**Vulnerability to snakebite envenoming: a global mapping of hotspots**

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# Summary

## Background

Snakebite envenoming is an under-resourced cause of mortality and morbidity which lacks global attention equivalent with its burden. Poor data on snake ecology and existing snakebite interventions limit accurate burden estimation initiatives. Low global awareness of the condition stunts new interventions, adequate health resources, and available health care. This study aims to synthesise currently available data to identify the most vulnerable populations at risk of snakebite, and where additional data to manage this global problem is needed.

## Methods

Using expert opinion, occurrence data, and a multivariate environmental similarity analysis, we produce contemporary range maps for 278 medically important snake species. By triangulating these data with geographical accessibility surfaces, a measure of health care access and quality, and information on antivenom availability, we identify the populations most vulnerable to morbidity and mortality, reflecting global and subnational heterogeneities.

**Findings**

Although a large proportion of the world’s population live in areas inhabited by snakes, a subset lives within remote areas lacking quality health care provisioning. Comparing opposite ends of the Healthcare Access and Quality Index shows a disproportionate coverage in reported antivenom availability, with antivenoms reported for just 119 of 278 snakes evaluated by WHO, while 10.95% of those living within snake ranges live more than one hour from population centres. In total, we identify nearly 93 million people living within these vulnerable geographies, including many sub-Saharan nations, the Indian subcontinent, Indonesia, and other parts of Southeast Asia.

## Interpretation

Identifying exact populations vulnerable to the most severe outcomes of snakebite envenoming at a subnational level is critical for prioritising new data collection and collation, reinforcing envenoming treatment, existing health care systems, and deploying currently available and future interventions. These maps can guide future research efforts on snakebite envenoming from both ecological and public health perspectives and better target future estimates of the burden of this neglected tropical disease.

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# Research in context

## Evidence before this study

Snakebite envenoming is a Category A neglected tropical disease, of particular public health importance in tropical areas of Africa, Asia, Latin America, and Papua New Guinea. It is estimated that up to 1·2 million people are envenomed annually, resulting in 81,000 to 138,000 fatalities, and while effective therapies exist to treat envenoming by some snakes of highest medical importance, there are many lacking such treatments. The global distribution of venomous snakes and vulnerable populations remains inadequately characterised, and thus, the lack of knowledge of subnational disease burden may impede production of antivenom supplies and distribution efforts among populations currently at risk. To investigate this further we searched all published articles archived in PubMed prior to the search date of March 1, 2017 using the search terms “snakebite”, “distribution”, “burden”. Contemporary studies have investigated venomous snake distributions and snakebite risk at national (several countries in Latin America) or subnational levels (India, Nigeria, Sri Lanka), but these studies did not encompass all medically important species and are limited in both geographic extent and spatial resolution. A more recent analysis mapped the distribution of venomous snakes in Central and Latin America but was restricted to widely studied species with ample occurrence data. While an important start, no study has coupled global ecological information on snake distributions with measures relating to public health capabilities to hone in on populations most vulnerable to this cause of mortality and morbidity.

## Added value of this study

We identify populations most vulnerable to 278 medically important snakes by utilising expert opinion, species ranges refined by publicly available occurrence data and multivariate analyses, information on effective therapies, and metrics of health care quality and accessibility. While a large proportion of the world’s population live in areas where such snakes could be present, proxy metrics such as the Healthcare Access and Quality Index and urban accessibility, paired with broad-scale information on market antivenom availability, provide a subnationally resolved, yet globally comprehensive picture of vulnerability, highlighting populations that could be most impacted.

## Implications of all the available evidence

We highlight locations where the combination of the presence of a variety of venomous snakes, inequalities in health care and accessibility, and possible lack of effective therapy may contribute toward increased vulnerability of snakebite envenoming. Our analyses can be used to inform the positioning of local-scale household surveys to assess the true risk of snakebite in areas where such estimates are currently lacking. This study highlights the importance of continuing to iterate, improve, and re-evaluate existing geographic assessments of snake distributions, and the need to incorporate spatially heterogeneous risk within future burden estimation efforts. This work is a first step in trying to identify and assist the most neglected populations of this newly designated neglected tropical disease.

# Introduction

Snakebite envenoming is a frequently overlooked cause of mortality and morbidity, responsible for 81,000 to 138,000 deaths annually,1,2 and between 421,000 and 1.2 million envenomings.3 Contact from venomous snakes, spiders, and scorpions contribute to 1.2 million years of life lived with disability (YLDs) annually.4 The burden remains poorly characterised due to underreporting; as snakebite is rarely notifiable, existing estimates are typically derived from extrapolated hospital records and community surveys.5 Snakebite primarily affects the poor rural communities of Asia and sub-Saharan Africa, where socioeconomic status and agricultural and other practices contribute to increased snake-human interaction.6 Venomous snakebites can also inflict a heavy burden on livestock, creating economic hardship for already impoverished communities.7 Medically important snake species , however, have a cosmopolitan distribution, making snakebite a global challenge.3

In June 2017, snakebite envenoming was classified as a Category A neglected tropical disease (NTD),8,9 and is on the World Health Assembly May 2018 agenda. Consequently, there is a renewed impetus to accurately assess the burden and distribution of snakebite to ensure appropriate prevention and control interventions are implemented, and that adequate resources and funding are allocated nationally and subnationally.10,11 For other NTDs, substantive global targets exist: Sustainable Development Goal target 3·3 aims to “end the epidemics” of NTDs by 2030,12,13 with routine reporting, surveillance, and notification architecture in place. As a new NTD, snakebite monitoring and evaluation should reflect these objectives.

Data on the presence of venomous snakes and occurrence of snakebites are sparse and incomplete at the global level, making estimation challenging.14,15 While some countries have performed household-level surveys to determine the incidence of snakebites,14,15 the global magnitude of this disease remains poorly characterised. Snakebite envenoming represents an interesting One Health challenge requiring clinical, ecological, and public health expertise to combat – consequently, we can approach this issue by considering vulnerability to snakebite envenoming as a nexus of ecological contexts and public health weaknesses, to provide an evidence base for targeting future quantitative studies.

Clinical challenges involve appropriate case diagnosis, and adequate provisioning of care whether supportive (such as ventilators) or direct treatment with antivenom, which may or may not be available at any given point of care. 2,16 Ascertainment of the correct antivenom can be challenging, 17 and current diagnostics can be expensive and slow. 18,19 Furthermore, nearly half of venomous snakes do not have antivenoms available (119/278 species as tracked by the World Health Organization [WHO]). 2,20 To comprehensively address snakebites, these clinical challenges need to be considered within an ecological context, understanding snake behaviour and life-history traits that contribute to the frequency and geographic distribution of snakebites.

To aid in focusing and adequately provisioning global resources, this study pairs ecological information with health care metrics to highlight key populations for attention. By contextualising contemporary knowledge on snake distributions with indicators of the quality of health care provisioning,21 the accessibility of these resources,22 and antivenom availability,20 we highlight populations vulnerable to the worst health outcomes of an envenoming event.

# Methods

## *Overview*

Range maps for 278 snakes were evaluated to consider their presence at a 5 x 5 km (grid cell) resolution. To identify most vulnerable populations, this ecological information was paired with three key metrics: the market availability of antivenom therapies as reported by the World Health Organization,20 accessibility to urban centres as a proxy for access to health care,22 and the Healthcare Access and Quality (HAQ) Index as a proxy for adequacy and efficacy of medical interventions at health care centres.21 Figure 1 demonstrates conceptually how populations lacking in all these measures should be seen as the most vulnerable populations, and how these measures could vary geographically.

## *Global list of snakes*

We assembled a list of snake species, utilising WHO guidelines for venomous snake species of medical importance (hereafter referred to as snakes),23 which define two tiers of medical importance reflecting both ecological knowledge on propensity to interact with humans and clinical grading of toxicity. Category one species are common or widespread snakes that result in high morbidity, disability, or mortality.Category two species are snakes capable of causing morbidity, disability, or death, or for which epidemiological or clinical data are lacking and/or which are less frequently implicated.

Where relevant, expert opinion range (EOR) maps were obtained from the WHO blood products online database or the Clinical Toxinology Resources database.20,24 Occurrence data for each species were obtained from the Global Biodiversity Information Framework (GBIF),25 VertNet,26 iNaturalist,27 iDigBio, and Ecoengine,28,29 using the “spocc” R package on May 29, 2017.30 Duplicate records (based upon shared collection year and latitude/longitude) and those missing latitude/longitude were removed.

Given the availability of data, we placed snakes into three groups: Group A (no available EOR map or species occurrence records); Group B (EOR map, but <5 species occurrence records), and Group C (EOR map, and ≥5 species occurrence records). Group A species (n = 9) were excluded from this analysis due to the lack of geographical information, reducing our species inclusion list to 278 [Group B (n = 99), Group C species (n = 179)] (Supplementary File 2).

*Multivariate Environmental Similarity Surface generation and species ranges*

For Group C species with sufficient occurrence records, potential updates to the EOR maps were assessed. Since publication of the WHO EOR maps in 2008, a wealth of data has become publicly accessible, and we sought to update each EOR given newly available evidence. Given variable data quality and metadata tags, we can leverage the entire dataset to identify potentially dubious records by applying a multivariate environmental similarity (MES) method. This method allows rapid identification of occurrence records outside of the EOR within the environmental range of other records (ie*,* interpolation) or beyond these limits (ie*,* extrapolation). Multivariate environmental similarity surfaces (MESS) measure the similarity between new environments (records outside of the EOR) and those in the training sample (records within the EOR), by identifying the maximum and minimum values of environmental data within the training sample, with respect to a set of predictor variables (covariates).31 We fitted species-specific MESS using occurrence records within the EOR, and eight bioclimatic covariates thought to influence snake distribution (see Supplementary File 1 for MESS parameters and covariate specifics).

Occurrence records outside of the currently accepted EOR were overlaid on top of each species-specific threshold MESS. Records located within cells of environmental interpolation (termed ‘MESS-positive’), were considered valid records of species occurrence. Proposed ranges were developed to encompass all valid MESS-positive records, generated by applying a buffer radius of 0·898° (approximately 100km at the equator) to each MESS-positive record to address potential species movement, and possible geo-positioning errors. 32,33 Buffered locations were masked by the threshold MESS to remove areas of environmental extrapolation, and merged with the currently accepted EOR to produce a proposed contemporary range.

## *Global distribution of snakes*

To reflect the geographic diversity of the snakes studied, we aggregated the different species ranges. Modified (Group C species with MESS-positive records, n= 96), or original EOR surfaces (Group B species, and Group C with no MESS-positive records, n = 182) were converted into 5 × 5 km raster (gridded) files. They were then stacked by summing overlapping cell values, resulting in three composite output layers: (i) a count of the number of unique Category one and/or Category two species per cell; (ii) a count of the number of unique Category one species per cell and; (iii) a count of the number of unique Category two species per cell.

*Pairing ecological measures with health system metrics*

To ~~evaluate~~ identify the extent to which snakebites could vary globally as a public health problem we evaluated three key dimensions: existence of any marketed antivenom therapy, quality of health care and treatment options available, and geographic accessibility to health care. Of the 278 snakes considered, the WHO antivenoms database documents that any form of antivenom (either monospecific or polyvalent) exists for 159 species.20 Coupling this availability information with each species’ range we identified the geographic distribution of species lacking listed antivenoms, stratified by WHO category.

To address differences in health care quality and therefore identify populations to whom treatment options may not be available or effectively deployed, we categorised the world to identify populations living within each decile of a composite indicator measure of health care, the HAQ Index.21 The HAQ Index provides a metric for national levels of personal health care access and quality, drawing from mortality rates from 32 causes that are amenable to health care. The Index uses risk-standardised cause-specific mortality rates derived from the Global Burden of Disease study,34 scaled to a common 0-100 value, and aggregated using weights derived from a principal component analysis. To construct deciles, countries were ranked based on HAQ Index score, and threshold values splitting countries into ten equally sized groups were identified. Due to variable numbers of administrative units, subnational locations were not used to construct decile thresholds; subnationals for which HAQ values were estimated were assigned to the corresponding nationally-derived decile based upon their value. To evaluate the appropriateness of the HAQ Index as a proxy metric for severe snakebite related outcomes, we analysed the relationship between published estimates of snakebite-specific mortality numbers and the index, mimicking analyses undertaken on other development indices and mortality outcomes.6

To reflect relative geographic isolation from health care, we coupled mortality data with a contemporary surface of accessibility to major population centres. Habib and Abubakar (2011) identified that, for a Nigerian cohort of cases, each hour delay between envenomation and antivenom administration was associated with an increased mortality outcome of 1·01% (95% CI 1·00–1·02).35 With this measure in mind, a contemporary surface of accessibility to high-density urban locations (travel time in minutes to locations with a population >50,000) was used to identify remote populations and compared with the mortality statistics above.22 To evaluate the suitability of a population centre based metric, versus a healthcare focussed measure, we performed a sensitivity analysis using published data on African healthcare facilities.36

Populations living within these geographic regions of vulnerability were enumerated using most recent gridded population estimates from WorldPop.37

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report. The corresponding authors had full access to all of the data in the study and had final responsibility for the decision to submit for publication.

# Results

*Global distribution of venomous snake species*

Through the combination of publicly available data, we provide a surface showing the ranges of 278 snakes per 5 × 5 km area globally. Our MESS validation method resulted in 96 species range amendments (Supplementary File 2). All code used throughout this study is available via <https://github.com/joshlongbottom/snakebite>.

Given the broad distribution of snakes, approximately 6·85 billion people live within the range of one or more of the species considered (Figure 2A). When filtered by medical classification, 5·80 billion people live within ranges of Category one species, and 5·53 billion people live within ranges of Category two species (Supplementary File 1, Figure 2). Hotspots of venomous snake diversity include the Congo Basin, Southeast Asia, and Latin America.

*Global variation in market antivenom availability*

Using the only openly available database on antivenom availability, we identified 119 species with no specific therapy (42·81% of all mapped species [119/278]). Of these, 24 species were Category one (22·17%) and 95 were Category two (79·83%) importance. Hotspots of species with no listed antivenom occur throughout West Africa (Ghana, ≤7 species per cell), Central Africa (Cameroon, ≤7 species per cell), South America (Colombia, ≤7 species per cell), and Central Asia (India, ≤6 species per cell) (Figure 2B; Supplementary File 1: Figure 3). Among Category one therapy-naïve species, Myanmar and Bangladesh have the highest number (≤3 species per cell), with areas in West Africa (Mali, Senegal, and Guinea) and Namibia having up to two therapy-naïve species per cell.

*Populations lacking access to quality health care*

Populations living within these snake species ranges vary greatly in terms of accessibility to population centres and presumed health care. While antivenoms are deployed in health facilities in some very small communities in some countries, this is not universal, and in the absence of exact data on antivenom access, required approximating the influence of traveling time to health care via a proxy of distance to centres with >50 000 inhabitants. Our time-delay surface (Figure 4) highlights that should envenoming occur in large areas of Ethiopia, Sudan, Algeria, Indonesia, Papua New Guinea, Colombia, and Peru, the time taken to travel to a city in which we may expect to find available treatment could worsen mortality outcomes by >25% (assuming linear scaling of the statistic from Habib and Abubakar35). For instance, 78·71% of the population living within ranges of any snake species studied within South Sudan (2 531 665 people), and 89·89% of those in Papua New Guinea (624 204 people), live >1 hour from locations with ≥50 000 people (Supplementary File 1: Figure 5); globally 10·95% of the potentially at-risk population live >1 hour from high-density urban areas, increasing the likelihood of delay-based mortality outcomes after envenoming.

Separating the populations living within species ranges by HAQ Index decile reveals large differences across the sociodemographic spectrum (Figure 3). Such differences are best highlighted when analysing populations by medical classification: 92·91% of the population within the lowest HAQ Index decile (approximately 389·58 million individuals) are at risk of exposure to a Category one snake, compared to 86.27% within the highest decile (approximately 1·612 billion individuals) (Supplementary File 1: Figure 4). Furthermore, 65·25% of the population within the lowest decile (272·91 million individuals) are at risk of exposure to any snake for which no effective therapy exists, compared to 27·79% (519·46 million individuals) within the highest HAQ Index decile (Figure 3).

To first identify vulnerable populations, geographic regions were highlighted where people living within the range of any snake species also lived more than three hours away from major urban centres, had health systems that scored within the lowest three deciles of the HAQ Index (Figure 5), and further stratified by the presence or absence of a WHO listed antivenom. Vulnerability estimates for HAQ Index deciles 1-10 are provided as Supplementary File 1: Figure 6. Within the lowest three deciles, we highlight regions where close to 93 million vulnerable individuals live (92.66 million, Table 1), with India, Indonesia, Ethiopia, and the Democratic Republic of the Congo ranking as the highest locations in absolute numbers. The majority of countries across Africa, many of which have some of the lowest scores on the HAQ Index, have vulnerable populations present.

# Discussion

Understanding the distribution of venomous snakes and their potential burden on health systems at national, regional, and global levels is vital for effective reduction and control of snakebite.8 By combining species range maps, available information on antivenoms, and measures of quality of and distance to health care, this study provides global contemporary maps of vulnerable populations for snakebite and its clinical complications. This analysis therefore provides a means of identifying communities in greatest need of support from herpetologists, clinicians, and public health experts alike and where to prioritise new data-collection activities.

While this analysis is not a substitute for a full global burden estimation process, there is overlap between vulnerable communities and existing burden estimates, with vulnerable countries such as Nigeria, Benin, Congo, Myanmar, and Papua New Guinea identified as burdensome in country-specific estimates,1 and South Asia and sub-Saharan Africa as regions with considerable mortality and morbidity.3 Comparing countries based upon vulnerability status shows that for vulnerable countries, national envenoming and death burden values were more likely to be estimates, as opposed to data-driven numbers (χ2 test at 90% significance, p=0.0476 [envenoming] and p=0.0517 [deaths]).3 Chippaux (2011) similarly shows that where data is available in sub-Saharan nations, it is not necessarily contemporary information.38 Where data gaps are present, analyses such as the one presented in this paper can aid in prioritising where to focus next.

These maps collate ecological and public health metrics, and identify opportunities where significant improvements and refinements can be undertaken to move from broad vulnerability assessment to a more nuanced and accurate description of the most burdensome populations.

## *Limitations*

Future efforts can focus on some of the key limitations of this study: quantifying the relative contribution of different snake species, the factors influencing snake-human interactions and subsequent likelihood of envenoming events, as well as snakebite-specific measures of local preparedness, effectiveness, and coverage of existing clinical countermeasures. Paucity of data available at the global scale, despite comprehensive coverage in several highly-developed countries, remains one of the largest limitations throughout this study. These estimates can inform further studies, allowing for the validation and updating of future vulnerability estimates. Ultimately, quantifying these additional components will allow for a move from dependence on global-level datasets and correlations to a bottom-up data synthesis.

Species mapping to reflect variation in snake presence is also critical. Fine-scale maps of American venomous snake species exist39 and should be extended globally - this analysis identifies 216 species requiring updated assessments of current ranges given the quality and quantity of records available. Further, this study establishes a systematic prioritisation based on medical importance (Supplementary File 1: Table 1). While species occurrence surveys can be formally conducted by Public Health initiatives, or during ecological assessments, citizen science plays a complementary role in facilitating broad scale data collection.40

This assessment considers the presence of any one venomous snake as a prerequisite for vulnerability, however different species contribute differently to envenoming risk. Species with a very high incidence of envenoming events, may be the dominant cause of high snakebite burden in a locality,[41](#_ENREF_41) regardless of the presence of other species,[42](#_ENREF_42) as reported for *Echis ocellatus*,[43](#_ENREF_43) *Daboia russelii,*[44](#_ENREF_44) and others.[45](#_ENREF_45) Identifying and quantifying at a local scale the important species, the risky human practices, and ongoing changes to subsequent interactions given climatic and socioeconomic change is necessary.[46](#_ENREF_46)Future vulnerability assessments can explicitly leverage inter-species differences and weight their relative contribution as a function of species-specific envenoming risk and associated burden. The transition of the WHO resource into a living database documenting contemporary antivenom availability, species taxonomic changes, higher-resolution distribution data, and other information will significantly aid in this effort.[47](#_ENREF_47),[48](#_ENREF_48)

Areas where snakes are present can be further evaluated to determine the true incidence of envenoming events. Local-scale household surveys assessing incidence of snakebite have been performed in several countries.[11](#_ENREF_11),[14](#_ENREF_14),[15](#_ENREF_15),[49](#_ENREF_49) . Questions relating to snakebite could also be nested within existing demographic and health surveys,[50](#_ENREF_50) minimising associated costs and informing current data-poor estimates. By integrating preventive measures with existing NTD management systems, many logistical obstacles to effective intervention may be overcome.[51](#_ENREF_51) Corresponding quantification of key risk behaviours will help reflect fine-scale population heterogeneity in exposure. Surveys such as the World Bank Living Standards Measurement Survey series may be utilised to obtain local-scale information on agricultural practices,[52](#_ENREF_52) further aiding the identification of communities most at risk and increasing understanding of the public health consequences of different land use. Through these steps, efforts to prevent envenoming events can be tailored to the specifics of any given population.

In many low- and middle-income countries, a multitude of barriers influence snakebite outcomes including health care, transport, and communications infrastructure, along with adequacy of and access to safe, effective, and affordable antivenom supplies, medical staff proficiency and training, and public health policy. When considering antivenom availability, this method is constrained to listings as reported by WHO.[20](#_ENREF_20) Since initial compilation, new antivenoms have become available (eg, EchiTAb-Plus-ICP),[53](#_ENREF_53) while others have ceased production (eg, Fav-Afrique by Sanofi).[47](#_ENREF_47) Market availability of antivenom products does not translate to in-field availability and efficacy; further information regarding country-specific, contemporary stockpiles and the positioning of antivenom holding centres is required. Given that some of the lowest HAQ deciles have the largest proportions of the population living in areas with snakes for which no antivenom is currently reported, documented socioeconomic differences may amplify inequalities in care.6 While health system indicators and accessibility metrics act as generalised correlates for a location’s ability to respond to cases, this will likely underestimate or overstate local vulnerabilities in some settings. Existing analyses of health systems show variation both nationally and subnationally in treatment seeking behaviours,[54](#_ENREF_54),[55](#_ENREF_55) in quality of primary point of care visits and referrals,[56](#_ENREF_56) and in general practitioner knowledge about the condition.[57](#_ENREF_57) However, the external validity of these existing surveys is unknown. This vulnerability analysis provides a foundation for identifying locations where further surveys of treatment seeking behaviours, quality of care, and existing coverage of antivenom stockpiles and supply chains, need to be assessed.

The global burden of snakebite can be assessed through an approach which integrates ecological information, human behavioural data, and snakebite-specific health system functioning. The impetus to reduce and control the burden of snakebite envenoming, a thorough cataloguing of snake presence and abundance, species-specific interaction profiles with humans, and detailed understanding of logistical hurdles to intervention delivery should be long-term objectives. Contemporary assessments, such as the resources presented, provide an immediate means of identifying key hotspots and most vulnerable communities where the need for such investigations are greatest.

**Contributors**

JL, DMP, and SIH conceived and planned the study. JL wrote the computer code, and designed and carried out the analyses with input from FMS and DMP. DJWe constructed the accessibility covariate data layer. JL produced all output figures. DJWi, DAW, NR, RRdC provided intellectual inputs into aspects of this study. All authors contributed to the interpretation of the results. JL wrote the first draft of the manuscript and all authors contributed to subsequent revisions.

**Declarations of interests**

The authors declare no competing interests.

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# Figures and Tables

**Figure 1. Conceptual overview of vulnerability to snakebite envenoming.** Vulnerability can be considered as the intersection of populations who live within the range of venomous snakes which have no antivenoms available, cannot easily access health care, and have poor-quality health care in delivery of antivenoms or ensuring necessary stocks. The intersection of all three defines the most vulnerable peoples. The figure to the right indicates that these factors vary in space and that by overlaying these features, the most vulnerable populations can be identified spatially (represented here by the boxes outlined in black).

**Figure 2. Venomous snake species ranges, and number of medically important venomous snake species per 5 x 5km location for which no effective therapy is currently listed by WHO.** A: Categories one and two venomous snake species count ranging from low (1) to high (13). Light grey (Panel A), represents locations where no medically important venomous snake species are present; B: Categories one and two venomous snake species with no effective therapy, counts range from low (1) to high (7). Light grey (Panel B) represents locations where snake species present have effective therapies listed by WHO, and dark grey (Panel B) represents locations where no medically important venomous snake species are present.

**Figure 3. Proportion of each HAQ Index decile.** Population living within the range of (left) one or more medically important venomous snake species (either category); (right) one or more medically important venomous snake species (either category), for which no effective therapy is listed.

**Figure 4.** **Average travel time to nearest major city for populations living within snake ranges.** Light grey pixels represent areas without the presence of venomous snake species of medical importance.

**Figure 5.** **Vulnerable population hotspots.** This map indicates the absolute numbers of people living in areas within the range of one or more medically important venomous snake species, and more than three hours away from major urban centres, for HAQ Index deciles 1-3. A: pixel-level vulnerability surface (vulnerability to all species of medically important snakes). B: Aggregated administrative level two vulnerability to all species of medically important venomous snakes. C: Aggregated administrative level two vulnerability to only those species for which no effective therapy is currently listed by WHO.

**Table 1. Vulnerable population count.** Country-level count of vulnerable peoples living within the range of one or more medically important venomous snake species, for which no effective therapy exists, and more than three hours urban centers with a population ≥50 000 provided per HAQ Index decile [ranging from 1 (low) to 10 (high)]. Please see Supplementary File 1 for vulnerability estimates not incorporating antivenom availability.

# Additional Files

**Supplementary file 1:**

**Figure 1. Schematic overview of the methods.** Overview of the methods representing input data (green, snip diagonal corner rectangle), analyses (orange, rectangle), intermediate outputs (blue, rounded rectangle, dashed) and final outputs (yellow, rounded rectangle).

**Table 1: Ranked species requiring range validation.** Species requiring range validation are prioritised based on medical category, number of out-of-range records, and average distance (decimal degrees) of out-of-range records. Species with an asterisk are species for which we provide a recommended amended range within our analysis (see Supplementary File 2 for range visualisations).

**Figure 2: Venomous snake species ranges and their overlap based upon proposed, amended ranges.** A: Categories one and two venomous snake species count ranging from low (1) to high (13); B: Category one venomous snake species count ranging from low (1) to high (8); C: Category two venomous snake species count ranging from low (1) to high (11). Grey represents locations where no venomous snakes within the different aggregations are to be found.

**Figure 3: Numbers of species with no listed antivenom, split by medical importance.** Each panel represents the number of venomous snake species per 5 x 5km cell for which no species-specific antivenom exists. Panel A: Category one medically important species; Panel B: Category two medically important species, ranging from low (blue, 1 species) to high (red, 7 species); Panel C. Both category one and category two medically important species, ranging from low (blue, 1 species), to high (red, 7 species).

**Figure 4: Proportion of each HAQ Index decile population living within ranges of medically important snake species.** A) One or more snake species (either category); B) One or more Category one species; C) One or more Category two species; D) One or more species lacking listed antivenoms (either category); E) One or more Category one species lacking listed antivenoms; F) One or more Category two species lacking listed antivenoms.

**Figure 5: Population time-delay plots, per HAQ Index decile.** Separate plots per HAQ Index decile (1-10), showing the percentage of the population living within n hours from urban centres with a population ≥50 000. Three letter codes represent each countries ISO3 code; numeric values following ISO3 codes (where applicable), represent the Food and Agriculture Organisation (FAO) Global Administrative Unit Layers (GAUL) code (administrative level one).

**Figure 6:** **Vulnerable population hotspots.** This map indicates the absolute numbers of people living in areas within the range of one or more medically important venomous snake species, and more than three hours away from major urban centres, for HAQ Index deciles 1-10. A: pixel-level vulnerability surface (vulnerability to all species of medically important snakes). B: Aggregated administrative level two vulnerability to all species of medically important venomous snakes. C: Aggregated administrative level two vulnerability to only those species for which no effective therapy is currently listed by WHO.

**Table 2:** **Vulnerable population count.** Country-level count of vulnerable peoples living within the range of one or more medically important venomous snake species for which no effective therapy exists and more than three hours urban centers with a population ≥50 000, provided per HAQ Index decile [ranging from 1 (low) to 10 (high)].

**Table 3. Genus inclusion list.**

**Table 4. Covariates used to construct each Multivariate Environmental Similarity Surface.**

**Figure 7. Visualisation of MESS construction and record evaluation process.** Panel A represents a stacked output of 100 MESS iterations, with cell values ranging from 0 to 100, generated using occurrence records within the currently accepted expert opinion range (black outline). Panel B represents a binary version of the stacked output (A), in which cells with a value ≥95 in (A) are classified as being cells of environmental interpolation, and cells <95 in (A) are classified as being cells of environmental extrapolation. Out-of-range records are then overlaid on top of the new binary surface (Panel C), and are classified as being MESS +ve or MESS –ve. Records which are MESS +ve contribute towards a new range recommendation (Panel D).

**Supplementary file 2:**

Species inclusion lists, incorporating species MESS, amended ranges or original EORs, where applicable.

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