Macroecological approach for scorpions (Arachnida, Scorpiones): beta-diversity in Brazilian montane forests

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Macroecological approach for scorpions (Arachnida, Scorpiones): beta-diversity in Brazilian montane forests

S.I.A. Foerster¹*, A.M. DeSouza², A.F.A Lira³

¹Programa de Pós-Graduação em Genética, Departamento de Genética, Universidade Federal de Pernambuco, Avenida da Engenharia, s/n, Cidade Universitária, CEP 50740-580, Recife, Brazil. stenioit@gmail.com

²Programa de Pós-Graduação em Ciências Biológicas, Departamento de Sistemática e Ecologia, Universidade Federal da Paraíba, Cidade Universitária, João Pessoa, Paraíba, CEP 58051-900, Brazil. adriendrix@gmail.com

³Programa de Pós-Graduação em Biologia Animal, Departamento de Zoologia, Universidade Federal de Pernambuco, Rua Prof. Moraes Rego s/n, Cidade Universitária, Recife, Brazil, CEP 50670-420. andref.lira@gmail.com

*Author for correspondence: stenioit@gmail.com
Macroecological approach for scorpions (Arachnida, Scorpiones): beta-diversity in Brazilian montane forests

S.I.A. Foerster, A.M. DeSouza, A.F.A Lira

Abstract

The montane forests of northeastern Brazil are patches of rainforests, surrounded by xeric vegetation, originated during the expansion of rainforests in the Pleistocene epoch. Their historical processes make these areas ideal for biogeographical investigations of organisms, particularly in groups with low dispersion and habitat specificity, such as scorpions. We perform a macroecological investigation of the community assembly process of scorpions, disentangling the pattern of β-diversity to test the hypothesis that the similarity in the composition of scorpion fauna in areas of montane forests and coastal rainforests is greater when these localities are geographically close. We also investigated if larger patches of montane forests exhibit a positive species-area relationship. Our results state that species replacement accounts for 71% of the total scorpion β-diversity in montane forest remnants. Additionally, scorpion assemblages were influenced by the spatial arrangement, with a higher similarity between the fauna of montane forests and coastal forests when these areas were geographically close. We did not find a species-area relationship in montane forest patches. The expressive contribution of species replacement to the overall β-diversity may reflect both the high environmental heterogeneity and the historical and independent colonization events that took place in these areas.

Keywords: Macroecology, Biogeography, Scorpiones, Ecology, Caatinga, Brejos de altitude, Scorpions.
Introduction

Biogeographers and ecologists studying the origin and the variation of species composition at a regional scale are able to progressively record the historical and evolutive processes that generate regional diversity patterns; however, much more can be done through providing empirical support for the development of effective conservation strategies, such as the geographical delimitation of natural reserves. The diversity of a given taxon on a regional scale can be expressed as a function of evolutionary factors such as the timing and level of differentiation between lineages, as well as ecological aspects, including events of expansion and contraction of suitable habitats (Graham and Fine 2008). Similarly, this same perspective can be applied to explain the mechanisms of community assembly (Graham and Fine 2008; Cavender-Bares et al. 2009). The variation in species composition between sites within a region of interest is defined as β-diversity (Whittaker 1960, 1972) and its origins have been discussed based on three main hypotheses: I. biotic interactions, assuming that species composition is uniform throughout large areas, emphasizing the role of the hierarchy of dominance among competing species in the structuring of communities (Legendre et al. 2005; Tuomisto and Ruokolainen 2006; Kunstler et al. 2012; Segre et al. 2014), especially in closely related species (Weiher et al. 2011); II. random autocorrelated fluctuations, assuming that species are equivalent in demographic and competitive aspects; however, they present random differences in their spatial dispersion capabilities that justify the variation in species composition among sites (Hubbell 2001; Tuomisto et al. 2003; Legendre et al. 2005; Tuomisto and Ruokolainen 2006; Chase et al. 2010; Carvalho et al. 2011; Myers et al. 2013; Gianuca et al. 2017), in this case, low dispersal rates are commonly related to increases in β-diversity (Soininen et al. 2007; Myers et al. 2013; Hawkins et al. 2015); and finally, III. environmental conditions, wherein species composition is modulated by
environmental characteristics (Legendre et al. 2005; Veech and Crist 2007; López-González et al. 2015; Alahuhta et al. 2017). According to the last hypothesis, the landscape is a mosaic that possesses its own set of environmental characteristics (Legendre et al. 2005), and increased levels of β-diversity are expected to occur in landscapes with high environmental heterogeneity (Heino et al. 2015; López-González et al. 2015; Liu et al. 2018).

The first step in understanding the β-diversity relies on its quantification and several methods are available to do so (Wilson and Shmida 1984; Koleff et al. 2003; Legendre and De Cáceres 2013; Legendre 2014); some of them based on partitioning β-diversity into its two components: species replacement and richness difference (Harrison et al. 1992; Williams 1996; Lennon et al. 2001; Baselga 2010, 2012; Baselga and Orme 2012; Legendre 2014). According to Legendre (2014), the replacement component is a result of species turnover (gain or loss) over an ecological gradient that is sufficiently long, while the richness difference represents quantitative changes in species richness among sites. Elucidating these components is a key factor that can guide the establishment of natural reserves (Baselga 2010). For example, a high contribution of richness difference indicates the priority of areas with high levels of α-diversity, while the dominance of species replacement implies that species composition is not uniform among sites, extending the conservation priority to several sites within a landscape (Legendre et al. 2005; Baselga 2010; Gianuca et al. 2017).

Fragmented landscapes with high environmental heterogeneity tend to harbor a great variability in species composition when compared to contiguous homogeneous regions (Freestone and Inouye 2006; Veech and Crist 2007; Astorga et al. 2014; Socolar et al. 2016). In addition, special attention is given to patterns of β-diversity in topographically heterogeneous landscapes, which might be involved with dispersal
limitation of species (Finn et al. 2006; Astorga et al. 2014; Gonzáles-Reyes et al. 2017).
The montane forest remnants (MFRs) of northeastern Brazil are good examples of heterogeneous environments with an altitudinal contrast. These areas are pockets of rainforests located at altitudes above 600 m (Veloso et al. 1991), surrounded by a matrix of xeric vegetation known as Caatinga (Andrade-Lima 1982), which is classified as a Seasonally Tropical Dry Forest (Pennington et al. 2000; Santos et al. 2012). The origin of MFRs goes back to the Pleistocene when the Atlantic rainforest penetrated the Caatinga domain during its expansion and persisting only in environments with a suitable microclimate after retraction (Andrade-Lima 1982). While the Caatinga domain receives less than 900 mm of precipitation per year, the orographic rainfall that reaches the MFRs results in up to 1800 mm of precipitation per year (Andrade et al. 2018). Aside from its topographical profile, the biotic component that results in the high heterogeneity of MFRs is its complex vegetation physiognomy, compounded by typical elements of the Atlantic forests of southeastern Brazil, and species related to the Amazon rainforest (Prance 1982; Rizzini 1997; Ferraz et al. 1998; Rodal and Nascimento 2002; Bandeira et al. 2003; Tabarelli and Santos 2004; Santos et al. 2007). At the same time, endemic species of several groups occur in MFRs; however, from an evolutive perspective, their biota is still underestimated (Santos et al. 2007). Arthropods, for example, are an extremely representative group in tropical forests, reaching around 75 % of total biomass, and playing a key role in many ecosystem services in these environments (Wilson and Kinne 1990; Laurance et al. 2002). Nevertheless, only a few studies on arthropods of MFRs are available today (e.g. Lourenço 1988; Bandeira and Vasconcellos 2004; Locatelli et al. 2004; Silva et al. 2007).

Among litter-dwelling arthropods, scorpions are sensitive to environmental disturbances in tropical forests, responding especially to the negative effects of habitat
fragmentation (Lira et al. 2015, 2016, 2017). Scorpions are primarily sedentary animals (Benton 1992; Peretti et al. 1999; Yamaguti and Pinto-da-Rocha 2006; Nime et al. 2016), with low dispersal rates (Polis 1985; Nime et al. 2016; Lira et al. 2018), and some degree of habitat specialization has been attributed to this taxon (Polis 1990; Prendini 2001; Bryson Jr et al. 2013; Monod et al. 2013; Ojanguren-Affilastro et al. 2016). In addition, environmental factors, such as temperature, precipitation, edaphic properties (hardness, texture, soil and litter cover), and vegetation physiognomy have been found to be essential for structuring scorpion assemblages at the local scale (Foord et al. 2015). Thus, if we consider the MFRs of northeastern Brazil as “moisture islands” distributed across a matrix of xeric vegetation (Caatinga Dry Forest), an asymmetric contribution of the species replacement and richness difference on the overall $\beta$-diversity of scorpion assemblages in areas of MFRs could be expected. In addition, if the MFRs act as refugia for scorpions in the semiarid region of Brazil, there must be a species-area relationship (Connor and McCoy 1979, 2001) in these landscapes. Considering that low-dispersal organisms, such as scorpions, are highly informative tools to analyze biogeographical patterns at different scales of time and space (Bryson Jr et al. 2016), we investigated the scorpion assemblages of MFRs, quantifying the contribution of species replacement and richness difference to the overall $\beta$-diversity of these arachnids. We also tested the hypotheses that the similarity in the composition of the fauna of scorpions in areas of MFRs and coastal Atlantic forests is greater when these areas are geographically close to one another, and larger remnants of montane forests support a greater number of species, that is, a positive species-area relationship.

Materials and methods

Occurrence data and field work
Data on the occurrence of scorpions were obtained from inventories conducted at seven montane forest locations in the state of Pernambuco (Figure 1), located in the municipalities of Águas Belas (09°5'3.24"S, 37°3'4.32"W), Bonito (Reserva Municipal Mata do Mucury 08°30'57.72"S, 35°42'54.67"W), Brejo da Madre de Deus (Reserva Particular do Patrimônio Natural Mata do Bitury: 08°14'16.33"S, 36°24'30.27"W), Caruaru (Parque Natural Municipal João Vasconcelos Sobrinho: 08°22'50.03"S, 36°02'18.41"W), Inajá (Reserva Biológica da Serra Negra: 08°39'10.47"S, 38°13'9.72"W), Taquaritinga do Norte (07°54'58.29"S, 36°02'01.02"W), and Triunfo (Mata da Furna dos Holandeses: 07°50'18.49"S, 38°4'39.74"W). Fieldwork was conducted between April and July 2016, by two collectors equipped with tweezers and ultraviolet light lanterns. In each MFR, random walks were performed in three nights (07:00 pm – 01:00 am). Specimens were placed in containers containing 70% alcohol, and were then sent to the laboratory for identification. Species identification was performed according to Lourenço (1982, 2002), and Esposito et al. (2017). Voucher specimens were deposited in the arachnid collections at the Universidade Federal de Pernambuco, and Universidade Federal da Paraíba. We also included additional information on scorpion fauna of the Araripe National Forest, a MFR situated on the Araripe Plateau, in the state of Ceará (07°20'42"S, 39°25'6"W), and of the coastal Atlantic forest (CAF) areas in northeastern Brazil (Table S1). As a criterion for the inclusion of literature data in our analyzes, studies that comprise similar field procedures (collections at night with ultraviolet light) and sample effort (hours/area) were prioritized. In this way, to access the scorpion fauna of the Araripe National Forest, data from Azevedo et al. (2016) were included, while for the CAF, data from Lira and Albuquerque (2014), Lira et al. (2017), and Lira et al. (2019) were considered. The species *Troglorhopalurus lacrau* (Lourenço & Pinto-da-Rocha, 1997) (= *Rhopalurus brejo* Lourenço, 2014) was removed
from the dataset of Araripe Plateau, because it is a troglobilous species (Esposito et al. 2017), and its microhabitat requirements does not necessarily reflect the environmental conditions provided by a MFR. For comparison purposes, data on the scorpion fauna of Caatinga Dry Forests were also included (Araújo et al. 2010; Carmo et al. 2013). Although the sampling procedures applied in these studies does not meet the criterion mentioned above, they are the unique inventories conducted in Caatinga areas near to the MFRs.

Data analysis

We used a binary matrix of scorpion species per sample site (only areas of MFRs), as the input for the ‘adespatial’ package (Dray et al. 2018) in R software version 3.5.1 (R Core Team 2018) to measure and partition β-diversity into its two components (replacement and richness difference), based on Podani-family decomposition of Sørensen dissimilarity coefficient (Legendre 2014). To evaluate the effect of the spatial arrangement on scorpion assemblages among all sample sites, we performed principal coordinates of neighbourhood matrix (PCNM) (Borcard and Legendre 2002; Borcard et al. 2004; Legendre and Borcard 2006), using as the input, a matrix containing the geographical distances between the sample sites obtained from their respective geographical coordinates. We applied a detrended correspondence analysis (DCA) (Hill and Gauch 1980; Gauch 1982) to measure the heterogeneity of our dataset (species × sites matrix), following the recommendations of Lepš and Šmilauer (2003), and Legendre and Legendre (2012). Subsequently, the spatial eigenfunctions from the PCNM were used as explanatory variables in a canonical correspondence analysis (CCA), to measure the effect of spatial configuration on the scorpion assemblages of the sample sites. A permutation test for CCA (ANOVA-like) was used to test the significance of the CCA
results under 9999 permutations, and the adjusted coefficient of determination ($r^2_{adj}$) was applied to quantify the contribution of the spatial data on the variable response (community composition); $r^2_{adj}$ was also obtained using 9999 permutations. The similarity between scorpion assemblages was measured using cluster analysis based on the Bray-Curtis index, which is performed using the unweighted pair-group method with arithmetic mean (UPGMA) agglomeration method, and by non-metric multidimensional scaling (NMDS). Finally, the species-area relationship (SAR) was performed using the power function, which is a non-linear model suitable to describe any type of SAR (Dengler 2009). All analysis (PCNM, DCA, CCA, ANOVA-like, $r^2_{adj}$, UPGMA, NMDS, and SAR) were performed in the R software using the ‘vegan’ package (Oksanen et al. 2018).

The area of the MFRs was obtained by means of overlaying altimetric images in SRTM format, and Landsat-8 bands downloaded from the Earth Explorer platform (https://earthexplorer.usgs.gov/). The Landsat-8 bands were collected by the Operational Land Imager Sensor, and correspond to the bands 8, 4, 3, and 2 (Barsi et al. 2014). These bands were combined in ArcGIS version 10.2 (ESRI 2013) to produce images in RGB color scheme with a final resolution of 15 m (Fig. S1 and S2). ArcGIS software was also used to overlay the Landsat-8 and SRTM images, as well as to delimit the MFRs based on altitude and vegetation cover, and subsequently, to calculate the area ($Km^2$) of that delimitations. Maps were also created with ArcGIS software, using images in SRTM format and shapefiles from World Wide Fund for Nature - WWF (Olson et al. 2001), representing the vegetation cover of the CAF (code NT0151), and the ecotonal zone between CAF and the Caatinga Dry Forests (code NT0152).

Results
The scorpion γ-diversity of MFRs comprises 12 species, while only six species are reported for the CAF. Six scorpion species that occur in MFRs are not shared with CAF: *Ananteris franckei* Lourenço, 1982, *Bothriurus rochai* Mello-Leitão, 1932, *Hadrurochactas araripe* Lourenço, 2010, *Jaguajir agamemnon* (C.L. Koch, 1839), *Jaguajir rochae* (Borelli, 1910), and *Tityus martinpaechi* Lourenço, 2001. On the other hand, each scorpion species from CAF is present in at least one MFR (Table 1).

β-diversity analysis revealed a high contribution of the species replacement component (71%), in contrast to that of richness difference (29%), resulting in an overall β-diversity of 0.3076. The dataset representing the scorpion assemblages of the sample sites are markedly heterogeneous (length of the first axis on DCA = 4.1075), and the scorpion species composition is influenced by the spatial arrangement of the sample sites (CCA: $F = 2.6331; P < 0.01$). In addition, the spatial configuration of the sample sites explained 51% ($r^2_{adj} = 0.5128$) of the variation in scorpion species compositions in these localities. Cluster analysis from the scorpion assemblage, using UPGMA, resulted in two groups: the western group, comprising Araripe and Triunfo, and the central-eastern group, comprising all remaining MFRs including the CAF (Figure 2). These clusters were corroborated by non-metric multidimensional scaling (Figure 3), that resulted in a weak stress (0.0594). Finally, the steepness of the species-area relationship, inferred by the power function, did not show statistical significance ($z = 0.0827; P = 0.4167$).

Discussion

This study describes the pattern of scorpion β-diversity in montane forest remnants of northeastern Brazil, emphasizing the contribution of the species replacement and the richness difference components to the overall β-diversity, as well as its
relationship with the spatial arrangement of the study sites. The high species replacement between MFRs (71%) implies that the composition of scorpion species in these areas may be distributed across an ecological gradient, indicating that these environments can act as a refugia for scorpion β-diversity. The theory that the MFRs of northeastern Brazil represent a refugium for several taxa has been discussed extensively by Andrade-Lima (1982) and Vanzolini (1981). Subsequent studies also demonstrated the importance of MFRs for the maintenance of vertebrates (Mares et al. 1985; Araújo and da Silva 2017; Rocha et al. 2018), and invertebrates (Paluch et al. 2011; Monteiro et al. 2016) in the semiarid region of Brazil. For scorpions, our results support the notion that the MFRs of northeastern Brazil represent a microrefugium (sensu Rull 2009) as these environments are small areas that provide suitable conditions for the persistence of some scorpion species outside their main distribution area, which is the case in the following species: *Ananteris mauryi* Lourenço, 1982, *Tityus braziliæ* Lourenço & Eickstedt, 1984 and *Tityus pusillus* Pocock, 1893. These three species are associated with moist habitats under the rainforest domain (Lourenço 1982, 1988, 2010; Bertani et al. 2008; Porto et al. 2013; Lira et al. 2018), being rare or absent in inventories carried out in areas of Caatinga Dry Forest, where *J. rochae*, *Bothriurus asper* Pocock, 1893 and *B. rochai* are the most abundant species (Araújo et al. 2010; Carmo et al. 2013). In addition to the faunistic differences regarding scorpion communities of the Caatinga Dry Forest and MFRs, the pattern of scorpion β-diversity observed in our study, with an expressive contribution of the species replacement, can be interpreted as a result of distinct colonization events and community assembly mechanisms that occurred in the MFRs. In theory, the community assembly of the scorpion assemblages in MFRs can be correlated with the expansion of the Amazon and Atlantic rainforests during the climatic fluctuations of the Quaternary period (see Sobral-Souza et al. 2015), which has been recognized as a key factor in the formation of
the current vegetation cover in the MFRs (Tabarelli and Santos 2004; Wang et al. 2004; Montade et al. 2014; Rohde et al. 2014).

Between the specific taxa that occur in the western MFRs (Table 1), the genus Hadrurochactas Pocock, 1893 corresponds to a typical element of the Amazonian rainforest (Lourenço 2010, 2016). The presence of this genus on the Araripe plateau and Maranguape region (other MFRs not included in our analysis) provides further evidence for the contribution of the Amazon rainforest to the scorpion community assemblage of these two MFRs, already suggested by Lourenço (1988, 2010). It must be taken into account, however, that the occurrence of the genus Hadrurochactas Pocock, 1893 in the Maranguape region and Araripe Plateau is limited to the type localities of Hadrurochactas brejo (Lourenço, 1988) and H. araripe. In addition, the single record of H. araripe was made in 1963, while for H. brejo, the date of collection is unknown (Lourenço, 1988). Thus, new expeditions are needed (and encouraged) to provide a better resolution on the geographical distribution of chactid scorpions outside the Guyana-Amazon region, that represents its main distribution range (Lourenço, 2010). On the other hand, our results indicate the contribution of the coastal Atlantic forest to the scorpion community assembly of the MFRs that comprise the central-eastern group (Figure 2). Within the central-eastern group, the MFRs of Bonito, and Taquaritinga do Norte are situated in an ecotonal zone between the Caatinga Dry Forest and CAF (Figure 1) known as ‘Agreste’ (Ferreira et al. 2018). This ecotone is defined as a subdivision of the Caatinga Dry Forest, and its vegetation cover is broadly composed by typical Caatinga elements, with high abundance of Cactaceae and Bromeliaceae (Andrade-Lima 1960). Despite this, these three MFRs are well-defined, containing a combination of topographic, climatic and vegetation profile that differs from the surrounding vegetation (Tabarelli and Santos 2004). The MFRs of central-eastern group harbor some scorpion species typically
associated with the coastal Atlantic forest, such as *A. mauryi*, *T. pusillus*, and *T. brazilae* (Lira and Albuquerque 2014; Lira et al. 2018), both absent in the MFRs of the western group (Table 1, Figure 2). The pattern of scorpion species distribution among MFRs of the central-eastern group and CAF, is very similar to those reported by Rodal and Sales (2008) for plant communities of MFRs situated in the eastern slope of the Borborema Plateau (a geomorphological formation that includes Bonito and Taquaritinga do Norte). Interestingly, the hypothesis of the historical contribution of the Amazon and the coastal Atlantic forests to the scorpion community assembly of the western and central-eastern MFRs, respectively, is in accordance with the distribution models of Neotropical rainforests proposed by Sobral-Souza et al. (2015). According to these models, during the last glacial maximum, the range of the Amazon forest extended close to the region of the western MFRs (Araripe Plateau), while the coastal Atlantic forests expanded to the regions comprising the central-eastern MFRs. In fact, there is botanical evidence supporting the theory that the vegetation of MFRs is a result of floristic disjunction of both the Amazon and coastal Atlantic forests (Costa et al. 2003). Therefore, the variation in the rainforest ranges due to climatic fluctuations during the Quaternary period has been considered an important factor in shaping the current patterns of diversity and distribution of several taxa in the Neotropics (Haffer 1969; Cabanne et al. 2008; Carnaval and Moritz 2008; Turchetto-Zolet et al. 2013). In this way, the historical cycles of expansion and contraction of the Neotropical rainforest during the Quaternary period may have favored the migration of scorpion species from the Amazon and coastal Atlantic forests to the western and central-eastern MFRs, respectively.

The matrix of xeric vegetation that separates the MFRs is represented by the Caatinga, which is a vast and well-defined area of Seasonally Dry Tropical Forest (SDTF) that occurs mainly in northeastern Brazil (Pennington et al. 2000; Santos et al. 2012).
According to our spatial analysis, the similarity in the composition of scorpion species of MFRs and CAF is greater when these areas are geographically close to one another (Figure 3). Further, the fact that that the geographical configuration explains 51% of the scorpion species composition on the MFRs indicates that the Caatinga vegetation surrounding the MFRs is an effective barrier to the migration of these arachnids. This is true especially for scorpions that require moist environments, such as *A. mauryi*, *T. brazilae*, *T. pusillus* and Chactidae species (genus *Hadrurochactas*) because the climatic and edaphic conditions present in the xeric Caatinga are not conducive for the presence of these species. Finally, the unexpected pattern of species-area relationship (SAR) reported in our study requires further investigation, including data from other MFRs to predict if the scorpion richness is correlated to the remnant area. For the time being, the absence of SAR and the high species replacement between the MFRs, clearly indicate that conservation strategies should not be targeted exclusively to large areas or areas with high α-diversity, as some small patches of MFRs also act as microrefugia, harboring species that could not persist in the matrix of xeric vegetation that surrounds these moist islands.

Using scorpion bionomics and evaluating the patterns of β-diversity of these arachnids, we provide the first macroecological approach testing hypotheses regarding the community assembly of this species in eight montane forest remnants of northeastern Brazil. Furthermore, we provide empirical support that could be useful for the delimitation of priority areas for conservation purposes. The expressive contribution of species replacement to the overall scorpion β-diversity is a reflection of high environmental heterogeneity, as well as the historical and independent colonization events that took place in the MFRs. The Caatinga vegetation that surrounds the MFRs is an effective ecological barrier for the flow of rainforest scorpions, allowing several
degrees of faunistic differentiation between the MFRs. A recent study demonstrates that the MFRs are one of the most transformed ecoregions of northeastern Brazil (Silva and Barbosa 2017). Thus, independent of the area of the remnant forest or the levels of α-diversity, conservation strategies should address all MFRs, because these areas are equally important in providing a suitable habitat not only for scorpions but to any taxa that require mesic conditions similar to those of rainforests, and markedly different from those of the Caatinga Dry Forest.

References


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Table 1. Composition of scorpion assemblages of montane forest remnants and coastal Atlantic forest areas of northeastern Brazil assessed in this study: Águas Belas (AGU), Bonito (BON), Brejo da Madre de Deus (BRE), Caruaru (CAR), Inajá (INA), Taquaritinga do Norte (TAQ), Triunfo (TRI), Araripe (ARA), and coastal Atlantic forest (CAF).

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Figure 1. Graphical representation of the relief of the state of Pernambuco and the southern portion of the state of Ceará in northeastern Brazil, showing the sampling localities of montane forests: Águas Belas (Agu), Bonito (Bon), Brejo da Madre de Deus (Bre), Caruaru (Car), Inajá (Ina), Taquaritinga do Norte (Taq), Triunfo (Tri), and Araripe (Ara). Service Layer Credits: Earth Explorer (USGS), WWF, IBGE.

Figure 2. Cluster analysis based on the UPGMA agglomeration method, showing the relationship of the scorpion fauna of eight montane forest remnants of northeastern Brazil and the coastal Atlantic forest. The scale represents the dissimilarity between the scorpion fauna of the localities assessed using the Bray-Curtis index.

Figure 3. Bidimensional representation of the NMDS performed from the dissimilarity matrix (Bray-Curtis) of scorpion species composition in the sampling localities: coastal Atlantic forest (CAF), Águas Belas (AGU), Bonito (BON), Brejo da Madre de Deus (BRE), Caruaru (CAR), Inajá (INA), Taquaritinga do Norte (TAQ), Triunfo (TRI), and Araripe (ARA).
Supplementary material

Table S1. Data on the scorpion fauna of coastal Atlantic forest of northeastern Brazil extracted from literature.

Figure S1. Graphical representation of the montane forest remnants (polygons) of the central-eastern group: Águas Belas (A), Bonito (B), Brejo da Madre de Deus (C), Caruaru (D), Inajá (E), and Taquaritinga do Norte (F). All pictures were constructed using Landsat-8 images captured in 2016 by the Operational Land Imager Sensor.

Figure S2. Graphical representation of the montane forest remnants (polygons) of the western group, showing the remnants of Triunfo (A), and Araripe (B). All pictures were constructed using Landsat-8 images captured in 2016 by the Operational Land Imager Sensor.
Graphical representation of the relief of the state of Pernambuco and the southern portion of the state of Ceará in northeastern Brazil, showing the sampling localities of montane forests: Águas Belas (Agu), Bonito (Bon), Brejo da Madre de Deus (Bre), Caruaru (Car), Inajá (Ina), Taquaritinga do Norte (Taq), Triunfo (Tri), and Araripe (Ara). Service Layer Credits: Earth Explorer (USGS), WWF, IBGE.

200x192mm (600 x 600 DPI)
Cluster analysis based on the UPGMA agglomeration method, showing the relationship of the scorpion fauna of eight montane forest remnants of northeastern Brazil and the coastal Atlantic forest. The scale represents the dissimilarity between the scorpion fauna of the localities assessed using the Bray-Curtis index.

Cluster analysis based on the UPGMA agglomeration method, showing the relationship of the scorpion fauna of eight montane forest remnants of northeastern Brazil and the coastal Atlantic forest. The scale represents the dissimilarity between the scorpion fauna of the localities assessed using the Bray-Curtis index.
Bidimensional representation of the NMDS performed from the dissimilarity matrix (Bray-Curtis) of scorpion species composition in the sampling localities: coastal Atlantic forest (CAF), Águas Belas (AGU), Bonito (BON), Brejo da Madre de Deus (BRE), Caruaru (CAR), Inajá (INA), Taquaritinga do Norte (TAQ), Triunfo (TRI), and Araripe (ARA).

124x109mm (300 x 300 DPI)