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Venomous snakes and climate change: ophidism as a dynamic problem

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Abstract Snakebite envenoming is an important public health problem worldwide and addressing this issue has turned into a challenge for applied science. In this sense, the study of the distributional patterns of problematic snakes is central in terms of public health. Global Climate Change is affecting the distributional ranges of snakes, so that decisions regarding treatment of ophidism (poisoning by snake venom) may also change spatially and/or temporally. Here, we assessed suitable climate spaces at present conditions and estimated potential future changes in the distributions of the five southernmost venomous snakes, responsible for almost 99 % of accidents in Argentina, by implementing an ensemble of forecasts between different algorithms and scenarios for 2030 and 2080. Present suitable climate spaces showed high concordance with known distribution of the species. Future projections show moderate "north to south" displacements of the snakes' suitable climate spaces, implying potential increments of suitable spaces in human populated areas in Argentina. Our results suggest the necessity of considering ophidism as a dynamic problem. In this regard, the analyses implemented here are useful tools in improving the assessment of snakebite envenoming in light of global climate change.

1 Introduction

Snakebite envenoming is an important public health problem around the globe, mainly in Africa, Asia and America (Kasturiratne et al. 2008; Cruz et al. 2009; Gutiérrez et al. 2010). According to the World Health Organization, approximately 2,500,000 venomous snakebites per year result in 125,000 deaths worldwide, most of which occur in the above mentioned continents. This represents a relevant but neglected problem, particularly because snakebites are not included in primary care programs in

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most of the affected countries (Cruz et al. 2009). The treatment of snakebite envenoming is based on the timely administration of animal-derived antivenoms. Hence, antivenoms should be carefully distributed based on the distribution of the problem (Gutiérrez 2012; Hansson et al. 2013). In this regard, knowledge regarding the distributional patterns (and potential changes) of venomous snakes becomes essential for the suitable treatment of ophidic accidents.

There has been recent development of effective methodological approaches to estimate high risk areas of ophidic accidents; however, they frequently do not include distributional information of the snakes (e.g. Leynaud and Reati 2009) or do not focus primarily on the analyses that allow the assessment of detailed distributional ranges and their potential changes (e.g. Hansson et al. 2013). Information about the distribution of venomous snakes is necessary not only to estimate areas of high risk of accidents, but also for collecting venom for antivenom production from the entire range of the species. The latter is particularly important given that there is intraspecific geographic variation in venom composition and that antivenom produced from the venom of one population may be less effective against the venom of another population of the same species (Harrison et al. 2003).

Global Climate Change (GCC) greatly affects the distributional patterns of biodiversity (Thomas et al. 2004), reason for which there is a growing consensus in that management decisions should be taken in light of this phenomenon (Araújo and Rahbek 2007). In this regard, Species Distribution Models (SDMs) are useful tools for the study of the distributional patterns of species and they allow the prediction of potential distributional changes caused by different or changing conditions (Franklin 2009). These tools establish correlations between occurrences of a species and environmental variables (among others) so that models can be projected into hypothetic future climate conditions to generate hypotheses about species responses (e.g. Loyola et al. 2012). SDMs have been used for many anthropic purposes in recent years such as agriculture (Ureta et al. 2012), impact of alien species (Nori et al. 2011a, b), conservation guidelines (Araújo et al. 2006; Lemes and Loyola 2013), and determining priority conservation areas (Faleiro et al. 2013; Nori et al. 2013). The models have also been used to address issues related to epidemiology (Lafferty 2009; Joyner et al. 2010; Porcasi et al. 2012) and potential changes in distributional ranges of venomous animals (Saupe et al. 2011).

Argentina, located in the austral portion of South America, is inhabited by 17 species of venomous snakes belonging to two families (Viperidae and Elapidae) and three different genera (*Bothrops*: 9 species; *Crotalus*: 1 species; *Micrurus*: 7 species) (Giraudo et al. 2012). Most of them are only marginally distributed in small portions of the north, while five are widely distributed: *Bothrops alternatus*, *B. ammodytoides*, *B. diporus*, *Crotalus durissus terrificus* and *Micrurus pyrrhocryptus*. These five species cause almost 99 % of snakebites occurring in Argentina (around 1,500 in the last 3 years; http://www.msal.gov.ar/index.php/home/boletin-integrado-de-vigilancia) and are therefore considered of major medical importance in the country (de Roodt 2009).

Increasing the knowledge of distributional ranges and suitable spaces of venomous snakes is fundamental in treating snakebite envenoming. In addition, it would be important to evaluate if GCC can produce changes in species' suitable climate spaces, which in turn could be important when addressing the problem. Therefore, the main aims of this study were to (a) determine the most suitable climate spaces of the five widely distributed venomous snakes in Argentina, (b) project the potential effects of GCC on their present distributions and (c) analyze the suitable climate spaces and their potential future changes in function of the distribution of reported cases of snakebite envenomation, human population and human dominated landscapes.

2 Methods

2.1 Snake species and data records

Bothrops alternatus, *B. ammodytoides*, *B. diporus* and *Crotalus d. terrificus* are terrestrial viperid snakes generally found in forests and open areas (Campbell and Lamar 2004, 2001; Leynaud and Bucher 2005). Envenomation by *Bothrops* species has necrotic and hemorrhagic effects, while the venom of *Crotalus d. terrificus* has neurotoxic effects (Queiroz et al. 2008; de Roodt 2009). *Micrurus pyrrhocryptus* is an elapid snake that inhabits forests and open areas; its venom is extremely toxic and also causes neurotoxic effects (Dokmetjian et al. 2009).

Our study began with a dataset of 614 records: 80 for *Bothrops alternatus*, 99 for *B. ammodytoides*, 111 records for *B. diporus*, 149 for *Crotalus d. terrificus*, and 174 for *Micrurus pyrrhocryptus*. Although the scope of the present study was to assess suitable climate spaces and potential changes of these snakes in the country, the used records represent the entire distributional ranges of the snakes, which (except for *B. ammodytoides*) extend to several neighboring countries. Data records (see Suppl. Fig. 1, Suppl. Table 1) were obtained from the herpetological collections of Colección Boliviana de Fauna, La Paz, Bolivia (CBF), Museo de Historia Natural Noel Kempff Mercado, Santa Cruz, Bolivia (MNKR), Museu de Zoologia, Universidade de São Paulo, São Paulo, Brazil (MZUSP), Fundación Miguel Lillo, Tucumán, Argentina (FML), Museo de Ciencias Naturales de La Plata, Argentina (MLP), Museo Argentino de Ciencias Naturales, Buenos Aires, Argentina (MACN), Centro de Zoología Aplicada, Córdoba, Argentina (CZA), and from relevant literature (e.g. Wüster et al. 2008; Minoli et al. 2011; Da Silva and Sites 2012; Carrasco et al. 2009, 2010; 2012).

2.2 Climatic data

We considered 20 variables for both current and future conditions: 19 bioclimatic plus altitude (availables in: www.worldclim.org for present conditions; http://www.ccafs-climate.org/ for future scenarios), all at a spatial resolution of 2.5 arc minutes for continental South America. First, we performed a pairwise Pearson correlation between all the variables and then selected 11 which did not show colinearity with other variables ($r > 0.75$): Annual Mean Temperature, Mean Diurnal Range, Mean Temperature of Wettest Quarter, Mean Temperature of Warmest Quarter, Mean Temperature of Coldest Quarter, Annual Precipitation, Precipitation of Driest Month, Precipitation Seasonality, Precipitation of Warmest Quarter and Altitude. Variables of current conditions corresponded to average conditions for the time period 1950–2000 (Hijmans et al. 2005). We considered two different time slices: 2030 (2010–2039) and 2080 (2070–2099) for the A1B emission scenario (which, according to overall predictions, can be considered as a "median" scenario, forecasting changes of between 1.7 °C and 4.4 °C between the periods 1980–1999 and 2090–2099). Additionally, due to the large uncertainty among different Global Circulation Models (GCMs) in species range projections (Diniz-Filho et al. 2009), and in order to cover a wide range of variation between them, we selected three different GCMs: the Third Generation Coupled Global Climate Model of Environment Canada Climatic Change (cccma-cgcm3.1); the Coupled Model version 4.0 of the Institut Pierre Simon Laplace (ipsl_cm4); and the Model HadCM3 of the Met Office of United Kingdom (ukmo_hadcm3). These GCMs comprise a considerable range of equilibrium climate sensitivities (values ranging from 3.3 °C to 4.4 °C). All of the future scenarios were developed by IPCC's Fourth Assessment Report (AR4) (IPCC 2007).

2.3 Modeling methods

Species distribution models (SDMs) estimate the relationship between species records and the environmental and/or spatial characteristics of the sites (Franklin 2009). By using the same variables for different environmental scenarios at different times, SDMs can be projected for future climatic conditions in order to study geographic responses of the species to climate changes (Franklin 2009). Since alternative SDM algorithms have different levels of accuracy under different circumstances and there is no single 'best' method, we combined multiple algorithms into an ensemble (Araújo and New 2007). This ensemble approach identifies areas of high consensus between algorithms producing more conservative projections than if using a single algorithm.

Under the selected schemes (one for present conditions, three GCMs for 2030 and three for 2080), we implemented four different algorithms: Envelope Score (Piñeiro et al. 2007), the Genetic Algorithm for Rule-set Production (GARP) with the selection of "Best subset" models (Anderson et al. 2003), Support Vector Machine (Schölkopf et al. 2001), and MaxEnt (Phillips et al. 2006). Using each of these four algorithms, we made seven projections for each of the five studied species (one for present and one for each of the three selected GCMs for 2030 and 2080). A total of 140 projections were performed (5 species×4 algorithms×7 scenarios) and then present and future projections were combined to identify areas where there was the most agreement in predicting the presence of the species using the methodological consensus approach proposed by Araújo and New (2007).

The ensembles were generated in order to identify only areas with the highest support as those that are suitable for the species. First, we selected a threshold value for all the projections by assuming absence of the species in all the pixels with values of suitability lower than the value at which at least the 95 % of the records are included in the prediction at present conditions (omission errors less than 5 %). Second, the projections were grouped by species and GCM scenario (four groups of four projections for each species; e.g. ipsl_cm4 projections for 2080 of the different four algorithms for *Bothrops ammodytoides*) and overlaid in ArcGis 9.3. Third, we assumed the presence of the species in those areas in which the majority of the algorithms agreed (75 %; at least three of the four). Finally, we used the same criterion to create a final map between the consensus maps of the different GCMs for the future slices for each species.

In order to test all of the individual projections, we assessed model performance using 20 % of the records as "test data" in order to calculate the area under the receiver operating characteristic curve (AUC/ROC). Finally, we overlaid present and future final predictions for each species in ArcGis in order to calculate the loss/gain of suitable climate spaces for the species under the effect of GCC. The final maps were made with a better level of detail for Argentina because the main objectives of the article are related to the public health system of that country.

2.4 Complementary GIS analyses

With the aim of analyzing the suitable climate spaces for medical importance snakes in Argentina, and particularly their potential future changes in function of distribution of snakebites in Argentina, we overlapped our predictions (for present and both future time slices) with a vector map containing reported cases of snakebites envenoming in each political province of the country during the last 3 years. That information was obtained from the Ministerio de Salúd de la República Argentina (http://www.msal.gov.ar/index.php/home/boletin-integrado-de-vigilancia). In order to determine the number of people inhabiting the suitable climate spaces for the snakes, and its potential future changes, we overlapped each of the final models with a population count grid of South America (i.e. a raster dataset containing the number of people for pixel; CIESIN et al. 2011). In addition, in order to interpret the changes in the number of people living in suitable climate spaces for each species, we superposed maps of the potential suitable surfaces at each time slice with a vector dataset showing the most important urban centers (more than 20,000 people) in Argentina. Finally, with the aim of determining the percentage of anthropized areas in the potential suitable surface for each of the studied species at the different time slices, we first discriminated all of the pixels occupied by different kind of crops or urbanized areas from a 2009 land-cover dataset of South America (ESA 2010) and then overlapped it with the climatic suitable spaces for each species at each time slice.

3 Results

In general, our validation tests showed good performances for the models: AUC values (for test data) varied between 0.79 (*Crotalus d. terrificus* with Envelope Score algorithm) and 0.97 (*Bothrops ammodytoides* with Support Vector Machine algorithm) with a mean of 0.91. According to our tests, the best model performances were those of *B. ammodytoides* (ranged from 0.92 to 0.97; MEAN: 0.952), whereas the lowest values where those of *Crotalus d. terrificus* (ranged from 0.79 to 0.9; MEAN: 0.85) (Table 1).

Climatically suitable spaces showed high concordance with regions in which the species have been recorded, with the exception of some commission errors discussed below (Fig. 1). Suitable climatic spaces for *Bothrops alternatus* covered southern Brazil, eastern Paraguay, Uruguay, and central and northeastern Argentina. Although the species is widely distributed in northeastern Argentina, a small area with high suitability values appears in the southeastern portion of Tucumán province, in the northwestern part of the country. This small portion of the suitability map corresponds to a distributional record from a FML collection which could be of dubious origin (Gustavo Scrocchi pers. com.) (Suppl. Fig. 1a; Fig. 1b). Climate suitable spaces

Table 1 Surface of climatic suitable spaces for the studied species at present, 2030 and 2080; and values of AUC/ROC for training and testing each of the algorithms for each species

Species			*B. ammodytoides*	*B. alternatus*	*B. diporus*	*C. d. terrificus*	*M. pyrrhocryptus*
Surface of suitable spaces [Km^2]	Entire range	Present	823,385	2,301,671	2,325,853	3,125,181	1,666,124
		2030	807,809	1,832,440	2,205,576	2,463,208	1,525,873
		2080	784,966	1,941,546	2,284,599	2,425,711	1,734,867
	Argentina	Present	823,385	998,710	1,437,431	956,924	1,428,391
		2030	807,809	821,805	1,409,396	971,104	1,447,050
		2080	784,966	1,063,842	1,644,685	1,323,975	1,606,577
AUC/ROC values	Train	BIOCLIM	0.97	0.93	0.92	0.82	0.92
		SVM	0.97	0.92	0.95	0.91	0.96
		GARP	0.96	0.91	0.91	0.88	0.93
		MAXENT	0.97	0.94	0.96	0.94	0.97
	Test	BIOCLIM	0.92	0.84	0.9	0.79	0.9
		SVM	0.97	0.93	0.94	0.9	0.95
		GARP	0.96	0.9	0.91	0.84	0.93
		MAXENT	0.96	0.91	0.92	0.88	0.95

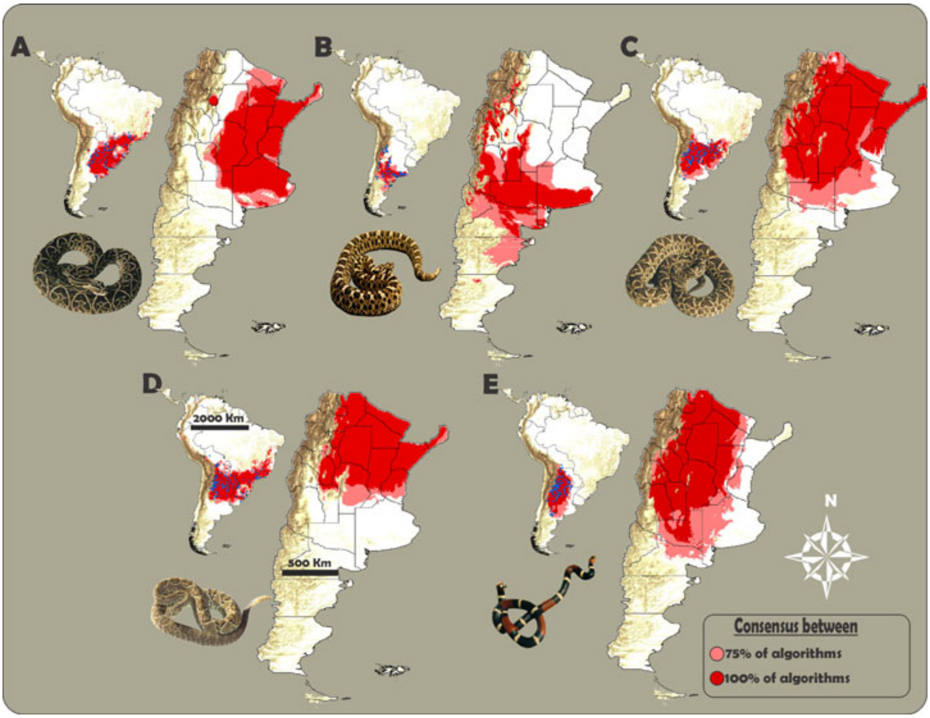

Fig. 1 Suitable climatic spaces at present climatic conditions obtained from the ensembles of the four algorithms for five snake species. **a** *Bothrops alternatus* **b** *Bothrops ammodytoides* **c** *Bothrops diporus* **d** *Crotalus durissus terrificus* **e** *Micrurus pyrrhocryptus*

Bothrops ammodytoides were within Argentina, latitudinal from Jujuy to Santa Cruz province and covering a large altitudinal gradient as well, from sea level (on the eastern coastal areas of Buenos Aires, Rio Negro and Chubut provinces) to Andean and extra Andean mountains in the center and west of the country (Suppl. Fig. 1b; Fig. 1b). Suitable climate spaces for *Bothrops diporus* included southern Brazil, eastern Paraguay, a big portion of Uruguay (without records; see discussion), and most of Argentina, with more than 80 % of the provinces being favorable for the presence of the species. This range covers a wide latitudinal gradient from the northern country border to northern Rio Negro province (Suppl. Fig. 1c; Fig. 1c). Suitable climate spaces for *Crotalus d. terrificus* covered southern Bolivia, southern Brazil, Paraguay, Uruguay, and north and central Argentina (except Andean and extra Andean mountainous areas) (see Suppl. Fig. 1d; Fig. 1d). Suitable climate spaces for *Micrurus pyrrhocryptus* covered southern Bolivia, southern Paraguay, and most of Argentina, from the northern country border to Rio Negro province (except Andean and extra Andean mountainous areas). For the five species, an important commission error is located in the central-eastern portion of Argentina (Suppl. Fig. 1e; Fig. 1e).

Our results showed that suitable climate spaces for each species will remain quite stable (in extension). However, for all the species, results showed a clear "north to south" pattern of change in their entire ranges towards the future (i.e. all of the species are projected to lose climatically suitable spaces in the northern portion of their distributions and to expand southwards). Except for *Bothrops ammodytoides*, that pattern of change could result in little retraction and a moderate to great increase of potential suitable spaces for the snakes within Argentina (Table 1; Figs. 2, 3, and 4a, b).

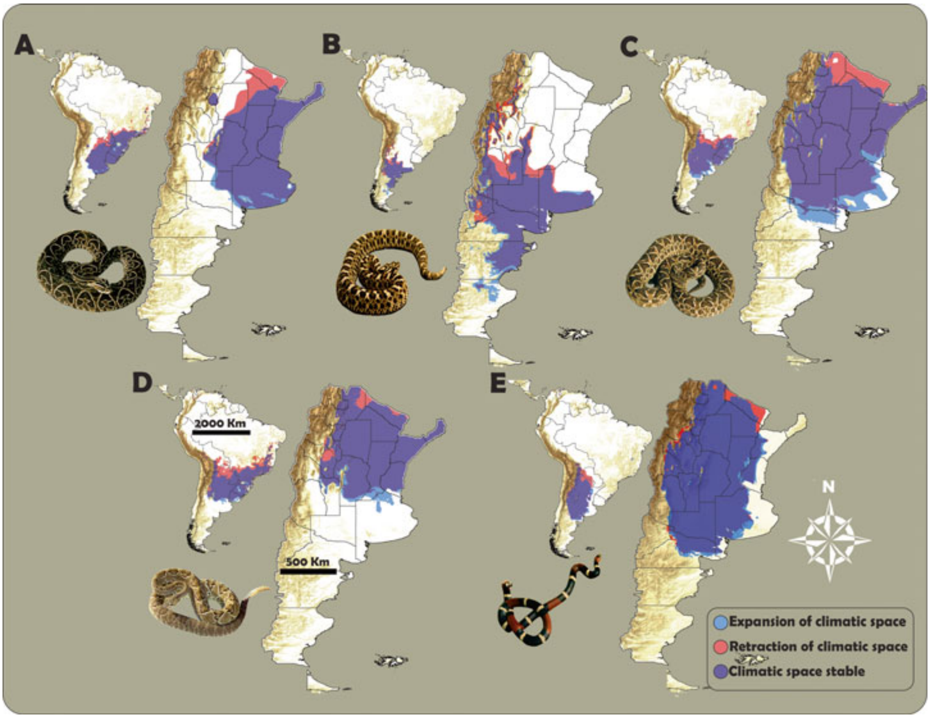

Fig. 2 Changes in climatic suitable climate spaces between present climatic conditions and 2030 for five snake species. **a** *Bothrops alternatus* **b** *Bothrops ammodytoides* **c** *Bothrops diporus* **d** *Crotalus durissus terrificus* **e** *Micrurus pyrrhocryptus*

In general terms, the greatest retractions of suitable climate spaces would be in the northern provinces of the country, in which most accidents occur. Additionally, the greatest expansions of suitable climate spaces would be in areas were fewer accidents occur today, located in the south and central east of the country (Fig. 5). The species with the highest amount of suitable climate spaces occupied by humans in Argentina at current conditions *Bothrops alternatus*, whereas the species with the least overlap with human population is *B. ammodytoides* (Figs. 4c, d and 5). Although the general pattern indicates a quite stable number of people affected toward the future in the entire range of the five species (see Fig. 4c), the surface of suitable climate spaces within Argentina of *B. diporus* and *Crotalus d. terrificus* would overlap with a much larger number of people and urban centers (Fig. 4d; Suppl. Fig. 2). Anthropized areas within each snake's suitable space vary greatly among the species; however, future changes in snakes' suitable climate spaces would not produce considerable changes in the percentage of current anthropized areas within each snake's suitable space (Fig. 4e, f; Suppl. Fig. 2).

4 Discussion

4.1 Ophidism and climate change

Although species distribution is the result of several different factors and does not depend exclusively on climatic conditions (Rodda et al. 2011), our results pinpoint that GCC will drive

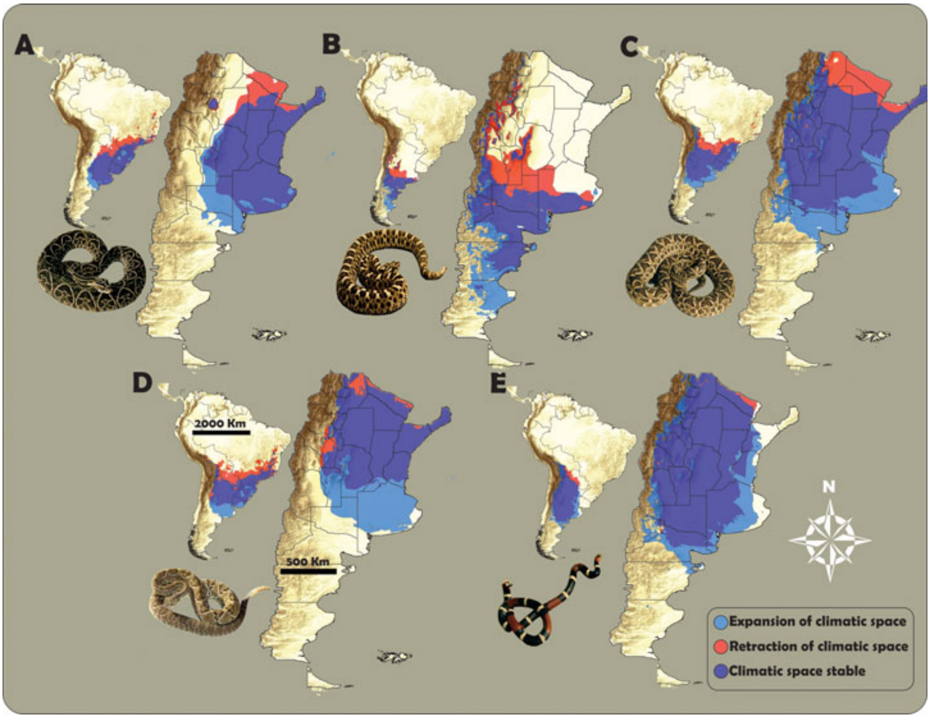

Fig. 3 Changes in suitable climate spaces between present climatic conditions and 2080 for five snake species. **a** *Bothrops alternatus* **b** *Bothrops ammodytoides* **c** *Bothrops diporus* **d** *Crotalus durissus terrificus* **e** *Micrurus pyrrhocryptus*

considerable changes and displacements in the areas with climatic suitable conditions for medically important snakes. This could produce changes in the potential "contact" between snake species and humans, which would alter the patterns of occurrence of snakebites and should be considered when addressing this worldwide problem.

An important aspect revealed by the present study is the potential net expansion within Argentina of the suitable climate spaces of four of the snake species, as a result of the "north to south" pattern of predicted change (Figs. 2, 3, and 4). For example, a retraction of the range of *Crotalus d. terrificus* would occur mostly in Paraguay and Brazil while expansion would occur mostly in Argentina, hence resulting in an increase of the potential suitable space for the species within the country. These potential net expansions, however, would occur in heavily anthropized provinces where there are actually few snakebites, while the slight retractions predicted for Argentina would occur in the provinces with the highest number of reported accidents. Another interesting aspect revealed by this study is the potential area of expansion of *Bothrops ammodytoides*. This species is the southernmost venomous snake in the world (Campbell and Lamar 2004; Carrasco et al. 2010) and its southern expansion would imply that ophidism could reach human populations never affected by it and thus without the appropriate infrastructure and/or adequate personnel to cope these accidents.

Our results also suggest a considerable increment in the potential incidence of two of the problematic snakes (*Bothrops diporus* and *Crotalus d. terrificus*) on the human population of Argentina (Fig. 4d). This would be due to the suitable climate spaces for this species reaching densely populated areas of the central-eastern portion of the country (Fig. 5). Note, however,

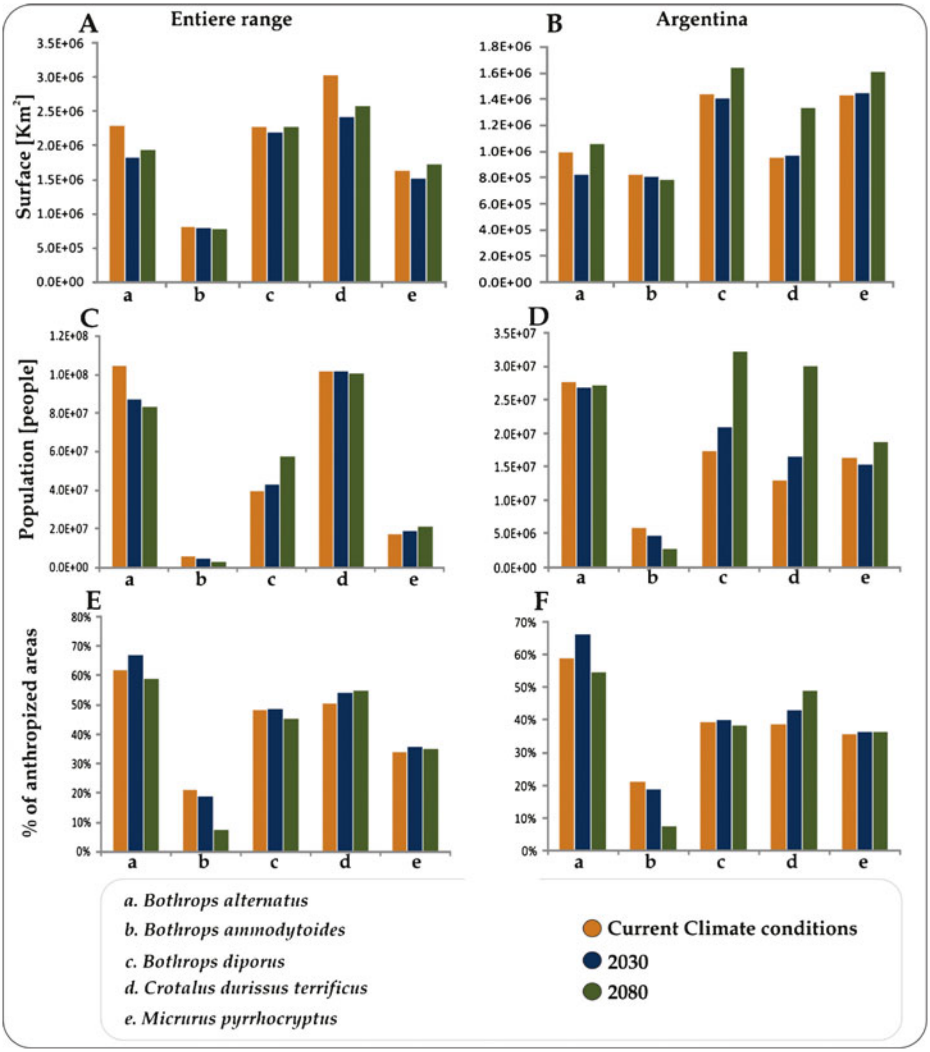

Fig. 4 Histograms showing the extension of suitable climate space for each snake species in their entire range (**a**) and in Argentina (**b**). Number of people inhabiting suitable climatic space for each snake species in their entire range (**c**) and in Argentina (**d**). The percentage of suitable climatic spaces of each snake species covered by antrophized surfaces in their entire range (**e**) and in Argentina (**f**)

that this forecast is strongly influenced by the biology of the species; independently of the "movements" of their suitable climate spaces, they should be able to tolerate the high anthropic disturbances of these areas (Suppl. Fig. 2). An example of adaptation to an anthropized area was recently documented for *Crotalus d. terrificus* (Bastos et al. 2005). In that study, the authors reported a case in which *C. durissus*' populations "invaded" different municipalities of Brazil, seemingly facilitated by different effects of human activity in those areas (open corridors created by agricultural activities and unusual floods).

It is important to note that, in some cases, losses of suitable climate spaces towards the future are located in areas in which the presence of the species is not confirmed with data records (e.g. see map of *B. ammodytoides*), thus changes in the distributions could be smaller

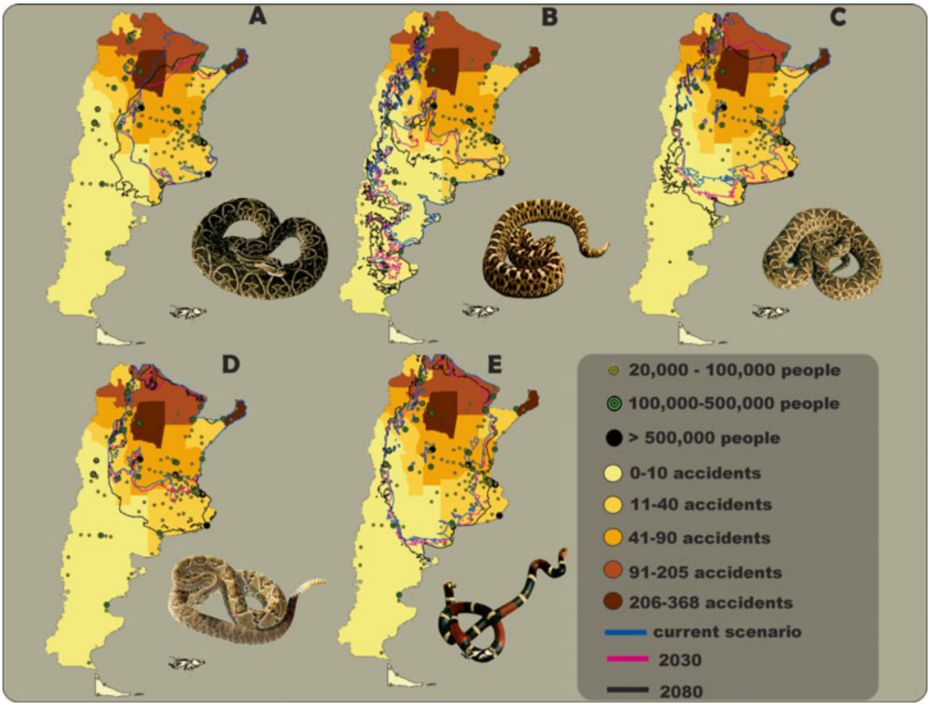

Fig. 5 Map showing the most important urban centers and the number of accident in the last 3 years in the political provinces of Argentina, combined with the suitable climate spaces at current condition, 2030 and 2080 for each snake species: **a** *Bothrops alternatus* **b** *Bothrops ammodytoides* **c** *Bothrops diporus* **d** *Crotalus durissus terrificus* **e** *Micrurus pyrrhocryptus*

than forecasted by our results (by an overestimation of lost spaces). On the other hand, the limited vagility of the species combined with the great fragmentation and degradation of many environments leads us to consider that many of the newer suitable climate spaces predicted in our results could not be occupied in the near future (Araújo et al. 2006), and therefore our results may be overestimating the gain of suitable climate spaces. These are limitations (or constraints) of the models employed, which increase the uncertainty of their predictions. Of course, if decisions are based on predictions like these they must be carefully considered before being implemented. For example, the presence/absence of snakes in areas where their suitable climate spaces are predicted to expand will have to be systematically monitored (by intensive field trips, queries in health centers, etc.) and, if necessary, quickly supplied with the appropriate antivenoms.

4.2 Snakes' distribution and conservation

Suitability maps based on present conditions for three of the species studied here (species of *Bothrops*) have been performed previously (Di Cola and Chiaraviglio 2011); those maps show some differences with the maps generated in our analyses. For example, the distribution of *Bothrops alternatus* extends more northwest in their maps than in ours. This may be because records of presence in that area used in their study belong to the closely related species *Bothrops jonathani* (Carrasco et al. 2009). Another noticeable difference worth mentioning is in regard to the southern limit of *Bothrops diporus*' distribution which, according to our results (and others; see Minoli et al. 2011), is found at a much higher latitude than the one obtained by Di Cola and Chiaraviglio (2011). We believe these differences are mainly due to different presence localities used to model the species, but also (perhaps to a lesser extent) by the different methodologies employed.

The resulting suitability maps for present conditions (Fig. 1) showed great concordance with known distributional records for the species (Suppl. Fig. 1). Nevertheless, we detected some commission errors which deserve to be discussed. The most evident and important commission error is the absence of records of the five studied species in central eastern Argentina (in southern Córdoba and Santa Fe, and northern La Pampa and Buenos Aires provinces) in which suitability is high (Fig. 1). Although we cannot discard a sample bias in our dataset, this zone corresponds to the Humid Pampas (Morrone 2006), the most productive ecoregion in the country in terms of crop and livestock production, which has been severely deforested for intensive human uses for many decades, even centuries (Morrone 2006; Nori et al. 2011c). Although this ecoregion presents favorable climatic conditions for the studied species, it is likely that historical human uses have rendered this region unsuitable (Suppl. Fig. 2).

Other commission errors may be explained by the lack of available records from unexplored areas where the species are probably actually present, for example central and southern areas of Santiago del Estero province which resulted highly suitable for *Crotalus d. terrificus* and *Bothrops diporus*. Regarding *B. ammodytoides*, the models predicted suitable climate spaces for the species in a small and isolated area in northern Santa Cruz province where it has not yet been recorded. The species has, however, been found some kilometers east of that locality, on the coast of Santa Cruz province (Scolaro pers. com., see Carrasco et al. 2010). The austral limit of *B. ammodytoide*s' distribution remains unclear probably because vast extensions of lands in austral Patagonia remain largely unknown. The northern limit of its distribution predicted by the model is a small area in the Andean region of Jujuy province, and hence, it is not surprising that the species has been observed recently in that area (Moreta, pers. com, see Carrasco et al. 2010). Finally, the absence of *B. diporus* records in Uruguay is also worth noting since our results pinpointed high suitability for the species in that country (Fig. 1c). This may be due to fuzzy taxonomical limits or exclusive ecological interactions (explained by their similar natural history) with the closely related species *B. pubescens*, present in Uruguay (Campbell and Lamar 2004).

Although we discussed the potential changes in snakes' suitable climate spaces in the previous section, it is important to highlight that the potential expansion of snakes' suitable spaces showed in the results does not necessarily imply expansions in the distributional range of the species. There is great variation in home ranges sizes and movement rates among snakes (Macartey et al. 1988); however, generally speaking the dispersal capacity of snakes is limited in relation to other vertebrates such as birds. These aspects have not yet been studied for the species mentioned in this study, but previous works show that phylogenetically related species (i.e. other viperid and elapid species) have home ranges of a few tens of hectares and movement rates of some tens of meters per day (e.g. Macartey et al. 1988; Sasa et al. 2009; Hoss et al. 2010). This limited vagility, combined with the great fragmentation and deforestation of many areas inhabited by the snakes studied here (e.g. Chaco or Pampas ecoregions; Nori et al. 2013), could lead to many suitable climate spaces that would never be colonized by the species.

Many studies have revealed the importance of GCC for conservation management (Thomas et al. 2004; Araújo and Rahbek 2007) and it is known that this phenomenon can strongly affect reptiles (Sinervo et al. 2010). Indeed, a decline in some populations of snakes in different regions of the globe have been noticed by some authors (Reading et al. 2010), and the causes of these declines may be multi-faceted, with GCC as a possible common cause. The snakes studied here have not yet been assessed for the IUCN Red List (IUCN 2013), but all of them are currently categorized as not threatened by the Asociación Herpetológica Argentina (Giraudo et al. 2012). Our results support that categorization, as they show widespread distributional ranges within Argentina, and since shifts in suitable climate spaces will only slightly affect the variety of environments they occupy. However, GCC could affect snakes' population at local scale. For example, 2080 future projections predict that the five species will almost, if not completely, lose suitable climate spaces in Paraguay (Figs. 2 and 3). In the same way, *Bothrops ammodytoides*, endemic to Argentina, will lose a considerable proportion of suitable spaces in the Puna and Prepuna, resulting in potential discontinuous and relatively small "refugia" for the species in those ecoregions. Finally, our results show minor changes in the percentage of climate suitable spaces occupied by anthropized areas for each snake; however, these areas could greatly expand in South America toward the future, which may have considerable impact on the status conservation of the snakes (Dobrovolski et al. 2011).

4.3 Final considerations

Despite the fact that SDMs have been frequently used in recent years for many anthropic purposes (Lafferty 2009; Joyner et al. 2010; Porcasi et al. 2012; Loyola et al. 2012; Ureta et al. 2012; Nori et al. 2013; Faleiro et al. 2013; Lemes and Loyola 2013), this methodology has never been applied in addressing the problem of human ophidism. As shown in the present study, SDMs could complement other efficient approaches developed for the treatment of snakebites (Cruz et al. 2009; Leynaud and Reati 2009; Gutiérrez 2012; Hansson et al. 2013), by incorporating important information regarding snakes' distributions. In this regard, ophidism could stop being seen as a "static" problem and begin to be addressed as a "dynamic" one, taking into consideration the effect of GCC on snakes' distributions.

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References

Anderson RP, Lew D, Peterson AT (2003) Evaluating predictive models of species' distributions: Criteria for selecting optimal models. Ecol Model 162:211–232

Araújo MB, New M (2007) Ensemble forecasting of species distributions. Trends Ecol Evol 22:42–7

Araújo MB, Thuiller W, Pearson RG (2006) Climate warming and the decline of amphibians and reptiles in Europe. J Biogeogr 33:1712–1728

Araújo MB, Rahbek C (2007) Conserving biodiversity in a world of conflicts. J Biogeogr 34:199–200

Bastos EGDM, De Araújo AFB, Silva HR (2005) Records of the rattlesnakes *Crotalus durissus terrificus* (Laurenti) (Serpentes, Viperidae) in the State of Rio de Janeiro, Brazil: A possible case of invasion facilitated by defororestation. Rev Bras Zool 22:812–815

Campbell JA, Lamar WW (2004) The venomous reptiles of the Western Hemisphere. Comstock, Ithaca

Carrasco PA, Harvey MB, Saravia AM (2009) The rare Andean pitviper *Rhinocerophis jonathani* (Serpentes: Viperidae). Zootaxa 2283:1–15

Carrasco PA, Leynaud GC, Scrocchi GJ (2010) Redescription of the southernmost snake species, *Bothrops ammodytoides* (Serpentes: Viperidae: Crotalinae). Amphibia-Reptilia 31:323–338

Carrasco PA, Mattoni CI, Leynaud GC, Scrocchi GJ (2012) Morphology, phylogeny and taxonomy of South American bothropoid pitvipers (Serpentes, Viperidae). Zool Scr 41:109–124

CIESIN, Columbia University, IFPRI, The World Bank, CIAT (2011) Global rural–urban mapping project, version 1 (GRUMPv1): Population count grid. NASA Socioeconomic Data and Applications Center (SEDAC), Palisades

Cruz LS, Vargas R, Lopes AA (2009) Snakebite envenomation and death in the developing world. Ethnic dis 19: 42–46

Da Silva JN, Sites JW (2012) Revision of the *Micrurus frontalis* Complex (Serpentes: Elapidae). Herpetol Monogr 13:142–194

de Roodt AR (2009) Ofidios venenosos y sus venenos. In: Montero R, Autino A (eds) Sistemática y Filogenia de los vertebrados, 2nd edn. Tucumán, Argentina, pp 233–241

Di Cola V, Chiaraviglio M (2011) Establishing species' environmental requirements to understand how the southernmost species of South American pitvipers (Bothrops, Viperidae) are distributed: A niche-based modelling approach. Austral Ecol 36:90–98

Diniz-Filho JAF, Mauricio Bini L, Fernando Rangel T, Loyola RD, Hof C et al (2009) Partitioning and mapping uncertainties in ensembles of forecasts of species turnover under climate change. Ecography 32:897–906

Dobrovolski R, Diniz-Filho JAF, Loyola RD, De Marco JP (2011) Agricultural expansion and the fate of global conservation priorities. Biodivers Conserv 20:2445–2459

Dokmetjian JC, Del Canto S, Vinzón S, De Jiménez Bonino MB (2009) Biochemical characterization of the Micrurus pyrrhocryptus venom. Toxicon 53:375–382

ESA (European Space Agency) (2010) Globcover 2009. Products Description and Validation Report.

Faleiro FV, Machado RB, Loyola RD (2013) Defining spatial conservation priorities in the face of land-use and climate change. Biol Conserv 158:248–257

Franklin J (2009) Mapping species distributions. Cambridge University Press, New York

Giraudo AR, Arzamendia V, Bellini GP, Bessa CA, Cinthia C et al (2012) Categorización del estado de conservación de las Serpientes de la República Argentina. Cuad Herp 26:303–326

Gutiérrez JM (2012) Improving antivenom availability and accessibility: Science, technology, and beyond. Toxicon 60:1–12

Gutiérrez JM, Williams D, Fan HW, Warrell D (2010) Snakebite envenoming from a global perspective: Towards an integrated approach. Toxicon 56:1223–1235

Hansson E, Sasa M, Mattisson K, Robles A, Gutiérrez JM (2013) Using geographical information systems to identify populations in need of improved accessibility to antivenom treatment for snakebite envenoming in Costa Rica. PLoS Neglect Trop D e2009

Harrison RA, Wüster W, Theakston RDG (2003) The conserved structure of snake venom toxins confers extensive immunological cross-reactivity to toxin-specific antibody. Toxicon 41:441–449

Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25:1965–1978

Hoss SK, Guyer C, Smith LL, Gordon W (2010) Multiscale influences of landscape composition and configuration on the spatial ecology of eastern diamond-backed rattlesnakes (Crotalus adamanteus). J Herpetol 44:110–123

IPCC (2007) Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change, 2007. Structure AR4:996

IUCN (2013) IUCN red list of threatened species. Version 2013:1

Joyner TA, Lukhnova L, Pazilov Y, Temiralyeva G, Hugh-Jones ME et al (2010) Modeling the potential distribution of Bacillus anthracis under multiple climate change scenarios for Kazakhstan. PloS one 5:e9596

Kasturiratne A, Wickremasinghe AR, De Silva N, Gunawardena NK, Pathmeswaran A et al (2008) The global burden of snakebite: A literature analysis and modeling based on regional estimates of envenoming and deaths. PLoS Med 5:1591–1604

Lafferty KD (2009) The ecology of climate change and infectious diseases. Ecology 90:888–900

Lemes P, Loyola RD (2013) Accommodating species climate-forced dispersal and uncertainties in spatial conservation planning. PloS one 8:e54323

Leynaud GC, Reati GJ (2009) Identificación de las zonas de riesgo ofídico en Córdoba, Argentina, mediante el programa SIGEpi. Pan Am J Public Health 26:64–69

Leynaud GC, Bucher EH (2005) Restoration of degraded Chaco woodlands: Effects on reptile assemblages. For Ecol Manag 213:384–390

Loyola RD, Lemes P, Faleiro FV, Trindade-Filho J, Machado RB (2012) Severe loss of suitable climatic conditions for marsupial species in Brazil: Challenges and opportunities for conservation. PloS one 7:e46257

Macartey JM, Gregory PT, Larsen KW (1988) A tabular survey of data movements and home range. J Herpetol 22:61–73

Martins M, Araujo MS, Sawaya RJ, Nunes R (2001) Diversity and evolution of macrohabitat use, body size and morphology in a monophyletic group of Neotropical pitviper (Bothrops). J Zool 254:529–538
Minoli I, Alvarez DJ, Avila LJ (2011) New records and geographic distribution maps for Bothropoides diporus Cope, 1862 (Reptilia: Viperidae). Check List 7:608–609
Morrone JJ (2006) Biogeographic areas and transition zones of Latin America and the Caribean islands based on panbiogeographic and cladistic analyses of the entomofauna. Annual Rev Entomol 51:467–494
Nori J, Akmentins MS, Ghirardi R, Frutos N, Leynaud GC (2011a) American bullfrog invasion in Argentina: Where should we take urgent measures? Biodivers Conserv 20:1125–1132
Nori J, Urbina-Cardona JN, Loyola RD, Lescano JN, Leynaud GC (2011b) Climate change and American bullfrog invasion: What could we expect in South America? PloS one 6:e25718
Nori J, Díaz-Gomez J, Leynaud GC (2011c) Biogeographic regions of Central Argentina based on snake distribution: Evaluating two different methodological approaches. J Nat Hist 45:1005–1020
Nori J, Lescano JN, Illoldi-Rangel P, Frutos N, Cabrera MR et al (2013) The conflict between agricultural expansion and priority conservation areas: Making the right decisions before it is too late. Biol Conserv 159: 507–513
Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecol Model 190:231–259
Piñeiro R, Fuertes Aguilar J, Munt DD, Nieto Feliner G (2007) Ecology matters: Atlantic-Mediterranean disjunction in the sand-dune shrub Armeria pungens (Plumbaginaceae). Mol Ecol 16:2155–2171
Porcasi X, Rotela CH, Introini MV, Frutos N, Lanfri S et al (2012) An operative dengue risk stratification system in Argentina based on geospatial technology. Geospat Health 6:31–42
Queiroz GP, Pessoa LA, Portaro FCV, Furtado MDFD, Tambourgi DV (2008) Interspecific variation in venom composition and toxicity of Brazilian snakes from Bothrops genus. Toxicon 52:842–851
Reading CJ, Luiselli LM, Akani GC et al (2010) Are snake populations in widespread decline? Biol Lett 6:777–80
Rodda GH, Jarnevich CS, Reed RN (2011) Challenges in identifying sites climatically matched to the native ranges of animal invaders. PLoS one 6:e14670
Sasa M, Wasko DK, Lamar WW (2009) Natural history of the terciopelo Bothrops asper (Serpentes: Viperidae) in Costa Rica. Toxicon 54:904–22
Saupe EE, Papes M, Selden PA, Vetter RS (2011) Tracking a medically important spider: Climate change, ecological niche modeling, and the brown recluse (Loxosceles reclusa). PloS one 6:e17731
Schölkopf B, Platt JC, Shawe-Taylor JS, Smola AJ, Williamson RC (2001) Estimating the support of a high-dimensional distribution. Neural Comput 13:1443–1471
Sinervo B, Méndez de la Cruz F, Miles DB et al (2010) Erosion of lizard diversity by climate change and altered thermal niches. Science 328:894–899
Thomas CD, Cameron A, Green RE et al (2004) Extinction risk from climate change. Nature 427:145–8
Ureta C, Martínez-Meyer E, Perales HR, Álvarez-Buylla ER (2012) Projecting the effects of climate change on the distribution of maize races and their wild relatives in Mexico. Global Change Biol 18:1073–1082
Wüster W, Peppin L, Pook CE, Walker DE (2008) A nesting of vipers: Phylogeny and historical biogeography of the Viperidae (Squamata: Serpentes). Mol Phylogenet Evol 49:445–59