PROJECTED FUTURE BIOCLIMATE-ENVELOPE SUITABILITY FOR REPTILE AND AMPHIBIAN SPECIES OF CONCERN IN SOUTH CENTRAL USA

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Abstract.—Future climate change has impacts on the distribution of species. Using species distribution models (SDM), we modeled the bioclimatic envelopes of four herpetofauna species in the South Central USA including two salamanders, the Sacramento Mountain Salamander (*Aneides hardii*) and the Jemez Mountains Salamander (*Plethodon neomexicanus*), one anuran, the Chiricahua Leopard Frog (*Lithobates chiricahuensis*), and one turtle, the Rio Grande Cooter (*Pseudemys gorzugi*). We used Generalized Linear Model, Random Forest, Boosted Regression Tree, Maxent, and Multivariate Adaptive Regression Splines, and binary ensembles to develop the present day distributions of the species based on climate-driven models alone. We projected future distributions of the species using data from four climate models run according to two greenhouse gas concentration pathways (RCP 2.6 and RCP 8.5). Our model results projected losses and gains in suitable bioclimatic envelopes for the years 2050 and 2070. The Boosted Regression Tree model consistently performed well among SDMs based on Area Under the Curve (AUC; range = 0.88 to 0.97) values and kappa statistics (K > 0.75).

Key Words.—Aneides hardii; Chiricahua Leopard Frog; climate-modeling; Jemez Mountains Salamander; Lithobates chiricahuensis; Plethodon neomexicanus; Pseudemys gorzugi; Rio Grande Cooter; Sacramento Mountain Salamander

INTRODUCTION

Questions remain regarding the effects of climate change on the current suitable environmental conditions for amphibian and reptile species in the South Central U.S. region. Climate variability and change affects biodiversity by modifying species habitats and interactions (Buckley and Jetz 2007; Sexton et al. 2009; Alvarez et al. 2017). The changes, such as a decrease of prairie wetland habitat and a decline of future wetland areas, could be damaging (Lannoo 2005), leading to reduction in species population as habitats disappear (Poiani and Johnson 1991; Halpin 1997). Climate change can also lead to shifts and contractions in species distributions (Daszak et al. 2005; Raxworthy et al. 2008; Sexton et al. 2009; Alvarez et al. 2017). In addition, shifts toward warmer temperatures could influence disease dynamics (Pounds et al. 2006) and trigger outbreaks (Harvell et al. 2002). While some species could adapt to climatic changes because of their genetic variability and ability to disperse (Davis et al. 1998; Kubisch et al. 2014), other species (e.g., reptiles and amphibians) may

not be mobile enough to adapt to local climate stresses through dispersal (Halpin 1997). Mac et al. (1998) highlighted the vulnerability of reptiles and amphibians to climate-driven habitat changes and Parmesan (2006) found amphibians to be more negatively affected by climate change than reptiles.

In the last few decades, several studies have demonstrated the negative influences (e.g., population declines) of altered patterns of temperature or rainfall on amphibian populations (Blaustein and Wake 1990; Vitt et al. 1990; Alford and Richards 1999; Pounds 2001; D'Amen and Bombi 2009). Decrease in temperature and rainfall amounts resulted in unusual amphibian breeding patterns (Saenz et al. 2006), changes in body condition (Reading 2007), and development of body mass (Harkey and Semlitsch 1988). Suboptimal habitat conditions resulting from reduced precipitation were seen as a threat to southeastern amphibians (Ashton and Ashton 1988; Walls et al. 2013) and terrestrial salamanders (Petranka 2010). Burrowes et al. (2004) concluded that a climate-linked epidemic was the most likely cause of the declines of amphibians in Puerto Rico. Studies

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like one conducted in Costa Rica by Pounds et al. (2006) have gone further by using species distribution models (SDM) to show warming temperatures are a driver of an observed mass extinction of amphibians. The direct relationship between continuing extinction of amphibians and global warming is also reflected in the International Union for the Conservation of Nature (IUCN) assessment report (IUCN 2016). While research is currently being conducted on amphibian population declines, there is little work being done regarding the projection of climate-driven shifts in amphibian habitats under future climate scenarios.

Similar to amphibians, little effort has been devoted to the evaluation and modeling of future scenarios of the effects of climate change on reptiles. Although most reptiles can tolerate warmer temperatures than amphibians due to their scale-covered skin (Pough et al. 2004) and sufficient mobility to evade thermal stress (Brown 1993), their primary habitats are still vulnerable (Alvarez et al. 2017). Reptile species that are semiaquatic and dependent on wetlands, streams, and rivers like Common Mud Turtles (Kinosternon subrubrum), American musk turtles (Sternotherus spp.), Riverine map turtles (Graptemys spp.), and Chicken Turtles (Deirochelys reticularia), could be affected by increased drought frequency (Gibbons et al. 2000). Also, previous studies have shown negative consequences of warming temperatures on turtles, including earlier ages of maturity (Frazer et al. 1993), faster growth rates (Stearns and Koella 1986), and decreased production of male offspring by temperature-dependent species (Janzen 1994). In the case of lizards, juvenile lizards may face more severe thermal limits (Thomas 2010). Sinervo et al. (2010) showed that, based on the study of Blue Spiny Lizard (Sceloporus serrifer) populations in Mexico, extinctions caused by climate change were reducing global lizard diversity. Sinervo et al. (2010) added that if global temperature continues to rise, global extinction could average 16% by 2050 and 30% by 2080, while equatorial extinctions could reach 23% by 2050 and 40% by 2080. A study in Texas for Canyon Lizards (Sceloporus merriami) indicated that a 2° C rise in air temperature could diminish species movement, causing energy shortfalls and population size reductions (Gibbons et al. 2000).

Many studies have considered the diverse amphibian and reptile species documented in Arizona and New Mexico (Turner et al. 2003; Flesch et al. 2010; Dixon et al. 2013; Boeing et al. 2014; Harings and Boeing 2014) and Texas (Rogers 1976; Owen 1989; Bogosian et al. 2012). However, we found no evidence in the literature describing the impact that varying future climate scenarios could have on habitats and distribution of key amphibian and reptile species in the South Central U.S. region. Species distribution models (SDMs) are valuable tools to better understand future steps for species management and policy (Elith and Leathwick 2009; Salas et al. 2017). Here we used ecological niche models (Elith and Leathwick 2009; Peterson et al. 2011) to project availability of suitable bioclimatic conditions for four herpetofauna species using various climate projections derived from general circulation models (GCMs) and post-processed via application of a simple statistical downscaling method. We contrasted future projected climate envelope suitability results produced from combinations of four GCMs and two greenhouse gas concentration trajectories for two future time periods. Our objective is two-fold: to develop models of present day and potential future distributions of suitable environmental conditions for the amphibian and reptile species in the South Central U.S. region, and to compare how bioclimatic envelope suitability is projected to change or shift directions from present to future.

MATERIALS AND METHODS

We divided the methodology (Fig. 1) into three steps: (1) selection and processing of herpetofauna species, the species range, and the bioclimatic variables; (2) modeling of current conditions, includes the selection of the SDMs and evaluation of the current bioclimatic conditions; and (3) modeling of future conditions, includes the selection of the GCMs, Representative Concentration Pathways (RCPs), and the projection of the current conditions to future conditions.

Study area.—The four herpetofauna species of interest, the Sacramento Mountains Salamander (Aneides hardii), Jemez Mountains Salamander (Plethodon neomexicanus), Chiricahua Leopard Frog (Lithobates chiricahuensis), and Rio Grande Cooter (Pseudemys gorzugi), are located within the southcentral region of the United States (Fig. 2). Descriptions of the species are discussed in the following section and a more detailed method in the selection of the species is available in Salas et al. (2016). The selected herpetofauna species are from a region known to have highly variable temperature and precipitation. The south-central U.S. is rich in cultural and natural resources along with an expanding metropolitan area, which highlights the importance of predicting future climate and considering how changes may affect available suitable habitat and therefore influence herpetofauna currently considered Species of Concern (South Central Climate Science Center. 2016. About Our Region. U.S. Geological Survey, National Climate Change and Wildlife Science Center (NCCWSC). Available from http://www.southcentralclimate.org/index.php/pages/ scus [Accessed 12 July 2016]).

Data sets.—After a rigorous selection process including feedback from valued stakeholders (see



FIGURE 1. The three major steps of the proposed methodology include: the input datasets, modeling of the present day bioclimatic conditions, and modeling of the future bioclimatic conditions. The final output is a projected bioclimatic envelope for the two years we selected, 2050 and 2070, which shows the suitable bioclimatic conditions for the four species.

Appendix 1 for more detailed methodology), we identified two salamanders and two highly aquatic species (one anuran and one turtle) as focal species. Original species data included 651 presence records, with 148 for Sacramento Mountains Salamander, 184 for Jemez Mountains Salamander, 294 for Chiricahua Leopard Frog, and 25 for Rio Grande Cooter. We obtained species occurrence datasets from Natural Heritage programs in New Mexico, Arizona, and Texas. The four terrestrial vertebrate species (three amphibians and one reptile) that we selected for this study are discussed in the following paragraphs. For the species, we only used presence data and count data because there was no sufficient absence data available. The other online sources of presence data used in this study are Biodiversity Information Serving Our Nation (BISON. http://bison.usgs.ornl.gov/#home) and herpetological collections data (HerpNET. http://www. herpnet.org). In this study, we limited the datasets combined across sources to the same date range for which historical climate data are available (1950 to 2000). Most of the occurrence were observed in the last 20 y. Also, we eliminated occurrences that fell outside the boundaries of species ranges provided by the U.S. Geological Survey (USGS; 2016) to reduce the number of records for which the species had been misidentified or were otherwise geographic outliers. While limiting our analysis on the species range could put a limit on our results, published studies indicated that SDMs could perform well in characterizing the natural distributions of species within their current range (e.g., Elith and Leathwick 2009). For all spatial data analysis, we used ArcGIS for Desktop 10.2 (Esri 2013).

Selected herpetofauna species.—The Sacramento Mountain Salamander is a species of Least Concern according to the IUCN Red List (IUCN 2016). However, the New Mexico Department of Game and Fish (NMDGF) has listed the species as a Species of Greatest Conservation Need (NMDGF 2006). They are known to occupy mixed mesic habitats, particularly Engelmann Spruce (*Picea engelmannii*) and Douglas Fir (*Pseudotsuga menziesii*) stands from 2,400–3,570 m in elevation. Their microhabitat is characterized by cover including logs, moist litter, bark, rocks, small woody debris, and rockslides (Degenhardt et al. 2005).



FIGURE 2. The study area in the south-central U.S. consisted of New Mexico, Texas, Oklahoma, and Arizona. The USGS Gap Analysis Program range (see methodology for details) of the four species: Sacramento Mountains Salamander (*Aneides hardii*), Jemez Mountains Salamander (*Plethodon neomexicanus*), Chiricahua Leopard Frog (*Lithobates chiricahuensis*), and Rio Grande Cooter (*Pseudemys gorzugi*) are shown in the inset. The black dots overlaid on each range represent the present distributions of the species.

Sacramento Mountain Salamanders also reside in tundra habitat up to 3,600 m, where individuals are associated with moss, lichen, and rocks (Moir and Smith 1970; Schad 2010; Johnston 2015). This species requires contiguous patches of habitat and is endemic to the Sacramento Mountains, Capitan Mountains, and Sierra Blanca in Lincoln and Otero counties of southern New Mexico, USA. Its range is largely within the Lincoln National Forest (Ramotnik 1997).

The Jemez Mountains Salamander is considered near threatened according the IUCN Red List (IUCN 2016) and listed by the NMDGF as a Species of Greatest Conservation Need (NMDGF 2006). They can be found in coniferous forests dominated by Blue Spruce (*Picea pungens*), Douglas Fir, Engelmann Spruce, Ponderosa Pine (*Pinus ponderosa*), Aspen (*Populus tremuloides*), White Fir (*Abies concolor*), New Mexico Locust (*Robinia neomexicana*), Oceanspray (*Holodiscus discolor*), and Rocky Mountain Maple (*Acer glabrum*) between 2,130 m to 3,435 m in elevation (Degenhardt et al. 2005). Individuals can be found under decaying logs and rocks in both flat areas and steep slopes, where eggs are presumed to be deposited in deeply fractured interstices of metamorphic subterranean rock (Degenhardt et al. 2005). The Jemez Mountains Salamander is restricted to the Jemez Mountains in Sandoval, Los Alamos, and Río Arriba counties of New Mexico, USA (Stebbins 2003; Degenhardt et al. 2005; Petranka 2010). This species exists as fragmented populations within an area of approximately 650–780 km² (NMDGF 2006).

The Chiricahua Leopard Frog is considered vulnerable according to the IUCN Red List (IUCN 2016), is federally listed as threatened, and listed by the NMDGF as a Species of Greatest Conservation Need (NMDGF 2006). This species is the most aquatic of the leopard frogs and requires access to vegetated permanent and semi-permanent water bodies ranging

TABLE 1. List of 19 bioclimatic variables used in bioclimaticenvelope model development. Names and descriptions are based on WorldClim (Hijmans et al. 2005). The abbreviation Temp. = temperature.

Variable	Description	Temporal Scale
Bioclim 1	Annual Mean Temperature	Annual
Bioclim 2	Mean Diurnal Range	Variation
Bioclim 3	Isothermality	Variation
Bioclim 4	Temperature Seasonality	Variation
Bioclim 5	Maximum Temp. Warmest Month	Month
Bioclim 6	Minimum Temp. Coldest Month	Month
Bioclim 7	Temperature Annual Range	Annual
Bioclim 8	Mean Temp. Wettest Quarter	Quarter
Bioclim 9	Mean Temp. Driest Quarter	Quarter
Bioclim 10	Mean Temp. Warmest Quarter	Quarter
Bioclim 11	Mean Temp. Coldest Quarter	Quarter
Bioclim 12	Annual Precipitation	Annual
Bioclim 13	Precipitation of Wettest Month	Month
Bioclim 14	Precipitation of Driest Month	Month
Bioclim 15	Precipitation Seasonality	Variation
Bioclim 16	Precipitation of Wettest Quarter	Quarter
Bioclim 17	Precipitation of Driest Quarter	Quarter
Bioclim 18	Precipitation of Warmest Quarter	Quarter
Bioclim 19	Precipitation of Coldest Quarter	Quarter

from seeps, thermal springs, wells, and stock tanks to intermittent creeks and river reaches within an altitudinal range between 1,000 and 2,710 m (Platz and Mecham 1979; Sredl et al. 1997a; Smith and Chiszar 2003). The Chiricahua Leopard Frog is found in Arizona and New Mexico in the USA and in Mexico (Platz and Mecham 1979). Their range is divided into two areas. Northern montane populations occur along the southern edge of the Colorado Plateau in central and eastern Arizona and west-central New Mexico. Southern populations occur in the mountains and valleys south of the Gila River in south-eastern Arizona and southwestern New Mexico and extend into Mexico along the eastern slopes of the Sierra Madre Occidental (Platz and Mecham 1979).

The Rio Grande Cooter is considered near threatened according to the IUCN Red List (IUCN 2016) and is listed by the NMDGF as a Species of Greatest Conservation Need (NMDGF 2006). This turtle species is restricted to riverine habitat and confined to large, deep pools from sea level to 1,100 m in elevation (Stebbins 2003). The Rio Grande Cooter range extends from south and west Texas along the Rio Grande and Pecos drainages. It expands north to Brantley Reservoir, including the Black and Delaware rivers, in southeastern New Mexico (Degenhardt et al. 2005). In July 2015, the U.S. Fish and Wildlife Service (USFWS) initiated a 12-month review of the status of this species prompted by the habitat loss threatening their survival (USFWS) 2016). In Mexico, the species range includes Coahuila and Nuevo Léon southwards to northern Tamaulipas (Iverson 1992; Seidel 1994).

Species distribution modeling.--We obtained a set of 19 raster-based bioclimatic variables from among the WorldClim datasets (Hijmans et al. 2005) to describe present environmental conditions and explore the relationship between bioclimatic conditions and species distribution patterns. WorldClim provides climate projections statistically downscaled using a Delta Method approach to a spatial resolution of 30 sec, roughly 900 m at the equator. The 19 rasterbased climatic variables were derived from temperature and precipitation values, represented in monthly (e.g., precipitation of driest month), quarterly (e.g., mean temperature of coldest quarter), seasonal (e.g., temperature seasonality), and annual trends (e.g., annual precipitation; Table 1). These variables were used to describe present environmental conditions and explore the relationship between bioclimatic conditions and species distribution patterns. We derived the eight sets of downscaled future climate projections used in this study from climate simulations produced by four GCMs using two sets of assumptions about future concentrations of greenhouse gases and other atmospheric constituents, with all eight being downscaled using the single method adopted by WorldClim.

We analyzed the bioclimatic condition-species distribution relationship using the following species distribution models/statistical algorithms for each species: Generalized Linear Model (GLM), Random Forest (RF; Breiman 2001; Liaw and Wiener 2002), Boosted Regression Tree (BRT; Elith et al. 2008), Maxent (Phillips et al. 2006; Phillips and Dudík 2008), and Multivariate Adaptive Regression Splines (MARS; Leathwick et al. 2006). We selected SDMs based on their performance with presence-only data (Elith et al. 2006). The models GLM, MARS, and BRT can be used for count data as well under the assumption that a count response could be modeled as Poisson (Talbert 2012). The GLM is a linear regression adapted to binary count data. The method uses stepwise procedure to select covariates in the model. The MARS non-parametric algorithm build flexible models by fitting piecewise logistic regressions. Though it has similarities with GLM, MARS is better in accommodating non-linear responses to predictors and at the same time lessens the effects of outlying observations. The model RF uses decision trees through random grouping of the covariates. Random Forest models both interactions of the variables and their nonlinear relationships and does not split the data into training and test as RF uses bootstrapping to fit individual trees (Breiman 2001). Like the Random Forest, BRT also uses decision trees, but the method is robust to missing observations. The model BRT uses cross-validation by choosing models based on model comparisons of evaluation metrics (Elith et al. 2008). Maxent is best for presence-only modeling. While observed absence is valuable in modeling, data is oftentimes not available and using only presence data is unavoidable (Talbert 2012). We used the modeling tool Software for Assisted Habitat Modeling (SAHM) run within VisTrails (Talbert 2012; Morisette et al. 2013) to create a workflow of the selected SDMs and develop bioclimatic-envelope models for present day conditions. When multiple species occurrences were present within a given pixel of the climatic data, a tool in SAHM consolidated them to a single occurrence per pixel. Because species lacked absence data, the tool randomly generated background points (i.e., pseudo-absences; Phillips and Dudík 2008) within a 95% minimum convex polygon defined by the presence data. We used the species ranges provided by the USGS National Gap Analysis Program (USGS 2016) to generate a template layer for each species. This template restricted model development and projection to the present-day geographic range of the species based on 8-digit hydrologic unit codes.

For each species, we removed one of each pair of highly correlated (r > 0.7; Dormann et al. 2013) environmental variables from the bioclimatic-envelope models to avoid collinearity among variables (Gama et al. 2015). We made the choices between variables based on the results of a species-specific literature search. In particular, we selected variables that were identified in one or more studies regarding the species of interest as having an effect on the range of the species or population dynamics. In cases where the results of the literature search could not differentiate between two highly correlated climatic variables, we used a qualitative assessment of the distribution of values of the variable at all presence points and of the relationship between the variable and species presence or pseudoabsence (Talbert 2012).

Through SAHM tool, we produced ensemble maps for the current distribution for each species. The ensemble map is a summation of binary maps generated from probability surfaces from each statistical modeling algorithm (Liu et al. 2005; Lobo et al. 2008; Stohlgren et al. 2010). We optimized the threshold by using Specificity = Sensitivity in discretizing the probability maps (Manel 2001). The final maps consisted of pixel values that represented the number of models in agreement to indicate that a particular pixel is suitable for the species. A pixel with a value of zero meant that none of the models identified bioclimatic suitability for the species at that location, while a value of 5 meant there was agreement across all five models. Finally, with SAHM ensemble tool, we introduced thresholds and run

the models to further exclude underperforming SDMs, those having low AUC values (AUC < 0.70; Poulos et al. 2012), and diversify the types of models selected to improve the performance of the ensembles (Du et al. 2012). We used the current distributions estimated by the ensemble SDMs and projected each to the future.

We assessed confidence in individual model results in terms of concordance among the different distribution models. We had higher confidence that environmental conditions were suitable for a species when three or more (at least 60% of) algorithms were in agreement (e.g., Rehfeldt et al. 2012). We compiled information on various measures of model performance, including the Area Under the Receiver Operating Characteristic (ROC) Curve (AUC) for the test data, correct classification rate (Co%; Fielding and Bell 1997; Warren and Seifert 2011), and the True Skill Statistic (TSS; Allouche et al. 2006) for each algorithm and species combination. The AUC value is the probability that the model would rank a randomly chosen presence observation higher than the randomly chosen absence observation. Swets (1988) classified values of AUC as follows: those > 0.9 indicated high accuracy (excellent), from 0.7 to 0.9 indicated good accuracy, and those <0.7 indicated low accuracy. The TSS is presented as an improved measure of model accuracy that, unlike the common kappa statistics (Cohen 1960; Allouche et al. 2006), is not dependent on species prevalence (i.e., the proportion of occurrence points for which the species is present). We checked other qualitative assessments of model performance, which included the inspection of calibration and deviance of residual plots. Calibration plots indicate whether models tend to over or under predict habitat suitability. Deviance of residual plots are used to identify individual data points that may require further inspection or whether there may be an important environmental layer missing from the model inputs (Morisette et al. 2013).

Projection to future conditions.-Informed in part by previously published evaluations of model performance (Taylor et al. 2011; Sheffield et al. 2013), we screened GCMs based upon their simulations of 20th Century climate across the continental USA and regions that overlap the study area, as well as the general areas inhabited by the focal species (e.g., Central and Western North America). We used values for bias of model output relative to observed historical data as one of several criteria to exclude GCMs. In particular, we excluded GCMs for which multiple variables had a relatively high bias (i.e., were more biased than two times the standard deviation of variation among biases of all models evaluated) or for which few evaluated variables were less biased (i.e., bias was less than half of the standard deviation of variation in bias among all models

TABLE 2. The Areas Under the Curve (AUC) associated with the test data and the percentages of occurrence points correctly classified (%Co) for the five different models. Model abbreviations are GLM = Generalized Linear Model, MARS = Multivariate Adaptive Regression Splines, BRT = Boosted Regression Tree, and RF = Random Forest. Species abbreviations are ANHA = Sacramento Mountains Salamander, LICH = Chiricahua Leopard Frog, PLNE = Jemez Mountains Salamander, and PSGO = Rio Grande Cooter. Not available (NA) values for BRT are due to the model not executing successfully due to an error related to sample size.

	GI	LM	MA	ARS	BI	RT	R	F	Ma	xent	Ense	mble
Species	AUC	%Co										
ANHA	0.91	86.1	0.90	87.0	0.94	87.9	0.88	86.5	0.92	87.8	0.96	87.4
LICH	0.73	66.6	0.78	70.7	0.97	91.8	0.86	90.5	0.85	76.8	0.98	93.8
PLNE	0.75	69.7	0.83	76.5	0.88	79.1	0.69	69.7	0.70	63.1	0.98	96.5
PSGO	0.78	74.7	0.92	87.4	NA	NA	0.93	84.0	0.90	82.1	0.98	96.0

evaluated). Also, we used large values (> 1 or < -1) for top of atmosphere energy imbalance (Wm²) to exclude models since these values may be an indication of long term drift in simulated climatic conditions (Forster et al. 2013). The final list of selected GCMs include: Community Climate System Model version 4 (CCSM4; Gent et al. 2011), Hadley Centre Global Environment Model version 2-Earth System (HadGEM2-ES; Collins et al. 2011), Model for Interdisciplinary Research on Climate version 5 (MIROC5; Watanabe et al. 2010), and Max Planck Institute Earth System Model, low resolution (MPI-ESM-LR; Block and Mauritsen 2013).

For future conditions, we used the downscaled data provided by WorldClim (Hijmans et al. 2005). We downloaded raster data for two RCPs (2.6 and 8.5) available for all selected GCMs and for two time periods (year 2050, the average for 2041 to 2060, and year 2070, the average for 2061 to 2080). We selected RCP 2.6 because it is the most aggressive among all RCPs in terms of greenhouse gas emissions reductions (Roeckner et al. 2010; Arora et al. 2011). Also, nearterm warming projected under RCP 2.6 is greater than under RCP 4.5, even though the greenhouse gas forcing is lower (Chalmers et al. 2012). For RCP 8.5, it is the most extreme scenario in that it entails the highest projected increase in the concentration of multiple greenhouse gases in the atmosphere (Vuuren et al. 2011) and associated increases in global surface temperatures (Knutti and Sedláček 2013).

We projected the bioclimatic-envelope models developed from present day conditions to potential future climatic conditions as simulated by the four selected GCMs that were statistically downscaled via the methodology of WorldClim for the years 2050 and 2070 and according to the two RCPs. To avoid generating hundreds of map results, again we used the SAHM ensemble tool to produce ensemble maps for the future distribution of each species. We combined each RCP result from the four GCMs. At the end, we have a set of projection maps for the year 2050 and another set for the year 2070 for each RCP and for each species. Finally, by ignoring areas for which output of fewer than three species distribution models and fewer than two GCMs overlap, we compared the current and future ensemble maps to determine stability, gains, and losses in suitable bioclimatic envelopes for the two projected years.

RESULTS

The performance of the five statistical models varied by species (Table 2). For instance, for the Sacramento Mountain Salamander, the AUC scores were highest for the BRT model, followed by Maxent, GLM, MARS, and RF. For the Chiricahua Leopard Frog, BRT scored the highest AUC, followed by RF, Maxent, MARS, and GLM. AUC values indicated strong discriminatory ability of the models, with most AUC values ≥ 0.70 . Only RF for the Jemez Mountains Salamander resulted to a slightly lower value (AUC = 0.69). Among the five models, BRT resulted in much higher quality (AUCs from 0.88 to 0.97), although it was only successful in modeling the amphibian species. The values of percent of occurrences correctly classified for BRT were also much higher than the other models (79.1% to 91.8%). Next to BRT, the MARS and Maxent models performed fairly well in terms of AUC, ranging from 0.70 to 0.92 for Maxent and 0.78 to 0.92 for MARS. Low percentages of occurrence points correctly classified (< 70%) were found for the GLM model.

The present day maps of suitable climate envelopes differed among the models. For instance, all models of the Chiricahua Leopard Frog showed medium to highly suitable conditions in the central eastern region of the species range, blanketing most of the reported presence distribution points (Fig. 3). However, among the five models, only RF and BRT identified highly suitable bioclimatic conditions in the central eastern region. These two suitability maps are associated with fairly high AUC values in Table 2 for RF (0.86) and BRT (0.97). MARS and Maxent highlighted suitable conditions in the western and southwestern regions, and GLM accentuated climate condition suitability more in the northeastern region.

Values for the True Skill Statistic (TSS) varied across species and models (Table 3). Similar to the results of the AUC, the BRT and RF models showed higher values



FIGURE 3. Bioclimate suitability maps derived from current climatic conditions for the Chiricahua Leopard Frog (*Lithobates chiricahuansis*), with point distribution shown in (a), using five common species distribution models: (b) BRT = Boosted Regression Tree; (c) GLM = Generalized Linear Model; (d) MARS = Multivariate Adaptive Regression Splines; (e) Maxent, and (f) RF = Random Forest. The map values range between 0 (blue, low probability) to 1(red, high probability).

in terms of the TSS. For the Chiricahua Leopard Frog (LICH), for instance, BRT scored the highest (TSS = 0.83) followed by RF (TSS = 0.59), while GLM scored the lowest among the five models with TSS = 0.32.

TABLE 3. The True Skill Statistics (TSS) for the five different models. Model abbreviations are GLM = Generalized Linear Model, MARS = Multivariate Adaptive Regression Splines, BRT = Boosted Regression Tree, and RF = Random Forest. Species abbreviations are ANHA = *Aneides hardii*, LICH = *Lithobates chiricahuensis*, PLNE = *Plethodon neomexicanus*, and PSGO = *Pseudemys gorzugi*. Note that Not Available (NA) is used for cases where BRT did not execute successfully due to an error related to sample size.

	GLM	MARS	BRT	RF	Maxent	Ensemble
Species	TSS	TSS	TSS	TSS	TSS	TSS
ANHA	0.72	0.74	0.74	0.73	0.76	0.85
LICH	0.32	0.41	0.83	0.59	0.54	0.91
PLNE	0.40	0.54	0.53	0.40	0.31	0.90
PSGO	0.51	0.75	NA	0.68	0.65	0.92

Overall, GLM had the lowest accuracy based on the TSS relative to the other four models.

For four of the five species, all five models identified potential suitable bioclimatic conditions (ensemble score = 5) for regions where species presence distribution points were found (Figs. 4a, 4c and 5). However, this was not entirely true for the Jemez Mountains Salamander (PLNE), where high agreement among models (ensemble score = 5) was found mostly south of those areas with species occurrence data (Fig. 4b). For the Chiricahua Leopard Frog, in addition, we identified a large potential climate envelope area in the southwest region, where no presence points were recorded (Fig. 4c).

The area where there was agreement among five models for the Sacramento Mountains Salamander (Fig. 4a) was limited to the distribution of the species as expected. Only 1% of the current USGS species range (254 mi²) was identified as containing potentially suitable bioclimatic conditions by all five models.



FIGURE 4. Present day bioclimatic-envelope ensemble model for the amphibian species (a) Sacramento Mountains Salamander (*Aneides hardii*); (b) Jemez Mountains Salamander (*Plethodon neomexicanus*); and (c) Chiricahua Leopard Frog (*Lithobates chiricahuensis*). A high score of 5 means that all species distribution models assigned that pixel as containing suitable bioclimatic conditions for the species.

Analyzing the agreement among at least three models, the area increased slightly to 295 mi². In the case of the Rio Grande Cooter, which had only four models of climatic suitability (Tables 2 and 3, Fig. 5), all four models identified about 2,318 mi² of the current USGS species range as containing suitable bioclimatic conditions. The area almost doubled to 11,806 mi² for agreement of three models or more, though this is still a very small area.

Other qualitative assessments of model performance included an inspection of the calibration and deviance of residual plots. No models had calibration plots that were without some form of over or under prediction. Some models were under predicting lower probabilities of occurrence and over predicting higher probabilities. Because the probabilities of occurrence were not reliable, but the AUC scores were fairly good, our use of binary plots in developing the model results was justified.

The maps of the projected climate envelopes of the Chiricahua Leopard Frog, Sacramento Mountains Salamander, Jemez Mountains Salamander, and Rio Grande Cooter show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non; Figs. 6–9). The total size area containing present suitable environmental conditions decreased slightly by 2050 for the Sacramento Mountains Salamander (293 mi²



FIGURE 5. Present day bioclimatic-envelope ensemble model for the single reptile species Rio Grande Cooter (*Pseudemys gorzugi*). A high score of 4 means that four species distribution models assigned that pixel as containing suitable bioclimatic conditions for the species. Only four species distribution models ran successfully for this species (see Tables 2 and 3).

average decrease of present climatic conditions for RCPs 2.6 and 8.5) and for the Rio Grande Cooter (27% average increase). The models suggest that the Rio Grande Cooter could spread northwest, possibly outside the studied USGS range (Fig. 9). In contrast, relative

to present day conditions, the SDM models simulate considerable loss of suitable habitat by 2070 for the Rio Grande Cooter (94% and 85% loss of presently suitable areas for RCPs 2.6 and 8.5, respectively). The year 2050 showed comparable loss of suitable climatic conditions for the Rio Grande Cooter (76% and 90% loss of presently suitable areas for RCPs 2.6 and 8.5, respectively; Fig. 9), with most of the current localities of species occurrence and suitable climatic conditions projected to become unsuitable.

Among the list of species, the Chiricahua Leopard Frog (Fig. 6) and the Jemez Mountains Salamander (Fig. 8) showed increased distribution of suitable bioclimatic conditions for all years by RCP combinations (see also Fig. 10). Chiricahua Leopard Frog habitat increases relative to the total area of currently suitable conditions for 2050 and 2070: averaged 50% and 51% for RCP 2.6 and RCP 8.5, respectively. The Jemez Mountains Salamander habitat increases 58% for RCP 2.6 at 2050, 57% for RCP 2.6 at 2070, 62% for RCP 8.5 at 2050, and 44% for RCP 8.5 at 2070. In fact, the loss of suitable climate conditions for the Jemez Mountains Salamander was < 1% of the current distribution of suitable conditions for all projected scenarios (Figs. 6 and 10). Finally, three of the five statistical models agreed that the majority of the southern portion of the current USGS range represented potentially suitable bioclimatic conditions for the Jemez Mountains Salamander in future (Fig. 8).



FIGURE 6. Comparison of ensembles of suitable bioclimatic conditions between present day and future for the Chiricahua Leopard Frog (*Lithobates chiricahuensis*). Future model ensembles based on bioclimatic data from General Circulation Models projected according to: (a) RCP 2.6 to the year 2050; (b) RCP 2.6 to the year 2070; (c) RCP 8.5 to the year 2050; (d) RCP 8.5 to the year 2070. Maps show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non).



FIGURE 7. Comparison of ensembles of suitable bioclimatic conditions between present day and future for the Sacramento Mountain Salamander (*Aneides hardii*). Future model ensembles based on bioclimatic data from General Circulation Models projected according to: (a) RCP 2.6 to the year 2050; (b) RCP 2.6 to the year 2070; (c) RCP 8.5 to the year 2050; (d) RCP 8.5 to the year 2070. Maps show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non).

DISCUSSION

Species modeling performance.---We expected the five species distribution models to provide different distributions of suitable bioclimatic conditions within species, as has been previously reported (Hirzel et al. 2006; Kumar et al. 2009; Stohlgren et al. 2010; Capinha and Anastácio 2011; Robert et al. 2016). Overall, the AUC values indicated fairly good discriminatory ability of the individual models with most AUC values ≥ 0.70 , although some models, such as GLM, had low values. We used both confusion matrix (percentages of true negatives, true positives, false negatives, and false positives) and area under the Receiver Operating Characteristic (ROC) curve as measures of adequacy of the models. The SAHM tool also used data subsets to look at differences between training data and test data. However, not all of these measures showed strong tests for all five statistical models. In fact, the AUC ranged

from mostly good values (0.70 to 0.90) to a few high values (> 0.90). Nevertheless, these measures were rather unequivocal assessments of the performance of the five models in depicting existing species distribution data.

Uncertainty and robustness of future projections.— Though many robust features can be identified in future projections, multiple limitations associated with the projection of species distributions into the future under different climate scenarios have been documented. Three broad categories of uncertainties affecting the climate variables used to drive the SDMs include (1) uncertainties in future greenhouse gas concentrations (Meinshausen et al. 2011), (2) limitations of the accuracy of GCM-simulated large-scale physical climate responses to changing greenhouse gas levels (Knutti and Sedláček, 2103), and (3) shortcomings and assumptions inherent to statistical downscaling



FIGURE 8. Comparison of ensembles of suitable bioclimatic conditions between present day and future for the Jemez Mountains Salamander (*Plethodon neomexicanus*). Future model ensembles based on bioclimatic data from General Circulation Models projected according to: (a) RCP 2.6 to the year 2050; (b) RCP 2.6 to the year 2070; (c) RCP 8.5 to the year 2050; (d) RCP 8.5 to the year 2070. Maps show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non).

methods used to refine GCM results with the aim of addressing GCM biases and to add finer levels of spatial detail (Barsugli et al. 2013; Dixon et al. 2016). By using data products derived from four GCMs and two RCPs, this study partially explores two of these three sources of climate variable uncertainty. Stoklosa et al. (2015) specifically discuss approaches to account for some uncertainties in the climate variables used to drive SDMs. Extrapolation beyond climate values used in developing SDMs for present day conditions (Thuiller et al. 2004) introduces another source of uncertainty. Furthermore, several authors have shown variability of future projections of suitable climatic conditions when using different climate models applied to the same species occurrence dataset (Bakkenes et al. 2002; Thuiller 2004). This variability of results makes assessment of future projections a complex effort. First, there is no way to know which single SDM could provide the most accurate information for a species,

although one could argue that the model with the highest accuracy in capturing present day distribution of suitable climatic conditions may give more accurate future projections. However, Thuiller (2004) reasoned that even when a model gives the highest AUC, it does not mean it provides the best estimate for the future distribution of suitable conditions, as every model is based on different assumptions. It is most fitting to use an aggregate of GCMs, the ensemble of future projections, as it represents the areas of agreement among individual model projections. The reliability of future conditions produced by ensembles may still be questioned, but ensemble results do represent the most conservative assessment of these conditions (Talbert 2012).

Caveats.—We purposely excluded non-climatic variables such as topography, vegetation cover, and land-use. Our analysis did not disregard the fact that



FIGURE 9. Comparison of ensembles of suitable bioclimatic conditions between present day and future for the Rio Grande Cooter (*Pseudemys gorzugi*). Future model ensembles based on bioclimatic data from General Circulation Models projected according to: (a) RCP 2.6 to the year 2050; (b) RCP 2.6 to the year 2070; (c) RCP 8.5 to the year 2050; (d) RCP 8.5 to the year 2070. Maps show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non).

variables other than climate could add explanatory power in the model. However, we chose to determine the explanatory power of the bioclimatic variables alone and did not want to restrict the distributions in present day and future by adding the non-climatic variables, especially for the more widely distributed species (e.g., the Rio Grande Cooter). The models we ran are based on the climate data alone and the projections were based on the occurrence records that were provided. We thought that unless there are dramatic changes to these non-climatic variables in future (i.e., future changes in vegetation and land-use), the majority of any shifts in distribution of suitable conditions between present day and future would be driven by the climatic variables that we focused on. In other words, these non-climatic variables would not lead to dramatic changes in the future distributions of suitable conditions. Apart from the lack of datasets projected according to the RCPs, scale is also an issue as vegetation and land-use datasets, for instance, are available at finer resolutions than the climate projections. However, we acknowledge the role that finer scale habitat changes, such as water availability, could play a significant role in species distributions. One important non-climatic variable that has shown to adjust the future distribution of suitable areas is the dispersal ability of the species (Bateman et al. 2013). However, dispersal behavior is hard to incorporate in model projections as it could also change over time. Finally, we reviewed the life history of each species to ensure that included climate variables are either known to be associated or could be associated with the species. Finer scale biotic factors that determine the species presence at the finer scale were not analyzed. We also did not analyze predator or prey effects nor did we analyze interspecific species competition. These factors operate a finer scale than our climate datasets.



FIGURE 9. Comparison of ensembles of suitable bioclimatic conditions between present day and future for the Rio Grande Cooter (*Pseudemys gorzugi*). Future model ensembles based on bioclimatic data from General Circulation Models projected according to: (a) RCP 2.6 to the year 2050; (b) RCP 2.6 to the year 2070; (c) RCP 8.5 to the year 2050; (d) RCP 8.5 to the year 2070. Maps show areas where ensembles agree (stable), future ensemble projects new suitable conditions (gain), present ensemble may be converted to unsuitable in the future (loss), and areas where conditions are unsuitable in the future (non).

Biological relevance of projections.—All five SDMs agreed that the distribution of the Sacramento Mountains Salamander within the three areas where it currently occurs, the Capitan, White, and Sacramento mountains of south-central New Mexico (Ramotnik 1997), contain the best climatic conditions for the species. With a minimal loss of suitable areas observed, our result confirms Ramotnik (1997) that highlighted no changes (i.e., expansion or contraction) of the range of the Sacramento Mountains Salamander in the last decade. When we first ran the model with annual precipitation as one of the predictors, areas near the Pecos River were classified as highly suitable. These areas are far away from known occurrences of the species. Based on the historical abundance of the Sacramento Mountains Salamander, the appropriate habitat for the species lies at 2,800 m above mean sea level (amsl; Ramotnik and Scott 1988). The integration of elevation into the modeling process has removed areas near the river (elevation around 1,000-1,500 m amsl) and the use of the seasonal precipitation as a predictor variable has eliminated the suitable conditions near the Pecos River. The majority of locations where the Sacramento Mountain Salamander are present continue to persist to year 2050.

The Jemez Mountains Salamander is the only species that had < 1% loss of area with currently suitable climatic conditions for all projected scenarios, making it the only species in this study that may not be at risk due to climate change since its current distribution would not be affected significantly based on these climate scenarios. In terms of elevation, the suitable bioclimatic envelope fit the requirement of the species of high elevation areas between 2,130 and 3,435 m. The mean temperature of the coldest quarter (Bioclim 11, Table 1) played a major role in the modeling process, as it ranked above others as a variable of importance in the individual SDMs. This importance of temperature of the coldest quarter as a determinant of suitable climatic conditions was not a surprise as the species has a low critical thermal maximum (Whitford 1968). Across GCMs, the climate envelopes of the species for years 2050 and 2070 are stable, with our model showing a likely expansion beyond the southern portion of the current localized range of the species. Whether populations of the Jemez Mountains Salamander would actually exist in the areas projected to be suitable in the future, specifically outside of Sandoval, Los Alamos, and Rio Arriba counties in north-central New Mexico, the idea would be impossible without assisted migration, given the limited mobility of the species and what is known about their current distribution and habitat preferences (not modeled). Mobility of the species is limited. For example, Painter (2000) reported a marked individual travelled a maximum distance of 1.5 m in 5 y.

Most models agreed that the present distribution of the Rio Grande Cooter is within suitable climatic conditions. In New Mexico, for instance, four models mapped suitable regions that extended to the Texan border. The result was different in the Texas populations, however, where fewer than four models identified areas where the species is currently found as containing suitable bioclimatic conditions. The low number of models in agreement could be attributed to the fewer number of recorded occurrences. Our models detected suitable climatic conditions that were within the elevation required for the species, as high as 1,082 m (Ward 1984) and near rivers and permanent tributary streams (Garrett and Barker 1987). There is a region located in Texas, outside the area with current day species occurrence data, where the future climate envelope is stable for the species in 2070 for both RCP 2.6 and RCP 8.5. Whether future occurrences would be recorded from this potentially suitable region depends on the migratory capacity of the species, as dispersal characteristics are largely unknown as well as the presence of suitable aquatic habitat. Based on what is currently known of the life history of the species, these turtles are non-migratory and prefer to stay in the same river reach (Degenhardt et al. 2005). Lastly, while a small percentage of the present suitable bioclimatic conditions remain stable in the future, our models showed that the Rio Grande Cooter could be put at a significant risk with climate change because of the loss of climatically suitable habitat.

A large region of the area modeled for present day conditions deemed suitable for the Chiricahua Leopard Frog is located in the mountains and valleys close to the Gila River in southeastern Arizona and southwestern New Mexico. These locations have been identified as part of the species range. In addition, potentially suitable conditions within 1,000 m to 2,710 m elevation (Sredl et al. 1997b) were identified near central Arizona outside the area sampled by the available species occurrence. The result of the projection of the climatic habitat-envelope was controlled by precipitation of the wettest quarter (Bioclim 16, Table 1) and temperature of the driest quarter (Bioclim 9, Table 1). With a strong correlation between river temperatures and air temperatures (e.g., Mohseni and Stefan 1999), Platz (1997) noted a positive correlation in the Ramsey Canyon population to changes in water temperature, while Altig et al. (1998) observed decreased oviposition by Chiricahua Leopard Frogs as water temperature decreases. Based on our results, there was stability in the distribution of suitable bioclimatic conditions into the future, irrespective of which trajectory of greenhouse gas concentrations was considered. For example, about 21 mi² of the species climate envelope in west-central New Mexico would remain stable in the year 2070 for RCP 8.5. The implication of these future projections for the Chiricahua Leopard Frog is encouraging as all scenarios showed stability of bioclimatic conditions for the species in the future relative to the present.

Life history is critical and underlying habitat features are important for species persistence. Species such as the Chiricahua Leopard Frog and Rio Grande Cooter may adapt to a changing climate if perennial water is present in sufficient quantity and at appropriate water temperatures (Ward 1984). Similarly, the Sacramento Mountain Salamander and Jemez Mountains Salamander may persist in their mountaintop habitats if microclimatic conditions provide sufficient moisture. By design, our models do not capture microclimate nor other local environmental characteristics such as stream temperature or soil moisture, but they do provide a strong climate change context for future explorations of species sustainability as affected by other drivers such as land use and water resources.

Our results show that creating an aggregate of models could provide better information than any single SDM, regardless of its accuracy, because it highlights the agreement among individual models. Based on available evaluation statistics, all five SDMs we tested performed fairly well in modeling present day climate envelope suitability, although a couple of them (BRT and RF) performed better than the rest. The models BRT and RF, unlike the other algorithms, automatically model interactions and nonlinear relationships, and are robust to missing observations. One of the challenges we had in this project was a model quantity dilemma. Our analyses created 480 models based on species, model algorithms, general circulation models and representative concentration pathways. We identified a process to focus on an ensemble approach to reduce this number for each species.

Did our method lead to accurate projection of potentially suitable climatic conditions in the future? We conclude that bioclimatic variables alone may not always correctly ascertain current or future suitable conditions. Our results for the Sacramento Mountain Salamander demonstrated that inclusion of topography might improve the model. We recommend suitable climate envelopes be identified and that speciesspecific non-climatic variables should be characterized to eliminate questionable modeled locations. Future research should incorporate dynamic processes (e.g., stream temperature) into the models to better capture the changing spatial structure of the species distributions, and information on species life history to aid in selecting the appropriate variables to model suitable conditions for the species. While we did incorporate life history in the selection process, future work should consider careful selection of the life-history traits of the species (Appendix 1).

Notably, different climate models and scenarios for increasing greenhouse gas concentrations resulted in different future distributions of suitable climatic conditions for the focal species. These climate models projected losses of suitable conditions in areas that are currently suitable, though the magnitude of loss varied among species and greenhouse gas concentration scenarios. We recommend that climate models be further enhanced with innovative methods to better address the effects of climate change on future distributions of species of conservation concern. Results of this study will be integrated into the Species of Concern (SOC) layer for the New Mexico Crucial Habitat Assessment Tool (NM CHAT. 2016. http://nmchat.org).

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Appendix 1

Species selection and datasets

We selected four herpetofauna species that were part of a list of 246 vertebrate species included in the development of the Species of Concern (SOC) layer for the New Mexico Crucial Habitat Assessment Tool (NM CHAT. Available from http://nmchat.org [Accessed 16 May 2016]). We narrowed the list to 81 potential focal species using the following five criteria: (1) a species distribution model has been or will be developed as part of the U.S. Geological Survey National Gap Analysis Program (Species Data and Modeling, 2016. Available from http://gapanalysis.usgs.gov/ species/data [Accessed 15 April 2015]); (2) the species is listed as a Species of Greatest Conservation Need for New Mexico (NMDGF 2006); (3) the species has a state rank of S1 (critically imperiled), S2 (imperiled), or S3 (vulnerable) for New Mexico (NM Conservation Information System. 2016. Available from http://nhnm.unm.edu/bcd/query [Accessed 3 September 2015]); (4) the species is a candidate for listing at the federal level (Species Reports. 2016. Available from http://ecos.fws. gov/tess public [Accessed 2 January 2016]), is listed in the Comprehensive Wildlife Conservation Strategy for New Mexico or Oklahoma as being in decline (NMDGF 2006; ODWC 2005) but is not listed as Threatened or Endangered at the federal level (Endangered Species Program. 2016. Available from http://www.fws.gov/endangered/species [Accessed 2 January 2016]; Species Reports. 2016. op. cit.), is listed by the Audubon society as being common but in decline (Christmas Bird Count. 2016. Available from https://www.audubon.org/conservation/science/christmas-birdcount [Accessed 17 February 2016]), or there is indication in various reports and journal articles that the species is vulnerable to climate change (Eaton and Scheller 1996; Johnson et al. 2004; Enquist and Gori 2008; Mitchell and Janzen 2010; Sorte and Jetz 2010; Zack et al. 2010; Coe et al. 2012; Bagne and Finch 2013; Foden et al. 2013; Friggens et al. 2013; Moyle et al. 2013; (5) the species' distribution (Species Data and Modeling. 2016. op. cit.; IUCN, Red List of Threatened Species. 2016. Available from http://www.iucnredlist.org [Accessed 28 May 2016]; Nature Serve Explorer. 2016. Available from http://explorer.natureserve.org [Accessed 17 February 2016]) intersects New Mexico and at least 50% of the species' distribution is within the study area or the distribution is entirely within the three Landscape Conservation Cooperatives (LCCs) that intersect New Mexico (Desert, Great Plains, and Southern Rockies). We obtained references providing information on species vulnerability to climate change from agencies, LCCs, and non-profit organizations that had performed assessments relevant for the study area, as well as from a literature review.

The potential focal species list was sent out for review by scientists and other individuals associated with the following agencies and organizations: Bureau of Land Management, George Miksch Sutton Avian Research Center, Natural Resources Conservation Service, NatureServe, New Mexico Department of Game and Fish, New Mexico State Land Office, Oklahoma Biological Survey, Oklahoma Department of Wildlife Conservation, Oklahoma State University, Playa Lakes Joint Venture, Texas Wildlife Department, The Nature Conservancy, US Fish and Wildlife Service, and US Forest Service. Science coordinators for the six LCCs that intersect the study area were also contacted.

After further refinements to the list, we selected a total of 20 terrestrial vertebrate species (Appendix Table), four of which were focused on here for bioclimatic-envelope model development. The species are fairly well distributed among the different terrestrial vertebrate taxonomic categories, though birds and mammals are better represented than reptiles and amphibians. The focal species range from having narrow geographic distributions and being highly endemic to the South Central region (e.g., Jemez Mountains Salamander (*Plethodon neomexicanus*)) to having fairly large

geographic distributions and being found well outside the region (e.g., Northern Bobwhite Quail (*Colinus virginianus*). The selected species are affected by a wide range of factors both directly and indirectly related to climate change, including drought and drying of aquatic habitats, wildfire, flooding, changes in vegetation type, and exposure to long periods of extreme temperatures. The species are found in a diversity of vegetation types including woodlands, shrublands, grasslands, riparian areas, and aquatic habitats.

Apart from the sources of species occurrence data we mentioned in the main body of the article, other online sources of species presence data gathered for the 20 focal species are the following: bird data (ORNIS. Available from http://www.ornisnet.org [Accessed 5 January 2016]), and vertebrate network (VertNet. Available from http://portal.vertnet.org [Accessed 5 January 2016]).

Scientific Name	Taxonomic Category	Common Name
Aneides hardii	Amphibian	Sacramento Mountain Salamander
Lithobates chiricahuensis	Amphibian	Chiricahua Leopard Frog
Plethodon neomexicanus	Amphibian	Jemez Mountains Salamander
Baeolophus ridgwayi	Bird	Juniper Titmouse
Callipepla squamata	Bird	Scaled Quail
Colinus virginianus	Bird	Northern Bobwhite Quail/Masked Bobwhite Quail
Cyrtonyx montezumae	Bird	Montezuma Quail
Gymnorhinus cyanocephalus	Bird	Pinyon Jay
Lagopus leucurus	Bird	White-tailed Ptarmigan
Peucaea cassinii/Aimophila cassinii	Bird	Cassin's Sparrow
Strix occidentalis lucida	Bird	Mexican Spotted Owl
Tympanuchus pallidicinctus	Bird	Lesser Prairie-Chicken
Baiomys taylori	Mammal	Northern Pygmy Mouse
Cynomys gunnisoni	Mammal	Gunnison's Prairie Dog
Cynomys ludovicianus	Mammal	Black-tailed Prairie Dog
Ochotona princeps	Mammal	American Pika
Vulpes velox	Mammal	Swift Fox
Zapus hudsonius luteus	Mammal	New Mexican Jumping Mouse
Aspidoscelis dixoni	Reptile	Gray-checkered Whiptail
Pseudemys gorzugi	Reptile	Western River Cooter

APPENDIX TABLE. The 20 focal species selected for bioclimatic-envelope model development.

BISON
Biodiversity Research and Teaching Collections - TCWC Vertebrates
CAS Herpetology (HERP)
CM Herps Collection
CUMNH Herpetology Collection
CUMV Amphibian Collection
Herpetology Collection
Herps Specimens
iNaturalist research-grade observations
KUBI Herpetology Collection
LACM Vertebrate Collection
MPM Herpetology (H)
Museum of Comparative Zoology, Harvard University
MVZ Herp Collection (Arctos)
NatureServe Network Species Occurrence Data
New Mexico Biodiversity Collections Consortium database
NMNH Vertebrate Zoology Herpetology Collections
Peabody Herpetology DiGIR Service
PSM Vertebrates Collection
SMNS Herpetologie
University of Alberta Museums, Amphibian and Reptile Collection
UTEP Vertebrates
HERPNET
Academy of Natural Sciences
American Museum of Natural History (AMNH)
Amphibians and reptiles at the University of Alaska Museum of the North
Arizona State University, Global Institute for Sustainability
Auburn University Museum
Bernice Pauahi Bishop Museum, Department of Natural Sciences
Borror Laboratory of Bioacoustics (BLB)
BYU Life Sciences
California Academy of Sciences (CAS)
Carnegie Museum of Natural History
Cincinnati Museum of Natural History
Cornell University Museum of Vertebrates (CUMV) - Amphibian Collection
Cornell University Museum of Vertebrates (CUMV) - Reptile Collection
Field Museum
Florida Museum of Natural History (UF)
Georgia Museum of Natural History (GMNH)
Georgia Southern University
Illinois Natural History Survey (INHS)

APPENDIX 2. List of institutions that provided data for BISON and HERPNET.

Los Angeles County Museum of Natural History (LACM) MCZ-Harvard University Michigan State University Museum (MSUM) Milwaukee Public Museum - Milwaukee Public Museum Museum of Natural Science (LSUMZ) Museum of Southwestern Biology (MSB) at The University of New Mexico MVZ Herp Observations MVZ Milton Hildebrand Collection National Museum of Natural History, Smithsonian Institution OZCAM Provider - Online Zoological Collections of Australian Museums Perot Museum of Nature and Science Raffles Museum of Biodiversity Research (RBMR) Redpath Museum, McGill University Royal Museum For Central Africa (Tervuren - Belgium) Royal Ontario Museum Sam Noble Oklahoma Museum of Natural History Specimens Sam Noble Oklahoma Museum of Natural History Tissues San Diego Natural History Museum Santa Barbara Museum of Natural History Senckenberg DiGIR Provider Staatliches Museum für Naturkunde Stuttgart Texas Cooperative Wildlife Collection (TCWC) Universidad Nacional Autonoma de Mexico - IBiologia - CNAR/Coleccion Nacional de Anfibios y Reptiles University Museum of Zoology Cambridge (UMZC) University of Alabama, Alabama Museum of Natural History University of Alberta Museums University of Arizona Museum of Natural History University of British Columbia University of Colorado Museum of Natural History University of Kansas Biodiversity Institute - Herpetology Collection University of Louisiana at Monroe University of Nebraska State Museum University of Nevada Reno University of Texas at Arlington University of Texas at El Paso - Herps Specimens University of Wyoming Museum of Vertebrates Utah Museum of Natural History (UMNH) UWBM Herpetology Collection Yale University Peabody Museum Zoological Institute RAS - Amphibian specimens Zoological Museum, Natural History Museum of Denmark