Climate change-related distributional range shifts of venomous snakes: a predictive modelling study of effects on public health and biodiversity

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Summary

Background Climate change is expected to have profound effects on the distribution of venomous snake species, including reductions in biodiversity and changes in patterns of envenomation of humans and domestic animals. We estimated the effect of future climate change on the distribution of venomous snake species and potential knock-on effects on biodiversity and public health.

Methods We built species distribution models based on the geographical distribution of 209 medically relevant venomous snake species (WHO categories 1 and 2) and present climatic variables, and used these models to project the potential distribution of species in 2070. We incorporated different future climatic scenarios into the model, which we used to estimate the loss and gain of areas potentially suitable for each species. We also assessed which countries were likely to gain new species in the future as a result of species crossing national borders. We integrated the species distribution models with different socioeconomic scenarios to estimate which countries would become more vulnerable to snakebites in 2070.

Findings Our results suggest that substantial losses of potentially suitable areas for the survival of most venomous snake species will occur by 2070. However, some species of high risk to public health could gain climatically suitable areas for habitation. Countries such as Niger, Namibia, China, Nepal, and Myanmar could potentially gain several venomous snake species from neighbouring countries. Furthermore, the combination of an increase in climatically suitable areas and socioeconomic factors (including low-income and high rural populations) means that southeast Asia and Africa (and countries including Uganda, Kenya, Bangladesh, India, and Thailand in particular) could have increased vulnerability to snakebites in the future, with potential effects on public human and veterinary health.

Interpretation Loss of venomous snake biodiversity in low-income countries will affect ecosystem functioning and result in the loss of valuable genetic resources. Additionally, climate change will create new challenges to public health in several low-income countries, particularly in southeast Asia and Africa. The international community needs to increase its efforts to counter the effects of climate change in the coming decades.

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Introduction

In the coming decades, climate change will continue to have various effects on global biodiversity, including the geographical redistribution of many species.[1,2] Climate-driven distributional range shifts are expected to differ across regions and species, could involve the expansion, contraction, or displacement of geographical range limits, and could even lead to the extinction of some species and lineages.[2,3] Redistribution of and reductions in biodiversity will have negative effects on basic ecosystem services, with effects on human wellbeing, including risks to food security.[4] Furthermore, biodiversity declines could result in the loss of valuable genetic resources and generate new interactions between humans and various vectors, pathogens, and venomous animals (eg, spiders, scorpions, snakes) in rural and urban settings.[5–7]

Venomous animals are a source of concern for human and veterinary health.[8–10] Every year, millions of envenomings via animal bites and stings occur worldwide, sometimes causing deaths and long-term physical and psychological sequelae.[8–10] Snakebite envenoming has been classified as a neglected tropical disease by WHO.[11] Annually, between 81 000 and 138 000 people are estimated to die and around 400 000 to be left with permanent disabilities as a results of snakebites, mainly in east Asia, sub-Saharan Africa, and in the Neotropical region.[8] Snakebites predominantly affect farmers and young rural workers in low-income countries,[12,13] and contribute to the reinforcing of the cycle of poverty.[13]

Research in context

Evidence before this study

Although we did not do a formal search of published work to identify relevant theoretical work, we searched the Global Biodiversity Information Facility for species occurrence data up to May 1, 2023. Venomous snakes play an important role in ecosystems and in contributing to human health (eg, zoonoses control, biotechnological and pharmaceutical development). Nonetheless, venomous snakes are also a major public health concern in tropical countries. Previous studies have shown that species distribution models are a powerful tool for studying the distribution of venomous snakes and have quantified the effect of climate change on the distribution patterns of species. However, such studies centred only on particular species or regions of the planet. Furthermore, no studies have integrated future climatic scenarios with socioeconomic scenarios, which are fundamental to understand and quantify the vulnerability of countries to snakebites.

Added value of this study

Our global analysis is the first, to our knowledge, to predict how climate change will affect the future (ie, in 2070) distribution of medically important venomous snakes at the species level, including highlighting instances where countries are likely to gain new snake species from neighbouring nations. Our analysis takes into consideration the dispersion potential of snake species and possible geographical barriers that limit species dispersion and also incorporated socioeconomic factors, which enabled us to predict that low-income countries in Africa and east and southeast Asia are likely to bear the brunt of increase in species richness (and the associated increased risk of envenomation).

Implications of all the available evidence

We projected that the effects of loss of biodiversity due to climate change and associated changes in the distribution of venomous snakes will be most pronounced in tropical regions, where extensive land is devoted to agriculture and rearing livestock, which increases the risk of snakebites in rural communities. Interventions from regional health authorities and the international community will be essential to maintain the ecological balance and assist low-income countries in facing new challenges to public health due to climate change.

In addition, snakebite envenoming is a crucial veterinary issue: it is associated with major loss of livestock, which has severe economic consequences and worsens the food crisis for families and communities in the poorest rural areas.[14]

Among the more than 2500 species of advanced snakes (superfamily Colubroidea), WHO has classed 109 species as the medically most relevant (ie, category 1), and an additional 142 species have been classed as medically important, but to a lesser degree (ie, category 2).[15] The abundance and geographical distribution of venomous snakes is likely to vary as a result of climate change and habitat transformation.[6] Xeric shrublands and grasslands are expected to expand in the coming decades,[16] and as a result the snake species associated with these habitats that have the capacity to tolerate or adapt to agricultural environments could increase their abundance locally and expand their geographical ranges.[17] Such range shifts could expand the habitats of some venomous species into new countries, potentially biting people and livestock in countries where such envenomation did not previously occur. Therefore, range shifts in venomous snakes could become a substantial challenge for public health systems in low-income countries, with potential complications in clinical management if the coverage of antivenoms is insufficient or if clinicians lack experience of treating snakebites.[6]

Other snake species could experience range contractions, leading to population declines or even extinction. Forest-dwelling species (which account for roughly 75% of species) are expected to be particularly vulnerable to threats such as logging, agricultural expansion, extractive activities, and urban development.[18] Venomous snakes play key roles in ecosystem structure and functioning: they are implicated in secondary seed dispersal and are essential components in food webs.[19–21] As prey, snakes constitute the primary diet of numerous mammals, birds, and other snakes. As predators, they control the population of several prey species, including rodents that transmit zoonotic diseases and damage crops and grains.[22] Additionally, snake venoms have potential uses in health care—eg, in the development of drugs and treatments for various diseases.[23] Thus, habitat loss or the extinction of venomous snake species could lead to irreparable damage to ecosystems and to human health and wellbeing.

Several studies[12,24] have applied modelling approaches to analyse the geographical ranges of venomous snakes and forecast future distributional changes in various geographical and climatic settings. In light of potential range shifts in the distribution of venomous snakes as a result of climate change, we aimed to use predictive modelling techniques to forecast the spatiotemporal dynamics in the distributional ranges of the snake species that are considered the highest risk to public health (ie, WHO categories 1 and 2) under different future climate scenarios. Furthermore, we aimed to identify which countries might gain new venomous snake species and which countries could be particularly vulnerable to snakebites in the future.

Methods

Study design and data sources

For this predictive modelling study, we used distribution data from the Global Biodiversity Information Facility. We aimed to include all 251 species of snakes of medical importance according to WHO, but the necessary data were available for only 209 species (ie, species with at least eight non-duplicated occurrence records—a standard cutoff for species distribution modelling): 94 category 1 species and 115 category 2 species (appendix pp 2–7). These species belonged to the subfamilies Viperinae and Crotalinae from the family Viperidae, Atractaspidinae from the family Lamprophiidae, and Elapinae and Hydrophiinae from the family Elapidae. In cases when the distribution range of a species encompassed more than one country and the species was classed differently in these countries, for our analyses the species was put in category 1. We filtered occurrence data with the CoordinateCleaner[25] package in R (version 4.2.1) to remove erroneous records (eg, capital cities, country centroids, zoos, ocean points), duplicate records (occurrences within each cell), and coordinates with more than 5 km uncertainties. Additionally, we inspected the data species by species to remove any records outside the known distribution area for each species.

Species distribution modelling

Species distribution models use occurrence data and the association between these data and local bioclimatic conditions to characterise the ecological preferences of species. These models can be projected across geographical areas with different climatic conditions (eg, future climate scenarios) to predict potentially suitable areas for the survival and reproduction of species. Species distribution models provide continuous measures of climatic suitability, which can be considered a proxy for the abundance of species. They are thus used to predict future changes in abundances and distributions of species.[2,3]

To build the species distribution models, we used temperature and precipitation variables from WorldClim at a resolution of 2·5 arcmins (5 km x 5 km). To avoid high correlation levels between climatic variables, we retained only variables with Pearson correlation values of less than the modulus of 0·7 for model building (appendix p 7). The same subset of bioclimatic variables was used for all species. Our approach was based on a maximum entropy algorithm as implemented in Maxent (version 3.4.4); details of optimisation of the species distribution models are in the appendix (p 1).[26] We used Maxent to model species distribution (rather than other algorithms such as Random Forest or General Linear Model), because it has previously been used effectively for squamates with scarce occurrence records[27] and has been widely used in snake distribution modelling.[28,29] Species distribution models were projected for 2070 with the general circulation models MIROC, HadGEM, MPI, MRI, and BCC under three Intergovernmental Panel on Climate Change representative concentration pathways (RCPs): RCP2.6-SSP1, RCP4.5-SSP2, and RCP8.5-SSP5. To estimate the areas with better climatic suitability for a higher number of venomous snake species (ie, species richness) in the present and future, we summed the suitability of each species calculated for each of the grids on the continuous probability maps, and then estimated the mean and SD of species richness among the five general circulation models (appendix p 8). Because the SD among the general circulation models was low (appendix p 8), we present only the MIROC6 models throughout the main text.

For more on **Global Biodiversity Information Facility** see https://www.gbif.org/

See **Online** for appendix

Data analysis

We assessed at the species level the proportion of potential area that each species could lose or gain in the future (ie, in 2070) within their biogeographical region. Continuous probability maps generated by Maxent were transformed into a binary system, where values of absence (0) and presence (1) were assigned below and above a threshold. To set the threshold, we used the 10% percentile criterion.[30] We used the present and future binary maps to estimate the proportion of the lost or gained area compared with the potential original area in each biogeographical region.

For each cell grid on the map, we quantified the difference in the sum of suitabilities (ie, species richness) between the future and present scenarios. For each country, we estimated the mean species richness lost or gained by 2070. Because snakebites are particularly common in low-income countries and in farming and pastoral communities,[8,14] we integrated climate projections with socioeconomic scenarios. We combined the climatic scenario assessments with socioeconomic projections for 2070 (RCP2.6-SSP1, RCP4.5-SSP2, and RCP8.5-SSP5) to predict which countries will have more suitable areas for snake species (thereby presenting a risk to public health). We estimated the average density of the rural population, and the proportion of total area used for annual C3 plantations, C3 perennial plantations, C4 annual plantations, and C4 perennial plantations, and for livestock rearing for each country. Rural population density data were obtained from Jones and O'Neill (2016),[31] and land-use data for agricultural plantations and livestock from Land-Use Harmonization (as described in Popp and colleagues, 2017).[32] Our results were presented in relation to the most recent available data for each country's gross domestic product per person (as of Sept 1, 2023).

To calculate the number of snake species that could cross country borders, we used the binary maps to quantify for each country the species that were unlikely to be documented in the present (absence) but had a high probability of being documented in the future (presence). To assign new species to a country in the future, new areas had to be in an adjacent country not more than 750 km linearly from the original area. Knowledge of snake

For more on **WorldClim** see https://www.worldclim.com/

For more on **Land-Use Harmonization** see https://luh.umd.edu

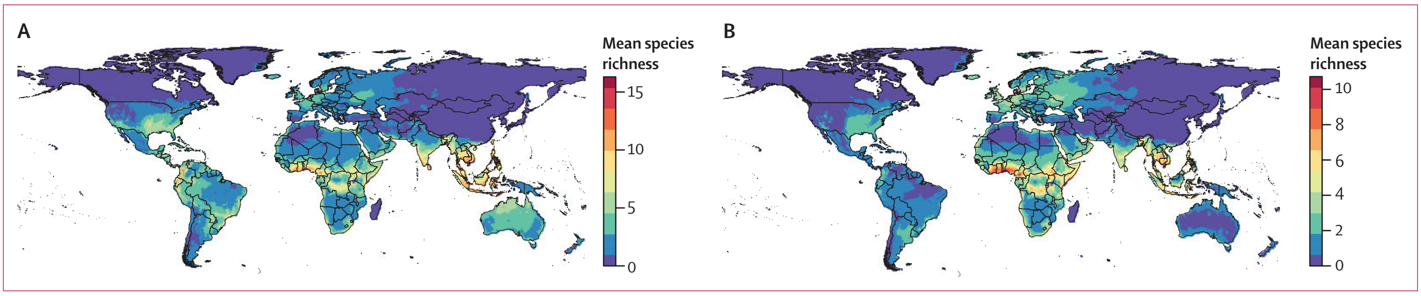

Figure 1: **Mean species richness of all category 1 and 2 snake species (A) and of category 1 species only (B) globally, 2070**
The map shown is for scenario RCP-8.5-SSP5 (2070), among five general circulation models (MIROC, HadGEM, MPI, MRI, and BCC). Mean species richness is represented by the sum of suitability.

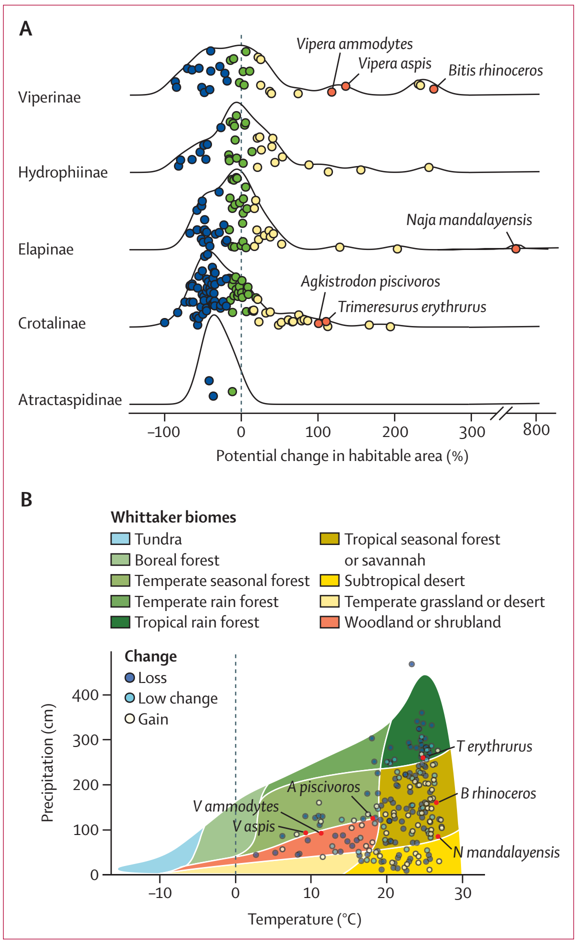

Figure 2: **Effects of climate change on the potential habitable areas for venomous snakes, 2070**
Potential area change for species within their biogeographical regions, grouped by subfamily (A). Biomes in which snake species decrease or increase their potential area of distribution (B). The graphs shown are for scenario RCP-8.5-SSP5. In both (A) and (B), loss describes a loss of at least 10% of distribution area, low change means less than 10% loss or gain of distribution area, and gain means an increase of at least 10% of distribution area. The labelled red dots represent category 1 species with the greatest potential to increase their distribution area.

species' home range and dispersal distances is still poor, and these factors can vary a lot intraspecifically (depending on sex), interspecifically, and according to the time of the year.[33–35] Species in the families Elapidae and Viperidae can move up to 300 m per day, accounting for more than 100 km per year, and more than 5000 km over 50 years.[36] Therefore, our 750 km estimate could be considered a conservative approach, with a maximum distance of 15 km moved per year. Additionally, this range also took into account the presence of strong geographical barriers, such as mountains and bodies of water, which would prevent snake dispersion.

Role of the funding source

The funders had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Our projections of future climatic suitability for the 209 included category 1 and 2 snake species showed that total species richness in 2070 was highest in South America, Africa, and south and southeast Asia (figure 1A; appendix pp 8–9). In South and Central America, high mean species richness was projected for Ecuador, northwest Colombia, Peru, a portion of the south, southeast, and northeast coast of Brazil, Panama, Costa Rica, Nicaragua, Guatemala, part of western Venezuela and Honduras, southern Mexico and Paraguay, and northeastern Argentina (figure 1A). In Africa, the highest mean species richness was projected for Ghana, Togo, Côte d'Ivoire, Benin, southern Nigeria, Cameroon, southern DR Congo, western Central African Republic, Uganda, Rwanda, Burundi, part of South Sudan, the Somalian coast, northwest Kenya, and the coast and south of Tanzania. In south and southeast Asia, high species richness was predicted mainly in southern and northeastern India, Bangladesh, Myanmar, Sri Lanka, Thailand, Viet Nam, Cambodia, Laos, the Philippines, central and western Indonesia, Malaysia, Brunei, and Timor-Leste (figure 1A). For projections of category 1 snake species only, mean species richness remained high in sub-Saharan Africa and in southeast Asia, but decreased in South America compared with projections of category 1 and 2 species richness (figure 1B). When projections were restricted to category 1 snakes, mean species richness also fell substantially in Australia (figure 1B).

When we compared the change in species richness over time, we projected that the most species will be lost in the Amazon region in South America and in southern Africa (appendix p 8). By contrast, regions of the eastern USA, northern Europe, and southeast Asia will gain substantial numbers of snake species (appendix p 8).

By 2070, we projected that climate change could result in the loss of habitable area for all snake subfamilies within their biogeographical regions (figure 2A). Some Viperinae (*Atheris squamigera*, *Montivipera xanthina*, and *Pseudocerastes fieldi*), Crotalinae (*Porthidium nasutum*, *Bothrops brazili*, and *Protobothrops elegans*), and Hydrophiinae (*Acanthophis pyrrhus* and *Austrelaps labialis*) were projected to lose more than 70% of their potential areas (figure 2A). Conversely, around 50% of species in the subfamily Viperinae were predicted to substantially gain climatically suitable potential areas (figure 2A). Three category 1 Viperinae—*Bitis rhinoceros* (251% increase), *Vipera aspis* (136% increase), and *Vipera ammodytes* (118% increase) had the highest increases in potentially suitable habitable areas (figure 2A). Likewise, some category 1 species in the Crotalinae and Elapinae subfamilies are also projected to substantially gain potentially suitable areas (figure 2A; appendix pp 2–7).

We projected that countries with extensive agricultural and livestock areas and lower gross domestic products would gain snake richness in 2070 (figure 3; appendix pp 10–11). Countries predicted to have an increase in snake species richness also had high rural population density, especially Bangladesh, Nepal, and Pakistan in

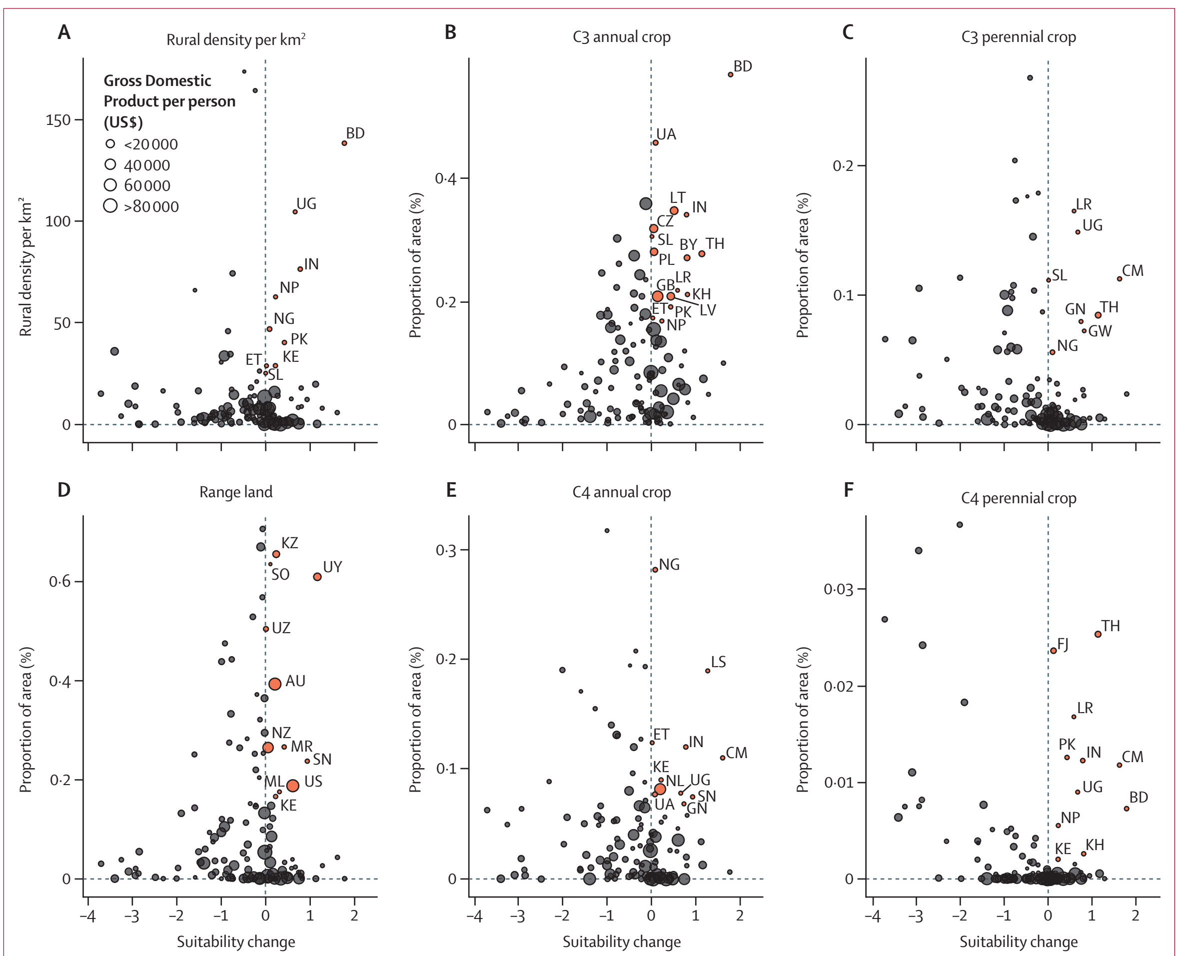

***Figure 3:* Projected vulnerability of countries to snakebites, by rural population and agricultural land use, 2070**

Depicted are scatterplots of the mean change in suitability of areas for habitation by venomous (category 1 and 2) snakes in climate scenario RCP8.5-SSP5 by mean density of rural population (A), and by the proportion of total country area devoted to C3 annual crops (B), C3 perennial crops (C), livestock land (D), C4 annual crops (E), and C4 perennial crops (F). Red dots represent the countries with gains in future climatic suitability for snake habitation that are in the upper quartile in each land-use category. AU=Australia. BD=Bangladesh. BY=Belarus. CM=Cameroon. CW=Curaçao. CZ=Czechia. ET=Ethiopia. FJ=Fiji. GB=UK. GN=Guinea. GW=Guinea-Bissau. IN=India. KE=Kenya. KH=Cambodia. KZ=Kazakhstan. LR=Liberia. LS=Lesotho. LT=Lithuania. LV=Latvia. ML=Mali. MR=Mauritania. NG=Nigeria. NL=the Netherlands. NP=Nepal. NZ=New Zeland. PK=Pakistan. PL=Poland. SL=Sierra Leone. SN=Senegal. SO=Somalia. TH=Thailand. UA=Ukraine. UG=Uganda. US=USA. UY=Uruguay. UZ=Uzbekistan.

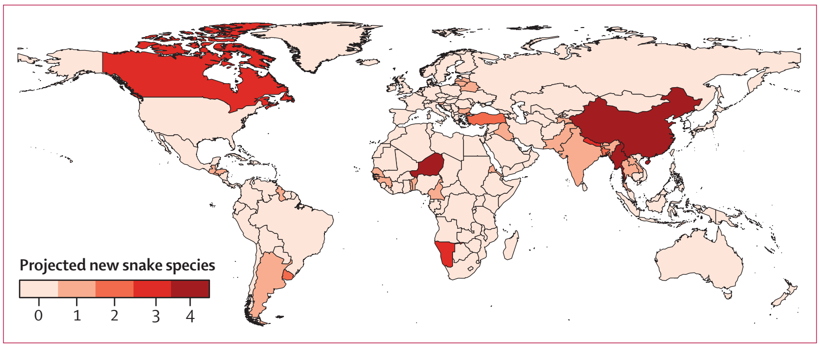

Figure 4: **Potential number of new snake species in each country, 2070**
The map shown is for scenario RCP-8.5-SSP5.

Asia, and Uganda and Kenya in Africa (figures 1A, 3A). Countries such as Bangladesh, India, Thailand, Uganda, Kenya, Liberia, Cameroon, Ukraine, and Lithuania were projected to have increases in snake richness in extensive agricultural areas (figures 1A, 3B, C). Nearly all of the largest production areas for annual (figure 3E) and perennial (figure 3F) C4 plants in 2070 were predicted to be in countries with low gross domestic products. For annual C4 plantations, Nigeria, Lesotho, and Cameroon are among the countries predicted to be most vulnerable to venomous snake bites due to increased species richness (figure 3E), whereas in terms of perennial C4 crops, Thailand, India, Pakistan, Bangladesh, Cameroon, Uganda, and Liberia are among the countires projected to be increasingly vulnerable (figure 3F). Some countries with low gross domestic products and high cattle production are also projected to have an increase in snake richness, including Somalia, Mali, Kenya, and Mauritania (figure 3D).

The countries projected to be most likely to gain new snake species from neighbouring countries were in Asia and Africa (figure 4). China, Myanmar, and Nepal were estimated to gain up to four new species each (figure 4). In Africa, the biggest gains in new species were predicted to occur in Niger and Namibia, and the highest number of species were predicted to cross country borders in west Africa more broadly (figure 4). The species predicted to have the potential to cross the greatest number of country borders in southeast Asia was *Naja mandalayensis* and in west Africa was *B rhinoceros*. Meanwhile, some species of venomous snakes that are associated with a high number of envenoming (eg, *Bothrops asper*, *Daboia russelii*, *Naja naja*, *Echis ocellatus*, and *Naja nigricollis*) will have an increase in climatically suitable areas, but were not projected to cross country borders (appendix pp 12–14).

Discussion

Climate change can substantially modify the distribution of biomes worldwide[16] and of the species that inhabit them.[2] Our predictive modelling approach provides information about the potential effects of climate change on the geographical distribution of medically important venomous snake species (WHO categories 1 and 2) worldwide. The integration of species distribution models with future climatic and socioeconomic scenarios enabled us to predict that climate change will have the greatest effect on the distribution of venomous snakes in low-income countries that are likely to contain extensive areas for agriculture and livestock rearing. Our findings suggest that climate change will lead to the loss of species in some countries and the gain of new species in others, with implications for both public health and conservation.

By 2070, South America and southern Africa are predicted to be the regions with the highest losses in venomous snake species. Both regions are also projected to have high rates of snake habitat loss which, in addition to the predicted impact of climate change, could produce profound effects on biodiversity.[22] Our predictions align with trends in the decline of tetrapods, including reptiles.[18] Low-income countries generally have fewer conservation programmes and more knowledge shortfalls about venomous snakes than do higher-income countries,[22] which limits the ability to develop strategies to mitigate and adapt to these effects of climate change.

When we analysed only species in WHO category 1, our results suggested increased climatic suitability for many species south of the Sahara and in southeast Asia in 2070. These regions already have the highest snakebite incidence and mortality,[8,37,38] and thus changes in the species composition of category 1 venomous snakes could have serious consequences in communities that are already vulnerable. The risks of mortality and disability in resident populations could increase, since many of these regions have restricted access to medical treatment after snakebites because of poor infrastructure, poor-quality treatment centres, transportation issues, low confidence in medical services, and poor availability and accessibility of effective antivenoms.[39] The availability of effective antivenoms could be particularly uncertain in cases in which snake species have been predicted to migrate to countries that they were previously not found in.[38,40] Furthermore, shifts in the geographical distribution of snakes are likely to increase envenomings of domestic animals, with negative social and economic outcomes.

Ecosystem health and human wellbeing are at risk from climate change.[6,41] Thousands of endangered species could become extinct in the coming decades.[18] Among reptiles, snakes are the main lineage of predators and fulfil a key role in the structure and functioning of ecosystems.[42] Additionally, venomous snakes are a highly important source of resources for pharmaceutical and biotechnological developments.[43] However, our models predicted that potentially suitable habitats for many venomous snakes will be substantially reduced. Such potential loss of venomous snake species could be even larger than estimated, because snakes are among the vertebrate lineages with the most evident Linnean shortfall (ie, low knowledge about living species).[44] Range contractions will be more intense in biomes with high temperatures and high precipitation, such as tropical rainforests, which is of great concern because such biomes have the highest diversity of venomous snakes and also represent the largest gaps in knowledge of extant biodiversity.[44] Therefore, the reduction of potentially suitable areas and the consequent reduction or extinction of snake populations or lineages could greatly alter ecosystem dynamics.

Our results suggest that several low-income countries in southeast Asia and Africa will become more climatically suitable for venomous snakes by 2070, and will have large expanses of agricultural and livestock areas. A previous study[45] in southeast Asia showed an increase in the incidence of snakebite envenoming during the monsoon periods for various reasons, but generally the floods associated with these periods increase the likelihood of encounters between snakes and humans as snakes seek shelter in drier places. According to the 2022 report of the UN's Intergovernmental Panel on Climate Change,[46] the increase in global temperatures will raise the risk of floods during the monsoon periods in southeast Asia. Likewise, floods are likely to become more common in other regions of the world with a high incidence of snakebites.[47] Thus, the risk of snakebites could increase even further.

Not only humans are likely to be affected by the predicted shifts in the distribution of venomous snake species. The incidence of envenomings of domestic animals is also likely to rise, with negative social and economic outcomes. Snakebites in livestock are of high concern in Africa, Asia, and Latin America, where rural communities depend on these animals as a direct source of income and food.[14] The loss of livestock and the resulting reduced agricultural productivity could impair the subsistence of these rural populations.[14,48]

Our results suggest that venomous snake species could expand their geographical distributions and cross political borders, thus invading countries where they are currently absent. We estimated that Nepal, China, Myanmar, Niger, and Namibia are likely to receive the highest number of new species by 2070. This scenario implies new public health challenges for these and other countries (mainly low-income ones). Snake venoms vary greatly within and between species, which complicates the design of antivenoms and limits the therapeutic efficacy of these treatments.[49] Therefore, the antivenoms generally used in those countries might not be effective for the neutralisation of the venoms of the introduced species, an issue that needs to be carefully considered by antivenom manufacturers and regulatory agencies.

Of the analysed species, *B rhinoceros* and *N mandalayensis* presented the highest potential to cross several borders between countries. *B rhinoceros* is distributed from Guinea to Togo in western Africa, whereas *N mandalayensis* is endemic to the central zone of Myanmar, inhabiting the acacia savannah and the Indaing forest (a seasonally dry tropical forest).[50] As a consequence of climate change, dry areas of the planet (to which these species are adapted) will expand.[16,51] The expansion of climatically suitable areas for *B rhinoceros* and *N mandalayensis* could increase the overlap between these species and human settlements, which could result in more snakebites. Meanwhile, among venomous snakes associated with a high toll of envenomings, deaths, and disabilities, our models suggest that climatically suitable areas for *B asper*, *D russelii*, *N naja*, *E ocellatus,* and *N nigricollis* will increase. Although these species are not predicted to cross borders, the expansion to areas with high climatic suitability could increase the number of snakebite envenomings.

Our study had several limitations. The models used in this study are based on an analysis of bioclimatic conditions and their predicted variations due to trends in climate change. However, additional variables are likely to also have a role in these future scenarios, including complex biotic factors (eg, changes in prey availability as a consequence of habitat destruction and diseases,[52] expanded distribution of snake predators, indiscriminate killing of some snake species by humans). Moreover, areas that we predicted could provide suitable climatic areas in 2070 might not be reached by species because of interspecific competition or simply because of the low potential of snake species dispersion. Similarly, deforestation can also modify the landscape structure, hindering the dispersion of specialist species, which are more vulnerable to anthropogenic impacts.[53] Additionally, stochastic factors, such as natural disasters, wars, and infectious pandemics can affect the future distribution of snake species, potentially limiting the predictive power of our models.

Overall, our findings emphasise that renewed regional and global efforts are needed to strengthen scientific research and conservation policies, particularly in countries that are likely to have the heaviest losses in snake species. Furthermore, the trans-border shift in snake habitats that we projected will necessitate collaboration between neighbouring countries, regional health authorities, and the international community, to ensure that low-income countries will be able to effectively face these new risks to public health due to climate change.

Contributors
PAM, TFA, MAO-T, and JMG conceived the study. PAM, IBdFT, TS-S, FFBdS, LAGL, and JC-S gathered the data, which were analysed by PAM. All authors had access to all study data, which were verified by PAM, IBdFT, TS-S, FFBdS, LAGL, JC-S, and TFA. PAM, IBdFT, TS-S, FFBdS, LAGL and JC-S wrote the first draft of the Article, which was revised by all authors. PAM was responsible for the final decision to submit the Article for publication.

Declaration of interests
We declare no competing interests.

Data sharing
All study data are available in publicly accessible databases (see Methods) and the appendix. For other data or codes, contact the corresponding authors.

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References

1 Chen IC, Hill JK, Ohlemüller R, Roy DB, Thomas CD. Rapid range shifts of species associated with high levels of climate warming. *Science* 2011; **333:** 1024–26.

2 Titley MA, Butchart SHM, Jones VR, Whittingham DMJ, Willis SG. Global inequities and political borders challenge nature conservation under climate change. *Proceed Natl Acad Sci USA* 2021; **118:** e2011204118.

3 Pecl GT, Araújo MB, Bell JD, et al. Biodiversity redistribution under climate change: impacts on ecosystems and human well-being. *Science* 2017; **355:** eaai9214.

4 Exposito-Alonso M, Booker TR, Czech L, et al. Genetic diversity loss in the Anthropocene. *Science* 2022; **377:** 1431–35.

5 Martinez PA, Andrade MA, Bidau CJ. Potential effects of climate change on the risk of accidents with poisonous species of the genus *Tityus* (Scorpiones, Buthidae) in Argentina. *Spat Spatiotemporal Epidemiol* 2018; **25:** 67–72.

6 Martinez PA, Gutiérrez JM, Olalla-Tárraga MÁ, Amado TF. Venomous animals in a changing world. *Glob Chang Biol* 2022; **28:** 3750–53.

7 McMichael AJ, Woodruff RE, Hales S. Climate change and human health: present and future risks. *Lancet* 2006; **367:** 859–69.

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

9 Chippaux JP, Goyffon M. Epidemiology of scorpionism: a global appraisal. *Acta Trop* 2008; **107:** 71–79.

10 Isbister GK, Fan HW. Spider bite. *Lancet* 2011; **378:** 2039–47.

11 Gutiérrez J. Snakebite envenomation as a neglected tropical disease. New impetus for confronting an old scourge. In: Machessy S, ed. Handbook of Venoms and Toxins of Reptiles, 2nd edn. Boca Raton, FL: CRC Press, 2021: 471–83.

12 Pintor AFV, Ray N, Longbottom J, et al. Addressing the global snakebite crisis with geo-spatial analyses—recent advances and future direction. *Toxicon X* 2021; **11:** 100076.

13 Harrison RA, Hargreaves A, Wagstaff SC, Faragher B, Lalloo DG. Snake envenoming: a disease of poverty. *PLoS Negl Trop Dis* 2009; **3:** e569.

14 Bolon I, Finat M, Herrera M, et al. Snakebite in domestic animals: first global scoping review. *Prev Vet Med* 2019; **170:** 104729.

15 WHO. WHO guidelines for the production, control and regulation of snake antivenom immunoglobulins. Geneva: World Health Organization, 2017.

16 Boonman CCF, Huijbregts MAJ, Benítez-López A, Schipper AM, Thuiller W, Santini L. Trait-based projections of climate change effects on global biome distributions. *Divers Distrib* 2022; **28:** 25–37.

17 Martín G, Erinjery J, Gumbs R, et al. Integrating snake distribution, abundance and expert-derived behavioural traits predicts snakebite risk. *J Appl Ecol* 2022; **59:** 611–23.

18 Cox N, Young BE, Bowles P, et al. A global reptile assessment highlights shared conservation needs of tetrapods. *Nature* 2022; **605:** 285–90.

19 Beri D, Bhaumik S. Snakes, the ecosystem, and us: it's time we change. New Delhi: George Institute for Global Health, 2021.

20 Schuett GW, Reiserer RS, Salywon AM, et al. Secondary seed ingestion in snakes: germination frequency and rate, seedling viability, and implications for dispersal in nature. *Front Ecol Evol* 2022; **9:** 761293.

21 Reiserer RS, Schuett GW, Greene HW. Seed ingestion and germination in rattlesnakes: overlooked agents of rescue and secondary dispersal. *Proceed Biol Sci* 2018; **285:** 20172755.

22 Mullin S, Seigel R. Snakes: ecology and conservation. New York, NY: Comstock Publishing, 2009.

23 Oliveira AL, Viegas MF, da Silva SL, Soares AM, Ramos MJ, Fernandes PA. The chemistry of snake venom and its medicinal potential. *Nat Rev Chem* 2022; **6:** 451–69.

24 Nori J, Carrasco PA, Leynaud GC. Venomous snakes and climate change: ophidism as a dynamic problem. *Clim Change* 2014; **122:** 67–80.

25 Zizka A, Silvestro D, Andermann T, et al. CoordinateCleaner: standardized cleaning of occurrence records from biological collection databases. *Methods Ecol Evol* 2019; **10:** 744–51.

26 Phillips SJ, Dudík M. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. *Ecography* 2008; **31:** 161–75.

27 Pearson RG, Raxworthy CJ, Nakamura M, Peterson AT. Predicting species distributions from small numbers of occurrence records: a test case using cryptic geckos in Madagascar. *J Biogeography* 2006; **34:** 102–17.

28 Yañez-Arenas C, Townsend Peterson A, Rodríguez-Medina K, Barve N. Mapping current and future potential snakebite risk in the new world. *Clim Change* 2016; **134:** 697–711.

29 Andrade-Díaz MS, Sarquis JA, Loiselle BA, Giraudo AR, Díaz-Gómez JM. Expansion of the agricultural frontier in the largest South American dry forest: identifying priority conservation areas for snakes before everything is lost. *PLoS One* 2019; **14:** e0221901.

30 Escalante T, Rodriguez-Tapia G, Linaje M, Illoldi-Rangel P, González-López R. Identification of areas of endemism from species distribution models: threshold selection and neartic mammals. *Revista Especializada en Ciencias Químico-Biológicas* 2013; **16:** 5–17.

31 Jones B, O'Neill BC. Spatially explicit global population scenarios consistent with the shared socioeconomic pathways. *Environ Res Lett* 2016; **11:** 084003.

32 Popp A, Calvin K, Fujimori S, et al. Land-use futures in the shared socio-economic pathways. *Glob EnvironChange* 2017; **42:** 331–45.

33 Brito JC. Seasonal variation in movements, home range, and habitat use by male *Vipera latastei* in northern Portugal. *J Herpetol* 2003; **13:** 155–60.

34 Hart KM, Cherkiss MS, Smith BJ, et al. Home range, habitat use, and movement patterns of non-native Burmese pythons in Everglades National Park, Florida, USA. *Animal Biotelemetry* 2015; **3:** 8.

35 Todd BD, Nowakowski AJ. Ectothermy and the macroecology of home range scaling in snakes. *Glob Ecol Biogeography* 2021; **30:** 262–76.

36 Macartney JM, Gregory PT, Larsen KW. Society for the Study of Amphibians and Reptiles: a tabular survey of data on movements and home ranges of snakes. *J Herpetol* 1988; **22:** 61–73.

37 Kasturiratne A, Wickremasinghe AR, De Silva N, et al. The global burden of snakebite: a literature analysis and modelling based on regional estimates of envenoming and deaths. *PLoS Med* 2008; **5:** 1591–604.

38 GBD 2019 Snakebite Envenomation Collaborators. Global mortality of snakebite envenoming between 1990 and 2019. *Nat Commun* 2022; **13:** 6160.

39 Chippaux JP. Snakebite in Africa. Current situation and urgent needs. In: Chippaux J-P, ed. Handbook of venoms and toxins of reptiles. Boca Raton, FL: CRC Press, 2021: 593–611.

40 Rashmi U, Khochare S, Attarde S, et al. Remarkable intrapopulation venom variability in the monocellate cobra (*Naja kaouthia*) unveils neglected aspects of India's snakebite problem. *J Proteomics* 2021; **242:** 104256.

41 Díaz S, Settele J, Brondízio ES, et al. Pervasive human-driven decline of life on Earth points to the need for transformative change. *Science* 2019; **366:** eaax3100.

42 Nowak EM, Theimer TC, Schuett GW. Functional and numerical responses of predators: where do vipers fit in the traditional paradigms? Biol Rev 2008; **83:** 601–20.
43 Bordon K de CF, Cologna CT, Fornari-Baldo EC, et al. From animal poisons and venoms to medicines: achievements, challenges and perspectives in drug discovery. *Front Pharmacol* 2020; **11:** 01132.
44 Moura MR, Jetz W. Shortfalls and opportunities in terrestrial vertebrate species discovery. *Nat Ecol Evol* 2021; **5:** 631–39.
45 Ochoa C, Bolon I, Durso AM, et al. Assessing the increase of snakebite incidence in relationship to flooding events. *J Environ Public Health* 2020; **2020:** 6135149.
46 Portner H-O, Roberts D, Tignor M, et al. Climate change 2022: impacts, adaptation and vulnerability. 2022. https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ (accessed Sept 1, 2023).
47 Chaves LF, Chuang TW, Sasa M, Gutiérrez JM. Snakebites are associated with poverty, weather fluctuations, and El Niño. *Sci Adv* 2015; **1:** e1500249.
48 Bolon I, Babo Martins S, Ochoa C, et al. What is the impact of snakebite envenoming on domestic animals? A nation-wide community-based study in Nepal and Cameroon. *Toxicon X* 2021; **9–10:** 100068.
49 Casewell NR, Jackson TNW, Laustsen AH, Sunagar K. Causes and consequences of snake venom variation. *Trends Pharmacol Sci* 2020; **41:** 570–81.
50 Slowinski JB, Wüster W. A new cobra (Elapidae: *naja*) from Myanmar (Burma). *Herpetologica* 2000; **56:** 257–70.
51 Sato H, Ise T. Effect of plant dynamic processes on African vegetation responses to climate change: analysis using the spatially explicit individual-based dynamic global vegetation model (SEIB-DGVM). *J Geophys Res Biogeosci* 2012; **117:** G03017.
52 Zipkin EF, Direnzo GV, Ray JM, Rossman S, Lips KR. Tropical snake diversity collapses after widespread amphibian loss. *Science* 2020; **367:** 814–16.
53 Franzén M, Schweiger O, Betzholtz PE. Species–area relationships are controlled by species traits. *PLoS One* 2012; **7:** e37359.