





Effect of climate change in lizards of the genus *Xenosaurus* (Xenosauridae) based on projected changes in climatic suitability and climatic niche conservatism

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Abstract

Accelerated climate change represents a major threat to the health of the planet's biodiversity. Particularly, lizards of the genus *Xenosaurus* might be negatively affected by this phenomenon because several of its species have restricted distributions, low vagility, and preference for low temperatures. No study, however, has examined the climatic niche of the species of this genus and how their distribution might be influenced by different climate change scenarios. In this project, we used a maximum entropy approach to model the climatic niche of 10 species of the genus *Xenosaurus* under present and future suitable habitat, considering a climatic niche conservatism context. Therefore, we performed a similarity analysis of the climatic niche between each species of the genus *Xenosaurus*. Our results suggest that a substantial decrease in suitable habitat for all species will occur by 2070. Among the most affected species, *X. tzacualtipantecus* will not have suitable conditions according to its climatic niche requirements and *X. phalaroanthereon* will lose 85.75% of its current suitable area. On the other hand, we found low values of conservatism of the climatic niche among species. Given the limited capacity of dispersion and the habitat specificity of these lizards, it seems unlikely that fast changes would occur in the distribution of these species facing climate change. The low conservatism in climatic niche we found in *Xenosaurus* suggests that these species might have the capacity to adapt to the new environmental conditions originated by climate change.

KEYWORDS

climatic variables, cloud forest, conservation, endemism, extinction, niche overlap, tropical, vulnerability

1 | INTRODUCTION

The climatic niche of a species is the set of climatic variables delimiting the necessary conditions for it to reproduce and survive (Bonetti & Wiens, 2014), which is determined by adaptation to its

environment (Zúñiga-Vega et al., 2017) and the legacy of ancestry (Ackerly & Reich, 1999). Considering this, studying the specialization to a limited set of climatic conditions of a species could be important for understanding its response to climate change (Deutsch et al., 2008). The changes in climate originated by anthropogenic activities

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can have serious potential consequences for most species (Albon et al., 2017), particularly those that strictly depend on specific conditions of habitat (Parmesan, 2006).

In this context, Wiens et al. (2010) and Liu et al. (2017) proposed that the threat of climate change can be analyzed by climatic niche conservatism. This concept refers to the retention of certain characteristics of the ancestral fundamental niche over time and space (Wiens et al., 2010). Accordingly, it has been suggested that if the climatic tolerance of a species is not extensive enough to face new environmental conditions, then those species with strong niche conservatism must migrate or become extinct (Jackson, Gergel, & Martin, 2015; Wiens et al., 2010). For example, some reports have shown that several lizard species tend to maintain similar thermal preferences despite inhabiting different types of environments (Andrews, 1998; Bogert, 1949; Díaz de la Vega-Pérez, Jiménez-Arcos, Manríquez-Morán, & Méndez-De la Cruz, 2013; Grigg & Buckley, 2013; Rocha & Vrcibradic, 1996; Schall, 1977). This represents strong evolutionary evidence of the presence of conservatism in optimal thermal preferences in these groups of vertebrates (Adolph, 1990; Menezes & Rocha, 2011; Pianka, 1970; Stevens, 1982; Winne & Keck, 2004).

Range-restricted species often are particularly vulnerable to extinction due to the climate change that is happening presently; therefore, endemic species could be strongly affected (Ballesteros-Barrera, Martínez-Meyer, & Gadsden, 2007; Malcolm, Liu, Neilson, Hansen, & Hannah, 2006). This condition could be even more problematic if these species tend to conserve their climatic niche (Wiens et al., 2010). Many studies have used species distribution modeling to predict habitat suitability of endemic species in the future (García, Ortega-Huerta, & Martínez-Meyer, 2013; Thuiller et al., 2006).

However, evaluating whether these studied species conserve their niche has not been performed commonly. Therefore, besides evaluating the availability of areas with suitable climatic conditions for species in the future, it is also important to evaluate whether species show a tendency to conserve their climatic niche, which would help provide more information to better understand their capacity of response to climate change; these data could be obtained from reptiles, because as ectothermic organisms, they are good models to use to assess the impacts of climate change (Huey & Kingsolver, 1993; Valenzuela-Ceballos, Castañeda-Gaytán, Rioja-Paradela, Carrillo-Reyes, & Bastiaans, 2015).

Lizards of the genus *Xenosaurus* comprise a group of northern forms of Laurasian origin with a diversification in North America; therefore, they are considered as one of the oldest groups of lizards (Macey et al., 1999; Bhullar, 2011; Figure 1). Currently, distribution of the *Xenosaurus* species is associated with mountain chains that occur from northeastern Mexico to Alta Verapaz, Guatemala (Bhullar, 2011). Species of *Xenosaurus* occur in a broad altitudinal range of approximately 500–2,360 m, and they can be found in a wide variety of habitats, ranging from xerophytic tropical scrub to tropical montane cloud forest, and tropical rain forest (King & Thompson, 1968). Most species of the genus share behavioral and physiological characteristics, such as being thermoconformists and thigmotherms with preferences for relatively low temperatures (García-Rico, Díaz de la Vega-Pérez, Smith, Lemos-Espinal, & Woolrich-Piña, 2015). Some authors have suggested that the entire genus *Xenosaurus* might be very susceptible to rapid environmental changes (Nieto-Montes de Oca, 1999; Sinervo et al., 2010), which could be supported by the fact that most of these species are microendemic and have



FIGURE 1 Some species of *Xenosaurus* included in this study (a) *Xenosaurus agrenon*, (b) *X. mendozai*, (c) *X. newmanorum*, (d) *X. phalaroanthereon*, (e) *X. platyceps*, and (f) *X. tzacualtipantecus*

restricted dispersal abilities (Zamora-Abrego & Ortega-León, 2016). No study, however, has properly evaluated how climate changes might influence this group of lizards; therefore, the following question becomes relevant: how would lizard species of *Xenosaurus* respond if the conditions of their climatic niche are modified because of climate change?

In this project, we evaluated: (a) the extent of areas with suitable climatic conditions for the occurrence of the *Xenosaurus* species in the near future (2070), considering that these lizards conserve their climatic niche; and (b) whether the various species of *Xenosaurus* have different climatic niches, which could be evidence of lack of niche conservatism, favoring taxa with reduced areas with suitable living conditions in the future.

2 | METHODS

2.1 | Taxon sampling

The genus *Xenosaurus* is composed of 12 described species: *Xenosaurus agrenon*, *X. arboreus*, *X. grandis*, *X. mendozai*, *X. newmanorum*, *X. penai*, *X. phalaroanthereon*, *X. platyceps*, *X. rackhami*, *X. rectocollaris*, *X. sanmartinensis*, and *X. tzacualtipantecus* (Nieto-Montes de Oca, García-Vázquez, Zúñiga-Vega, & Schmidt-Ballardo, 2013). Additionally, six more species were recognized but not described by Nieto-Montes de Oca et al. (2017). We included 10 species of *Xenosaurus* in this study, following the taxonomy proposed by Nieto-Montes de Oca et al. (2017) in a phylogenetic analysis of the genus based on RADseq data: *X. agrenon*, *X. grandis*, *X. mendozai*, *X. newmanorum*, *X. phalaroanthereon*, *X. platyceps*, *X. rackhami*, *X. rectocollaris*, *X. sanmartinensis*, and *X. tzacualtipantecus*. The species *X. arboreus*, *X. penai*, and the other six species mentioned

but not described by Nieto-Montes de Oca et al. (2017) were not included in this analysis because available information is scarce. Occurrence data of the *Xenosaurus* species were obtained from three sources: (a) field geographic records collected by the authors in a period of more than 10 years, since 2006, (b) published records (Ballinger, Lemos-Espinal, Sanoja-Sarabia, & Coady, 1995; Ballinger, Lemos-Espinal, & Smith, 2000; García-Rico et al., 2015; Lemos-Espinal & Smith, 2005; Lemos-Espinal, Smith, & Ballinger, 2003a,b; Nieto-Montes de Oca, 1999; Rojas-González, Jones, Zúñiga-Vega, & Lemos-Espinal, 2008; Woolrich-Piña, Lemos-Espinal, Oliver-López, & Smith, 2012; Zamora-Abrego & Ortega-León, 2016), and (c) unpublished data of ANMO. The number of occurrence records collected for each species was *X. agrenon* (25), *X. grandis* (110), *X. mendozai* (60), *X. newmanorum* (40), *X. phalaroanthereon* (12), *X. platyceps* (62), *X. rackhami* (70), *X. rectocollaris* (31), *X. sanmartinensis* (41), and *X. tzacualtipantecus* (40). The database for this study consisted of 491 geographic records (Figure 2).

Specimen sampling was performed on public and private lands, with the corresponding permission of the owners. Fieldwork was carried out under the scientific collecting permit SGPA/DGVS/02419/13, granted by the Mexican Secretary for Environment and Natural Resources (SEMARNAT). We only obtained records based on observation and invasive procedures were not performed on the lizards.

2.2 | Selection of climatic variables

Climatic information was obtained from the 19 current climatic layers available in WorldClim (Hijmans, Cameron, Parra, Jones, & Jarvis, 2005). These were used to describe the climatic niche of each *Xenosaurus* species. These climatic layers contain annual means of the

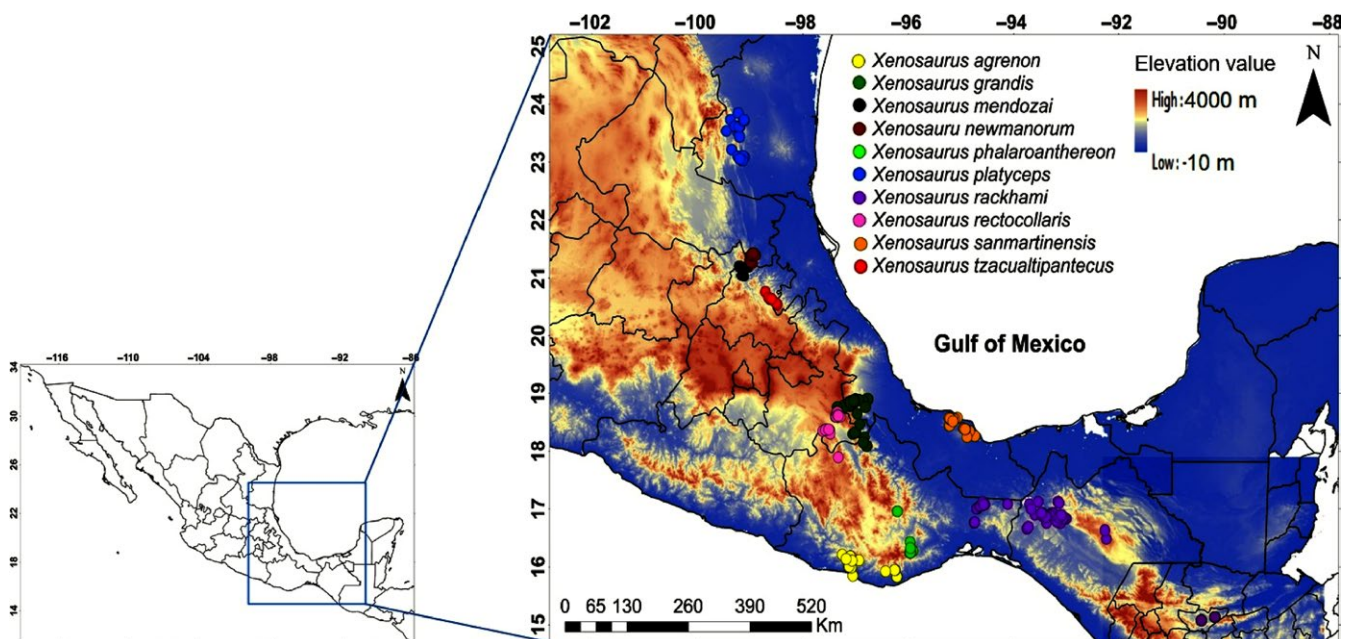


FIGURE 2 Distribution of the records of the 10 species of *Xenosaurus*. Map showing the records evaluated in our study

meteorological conditions recorded from the period 1950–2000 with a spatial resolution of 2.5 arc-minutes. We trimmed the spatial extent of the variables in ArcGIS to include the area from Mexico and Guatemala and included the resolution of our data in one km² (ESRI 2014).

Subsequently, to identify the variables with the greatest contribution in explaining the spatial-environmental variation for each species, an analysis of bivariate correlation of Pearson was performed among all the environmental variables pairs to check for collinearity among the input variables in the program STATISTICA ver 10 (StatSoft Inc, 2004; Merow, Smith, & Silander, 2013; Varela, Anderson, García-Valdés, & Fernández-González, 2014), and only variables with correlation values of less than 0.7 ($r < 0.7$) were retained. Seven climatic variables were selected when performing this procedure: Bio1 (annual mean temperature), bio7 (annual range temperature), bio11 (annual mean temperature of the coldest quarter), bio12 (annual precipitation), bio 14 (precipitation of the driest month), bio17 (precipitation of the driest quarter), and bio18 (precipitation of the warmest quarter).

2.3 | Climatic niche modeling (habitat suitability)

We used the Maximum Entropy modeling method (Phillips, Anderson, & Schapire, 2006) implemented in the software MaxEnt version 3.3.1 (Phillips, Dudik, & Schapire, 2004), to develop niche models of habitat suitability for each *Xenosaurus* species. MaxEnt is a maximum entropy-based program that estimates the probability distributions of a species in a geographic space using occurrence records and environmental data (Phillips et al., 2006). This modeling algorithm only requires presence data and has relatively good performance when compared to other presence-only methods (Elith et al., 2006). To establish the areas that maintain the environmental conditions of the species and that could be occupied by them (Burgman & Fox, 2003; Elith et al., 2011), MaxEnt generates habitat suitability maps scaling from zero (low suitability) to 1 (high suitability; Elith et al., 2011). Data of the seven bioclimatic variables used for the study were collected for the whole background using the software ArcMap version 10.3.

Successful calibration is important for datasets that suffer from sampling bias and for studies that require transfer models through space or time, for example, climate change response (Elith, Kearney, & Phillips, 2010; Moreno-Amat et al., 2015). Therefore, for the construction of the models, the dataset used in MaxEnt was randomly divided as follows: 75% of the data was used for the model construction or calibration, and the remaining 25% was used to evaluate the adjustment of the model (Cianfrani, Lay, Hirzel, & Loy, 2010).

Information obtained from each model was projected in order to identify potential areas under current climatic conditions and the scenario of the climate change RCP85-2070. We used projections to the year 2070 employing the environmental variables records available on the WorldClim database, which are calculated from future climate projections of General Circulation Models (Hijmans et al., 2005). The RCP 85 assumes that global greenhouse gas concentration trajectories will continue to rise throughout the XXI century and will stabilize in the year 2100 (Meinshausen et al.,

2011). We evaluated MaxEnt model performance using a fifteen-fold cross-validation of the area under the curve (AUC) of the receiver operating characteristic curve (ROC). Models with an AUC score of 0.5 indicated a model performing randomly, while models with an AUC score of 1 indicated a perfect model (Lobo, Jiménez-Valverde, & Real, 2007; Phillips, Dudik, & Schapire, 2004). The best model among the 15 cross-validations for each species (the model with the highest AUC) was converted into a binary map (presence-absence), using the logistic threshold considering maximum training sensitivity plus specificity, which had the best characteristics for each model. These conversions were performed in ArcMap version 10.3. Finally, to assess the impact of climate change in *Xenosaurus*, the percentage of change between current and future conditions was obtained using the formula: % of change = $[(S1-S0)/S0]*100\%$, where S0 is the suitable area for each species according to the baseline scenario and S1 is the suitable area for each species under future climatic conditions (Gutiérrez & Trejo, 2014).

2.4 | Similarity of climatic niche

Comparison of climatic niche among the 10 species of the genus was carried out using the analytical framework developed by Broennimann et al. (2012) available in the library ecospat (Di Cola et al., 2017) for R version 3.3.2 R Core Team, including the environmental variables retained in the analyses of bivariate correlation. We used the Principal Component Analysis Approach (PCA-environmental), where we extracted the first two axes of a PCA including the seven bioclimatic variables selected in our study to represent the climatic niche. Environmental space was divided in a grid of 100 × 100 cells, and each cell represented a single vector of the environmental conditions that occur in one or more sites in the geographic space (Broennimann et al., 2015; Hu et al., 2016). A Kernel density function was employed to calculate the density of occurrence of each species and number of sites, with particular environmental conditions for each cell of the environmental space.

Niche overlap between species in the environmental space was measured by the Schoener D metric (Schoener, 1970), and niche similarity tests were performed according to Warren, Glor, and Turelli (2008), using 100 randomizations in the null model. When the observed niche overlap value was significant ($p < 0.05$) based on this two-way test (similarity of species A vs. B and of species B vs. A), the climatic niches of both species were considered similar, indicating that one species predicts the climatic niche of the other better than would be expected by chance under a specific null model.

3 | RESULTS

3.1 | Habitat suitability modeling

Distribution models showed an AUC value above 0.74 for the 10 species of *Xenosaurus*, thus suggesting that the obtained models had high quality and the bioclimatic variables that most contribute

TABLE 1 Comparison of the top model runs for each species. Values of area under the receiver operating curve (AUC), maximum training sensitivity plus specificity of the models of habitat suitability of the 10 species of the genus *Xenosaurus* are represented. The bioclimatic variables that contributed the most to their construction for each species of *Xenosaurus* were: Bio1 (annual mean temperature), bio7 (annual range temperature), bio11 (annual mean temperature of the coldest quarter), bio12 (annual precipitation), bio 14 (precipitation of the driest month), bio17 (precipitation of the driest quarter), and bio18 (precipitation of the warmest quarter)

Species	Highest AUC current/Maximum test sensitivity plus specificity threshold	Four more important variables and percent of contribution
<i>Xenosaurus agrenon</i>	0.79/0.7	Bio 7(44.2), bio 12(35), bio 14(13.8), bio 1(6)
<i>Xenosaurus grandis</i>	0.93/0.3	Bio 12(41.7), bio 14(27), bio 7(9.4), bio 11(9.2)
<i>Xenosaurus mendozai</i>	0.96/0.09	Bio 14(47.5), bio 7(31.2), bio 12(20.1), bio 11(0.5)
<i>Xenosaurus newmanorum</i>	0.91/0.8	Bio 14(65.1), bio 18(22.9), bio 7(11.9), bio 17 (2.3)
<i>Xenosaurus platyceps</i>	0.94/0.7	Bio 14(36.7), bio 7(29.8), bio 18(13.5), bio 17(13.3)
<i>Xenosaurus phalaroanthereon</i>	0.86/0.5	Bio 7(75.3), bio 17(15.2), bio 12(4.3), bio 1(4.1)
<i>Xenosaurus rackhami</i>	0.88/0.4	Bio 7(67.4), bio 12(19.3), bio 14(7.2), bio 18(2.3)
<i>Xenosaurus rectocollaris</i>	0.74/0.5	Bio 7(36.9), bio 1(35.3), bio 12(25.3), bio 17(2.5)
<i>Xenosaurus sanmartinensis</i>	0.95/0.9	Bio 14(42.5), bio 7(34), bio 12(21.2), bio 11(2.3)
<i>Xenosaurus tzacualtipantecus</i>	0.83/0.8	Bio 14(80.8), bio 11(18.7), bio 18(1), bio 17(0.5)

to the models' calibration were Bio7 = Temperature Annual Range, Bio12 = Annual precipitation, and Bio14 = Precipitation of driest month (Table 1).

Considering a scenario of climatic niche conservatism, all *Xenosaurus* species showed a decrease in their areas of habitat suitability in the future. *Xenosaurus tzacualtipantecus* showed the smallest suitable area (55.13 km²), whereas the model obtained for *X. rackhami* had the largest suitable area (16,203.11 km²) under current climatic conditions. On the other hand, the projected models for the year 2070 showed a 100% area loss for *X. tzacualtipantecus*, whereas *X. rackhami* maintained the largest suitable area (11,333.18 km²) (Table 2; Figure 3).

3.2 | Similarity of climatic niche (conservatism)

The results of the analyses of climatic niche similarity are presented in Table 3. In general, the values of climatic niche similarity among *Xenosaurus* species were low, suggesting low niche conservatism in this genus. Only the following species pairs showed climatic niche similarity ($p \leq 0.05$): *X. grandis*-*X. platyceps*, *X. mendozai*-*X. platyceps*, *X. platyceps*-*X. rackhami*, *X. phalaroanthereon*-*X. rackhami*, and *X. rackhami*-*X. sanmartinensis*. Finally, *X. agrenon*, *X. rectocollaris*, *X. newmanorum*, and *X. tzacualtipantecus* were not significantly similar to any of the other nine species of the genus (Table 3; Figure 4).

4 | DISCUSSION

Most of the *Xenosaurus* species studied in this research showed a decrease in habitat suitability in the future considering a climatic niche conservatism scenario (Díaz de la Vega-Pérez et al., 2013; Rocha & Vrcibradic, 1996). Thus, it would be expected that the species of lizards of this genus should be vulnerable to climate change because this will modify the environmental parameters of the climatic niche where the species occur (Gabriel, Robock, Xia, Zambri, & Kravitz, 2017). For example, the results of the niche models for species *X. grandis*, *X. mendozai*, *X. phalaroanthereon*, *X. rectocollaris*, and *X. tzacualtipantecus*, which inhabit temperate and cold ecosystems, showed a dramatic decrease in their habitat suitability by 2070. Similar patterns have been reported by Espinosa and Ocegueda (2008) and Villers-Ruiz and Trejo-Vázquez (1997), who mentioned that the distribution range of vegetation of ecosystems with Nearctic affinities (associated with cold climates) will decrease due to climatic change. Therefore, on the basis of the aforementioned evidence, it is reasonable to infer that the genus *Xenosaurus* will be exposed to a high vulnerability risk due to climatic change. In this sense, Lemos-Espinal et al. (2003a) pointed out that *X. grandis* might persist in croplands that provide the minimum requirements of microhabitat and native vegetation cover. However, the areas predicted by its habitat suitability model in the future, include croplands and urban settlements, which reduce the

TABLE 2 Area with suitable climatic conditions in the present and projected future and rate of change of habitat suitability

Species	Current suitable area (km ²)	2070 projected area (km ²)	Change rate (%)
<i>Xenosaurus agrenon</i>	8,356.33	6,754.87	-19.17
<i>Xenosaurus grandis</i>	10,693.59	2,654.21	-75.18
<i>Xenosaurus mendozai</i>	13,539.78	6,444.62	-52.40
<i>Xenosaurus newmanorum</i>	70.10	40.67	-41.99
<i>Xenosaurus phalaroanthereon</i>	75.65	10.78	-85.75
<i>Xenosaurus platyceps</i>	2,168.36	1,601.22	-26.15
<i>Xenosaurus rackhami</i>	16,203.11	11,333.18	-30.6
<i>Xenosaurus rectocollaris</i>	1,102.33	402.59	-63.47
<i>Xenosaurus sanmartinensis</i>	134.29	75.63	-43.68
<i>Xenosaurus tzacualtipantecus</i>	55.13	0	-100

possibility of occupying these sites due to the particular ecological characteristics of this species, such as high microhabitat specificity and low dispersion capacity, and therefore, the future survival of its populations will be at high risk (King & Thompson, 1968).

On the other hand, habitat suitability area for species with tropical affinities (tropical montane cloud forests), such as *X. agrenon*, *X. newmanorum*, *X. platyceps*, *X. rackhami*, and *X. sanmartinensis* (Lemos-Espinal, Smith, & Woolrich-Piña, 2012), diminishes to a lesser extent than that of species of temperate and cold environments. Important portions of the climatic niche of these, however, are lost. For example, for the species *X. newmanorum*, the suitable habitat to live in the north of the state of Hidalgo will disappear. An analysis of potential future ecosystem distributions in South America suggests that large extensions of Amazonian rainforest could be replaced by tropical savannahs due to the increase in temperature and decreased rainfall (Lapola, Oyama, & Nobre, 2009). Even if environmental conditions were maintained in the future, changes in vegetation structure could affect these tropical species negatively (Turner, 1996).

According to the variables that contributed the most to the climatic niche models (see Table 1), it is evident that precipitation regime is very important for *Xenosaurus* lizards; also, our results indicate that a decline in precipitation conditions for this species in the area they inhabit is expected under all scenarios, causing more hostile environments for the lizards. For example, Lavergne, Mouquet, Thuiller, and Ronce (2010) noted that organisms might not be able to adapt to climate change if the rate of change is too rapid and the demography is not sufficiently dynamic. Therefore, one of the crucial questions in the debate on ecological effects of climate change is whether species will be able to adapt rapidly enough to keep up with the rapid pace of changing climate (Parmesan, 2006; Wiens et al., 2010).

Our results show that members of the genus *Xenosaurus* have a low similarity among their climatic niches, suggesting low niche conservatism and a tendency to niche shift. Such patterns have been found already in other animal species (Pyron & Burbrink, 2009;

Rodrigues, Pacheco Coelho, & Diniz-Filho, 2016; Strubbe, Beauchard, & Matthysen, 2015). This also might explain the high environmental variability reported for most of the species of *Xenosaurus* (King & Thompson, 1968; Nieto-Montes de Oca, Campbell, & Flores-Villela, 2001). Besides, according to the lack of conservatism, *Xenosaurus* species presenting strong reductions in their habitat suitability area in the future, such as *X. phalaroanthereon*, *X. rectocollaris*, and *X. tzacualtipantecus*, might not have the ability to successfully adapt quickly to different conditions imposed by climatic change (Wiens et al., 2010).

The similarity of the climatic niche found in this study does not show a grouping pattern similar to those reported in the recent phylogeny of the *Xenosaurus* lineage proposed by Nieto-Montes de Oca et al. (2017). Therefore, these results might represent clear evidence that lizard species of *Xenosaurus* do not conserve their ancestral climatic niche. For instance, our results showed that there is only similarity of the climatic niche among the species *X. grandis*, *X. mendozai*, *X. phalaroanthereon*, *X. platyceps*, *X. rackhami*, and *X. sanmartinensis*. If we compare our results with the recent phylogeny, however, only the species *X. platyceps* and *X. mendozai* that belong to the most northern clade (clade *newmanorum*), and the species *X. rackhami* and *X. sanmartinensis* of the most southern clade (clade *rackhami*) present niche similarity among closely related species, reflecting the little similarity of the climatic niche among the species in this study. Therefore, our findings could be interpreted in light of the group's evolutionary history, considering that *Xenosaurus* taxa are found in independent evolutionary trajectories (Nieto-Montes de Oca et al., 2017). For example, each species presents different strategies and thermal needs that could also be promoting the variation of life histories presented by each of the species, determined in turn by local adaptations that characterize the populations (Zúñiga-Vega et al., 2017).

Even the lack of niche conservatism, might not be enough for *Xenosaurus* to successfully adapt in the future. For example, there is evidence that most of the species of *Xenosaurus* need a dense vegetation

FIGURE 3 Habitat suitability area from models projected in current and future (2070 RCP85) climatic conditions. Gray color areas represent the climatic niche projected for the species (a) *Xenosaurus agrenon*, (b) *X. grandis*, (c) *X. mendozai*, (d) *X. newmanorum*, (e) *X. phalaroanthereon*, (f) *X. platyceps*, (g) *X. rackhami*, (h) *X. rectocollaris*, (i) *X. sanmartinensis*, and (j) *X. tzacualtipantecus*

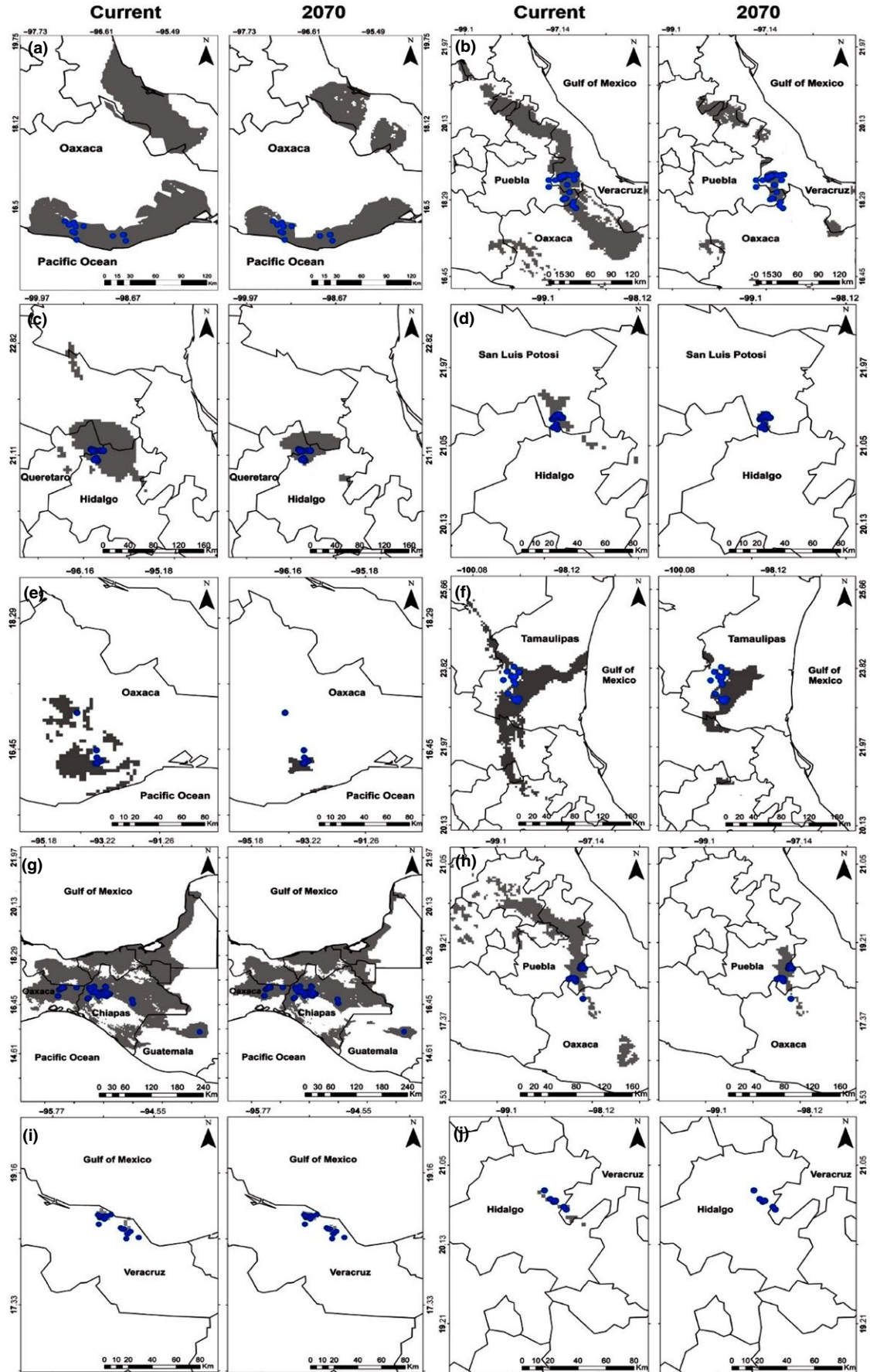


TABLE 3 Similarity indices (overlap) of the climatic niche of the species (D) and significance (PD). Species abbreviations are: *Xenosaurus agrenon* (sp1), *X. grandis* (sp2), *X. mendozai* (sp3), *X. newmanorum* (sp4), *X. platyceps* (sp5), *X. phalaroanthereon* (sp6), *X. rackhami* (sp7), *X. rectocollaris* (sp8), *X. sanmartinensis* (sp9), and *X. tzacualtipantecus* (sp10)

Species	Sp2	Sp3	Sp4	Sp5	Sp6	Sp7	Sp8	Sp9	Sp10
Sp1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.217 PD = 0.207-0.009	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp2	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.019 PD = 0.019-0.019 ^a	D = 0 PD = 1-1	D = 0.172 PD = 0.772-0.029	D = 0.060 PD = 0.009-0.217	D = 0.127 PD = 0.009-0.485	D = 0 PD = 1-1
Sp3	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.229 PD = 0.029-0.029 ^a	D = 0 PD = 1-1	D = 0.042 PD = 0.475-0.009	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp4	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.022 PD = 0.732-0.009	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp5	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.068 PD = 0.772-0.009	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp6	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.218 PD = 0.009-0.019 ^a	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp7	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0.013 PD = 0.72-0.01	D = 0.349 PD = 0.009-0.019 ^a	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp8	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp9	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1
Sp10	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1	D = 0 PD = 1-1

Note. ^aClimatic similarity.

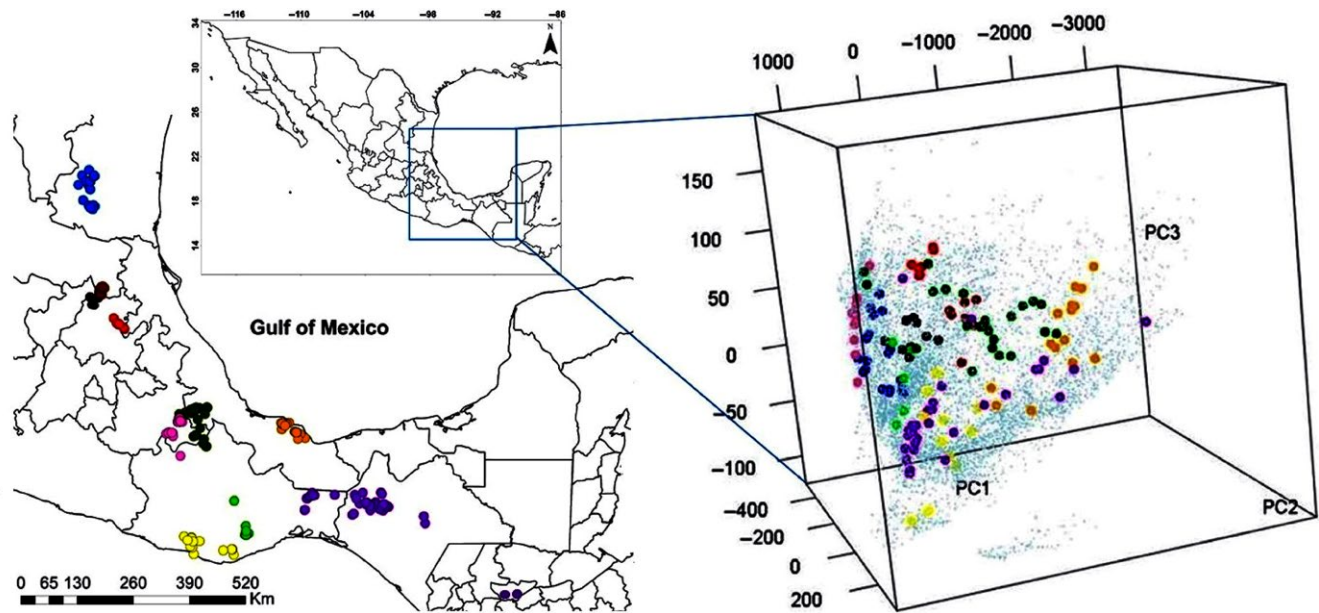


FIGURE 4 Distribution of the genus *Xenosaurus* in the PCA of climatic space. The figure shows the environmental space of *Xenosaurus agrenon* (yellow dots), *X. grandis* (dark green dots), *X. mendozai* (black dots), *X. newmanorum* (brown dots), *X. phalaroanthereon* (light green dots), *X. platyceps* (sharp blue dots), *X. rackhami* (purple dots), *X. rectocollaris* (pink dots), *X. sanmartinensis* (orange dots), and *X. tzacualtipantecus* (red dots). Small dots in blue color show the climatic space

cover to survive and reproduce. Authors such as Nieto-Montes de Oca (1999), Lemos-Espinal and Smith (2005), and Lara-Tufiño, Ramírez-Bautista, Hernández-Austria, Wilson, and Berriozabal-Islas (2013) pointed out that native vegetation cover provides suitable conditions of humidity and temperature for thermoregulation; therefore, these factors are necessary for the persistence of the species. Thus, if vegetation is disturbed by anthropogenic activities or by climate change, *Xenosaurus* species might lose most of their needed micro-climatic conditions.

In conclusion, we found that *Xenosaurus* species will face strong reductions in their suitable climatic area due to climate change and that the low values obtained from the indices of climatic similarity among the *Xenosaurus* species suggest that they could respond to local environmental changes. The persistence of the species of *Xenosaurus*, depends on several factors, such as speed of climate change, accessibility of areas to migrate, vegetation structure, dispersion rate, thermal tolerances, and the change in dimensions of the biotic niche (e.g., new predators and competitors; Loarie et al., 2009). Then, even our optimistic finding of niche shift might not be enough for these species to prevail. For example, species of *Xenosaurus* need micro-environmental conditions for survival and reproduction (Ballinger et al., 1995; Lemos-Espinal & Smith, 2005). Therefore, our models could have biases in their accuracy, because these models only consider environmental variables at macro-scale levels and do not take into account micro-environmental conditions and interactions (Mateo, Felicísimo, & Muñoz, 2011). Therefore, we propose to do more fine-scale studies of ethology and thermal ecology (López-Alcaide, Nakamura, Macip-Ríos, & Martínez-Meyer, 2014) in order to establish greater precision in our understanding of the response of these species to increase in the ambient temperature.

Finally, in order to cushion the effects of global climate change, we propose to maintain the remnants of native vegetation, as well as rocky outcrops where *Xenosaurus* populations live, in order to maintain specific habitat conditions. In addition, the conservation status of these lizards must be carefully reviewed in order to fulfill the central obligations of species conservation, particularly for such a vulnerable group.

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CONFLICT OF INTEREST

None declared.

AUTHOR CONTRIBUTIONS


C.B.I., J.F.M.R., A.R.B. and J.L.B.L. conceived the study; C.B.I., A.R.B. and A.N.M. collated the data, and C.B.I. analyzed the data. All authors contributed to the writing, led by C.B.I.

DATA ACCESSIBILITY

The location data for the lizards are confidential, because the populations are at severe risk of extinction, due to factors of excessive scientific collection and traffic of species. If the data are required, one can contact C.B.I and A.R.B and we will provide the data.

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