



Predicting *Ambystoma ordinarium* distribution under different climate scenarios in central Mexico

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Global climate change represents one of the most important threats to wildlife populations. Amphibians, specifically salamanders, are particularly susceptible to the effects of a changing climate due to their restrictive physiological requirements and low vagility; however, little is known about which amphibian species are more vulnerable to climate change. Therefore, we aimed to forecast changes in the distribution of the mountain stream salamander, *Ambystoma ordinarium*, using different climate scenarios. Approximately 70 representative presence records were selected to model the current potential distribution and two scenarios based on 2070 climate projections (RCP 2.6 and RCP 8.5) using the MaxEnt algorithm and three global climate models (BCC-CSM1-1, CCSM4 and HadGEM2-ES). A total of three scenarios were simulated using the 10-percentile training presence as the threshold rule. For all scenarios, the average of the area under the receiver operating characteristic curve for the replicated runs was greater than 0.95 ± 0.005 , representing good performance for the current and projected geographical distributions of *A. ordinarium*. Under the most conservative scenario, of a total area of 45,876 km², an average potential distribution area of 5,627 km² was defined for current conditions, decreasing to 4,406 km² for BCC-CSM1-1 in the optimistic scenario (RCP 2.6) and decreasing to 4,020 km² for CCSM4 in the pessimistic scenario (RCP 8.5). The results are useful for the development of future conservation plans, identifying landscapes with high probability to be further affected by climate change and to target potentially resilient habitats that provide consistent climatic conditions for *A. ordinarium* in the face of environmental changes.

Keywords: *Ambystoma ordinarium*; Global climate models; MaxEnt; Salamanders; Species distribution model.

INTRODUCTION

In recent years, amphibians have undergone dramatic declines, and a number of hypotheses exist to explain these declines (Beebee & Griffiths, 2005). Of the 6,682 amphibian species listed on the IUCN Red List in 2018 (IUCN Red List version 2018-1), approximately 41% are threatened with extinction, and, as a group, they are declining more rapidly than birds or mammals, making them the most threatened group of species known to date (Frost, 2018; Jetz & Pyron, 2018; Pyron, 2018). Since the first global assessment of all amphibians was completed in 2004 (Stuart et al., 2004), their situation has worsened. Even when numerous studies have documented the decline in amphibian populations, the complexity of synergistic factors that contribute to the high levels of amphibian imperilment remains unclear (Kerby et al., 2010; Bucciarelli et al., 2014; Campbell et al., 2016). Most of the suggested causes are related to habitat loss and modification, unsustainable exploitation, diseases, pollution, introduction of non-native species and eutrophication of water bodies (Collins & Storer,

2003; Rachowicz et al., 2006; Hayes et al., 2010; Kilpatrick et al., 2010; Jetz & Pyron, 2018; Nowakowski et al., 2018). Climate change has played a significant role in the decline of many species and has been identified as a major and important indirect threat to amphibian populations in recent decades (Pounds et al., 2006). In addition, general climate change scenarios predict a reduction in water availability (Ochoa-Ochoa et al., 2012; 2013), compromising the persistence of aquatic environments and the ability of amphibians inhabiting them to complete their life cycles (Feder & Lynch, 1982; Vörösmarty et al., 2010; Ochoa-Ochoa et al., 2012).

In Mexico, the prioritisation of areas for conservation of biodiversity has traditionally involved natural protected areas (NPAs). The selection of these priority conservation areas has included criteria such as their scenic, historic, cultural and archaeological value or mere availability, with little or no consideration of the geographical distribution of particular biological groups of conservation interest and the variables determining their distributions (Urbina-Cardona & Flores-Villela, 2010). NPAs have usually been established in regions where no previous rigorous place

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prioritisation has been performed (Sánchez-Cordero et al., 2005) but have been the most common instrument used in Mexico for natural resource management and conservation (Bello-Pineda et al., 2013). However, the effective conservation of biodiversity requires not only basic knowledge of this component but also knowledge of the distribution of local and regional biodiversity and those areas where biodiversity is most concentrated to identify the temporal and spatial patterns that govern the fate of biodiversity. Because spatial conservation prioritisation should seek to anticipate the impacts of climate change on biodiversity and how species distributions will respond to such changes, the use of models to infer the distribution of species/populations (e.g., ecological niche models) is an adequate approach to identify priority areas for conservation, management and restoration (Pearson & Dawson, 2003).

Species distribution models (SDMs) coupled to geographic information systems (GIS) have proven to be a powerful tool for predicting potential species distributions (Ruiz-Luna et al., 2017; Escalera-Vázquez et al., 2018). Although these techniques are not new, most of the recent advances have focused on the development of distribution models for plant species, and studies regarding the ecological niche modelling of species related to aquatic systems are scarce (e.g., Domínguez-Domínguez et al., 2006; Zambrano et al., 2006; Contreras et al., 2009; Ruiz-Luna et al., 2017).

Although several studies on ambystomatid species have been conducted in Mexico (Arredondo et al., 2017; Heredia-Bobadilla et al., 2016; 2017; Lemos-Espinal et al., 2016; 2017), few have included *Ambystoma ordinarium* as a study subject. Particularly for *A. ordinarium*, recent reports indicate that populations have declined dramatically (IUCN, 2015), and it is catalogued as endangered by the IUCN Red List of Endangered Species [category B1ab (iii, iv, v)] and is under special protection (Pr) by Mexican Law (NOM-059-SEMARNAT-2001; DOF, 2010). Despite this, almost all studies have been limited to evaluating the abundance, growth and spatial activity (Alvarado-Díaz et al. 2013), diet (Ruiz-Martínez et al. 2014), and phylogeny (Hime et al., 2016) of this species. More recently, Soto-Rojas et al. (2017) studied the effects of habitat quality on morphological abnormalities in this species. Surprisingly, only Escalera-Vázquez et al. (2018) described an approximation of the distribution of *A. ordinarium* using spatial distribution models. Therefore, to accomplish in situ conservation, management and restoration actions, it becomes urgent to identify and prioritize areas where populations of this salamander still exist.

In the present study, we define spatial priorities for conservation to help buffer the impacts of a changing climate using the distribution of *A. ordinarium* as a model. Additionally, we present a spatial analysis based on a climatic niche model with the maximum entropy algorithm to predict the distribution of *A. ordinarium* under different climate scenarios. The information presented here is relevant to prioritising conservation efforts regarding management plans in an area that has experienced a variety of land use changes over the

past century that have enhanced in the last decade, including forest clearing followed by subsequent habitat fragmentation due to agricultural uses and urbanization.

Study area

The distribution of *A. ordinarium* is restricted to the central part of Mexico, encompassing part of the Trans-Mexican Volcanic Belt (TMVB) and limited areas in the higher parts of the Sierra Madre del Sur (Fig. 1). This region presents significant topographic relief and is characterised by an altitudinal range of 1800–3420 m a.s.l., a temperate climate with summer rains, mean annual temperatures of 14–18 °C, and mean annual precipitation of approximately 800 mm (Carlón-Allende et al., 2009). The TMVB is a mass of volcanic rock and other igneous manifestations from the middle to late Miocene, is volcanically active and is considered to be the highest rock-type province in Mexico with the most variation in relief (Gómez-Tuena et al., 2007). On the other hand, the Sierra Madre del Sur is a Mesozoic-Cenozoic magmatic arc in southern Mexico associated with the subduction of the Cocos plate along the Acapulco trench beneath mainland southern Mexico (Ducea et al., 2004).

METHODS

Field survey and Data Preparation

We compiled data on the distribution of *A. ordinarium* from multiple available sources, including VertNet (<http://www.vertnet.org/>), the Global Biodiversity Information Facility (<https://www.gbif.org/>) and localities reported in published papers and the grey literature (e.g., theses, reports, etc.). To improve the accuracy of the modelling outputs, we did not include locality reports with fewer than four decimal places in the latitude/longitude coordinate fields. From these historical records, localities throughout the known geographic range of *A. ordinarium* were visited in a survey conducted from 2013 to 2015 during both the dry and rainy seasons. In each location, surveys were performed from 800–1200 h and 1600–2000 h based on a 300-m downstream and 300-m upstream transect using the location record as the midpoint of the transect. In clear-water locations, we used visual detection and hand nets to capture individuals; on the other hand, if turbidity was high, we used seine nets (2 m long, 4 mm mesh size) every 50 m along the transect depending on the habitat and terrain characteristics (e.g., rocks, pebbles, riparian vegetation); collected individuals were released in situ. Because sampling was focused on recording larvae/and/or paedomorphic individuals and the presence (and not the abundance) of individuals of this species, we considered that the time and date of sampling represent the daily variation in temperature needed to maximise the detectability of this salamander species (Hyde & Simons, 2001). Additionally, most of the mountain streams in this region present characteristics such as a low depth and flow rate and clear water, which allow for better detectability of salamanders in the streams (Soto-Rojas et al., 2017). To identify new/unreported localities for this species, we explored streams and rivers included in the basin that

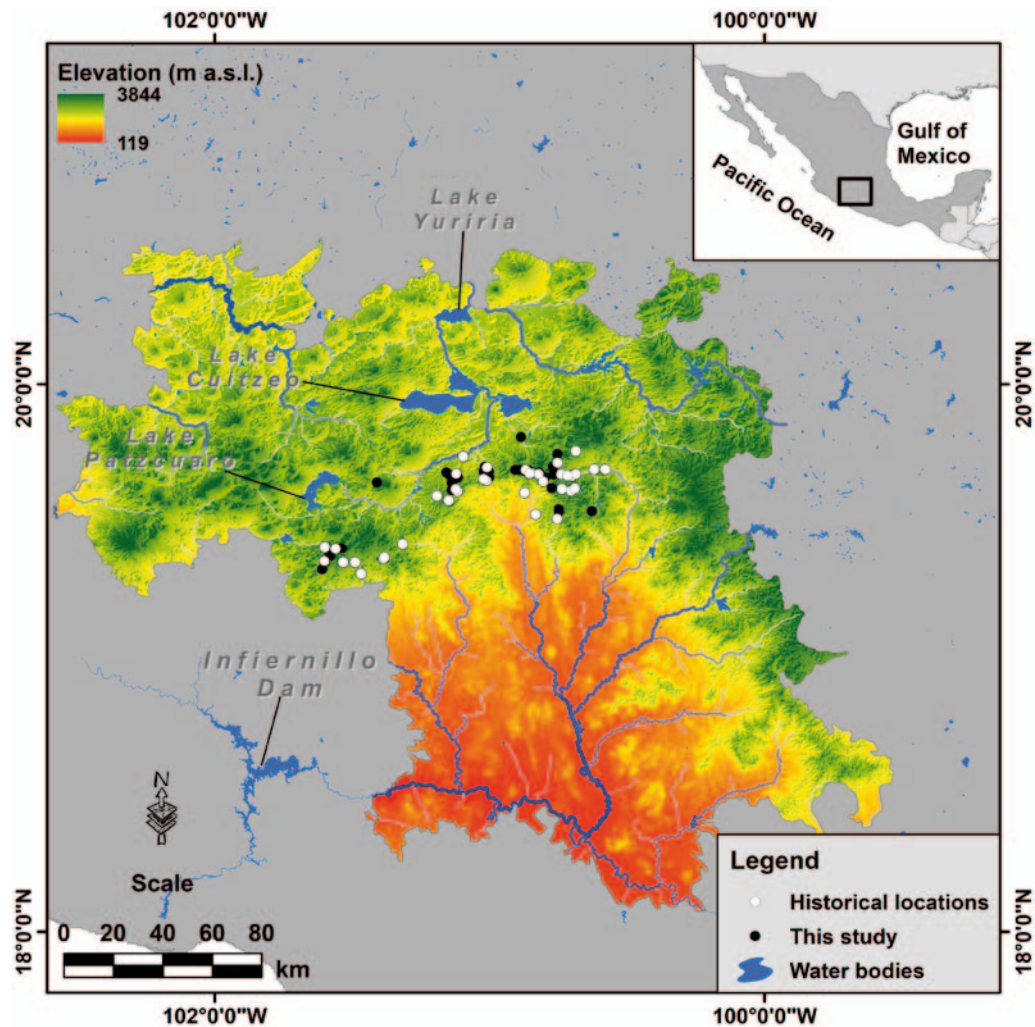


Figure 1. Geographic location of the study area. Dots represent localities for *A. ordinarium* used for modelling its distribution.

were not considered in the historical data. New locations were recorded using a Garmin Montana 680 GPS device (± 2 m accuracy).

Selection of Climate Scenario

We accounted for the known variability in the projected climate data by modelling the climatic niche with three future global climate models (based on projected data to 2070) and uncertainty among mathematical simulations based on the Beijing Climate Center Climate System Model (BCC-CSM1-1, Wu et al., 2013), the Community Climate System Model Version 4 (CCSM4, Gent et al., 2011), and the Met Office Hadley Centre model (HadGEM2-ES, Martin et al., 2011). Climatic models were chosen based on the availability of the projected data in representative concentration pathways (RCPs) 2.6 and 8.5 adopted by the Intergovernmental Panel on Climate Change (IPCC) in its Fifth Assessment Report (AR5). The RCPs represent a range of greenhouse gas concentrations denoted by the amount of radiative forcing (i.e., the difference in the sunlight absorbed by the Earth and the energy radiated back to space) projected into the future compared to pre-industrial values (van Vuuren et al., 2011). RCP 2.6 is considered to be an optimistic scenario in which greenhouse gas concentrations are

projected to decrease over the long term, whereas RCP 8.5 indicates an extreme scenario in which greenhouse gas concentrations are projected to increase drastically in the future (Sutton et al., 2015).

Recent (1950–2000) bioclimatic data and projected climate scenarios (BCC-CSM1-1, CCSM4, HadGEM2-ES) in RCPs 2.6 and 8.5 were available during the implementation of this study. Because we focused on a climatic niche model, we limited our modelling efforts to variables representing temperature and precipitation patterns. These variables were selected because precipitation and temperature show the highest correlation with the movement, migration, and reproductive activity of *Ambystoma* species (Sexton et al., 1990; Palis, 1997; Escalera-Vázquez et al., 2018). For the modelling, we used all 19 bioclimatic variables at 30 arc-second resolution (≈ 1 km) downloaded from the WorldClim global climate data project (version 1.4, release 3; <http://www.worldclim.org/bioclim>; Hijmans et al., 2005). We extracted the values for each environmental variable by location and created a correlation matrix using the raster (Hijmans et al., 2017) and rgdal (Bivand et al., 2018) packages in the R software (version 3.3.1; R Core Team, Vienna, Austria; <https://www.r-project.org/>). To avoid orthogonality of the variables, we removed highly

correlated variables (Pearson method, $r \geq 0.85$) and modelled the distribution of *A. ordinarium* based on the current and projected climatic data. No additional ancillary layers were considered.

Climate Modelling using Maximum Entropy

We constrained our models to the limits of the study area, which are defined by three physiographic subprovinces (Neovolcanica Tarasca, Sierras and Bajíos Michoacanos and Mil Cumbres) of the TMVB together with the subprovince Depresión del Balsas of the Sierra Madre del Sur and delimited by the extreme geographic coordinates: $-102^{\circ} 43.5'$ W and $20^{\circ} 39.5'$ N in the upper left corner and $-99^{\circ} 22'$ and $17^{\circ} 56.5'$ in the lower right. We clipped all BioClim variables using standard geoprocessing techniques within the QGIS 2.16.1 software. This procedure avoids the assumptions of no potential for dispersal or unlimited dispersal (e.g., Milanovich et al., 2010) and reduces potential bias by removing climatic habitats where the species may be unable to disperse.

We used the Maximum Entropy Algorithm (MaxEnt) v3.4.1 program, https://biodiversityinformatics.amnh.org/open_source/maxent/) to model the current and projected distribution of *A. ordinarium*. We chose this model over other correlative presence-only distribution models because of the utility and accuracy of this method as a species distribution modelling technique (e.g., Phillips et al., 2006; Ruiz-Luna et al., 2017; Escalera-Vázquez et al., 2018).

Locality data were randomly divided into training and test sets, which included 75 % and 25 % of the data, respectively. We ran the MaxEnt algorithm under the “auto-features” mode (Phillips & Dudík, 2008) with the default regularisation multiplier value (equal to 1) with a bootstrap replicated runs approach (100 replicates) to obtain a mean estimate of the potential distribution. The maximum number of iterations under which the algorithm converges was set at 1000. We employed the 10-percentile training presence threshold rule, converting continuous models to binary predictions to finally determine the suitable and unsuitable climate distributions (Lemes & Loyola 2013; Escalera-Vázquez et al., 2018). The resulting species distribution-climatic niche was projected onto the current and RCP 2.6 and the RCP 8.5 climate projections. The prediction results of the SDMs were evaluated using the area under the receiver operating characteristic curve (AUC) (Elith et al., 2011) averaged over 100 replicate models.

The impact of climate change was assessed by calculating the change in the suitable area for *A. ordinarium* based on the predicted map of the current climate and each of the future climate change scenarios. To identify the loss/gain areas, we calculated the percent overlap between the current distribution threshold layer and each of the projected thresholded raster cells for each GCM/RCP combination within the QGIS 2.16.1 software.

RESULTS

After data cleaning, 70 locations were included in the modelling processes. Based on the Pearson correlation matrix of environmental variables, the number of layers was reduced from 19 to 8 ($r \geq 0.85$). This provided non-redundant information that was useful for modelling (Table 1). The three main variables were BIO02 - Mean Diurnal Range, BIO06 - Min Temperature of Coldest Month, and BIO14 - Precipitation of Driest Month (Table 1). BIO02 was the environmental variable with the highest contribution in almost all simulations (>30 %).

The mean AUC for the *A. ordinarium* distribution models based on the current climate was 0.966 (range = 0.909–0.993; SD = 0.017), with the AUC being significantly better than random. The mean AUC that showed the lowest value varied depending on the global climate model and the RCP considered, with the mean AUC = 0.969 (range = 0.924–0.990; SD = 0.013) for CCSM4 in the “optimistic” scenario and the mean AUC = 0.967 (range = 0.909–0.990; SD = 0.016) for HadGEM2-ES in the “pessimistic” scenario.

As stated above, our study area is constrained by three physiographic subprovinces of the TMVB and one subprovince of the Sierra Madre del Sur, together accounting for an area of 45,876 km² with elevations between 120 and 3,850 m a.s.l. (mean = 1,685 m and std. dev. = 734 m) and a slope ranging from 0 to 80° (mean = 12° and std. dev. = 10°). Agriculture and evergreen forest are the two most prevalent land cover types, covering approximately 65 % of the study area.

Using the 10-percentile training presence (10 ptp) as the threshold rule, we obtained an average area of 5,630 km² (12.3 % of the total study area) for the potential distribution of this species. Our results suggest the presence of three main fragments with high habitat suitability for *A. ordinarium* and several isolated patches of minor extent (Fig. S1). The greatest patch is in the central mountain part of the study area (approximately 19.7° N, -100.9° W), a second patch is located to the south of Lake Patzcuaro (approximately 19.4° N, -101.5° W), and a third patch follows a narrow band through the central and south-eastern part of the mountain system (approximately 19.1° N, -100.0° W). Approximately 98 % of the predicted area is within an elevation range of 1,900 to 3,000 m a.s.l. (mean = 2,382 m and std. dev. = 262 m).

According to the Land Use and Vegetation Chart (Series VI; scale 1:250,000; edition 2017) published by the National Institute of Statistics and Geography (INEGI according to its name in Spanish), the main land cover and land use within the predicted area is evergreen forest (62.5 %), followed by agriculture (26.7 %). It is important to mention that of the 3,515 km² of forest, 731 km² has already shown some degree of disturbance (Fig. S1).

The high-suitability area calculations for the future varied depending on the GCM and RCP considered. A decrease to 4,410 km² is expected for BCC-CSM1-1-Optimistic Scenario (RCP 2.6). The greatest loss in habitat is predicted using the CCSM4 Global Climate Model with RCP 8.5, decreasing to 4,020 km². The projected mean

change in the *A. ordinarium* suitable climatic habitat size by 2070 varied depending on the GCM and RCP used, even the most “optimistic” scenario projected an approximately 15 % reduction in the suitable climatic range, mostly distributed in the east and south-southeast (Table 1; Fig. 2).

Although a habitat reduction is predicted for all scenarios, the eastern part of Lake Patzcuaro, the south-eastern part of the study area and all isolated patches are predicted to lose the greatest area. For all simulations, the area expected to remain with no change is approximately 2,700 km², while the projected climatic habitat loss by the year 2070 (only predicted in the current scenario) is approximately 1,880 km² (Fig. 3).

DISCUSSION

In this study, we modelled the potential geographical distribution of *A. ordinarium* in central Mexico under current and future climate scenarios and highlighted that future climate change might not only reduce the distribution range of *A. ordinarium* but also increase the fragmentation in the region, producing isolated populations.

Regarding the environmental variables considered in this study, some authors suggest that biotic interactions among species and the ability of species to disperse may lead to erroneous results using only models containing environmental-bioclimatic variables (Woodward & Beerling, 1997; Davis et al., 1998). However, a recent study by Bucklin et al. (2015) indicated that the incorporation of additional predictors has relatively minor effects on the accuracy of climate-based species distribution models. Therefore, although there are more variables available (e.g., solar radiation, elevation, slope), we agree with Duan et al. (2016) that the addition of other climatic variables would increase the danger of model over-fitting. Thus, given the low dispersal ability of *A. ordinarium* and its semi-permeable skin that makes it sensitive to changes in the thermal and hydric environment (Ochoa-Ochoa et al., 2012), we can consider higher correlations with variables that are more functionally related to biological traits, such as temperature and rainfall (e.g., Beneski et

al., 1986; Homan et al., 2008; Contreras et al., 2009). In addition, the environmental variables considered in this study are critical factors in all global climate models.

Although previous studies have suggested the potential importance of elevation in defining salamander distributions (Dillar et al., 2008; Searcy & Shaffer, 2014), our study excluded this layer following the recommendations of Elith & Leathwick (2009), who consider that elevation rarely directly affects the distribution of species. For example, in the studied area, an increase in elevation is generally related to higher annual precipitation and lower annual temperatures. Therefore, high-elevation areas may indirectly provide the temperate/moist environments required for *A. ordinarium* and amphibian species that depend on moisture for cutaneous respiration when metamorphosis occurs. In addition, the reduced set of environmental predictors used were generated at a regional scale, similar to other previous studies in which the distributions of salamanders were modelled (Rissler & Apodaca, 2007; Milanovich et al., 2010; Sutton et al., 2015). In this regard, our models generated predictions over very large areas by using spatial data that were readily available. Therefore, the methodology applied here can be easily adapted to predict the distributions of other paedomorphic ambystomatid species related to streams at a regional scale (e.g., *A. altamirani*, *A. leorae*, *A. rivulare*).

Although a plethora of information exists about *Ambystoma* spp. in Mexico, only a few studies have explored the use of SDMs for predicting their geographical distribution. Contreras et al. (2009) attempted to predict the species distribution of *A. mexicanum* (axolotl) at a local scale, generated microclimatic and water quality layers at high resolution (1 m²) and used them as predictors. They argued that the recorded variables for Lake Xochimilco were not sufficiently fine to represent the actual heterogeneity of the system. In the present study, this approach was not possible due to the wider range of the natural distribution of *A. ordinarium* and equipment limitations. Particularly for *A. ordinarium*, Escalera-Vázquez et al. (2018) made a first approximation of the spatial distribution of this species. According to their results, the area predicted by the model is characterised

Table 1. Bioclimatic variables and its contribution (%) in the modelling of the potential distribution of *A. ordinarium*. Bold numbers represent the variables that have higher percent of contribution. Estimated area is in km² and figures are rounded to the nearest tens. The RCP 2.6 represent the Optimistic Scenario; whereas the RCP 8.5 represents the Pessimistic Scenario. Global Climatic Models are: BC = BCC-CSM1-1; CC = CCSM4; HG = HadGEM2-ES.

Bioclimatic variable	Current	RCP 2.6			RCP 8.5		
		BC	CC	HG	BC	CC	HG
BIO2 - Mean diurnal range (Mean of monthly (max temp - min temp))	35.4	32.3	38.2	32.6	31.9	30	30.6
BIO3 - Isothermality (BIO2/BIO7) (*100)	3	0.2	0.8	0.5	2.2	2.7	6
BIO4 - Temperature seasonality (standard deviation *100)	8	6.3	5.9	9.2	4.9	8.2	4.1
BIO6 - Min temperature of coldest month	21.4	13.7	28.9	21.8	20.8	22	10.5
BIO12 - Annual precipitation	2.9	3	2.7	2.8	3.6	3.3	2.2
BIO14 - Precipitation of driest month	21.3	34.7	12.9	20.9	30.9	23.7	35.1
BIO15 - Precipitation seasonality (Coefficient of Variation)	6.9	8.3	9.6	11.2	5	9.3	8
BIO18 - Precipitation of warmest quarter	1.2	1.5	1.1	1	0.7	0.7	3.5
Area (km ²)	5630	4410	4820	4640	4550	4020	5220

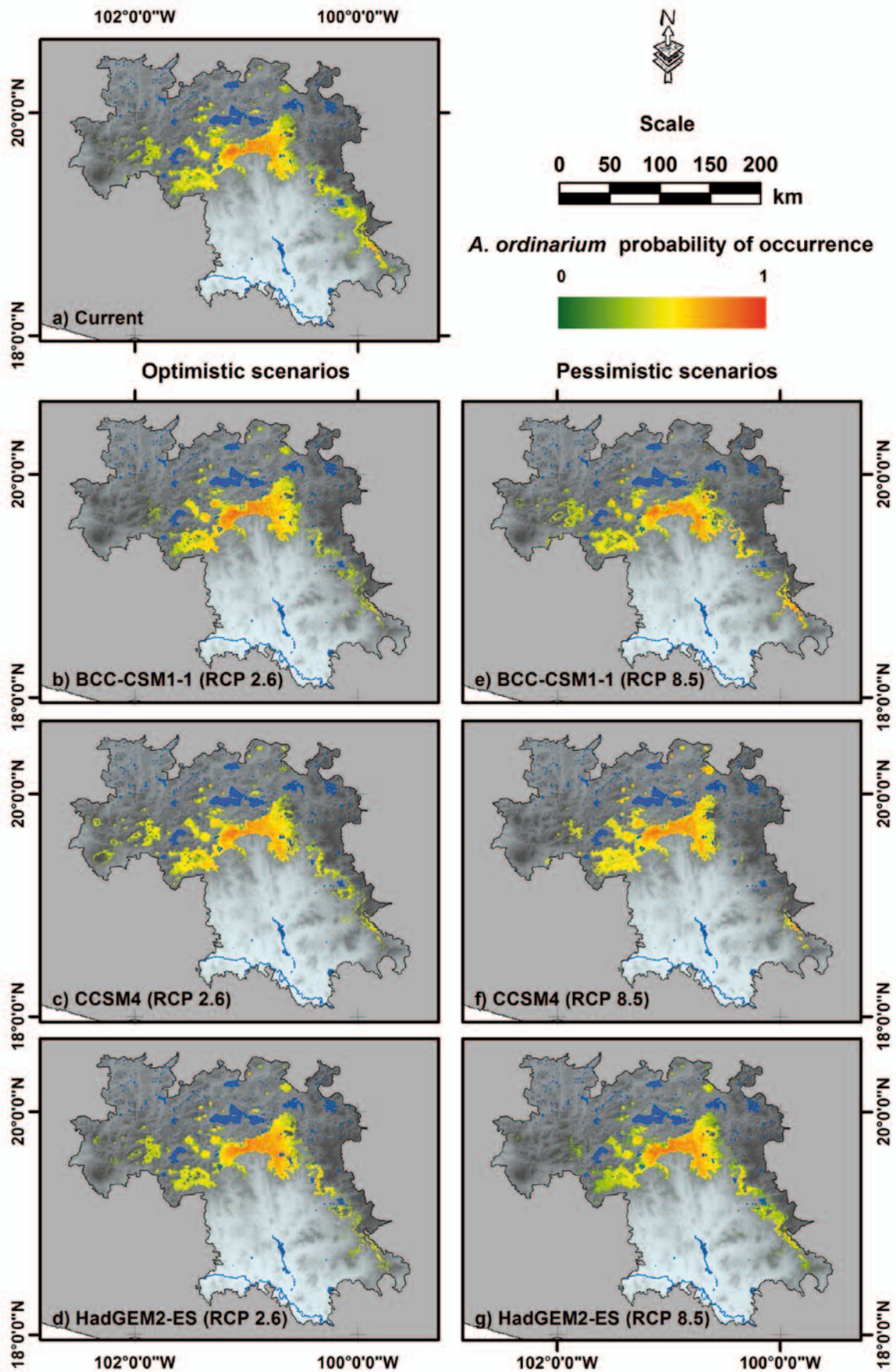


Figure 2. Potential distribution models for the Michoacán stream salamander (*A. ordinarius*) calculated for both current and projected scenarios with three global climate models (BCC-CSM1-1, CCSM4 and HadGEM2-ES) and two representative concentration pathways (RCP 2.6 and 8.5). Warmer colours show areas with higher probabilities of occurrence.

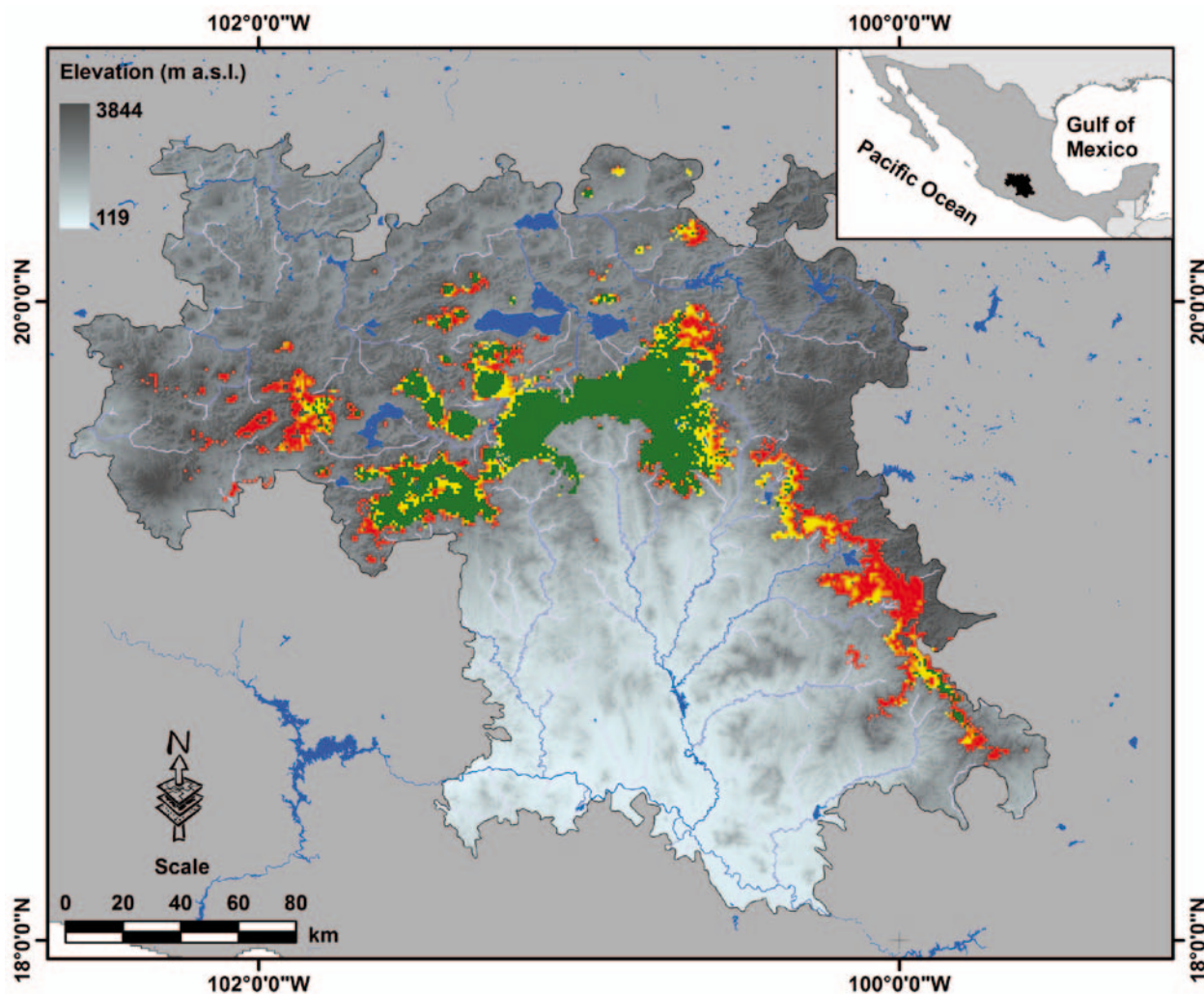


Figure 3. Simulated distribution of suitable climate space for *A. ordinarius* based on the overlap between current and projected distribution models. Green represents areas of no change, yellow represents areas predicted by at least two models, and red represents lost area.

by higher altitudes and irregular topography with forest in the central and south-eastern part of the total distribution area of the species, highlighting a reduction of nearly 253 km² of forest in 16 years (1997-2013). According to our results, if the trend detected by Escalera-Vazquez et al. (2018) continues, an additional reduction of 901 km² in forest is expected by 2070. However, none of these studies forecasted potential future distributions under various climate scenarios to understand the possible responses of amphibians to future climate change.

Although the IUCN recommends that the extent of occurrence is quantified by drawing a minimum convex polygon around known or inferred presence localities, the use of SDMs has already been applied to inform IUCN Red List assessments (de Castro et al., 2014; Syfert et al., 2014). Our findings suggest that the current predicted extent is greater than the extent of occurrence for *A. ordinarius* reported by the IUCN (4,357 km²). This result is consistent with that reported in Syfert et al. (2014) and provides useful additional information about how much larger the actual extent of occurrence could be and where it is likely to extend geographically. In contrast with the methodology recommended by the IUCN, we used data from multiyear resurveys for higher confidence,

making the model more reliable (de Castro et al., 2014). Additionally, as Kerby et al. (2010) suggested that amphibians are more resilient to anthropogenic changes than expected, the assumption of the dramatic decrease in *A. ordinarius* populations could be a misinterpretation of data obtained from low-effort surveys.

Our results provide information on a species highly associated with aquatic ecosystems, suggesting that the major problems that this species will face in the next 50 years are those related to climatic change and water scarcity (Rissler & Apodaca, 2007; Dillars et al., 2008; Contreras et al., 2009; Milanovich et al., 2010). In addition, regional climate change over the long term represents the greatest threat to the persistence of resilient landscapes that amphibians inhabit (Suazo-Ortuño et al., 2015). The TMVB is one of the most ecologically degraded areas in Mexico, which is related to the proximity to highly urbanised areas, and is heavily impacted by agricultural activities (Sunny et al., 2017). Our findings are in accordance with those reported by Sunny (2017) and suggest that the TMVB is vulnerable to effects from climate change, as evidenced by a relatively large projected loss of the *A. ordinarius* climate niche.

It has been suggested that due to their low dispersal

capacities and small home ranges, almost all *Ambystoma* species in the TMVB are threatened by habitat loss, fragmentation, the contamination of rivers and lakes and the introduction of nonnative species (Heredia-Bobadilla et al., 2016; Soto-Rojas et al., 2017; Estrella-Zamora et al., 2018). On one hand, habitat transformation can result in small, isolated and fragmented populations, increasing the chance of inbreeding and lower genetic variability (Heredia-Bobadilla et al., 2016). On the other hand, the introduction of non-native species can help spread emerging amphibian diseases. Indeed, the results found by Estrella-Zamora et al. (2018) suggest that *A. altamirani* is less abundant in the presence of *Oncorhynchus mykiss*, probably associated to higher predation and consumption on salamander larvae by this trout species (McGarvie & Cox, 2007). Particularly for *A. ordinarium*, Soto-Rojas et al. (2017) recorded the presence of *O. mykiss* at three sites in the 16 streams sampled in the TMVB. These studies demonstrated a strong negative association between nonnative *O. mykiss* and amphibians.

Considering that *A. ordinarium* occurs in habitats adjacent to riparian habitats, the potentially high vulnerability of this species to climate change suggests the need for the implementation of conservation measures (e.g., maintenance of riparian forest as a buffer area as well as the conservation of habitat connectivity) to mitigate potential climatic impacts. Indirectly, our results highlight the importance of taking immediate conservation, management and restoration actions in this region, where anthropogenic impact is high, mainly related to the increase in the area used for plantations (e.g. avocado), urbanisation, and deforestation at higher elevations. Likewise, our pessimistic model should be considered because central Mexico is a hotspot for problems associated with water security and biodiversity loss in rivers in the upcoming decades (Vörösmarty et al., 2010). In this study, we used *A. ordinarium* as a model species in indirectly identify environments where high levels of interaction between terrestrial and aquatic ecosystems occurs. This information is useful for the implementation and development of restoration and conservation plans. Although long-term solutions to climate change are complex and seemingly inaccessible to many land managers, strategic conservation planning is a proactive and tangible approach to providing climate refugia (Sutton et al., 2015). Such efforts should be oriented towards tight coordination among local people, authorities, and academia to promote long-term sustainable management.

Finally, although our models were generated with a sufficiently high discriminatory power to be useful and could be considered better than the results obtained by chance (e.g., AUC > 0.7, Ruiz-Luna et al., 2017), our results should be considered with caution because a) many factors other than climate itself play an important role in determining species distributions over time (Pearson & Dawson, 2003), b) the low number of presence data used for training could have an influence on the model performance, and c) no observations of species occurrence are available from the training data

to directly support the projected predictions (Elith & Leathwick, 2009).

CONCLUSIONS

Our study represents the first regional attempt to predict the range of distribution of *A. ordinarium* and its changes under future climate scenarios. Overall, our study provides a conservation tool that can be used to identify priority habitats for *A. ordinarium* conservation. The spatial limits detected here widen the traditional limits reported by the IUCN. Understanding the spatial distributions of threatened, endangered, and sensitive amphibian species and their habitat occupancy is an important component of regional conservation planning. If this information is readily available to managers of large and heterogeneous landscapes, conservation planning efforts will be more informed and potentially more effective.

ACKNOWLEDGEMENTS

We thank two anonymous reviewers for helpful comments on an earlier version of the manuscript. The study was supported by the CONACYT Research Fellow (Cátedras CONACYT–Project No. 148). Field work was financed through the project CONACyT-CB201501-259173. The collected data were part of a postdoctoral research grant provided to L.H.E.V. through the “Estancias Posdoctorales Vinculadas al Fortalecimiento de la Calidad del Posgrado Nacional, 2014 (3)”. Individuals of *A. ordinarium* were collected and field work was conducted in accordance with Mexican laws and with permits received from the Mexican Ministry of Environment and Natural Resources (Secretaría de Medio Ambiente y Recursos Naturales SEMARNAT; permit number GPA/DGVS/04187/13).

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Accepted: 19 December 2018

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