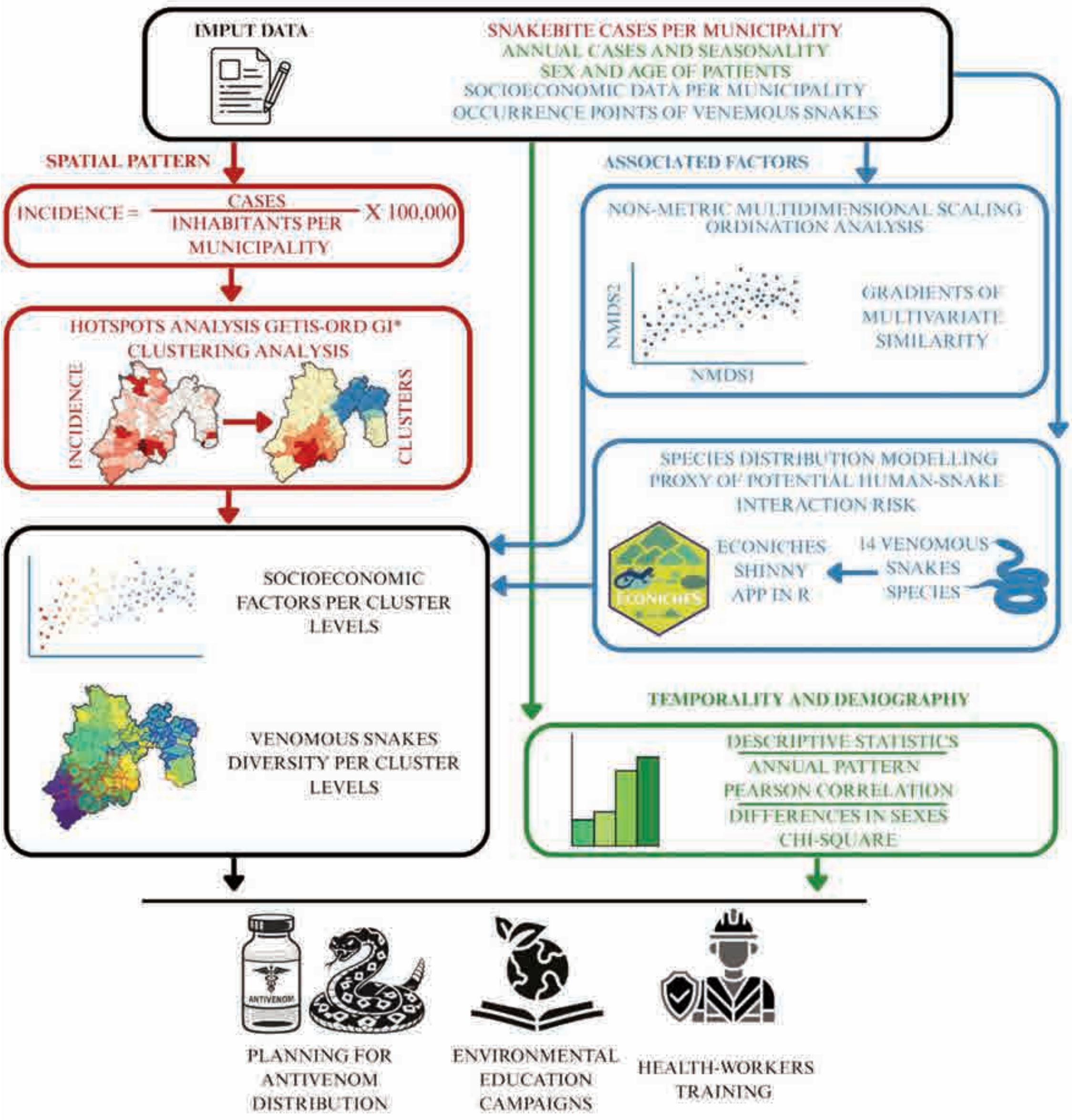

Figure 1. Workflow summarizing data sources, analytical steps, and integration of spatial, socioeconomic, biological, and temporal analyses used to assess snakebite patterns in the State of Mexico and support public health decision-making.

Venomous snake diversity

We obtained occurrence points of the 14 species of venomous snakes recorded for the State of Mexico from Global Biodiversity Information Facility (GBIF, 2025) that consisted of georeferenced point features and corresponding to observations collected between 2000 and 2020, a period selected to encompass recent taxonomic revisions and species delimitations within the study group. After data cleaning considering actual taxonomy, known distribution (Campbell & Lamar, 2004) and spatial thinning of occurrence records to reduce spatial autocorrelation, we used the following numbers of georeferenced occurrence records for each species: *Agkistrodon bilineatus* 138, *C. aquilus 272*, *C. culminatus* 106, *C. intermedius* 44, *C. molossus* 1,306, *C. polystictus* 120, *C. ravus* 445, *C. scutulatus* 440, *C. tlaloci* 26, *C. transversus* 50, *C. triseriatus* 632, *M. browni* 79, *M. laticollari* 32, and *M. tener* 190. Occurrence records were spatially distributed across the known national range of each species and used to characterize environmental conditions within the accessible area (M) for model calibration. To model species' potential distributions, we used the EcoNicheS Shiny application in R (Sunny *et al*., 2025), which streamlines ensemble niche-modelling workflows. First, we prepared environmental predictors by loading the 19 WorldClim bioclimatic variables (Fick & Hijmans, 2017) representing long-term historical climate conditions (1970–2000) at a spatial resolution of 30 arc-seconds into the app's 'Environmental Data' module allowing EcoNicheS to calculate multicollinearity diagnostics. We then excluded five highly correlated variables (Pearson |r| > 0.7 according with Dormann *et al*., 2013) retaining 14 of them (BIO1, BIO2, BIO3, BIO5, BIO7, BIO8, BIO9, BIO12, BIO14, BIO15 and BIO19) that capture temperature and precipitation seasonality and extremes. Further, EcoNicheS's 'Pseudoabsence' module was applied, generating 10,000 background points stratified across environmental space, ensuring that background samples represented the range of climatic conditions available within the accessible area and were drawn from within the accessible area but outside of known occurrence envelopes. These background points represent 'pseudoabsences' used in presence-only species distribution models to characterize available environmental conditions. For algorithm selection, we chose five complementary methods: MaxEnt, maximum entropy for ecological modelling; MaxNet, an improved and fully implemented version of MaxEnt in the R programming language; Multivariate Adaptive Regression Splines (MARS); Surface Range Envelopes (SRE); and Classification Tree Analysis (CTA), and used them to capture a range of modelling approaches from correlative to machine-learning and assembling methods as this would reduce dependence on any single algorithm. Model calibration employed a block cross-validation strategy in which occurrence data were divided into geographically distinct subsets. Models were trained on some spatial blocks and evaluated on others, allowing assessment of predictive performance across different regions and reducing the influence of spatial autocorrelation. We allocated 80 % of the data to training and 20 % to testing running 10 replicates per algorithm to quantify variability in model performance. We evaluated each run using the Receiver Operating Characteristic (ROC) curve, performing 500 bootstrap iterations to calculate the mean Area Under the Curve (AUC), which summarizes the model's ability to discriminate between presence and background locations (Fielding & Bell, 1997), along with 95 % confidence intervals. Subsequently, we summed the values of the assemble models of the venomous snake species occurring in the State of Mexico and estimated the potential of the venomous snakes' diversity with the QGIS 3.16 raster calculator, which provided a biological proxy of areas with higher potential co-occurrence of multiple venomous snake species (Calabrese *et al*., 2014; D'Amen *et al*., 2015; Tobeña *et al*., 2016). Using the QGIS zonal statistics tool, we calculated the mean diversity for each municipality polygon and compare it applying a Kruskal-Wallis test, since data do not fit to a normal distribution, between hotspot categories. Additionally, we performed the Mann-Whitney U test for *post hoc* pair-wise comparisons to identify which hotspot categories differed significantly from each other. Hypothesis tests (the null hypothesis was that venomous snake diversity does not differ among hotspot categories) were conducted in the software paleontological statistics (PAST) 4.06 (Hammer *et al*., 2001) with α=0.05. We compared venomous snake diversity among municipalities classified by hotspot analysis, rather than directly correlating diversity with incidence, to focus on statistically defined risk categories and to minimize the influence of small and unstable incidence values.

Results

Incidence

During the study period (2003–2024), a total of 3,972 snakebite cases were registered in the State of Mexico, corresponding to an overall incidence rate of 24.48 cases per 100,000 inhabitants. On average, each municipality reported 32 cases over the 22-year period (180 cases per year for the State of Mexico as a whole), yielding mean incidence rates of 50.59 per 100,000 inhabitants per municipality for the entire period from 2023 to 2024 and 1.11 per 100,000 inhabitants per year. Raw case counts by municipality identified Toluca de Lerdo (central) as the most affected (439 cases), followed by Tenancingo de Degollado (southwest; 413 cases) and Atlacomulco (northwest; 258 cases; Figure 2A; Figure 1S). Fifteen municipalities recorded zero snakebites: Almoloya del Río, Atenco, Ayapango, Capulhuac, Chiconcuac, Cocotitlán, Melchor Ocampo, Nopaltepec, Otzoloapan, Papalotla, Teoloyucán, Teotihuacán, Tezoyuca, Tonanitla, and Tonatico (see Figure 2A and Figure 1S). Incidence-rate mapping showed Tepetlixpa (southeast) with the highest rate (589 per 100,000), followed by Coatepec Harinas (southwest; 571 per 100,000) and Tenancingo (southwest; 413 per 100,000) (Figure 2B; Figure 1S). Municipality-level snakebite incidence showed substantial heterogeneity across the State of Mexico. More than 40% of municipalities recorded ≥10 cases during the study period, yielding relatively stable incidence estimates with narrow Poisson confidence intervals, whereas approximately one third of municipalities reported fewer than five cases, resulting in wide confidence intervals and greater statistical uncertainty. Municipalities with extreme incidence values were frequently characterized by low case counts. All municipalities within the upper decile of incidence were based on ≥10 cases and therefore correspond to statistically stable estimates. A full listing of municipality-level incidence, case counts, confidence intervals and stability classification is provided in Supplementary Table S1 to facilitate transparent interpretation. Annual incidence increased from 0.6 per 100,000 in 2003 to 0.9 in 2024, peaking at 1.5 in 2021 (Figure 3A). The linear regression indicated a positive temporal trend, explaining approximately 50% of the inter-annual variability (Figure 3A). Seasonally, most bites occur in summer (88 cases on average), then spring (52), with fewer in autumn (28) and winter (14; Figure 3B). Males (2,235 cases; 56.4%) were bitten significantly more often than females (1,737 cases; 43.6%; χ^2 = 62.4, P < 0.0001; Figure 3C). Both sexes showed the highest incidence in the 25–44 year age group, although all age classes, from <1 year to >65 years, recorded at least one snakebite case during the study period in the State of Mexico (Figure 3C). Getis-Ord Gi* analysis classified 48 municipalities as coldspots (northeast; 2 at 90% confidence, 7 at 95%, 39 at 99%), 50 as non-significant, and 27 as hotspots (south and centre; 9 at 90%, 11 at 95%, 7 at 99%; Figure 2C).

Socioeconomic factors

Municipalities identified as coldspots exhibited higher proportions of residents with bachelor's degrees, greater employment in the services sector, and a predominance of business-related occupations (Figure 4). Figure 4 displays the NMDS ordination of municipalities based on socioeconomic variables. Each point represents a municipality, and distances among points reflect similarity in socioeconomic composition. The first dimension (NMDS1) captures gradients in education level, economic sector, and occupational division, with positive values associated with higher proportions of residents with bachelor's degrees and service- and business-related employment, and negative values with greater participation in primary and agricultural activities. The second dimension (NMDS2) does not clearly separate hotspot categories. No clear associations emerged for hotspots or non-significant municipalities. ANOVA confirmed that coldspots differ significantly from hotspots and non-significant areas in the NMDS1 dimension (reflecting education level, economic sector, and occupational division) but not in the NMDS2 (Table 1). Hotspots and non-significant municipalities differed only along the second NMDS dimension, which reflects residual variation in economic activity and occupational composition not captured by the primary socioeconomic gradient represented by NMDS1.

Venomous snake diversity

The modelled maximum occurrence probability for *M. tener* was 0.4640, suggesting its marginal presence in the State of Mexico, whereas all other species showed probabilities ≥ 0.6158, indicating established distributions (Table 2). This distinction is relevant for interpreting the modelled venomous snake diversity, as species with marginal distributions are less likely to contribute consistently to human–snake encounters and may otherwise inflate diversity estimates. The Mann–Whitney U test revealed no significant differences in venomous snake diversity between hotspot and coldspot municipalities. However, coldspots differed significantly from non-significant municipalities (Table 2). Figure 2D provides a spatial visualization of the modelled venomous snake diversity across the State of Mexico.

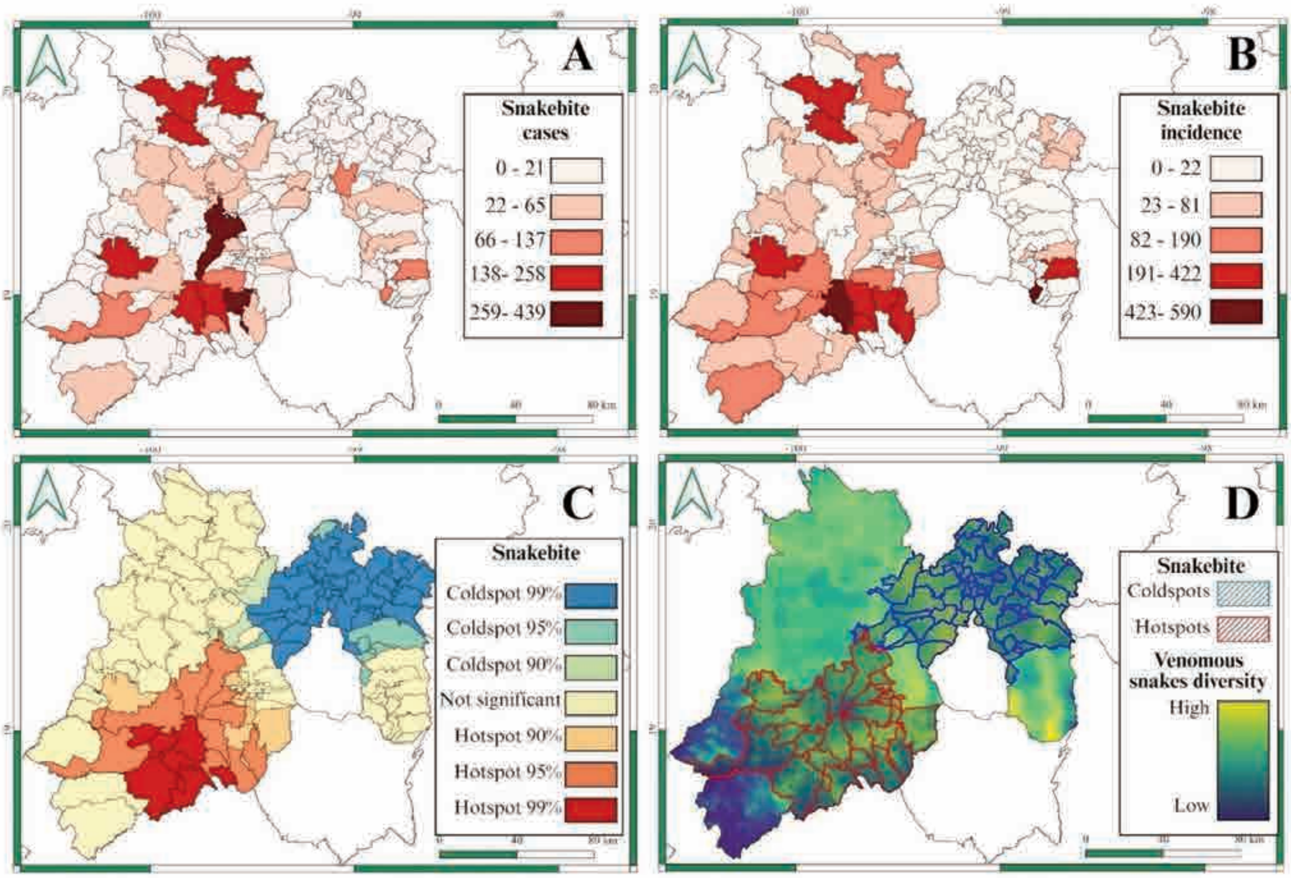

Figure 2. Municipality-level distribution of snakebite indicators in the State of Mexico. **A**) Raw snakebite case counts per municipality classified using natural breaks (in order to maximize between-class differences and highlight spatial heterogeneity among municipalities); **B**) Municipality-specific snakebite incidence rates (per 100,000 inhabitants) classified using natural breaks; **C**) Getis–Ord Gi* hotspot and coldspot classification of municipality-level snakebite incidence; **D**) Modeled venomous snake diversity aggregated at the municipal level, overlaid with Gi* hotspot and coldspot classifications of snakebite incidence.

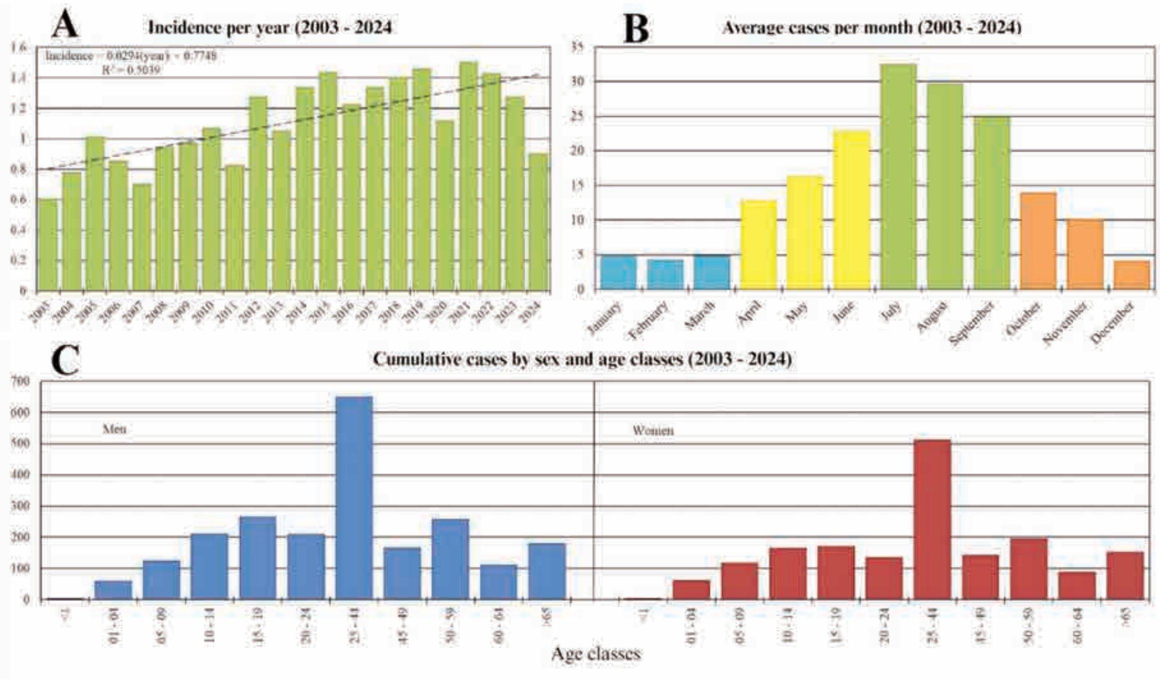

Figure 3. Temporal and demographic patterns of snakebite incidence in the State of Mexico 2003-2024. **A**) Annual snakebite incidence per 100,000 inhabitants with linear trend; **B**) Average number of snakebite cases per month across the study period, grouped by season (winter=January–March, blue; spring=April–June, yellow; summer=July–September, green; autumn=October–December, orange); **C**) Cumulative number of snakebite cases by sex and age class for the entire study period.

Table 1. Differences in socioeconomic variables according to the significance of the hotspots analysis for snakebites in the State of Mexico.

	Dimension 1		Dimension 2	
	ANOVA	**p-value**	**ANOVA**	**p-value**
Inhabitants' degree	20.960	**0.0002***	2.097	0.4288
Economic activity sector	29.04	**<0.0001***	3.304	**0.0305***
Occupational division	23.47	**<0.0001***	5.564	0.3256
	Tukey's test	**p-value**	**Tukey's test**	**p-value**
Coldspots/Not significant ID	7.970	**<0.0001***	0.126	0.9956
Not significant/Hotspots ID	0.798	0.8393	2.685	0.1434
Coldspots/Hotspots ID	7.487	**<0.0001***	2.560	0.1706
Coldspots/Not significant EAS	8.555	<0.0001*	1.139	0.7003
Not significant/Hotspots EAS	2.420	0.2051	3.614	**0.0315***
Coldspots/Hotspots EAS	9.589	**<0.0001***	2.631	0.1547
Coldspots/Not significant OD	7.145	**<0.0001***	2.423	0.2045
Not significant/Hotspots OD	2.994	0.0905	4.688	**0.0034***
Coldspots/Hotspots OD	8.974	**<0.0001***	2.619	0.1572

*bold and * denotes statistically significant values denotes statistically significant values. Dimension 1 and Dimension 2 correspond to the first two axes of the NMDS ordination; ID, inhabitants' degree; EAS, economic activity sector; OD, occupational division.*

Table 2. Differences in diversity of venomous species according to the significance of the hotspots analysis for snakebites in the State of Mexico.

	Kruskall Wallis test	**p-value**
Between groups	5.537	0.0627
	Mann-Whitney U test	**p-value**
Coldspots/Not significant	870	**0.0192**
Not significant/Hotspots	543	0.1604
Coldspots/Hotspots	631	0.8555

*bold and * denotes statistically significant values*

Discussion

Our methodology effectively identified snakebite hotspots in the State of Mexico, underscoring the need for targeted anti-venom distribution in southern municipalities and their neighbouring municipalities, which are characterized by historically lower accessibility to healthcare services (Garrocho, 1990). Importantly, municipalities with few recorded cases or low incidence may still be epidemiologically relevant when they are spatially associated with neighbouring municipalities exhibiting high incidence. Therefore, strategic planning for antivenom distribution, environmental education campaigns aimed at reducing risky human behaviours during human–snake encounters, and health-worker training should incorporate a spatial neighbour principle. That's because hotspot analysis identifies areas of elevated risk influenced by surrounding municipalities, not only by locally reported incidence, thereby helping to reduce reporting bias arising from the administrative assignment of snakebite cases to the municipality of medical care rather than occurrence. Interpretation of municipality-level incidence must consider the well-known small numbers problem in small-area epidemiology, whereby rates based on low case counts are subject to increased random variation (Waller & Gotway, 2004). In this study, this limitation was explicitly addressed by reporting raw case counts together with exact

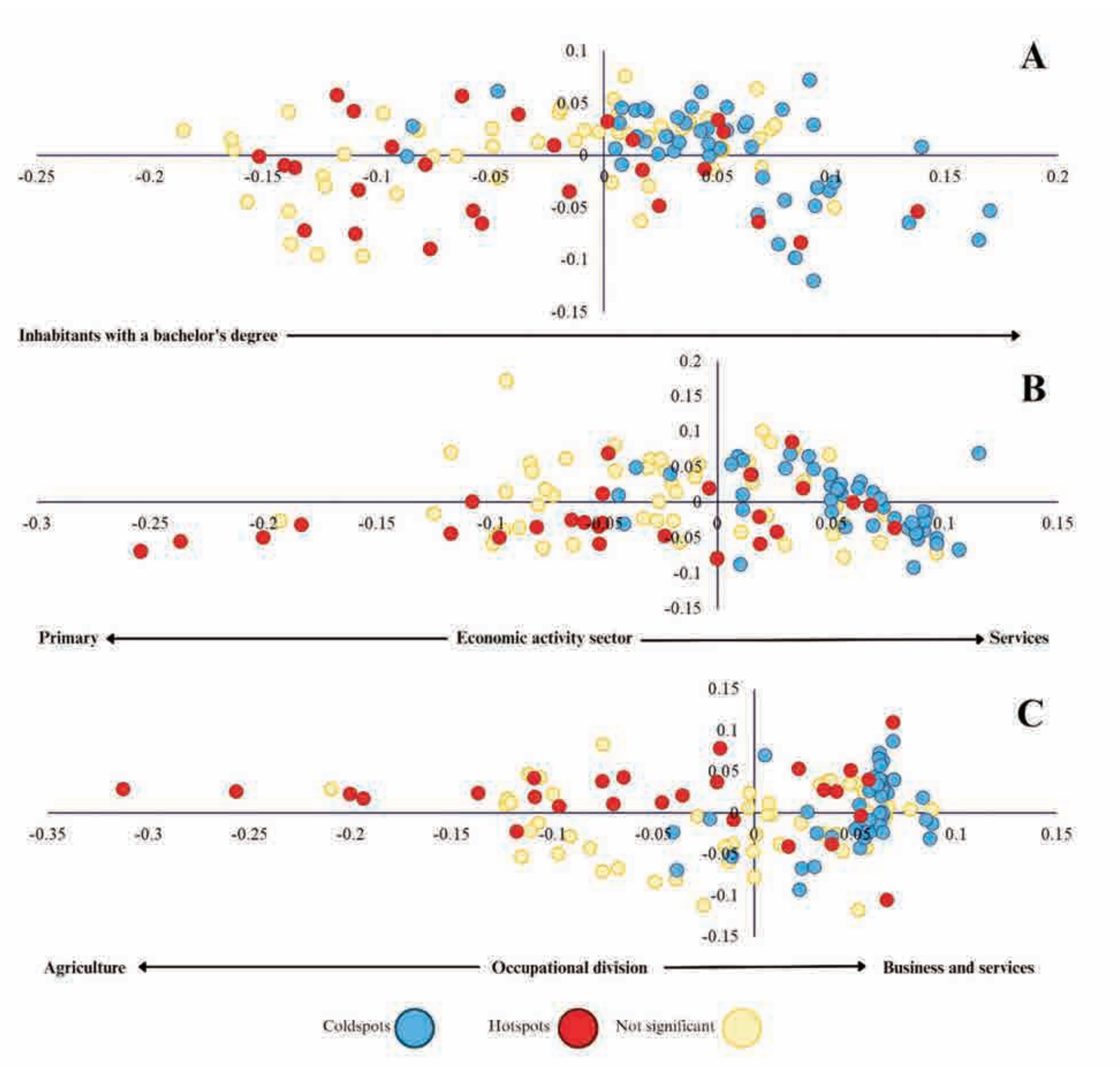

Figure 4. Non-Metric Multi-Dimensional Scaling (NMDS) ordination of municipalities based on socioeconomic variables. **A**) education level; **B**) economic activity sector; and **C**) occupational division) in the State of Mexico. Each point represents a municipality, coloured according to snakebite hotspot classification (hotspot, coldspot, non-significant). Axis values correspond to NMDS dimensions; relative positions indicate similarity in socioeconomic composition. Positive values of NMDS1 are associated with higher proportions of residents with bachelor's degrees, employment in the services sector and business-related occupations, whereas negative values correspond to lower proportions of residents with bachelor's degrees and greater participation in primary economic activities and agriculture.

Poisson confidence intervals. Importantly, the fact that some municipalities were identified as hotspots and exhibits a high incidence value was consistently supported by higher case counts and comparatively narrow confidence intervals, indicating that these estimates are statistically stable rather than artefacts of population size. As with any analysis based on administrative units, hotspot results may also be influenced by the Modifiable Areal Unit Problem (MAUP); however, this limitation does not invalidate the Getis-Ord Gi* results and requires cautious interpretation of local clusters (Waller & Gotway, 2004). The use of a fixed distance band based on centroid-to-centroid distances applies to a consistent spatial scale across municipalities, partially mitigating the effects of heterogeneous size and shape.

Epidemiological and demographic overview

Our results align with previous findings by Luna-Trejo (2018), who analysed snakebites in the State of Mexico from 2004 to 2016, reporting a similar average of 180 cases per year identifying the Tenancingo health jurisdiction (an administrative health unit responsible for coordinating surveillance and healthcare services across multiple municipalities), located in the south of the state, as the most affected, despite differences in study period and data compilation approaches. This jurisdiction includes municipalities with the highest incidence rates observed in our study and classified as hotspots, such as Coatepec Harinas, Ixtapan de la Sal, and Tenancingo (*Figure 1S)*. At the national level, the State of Mexico ranked sixth in snakebite cases in 2024 (Dirección General de Epidemiología, 2024). In México, snakebite epidemiology has also been studied in six other states: Aguascalientes, Veracruz, Yucatán, Baja California Sur, Baja California and Zacatecas. In Veracruz, between 2003 and 2012, Yáñez-Arenas (2014) reported an incidence of 49.2 cases per 100,000 inhabitants. For Yucatán, Yáñez-Arenas *et al*. (2016) documented an incidence of 41.9 cases per 100,000 inhabitants during the same period. In Baja California Sur, Cruz-Ramírez *et al*. (2025) recorded an incidence of 33.09 cases per 100,000 inhabitants between 2003 and 2018, while the incidence was 7.62 cases per 100,000 inhabitants in Baja California, the maximum incidence in Zacatecas was 3.34 cases per 100,000 inhabitants, and Aguascalientes was the least affected state with only 1.24 cases per 100,000 inhabitants (Rodríguez-Canseco *et al.*, 2021; Lara-Galvan *et al.*, 2025). Three of these states, Veracruz, Yucatán and Baja California Sur, showed higher incidence rates than that of the State of Mexico (24.48 cases per 100,000 inhabitants). However, in contrast to these regions where the number of cases remained relatively stable over time, the State of Mexico exhibited a clear increasing trend in snakebite cases across the study period, which may be explained by structural factors related to healthcare access and reporting. Recent nationwide analyses show that snakebite incidence in Mexico is strongly influenced by the spatial distribution of healthcare facilities that acts as a major source of reporting bias by concentrating case records in municipalities with greater hospital availability (Rangel-Camacho *et al.*, 2025). In parallel, health system reforms implemented in the State of Mexico over the last two decades have expanded institutional coverage and access to public healthcare services, particularly in previously underserved areas, leading to improved case detection and notification (Contreras-Landgrave & Tetelboin-Henrion, 2011). Additionally, climate change may also contribute to the increasing snakebite incidence observed in the State of Mexico. Recent epidemiological syntheses indicate that climate-driven shifts in snake behaviour and habitat suitability are likely to influence snakebite burden and should be considered in long-term surveillance and risk assessment (Bhaumik *et al*., 2022).

Socioeconomic factors related to snakebites

The annual increase in snakebite cases may be explained by socioeconomic dynamics, as indicated by the results of the NMDS analysis, which showed that occupational divisions and economic activity sectors are associated with snakebite incidence. Granados-Alcantar and Quezada-Ramírez (2018) documented that between 1990 and 2015, the State of Mexico was one of the primary destinations for internal indigenous migration. This mobility was largely tied to the agricultural labour niche, suggesting a link between rising numbers of indigenous agricultural workers and increased exposure to snakes. This hypothesis is supported by ecological evidence showing that rattlesnakes often inhabit agroecosystems. Species such as *C. aquilus* (Meik *et al.*, 2007), *C. polystictus* (Martínez Vaca-León *et al.*, 2019), and *C. triseriatus* (Sunny *et al.*, 2015; Sunny *et al.*, 2019; Soria-Díaz *et al.*, 2021) have been observed in or near cultivated areas, increasing the likelihood of human–snake encounters. This also helps explain the demographic patterns observed: men suffer more bites than women and most cases occur in the 25–44 age range. Escobar-Latapí (2020) reported that in 2019, 4.46 million men and 3.12 million women were employed in agriculture in Mexico. Since men are more likely to work in this high-risk sector, they are at a higher risk for snakebites. Similarly, the predominance of cases in the 25–44 age group aligns with the fact that this is the most economically active population in the primary sector (Siria-Hernández & Arellano-Bravo, 2009). In addition, informal child labour can contribute to vulnerability. Although the legal working age in Mexico is 15, it is documented that children as young as 12 are engaged in informal agricultural labour (Escobar-Latapí *et al.*, 2019), which may account for the increase in cases among adolescents. Age-specific patterns should be interpreted cautiously, as case counts are not adjusted for the population age structure.

The association between education and snakebite incidence is also well established. A lower level of education is linked to higher vulnerability, while improvements in environmental education have been shown to reduce snakebite occurrence and severity (Gosh *et al*., 2008; Togridou *et al*., 2020; Samuel *et al.*, 2020). Training healthcare professionals and community members can reduce the risk of complications and mortality (Harrison & Gutiérrez, 2016). Additionally, misinformation or fear often leads people to attack or kill snakes, increasing the chance of being bitten (Pandey *et al.*, 2016). While general education about snakes remains important, our hotspot analysis allows for targeted educational campaigns in the most vulnerable regions to maximize impact.

Biological factors related to snakebites

The seasonal increase in snakebites during spring and summer is likely tied to the biology of venomous snakes. In summer, many *Crotalus* species give birth (Setser *et al*., 2012; Pérez-Mendoza *et al.*, 2018), increasing encounters with gravid females and neonates (Pérez-Mendoza *et al.*, 2018). This season also coincides with peak activity levels for crotalids (Goldberg, 1999). Mating periods in *Crotalus* can occur in spring, summer, or both, and are followed by increased movement and visibility of adult males, reproductive females and juveniles (Schuett *et al*., 2002; Pérez-Mendoza *et al.*, 2018; Aldridge *et al.*, 2020). Similarly, Greene *et al.* (2021) reported that most *M. tener* bites in North America occurred during spring and summer, a pattern also seen in the venomous species from the State of Mexico. In contrast, rattlesnakes undergo winter dormancy (Schuett *et al.*, 2006; Nordberg & Cobb, 2016). Although occasional activity may occur in winter, snake abundances decline sharply, reducing the likelihood of encounters and bites.

Unexpectedly, coldspots exhibited lower venomous snake diversity than non-significant municipalities, but none of these differed from the hotspots. This result highlights that venomous snake diversity alone is not a direct proxy for snakebite risk, reinforcing the importance of incorporating spatial clustering and socioeconomic exposure when assessing snakebite epidemiology. Future studies should consider abundance, as well as human behavioural factors. Indeed, snakebites are often triggered by human actions. Encounters are frequently intentional, even with good intentions such as relocating the animal (Greene *et al.*, 2021) but can result in bites. Others occur during attempts to kill snakes (Pandey *et al*., 2016), leading to harm for both snake and human (Sunny *et al*., 2015; Onyishi *et al.*, 2021). Additionally, free handling of venomous snakes for social media exposure remains a dangerous and irresponsible trend (Fry, 2008).

Conclusions

This study successfully identified and categorized municipalities with high snakebite incidence in the State of Mexico. Particular attention is needed in southern municipalities due to their strong links to agricultural and fieldwork activities. The observed correlation between low education levels and snakebite risk supports the implementation of targeted interventions, including environmental education and emergency response training, especially in these high-risk areas. Conservation of venomous snakes also plays a preventive role. Aligning snake conservation with the network of Natural Protected Areas and current environmental legislation offers a dual benefit: preserving biodiversity and reducing snakebite risk. Protecting ecosystems not only maintains ecological balance but also promotes safer environments for local communities, highlighting the essential connection between biodiversity conservation and public health.

References

Aldridge RD, Siegel DS, Goldberg SR, Pyron RA, 2020. Seasonal timing of spermatogenesis and mating in squamates: a reinterpretation. Copeia 108:231–64.

Auchincloss AH, Gebreab SY, Mair C,Diez Rox AV, 2012. A review of spatial methods in epidemiology, 2000–2010. Annu Rev Public Health 33:107–122.

Bénard-Valle M, Carbajal-Saucedo A, de Roodt A, López-Vera E, Alagón A, 2014. Biochemical characterization of the venom of the coral snake *Micrurus tener* and comparative biological activities in the mouse and a reptile model. Toxicon 2014;77:6–15.

Bhaumik S, Beri D, Jagnoor J, 2022. The impact of climate change on the burden of snakebite: Evidence synthesis and implications for primary healthcare. J Fam Med Prim Care 11:6147–58.

Borja M, Neri-Castro E, Castañeda-Gaytán G, Strickland JL, Parkinson CL, Castañeda-Gaytán J, Ponce-López R, Lomonte B, Olvera-Rodríguez A, Alagón A, Pérez-Morales R, 2018.Biological and proteolytic variation in the venom of *Crotalus scutulatusscutulatus* from Mexico. Toxins (Basel) 8:1–19.

Calabrese JM, Certain G, Kraan C, Dormann CF, 2014. Stacking species distribution models and adjusting bias by linking them to macroecological models. Glob Ecol Biogeogr 23:99–112.

Campbell JA, Lamar WW, 2004. The venomous reptiles of the western hemisphere. Comstock Publishing.

Carbajal-Saucedo A, López-Vera E, Bénard-Valle M, Smith EN, Zamudio F, de Roodt AR, Olvera-Rodríguez A, 2013. Isolation, characterization, cloning and expression of an alpha-neurotoxin from the venom of the Mexican coral snake *Micrurus laticollaris* (Squamata: Elapidae). Toxicon 66:64–74.

Castoe TA, Spencer CL, Parkinson CL, 2007. Phylogeographic structure and historical demography of the western diamondback rattlesnake (*Crotalus atrox*): a perspective on North American desert biogeography. Mol Phylogenet Evol 42:193–212.

Cervantes-Zamora Y, Cornejo-Olgín SL, Lucero-Márquez R, Espinoza-Rodríguez JM, Miranda-Viquez E, Pineda-Velázquez A, 1990. Provincias fisiográficas de México [cited 2021 Aug 10]. Available from: http://conabio.gob.mx/informacion/metadata/gis/rfisio4mgw.xml

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, 2021. División política municipal 1:250000 [cited 2026 Jan 23]. Available from: http://geoportal.conabio.gob.mx/metadatos/doc/html/mun22gw.html

Contreras-Landgrave G, Tetelboin-Henrion C, 2011. El seguro popular de salud y la reforma a las políticas de salud en el Estado de México. Rev Gerenc Polit Salud21:10–32.

Cruz-Ramírez K, Sigala-Rodríguez JJ, Gómez-Martínez RF, Villalobos-Juárez I, 2025. Epidemiología de las mordeduras por serpiente y distribución de faboterápicos en Aguascalientes. México. Rev Latinoam Herpeto l8:69–83.

D'Amen M, Dubuis A, Fernandes RF, Pottier J, Pellissier L, Guisan A, 2015. Using species richness and functional traits predictions to constrain assemblage predictions from stacked species distribution models. J Biogeogr 42:1255–66.

Da Costa MKB, Da Fonseca CS, Navoni JA, Freire EMX, 2019. Snake bite accidents in Rio Grande do Norte state, Brazil: Epidemiology, health management and influence of the environmental scenario. Trop Med Int Health 24:432–442.

Dirección General de Epidemiología. Boletín Epidemiológico Nacional,2024.Histórico Boletín Epidemiológico [cited 2024 Jun 20]. Available from: https://epidemiologia.salud.gob.mx/gobmx/salud/documentos/boletin/2024.zip

Dormann CF, Elith J, Bacher S, Buchmann C, Carl G, Carré G, Marquéz JRG, Gruber B, Lafourcade B, Leitão PJ, Münkemüller T, McClean C, Osborne PE, Reineking B, Schröder B, Skidmore AK, Zurell D, Lautenbach S, 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36:27-46.

Escobar-Latapí A, 2020. Women and men in farm work in Mexico: trends and gaps, 2005–2019. CIESAS Bull1:1–5.

Escobar-Latapí A, Martin P, Stabridis O, 2019. Farm labor and Mexico's export produce industry, Wilson Center.

Fick SE, Hijmans RJ, 2017. WorldClim 2: new 1 km spatial resolution climate surfaces for global land areas. Int J Climatol 37:4302–4315.

Fielding AH, Bell JF, 1997. A review of methods for the assessment of prediction errors in conservation presence/absence models. Environ Conserv 24:38–49.

Fry BG. 2008. Snakebite: when the human touch becomes a bad touch. Toxins (Basel) 10:170.

García E, 2004. Modificaciones al sistema de clasificación climática de Köppen, UNAM.

Garrocho C, 1990. Localización geográfica de los servicios de salud en un subsistema de asentamientos rurales del Estado de México. Estud Demogr Urbanos 5: 127–148.

GBIF, 2025. GBIF occurrence download. [cited 2025 Jul 3]. Available from: https://doi.org/10.15468/dl.zatxey

Getis A, Ord JK, 1992. The analysis of spatial association by use of distance statistics. Geogr Anal 24:189–206.

Goldberg SR, 1999. Reproduction in the blacktail rattlesnake, *Crotalus molossus* (Serpentes: Viperidae). Tex J Sci 51:323–8.

Gosh S, Maisnam I, Murmu BK, Mitra PK, Roy A, Simpson ID, 2008. A locally developed snakebite management protocol significantly reduces overall antivenom utilization in West Bengal, India. Wilderness Environ Med 19:267–74.

Granados-Alcantar JA, Quezada-Ramírez MF, 2018. Trends in internal migration among the indigenous population in Mexico, 1990–2015. Estud Demogr Urbanos 33:327–63.

Greene S, Ruha AM, Campleman S, Brent J, Wax P, 2021. Epidemiology, clinical features, and management of Texas coral snake (*Micrurus tener*) envenomations reported to the North American Snakebite Registry. J Med Toxicol 17:51–56.

Gutiérrez JM, Calvete JJ, Habib AG, Harrison RA, Williams DJ, Warrell DA, 2017. Snakebite envenoming. Nat Rev Dis Primers 3:17063.

Hammer Ø, Harper DAT, Ryan PD, 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontol Electron 4:1–9.

Harrison RA, Gutiérrez JM, 2016. Priority actions and progress to substantially and sustainably reduce the mortality, morbidity and socioeconomic burden of tropical snakebite. Toxins (Basel) 8:1–14.

INEGI,2021. Censo de Población y Vivienda 2020[cited 2021 Aug 10]. Available from: https://www.inegi.org.mx/programas/ccpv/2020/default.html

Kasturiratne A, Wickremasinghe AR, de Silva N, Gunawardena NK, Pathmeswaran A, Premaratna R, Savioli L, Lalloo DG, Janaka de Silva H, 2008. The global burden of snakebite: a literature analysis and modelling based on regional estimates of envenoming and deaths. PLoS Med 5:e218.

Lara-Galvan JL, Montesino-San Martín M, Herrero-Otero X, Martínez-Montoya JF, Sigala-Rodríguez JJ, Marcia-Barbosa A, 2025. Venomous snakebite risk and its implications in Zacatecas State, Mexico 2007-2017. Geospat Health 20:1404.

Lawson AB, 2006. Statistical methods in spatial epidemiology. Wiley.

Legendre P, Legendre L, 2012. Numerical ecology, developments in environmental modelling. Elsevier.

Lemos-Espinal JA, Smith GR, 2020. A conservation checklist of the amphibians and reptiles of the State of Mexico, Mexico with comparisons with adjoining states. Zoo Keys 953:137–59.

Longbottom J, Shearer FM, Devine M, Alcoba G, Chappuis F, Weiss DJ, Ray SE, Ray N, Warrell DA, Ruiz de Castañeda R, Williams DJ, Hay SI, Pigott DM, 2018. Vulnerability to snakebite envenoming: a global mapping of hotspots. Lancet 392:673–84.

Luna-Trejo J, 2018. Análisis epidemiológico del accidente por animales venenosos en el Estado de México del 2004 al 2016 [bachelor’sthesis]. Universidad Autónoma del Estado de México.

Martínez Vaca-León OI, Maya-García SJ, Manjarrez J, Estrada-García LE, 2019. Snake interspecific aggregation: *Crotalus polystictus*, *Thamnophis eques* and *T. scaliger*. Herpetol Notes12:327–329.

Meik JM, Mociño-Deloya E, Setser K, 2007. New distribution records for the Querétero dusky rattlesnake *Crotalus aquilus* (Viperidae), with comments on morphology and habitat use. West N Am Nat 67:601–604.

Monroy-Vilchis O, González-Desales GA, Balbuena-Serrano A, Robles-Rodríguez J, Zarco-González MM, 2024. Potential distribution of *Agkistrodon bilineatus* (Squamata: Viperidae) and first records in Central Mexico. Caldasia 46:361–370.

Monter-Pozos A, Reyes-Velázquez EA, Hernández-Gallegos O, Gómez-Benitez A, 2025. Filling gaps: on the distribution of *Crotalus intermedius* Troschel, 1865 (Squamata, Viperidae) and its first record in the State of Mexico, Mexico. Check List 21:443–450.

Neri-Castro E, Bénard-Valle M, Gil G, Borja M, López-de León J, Alagón A, 2020. Serpientes venenosas en México: una revisión al estudio de los venenos, los antivenenos y la epidemiología. Rev Latinoam Herpetol 3:5–22.

Nordberg EJ, Cobb VA, 2016. Midwinter emergence in hibernating timber rattlesnakes (*Crotalus horridus*). J Herpetol 50:203–8.

Onyishi IE, Nwonyi SK, Pazda A, Prokop A, 2021. Attitudes and behaviour toward snakes on the part of Igbo people in southeastern Nigeria. Sci Total Environ 763:1–37.

Ord JK, Getis A, 1995. Local spatial autocorrelation statistics: distributional issues and an application. Geogr Anal 27:286–306.

Pacheco-Barrios K, Cardenas-Rojas A, Giannoni-Luza S, Fregni F, 2020.COVID-19 pandemic and Farr’s law: A global comparison and prediction of outbreak acceleration and deceleration rates. PLoS ONE 15:e0239175.

Palci A, LeBlanc ARH, Panagiotopoulou O, Cleuren SGC, Mehari-Abraha H, Hutchinson MN, Evans AR, Caldwell MW, Lee MSY, 2021. Plicidentine and the repeated origins of snake venom fangs. Proc Biol Sci 288:e20210062.

Pandey DP, Pandey GS, Devkota K, Goode M, 2016. Public perceptions of snakes and snakebite management: implications for conservation and human health in southern Nepal J Ethnobiol Ethnomed 12:1–24.

Pebesma E, Bivand R, 2023. Spatial data science with applications in R. Chapman & Hall.

Pérez-Mendoza HA, Sanabria-Tobón SR, Jaramillo-Alba JL, Solano-Zavaleta I, Vázquez-Vega LF, Díaz de la Vega-Pérez AH, 2018. Reproductive traits of dusky rattlesnakes (Crotalus triseriatus) in Central Mexico. J Herpetol 52:6–11.

Rangel-Camacho R, Yáñez-Arenas C, Chippaux JP, Martínez G, 2025. Socioeconomic and ecological drivers of snakebite incidence in Mexico: A spatial analysis of risk factors. PLoS Negl Trop Dis 9:e0013582.

Rodríguez-Canseco JM, Arnaud-Franco G, Gutiérrez-López E, Romero-Figueroa G, 2021. Epidemiological overview of snakebites in the Baja California peninsula, Mexico (2003–2018). Gac Med Mex 157:579–585.

Samuel SP, Chinnaraju S, Williams HF, Pichamuthu E, Subharao M, Vaiyapuri M, Arumugam S, Vaiyapuri R, Baksh MF, Patel K, Trim SA, Duncombe TE, Vaiyapuri S, 2020. Venomous snakebites: rapid action saves lives – a multifaceted community education programme increases awareness about snakes and snakebites among the rural population of Tamil Nadu, India. PLoS Negl Trop Dis 14:e0008103.

Schield DR, Card DC, Adams RH, Jezkova T, Reyes-Velasco J, Proctor FN, Spencer CL, Herrmann HW, Mackessy SP, Castoe TA, 2015. Incipient speciation with biased gene flow between two lineages of the Western Diamondback Rattlesnake (*Crotalus atrox*). Mol Phylogenet Evol 82:213–223.

Schuett GW, Carlisle SL, Holycross AT, O’leile JK, Hardy DL, Van Kirk EA Sr, Murdoch WJ, 2002. Mating system of male

Mojave rattlesnakes (*Crotalus scutulatus*): seasonal timing of mating, agonistic behavior, spermatogenesis, sexual segment of the kidney, and plasma sex steroids, In: Schuett GW, Höggren H, Douglas ME, Greene HW, editors. Biology of the vipers, Eagle Mountain Publishing. 515–532 pp.

Schuett GW, Repp RA, Taylor EN, DeNardo DF, Early RL, Van Kirk EA, Murdoch WJ, 2006. Winter profile of plasma sex steroid levels in free-living male western diamond-backed rattlesnakes, *Crotalus atrox* (Serpentes: Viperidae). Gen Comp Endocrinol 149:72–80.

Setser K, Mociño-Deloya E, Pleguezuelos JM, Lazcano D, Kardon A, 2012. Reproductive ecology of female Mexican lance-headed rattlesnakes. J Zool 281:175–182.

Siria-Hernández CG, Arellano-Bravo A, 2009. Mordeduras por serpiente venenosa: panorama epidemiológico en México. Salud Publica Mex 51:95–96.

Soria-Díaz L, Astudillo-Sánchez CC, Gómez-Ortiz Y, Manjarrez J, Mundo-Hernández V, Rubio-Blanco T, Domínguez-Vega H, 2021. Hidden in plain sight: detectability and habitat selection of the Central Plateau dusky rattlesnake in anthropized landscapes. Herpetol J 31:91–98.

Sunny A, Gandarilla-Aizpuro FJ, Monroy-Vilchis O, Zarco-Gonzalez MM, 2019. Potential distribution and habitat connectivity of *Crotalus triseriatus* in Central Mexico. Herpetozoa 32:139–148.

Sunny A, Marmolejo C, Vidal-López R, Falconi-Briones FA, Cuervo-Robayo AP, Bolom-Huet R, 2025. EcoNicheS: enhancing ecological niche modeling, niche overlap and connectivity analysis using the shiny dashboard and R package. Peer J 28:e19136.

Sunny A, Monroy-Vilchis O, Zarco-González MM, Mendoza-Martínez GD, Martínez-Gómez D, 2015. Genetic diversity and genetic structure of an endemic Mexican dusky rattlesnake (*Crotalus triseriatus*) in a highly modified agricultural landscape: implications for conservation. Genetica 143:705–16.

Tobeña M, Prieto R, Machete M, Silva MA, 2016. Modeling the potential distribution and richness of cetaceans in the Azores from fisheries observer program data. Front Mar Sci 3:1–19.

Togridou A, Graham SA, Owens JB, Santra V, Bharti O, Malhotra A, 2020. Prevention is better than cure: snakebite education in India. Educ Sci 10:75–96.

Waller LA, Gotway CA, 2004. Applied spatial statistics for public health data. Wiley.

World Health Organization, 2019. Snakebite [cited 2021 Aug 10]. Available from: https://www.who.int/health-topics/snakebite#tab=tab_1

Yañez-Arenas C, 2014. Análisis temporal y geográfico del envenenamiento por mordedura de serpiente en Veracruz, México (2003–2012). Gac Med Mex 150:60–64.

Yañez-Arenas C, Yañes-Arenas A, Martínez-Ortíz D, 2016. Panorama epidemiológico de las mordeduras por serpiente venenosa en el Estado de Yucatán, México (2003–2012). Gac Med Mex 152:568–574.

Zar JH, 1999. Biostatistical Analysis, Prentice Hall.

Online supplementary materials

Table S1. *The total number of reported snakebite cases and the cumulative incidence per 100,000 inhabitants over the study period for each municipality is reported. Incidence estimates are accompanied by exact Poisson 95% confidence intervals, which were derived from the expected rate parameter (λ) to quantify uncertainty associated with varying population sizes and low case counts. The lower and upper bounds of incidence reflect the range within which the true underlying rate is expected to fall given the observed data. An additional indicator identifies municipalities with very low numbers of cases, for which incidence estimates may be less stable due to increased random variation. Together, these metrics allow transparent evaluation of the robustness of municipality-level incidence values and support their interpretation in subsequent spatial and hotspot analyses.*

Figure S1. *Municipalities of the State of Mexico explicitly mentioned in the main text, highlighted to facilitate geographic interpretation of the results. This figure includes municipalities discussed due to their absence of reported snakebite cases, high raw case*

Received: 23 November 2025; Accepted: 15 January 2026.

Contributions: Aldo Gómez-Benitez, study concept and design, data analysis, acquisition and interpretation, manuscript original drafting; Erika Adriana Reyes-Velázquez, study concept, data analysis and interpretation, manuscript original drafting and critical review; Edgar Oviedo-Hernández, data analysis, manuscript original drafting and critical review, Laura Sonia Arzate-Garay, data analysis, manuscript critical review, Justin Lloyd Rheubert, study design, data analysis, manuscript critical review, Oswaldo Hernández-Gallegos, study concept, data interpretation, manuscript critical review. All the authors read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

Conflict of interest: the authors declare that they have no competing interests.

Ethical approval and informed consent: not applicable.

Availability of data and materials: the datasets used and/or analysed during the current study are available upon reasonable request from the corresponding author.

Funding: not applicable.