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ECOLOGICAL NICHE MODELS OF TITYUS SERRULATUS LUTZ & MELLO, 1922 AND *TITYUS STIGMURUS* (THORELL, 1876) (ARACHNIDA: SCORPIONES)

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ABSTRACT

Scorpions are venomous animals with high plasticity and could serve as models to biogeographic, natural history and evolutionary studies. Ecological niche modeling can help in understanding essential characteristics from species geographic distribution, also allowing prediction of future distribution patterns. Our goal was modeling the ecological niche of the scorpion species *Tityus serrulatus* and *Tityus stigmurus*, as well as identifying the variables that influence their distribution in different biomes and their occurrence boundaries in Amazon, Caatinga and Cerrado. Data was obtained from 12 Brazilian arachnological collections. Bioclimatic variables were obtained from the Worldclim database and niche modeling was implemented through the Maximum Entropy algorithm. Results showed the Atlantic Forest biome both influences species distribution and is the only biome showing a distributional overlap between *T. serrulatus* and *T. stigmurus*. For *T. serrulatus*, the most important variable was the average annual temperature, which is usually high. For T. stigmurus, variation in temperature had the greatest influence. Temperature limits range in both species: *T. serrulatus* apparently does not support elevated temperatures, while *T. stigmurus* suffers with constant temperature variations.

Keywords: Ecological Niche Models. Scorpions. Buthidae. *Tityus serrulatus*. *Tityus stigmurus*.

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RESUMO
Escorpiões são animais peçonhentos com alta plasticidade e podem servir como modelos para estudos biogeográficos, de história natural e evolutivos. A modelagem de nicho ecológico pode auxiliar na compreensão de características essenciais da distribuição geográfica das espécies, além de permitir a previsão de padrões futuros de distribuição. Nosso objetivo foi modelar o nicho ecológico das espécies de escorpiões *Tityus serrulatus* e *Tityus stigmurus*, bem como identificar as variáveis que influenciam sua distribuição em diferentes biomas e seus limites de ocorrência na Amazônia, Caatinga e Cerrado. Os dados foram obtidos de 12 coleções aracnológicas brasileiras. As variáveis bioclimáticas foram obtidas do banco de dados WorldClim e a modelagem de nicho foi implementada por meio do algoritmo de Máxima Entropia. Os resultados mostraram que o bioma Mata Atlântica influencia a distribuição das espécies e é o único bioma que apresenta sobreposição de distribuição entre *T. serrulatus* e *T. stigmurus*. Para *T. serrulatus*, a variável mais importante foi a temperatura média anual, que geralmente é elevada. Para *T. stigmurus*, a variação de temperatura exerceu maior influência. Os limites de temperatura diferem entre as espécies: *T. serrulatus* aparentemente não suporta temperaturas elevadas, enquanto *T. stigmurus* sofre com variações constantes de temperatura.

Palavras-chave: Modelos de Nicho Ecológico. Escorpiões. Buthidae. *Tityus serrulatus*. *Tityus stigmurus*.

RESUMEN
Los escorpiones son animales venenosos con alta plasticidad y pueden servir como modelos para estudios biogeográficos, de historia natural y evolutivos. La modelización de nicho ecológico puede ayudar a comprender características esenciales de la distribución geográfica de las especies, además de permitir la predicción de futuros patrones de distribución. Nuestro objetivo fue modelar el nicho ecológico de las especies de escorpiones *Tityus serrulatus* y *Tityus stigmurus*, así como identificar las variables que influyen en su distribución en diferentes biomas y sus límites de ocurrencia en la Amazonía, Caatinga y Cerrado. Los datos fueron obtenidos de 12 colecciones aracnológicas brasileñas. Las variables bioclimáticas se obtuvieron de la base de datos WorldClim y la modelización del nicho se implementó mediante el algoritmo de Máxima Entropía. Los resultados mostraron que el bioma Mata Atlántica influye en la distribución de las especies y es el único bioma que presenta superposición de distribución entre *T. serrulatus* y *T. stigmurus*. Para *T. serrulatus*, la variable más importante fue la temperatura media anual, que generalmente es elevada. Para *T. stigmurus*, la variación de temperatura tuvo la mayor influencia. Los límites de temperatura difieren entre ambas especies: *T. serrulatus* aparentemente no soporta temperaturas elevadas, mientras que *T. stigmurus* sufre con variaciones constantes de temperatura.

Palabras clave: Modelos de Nicho Ecológico. Escorpiones. Buthidae. *Tityus serrulatus*. *Tityus stigmurus*.

1 INTRODUCTION

The fauna of Scorpions across the world encompasses 16 families, 190 genera and 2,100 species.One third of this diversity belongs to the family Buthidae, including approximately 1,082 species capable of causing severe or lethal accidents in humans (Fet *et al.*, 2000; Chippaux and Goyffon, 2008; Stockmann, 2015). Despite its low species diversity when compared to other arachnids, the Order Scorpiones is widely distributed in all continents (except Antarctic) and were accidentally introduced in New Zealand and England (Polis, 1990; Lourenço, 2015). The genus *Tytius* (family Buthidae) shows the highest diversity, with over 50 species, representing approximately 60% of Neotropical scorpion fauna. The evolutionary success of this family is usually regarded as consequence of its easy adaptation to both conserved and degraded anthropic areas (Lourenço, 2015). In Brazil, 4 families and 131 species occur (Lourenço, 2015; Pucca *et al.*, 2015), including those of medical importance: *Tityus serrulatus* Lutz & Mello, 1922, *Tityus bahiensis* Perty, 1833, *Tityus stigmurus* (Thorell, 1876) and *Tityus obscurus* Gervais, 1843 (Brazil, 2009; Lira-da-Silva *et al.*, 2009; Cupo, 2015).

All scorpions are admittedly venomous and their poison show biochemical characteristics allowing adaptability to different kinds of preys. It is composed by a mix of soluble and non-soluble components, with toxic and low molecular weight fractions (Gazarian *et al.*, 2005). The scorpion poison is regarded as extremely versatile and effective against both arthropods and vertebrates (Bordon, Cologna & Arantes, 2015).

Accidents involving scorpions are considered an alarming public health issue, especially in Brazil, where it has been increasing for the last 16 years. There was an increase of 323% in the incidence rate, with the average for the period being of 19.6 accidents per 100,000 inhabitants (Reckziegel andPinto, 2014). In 2013 and 2014, 78,091 and 88,246 accidents were registered, respectively, resulting in considerable social and economic impact in the country (Cupo, 2015; Pucca *et al.*, 2015; Wen *et al.*, 2015).

Lourenço (2015) and Stockman (2015) report that scorpion occurrence records come from a diverse range of environments, from desert-like regions with low humidity to temperate and subpolar climate areas. Nevertheless, some species can readily adapt and colonize degraded anthropic areas, especially in tropical regions in places with minimal vegetation cover. They also greatly proliferate in cities, due to their ability to reproduce through parthenogenesis, resulting in opportunistic, invader, colonizer, dominant populations, greatly adapted to dispersion (Camargo and Ricciardi, 2000).

The presence and proliferation of some scorpion species in cities is contingent on physiognomic and socio-economical characteristics, such as high demographic density, uncontrolled growth, lack of basic sanitation and waste accumulation (Brazil, 2009). Adaptive behavior in big urban centers has been reported only for *T. serrulatus* and *T. stigmurus*, highly plastic species that quickly and effectively adapt and colonize anthropic environments, with high reproduction and survival rates and a typical r-strategist behavior, which can be seen in most scorpions (Lourenço, 2015; Stockmann, 2015).

The main issue is most studies about scorpions in Brazil focus on poison, accident epidemiology and systematics. Explanations for this might reside in the lack of specialists in this group, coupled with the medical importance of scorpions and their poison. Studies on natural history, phylogeography, biogeography and bioecology of species, aiming to explain areas of likely occurrence, future distribution or even range boundaries for the main Brazilian biomes, are still scarce. Research on spatial distribution in Brazil, even most recent ones, deal with geopolitical, instead of biome, distribution, and are therefore of little contribution to the real vision of species establishment.

On this topic, Lourenço (2015) highlights the importance of knowing aspects of natural history in aiding identification of ecological niches and ideal conditions suitable to the species occurrence, supporting biogeographic studies. Ecological niche is here treated as an n-dimensional space including the essential interactions and conditions for existence of a species (Begon, Townsend and Harper, 2007). Ecological niche modeling is therefore a promising tool in predicting potential and future distribution for several species, usually based on bioclimatic and/or environmental variables (Oliveira *et al.*, 2014). This method consists in generating models (maps of occurrence probability) for a species based on data about its realized niche from environmental, bioclimatic and/or spatial variables, in order to predict potential distribution (Anderson *et al.*, 2002; Colwell and Rangel, 2009). It has been effective in extrapolating distribution patterns, areas of fundamental niche and future predictions (Terribile *et al.*, 2012), and has been used in studies with several groups of animals, supporting inferences on biogeography and phylogeography (Carnaval and Moritz, 2008; Werneck *et al.*, 2011), conservation biology (Dominguez-Dominguez *et al.*, 2006; Dias *et al.*, 2011) and evolutionary biology (McComarck *et al.*, 2009).

Considering the two most important scorpion species regarding public health in Brazil, *Tityus serrulatus* and *T. stigmurus*, our goal in this paper was answering the following questions: (1) how are the occurrence reports from both species spatially distributed in Brazil and its biomes? (2) which areas in the biomes show high suitability for both species in current and future (year 2070) climatic conditions? and (3) which environmental variables influence their distribution?

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Our objective was, therefore, to understand how the populations of these species are distributed in the Brazilian biomes and which variables influence this distribution today and in the future.

2 MATERIALS AND METHODS

To answer the questions above, we modeled the ecological niche of *T. serrulatus* and *T. stigmurus* in Brazilian biomes as well as their range boundaries in Amazonia, Caatinga and Cerrado biomes.

2.1 STUDY AREA

Distance between extreme northern and southern sites in Brazil, as well as between extreme eastern and western ones, is approximately 4,300 km. The country encompasses an area equal to 8,515,767 km^2 and a population of 202,768,562 inhabitants, showing a urbanization rate of 84.36% and a demographic density of 22.43 hab/km^2 (IBGE, 2014). Climate is generally warm and humid all over the territory, with dry and arid areas in northeastern Brazil. Thermal amplitude and pluviosity result from the six climate types occurring in the country (Tropical, Atlantic Tropical, Mountain Tropical, Subtropical, Equatorial and Semiarid), with a temperature range as high as 10 ºC and a pluviosity range as high as 1000 mm/year (INMET, 2011; IBGE, 2014)

Brazilian landscapes show most of the phytophysiognomies known for tropical areas, encompassing six main biomes: Amazon, Caatinga, Cerrado, Atlantic Forest, Pampas and Pantanal (Ab’Sáber, 2003; Brazil, 2015). Amazon is the biggest Brazilian biome, characterized by a warm and wet climate with high pluviosity rates, showing diverse phytophysiognomies, ecosystems and many areas of endemism, as well as a great biodiversity. The Cerrado is the second biggest Brazilian biome and constitutes mainly savanna-like areas. Along with the Atlantic Forest, it is considered a biodiversity hotspot (Myers *et al.*, 2000; Ab’Sáber, 2003). The Caatinga, an exclusively Brazilian biome, shows elevated temperatures, low pluviosity and completely arid areas. Its phytophysiognomy is composed basically by areas known as “agreste” and “sertão”, presenting high levels of degradation (Ab’Sáber, 2003; Brazil, 2015). For the model species in this study, we discuss the restraints these biomes may impose on their range and survival.

2.2 MODEL SPECIES

The model species in this study are *Tityus serrulatus* and *T. stigmurus*; both belong to the *T. stigmurus* species complex, which include also *T. aba* Candido, Lucas, Souza, Diaz and Lira-da-Silva, 2005, *T. kuryi* Lourenço, 1997, *T. martinpaechi* Lourenço, 2001 and *T. melici* Lourenço, 2003 (De Souza *et al.*, 2009). This complex was originally proposed by Mello-Leitão in 1945, and went through several reviews that included synonymization, inclusion and exclusion of species. *T. serrulatus* is the most controversial species in this complex; its validity has been questioned since its description and it has been synonymized with two other species (*T. lamottei* Lourenço, 1981 and *T. acutidens* Mello-Leitão, 1933) by De Souza *et al.* (2009) and subspecies (*Tityus serrulatus vellardi*) by Lourenço (1981). Known to be a parthenogenic species (Matthiesen, 1962), sexual populations have been recorded since 1999 (Lourenço and Cloudsey-Thompson, 1999 and De Souza *et al.* 2009), and confirmed and expanded in 2014 (Dos Santos *et al.*, 2014).

T. serrulatus is considered the most dangerous species in South America, due to its high accident incidence and severity, with can lead to death (in ages ranging from 0-14 and from 60 years old), due to its poison toxicity (Cupo, 2015; Pucca *et al.*, 2015). This species is originally endemics to Brazil, described for the city of Belo Horizonte (Minas Gerais), with occurrences recorded from Piauí to Rio Grande do Sul and in Argentina (Camargo and Ricciardi, 2000; Pucca *et al.*, 2015).

T. stigmurus, also endemics to the country, occurs in northeastern Brazil, except in the state of Maranhão, and in southern Brazil, north of Minas Gerais (Brazil and Porto, 2010). It was initially described for the state of Pernambuco and the accidents it causes are very similar to the ones caused by *T. serrulatus*, although with lower severity (Lira-da-Siva, Amorim & Brazil, 2000; Amorim *et al.*, 2002; Alves *et al.*, 2007; Lira-da-Silva *et al.*, 2009). In 2010, Ross identified parthenogenic and year-round reproduction in this species.

2.3 DATA SAMPLING

We analyzed 2,629 occurrence records of *T. serrulatus*, in 421 localities, and 1,785 for *T. stigmurus*, in 97 localities. Data was obtained by consulting twelve arachnological collections in Brazil between 2009 and 2014 (Table 1).

2.4 ECOLOGICAL NICHE MODELING

Bioclimatic variables used in the analysis were obtained in the database *WorldClim* (Global Climate Data, available in http://www.worldclim.org), in 2.5’ (approximately 4.5 km cell size) and cropped to South America using the software R 3.1.3. We performed a factor analysis, in the software R, to select the least correlated variables to use in niche modeling. The selected variables were annual mean temperature (BIO01), temperature annual range (BIO07), precipitation of wettest month (BIO13), precipitation of driest month (BIO14) and

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precipitation of wettest quarter (BIO16), which is in accordance with Oliveira *et al.* (2014) and Terribile *et al.*, (2012) for the Neotropics.

We selected the scenario MIROC-5, which predicts a rainier climate for the Earth starting in 2014 decade, and the mode RCP 6.0, which admits a maximum saturation of 60% of CO_2 between 2060 and 2080. As projections were made for the most distant possible future, we used scenarios for the year 2070 (the closest year to the end of the century with an established bioclimatic projection).

Ecological niche modeling was performed in the software MAXENT® (Phillips, Anderson and Schapire, 2006; version 3.3.3e) for current and future climate. AUC (Area Under the Curve) tests, which estimate model accuracy, were performed in order to yield higher credibility. In this analysis, we used 100% of data, with 75% as training data and 24% as testing data. Accuracy measurements indicate the model predictive power based on real data from the species distribution, and ranges from 0.0 to 0.5 for random models, and from 0.5 to 1.0 for totally predicted models. Accuracy measurements indicated validity of the presented data (Swets, 1988). The more accurate a model is, the closer to reality it is. Therefore, AUC values over 0.5 indicate good model accuracy (Pearson, 2007; Phillips *et al.*, 2006). We also performed a Jackknife analysis to estimate the variance and tendency of each variable in the model (Efron, 1980).

3 RESULTS

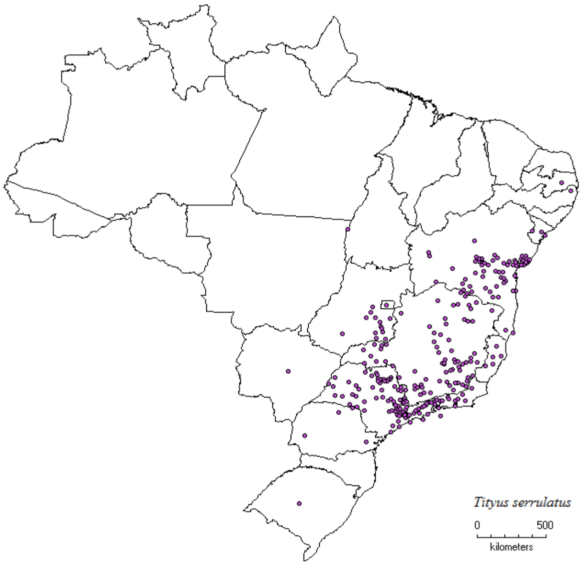
The actual distribution (realized niche) of records of *T. serrulatus* in Brazil encompasses areas of Atlantic Forest, Caatinga and Cerrado in the following states: Paraíba, Pernambuco, Sergipe, Bahia, Tocantins, Distrito Federal, Goiás, Mato Grosso do Sul, Espírito Santo, Minas Gerais, Rio de Janeiro, São Paulo, Paraná e Rio Grande do Sul (a single record in the Pampas region) (Figure 1). Ecological niche modeling indicated areas with high likelihood for this species' occurrence located in Atlantic Forest sites, a decrease in the probable range in the future – 2070 (areas with warmer colors) and absence of new areas of occurrence with significant value (Figure 2).

According to the thresholded model, there is a reduction in the range of *T. serrulatus* for the predicted future (2070) in areas of Cerrado, in the center of the map, and in part of the Atlantic Forest (Figure 3), in accordance with the modeling data. This model (presence and absence) sets a threshold, where the warm color indicates high probability of occurrence, whereas the cold color indicates null probability, generated from the overlap of occurrence intervals. Therefore, the null probability threshold varies between -1 and 0, and the high probability threshold varies between 0 – 1. Area under the curve shows the model is adequate and yields good answers for the prediction of occurrence areas both in current and future climate (Appendix 1). The farther the model curves are from the randomization line (closer to 1), the better the answer of the model to the data in the analysis, which indicates results are close to real. Accuracy values for current and predicted models were very close.

The bioclimatic variable BIO1 (annual mean temperature) was the one that contributed the most for the range of *T. serrulatus* in predicted areas, according to Jackknife results (Appendix 2). This analysis yields two estimates, the gain percentage each variables bring to the model and the result of a model reevaluation in each permutation among variables and the consequent drop in accuracy levels. For the species' predicted model, this variable was also the most important variable, confirming Jackknife results for current and future climate (Appendix 3).

Figure 1

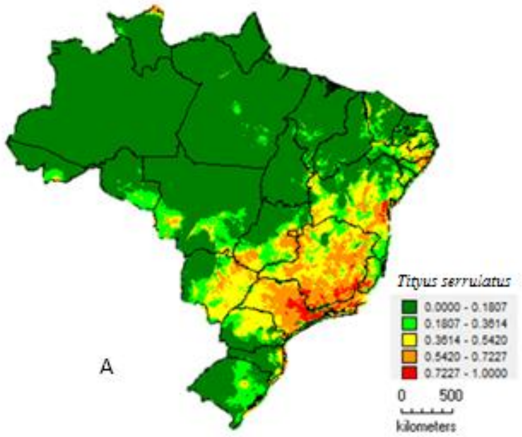
Distribution of occurrence records for Tityus serrulatus in Brazil



Source: The authors.

Figure 2

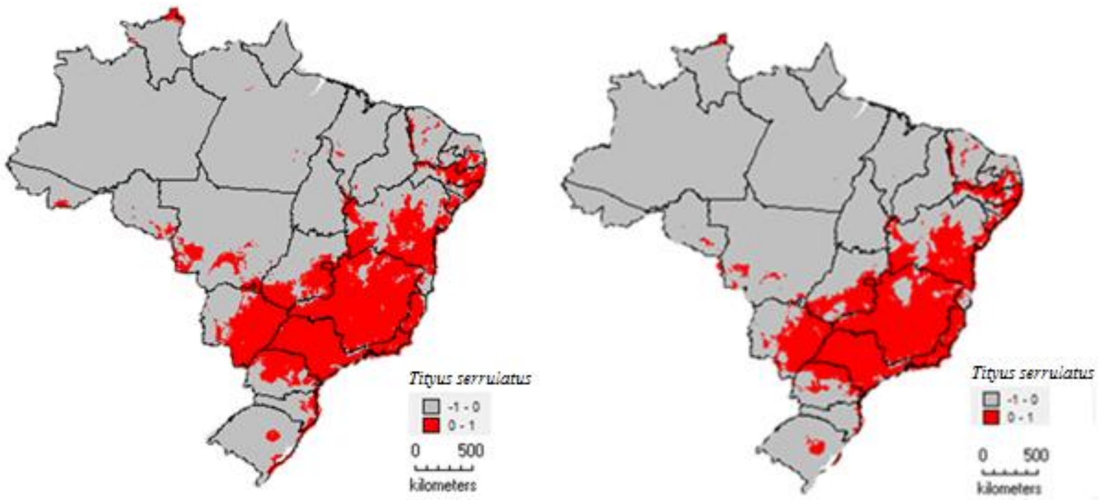
Ecological niche modeling for Tityus serrulatus in Brazil. (A) Current (1950-2000); (B) Future (2070)



Source: The authors.

Figure 3

Thresholded maps for Tityus serrulatus (A) Current (1950-2000); (B) Future (2070)



Source: The authors.

The actual distribution (realized niche) of records of *Tityus stigmurus* in Brazil also encompassed areas in the Atlantic Forest, Caatinga and Cerrado in northeastern Brazil, from Piauí to Bahia, with a increase in its range for southeastern Brazil, in Rio de Janeiro and São Paulo states (Figure 4). Ecological niche modeling for this species also showed areas with highest occurrence probabilities located in the Atlantic Forest, like in *T. serrulatus*. Current and predicted distribution models showed a slight expansion of occurrence in a Caatinga region in Ceará state, as well as a decrease of occurrence in regions of Atlantic Forest along

Sergipe and Bahia states in northeastern Brazil, and Santa Catarina (southern Brazil) and Rio de Janeiro (southeastern Brazil) states (Figure 5). Presence-absence models indicated a higher probability of occurrence in the Atlantic Forest, Caatinga and Cerrado, both in current and predicted models (Figure 6), and the area under the curve showed high accuracy values for the current model and even more for the future model (Appendix 4).

Bioclimatic variables BIO1 (annual mean temperature) and BI07 (temperature annual range) contributed the most for the distribution of *T. stigmurus*. Whereas the mechanism generating the graphic indicates BIO1 as the most important, the table shows BIO7 as the one that contributed the most (Appendix 5). Jackknife analyses for the future show the same result: BIO1 and BIO7 (Appendix 6). This apparent incongruity actually suggests that, in a combined way, closer to the real environment, BIO7 is the most important for the species, since decrease in model accuracy is significant when this variable is removed.

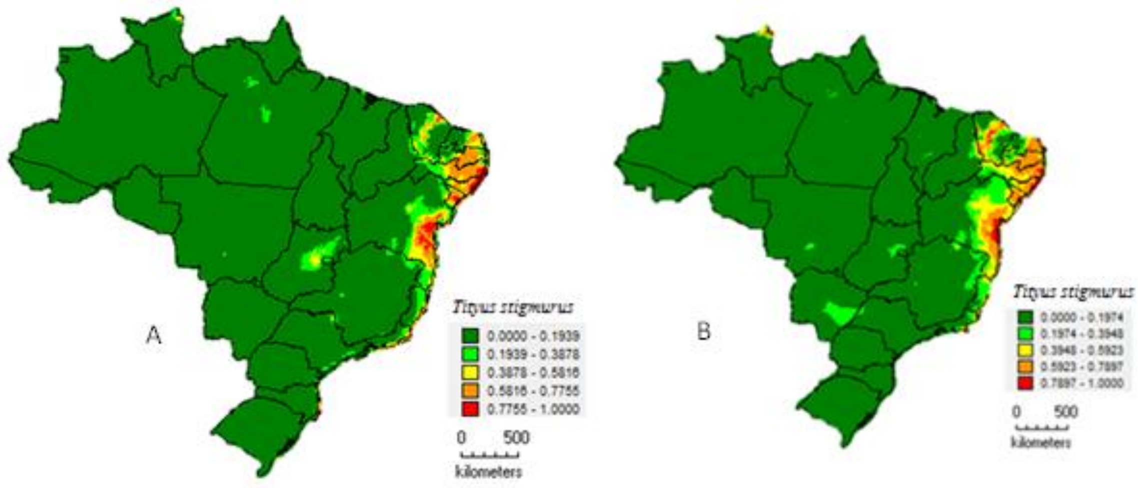
Figure 4

Distribution of occurrence records for Tityus stigmurus in Brazil

Source: The authors.

Figure 5

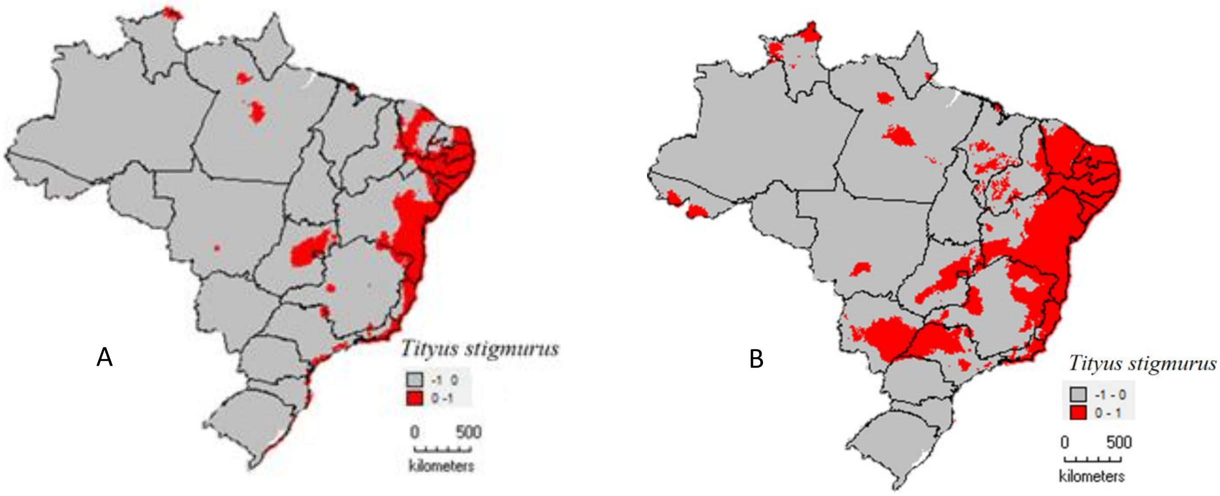
Ecological niche modeling for Tityus stigmurus in Brazil. (A) Current (1950-2000); (B) Future (2070)



Source: The authors.

Figure 6

Thresholded maps for Tityus serrulatus (A) Current (1950-2000); (B) Future (2070)



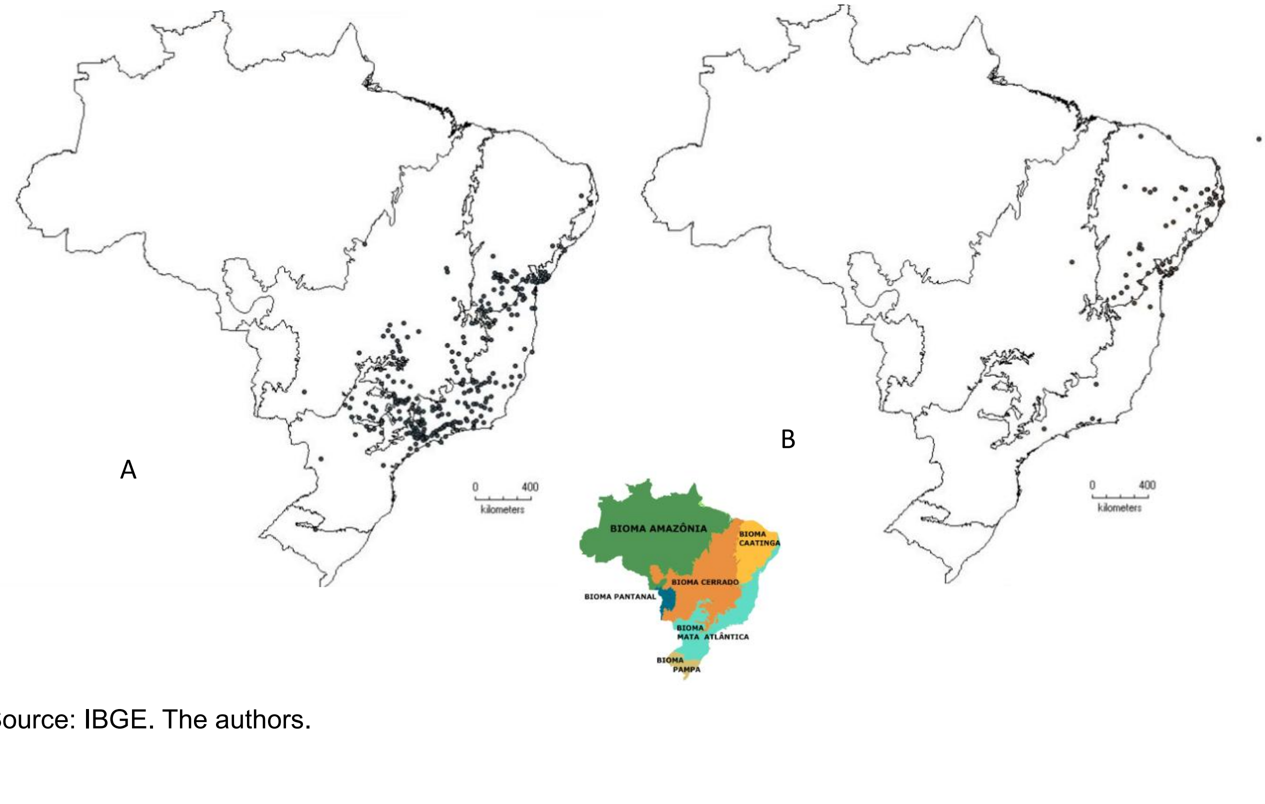
Source: The authors.

Distribution records of *T. serrulatus* and *T. stigmurus* were plotted also on a shapefile of Brazilian biomes (Figure 7). Results show the species occur in the Atlantic Forest, Caatinga and Cerrado, with an isolated record for *T. serrulatus* in the Pampas. Nevertheless, the region where both species occur is the Atlantic Forest, this information corroborated by the overlap of the models generated, indicating the strong influence of this biome in the distribution of the species.

T. serrulatus has a distribution concentrated in the Atlantic Forest with small areas of probable occurrence in Cerrado, whereas *T. stigmurus* shows higher occurrence probability in Atlantic Forest and Caatinga regions (Figures 8 and 9). This model also showed an overlap in the occurrence range for these species in the Atlantic Forest, although with some specificities: *T. serrulatus* is distributed almost entirely in the biome, with higher occurrence in southern areas, in regions with the highest temperature variation and lowest temperature records, whereas *T. stigmurus* is concentrated in northern areas, with less variation and more elevated temperatures. Occurrence limits for *T. serrulatus* are in Paraíba (São José da Mata; 07°10’54’’S 35°59’05’’W) in the north, Mato Grosso do Sul (Campo Grande; 20°28’11’’S 54°37’12’’W) in the west and Rio Grande do Sul (Porto Alegre; 30°02’04’’S 51°13’03’’W) in the south. For *T. stigmurus*, occurrence limits are Piauí (Picos; 07°04’39’’S 41°28’02’’W) in the north, Bahia (Barreiras; 12°08’51’’S 44°59’43’’W) in the west and São Paulo (Cajamar; 23°21’19’’S 46°52’42’’W) in the south.

Figure 7

Distribution of Tityus serrulatus (A) and Tityus stigmurus (B) in Brazilian biomes. Biomes



Source: IBGE. The authors.

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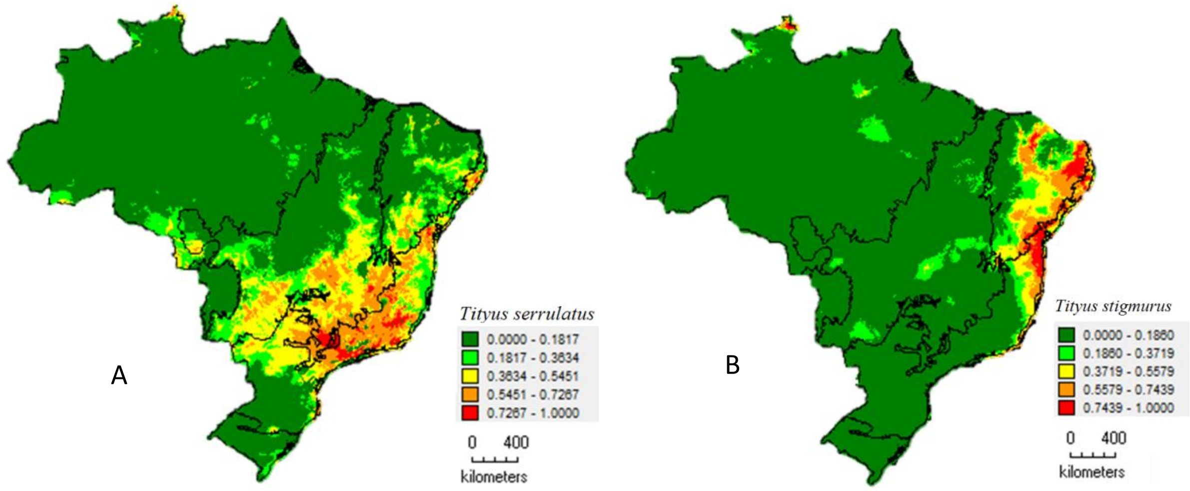
Figure 8

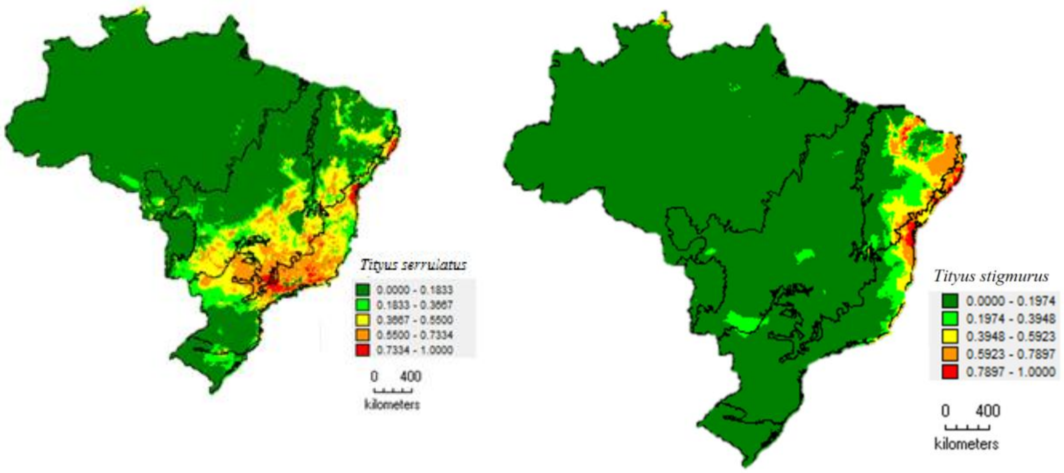
Current ecological niche models with distribution for Brazilian biomes. (A) Tityus serrulatus; (B) Tityus stigmurus



Source: The authors.

Figure 9

*Future niche models (2070) with distribution for Brazilian biomes. (A) Tityu***s** *serrulatus; (B) Tityus stigmurus*



Source: The authors.

4 DISCUSSION

The geopolitical distribution of *Tityus serrulatus* in Brazil has been recorded for the states of Rondonia, Piauí, Ceará, Rio Grande do Norte, Sergipe, Bahia, Goiás, Mato Grosso, Espírito Santo, Minas Gerais, Rios de Janeiro, São Paulo, Paraná, Santa Catarina and Rio Grande do Sul (Lourenço and Cloudsley-Thompson 1996, 1999; Torres *et al.*, 2002; Bortoluzzi, Querol and Querol, 2007; Brazil *et al.*, 2009; De Souza *et al.*, 2009; Lira-da-Silva *et al.*, 2009; Porto, Brazil & Lira-da-Silva, 2010; Almeida, 2010; Pucca *et al.*, 2015). We extend the range of this species to the states of Pernambuco, Paraíba, Distrito Federal, Mato Grosso do Sul and Tocantins. Our records indicate the northernmost limit is São José da Mata (Paraíba; 07°10’54’’S 35°59’05’’W), the southernmost one is Porto Alegre (Rio Grande do Sul; 30°02’04’’S 51°13’03’’W) and the westernmost one is Campo Grande (Mato Grosso do Sul; 20°28’11’’S 54°37’12’’W). We cannot reject the possibility this species was introduced through the Brazilian highway network along with the shipment of several materials, especially for construction. Lourenço and Eickstedt (2009) report the introduction of this species in Rondonia and Paraná states; Torres *et al*. (2002) report an accident in Porto Alegre (Rio Grande do Sul) during handling of products from other states; and Bortoluzzi *et al.* (2007) suggest the record of two specimens in Uruguaiana (Rio Grande do Sul) in a transportation company facility, might be due to its operation in several states in Brazil.

Tityus stigmurus has been recorded for northeastern Brazil (except Maranhão), and southeastern Brazil, in Minas Gerais state (Lourenço and Cloudsley-Thompson, 1996; De Souza *et al*., 2009; Almeida, 2010; Lira-da-Silva et al., 2009; Brazil and Porto, 2010; Porto, Brazil and Lira-da-Silva, 2010; Pucca *et al*., 2015). We extend the geopolitical distribution of this species to the states of Rio de Janeiro and São Paulo. Our records indicate its limits to be Picos in Piauí state (north; 07°04’39’’S 41°28’02’’W), Cajamar in São Paulo state (south; 23°21’19’’S 46°52’42’’W) and Barreiras in Bahia state (west; 12°08’51’’S 44°59’43’’W).

According to Stockmann (2015), *T. serrulatus* and *T. stigmurus* follow an r-selection ecological strategy, being opportunistic species that readily colonize their surroundings and have shorter and more frequent reproduction cycles. Despite the modification of their natural habitat in areas with intense anthropization, this does not constitute a problem, since both species are considered synanthropic and, in adequate conditions, show great capacity of adaptation, favoring their expansion.

These observations are in agreement with biogeographic characteristics mentioned by Lourenço (1986a) for the family Buthidae, one of the best-represented families in South America, due to its high plasticity and capacity of living and adapting to almost every type of environment and phytophysiognomy. This author also highlights the polymorphism shown by the vegetation in the continent, which created several favorable habitats for the occurrence and diversification of Scorpions, especially in the Andes region.

Results from distribution and ecologic niche modeling are congruent and high accuracy values confirm the validity of these models. These results, however, should be interpreted carefully, as actual distribution is based on occurrence records for the species, and models are based on biotic variables and are, therefore, limited. Regarding the first issue, data came from arachnological collections with research groups and professionals specialized in the group. Sampling and recording in these collections are naturally larger, implying that absence of records does not necessarily mean the species does not occur there. Regarding the second issue, if we account the variety of ecological niche concepts, modeling is limited to study the so-called “Grinnellian niche” (Sóberon, 2007), whereas several factors might influence the survival of a species in a specific area, not only abiotic conditions and variables. This bias, however, do not invalidate the importance of ecological niche modeling studies on forecasting areas with suitable conditions for species. For Scorpions, the present study can be considered pioneer. According to Buckley *et al*., (2009), Beatty and Provan (2010) and Lawson (2010), ecological niche models have been used for phylogenetic inferences in seaweed species (Neiva *et al.*, 2014), identification of geographic barriers and glacial refugia in the Atlantic Forest (Carnaval and Moritz, 2008), and even to identify or separate genetically distinct populations undergoing sympatric speciation (Peterson and Holt, 2003); they are also used to fill the gap of non-sampled areas which show basic conditions for the occurrence of the focal species.

Results show *T. serrulatus* and *T. stigmurus* are distributed along the same biomes: Atlantic Forest, Caatinga and Cerrado, in agreement with previous studies on the distribution of these species in Bahia state (Brazil *et al*., 2009; Porto, Brazil & Lira-da-Silva, 2010). Niche models indicate high occurrence probability of these species in Atlantic Forest regions, suggesting this biome exerts strong influence on their survival. However, this data is biased by the collections from which they came. According to Brazil & Porto (2010), 28 research groups in Brazil work with at least one research line about Scorpions. The two most active groups, which also most publish on this theme, are located in Bahia and São Paulo, both in Atlantic Forest regions. Therefore, we can assume this influence may result in larger sampling in these areas over others.

T. serrulatus is considered to be a typical species from transition and ombrophilous forests (Lourenço and Cloudsley-Thompsom, 1999). Its occurrence was strongly related to the annual mean temperature, both for current and future modeling. The mechanism for variable contribution analysis indicated this variable is responsible along for 57.1% of influence on the occurrence probability for the species. In future modeling, this variable accounts for 57.8% of the occurrence probability. Natural history data show this species inhabits warm and wet climate areas, reproducing all over the year (Lourenço and Eickstedt, 2009; Brazil and Lira-da-Silva, 2010). The Atlantic Forest offers these exact conditions and, even in anthropic regions in this biome, annual mean temperature variation is not high. However, there seems to be a temperature limit for the species. This inference is based on the fact the species tends to disappear in regions with elevated temperature, such as the

Caatinga and the upper region of the Atlantic Forest. Despite that, *T. serrulatus* presents larger occurrence in the southern portion of the Atlantic Forest, where there is a larger temperature variation along the seasons and lower temperature records during the winter. In Bahia, Brazil *et al*., (2009) reported this species shows a wide distribution, predominantly in forested environments similar to semi-deciduous seasonal forest, deciduous seasonal forest, dense ombrophilous forest, besides Cerrado, Caatinga and regions of ecological tension and with fluvial-marine influences (Restinga), with vertical distribution ranging from 8 to 1027 m.

Despite the incongruence observed in the analyses used to evaluate variable contribution, occurrence of *T. stigmurus* was explained by temperature annual range, where decrease of accuracy values was most expressive. Variable contribution analysis also showed temperature annual range contributed the most to explain the model (43.1% for current prediction and 40.5% for future prediction). If we associate these results to the data of original distribution, which showed the species distributed mainly in Caatinga areas and in elevated areas in the Atlantic Forest, where temperature is more elevated and constant, and that highest occurrence probability in the models are also for these areas, we can infer temperature variation is in fact the factor that most influences the occurrence of *T. stigmurus.* This is probably the limiting factor for the occurrence of this species in areas where temperature oscillations are constant, or even where temperature is lower, distinct to what happens to *T. serrulatus*. Higher probability in Caatinga in the models generated in this work do not agree with occurrence data for *T. stigmurus* in Bahia, which are predominantly in forested environments with altitude ranging from 5 to 1268m (Brazil *et al.*, 2009).

T. serrulatus and *T. stigmurus* are synanthropic animals, with high rates of proliferation and colonization in urban environments (Lourenço and Eickstedt, 2009). If we relate this fact to the loss of preserved areas and consequent urbanization undergone in the Atlantic Forest, which included it in the biodiversity hotspot list, it becomes clear the relation of this biome with the species studied herein. Besides, in this same biome we see the overlap region of occurrence records for these species, previously pointed out by Brazil *et al*. (2009). *Tityus stigmurus* is an aggressive species when associated to other species (personal observation) and this may explain why, in co-occurrence regions, it has been a more effective competitor and have colonized the main urban areas, to the detriment of *T. serrulatus*. In anthropic environments where *T. stigmurus* occur, even in regions with records for both species, *T. serrulatus* is restricted to forest fragments, whereas *T. stigmurus* colonized urban areas, as seen for example in the city of Salvador (Bahia) (Amorim *et al.,* 2002; Brazil *et al*., 2009).

A factor that might contribute to the actual and modeled distribution observed is the probable competitive exclusion ongoing between the model species and native species in the biomes where *T. serrulatus* and *T. stigmurus* do not show adaptive success. The competitive exclusion principle, proposed by Gause (1934), suggests animals that require equal resources cannot coexist, unless other ecological factors are different. When such situation occurs, one species will overcome the other, leading it to extinction, or generating strong ecological and evolutionary pressures leading the second species to occupy a different niche (Hardin, 1960). If we observe, for example, the Amazon region, we can notice there is no occurrence record for these species, where the main scorpion there found is *Tityus obscurus* (Gervais, 1843), one of the 4 species considered of medical importance in Brazil (Brasil, 2009). Large-sized and aggressive, *T. obscurus* occurs in all the biome, from Brazil to French Guiana, Ecuador, Venezuela, Guyana and Panama, apparently being well adapted to high temperatures and humidity in this environment (Fet *et al*., 2000; Lourenço and Leguin, 2008). Despite having a less lethal poison for humans than *T. serrulatus* and *T. stigmurus*, it can feed on insects, other Scorpions and small vertebrates (Cozijin, 2009). Its poison also cause serious accidents and might cause death (Hommel *et al.*, 2000; Pardal *et al*., 2014a; Pardal *et al.,* 2014b). This suggests that, perhaps, *T. obscurus* is a competitor for *T. serrulatus* and *T. stigmurus* in a biome where it is well adapted.

Another example, in a different biome, is the occurrence of two Scorpions in the genus *Rhopalurus* in Caatinga, also well adapted and predominant in this biome: *Rhopalurus rochai* (Borelli, 1910) and *Rhopalurus agamemnom* (C. L. Koch, 1839). These are large-sized, robust animals with no medical importance (Lira-da-Silva *et al.*, 2009). They inhabit not only Caatinga, but also part of the Brazilian Cerrado, being well adapted to high temperatures and water scarcity (Lourenço, 1986b; Lourenço and Pinto-da-Rocha, 1997; Yamaguti, 2011). These species might also constitute competitors, especially for *T. serrulatus*, which apparently does not support elevated temperatures.

In Cerrado, the predominant Scorpion is *Tityus trivittatus* Kraepelin, 1898, which occurs all the way to the final portion of Pampas and central region of Argentina. Those are medium-sized animals, with sexuate or facultative parthenogenic reproduction, and the greatest etiological agents in Argentina (Maury, 1997; Piola *et al*., 2006). In Brazil, there are no reports of serious accidents caused by this species. According to Lourenço and Cuellar (1994), *T. serrulatus* was initially restricted to Cerrado, which was considered its center of dispersion to other biomes. The question is whether the low occurrence of this species in this biome today is due to a process of competitive exclusion with *T. trivittatus* or to other biotic and/or abiotic factors.

Regarding the prediction done through ecological niche modeling, previous studies show its importance to extrapolate patterns, propose conservation areas based on species

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distribution and determine areas with future bioclimatic conditions suited to the species (Terribile *et al*., 2012; Oliveira *et al.*, 2014). In this study, however, we did not find significant predicted distribution areas to be accounted for, according to the usual parameters used in the model, except for *T. stigmurus*, where it is evident the arising and expansion of an occurrence area in northern Caatinga. Although this species already occurs in this biome, predictions allows us to note that, even if the future presents a rainier and wetter global scenario, this species is effectively well adapted to the biome, being capable of expanding its occurrence area in it, despite the adverse bioclimatic situation for the species' habits noted so far.

5 CONCLUSIONS

T. serrulatus and *T. stigmurus* are distinctively distributed in the Atlantic Forest, Caatinga and Cerrado, with overlapping area for both species in the Atlantic Forest, which presents the most favorable bioclimatic conditions for occurrence of both species.

Temperature seems to be the limiting factor for the occurrence of both *T. serrulatus* and *T. stigmurus*. Whereas the former apparently does not tolerate elevated temperatures and low humidity environments, the latter seems to be limited by temperature variation.

T. serrulatus is almost entirely distributed in the overlapping range for both species in the Atlantic Forest, including areas with lower temperature in southern portions, while *T. stigmurus* range seems to concentrate around northern areas, with higher temperatures and less temperature variation along the year.

Although literature indicates Cerrado was the site of initial dispersion for *T. serrulatus*, its low record numbers in this biomes indicates a probable competitive exclusion process with *T. trivittatus*, a species in the same genus and typical to Cerrado. This hypothesis, however, still needs to be investigated. The scarcity of records of *T. serrulatus* in Caatinga suggests the limiting factor for its occurrence might be elevated temperatures and a probable competitive exclusion process with species in the genus *Rhopalurus* (*R. rochai* e *R. agamemnom*), with the environment favoring their abundance (this hypothesis also needs further investigation).

Regarding *Tityus stigmurus*, it clearly showed its high adaptive success in the Caatinga biome, which presents all bioclimatic characteristics suited for the species (elevated temperature with minimum variation and low humidity). As for the Cerrado, both environmental bioclimatic characteristics and the presence of a competitor, *T. trivittatus*, might currently limit their occurrence.

Scarcity of data in the Amazon regions helps explain the absence of *T. serrulatus* and *T. stigmurus* in this biome, but limits us to infer such absence might be due to factors generated by competitive exclusion with *T. obscurus*, or to bioclimatic or ecological niche conditions adverse to the species.

These questions open new lines of research about the distribution of Brazilian Scorpions, which are still data deficient.

Finally, we conclude the best approach for biogeographic studies with highly plastic and synanthropic species is through biome use, and not state geopolitical boundaries. We suggest future studies should use characteristics such as anthropization and urbanization associated to biome maps, in order to raise inference on the impact of these environmental disturbances in the species distribution.

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AUTHOR CONTRIBUTIONS

COA gathered the samples, developed tools for data collection, performed bioinformatics analysis of sequence data analyzed the data, and wrote the manuscript. TKB edited the manuscript. RMLS gathered the samples, developed tools for data collection, and wrote the manuscript.

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APPENDIX

Tables (for each table, the legend should be placed before the body of the table).

Table 1

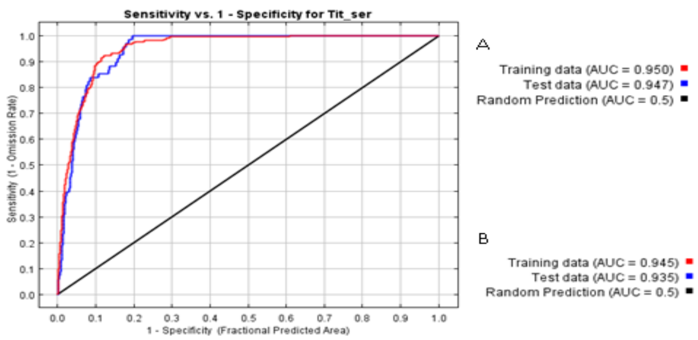
Institutions in which arachnological collections were consulted, separated by Brazilian state

State	Institution	Number of specimens	
		Tityus serrulatus	*Tityus stigmurus*
Rio Grande do Norte	Centro de Controle de Zoonoses, Secretaria Municipal de Saúde de Natal, Rio Grande do Norte, Brasil (CCZ/RN)	0	62
Paraíba	Centro de Assistência Toxicológica, Secretaria de Saúde da Paraíba, Brasil (CEATOX/PB)	0	373
Sergipe	Laboratório Central de Saúde Pública de Sergipe - Instituto Parreira Horta, Secretaria de Saúde de Sergipe, Brasil (LACEN/SE)	0	14
Pernambuco	Centro de Assistência Toxicológica, Secretaria de Saúde de Pernambuco, Brasil (CEATOX/PE)	0	164
Bahia	Centro de Informação Antiveneno, Secretaria de Saúde da Bahia, Brasil (CIAVE/SESAB/BA)	419	280
	Museu de História Natural da Bahia – MHNBA/Universidade Federal da Bahia, Brasil (MHB/UFBA)	1033	295
	Núcleo de Ofiologia e Animais Peçonhentos da Bahia/Universidade Federal da Bahia, Brasil (NOAP/UFBA)	786	486
	Universidade Estadual do Sudoeste da Bahia, Brasil (UESB)	0	09
	Universidade Federal de Pernambuco, Brasil (UFPE)	0	4
Rio de Janeiro	Museu Nacional da Universidade Federal do Rio de Janeiro, Brasil (MNUFRJ)	45	22
São Paulo	Instituto Butantan, Brasil (IB)	311	56
	Museu de Zoologia da Universidade de São Paulo, Brasil (MZUSP)	35	20
Total	-	2.629	1.785

Source: The authors.

Figure 10

Area under the curve, showing model accuracy. (A) AUC values for current (1950-2000) and (B) future (2070) models



Source: The authors.

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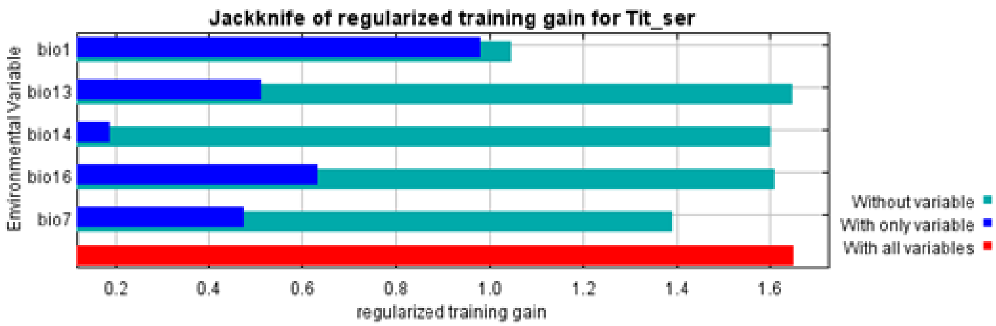
Figure 11

Jackknife and variable contribution analysis for current model of Tityus serrulatus (1950-2000)

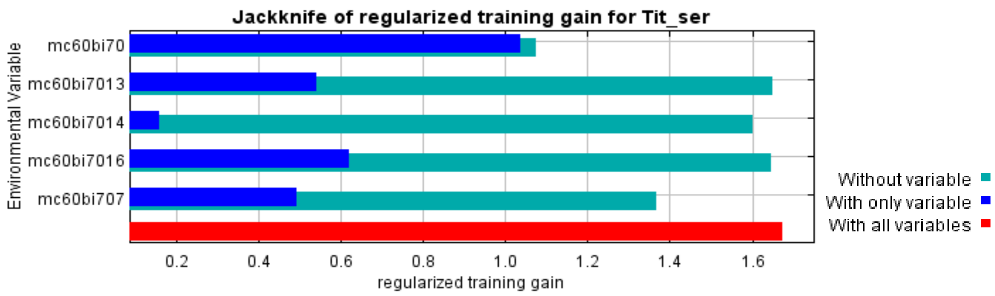


Variable	Percent contribution	Permutation importance
bio1	57.1	57.4
bio7	22.7	20.7
bio16	13.5	11.2
bio14	3.8	5.2
bio13	2.9	5.5

Source: The authors.

Figure 12

Jackknife and variable contribution analysis for future model of Tityus serrulatus (2070)

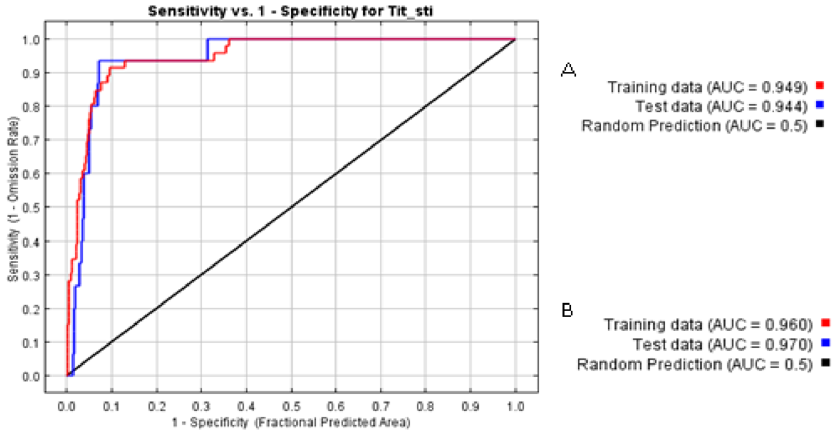


Variable	Percent contribution	Permutation importance
mc60bi70	57.8	45.9
mc60bi707	21.1	23.6
mc60bi7016	14.9	15.1
mc60bi7014	4.8	5.8
mc60bi7013	1.3	9.7

Source: The authors.

Figure 13

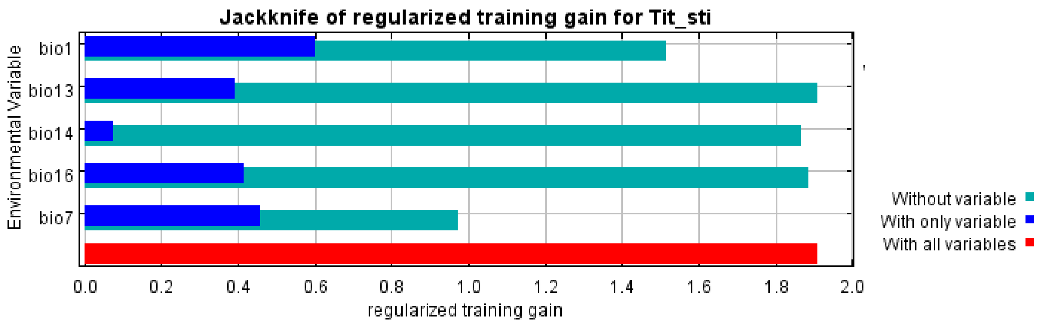
Area under the curve, showing model accuracy. (A) AUC values for current (1950-2000) and (B) future (2070) models



Source: The authors.

Figure 14

Jackknife and variable contribution analysis for current model of Tityus stigmurus (1950-2000)



Variable	Percent contribution	Permutation importance
bio7	43.1	56.4
bio16	27.7	23.5
bio1	22.7	14.3
bio13	4.4	0
bio14	2.2	5.8

Source: The authors.

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Figure 15

Jackknife and variable contribution analysis for future model of Tityus stigmurus (2070)

Variable	Percent contribution	Permutation importance
mc60bi707	40.5	47.9
mc60bi70	23.5	10.9
mc60bi7016	22	34
mc60bi7013	7.8	2.6
mc60bi7014	6.2	4.6

Source: The authors.