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CLINICAL RESEARCH

Snakebites and climate change in California, 1997–2017

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ABSTRACT

Background: Climate change effect on flora and fauna has been scientifically documented, but the effect on North American venomous snakebites is unknown. The objectives were to examine Californian snakebite incidence and correlate with weather patterns and climate changes.

Methods: A retrospective analysis of snakebites reported to the Californian Poison Control System from 1 September 1997 to 30 September 2017. Venomous snakebite reports were aggregated by caller zip code, and correlated per county with weather data, air temperature, precipitation, population data, eco-regions, and land characteristics. Time series decomposition by seasonality and trend, regression, and autocorrelation were used to assess association between climate variables and incidence.

Results: There were 5365 reported venomous snakebites during the study period, with a median age of 37 years (22–51) with 76% male ($p < .001$, 95% CI 75.6–77.9%). Most snakebite outcomes were coded as minor (1363, 25%) or moderate (2607, 49%), with three deaths. Adjusted for population, the annualized incidence of snakebites statewide slightly decreased (rho $= -0.11$, $p = .65$). The snakebite incidence per million people rose after a period of no drought and declined during drought ($r = -0.41$, $p \ll .01$). Snakebite incidence decreased by 6-month prior drought (−3.8% for each 10% increase in drought), and increased by 18-month prior precipitation (+3.9% for each 10% increase in precipitation).

Conclusions: Patterns of precipitation and drought had a significant and predictive effect on snakebites in California over a 20-year period. Snakebite incidence decreased following drought, and increased after precipitation.

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Introduction

There are an estimated 1.2–5.5 million snakebites annually around the world, with approximately 20,000–94,000 attributed annual deaths [1]. The annual cost burden of snakebites is significant, and worldwide morbidity and mortality represent a neglected global public health problem [1,2]. In the United States, there are approximately 7,000–10,000 annual emergency department visits from snakebites [3], with 32–60% from venomous species, the majority being pit vipers [3,4], and 5–7 annual fatalities per year [3–5]. Individual expenses from antivenom and intensive care unit stays can cost upwards of $153,000 for a single patient [6].

Snakes are poikilothermic animals whose activities, life cycle, and geographic distribution are closely tied to ambient temperature [7,8], and vary as a result of climate change [9]. Global climate change's effect on flora and fauna has been scientifically documented [10]. There is at minimum a 99% chance that average global temperatures have significantly increased since 1950 to present times [11], and this global warming or "climate energizing" frequently results in increased extreme weather patterns [12,13]. These fluctuations of extreme weather (both drought and high precipitation) impact human health through an increase of natural disasters such as intense heat waves, droughts, and coastal flooding [14]. Likewise, climate change in North American is associated with changing distribution of venomous species that may lead to increased human morbidity [12,15,16]. Climate change has been described as the greatest global threat of the twenty-first century [17], but the effect on snakebites in North America has not been examined.

There is some evidence for increased incidence of snakebites with warming temperatures, however interpretation is limited to Central American meteorological patterns [9], and the current literature on snakebites in the United States provide limited insight into this relationship [3,18]. With the recent most severe drought and precipitation seasons ever recorded in California [19], we sought to correlate the relationship of climate trends with snakebite incidence in California over 20 years. The study's primary hypotheses was that the severity of drought would correlate with increased incidence of snakebites, and could be predicted by weather patterns.

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Supplemental data for this article can be accessed here.

Methods

Study design and database

This was a retrospective cross-sectional study of snakebites reported to the California Poison Control System (CPCS) during the 20-year period from 1 September 1997 to 30 September 2017. The CPCS is comprised of four regional poison control centers (PCC): Fresno, Sacramento, San Diego, and San Francisco. The CPCS receives approximately 320,000 consultations annually from patients and health care providers in the state of California and is available 24 hours per day. Calls are managed by specialists in poison information (SPI) who are licensed pharmacists or nurses with specialized training in clinical toxicology with medical toxicologists available as needed. Cases judged to have potentially significant toxicity are followed from initial phone call through to outcome. For each consultation, a detailed electronic case record is created in Visual Dotlab™ (VDL, WeBeMe Software) according to the guidelines of the American Association of Poison Control Centers (AAPCC), which includes text-based notes of the case in addition to coded entries for demographic and clinical variables including age, sex, type and circumstances of bite, symptoms, treatments, and medical outcome. Every note entered in VDL is permanent and automatically time-stamped. Institutional review board approval was granted through Stanford University School of Medicine and University of California San Francisco.

Study setting and population

The VDL database was queried for all cases coded with AAPCC generic codes and POISINDEX identification codes for "snake" in any configuration. Each case was included if there was a snakebite, excluded if no snakebite on review or identified as a non-venomous snakebite. The cases were then analyzed by date and time, patient age, sex, bite site, call site, treatment, and medical outcomes. Cases were grouped by the caller's five digit zip code to one of California's 58 counties. As all PCC cross-cover their calls, the origin of the caller allowed a more accurate analysis of region where the snakebite occurred, rather than the regional PCC catchment area. Medical outcome codes are set by National Poison Data System (NPDS), and include the following eight categories: (1) No effect; (2) Minor effect; (3) Moderate effect; (4) Major effect; (5) Death; (6) Unrelated; (7) Unknown and (8) Not available.

Supporting data sources

County-level drought data were obtained from the US Drought Monitor for 2000–2017 [20], which categorizes drought by five severity classes: D0 (non-drought and abnormally dry conditions) and D1–D4 as increasing levels of drought. For county-level analyses we calculated the fraction of land in drought (D1–D4) compared to that fraction not in drought (D0 or less). This drought severity score (DS) was calculated as the total fraction of area experiencing any level of drought.

Air temperature (°C) and precipitation (kg/m^2) were obtained from the National Aeronautics and Space Administration's North America Land Data Assimilation Systems (NLDAS) dataset from 1979 to 2017 [21], which are produced through re-analysis simulation of weather systems on a uniform grid. Grid points located within each California county were binned and averaged by county.

Demographic time series were taken from US Census Bureau annual summaries including population data from the US Census Bureau summarized by the National Institutes of Health's National Cancer Institute from 1960 to 2016 [22]; county-level demographic data from the US Census Bureau including age and sex characteristics for 2016 [23].

Geographic and ecological classifications were the most recent data available, including Level III eco-regions of California as defined in 2000 from the US Environmental Protection Agency [24]; and land cover classifications from the National Land Classification Database (NLCD) Multi-resolution Land Characteristics Consortium for 2011 [25]. These data correspond to a single point in time classification of geographic areas by ecological characteristics and are updated periodically but as they change infrequently and we used the most recent and highest resolution data available. Eco-regions subdivide the state of California into the major ecological zones while NLCD provide finer classifications based on the land cover. For county-level analyses, the percentage of each land-cover and eco-region class was calculated to determine the fractional quantities and the dominant (greatest fractional) classification was used.

Within each county and for each week, month, season and year, population adjusted incidence was calculated as number of reported snakebites per million individuals. Total precipitation, DS, and average air temperature were then calculated for the same time periods and geographic areas to produce an aligned dataset. Seasonal analyses defined Winter as December–February, Spring as March–May, Summer as June–August, and Autumn as September–November. Temperature anomalies were identified by comparing reported temperature to the long-term average temperature for the same geography over the entire 20-year period.

Data analysis

To assess the hypotheses that incidence of snakebites would increase with increased DS and could be predicted by weather patterns, a Welch two-sample *t*-test was used to identify potential significant relationships between incidence and (a) drought severity or (b) identification of an atypically warm winter. Additionally, time series modeling was performed using seasonal decomposition by Loess [26]. This method works by isolating periodic patterns from the overall trend through fitting a Loess curve to the month-aggregated time series. The remaining seasonally decomposed time series is smoothed to identify the residual trend. Residuals were calculated as the exceptions from this combined season-trend model. Cross-correlation coefficients were calculated to determine time series correlation at multiple lags (in months). Dynamic linear lagged time series regression was used to develop predictive models between outcome (snakebite incidence) and covariates (temperature, drought, and precipitation) [27].

As a secondary outcome, we performed an analysis of incidence of snakebites with respect to environmental and demographic variables in each county-year combination. Multiple least-squares linear regression was used to determine the relationship between demographic and environmental covariates and overall snakebite incidence. Finally, least-squares linear regression was used to determine long-term trends in population adjusted incidence. All analyses were performed using the R Statistical Computing Environment version 3.3.3 [28].

Results

Long-term trends and characteristics

A total of 5365 snakebites were reported to the CPCS from 1 September 1997 through 30 September 2017. All bites were reported from rattlesnakes. The majority of snakebite reports were called from health care facilities (4607, 85.9%) versus private residences (671, 12.6%), with the distribution of number of cases per county and incidence (number of cases per 1 million residents) shown in Figures 1 and 2.

The median age of all persons with reported snakebite was 37 years old (IQR = 22–51). Males were significantly more likely than females to be injured (76.6%, 95% CI = 75.6–77.9%, $p < .01$) with median age of males 36 (IQR = 22–51) and females 40 years old (IQR = 20–54) (Figure 3). For patients between 20 and 30 years old, the ratio of male to female patients was 5:1, with prevalence among males at all ages greater than 2:1.

Table 1 describes the demographics, snakebites, call sites, severity, and treatments. The majority of snakebites occurred in the Spring or Summer and in counties dominated by shrub or scrub (Figure 4). Among the 3580 (67%) of reports with detailed treatment data, the most common intervention was FAb antivenom (59%). Controlling for population showed that increased population density equated to greater number of snakebites (Supplementary Appendix Figure 1), however, rural areas where snakes natural habitat is more common had a greater incidence of snakebites per capita (Supplementary Appendix Figure 2). When taken in the aggregate and adjusting for population, the annualized incidence of snakebites did not significantly change during the study period (rho = −0.11, $p = .65$) (Figure 5).

Weather patterns and snakebite incidence

Season and trend decomposition were used to explore snakebite incidence over the study duration and interrelated with drought, precipitation, and temperature. It is assumed

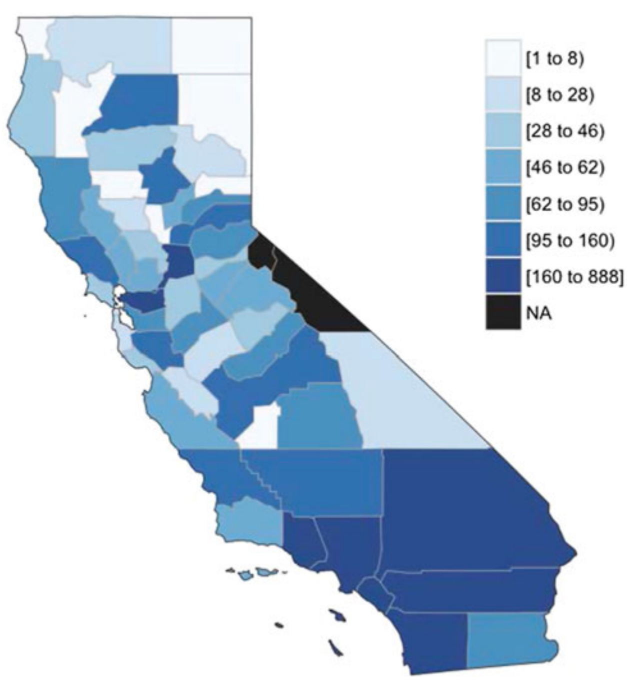

Figure 1. Number of snakebite cases per county.

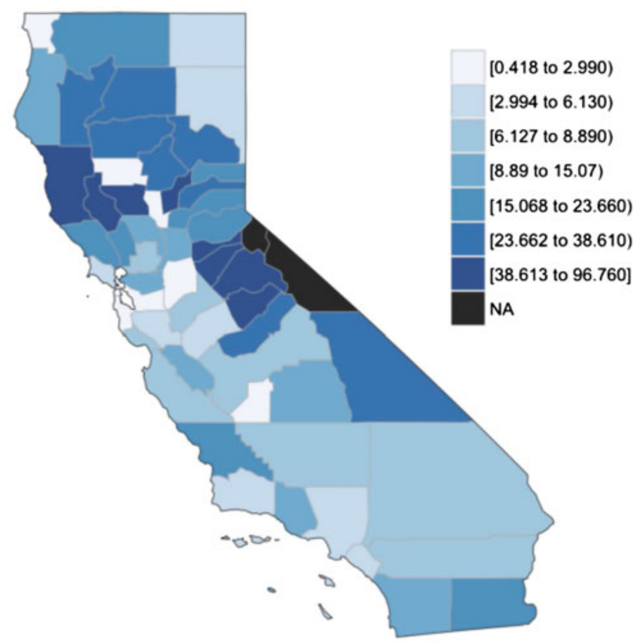

Figure 2. Snakebite incidence in number of cases per 1 million residents per county.

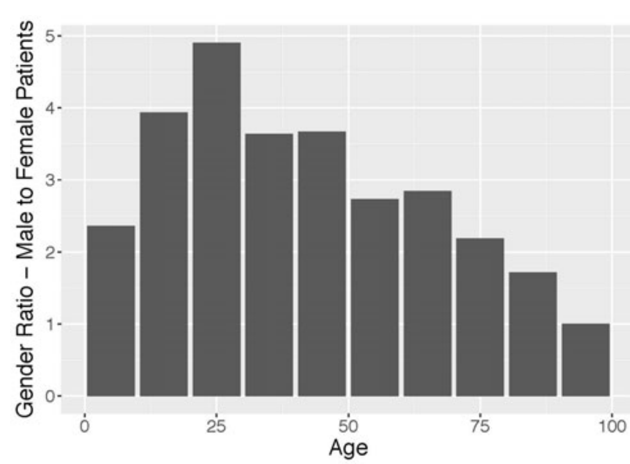

Figure 3. Ratio of male to female snakebites compared to age of patient.

Table 1. Demographic and environmental variables of snakebites.

Variable	N (%)
Sex	
Male	4110 (77)
Outcome	
No effect	234 (4.4)
Minor effect	1363 (25)
Moderate effect	2607 (49)
Major effect	440 (8.2)
Death	3 (0.1)
Unrelated	93 (1.7)
Unknown	582 (11)
Call site	
Own residence	671 (13)
Other residence	13 (0.2)
Workplace	10 (0.2)
Healthcare Fac.	4607 (86)
Restaurant	19 (0.4)
Other	45 (0.8)
Exposure site	
Own residence	4725 (88)
Other residence	22 (0.4)
Workplace	89 (1.7)
School	4 (0.1)
Restaurant	445 (8.3)
Public area	24 (0.4)
Other	18 (0.3)
Unknown	38 (0.7)
Treatment	
Antibiotics	148 (2.8)
Antivenin	1361 (25)
Intravenous fluids	1174 (22)
Antihistamines	243 (4.5)
Intubated	63 (1.2)
Steroids	50 (0.9)
FAB antibody	2120 (40)
Unknown	1785 (33)
Primary land cover class	
Cultivated crops	675 (13)
Evergreen forest	1194 (22)
Grassland	466 (8.7)
Mixed forest	148 (2.8)
Open water	66 (1.2)
Scrub	2761 (51)
Primary ecological region	
Central California Foothills and Coastal Mountains	1060 (20)
Central California Valley	582 (11)
Eastern Cascades Slopes and Foothills	4 (0.1)
Klamath Mountains/California High North Coast Range	242 (4.5)
Mojave Basin and Range	561 (10)
Sierra Nevada	927 (17)
Sonoran Basin and Range	62 (1.2)
Southern California Mountains	390 (7.3)
Southern California/Northern Baja Coast	1482 (28)
Season	
Fall (September–November)	1324 (25)
Spring (March–May)	1855 (35)
Summer (June–August)	2023 (38)
Winter (December–February)	163 (3.0)

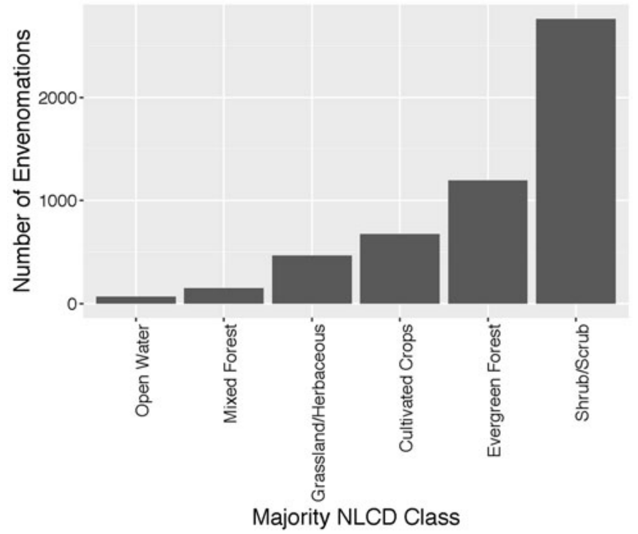

Figure 4. Number of snakebites per class of land cover.

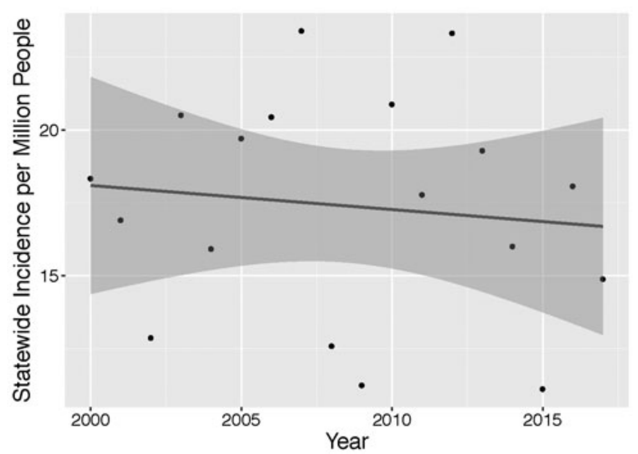

Figure 5. Statewide annualized incidence of snakebite per million people over 20 years.

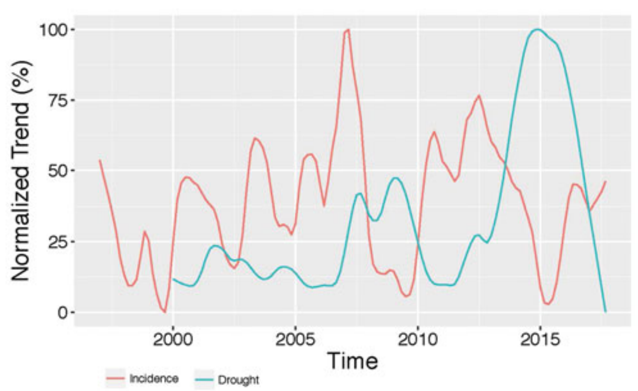

Figure 6. Normalized, seasonality adjusted drought compared with snakebite incidence.

that high temperatures and low precipitation predispose drought, while the opposite is true for the recovery from drought. All three variables were tested independently to determine which indicator provided the best predictive accuracy of incidence and on what time scale. The incidence of snakebite per million people declined during drought (mean in drought = 15.10, mean outside drought = 18.57, 95% CI difference = 0.12–6.83, $p = .04$). Figures 6 and 7 show this analysis statewide with the trend normalized to a percentage to allow direct comparability; incidence rose after a period of no drought, and declined during periods of drought ($r = -0.41$, $p \ll .01$) (Supplementary Appendix Figures 3 and 4 shows this relationship in the top nine counties by incidence).

Statistically significant correlations were found between both lagged precipitation (i.e., precipitation from previous months) and snakebite incidence (maximum rho = −0.52, $p \ll .01$ at 18 months prior) and drought and incidence (maximum rho = −0.17, $p = .01$ at 6 months prior). Temperature, including temperature ratio to long-term average, did not appear well correlated with incidence on its own. Precipitation and drought appeared well correlated with each other (for every 9.5% decrease in 18 month prior precipitation there was a 10% increase in 6-month prior drought); and a fitted model for snakebite incidence as a function of this performed well ($r^2 = 0.52$, residual standard error = 13%) (Supplementary Appendix Table 1). Taking each predictive variable in isolation (due to their mutual dependence) and adjusting for seasonal fluctuations, excess snakebite incidence could be calculated directly from the six month prior drought at a rate of −3.8% per +10% increase in drought, and +3.9% for each 10% increase in 18 month prior precipitation across the state of California (Figure 8) and counties.

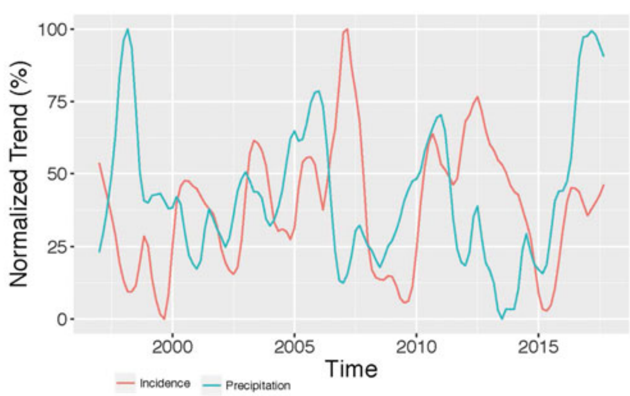

Figure 7. Normalized, seasonality adjusted precipitation compared with snakebite incidence.

Discussion

Our 20-year analysis of snakebites in California showed a well-correlated inverse relationship between snakebite incidence and severe drought phases, with a predictable increase of snakebites following precipitation. This is in contrast to popular press reports of increased snakebites with drought conditions [29,30], and Central American research that reported increased incidence of snakebite during high temperatures of El Niño Southern Oscillation (ELSO) [9]. This study also analyzed the effect of altitude and precipitation on the periodicity of regional snakebites, and found that while climate changes had a predictable effect on incidence, snakebites clustered in regions with the highest precipitation [9]. These low altitude humid regions with the hottest temperatures also saw heavier precipitation [9], which is opposite the arid drought conditions of California. As such, we cannot extrapolate the Costa Rican impact of ELSO and temperature to observed Californian trends. It has been theorized that a snake's foraging activity and subsequent human interaction may increase during hot temperatures [31,32], as a combination of decreased rodent population, riskier foraging behavior, and increased activity levels may be seen [31,33]. This has been supported by increased snakebites of sheep during drought [34]. However, these prey assumptions may be incorrect, as studies in the United States have found greater rodent populations [31,35], and by proxy, rodent vector diseases that increased during heavy precipitation phases and decreased during drought [36]. Likewise, high snakebite incidence patterns in areas with heavy precipitation have been found to have the greatest rodent populations [9]. As snakes are predominantly ambush predators of rodents and small animals [37]; the large increases of snakebite following the wettest winters in California likely reflect increased snake productivity following herbivore prey population growth.

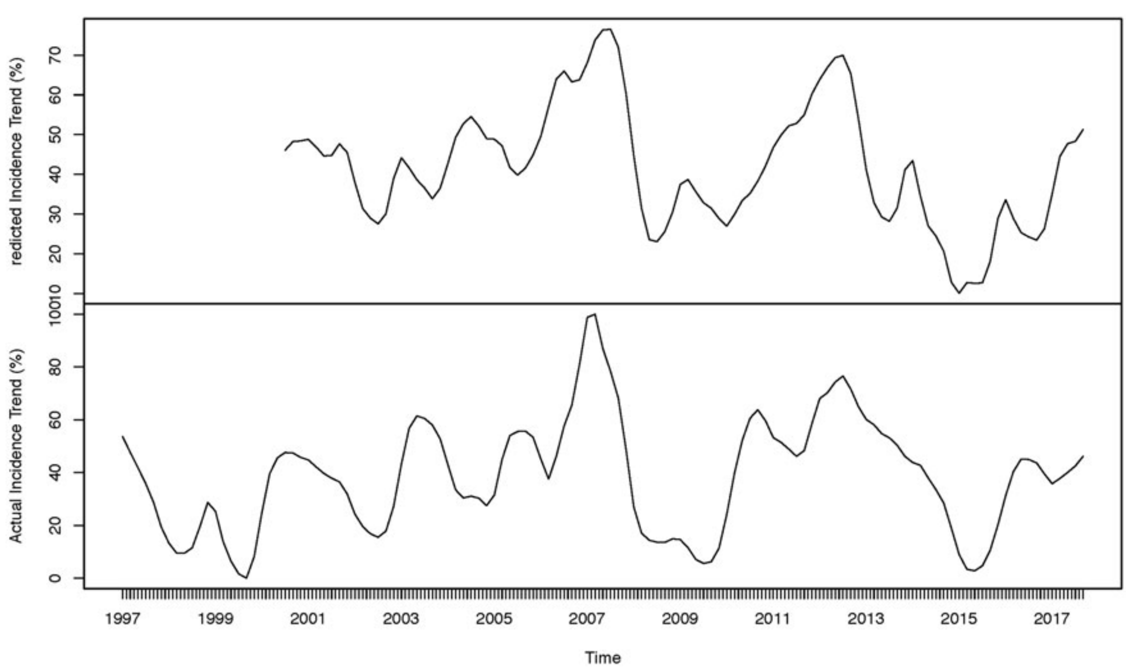

Figure 8. Predicted snakebite incidence trend using seasonality adjusted, normalized 18-month prior precipitation and 6-month prior drought indicator as predictor variables.

The patient demographics of our study were consistent with known epidemiologic trends of snakebites. The predominance of male victims were similar to the 69–79% found in state and national registries [3,18,38]. The average age of our patients was slightly higher than other registry studies [18,38], but similar to those treated in emergency departments [3], with similar fatality rates [39,40]. Approximately, 10–15% more CPCS consults were for moderate envenomations than the national average [40]. This may be due to reporting bias: as the relatively high prevalence of snakebites in California [39], regional health care providers may be comfortable without CPCS assistance and under-report snakebites with minor or no clinical effects.

Fifty-nine percent of our patients with recorded interventions received Crotalidae Polyvalent Immune Fab antivenom (FabAV; CroFab®) compared to 84% from 2013 to 2015 [38]. FabAV was approved by the US Food and Drug Administration in 2000, and has since become the mainstay of treatment with an 8% incidence of immediate hypersensitivity [41], and a 14% use increase seen in the 7 years following approval [40]. As 38% of our patients were treated with whole IgG Wyeth antivenin (which is no longer produced in the United States) [42], it is likely that the relatively low use of FabAV seen is due to a 20-year average, rather than current practice.

There was a visible comparative trend statewide with extreme weather fluctuations: the population adjusted incidence of snakebites fell in 2002–2005 and 2007–2010 during periods of drought. In 2015–2016, snakebites declined to their nadir with the most severe drought on record. After accounting for seasonal trends, we observed that prior precipitation was a strong predictor of snakebites, with incidence peaks following the heavy precipitation years of 2006 and 2011.

Limitations

Snake identification was not performed by professional herpetologists, and there was no independent verification of CPCS data, so the "rattlesnakes" reported may reflect a tendency to attribute all snakebites in an area to the predominant type [39]. The clinical outcome was unknown in 11% of the cases, and deemed unrelated to the bite in 1.7%. While lower than the 30% lost to follow-up of other AAPCC snakebite studies [39], our losses may still have affected the conclusions. The database did not provide the zip code of the injured patient, so we opted to rely on the zip code of the originating initial call to CPCS, rather than the consulted PCC which lacked locational accuracy. The initial calls were most frequently placed from a hospital setting, which means that the zip codes obtained were likely to be reflective of the general region where the bite occurred, but may not be geographically precise. This dataset cannot account for those snakebites that did not consult CPCS, and while consistent with the CPCS analysis model, it is likely an underestimate of total incidence.

We controlled for population changes per county, but could not account for changes in potential at-risk activities (e.g., an increase or decrease in outdoor recreation over time or activity changes during drought conditions). We cannot exclude the possibility that changes in the medical culture or technology of snakebite reporting may be a confounding variable. While we believe these limitations have not impacted the primary outcome of the study, future work could seek to include additional controls.

Integration and alignment of co-variate data presented unique challenges. NASA-provided re-analysis weather data are available on a uniform grid that is not aligned with geographic features, where aggregation results in more data for larger counties and less data for smaller. Particularly, San Francisco county was excluded from our analysis due to lack of available data. Climatological variable analysis was not possible at county resolution. While US Census data (population and demographics) did not present similar challenges, current-year census statistics were unavailable so 2016 data were used as a proxy for 2017. Unavailability of drought data prior to 2000 limited our analysis of that variable to the coincident years of 2000–2017 and prevented direct comparison with precipitation, air temperature, and incidence during the years 1997–1999. Future studies may consider analysis at smaller spatial resolutions if higher resolution long-term climatological data are made available.

Conclusions

Climate and extreme weather patterns appear to have had a significant and predictive effect on human–snake interactions in California over a 20-year period. The novel finding that snakebite incidence decreased following drought, and increased following precipitation has not been previously reported. This study confirms prior results for the demographic and geographic distribution of snakebites, and presents new results describing the interaction with climatological variables that emerged only when adequately adjusting for population growth and seasonality. Awareness of these trends may assist the public with seasonal snakebite risk assessment, medical provider preparations for antivenom requirement, and appropriate resource allocation to further study the impact of climate change on venomous species and human health.

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Disclosure statement

The authors declare no conflicts of interest, funding, or financial benefit arising from this study.

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