# Venomous snakebite risk and its implications in Zacatecas State, Mexico 2007-2017

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## Abstract

Zacatecas is a Mexican state from where there are few studies about biodiversity, venomous ophidians and people's experience of snakebites. In the state, there are 12 species of venomous snakes distributed in three genera: *Crotalus*, *Micruroides* and *Micrurus*, which could represent some risk for the locals. The objective of this study was to make use of Geographic Information Systems (GIS) and programming to determine the relationship between population variables and the number of snakebites registered by the Zacatecas Health Services (SSZ) from 2007 to 2017 at the municipal level. Climatic, social and biological variables were used to gain a better understanding of the situation. It was found that men working in livestock breeding, agriculture, subsistence hunting or mining are more vulnerable, especially if older than 65. The municipalities of Concepción del Oro, Villa de Cos, El Plateado de Joaquín Amaro, Loreto and Ojocaliente exhibit the highest risk, while special monitoring must be conducted in Guadalupe, Fresnillo and Zacatecas due to their high population density, as well as in Valparaíso on account of its rich venomous ophidian fauna. Additionally, it is suggested to carry out preventive actions and detailed data gathering about snakebites to guarantee information quality. This study constitutes the first formal, detailed work about the epidemiological panorama of envenoming caused by the bite of a snake (ophidiotoxicosis) in Zacatecas from which further investigation and modelling may derive.

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## Introduction

Mexico is a country with great biological diversity (Martínez-Meyer *et al.*, 2014), highlighting reptiles, with 864 species (44.9%) of the planet families, among which, more than half (493 species, 57%) are endemic to Mexico (Flores-Villela & García-Vázquez, 2014). Additionally, Mexico is considered the country with the greatest number of venomous reptiles in the world, comprising two families of venomous snakes, namely, Elapidae and Viperidae (Neri-Castro *et al.*, 2020), together with the Helodermatidae family within the lizards (Reiserer *et al.*, 2013). The former is composed of two terrestrial genera, *Micrurus* and *Micruroides* (Neri-Castro *et al.*, 2014), while within the Viperidae family, we encounter several genera, one of which is *Crotalus*, the iconic rattlesnakes (Lazcano-Villarreal *et al.*, 2010).

The co-existence between Mexican human population and venomous reptiles creates a certain risk, which, in this case, is defined as the likelihood of a snake-related (ophidian) accident to be registered. Additionally, the capacity of Mexican people to cope with this disease is termed vulnerability, which comprises two dimensions: i) Susceptibility or the characteristics of the population to increase or decrease the effects of envenoming caused by the bite of a snake (ophidiotoxicosis); ii) Exposure, that is, the degree of interaction between the population and the factors enhancing the pathogen (Hammer *et al.*, 2019).

A great number of studies about Mexican venomous snakes exist (Campbell & Lamar, 2004; Paredes-García *et al*., 2011; Maritz *et al*., 2016; Ávila-Villegas, 2017; Lara-Galván *et al*., 2020), where their diversity, distribution, ethnobiological perception or conservation is analysed. Indeed, research has proven that spatial variation in snakebite risk is tightly related with local density and diversity of venomous species (Martín *et al.*, 2022), since the probability of encounters and envenoming considerably augments in regions with high venomous species richness. Latin America is one of such regions, where genera like *Bothrops*, *Crotalus* and *Lachesis* are responsible for most ophidian accidents (Chippaux, 2017). Focusing on Mexico, Yáñez-Arenas *et al.* (2014), based on ecological niche modelling, correlated the presence of *B. asper* and *C. simus* with areas of higher snakebite risk in the state of Veracruz, meaning that the distribution and abundance of venomous snakes can explain, to a great extent, the spatial variability of snakebites.

As for ophidiotoxicosis, ophidism or ophidian accidents (Gil-Alarcón *et al.*, 2011), there are documents that analyse this problem at a large scale, such as those by Tay-Zavala *et al.* (2002) and Chippaux (2017), or even at a regional level (Luna-Bauza *et al*., 2004). Regarding the state level, Yáñez-Arenas *et al.* (2016) evaluated geographical and temporal patterns of ophidism in Yucatán, whilst Rodríguez-Canseco *et al*. (2021) used descriptive and retrospective statistical techniques to estimate annual average and snakebite incidence rates per 100,000 inhabitants in the Baja California Peninsula. A similar approach was adopted by Morales-Ríos *et al.* (2023) for Veracruz, one of the states exhibiting highest venomous snakebite incidence. However, research is still scarce in certain regions of Mexico, such as the state of Zacatecas, in which, despite the existence of studies about venomous herpetofauna (Ahumada-Carrillo *et al*., 2012; Sigala-Rodríguez *et al*., 2020; Lara-Galván *et al.,* 2020, 2023, Gámez-Gallegos *et al*., 2024), public health issues linked to these organisms are not explored.

Yet, as ophidiotoxicosis is a disease that depends on a wide range of factors (Ochoa *et al.*, 2021), its risk has been estimated through many statistical techniques. Among others, integrated nested Laplace approximations (INLA) enable the estimation of complex epidemiological parameters in a short time. In addition, INLA is particularly useful to analyse scattered data, which is the case of snakebites; hence its increasingly frequent use in this type of research. For instance, Ochoa *et al.* (2021) used INLA to assess snakebite risk in both humans and livestock in Terai, Nepal, considering different environmental and socioeconomic variables. Besides, Lee *et al.* (2025) proved, through the use of INLA, that deforestation was a significant variable for ophidiotoxicosis in South Korea.

It is noteworthy that Mexico is one of the countries with most ophidiotoxicosis-related problems (Chippaux, 2017), which makes it necessary to increment knowledge about the risk of venomous snakebites (ophidism). Likewise, the World Health Organization (WHO) considers ophidism a neglected tropical disease (NTD) and associates it with devastating health, social and economic consequences (WHO, 2025). In addition, the relationship between snakebites and species diversity must be established at the municipal level, with the aim of maintaining close epidemiological surveillance. To do that, Geographic Information Systems (GIS) and programming are useful tools, permitting graphic, detailed spatial and temporal analysis to identify risk levels, through the elaboration of risk modelling and diversity maps (Schrödle & Held, 2011; Sarkar *et al*., 2019; Ortega-Sánchez *et al*., 2024). Thus, they enable monitoring areas with the highest risk (Dipayan, 2017), so that health services can prioritise prevention efforts in such zones.

The main aim of this research was to assess the relationship between venomous snakebites (entirely caused by rattlesnakes), the diversity of venomous species, and the human population of Zacatecas municipalities. For this purpose, it was necessary to integrate several variables in the study of venomous snakebite risk. Some of them may be the social aspect (*e.g.*, the use of suitable clothing and accessibility to health services) along with biological and ecological factors (habitat conditions) related to venomous species diversity. In this sense, precipitation and temperature are considered strongly correlated variables with snakebite risk (Ochoa *et al.*, 2021), since they determine the presence or absence of each species by influencing plant formations, resulting in a greater number of microhabitats for these organisms, as well as for their prey and predators. Altogether, this information will provide decision-makers a better perspective about the snakebite epidemiological panorama in Zacatecas.

## Materials and Methods

### Study area

The state of Zacatecas is located in the north-central region of Mexico (Figure 1), with four physiographic provinces converging in its territory (Cervantes-Zamora *et al*., 1990), which gives it a wide variety of ecosystems. The population is over 1.5 million inhabitants, distributed around 58 municipalities, with Fresnillo, Guadalupe and Zacatecas being the most populated ones (INEGI, 2020). Population density in the state is low, with scattered urban centres of medium and low population sizes fairly distant from each other, leading to low accessibility. For a better management of epidemiological data, Zacatecas Health Services (SSZ) divide the state into seven Health Districts (HD) (SSZ, 2024) depicted in Figure 1.

The elevation of the capital in Zacatecas is of around 2,400 metres above sea level. In general, the climate is semi-dry, temperate dry and semi-cold and sub-humid, with scarce rainfall throughout the year. As a result, arid and semi-arid zones distribute around three quarters of the state, where xerophilous shrub-land and grassland dominate. In addition, temperate forests and dry forests cover 20% and 5% of the state´s surface, respectively (INEGI, 2010). Regarding topography, the state is mainly characterised by rocky terrains, deep canyons, mountain ranges and flatlands (SGM, 2018). According to INEGI (2017), the main economic activities within the state are agriculture, livestock breeding and subsistence hunting, in the primary sector, as well as mining, in the secondary sector.

### Approach

Snakebite data from the municipalities in Zacatecas was obtained from a variety of sources (Table 1) in order to calculate rattlesnake bite risk, showing municipalities with higher risk and in

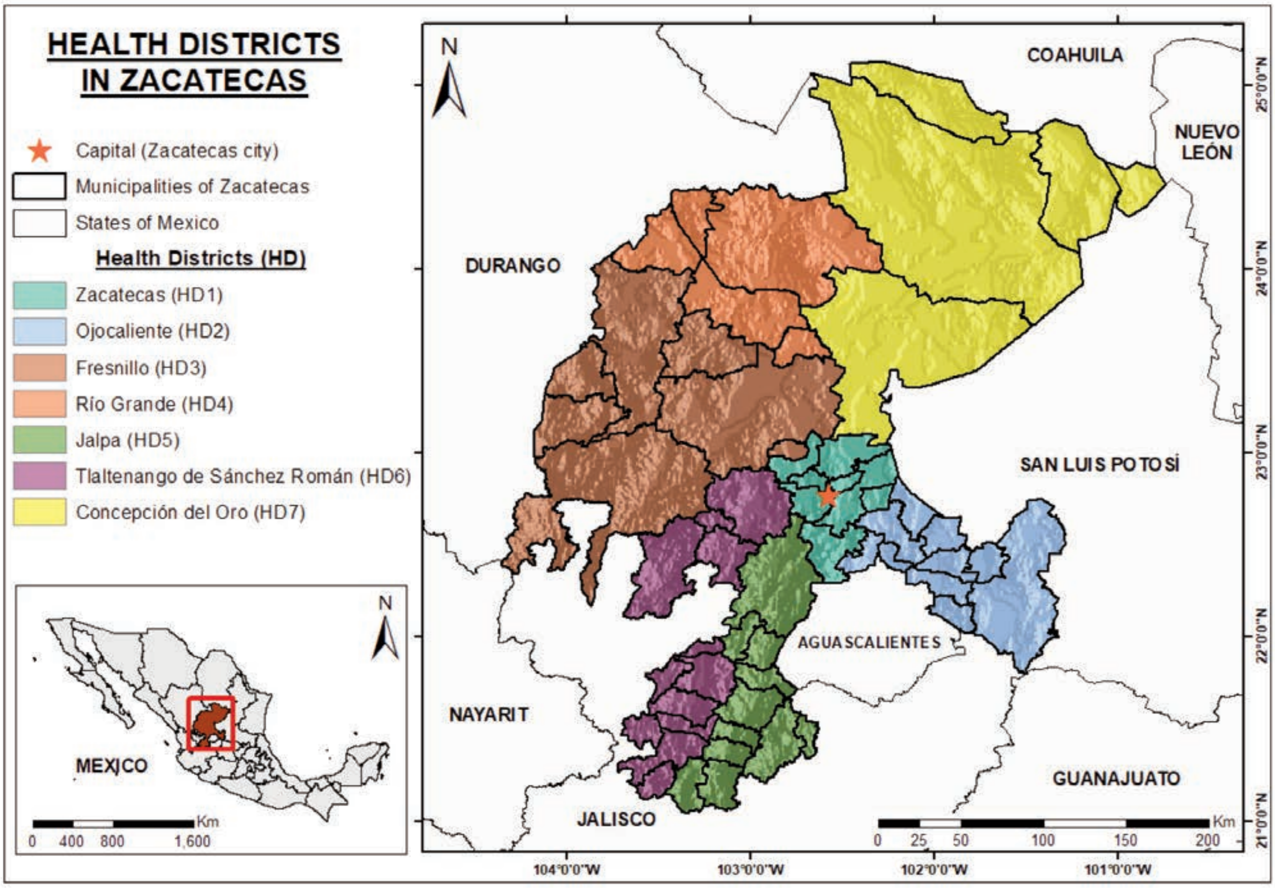


**Figure 1.** Health Districts (HDs) in the state of Zacatecas according to SSZ, 2024. Health Districts and the municipalities that they contain: **Zacatecas (HD1):** Calera, Genaro Codina, Guadalupe, Morelos, Pánuco, Trancoso, Vetagrande and Zacatecas; **Ojocaliente (HD2):** Cuauhtémoc, General Pánfilo Natera, Loreto, Luis Moya, Noria de Ángeles, Ojocaliente, Pinos, Villa García, Villa González Ortega and Villa Hidalgo; **Fresnillo (HD3):** Chalchihuites, Fresnillo, General Enrique Estrada, Jiménez del Teúl, Sain Alto, Sombrerete and Valparaíso; **Río Grande (HD4):** Cañitas de Felipe Pescador, General Francisco R. Murguía, Juan Aldama, Miguel Auza and Río Grande; **Jalpa (HD5):** Apozol, Apulco, General Joaquín Amaro, Huanusco, Jalpa, Juchipila, Mezquital del Oro, Moyahua de Estrada, Nochistlán de Mejía, Tabasco and Villanueva; **Tlaltenango de Sánchez Román (HD6):** Atolinga, Benito Juárez, Jerez, Momax, Monte Escobedo, Susticacán, Tepechitlán, Tepetongo, Teúl de González Ortega, Tlaltenango de Sánchez Román, Trinidad García de la Cadena and Santa María de la Paz; **Concepción del Oro (HD7):** Concepción del Oro, El Salvador, Mazapil, Melchor Ocampo and Villa de Cos.

**Table 1.** Category and data sources utilised in the research.

| Category | Data | Reference |
|---|---|---|
| Epidemiological indicators | Venomous snakebite records. | Zacatecas Health Services (SSZ). |
| Biological indicators | Diversity of rattlesnakes per municipality. | Lara-Galván *et al*., (2020); Villalobos-Juárez *et al*. (2025). |
| | Diversity of coralsnakes per municipality. | Ahumada-Carrillo & Vázquez-Huízar (2012); Lara-Galván *et al*., (2023); Gámez-Gallegos *et al*., (2024). |
| | Diversity of beaded lizards per municipality. | Ávila-Villegas (2007). |
| Socio-demographic indicators | Population size (per municipality) | WORLDPOP (2019). |
| | Population density (per municipality) | WORLDPOP (2019). |
| | Human Development Index (per municipality) | INEGI (2017). |
| | Social aspects. | Zacatecas Health Services (SSZ). |
| Climatic indicators | Annual local precipitation. | SMN, CONAGUA (2018). |
| | Mean maximum and minimum local temperature. | SMN, CONAGUA (2018). |

which greater health surveillance must be applied. These methodological stages are displayed in Figure 2 and described below.

## Compilation of ophidiotoxicosis and biological diversity data (step 1)

Venomous snakebite records were obtained from SSZ (*Supplementary materials: Appendix 1)*. The absence of envenomation caused by the Elapidae (*M. distans* and *M. euryxanthus*) and Helodermatidae (*H. horridum*) families was emphasised, which means that all the ophidian accidents presented here correspond to organisms of the *Crotalus* genus. SSZ provided ophidiotoxicosis cases for the years 2007-2017 (*Supplementary materials: Appendix 1)*. Data includes the municipality where the snakebite occurred, the gender of the affected person and the age range (0-4; 5-9; 10-14; 15-19; 20-24; 25-44; 45-49; 50-59; 60-64; and ≥ 65 years). It is noteworthy that age ranges were determined by the SSZ. Additionally, a literature review was done with the objective of identifying the number of venomous species per municipality. This was based on the following publications: Ávila-Villegas, 2007; Lara-Galván *et al*., 2020, 2023; Gámez-Gallegos *et al*., 2024; and Villalobos-Juárez *et al*., 2025, thanks to which it was possible to also determine a potential relationship between snakebite numbers and the venomous snake diversity in Zacatecas (Hernández & Bravo, 2009; Fernández-Badillo *et al*., 2021). (*Supplementary materials: Appendix 2)*

## Explanatory variables of risk (step 2)

### *Population*

The National Statistics, Geography and Computing Institute (INEGI) is the only institution in Mexico in charge of conducting a population census, which is done every ten years. It is complemented with rapid surveys performed every five years. Given that annual population estimates are a highly relevant variable in the elaboration of risk models, population numbers at the municipal level were based on WORLDPOP (2019) data. By means of this, the annual number of inhabitants for each municipality was approximated for the study period.

### *Climate*

Local climate data about annual precipitation and mean maximum and minimum temperature was obtained from the weather station network (https://smn.conagua.gob.mx/) of the National Meteorological Service (SMN) and the National Water Commission (CONAGUA) from 2007 to 2016 (data for 2017 were not available) (SMN & CONAGUA, 2018). 161 stations were selected within the state, and a 50 km buffer was applied to the state boundary to reduce edge effects, which added another 183 stations. As the weather station network does not cover the totality of the territory, spatial interpolation of climate data was carried out by the Kriging method, which is appropriate for the interpolation of quantitative variables, minimising variance and fitting well with the reality (Oliver & Webster, 1990).

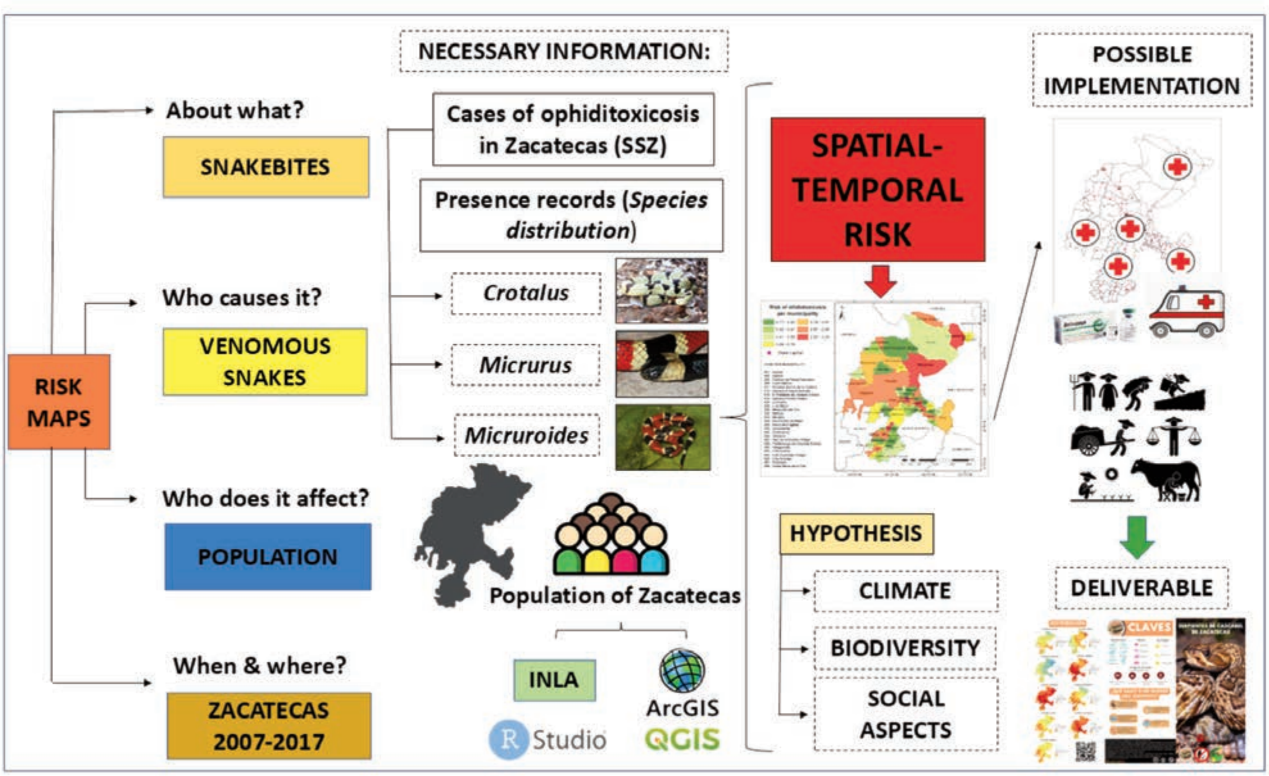


**Figure 2.** Workflow for the epidemiological analysis of venomous snakebites in Zacatecas, Mexico. Photos by Jesús Lenin Lara-Galván (*Crotalus*), Iván Trinidad Ahumada-Carillo (*Micrurus*), Eric Centenero-Alcalá (*Micruroides*), Erika Adriana Reyes-Velázquez (brochure).

## Health workers' and locals' information (step 3)

In order to obtain data about clinic management and the procedures to be implemented in case of ophidian accident, semi-structured surveys were applied to SSZ staff from both rural and urban contexts. Thanks to this, different data was gathered, for example, clothing at the time of the accident, data about the snakebite (time, place and circumstances), and undertaken assistance strategies since the patient's arrival up to their adequate treatment. This approximation enabled the compilation of empirical knowledge, which gave insight into the factors associated with the exposure to a venomous snake in the study area. Local people were similarly interviewed to obtain empirical knowledge about these accidents ("Lara-Galván *et al.* (in press). From fear to admiration: Traditional and local knowledge about rattlesnakes in Zacatecas, Mexico. Etnobiología").

## Standardised Morbidity Ratio (step 4)

Morbidity refers to the index or rate of sick people (in this case, people who suffered from an ophidian accident) in a certain place and time, whereas mortality rate is related to the number of deaths within a certain population and time (PAHO, 2020). In order to know the snakebite incidence rate in Zacatecas, it was necessary to compute the Standardised Morbidity Ratio (SMR). This measure was used to compute the relative ophidiotoxicosis risk, using the following mathematical operation:

$$R_j = O_j / N_j \qquad \text{Eq. 1}$$

where $Rj$ is the ratio sought; $Oj$ is the number of snakebite cases per age group $j$; and $Nj$ the number of inhabitants per age group $j$.

Afterwards, the expected SMR was computed based on standard values, which were subsequently multiplied by the population of each municipality. Then, a ratio between observed SMR and expected SMR was calculated, giving rise to a normalised result. To generate risk maps, the package INLA was used (Rue *et al.*, 2009), implemented in R software, version 4.4.1 (R Core Team, 2016). With this package, risk models were designed using observed cases, expected populations and explanatory variables as input data. These were integrated in a hierarchical, Bayesian model that can include fixed and random effects like spatio-temporal structures (Rue *et al.*, 2009). One of the main advantages of this algorithm, compared to other methods, is its capacity to make precise estimations of parameters with low computational cost (Ferkingstad & Rue, 2015).

Moreover, within the INLA package, there are different types of models. On the one hand, the Additive Linear Model (ALM) is a parametric model that assumes additive linear effects of the explanatory variables, whilst the Linear Model With Interaction (LMWI) is also linear, but includes interactions between variables. On the other, NONPAR_ADDIT and NONPAR_ADDIT2 are additive, non-parametric models that allow non-linear relationships, by using random walk-based smoothing, of 1st (RW1) and 2nd (RW2) order, respectively. The INLA package also offers several parameters to select the best model, such as: a) the deviance information criterion – DIC (Spiegelhalter *et al.*, 2002); b) the Watanabe-Akaike information criterion – WAIC (Watanabe, 2010); and c) logarithmic scoring – LS (Gneiting *et al.*, 2007). The values of the three selection criteria are shown in Table 2, where the model with lowest (best) score was selected (Cangrejo-Esquivel *et al.*, 2022). In this case, the most suitable model was DIC, since it better reflects the balance between the fitting quality and the complexity of the model, avoiding both overfitting and the loss of information (Spiegelhalter *et al.*, 2002).

To obtain the DIC criterion, the entire function was considered for the parameters introduced in the model (relationship snakebite cases – population), constructed through Monte Carlo chains (MCMC), which permit the measurement of the complexity of the interrelation between the aforementioned parameters. For that reason, the non-parametric model with interaction with RW1 (NONPART_INT) was chosen.

# Results

A total of 936 rattlesnake bites were recorded for the state of Zacatecas, between 2007 and 2017. These ophidian accidents were distributed over 49 of the 58 municipalities (*i.e.*, 84%). Records are detailed per HD (Appendix 1) and age range (Table 3). Additionally, rattlesnake incidences were calculated (Figure 3) and contrasted with diversity of venomous snakes per municipality (Figure 4).

With approximately 310,000 inhabitants, HD1 (Zacatecas) is the main urban centre of the state and is the HD with the greatest number of rattlesnake bites (308 cases), with Guadalupe and Zacatecas municipalities exhibiting the greatest number of incidents. The combination of risk and exposure makes this geographic area highly vulnerable, mainly due to its population density (INEGI, 2020). This high risk may be associated with the fact that at least one venomous snake species is present in each of these municipalities. HD2 (Ojocaliente) is second in number of snakebite cases, highlighting the municipalities of Loreto, Ojocaliente and Pinos. It is therefore recommendable to closely monitor these areas, especially the latter two municipalities, because of their relatively high venomous snake diversity (Appendix 1).

Within HD3 (Fresnillo), with 83 snakebites registered, Fresnillo is the third municipality with regard to ophidian accidents (Appendix 1) and also the most populated one (INEGI, 2020). Additionally, some of the municipalities within this HD are the most diverse in terms of venomous snake species, such as Sombrerete and Valparaíso, with six and seven species each, respectively (Figure 4). Within HD4 (Río Grande), the municipalities with the greatest number of cases are Río Grande and Juan Aldama. Special surveillance must be carried out in HD5 (Jalpa) concerning knowledge of rattlesnake species, snakebite cases and anti-venom availability, since eight of the twelve venomous snake species are distributed in this HD (Appendix 1), although snakebite cases are scarce. Species like *C. pricei* are relatively rare in the state, with few occurrence records, just like *C. aquilus*; in addition, as aforementioned, *M. distans* did not have any report of bites, according to SSZ.

Conversely, in HD6 (Tlaltenango de Sánchez Román), snakebite cases are low, with the exception of Jerez and Tlaltenango de Sánchez Román. However, this is also a HD with a small number of inhabitants (roughly 132,000). Finally, it is noteworthy that although HD7 (Concepción del Oro) is one of the largest HDs in the state, it only presented 99 venomous snakebites, *i.e.*, the third with the lowest incidence. This could be attributed to the municipalities in HD7 having very low populations. Nevertheless, the rattlesnake species present in the region are bigger in size (for example, *C. atrox*).

As for the age, people on the 25-44 range are the most affected ones, with 266 cases, followed by the 15-19 range, with 111 snakebite cases. Infant snakebite cases are alarming too (Table 2), and SSZ workers mentioned that ophidian accidents happened even to children under one year old.

### *SMR and risk maps*

In Table 3, the SMR of snakebite in Zacatecas can be observed, considering all the ophidian accidents that took place in 11 years and the population per age group. Age group 10 (≥65 years) bears the highest incidence rate (24.85 cases per 100,000 inhabitants), because, even though total population is similar to age group 1 (0-4 years), snakebite cases are three times greater. Conversely, incidence rate is lowest at age group 9 (60-64 years, 1.18 cases per 100,000 inhabitants). Moreover, age group 6 (25-44 years), which was found to be the most affected by snakebites by far, merely has the sixth highest incidence rate, with a value of 6.10 cases per 100,000 inhabitants (Table 3). Consequently, as the SMR considers ophidian accidents as a function of total population, it offers a different perspective about which age groups are most affected.

**Table 2.** Selection criteria values obtained in different models of the standardised morbidity ratio.

| Model | Selection criteria DIC | WAIC | LS |
|---|---|---|---|
| The additive linear model - ALM | 1787.190 | 1859.240 | 1.460600 |
| The linear model with interaction - LMWI | 1794.560 | 1868.271 | 2.246734 |
| NONPAR_ADDIT[a] | 1726.126 | 1835.406 | 1.447176 |
| NONPAR_INT[b] | 1253.863 | 1231.185 | 2.511824 |
| NONPAR_ADDIT2[c] | 1727.338 | 1832.013 | 1.443390 |
| NONPAR_INT2[d] | 1253.966 | 1230.134 | 2.520732 |

DIC, the deviance information criterion; WAIC, the Watanabe-Akaike information criterion; LS, logarithmic scoring; [a]Non-parametric additive model with RW1; [b]Non-parametric model with interaction with RW1; [c]Non-parametric additive model with RW2; [d]Non-parametric model with interaction with RW2.

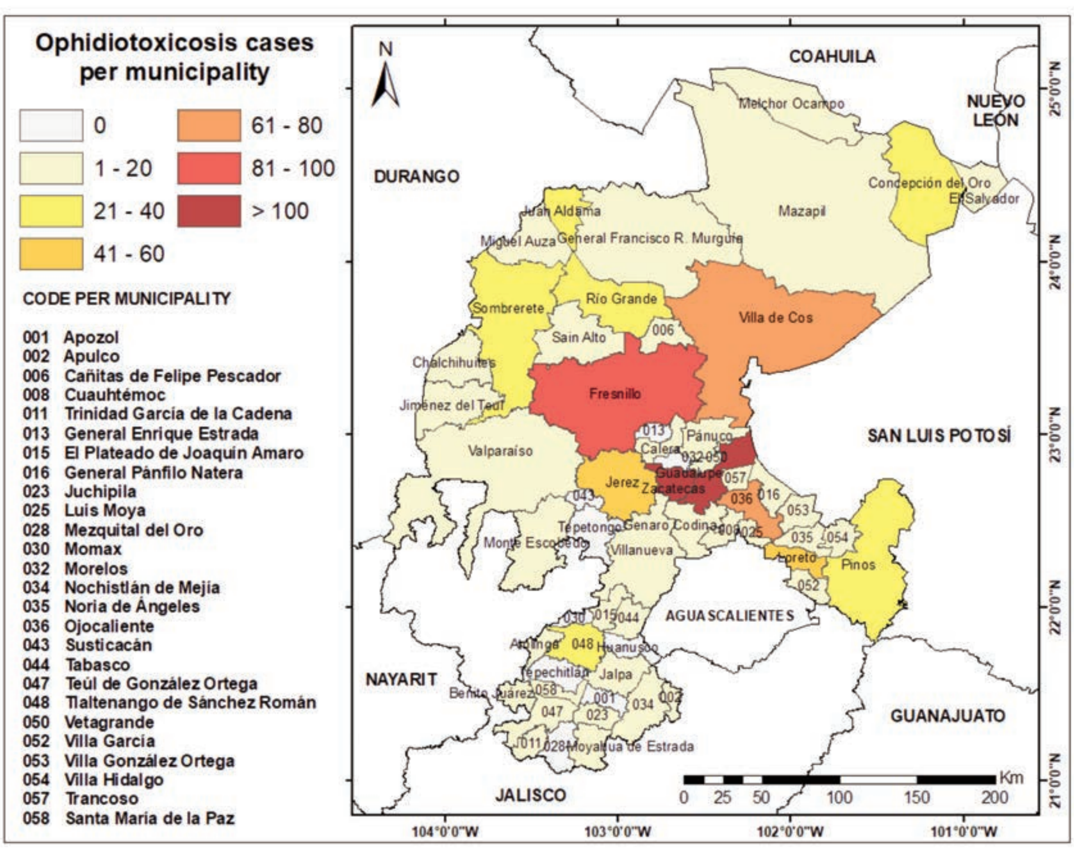


**Figure 3.** Ophidiotoxicosis cases per municipality in Zacatecas, Mexico.

### *Spatial-temporal risk models*

Figure 5 shows normalised ophidiotoxicosis risk per municipality, ranging from 0.17 to 3.34. The municipalities of Concepción del Oro (HD7), Villa de Cos (HD7), Ojocaliente (HD2) and El Plateado de Joaquín Amaro (HD5) exhibit the highest risk. Other densely populated municipalities like Guadalupe, Fresnillo and Zacatecas also show a moderately high rattlesnakebite risk. Likewise, municipalities of medium population size, such as Jerez or Tlaltenango de Sánchez Román, register values ranging from 0.97 to 2.50. Scarcely populated municipalities like Atolinga, Jiménez del Teúl, Melchor Ocampo and Teúl de González Ortega also exhibit significant risk, similar to medium-sized municipalities.

**Table 3.** Venomous snakebites and incidence rate per age group in Zacatecas, Mexico.

| Age range (years) | $O_j$ (2007-2017) | $N_j$ (2007-2017) | SMR (cases per 100,000 inhabitants) |
|---|---|---|---|
| 0-04 | 30 | 364,114 | 8.23 |
| 05-09 | 57 | 1,710,470 | 3.33 |
| 10-14 | 69 | 1,669,895 | 4.13 |
| 15-19 | 111 | 1,544,063 | 7.19 |
| 20-24 | 84 | 1,348,946 | 6.23 |
| 25-44 | 266 | 4,363,130 | 6.10 |
| 45-49 | 71 | 1,706,065 | 4.16 |
| 50-59 | 99 | 1,225,290 | 8.08 |
| 60-64 | 54 | 457,914 | 1.18 |
| ≥ 65 | 95 | 382,292 | 24.85 |

$O_j$, the number of snakebite cases per age group; $N_j$, the cumulative population per age group; SMR, the standardised morbidity ratio ($O_j$ / $N_j$), *i.e.*, the incidence rate $R_j$.

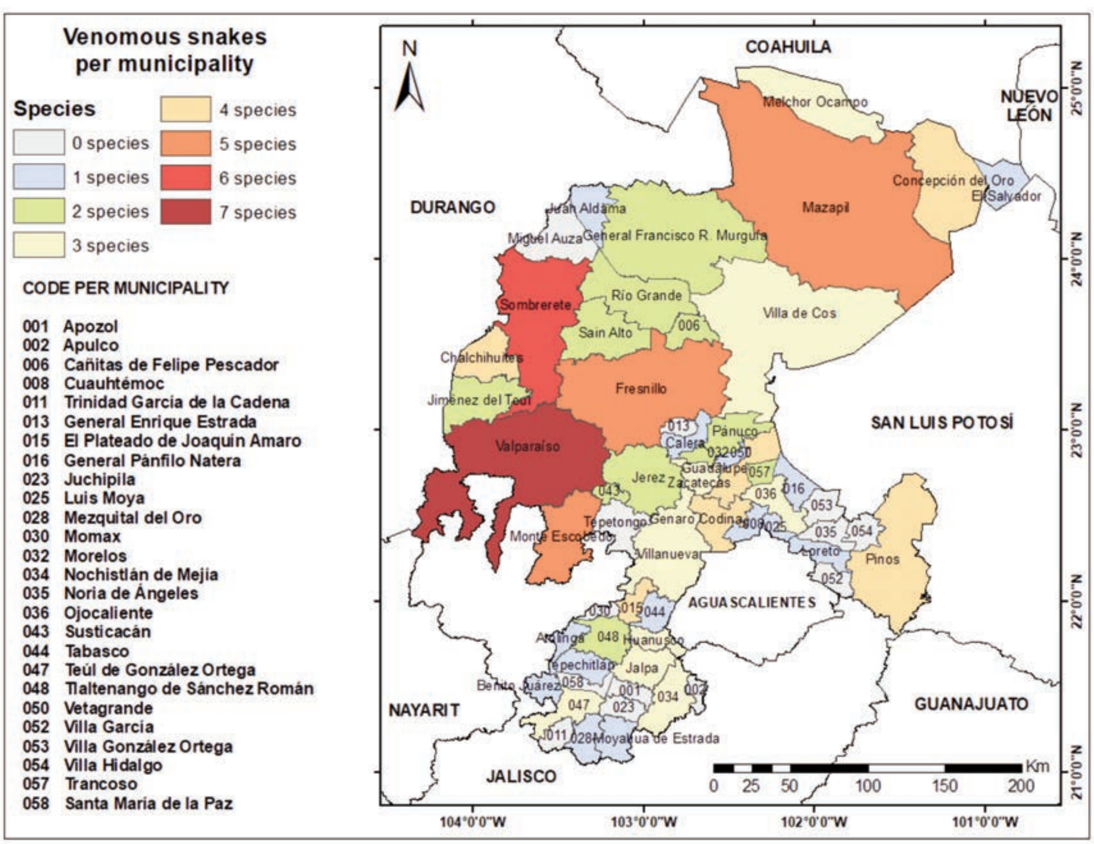


**Figure 4.** Number of venomous snake species per municipality in Zacatecas, Mexico.

### *Climate*

Figure 6 shows the number of snakebite cases in Zacatecas per year, compared to maximum and minimum temperature, as well as annual precipitation. The years registering a larger amount of accidents were 2015 and 2016, with 139 and 101 cases, respectively, and both years recorded abundant precipitation and milder temperatures. In contrast, there were only 37 cases in 2011, coinciding with significantly lower precipitation values and more extreme temperatures.

## Discussion

The presence of at least one venomous snake species is reported for 45 of the 58 municipalities in the state of Zacatecas. It must be clarified that these organisms could also exist in the remaining municipalities, but field work using habitat suitability maps by Lara-Galván *et al.* (2020, 2023) must be done in these areas to complete information gaps. Snakebites are reported in 49 municipalities of Zacatecas, which implies that some municipalities that do not have any venomous snake occurrence records must actually have the presence of these organisms (*e.g.*, Apulco, Juchipila, Miguel Auza, Noria de Ángeles, Santa María de la Paz, Trinidad García de la Cadena, Villa García, Villa González Ortega and Villa Hidalgo). Therefore, the snakebite database presented in this study provides additional information about the presence of venomous ophidians in the state, and based on this information, field work efforts in the aforementioned municipalities should be intensified.

Rattlesnakebite data are presented per municipality, for both sexes and all age groups reported by SSZ. In relation to this, health authorities do not have any record of humans dying of ophidiotoxicosis; however, during field work, locals mention that an infant under one year old had died in the municipality of Pinos due to a snakebite, but was not reported to the health service. In fact, this is a generalised situation in the state, where these events are not reported to the National Epidemiological Surveillance System (SINAVE) continuously (Neri-Castro *et al.*, 2020). This is attributed to the lack of local knowledge about the process that needs to be followed, as well as the perceived uselessness in doing it.

It is essential to improve the way to compile information, so that the snakebite database will keep growing, and has more complete and accurate information, including aspects such as the municipality where snakebites have occurred (regardless of the municipality where assistance was provided). This point is also underlined by Neri-Castro *et al.* (2020), who recommend that the documentation of data about involved species, envenomation level, the number of anti-venom vials applied, as well as follow-up information for each snakebite event. This information, together with more intense field work, would improve future risk models. In this sense, the municipalities that have not yet registered any snakebite should not be neglected, since some of them (*e.g.*, Huanusco, Mezquital del Oro, Morelos, Susticacán, Tepechitlán) have presence records of at least one venomous snake species

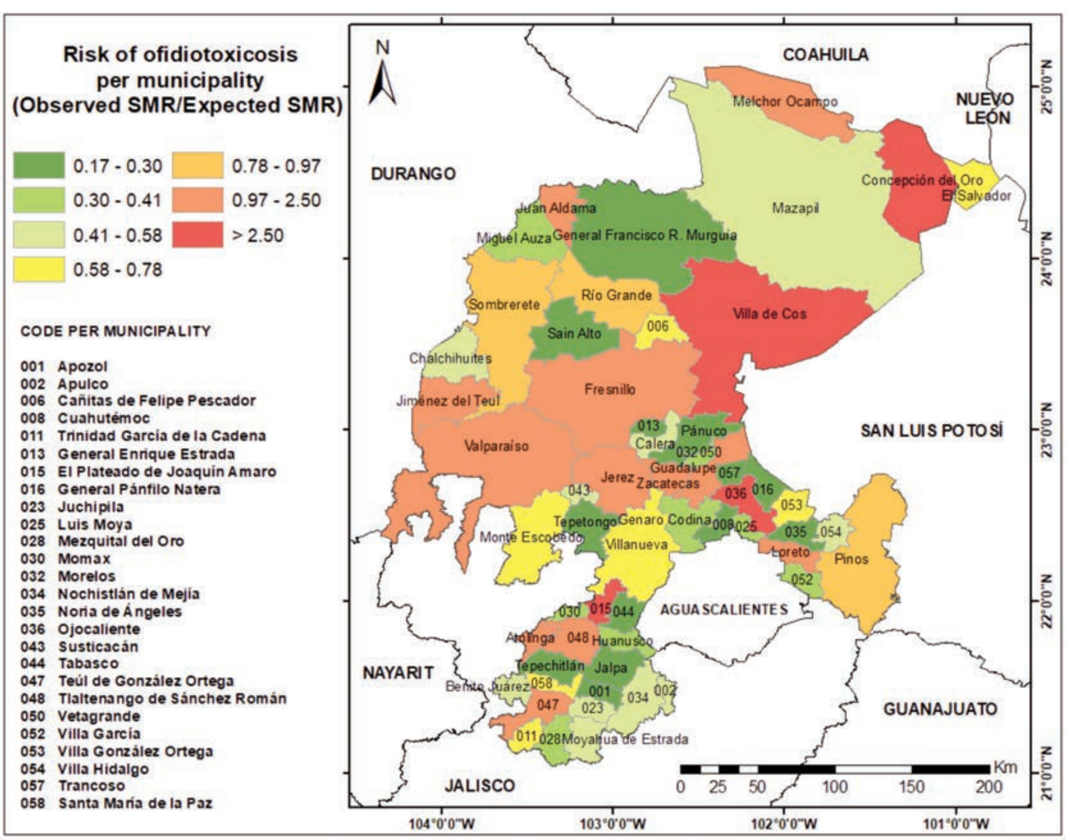


**Figure 5.** Normalised rattlesnake ophidiotoxicosis risk at a a municipal level in Zacatecas, Mexico.

(*Supplementary materials: Appendix 1*). From the geographic point of view, it is important to confirm that HD1, where some of the largest urban centres of the state are located, displays high vulnerability to ophidian accidents. This is consistent with Gil-Alarcón *et al.* (2011), Pitts *et al.* (2017) and Lazcano-Juárez *et al.* (2022), who stated that *Crotalus* rattlesnakes are present both in urbanised and semi-urbanised areas.

Concerning HD2, it is noteworthy that four species of rattlesnakes have been reported in Pinos and this municipality is adjacent to the state of San Luis Potosí (outside of the study area), which is marked as a hotspot for ophidian accidents in the country, following the epidemiological map by Chippaux (2017). Furthermore, according to SSZ workers, accidents happening in neighbouring municipalities from San Luis Potosí come to Pinos for medical assistance, since this is the most important urban centre in the region. This may overestimate the risk within the municipality, since there is no precise data about the actual location of these events.

Concepción del Oro and Villa de Cos (both in HD7) were some of the municipalities that presented highest ophidiotoxicosis risk. One of the main reasons is that the species present in this HD have generally bigger sizes, meaning that they possess a longer striking distance, so they can bite more easily. For example, one of the predominant species is *C. atrox* (Lara-Galván *et al.*, 2020), whose maximum total length is approximately 2,235 mm (Lemos-Espinal *et al.*, 2015), causes the majority of snakebites in North America (Uetz *et al.*, 2025). Other medium-sized species are similarly distributed in HD7, like *C. molossus,* with a total length of 1,330 mm and *C. scutulatus*, with a total length of 1,400 mm (Lemos-Espinal *et al.*, 2015) and one of the most powerful venoms within the genus (Neri-Castro *et al.*, 2020). This is consistent with Maguiña-Vargas *et al.* (2020), who state that the highest human death risk is linked to bigger-sized organisms, and these are widely distributed in this HD (Lara-Galván *et al.*, 2020). In addition, this HD has relatively low values of the Human Development Index (INEGI, 2017), especially in Mazapil (0.8321), El Salvador (0.8711) and Melchor Ocampo (0.8795) municipalities. This index is negatively correlated with the probability of suffering from an ophidian accident (WHO, 2019).

Municipalities like Atolinga, Jiménez del Teúl, Melchor Ocampo and Teúl de González Ortega also present considerably high bite risk, but it is necessary to bear in mind that, due to their low population sizes, a single case can considerably elevate the incidence rate. In the case of Valparaíso, the high diversity of venomous species (*Supplementary materials: Appendix 1*), particularly rattlesnakes, could explain its medium-high value. Fresnillo and Concepción del Oro are other examples of municipalities that registered a great number of snakebites and have a high diversity of venomous snake species. However, it must be pointed out that no clear correlation between snakebite and venomous snake diversity per municipality was found in the state of Zacataecas. Unlike previous studies in other Mexican states (Yáñez-Arenas *et al.*, 2014; Martín *et al.*, 2022). This could be attributed to the low level of detail of the provided data by the SSZ, so the significance of snake diversity cannot be ruled out in the study area.

Climate may potentially impact the relationship between the number of snakebite cases and the abundance of these species in different municipalities (Figure 6). As locals mention, rattlesnakes are more active during summer and early autumn (coincident with the rainy season), which is also pointed out by Diller & Wallace (1984), Luna-Bauza *et al.* (2004) and Gatica-Colima (2013). This suggests that 2011 might not have had the minimum humidity necessary for the development of these organisms, which probably stayed in a latent state, something that has been noticed in nearby areas (Lara-Galván *et al.* (in press). "Amphibians and Reptiles of Salinas, a municipality in semi-arid region of San Luis Potosí, Mexico. Reptiles & Amphibians"). This implies that snakes were less active during this year, resulting in lesser bites. Unfortunately,

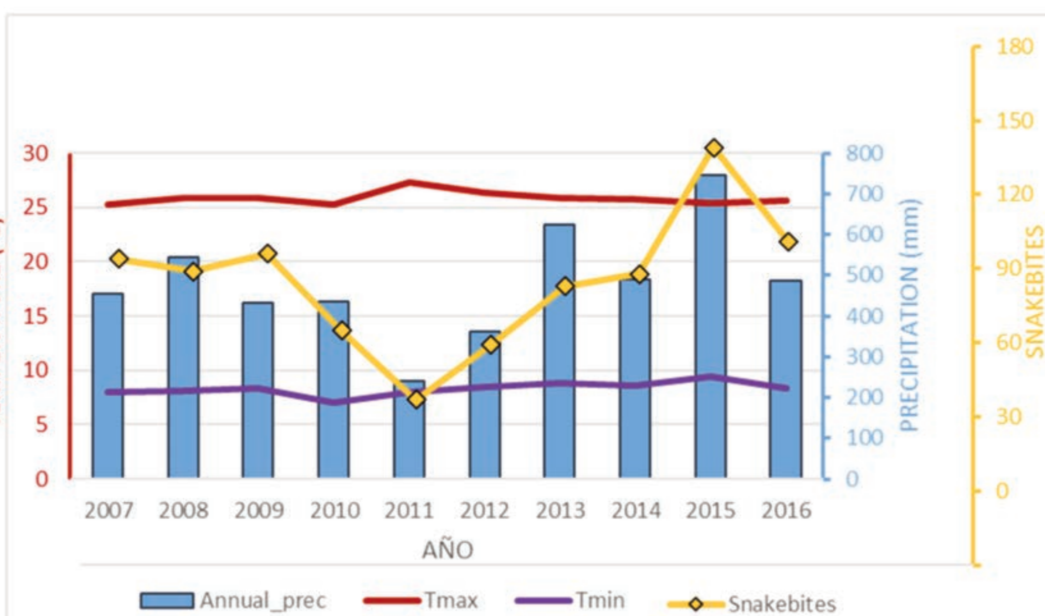


**Figure 6.** Relationship between ophidiotoxicosis and climatic variables in Zacatecas.

presence records of rattlesnakes at an annual scale are not available, which would enable direct comparison between climatic data, presence records and ultimately, ophidiotoxicosis cases.

Regarding socioeconomic factors, most incidents affect men, rather than women. Based on interviews (Lara-Galván *et al.* (in press). "From fear to admiration: Traditional and local knowledge about rattlesnakes in Zacatecas, Mexico. Etnobiología") to local people in many municipalities of Zacatecas, men usually have jobs closely linked to the field, such as livestock breeding (cattle, horses and sheep), agriculture (sowing and harvest), subsistence hunting (collection of rattlesnakes or mammals, such as the Mexican woodrat or the striped skunk) or mining, which increases the possibility of snake encounters (Neri-Castro *et al.*, 2020). This is of particular importance, because very often, the distance between accident locations and the closest medical centres is too long and the roads are unpaved and/or sinuous, which reduces accessibility and may hinder timely treatment. Furthermore, locals do not take the necessary precautionary measures to deal with these organisms. For instance, they do not use herpetological hooks or wear snake handling gloves, protective leggings or boots, and some even work in the field bare feet (Ochoa *et al.*, 2021).

Some of the limitations that arose during the study lie in the quality and availability of the information provided by the SSZ. In fact, very frequently, the bite-causing species, the affected body part and the specific age of the patients are not indicated, which hinders a more robust statistical analysis. In addition, access to updated information is restricted, which delays information systematisation. Another improvable aspect is that the exact location of the snakebite is not registered; instead, the municipality where the accident was treated is recorded. Indeed, some of the collaborators in the SSZ mention that there is a reduced stock of anti-venoms in rural areas, with most of them being concentrated in the most populated municipalities (namely, Fresnillo, Guadalupe and Zacatecas). That is why many patients prefer to attend these health centres, which may differ from those closer to the accident location. This generates inconsistencies in the registration and timely treatment of these cases. However, considering the available data, this study constitutes a good approximation to the snakebite epidemiological situation in the state, from which future works may derive.

Finally, the WHO (2017) included ophidism in the list of NTDs. This highlights the necessity to generate more scientific knowledge to guarantee a balanced distribution of anti-venoms in different regions across the territory (Neri-Castro *et al.*, 2020). Moreover, the study of different characteristics of herpetofauna, the collection of reliable data and the elaboration of risk maps with GIS and other spatial analysis techniques lead to more integrated epidemiological investigations, thanks to which a more balanced distribution of anti-venoms can be achieved (Lomonte, 2012; Ortega-Sánchez *et al.*, 2024).

## Conclusions

This investigation constitutes the first formal, detailed epidemiological study about ophidiotoxicosis in the state of Zacatecas. To do this, information about ophidian accidents was gathered during the period 2007-2017, which increased knowledge about the diversity of venomous snakes in the state. It was found that demographic factors such as population size, sex or age have a strong influence on risk incidence.

Densely populated municipalities report a greater number of snakebites, due to higher population size and the location of the main health centres that have a greater stock of anti-venoms. Some municipalities of low population sizes also display high risk, since one single case may increase it significantly. In several cases, an apparent relationship between risk and venomous species diversity is found. For example, Fresnillo and Concepción del Oro registered a great number of snakebites and have a high diversity of venomous snake species, including *C. atrox*, the largest of the species in the state. Nevertheless, overall, no clear correlation between snake diversity and snakebite risk in the state was identified.

As for climate data, precipitation is tightly related to the activity of these organisms in the study area, which ultimately leads to a higher probability of ophidiotoxicosis. However, data is scarce to establish a statistically robust relationship between these variables. In addition, people working in field activities such as agriculture, livestock breeding, subsistence hunting and mining are more prone to suffer from these accidents, as they have a higher probability of encountering these organisms.

Obtaining reliable data is of vital importance to improve the quality of the information. For example, a unified interview protocol would guarantee more homogeneity in the obtained results, which would enable the establishment of more robust statistical methods that would help improve predictive risk models.

### Recommendations

Based on the aforementioned information, preventive measures are suggested regarding ophidian accidents, in order to improve the negative perception about these organisms and thus, facilitate their conservation. To do this, two aspects are proposed: i) Improvement on the compilation of data on ophidian accidents; ii) environmental education, both in main urban and remote rural areas, about preventive measures, as well as diversity, ecological function, conservation, and danger of venomous snakes in Zacatecas.

As for the improvement of data collection, a structured, homogenised survey is proposed to obtain more detailed and reliable data, compiled by health staff properly trained for it. This would include data about: i) medical centre (assistance unit, locality, date and approximate time of snakebite and of arrival at the hospital); ii) patient information (age, sex, education level, job); iii) ophidian accident circumstances (place, activity that the affected person was carrying out at the moment of the snakebite, whether they had any protection on them during the incident, part of the body that was affected, symptomatology, knowledge about assistance centres, etc.); iv) clinical evolution of the patient.

Regarding environmental education, the elaboration and dissemination of brochures and informative posters about venomous snake species in Zacatecas is proposed, as well as an illustrated guidebook containing biological information about the species. Similarly, workshops could be offered to the local population in rural areas to provide them with preventive measures and guide them towards the procedure they should follow in the case of an encounter or snakebite. Finally, it is desirable that health centres have infographics about the species and risk in the area where they give assistance, so that the staff can identify the organism that produced the snakebite.

All this information would be of vital importance to feed predictive risk models and improve their quality and detail. This would allow to distribute antivenoms in a more balanced way across the state, while also saving costs for local people by travelling more rapidly to centres with available anti-venoms, as well as by preventing hospital saturation during provision of medical assistance for ophidian accidents.

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*Online supplementary materials*

*Appendix 1*

*Appendix 2*