12-31-2015

Final Report: Predicting Effects of Climate Change on Riparian Obligate Species in the Southwestern United States

Jacek Tomasz Giermakowski

James R. Hatten

Matthew J. Johnson

Jennifer A. Holmes

Erika M. Nowak

See next page for additional authors

Recommended Citation

Giermakowski, J. T., Hatten, J. R., Johnson, M. J., Holmes, J. A., Nowak, E. M., & Peters, M. (2015). Final Report: Predicting Effects of Climate Change on Riparian Obligate Species in the Southwestern United States. https://doi.org/10.25844/HA9K-PK12

Authors
Jacek Tomasz Giermakowski, James R. Hatten, Matthew J. Johnson, Jennifer A. Holmes, Erika M. Nowak, and Michael Peters

Final Report: Predicting Effects of Climate Change on Riparian Obligate Species in the Southwestern United States

P.I. – Matthew J. Johnson, Northern Arizona University, PO Box 5614, 525 S. Beaver St., Chemistry Bldg. 20, Rm. 125, Flagstaff, AZ 86011. Phone: 928-523-7764, Fax: 928-556-9111, email: matthew.johnson@nau.edu

Submitted to US Department of the Interior, Bureau of Reclamation, Desert Landscape Conservation Cooperative

Permanently archived in the University of New Mexico Institutional Repository (https://repository.unm.edu/) with the identifier http://hdl.handle.net/1928/31796

Agreement Number: R11AC81532

Reporting period: 1/1/2012 -12/31/2013

Authorship and affiliations: J. Tomasz Giermakowski[1], James R. Hatten[2], Matthew J. Johnson[3], Jennifer A. Holmes[3], Erika M. Nowak[3], Michael Peters[3]

[1]University of New Mexico, Albuquerque, NM. tomas@unm.edu, 505-277-5130
[2]U.S. Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory, Cook, WA
[3]Northern Arizona University, Flagstaff, AZ

Suggested citation:

Giermakowski, J.T., J.R. Hatten, M.J. Johnson, J. A. Holmes, E.M. Nowak, M. Peters. 2015. Final Report: Predicting Effects of Climate Change on Riparian Obligate Species in the Southwestern United States. Submitted to United States Department of the Interior, Bureau of Reclamation, Desert Landscape Conservation Cooperative; Agreement Number: R11AC81532. Albuquerque, New Mexico: University of New Mexico, December 31, 2015. http://hdl.handle.net/1928/31796

CONTENTS

ABSTRACT

The Lower Colorado River and Rio Grande Basins are home to many riparian vertebrate species with different degrees of rarity. In our study, we focused on two species of birds and two species of gartersnakes that are associated with riparian areas: the Yellow-breasted Chat (*Icteria virens*), the Yellow Warbler (*Setophaga petechia*), the Northern Mexican Gartersnake (*Thamnophis eques megalops*) and the Narrow-headed Gartersnake (*T. rufipunctatus*). While the extent of distributions of these species is relatively large, they are often patchily distributed in populations that are small; in addition, both gartersnake species are listed as threatened under the Endangered Species Act. Aside from detrimental effects of direct habitat loss and degradation throughout the southwestern United States, future changes in water availability might threaten the long-term persistence of populations of any one of these species. To evaluate this vulnerability at a landscape scale, we built species distribution models under current and future projected climates for each species. For modeling, we relied on climatic and hydrological predictions (downscaled CMIP3 climate and hydrology projections) developed by the Bureau of Reclamation and its partners as part of the West-Wide Climate Risk Assessments within the WATERSmart initiative. We also relied on NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS) to derive a spatially explicit index that quantifies riparian vegetation in space and time. Using downscaled climate projections and other landscape data, we were able to project these riparian vegetation metrics forward in time. The projected changes in water availability by end of the century will directly affect the availability of permanent water and riparian vegetation creating the habitats of our study species. Our results suggest significant and negative changes in future landscape suitability for all species (up to 64% loss of suitable area), which are in addition to already identified threats facing these species. Best models included the index of riparian vegetation (linked to water availability) as an important component of the predictions, but we also note that finer scale examination of hydrology and climate effects on habitats would be much more useful for effective management.

1 INTRODUCTION

Riparian areas provide critical habitat for wildlife throughout the Southwest (Johnson et al. 1985, Skagen et al. 2005). Numerous southwestern species require riparian vegetation and corridors for breeding, foraging, shelter, and dispersal. For example, many riparian-obligate birds are dependent on dense, lush riparian vegetation for food and shelter (Paxton et al. 2007); whereas gartersnakes depend on ground vegetation and litter for cover (Rossman et al. 1996, Nowak and Santana-Bendix 2002, Nowak 2006). Recent changes in the composition and distribution of riparian vegetation have resulted in the imperilment of many riparian obligate species such as the threatened Northern Mexican Gartersnake (*Thamnophis eques megalops*) and Narrow-headed Gartersnake (*Thamnophis rufipunctatus*), both species listed recently as threatened under the Endangered Species Act (United States Fish and Wildlife Service 2014).

Riparian areas are considered one of the most altered and vulnerable habitats in the southwestern United States, partly because land- and water-use practices in the last century have led to the widespread degradation of these areas (Webb et al. 2007) and also because they are heavily dependent on climatic conditions that affect ground and surface water derived from rainfall and snowpack (Perry et al. 2012). Paleorecords indicate that the last 16 years (2000 to 2015) was one of the lowest periods for natural flow in the Colorado River basin (Meko et al. 2007). Climate change is predicted to have a severe effect on vegetation throughout the Southwest by increasing the frequency and severity of drought, which in turn will decrease water availability and negatively affect riparian health (Seager et al. 2007). Exacerbating this is the rapid human population growth of the Southwest, which has the highest growth rate in the United States (Barnett et al. 2008, Cayan et al. 2010). Surface-water supplies are fully allocated and a growing population is increasingly relying on groundwater in much of the region. As droughts and human pressure increase, riparian vegetation is likely to decrease in abundance and vigor, leading to decreased cover and humidity, and increased water temperatures. These changes are expected to have lasting effects on riparian-obligate wildlife. Consequently, a conservation challenge is to generate quantitative predictions of how variability and changes in climate will affect the amount and quality of riparian wildlife habitat in the future and in turn, the species associated with these habitats.

The prediction of future conditions of riparian areas relies on current knowledge of a variety of functional variables. At a coarse scale, the distribution and abundance of riparian habitats depends on valley form, surface and groundwater availability, flow history (e.g., years since last scouring flood), and anthropogenic activities (Rosgen 1996, Committee on Riparian Zone Functioning and Strategies for Management 2002). Some of the most successful approaches in modelling current patterns of riparian vegetation have used aerial-photo interpretation and collection of extensive field data (e.g. Wallace et al. 2013), in addition to evaluating wastewater subsidy (Villareal et al. 2012). These inherent and complex interactions make predictions of future conditions difficult without proven modeling techniques but some linkages between climate and the condition of riparian vegetation have been made (e.g., Glenn et al. 2001). For example, hydrologists have developed a variety of tools, including numerical models, to characterize and predict hydrologic processes such as flood recurrence intervals, surface-water flows, and groundwater levels and flows. Inputs to these models often include human-related factors such as groundwater withdrawals and land-use changes, and climate factors such as precipitation and groundwater recharge (Committee on Riparian Zone Functioning and Strategies for

Management 2002). The resulting simulations can be used to estimate the effects of various resource management actions (e.g., Leake et al. 2008) and climate patterns on availability of water to ecological systems. In addition, geologists have developed conceptual and numerical models of sediment transport and sorting in valleys, and of channel morphologic adjustment--processes that determine the distribution of materials and landforms that comprise the substrate for riparian vegetation. Riparian ecologists understand many of the conditions and processes controlling the distribution and abundance of different types of riparian vegetation and have generated models relating different components of streamflow to response of individuals, populations, and communities (Merritt et al. 2010). Finally, remote sensing experts have developed GIS-based models that help identify and quantify riparian habitat available to wildlife, especially focusing on using land-cover and vegetation to improve their accuracy (Hatten and Paradzick 2003, Wallace et al. 2013, Villareal et al. 2014). These types of GIS-based models allow for rapid and relatively inexpensive identification of potentially important habitat while allowing linking with hydrologic and geomorphic models that quantify water availability. The integration of hydrologic, geomorphic, ecological, and remote sensing models is therefore a worthy framework for modeling species distributions and can provide valuable management insights.

Development and evaluation of multivariate techniques for modeling biological distributions, or species distribution modeling (SDM), has experienced an explosive growth in the last decade (Elith and Leathwick 2009, Franklin 2013). This is partly because SDMs can provide a useful tool for a variety of management-related applications (Guisan et al. 2013). Here we developed SDMs based on existing data that include likely effects of climate change on riparian-linked species of birds and reptiles. We selected the Yellow-breasted Chat, the Yellow Warbler, and the federally threatened Northern Mexican Gartersnake and Narrow-headed Gartersnake as our target species because there is extensive data on their current and former distributions. The selection of endothermic birds and ectothermic snakes provides a unique contrast that spans a range of riparian mesopredator niches (after Nowak et al. 2008, van Riper et al. 2014). All four species face similar threats that include loss of permanent flowing water, changes to vegetation structure and composition, introduction of non-native invasive predators, loss of native prey species, and changes in hydrological processes and biotic composition resulting from catastrophic wildfires (United States Fish and Wildlife Service 2014).

The goals of our project were twofold. First, we sought to provide regional assessments on the suitability of the landscape for these riparian species. Second, we wanted to evaluate the importance of water availability in the future by focusing on hydrological variables linked to riparian vegetation. We developed species-specific conceptual diagrams that identified important links between climatic, geological, biotic variables, and population parameters. We then built SDMs to evaluate future predicted changes in landscape suitability. We relied on downscaled predictions of current and future climatic and hydrological variables developed by the Bureau of Reclamation using NASA's Moderate-Resolution Imaging Spectroradiometer (MODIS) data to derive spatially explicit metrics that quantify the availability of riparian vegetation in space and time. Using Reclamation data, we were also able to project these vegetation metrics over time. We based our approach on first linking hydrological data on water availability to current estimates of vegetation indices, and then assessing the role of vegetation in the model.

2 METHODS

2.1 MODELING OVERVIEW

We evaluated the distributions of four focal species west of the 100th meridian, inside the Colorado and Rio Grande basins, USA (Figure 1). The project area covers a broad range of geographic, topological, and climatic influences within a diverse array of ecosystems, totaling 946,368 km^2. For model development and testing, we used all areas within 12 km of all streams and rivers with a mean annual flow greater than 10 cfs (cubic feet per second; Figure 1). The 10 cfs threshold was determined after overlaying available presence data for the focal species and identifying the minimum mean annual flow at which there were data documenting presence of species. This balances errors of omission and commission. The minimum mapping unit was approximately 144 km^2 (circa 12 X 12 km), with each cell corresponding to the finest scale dataset available from Bureau of Reclamation (section 2.3). We selected two species of birds and two species of snakes for modeling that are associated with riparian areas: the Yellow-breasted Chat, the Yellow Warbler, the Northern Mexican Gartersnake and the Narrow-headed Gartersnake. While the extent of occurrence of these species is relatively large, their populations are often small and patchily distributed across the landscape.

Before we could project suitability into the future, we created baseline SDMs for each species. We accomplished this in a two-step process. First, we developed a linear regression model that predicted riparian vegetation greenness from baseline climate and hydrologic data (sections 2.3 and 2.4). Second, we used binary logistic regression (birds) or Maxent (reptiles) to predict the current distributions of each species using historical species occurrence data, baseline climate and hydrology data, landscape variables (terrain ruggedness and insolation), and the predicted riparian vegetation greenness derived in the first step. Birds and non-avian reptiles required different modeling approaches due to differences in the availability of presence records for each group and the methods with which these data were collected.

We projected future ranges of each species for 2039 and 2099 in several steps. First, we populated each species' SDM with six General Circulation Model (GCM) simulations of current climate (five individual models and one ensemble model [average of five]), producing six range maps that had continuous probabilities for any location (0 – 99%). Second, we reclassified each range map into binary format, so a given cell was considered suitable or unsuitable after calculating a probability threshold that maximized sensitivity and specificity for each species (e.g. 0.5; Liu et al. 2013). Third, we overlaid and summed the six binary range maps so each cell had a value from zero to six. A cell value of zero indicates that none of the algorithms predicted suitability for that location while a value of six indicates that models based on all six GCM simulations predicted suitability for that location. Fourth, we identified all cells where at least five of the six predictions agreed a location was suitable (i.e., ≥ 83% certainty) and created a composite range map. Fifth, we identified changes in ranges of species between 2009 and 2039, and between 2009 and 2099, through grid subtraction (differencing) the two binary range maps. The resulting calculations allow for comparisons of areas where suitability persists, is lost, or where suitable areas are likely to form in the future. We dealt with uncertainty when modeling future suitability by selecting the most accurate subset of GCMs when hind-casting southwest climate (Garfin et al. 2010), and by setting a high (83%) agreement threshold (van Riper et al. 2014).

2.2 DATA FOR MODELING SPECIES DISTRIBUTIONS

We obtained bird locations from the Avian Knowledge Network eBird database (Iliff et al. 2009; Sullivan et al. 2014) and only used vetted data that represented records between January 1990 and July 2009. For our analyses we considered a species present if there was a single record within an approximately 144 km^2 (12 km x 12 km) cell. To eliminate pseudo-replication, only one detection per cell was considered in model construction and verification. After buffering, filtering, and reconciling species names used in different data sources, there were 413 presence locations for Yellow-breasted Chat and 168 for Yellow Warbler. We complemented these datasets with randomly generated absence data (1,216 for YBCH and 99 for YEWA) within the riparian areas (within 12 km of all streams and rivers).

We obtained gartersnake locations from the Global Biodiversity Information Facility (http://gbif.org), Vertnet (http://vertnet.org), and unpublished data from the Arizona Game and Fish Department's Heritage Data Management System. We normalized reptile taxonomic designations and used openRefine software (http://openrefine.org) to standardize geographic and taxonomic data associated for each occurrence record. Due to the restricted distribution of these species in riparian habitats with permanent water (Rossman et al. 1996), each record was considered for georeferencing (assignment of geographical coordinates) if only a verbal description of a locality was available. We followed the georeferencing protocols for natural history museum collections of vertebrates (see http://www.vertnet.org) and relied on GEOLocate web application (Bart and Rios 2015) for coordinate assignments. Only those records that had an error radius of less than 5 km (thus most likely to be within one analysis cell) were considered fit for use and saved for further analyses. Once each occurrence record was evaluated and assigned a geographic coordinate, each point was assigned to the nearest centroid in the climate data. Duplicate points were removed and the presence and absence layers were merged (where presence and absence overlapped, presence was chosen). The data for gartersnakes consisted of 209 georeferenced records for the Northern Mexican gartersnake and 277 georeferenced records for Narrow-headed gartersnake, which covers the time period from 1940 to 2009.

2.3 CLIMATE AND HYDROLOGY PROJECTIONS AS ENVIRONMENTAL VARIABLES

The variables used in the construction of SDMs were selected from a subset of variables identified in conceptual models (Section 9.1). We followed the same procedure for identifying variables as in our related effort (van Riper et al. 2014), including a critical evaluation of factors affecting the species' persistence and environmental conditions linked to its occurrence. We used a differing number of variables for construction of SDMs, depending on species. Table 1 shows examples of the variables used and their calculation.

For both current and future climate variables we relied on the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. This was supplemented by archived data provided by the Bureau of Reclamation (Meehl et al. 2007, Bureau of Reclamation 2012). From this dataset, we downloaded and processed climatic variables for each of five models (CNRM, CSIRO, ECHAM, NCAR, and UKMO) under the A1B scenario, a scenario that assumes rapid economic growth and quick spread of new technologies that balance emphasis on all energy sources. These variables were evapotranspiration, precipitation, soil moisture content, maximum temperature, minimum temperature, mean temperature (calculated from the maximum and minimum temperatures), and surface runoff. The five individual GCMs were selected based on their ability to successfully hind cast 20th century climate, especially the precipitation seasonality that is critical for ecosystems in the four-corners region (Garfin et al. 2010). Each downloaded file was converted into a raster file for the Rio Grande and Colorado River watersheds and datasets were merged. The final step in data preparation included a conversion of all data to ESRI ASCII grid format for compatibility with a variety of GIS software. For some variables (Table 1), ASCII grids were blended into seasonality components using a customized program by one of the authors (MP), but we relied on ArcMap software (ESRI Inc., Redlands, CA, USA) for the majority of data manipulation.

2.4 Calculation of riparian vegetation indices

We downloaded and prepared data on riparian vegetation greenness in our study system from the Moderate Resolution Imaging Spectroradiometer (MODIS) platform. Specifically, we relied on product MCD43A4, which provides 500-meter reflectance data from a combined product of two satellites with the MODIS sensor (Terra and Aqua). The MODIS data have the highest spatial (500 m) and temporal (16–day) resolution available globally (Huete et al. 2010). We used data on the enhanced vegetation index (EVI) for every 16–day period for 10 years (2000–2009) for the Colorado and Rio Grande watersheds. This index (EVI) represents the difference in reflection between the near infrared and red parts of the electromagnetic spectrum, which represents amount of photosynthetic activity in the observed vegetation (Turner et al. 2003). High EVI values (maximum of 10000) indicate high of vegetation "greenness" or photosynthetic activity; EVI values near or below zero characterize land with no vegetation, such as lava fields, water, or bare soil. We used raw EVI values (data range -854 to 9452) because they correlate strongly with vegetation biomass, leaf area and gross primary productivity (Zhang et al. 2003, Sims et al. 2006, Huete et al. 2010, Solano et al. 2010), and other ecologically meaningful factors, such as shade availability (Justice et al. 2002, Huete et al. 2006).

Processing of satellite imagery was done with software tools provided by the MODIS land quality assessment group (Roy et al. 2002). In order to increase the quality of data used, we excluded any pixels that received a quality rating lower than "good" by the NASA processing center (as available in MODIS product MCD43A4). We also excluded pixels from analyses when good quality pixels covered less than 50% of the cell of interest (the rest of the data used in this study were of much coarser resolution). In addition, we applied a 5 x 5 low-pass smoothing kernel to reduce any effect of outliers or rogue pixels when calculating EVI values across space. After EVI extraction at appropriate time and spatial scales, we used TIMESAT software (Jönsson and Eklundh 2004) to calculate metrics that represent different characteristics of vegetation in time. We derived seasonality statistics from these data, which we then used to relate to climate variables and as variables in SDMs, ultimately relying on a 10 year mean of the maximum EVI during the growing season (following spring green-up) as the variable best representing riparian vegetation greenness.

2.5 Predicting riparian vegetation greenness

An important component of our SDMs is the incorporation of greenness as a predictor variable, representing vegetation within approximately 12 km (i.e., the scale of climate data used in this study) of any creek or river where a mean annual flow is calculated to be greater than 10 cfs. Using the National Hydrological Database, we calculated a 12 km buffer around streams where mean annual flow is greater than 10 cfs and generated 5,000 random points within the buffered area. We then attributed these locations with a 10–year mean of the maximum EVI for the growing season (following spring green-up, see previous section) and ensemble CMIP3 data. Our approach required that we be able to predict riparian vegetation greenness (EVI obtained from MODIS) under baseline predictions, then be able to predict greenness in 2039 and 2099. We calculated greenness for baseline conditions (2009) with multiple linear regression, statistically coupling baseline CMIP3 climate and hydrology variables, and landscape variables (insolation and terrain ruggedness) with EVI data. We then used the derived linear regression and future ensemble CMIP3 data to calculate EVI values for 2039 and 2099.

2.6 Construction and Evaluation of Species Distribution Models

Birds and gartersnakes required a different modeling approach due to differences in the availability of occurrence records for each taxon: presence-absence for birds and presence only data for gartersnakes. For birds we used binary logistic regression (Hosmer and Lemeshow 2000) to identify important environmental variables and develop species distribution models because presence-absence data are binary (Keating and Cherry 2004). We used Arc/Info® GRID (ESRI Inc., Redlands, CA, USA) to calculate and map the probability that a bird species would be present within each cell. In contrast, for gartersnakes, we used a maximum entropy modeling approach (Maxent; Elith et al. 2010) because it is well suited for evaluating relationships between predictor variables and species whose occurrence is based on museum records that are presence-only data. We used Maxent to calculate and map the probability that either species of gartersnake would be present, as well as Maxent's built-in functions for random seeds, background selection, cross-validation, and model averaging (Phillips and Dudík 2008).

3 Results

3.1. Calculated Riparian Vegetation Index

The best multiple linear regression that applied baseline CMIP3 data and landscape variables to predict a riparian vegetation index (EVI) explained 44% of variation and behaved well spatially, although smoothing was evident in several areas (see Appendix 9.2). Variables that were included in the best regression equation were: average maximum temperatures between May and August; basin area above a given location; insolation calculated for May 1st; terrain ruggedness obtained from a digital elevation model; average minimum temperatures between May and August; average evapotranspiration between May and August; average precipitation in spring (March – May); and average precipitation in Fall (September – November). The short time horizon projection (2039) showed that riparian vegetation greenness decreased most in the headwaters of the Gila and Salt Rivers, while the longer time horizon (by 2099) showed riparian vegetation greenness decreased throughout much of southern Arizona and New Mexico, including all major drainages of the Gila, Lower Colorado, Rio Grande, and Pecos Rivers (Figure 2).

3.2. Current Distributions

Models of species distribution that relied on climate and abiotic variables produced statistically robust predictions of currently suitable areas for all bird and gartersnake species. Classification accuracies for SDMs, measured as Area Under Curve (AUC) of a receiver operating characteristic in Maxent, varied from 0.94 (EVI–based model for Narrow-headed Gartersnake; Table 2) to 0.73 (non–EVI based model for Yellow Warbler). Ten out of 14 variables retained in the models are in every species' model (Table 3). Stream flow (as runoff) was retained as a variable in models for both gartersnake species, but was not retained in either bird species; furthermore, soil drainage index was retained only in the Narrow-headed Gartersnake model (Table 3). The suitability of landscape for both gartersnakes is best modeled with maximum summer temperatures and precipitation totals, seasonal EVI, and terrain roughness index (TRI). For the Northern Mexican Gartersnake, the three most important variables, in descending order, were maximum summer temperature, EVI and summer precipitation, whereas for the Narrow-headed Gartersnake, summer precipitation, TRI, and EVI were most important (Table 4). For the Yellow-breasted Chat, the three most important variables (in descending order) were TRI, average maximum temperatures during the breeding season (May–August), and EVI. In contrast, the three most important variables for the Yellow Warbler were average minimum breeding season temperatures (May–August), mean precipitation in the fall, and TRI (Table 4).

3.3. EFFECTS OF MODELED VEGETATION INDICES AND PROJECTED DISTRIBUTIONS

The effect of including EVI in modeling current landscape suitability varied among species by up to 10% as measured in percent of area (Table 5). For gartersnakes, the inclusion of EVI resulted in a 2.8% decrease of predicted area for the Narrow-headed Gartersnake and a 9.5% increase in predicted area for the Northern Mexican Gartersnake. For the bird species, including EVI in the models resulted in decreased areas of current predicted suitability for Yellow-breasted Chat by 3.8%, and an 8.7% increase for the Yellow Warbler. Each SDM contained between four and nine parameters, with models that included EVI having more parameters in the model. When examining models that did not include EVI, temperature or precipitation variables were the most influential predictors for all species, with averages of breeding season temperatures being the most important variables for birds, and winter temperatures and summer precipitation the most important for gartersnakes. TRI was the most important variable for the Yellow-breasted Chat, but TRI ranked third in importance for the Yellow Warbler.

Species distribution models indicate that areas of suitable landscape will decrease by the end of the century (i.e. 2099) for all four species when riparian EVI is included in the models (Figures 3–7). For gartersnakes, all predictions, regardless of inclusion of EVI, indicate a reduction of suitable areas. Short-term (i.e. 2039), models showed a suitable area decrease of 24% for the Northern Mexican Gartersnake, when EVI is included and a 28% decrease when EVI is excluded. The suitable area decrease differential is larger (and reversed) by 2099: suitable area decreases by 62% when EVI is included but decreases by only 7% when EVI is excluded (Figure 7). For the Narrow-headed Gartersnake, predicted suitable areas decrease by a larger amount when EVI is excluded from the models for both short-term and long-term calculations. Suitable areas for Narrow-headed Gartersnake decrease by 32% when EVI is included and by 51% when EVI is excluded by 2039. The loss of suitable area increases to 42% when EVI is included and 62% when EVI is excluded by 2099 (Figure 7). Predictions for Yellow-breasted Chat change from a reduction to an expansion of suitable landscape when EVI is excluded as a variable: suitable landscape contracts by 2099 by 32% when EVI is included, but increases by 61.3% when EVI is excluded (Figure 7). On the other hand, predictions for the Yellow Warbler indicate a contraction of up to 64.9% by 2099 when EVI is included and up to 48.3% when EVI is not included (Figure 7).

4 DISCUSSION AND CONCLUSIONS

4.1 ANALYSES OF SPECIES DISTRIBUTION MODELS

This work is among the first to incorporate downscaled predictions of current and future climatic and hydrological variables from the Bureau of Reclamation's WaterSmart and NASA's MODIS programs to evaluate vulnerability of carefully-selected riparian birds and reptiles to changing climate and water availability at a coarse landscape scale. The projected changes in water availability by end of the 21st century will directly affect surface runoff and consequently rivers and streams (whether permanent or ephemeral). Changes in water availability will thus affect the riparian vegetation that maintains the current habitat requirements and needs of our study species. Our results suggest significant and negative changes in future landscape suitability (up to 64% of currently suitable areas) for the two bird and two gartersnake species. These projected losses may additively increase threats from habitat loss and introduction of invasive predators (Webb et al. 2007, US Fish and Wildlife Service 2014).

Best species distribution models included indices of riparian vegetation (linked to water availability) as an important component of the predictions. Our results confirm that models that include EVI performed better than those where EVI was excluded, therefore we chose to include EVI in future prediction models because of a direct link between riparian vegetation and hydrology in the southwestern United States. Several studies have shown that remotely sensed variables improve SDM performance (e.g. Shirley et al. 2013, Wilson et al. 2013), although at regional scales the addition of vegetation indices does not necessarily improve models because of collinearity (Thuiller et al. 2004). In this work, several lines of evidence demonstrate the advantage of including landscape and vegetation variables in modeling potential species distribution. First, suitable areas from EVI-based predictions were generally patchier, reflecting a coarser nature of riparian habitats in the region. Second, EVI-based models had higher classification accuracies. Third, even though the importance of different variables was species-specific, EVI was consistently one of the top three most important predictors for three out of four species.

Future suitability of landscape varies in time for the two bird and two gartersnake species examined, but also shows a downward trend in suitability for all species, which is consistent with other studies (Bucklin et al. 2012, Foden et al. 2013, Urban 2015). Yellow-breasted Chat and Yellow Warbler showed declines in suitable area in both the short- and long-term time horizons, with loss of suitability projected to occur primarily on the edge of their distributions. For the Yellow-breasted Chat, a proportionally small area is projected to become suitable, mainly along the northern edge of its range; whereas no areas were projected to become suitable for the Yellow Warbler.

Currently, the Narrow-headed and Northern Mexican gartersnakes are known to occur in very few areas (US Fish and Wildlife Service 2014), thus the mapped suitable areas would appear to greatly overestimate the actual area of occupancy. For the Northern Mexican Gartersnake, however, our models predict suitable habitat along the Lower Colorado River, an area with a recently discovered, disjunct population (Lester and Swackhamer 2015). The gartersnake species are particularly difficult to detect in the field due to cryptic coloration and secretive behaviors, making quantification of their distributions challenging (Nowak 2006, Emmons and Nowak 2016). However, our modeling indicates that the edges of their ranges are likely to become unsuitable in the near future. This is in addition to other threats, as the Narrow-headed Gartersnakes appear to be losing habitat to climate change-mediated catastrophic wildfire (Jennings and Christman 2015, Nowak and Drost 2015). The aquatic ecology of both species is also reflected in the response of modeling predictors, which for both gartersnakes include the amount of summer precipitation and EVI within the top three important variables. Northern Mexican Gartersnakes are more tolerant of warm conditions, thus summer temperatures are an important variable for their distribution; whereas the Narrow-headed Gartersnake appears to be more restricted to habitats with cooler air and water temperatures (Rosen 1991, Nowak 2006). Northern Mexican Gartersnakes are known to be particularly drawn to dense vegetative cover (Emmons and Nowak 2016), supporting our assessment that EVI is particularly important for this species. In contrast to birds, important modeling variables for gartersnakes also include several variables related to hydrology, especially for Narrow-headed Gartersnake, providing meaningful contributions to predicting potential distributions.

Major caveats to the results of this study include issues of scale and model uncertainty. First, choosing an appropriate scale is paramount to an effective use of landscape variables, particularly those derived from remote sensing (Cord et al. 2013). Here we chose a coarse regional scale that would allow maximizing the amount of data available for large temporal and spatial extents. We also addressed model uncertainty by using an ensemble of five GCM models, as well as a consensus approach (five out of six) for binary habitat maps, thus relying on the effectiveness of consensus rather than on evaluating which models best suit a particular species or area. This approach is more effective in coarse-scale evaluations of potential species distribution and has been used previously in several instances (e.g., Buisson et al. 2009, Cord et al. 2013).

4.2 Actionable Science and Management

This project uses downscaled modeling to link impacts of climate change to potential changes in four riparian species on state and federal lands that are managed within the Desert Landscape Conservation Cooperative (LCC). A unique aspect of this project is the link of hydrological data to indices of riparian vegetation greenness. We modeled the landscape suitability for riparian bird and gartersnake species using vegetation metrics derived from satellite measurements. By using WATERSmart data, we also computed future projected changes in riparian vegetation. Through this project, major investments have been made in gathering data and development of methods for forecasting the effects of climate change on riparian species. The Desert LCC could capitalize on these existing resources as a framework for analysis of the effects of climate change on other riparian species.

We produced maps and GIS layers for the two gartersnake and two bird species that explicitly show how and where riparian vegetation is expected to change, and potentially influence the suitability of habitat for these riparian-obligate species. These analyses can form the foundation for a decision support system whereby managers can evaluate the effects of climate-change on local landscape suitability; however, we do not recommend the use of these results as a substitute for thorough, ground-truth surveys of species presence, especially given the poor state of knowledge on the distributions of extant gartersnake populations. While maps can guide monitoring efforts, they should be treated as probabilistic expressions of suitability of landscape. The most effective use of maps produced here may be for comparison of potential landscape suitability for a particular species between different areas. This can help identify conservation opportunities for specific areas.

The scale of the data used in this project (12 km) is useful for regional planning, but a finer scale (at resolution of less than 1 km) would be much more useful for effective management, particularly for species, such as gartersnakes, that are dependent on permanent water sources and are unlikely to occur far from riparian areas. Nevertheless, the advent of remotely sensed data coupled with advanced hydrological modeling provides a valuable set of variables that greatly improve the ability to effectively evaluate conservation opportunities in the future for riparian species, particularly in the southwestern United States.

5 ACKNOWLEDGEMENTS

We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP's Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. The Office of Science, U.S. Department of Energy, provided support for this dataset. We thank Mason Ryan and Miguel Villareal whose reviews and comments greatly improved this manuscript. We would also like to thank Iain Emmons, Randy Jennings and Bruce Christman for contributions to the data and this study. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement of the U.S. Government.

6 LITERATURE CITED

Barnett, T. P., D. W. Pierce, H. G. Hidalgo, C. Bonfils, B. D. Santer, T. Das, G. Bala, A. W. Wood, T. Nozawa, A. A. Mirin, D. R. Cayan, and M. D. Dettinger. 2008. Human-Induced Changes in the Hydrology of the Western United States. Science 319:1080–1083.

Bart, H.L. and N.E. Rios. 2015. GEOLocate Web Application [Computer Software]. Tulane University, New Orleans, LA, USA. Retrieved from http://www.museum.tulane.edu/geolocate/

Bucklin, D. N., J. I. Watling, C. Speroterra, L. a. Brandt, F. J. Mazzotti, and S. S. Romañach. 2012. Climate downscaling effects on predictive ecological models: a case study for threatened and endangered vertebrates in the southeastern United States. Regional Environmental Change 13:57–68.

Buisson, L., W. Thuiller, N. Casajus, S. Lek, and G. Grenouillet. 2010. Uncertainty in ensemble forecasting of species distribution. Global Change Biology 16:1145–1157.

Bureau of Reclamation, United States Department of the Interior. 2012. Colorado River Basin Water Supply and Demand Study Report. Available at http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/Study%20Report/CRBS_Study_Report_FINAL.pdf

Cayan, D. R., T. Das, D. W. Pierce, T. P. Barnett, M. Tyree, and A. Gershunov. 2010. Future dryness in the southwest US and the hydrology of the early 21st century drought. Proceedings of the National Academy of Sciences 107:21271–21276.

Committee on Riparian Zone Functioning and Strategies for Management. 2002. Riparian Areas: Functions and Strategies for Management. National Academies Press, Washington, D.C.

Cord, A.F., Meentemeyer, R.K., Leitão, P.J. and Václavík, T. 2013. Modelling species distributions with remote sensing data: bridging disciplinary perspectives. Journal of Biogeography, 40:2226–2227.

Emmons, I.D. and Nowak, E.M. 2016. Northern Mexican Gartersnake (*Thamnophis eques megalops*) Habitat Use and Ecology: Monitoring Surveys and Radiotelemetry in the Verde Valley, Arizona. Unpublished final report to Arizona Game and Fish Department Heritage Fund in fullfilment of IIAPM Program Grant # I12028. Colorado Plateau Research Station, Northern Arizona University, Flagstaff, AZ.

Elith, J., M. Kearney, and S. Phillips. 2010. The art of modelling range-shifting species. Methods in Ecology and Evolution 1:330–342.

Elith, J., J. R. Leathwick. 2009. Species distribution models: Ecological explanation and prediction across space and time. Annual Review of Ecology, Evolution, and Systematics 40:677–697.

Foden, W. B., S. H. M. Butchart, S. N. Stuart, J.-C. Vié, H. R. Akçakaya, A. Angulo, L. M. Devantier, A. Gutsche, E. Turak, L. Cao, S. D. Donner, V. Katariya, R. Bernard, R. A. Holland, A. F. Hughes, S. E. O'Hanlon, S. T. Garnett, C. H. Sekercioğlu, and G. M. Mace. 2013. Identifying the world's most climate change vulnerable ppecies: A systematic trait-based assessment of all birds, amphibians and corals. PloS one 8:e65427.

Franklin, J. 2013. Species distribution models in conservation biogeography: developments and challenges. Diversity and Distributions 19:581–592.

Garfin, G. M., J. K. Eischeid, M. Lenart, K. L. Cole, K. Ironside, and N. Cobb. 2010. Downscaling climate projections to model ecological change on topographically diverse landscapes of the arid southwestern United States. Pages 21–44 *in* C. van Riper III, B. F. Wakeling, and T. D. Sisk (Eds.). The Colorado Plateau IV; Shaping Conservation Through Science and Management. University of Arizona Press, Tucson, Arizona, USA.

Glenn, E. P., F. Zamora-Arroyo, P. L. Nagler, M. Briggs, W. Shaw, and K. Flessa. 2001. Ecology and conservation biology of the Colorado River Delta, Mexico. Journal of Arid Environments 49:5–15.

Guisan, A., R. Tingley, J. B. Baumgartner, I. Naujokaitis-Lewis, P. R. Sutcliffe, A. I. T. Tulloch, T. J. Regan, L. Brotons, E. McDonald-Madden, C. Mantyka-Pringle, T. G. Martin, J. R. Rhodes, R. Maggini, S. a. Setterfield, J. Elith, M. W. Schwartz, B. a. Wintle, O. Broennimann, M. Austin, S. Ferrier, M. R. Kearney, H. P. Possingham, and Y. M. Buckley. 2013. Predicting species distributions for conservation decisions. Ecology Letters 16:1424–1435.

Hatten, J. R., and C. E. Paradzick. 2003. A multiscaled model of southwestern willow flycatcher breeding habitat. Journal of Wildlife Management 67:774–788.

Hosmer, D. W., and S. Lemeshow. 2000. Applied Logistic Regression. 2nd ed. Wiley Series in Probability and Statistics.

Huete, A., K. Didan, W. van Leeuwen, T. Miura, and E. Glenn. 2010. MODIS Vegetation Indices. Pages 579–602 *in* B. Ramachandran, C. O. Justice, and M. J. Abrams, (Eds.). Land Remote Sensing and Global Environmental Change: NASA's Earth Observing System and the Science of ASTER and MODIS. Springer Science+Business Media, New York, New York, USA.

Huete, A. R., K. Didan, Y. E. Shimabukuro, P. Ratana, S. R. Saleska, L. R. Hutyra, W. Yang, R. R. Nemani, and R. Myneni. 2006. Amazon rainforests green-up with sunlight in dry season. Geophysical Research Letters 33:L06405.

Iliff, M., L. Salas, E. R. Inzunza, G. Ballard, D. Lepage, and S. Kelling. 2008. The Avian Knowledge Network:

a partnership to organize, analyze, and visualize bird observation data for education, conservation, research, and land management. Tundra to Tropics: Connecting Birds, Habitats and People. Proceedings of the 4th International Partners in Flight Conference:13–16.

Jennings, R.D. and B.L. Christman. 2015. Comparisons of the Population Status of the Narrow-headed Gartersnakes Among Sites Experiencing Post-fire Flows and Receiving TranslocationsWith an Unaffected Population. Unpublished report to New Mexico Department of Game and Fish Share With Wildlife Program. Gila Center for Natural History, Western New Mexico State University, Silver City, New Mexico, USA.

Johnson, R. R., C. D. Ziebell, D. R. Patton, P. F. Ffolliott, and R. H. Hamre. 1985. Riparian Ecosystems and Their Management: Reconciling Conflicting Uses. USDA Forest Service General Technical Report RM-120.

Jönsson, P., and L. Eklundh. 2004. TIMESAT—a program for analyzing time-series of satellite sensor data. Computers & Geosciences 30:833–845.

Justice, C. O., J. R. G. Townshend, E. F. Vermote, E. Masuoka, R. E. Wolfe, N. Saleous, D. P. Roy, and J. T. Morisette. 2002. An overview of MODIS Land data processing and product status. Remote Sensing of Environment 83:3–15.

Keating, K. A., and S. Cherry. 2004. Use and interpretation of logistic regression in habitat-selection studies. Journal of Wildlife Management 68:774–789.

Leake, S. A., D. R. Pool, and J. M. Leenhouts. 2008. Simulated Effects of Ground-Water Withdrawals and Artificial Recharge on Discharge to Streams, Springs, and Riparian Vegetation in the Sierra Vista Subwatershed of the Upper San Pedro Basin, Southeastern Arizona (ver. 1.1, April 2014). U.S. Geological Survey Scientific Investigations Report 2008-5207.

Lester, M. B., and J. B. Swackhamer. 2015. Geographic Distribution: *Thamnophis eques megalops* (Brown Gartersnake). Herpetological Review 46:577.

Liu, C., M. White, and G. Newell. 2013. Selecting thresholds for the prediction of species occurrence with presence-only data. Journal of Biogeography 40:778–789.

Meehl, G. A., C. Covey, K. E. Taylor, T. Delworth, R. J. Stouffer, M. Latif, B. McAvaney, and J. F. B. Mitchell. 2007. THE WCRP CMIP3 multimodel dataset: A new era in climate change research. Bulletin of the American Meteorological Society 88:1383–1394.

Meko, D.M., C.A. Woodhouse, C.A. Baisan, T. Knight, J.J. Lukas, M.K. Hughs, and M.W. Salzer, 2007. Medieval Drought in the Upper Colorado River Basin. Geophysical Research Letters 34:L10705

Merritt, D. M., M. L. Scott, N. L. Poff, G. T. Auble, and D. A. Lytle. 2010. Theory, methods and tools for determining environmental flows for riparian vegetation: riparian vegetation-flow response guilds. Freshwater Biology 55:206–225.

Nowak, E.M. 2006. Monitoring surveys and telemetry of narrow-headed gartersnakes (*Thamnophis rufipunctatus*) in Oak Creek, Arizona. Unpublished final report to Arizona Game and Fish Department Heritage Fund, IIPAM Program. USGS Southwest Biological Science Center Colorado Plateau Research Station, Flagstaff, Arizona, USA.

Nowak, E.M., and C. Drost. 2015. Effects of wildfires on Threatened narrow-headed Gartersnakes: 2014 surveys interim report. USGS Forest and Rangeland Ecosystem Science Center, Colorado Plateau Field Station, Flagstaff, Arizona, USA.

Nowak, E.M., and M.A. Santana-Bendix. 2002. Status, distribution, and management recommendations for the narrow-headed gartersnake (*Thamnophis rufipunctatus*) in Oak Creek, Arizona. Final report to Arizona Game and Fish Department in fulfillment of Heritage Grant I99007. USGS Forest and Rangeland Ecosystem Science Center, Colorado Plateau Field Station, Flagstaff, Arizona, USA.

Nowak, E. M., T. C. Theimer, and G. W. Schuett. 2008. Functional and numerical responses of predators: Where do vipers fit in the traditional paradigms? Biological Reviews 83:601–620.

Paxton, E. H., M. K. Sogge, S. L. Durst, T. C. Theimer, and J. R. Hatten. 2007. The Ecology of the Southwestern Willow Flycatcher in Central Arizona — a 10-year Synthesis Report. U.S. Geological Survey Open File Report 2007-1381.

Perry, L. G., D. C. Andersen, L. V. Reynolds, S. M. Nelson, and P. B. Shafroth. 2012. Vulnerability of riparian ecosystems to elevated CO_2 and climate change in arid and semiarid western North America. Global Change Biology 18:821–842.

Pettorelli, N., S. Ryan,, T. Mueller, N. Bunnefeld, B. Jędrzejewska, M. Lima, and, K. Kausrud. 2011. The Normalized Difference Vegetation Index (NDVI): unforeseen successes in animal ecology. Climate Research 46:15–27.

Phillips, S., and M. Dudík. 2008. Modeling of species distributions with Maxent: new extensions and a comprehensive evaluation. Ecography:161–175.

Rosen, P.C. 1991. Comparative field study of thermal preferenda in garter snakes (*Thamnophis*). Journal of Herpetology 25:301-312.

Rosgen, D. L. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado, USA.

Rossman, D. A., N. B. Ford, and R. A. Seigel. 1996. The Gartersnakes: Evolution and Ecology. Animal Natural History Series. University of Oklahoma Press, Norman, Oklahoma, USA.

Roy, D. P., J. S. Borak, S. Devadiga, R. E. Wolfe, M. Zheng, and J. Descloitres. 2002. The MODIS Land product quality assessment approach. Remote Sensing of Environment 83:62–76.

Seager, R., M. Ting, I. Held, Y. Kushnir, J. Lu, G. Vecchi, H.-P. Huang, N. Harnik, A. Leetmaa, N.-C. Lau, C. Li, J. Velez, and N. Naik. 2007. Model Projections of an Imminent Transition to a More arid climate in southwestern North America. Science 316:1181–1184.

Shirley, S.M., Yang, Z., Hutchinson, R.A., Alexander, J.D., McGarigal, K. and Betts, M.G. 2013. Species distribution modelling for the people: unclassified landsat TM imagery predicts bird occurrence at fine resolutions. Diversity and Distributions, 19:855–866.

Sims, D. A., A. F. Rahman, V. D. Cordova, B. Z. El-Masri, D. D. Baldocchi, L. B. Flanagan, A. H. Goldstein, D. Y. Hollinger, L. Misson, R. K. Monson, W. C. Oechel, H. P. Schmid, S. C. Wofsy, and L. Xu. 2006. On the use of MODIS EVI to assess gross primary productivity of North American ecosystems. Journal of Geophysical Research 111:G04015.

Skagen, S. K., J. F. Kelly, C. Van Riper, R. L. Hutto, D. M. Finch, D. J. Krueper, and C. P. Melcher. 2005. Geography of spring landbird migration through riparian habitats in southwestern North America. Condor 107:212–227.

Solano, R., K. Didan, A. Jacobson, and A. R. Huete. 2010. MODIS Vegetation Index User's Guide (MOD13 Series). Tucson, Arizona, USA.

Sullivan, B. L., J. L. Aycrigg, J. H. Barry, R. E. Bonney, N. Bruns, C. B. Cooper, T. Damoulas, A. A. Dhondt, T.

Dietterich, A. Farnsworth, and D. Fink. 2014. The eBird enterprise: an integrated approach to development and application of citizen science. Biological Conservation 169:31–40.

Thuiller, W., L. Brotons, M. B. Araújo, and S. Lavorel. 2004. Effects of restricting environmental range of data to project current and future species distributions. Ecography 27:165–172.

Turner, W., S. Spector, N. Gardiner, M. Fladeland, E. Sterling, and M. Steininger. 2003. Remote sensing for biodiversity science and conservation. Trends in Ecology & Evolution 18:306–314.

Urban, M. C. 2015. Accelerating extinction risk from climate change. Science 348:571–573.

U.S. Fish and Wildlife Service (USFWS). 2014. Endangered and Threatened Wildlife and Plants; Threatened Status for the Northern Mexican Gartersnake and Narrow-Headed Gartersnake; Final Rule. Federal Register 79:38678–38746.

van Riper, C., J.R. Hatten, J. T. Giermakowski, D. Mattson, J.A. Holmes, M.J. Johnson, E. M. Nowak, K. Ironside, M. Peters, P. Heinrich, K. L. Cole, C. Truettner, C. R. Schwalbe. 2014. Projecting climate effects on birds and reptiles of the Southwestern United States: U.S. Geological Survey Open-File Report 2014–1050, 100 p. http://pubs.usgs.gov/ofr/20141050/

Villarreal, M. L., S. Drake, S. E. Marsh, and A. L. McCoy. 2012. The influnce of wastewater subsidy, flood disturbance and neighbouring land use on current and historical patterns of riparian vegetation in a semi-arid watershed. River Research and Applications 28:1230-1245.

Villarreal, M. L., C. van Riper, and R. E. Petrakis. Conflation and aggregation of spatial data improve predictive models for species with limited habitats: A case of the threatened yellow-billed cuckoo in Arizona, USA. Applied Geography 47:57-69.

Wallace, C. S. A., Villarreal, M. L., & van Riper III, C. 2013. Influence of monsoon-related riparian phenology on yellow-billed cuckoo habitat selection in Arizona. Journal of Biogeography 40:2094–2107.

Webb, R. H., S. A. Leake, and R. M. Turner. 2007. The Ribbon of Green: Change in Riparian Vegetation in the Southwestern United States. University of Arizona Press, Tucson, Arizona, USA.

Wilson, J.W., J. O. Sexton, R. T. Jobe, and N. M. Haddad. 2013. The relative contribution of terrain, land cover, and vegetation structure indices to species distribution models. Biological Conservation 164:170–176.

Zhang, X., M. A. Friedl, C. B. Schaaf, A. H. Strahler, J. C. F. Hodges, F. Gao, B. C. Reed, and A. R. Huete. 2003. Monitoring vegetation phenology using MODIS. Remote Sensing of Environment 84:471–475.

7 TABLES

Table 1. A selection of varying (non–static) variables used to model the baseline distribution of gartersnakes and birds and the formulas used to calculate them. Variables were calculated with a different starting and ending month for each species.

VARIABLE	SUB VARIABLE	STATISTIC	START	END	FORMULA
ACTUAL EVAPOTRANSPIRATION	monthly mean	mean	May	August	(AET(May)+AET(Jun)+…+AET(Aug))/4
PRECIPITATION	monthly mean	SD	May	August	STDEV(Precip(May),Precip(Jun),…,Precip(Aug))
PRECIPITATION	total	sum	May	August	(Precip(May)+Precip(Jun)+…+Precip(Aug))
PRECIPITATION	total	sum	Jan	Dec	(Precip(Jan)+Precip(Feb)+…+Precip(Dec))
SURFACE RUNOFF	monthly mean	SD	May	August	STDEV(SurfRunoff(May),SurfRunoff(Jun),…,SurfRunoff(Aug))
SURFACE RUNOFF	total	sum	May	August	(SurfRunoff(May)+SurfRunoff(Jun)+…+SurfRunoff(Aug))
SURFACE SOIL MOISTURE	monthly mean	mean	May	August	(SSM(May)+SSM(Jun)+…+SSM(Aug))/4
TEMPERATURE	monthly max	mean	May	August	(Tmax(May)+Tmax(Jun)+…+Tmax(Aug))/4
TEMPERATURE	monthly max	SD	May	August	STDEV(Tmax(May),Tmax(Jun),…,Tmax(Aug))
TEMPERATURE	monthly mean	mean	May	August	(Tave(May)+Tave(Jun)+…+Tave(Aug))/4
TEMPERATURE	monthly mean	SD	May	August	STDEV(Tave(May),Tave(Jun),…,Tave(Aug))
TEMPERATURE	monthly min	mean	May	August	(Tmin(May)+Tmin(Jun)+…+Tmin(Aug))/4
TEMPERATURE	monthly min	SD	May	August	STDEV(Tmin(May),Tmin(Jun),…,Tmin(Aug))

Table 2. Summary of model accuracies calculated as area under the curve (AUC) of the receiver-operating characteristic (ROC) for test classification data.

MODEL TYPE	**SPECIES**			
	Northern Mexican Gartersnake	**Narrow-headed Gartersnake**	**Yellow-breasted Chat**	**Yellow Warbler**
	THEQ	**THRU**	**YBCH**	**YEWA**
WITH EVI	0.819	0.937	0.773	0.742
WITHOUT EVI	0.809	0.941	0.756	0.727

Table 3. List of variables retained in baseline SDMs and used for modeling the future distribution of reptiles and birds in this study. For each species and variable, 'x' denotes that the variable was used. Month abbreviations denote the months on which the statistical calculation (mean or total) is based.

VARIABLE TYPE	**VARIABLE**	**SPECIES**			
		THEQ	**THRU**	**YBCH**	**YEWA**
STATIC	Distance to divide	x	x	x	x
	Soil drain index		x		
	Insolation (May 1st)	x	x	x	x
	Terrain roughness index (TRI)	x	x	x	x
VARYING	Enhanced Vegetation Index (EVI)	x	x	x	x
	Winter precipitation (total)	Nov-Mar	Nov-Mar	Nov-Mar	Nov-Mar
	Fall precipitation (total)				Sep-Dec
	Summer precipitation (total)	Jul-Sep	Jul-Sep	May-Aug	May-Aug
	Winter temperature (minimum)	Dec-Feb	Nov-Mar	Nov-Mar	Nov-Mar
	Summer temperature (maximum)	Mar-Nov	Apr-Oct	May-Aug	May-Aug
	Summer temperature (minimum)				May-Aug
	Evapotranspiration	Mar-Nov	Apr-Oct	May-Aug	May-Aug
	Surface soil moisture	Mar-Nov	Apr-Oct	May-Aug	May-Aug
	Streamflow (as runoff)	Mar-Nov	May-Oct		

Table 4. Rank importance of variables for current (baseline) SDMs that included EVI.

RANK	**SPECIES**			
	THEQ	**THRU**	**YBCH**	**YEWA**
1	Summer temperature	Summer precipitation	TRI	Summer temp (min)
2	EVI	TRI	Summer temp (max)	Fall precipitation
3	Summer precipitation	EVI	EVI	TRI
4	Distance to divide	Distance to divide	Fall precipitation	Winter precipitation
5	Runoff	Summer temp	Spring precipitation	EVI
6	TRI	Runoff	Evapotranspiration	
7	Evapotranspiration	Surface soil moisture	Summer temp (min)	
8	Insolation	Evapotranspiration		
9	Surface soil moisture			

Table 5. Effect (in percent change in predicted current suitable area) of including EVI data in models.

EFFECT	**SPECIES**			
	THEQ	**THRU**	**YBCH**	**YEWA**
CHANGE IN AREA PREDICTED	+9.5%	-2.8%	-3.8%	+8.7%

8 FIGURES

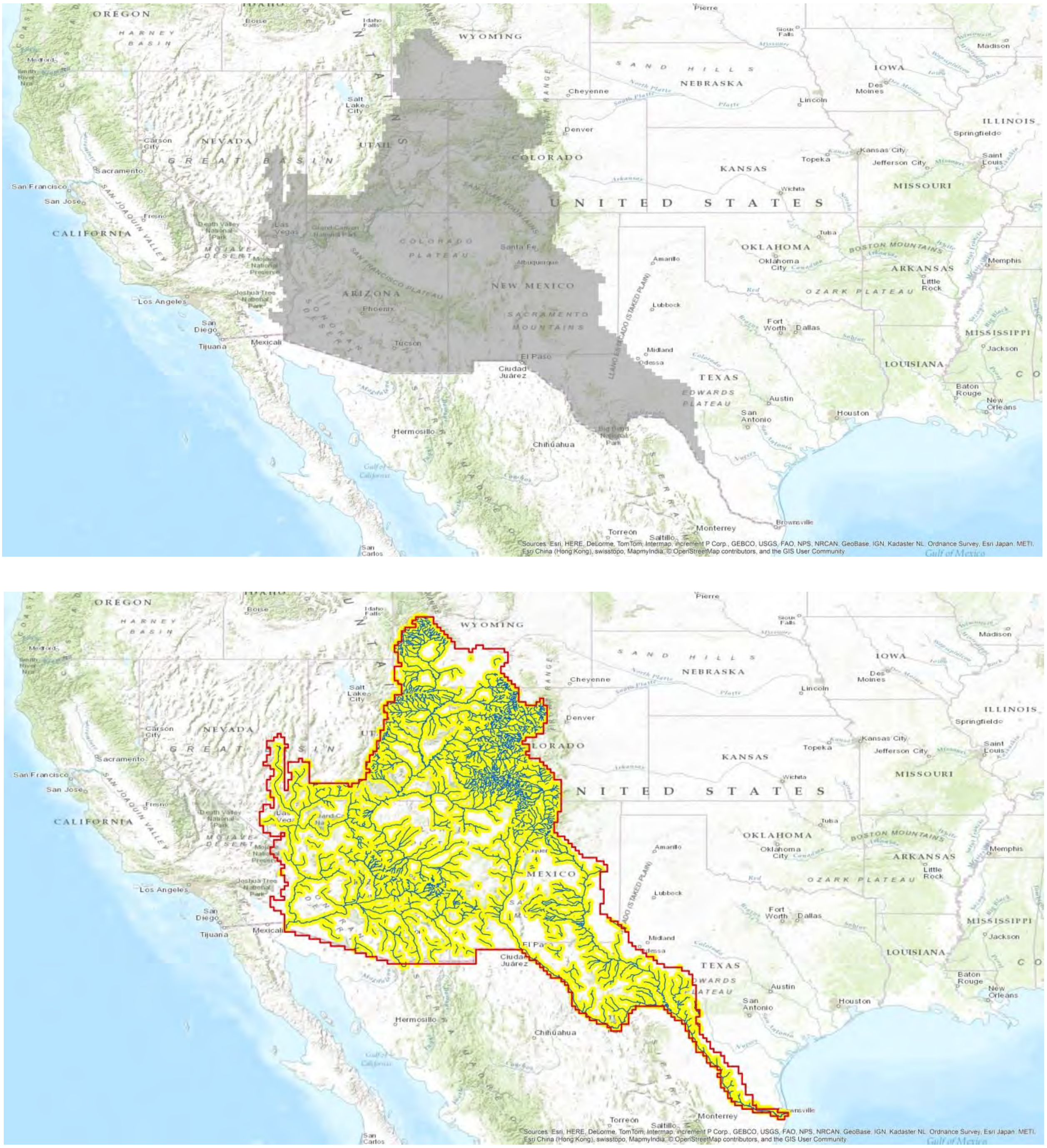


Figure 1. The project area (in gray; above) and all areas considered for modeling (in yellow; below).

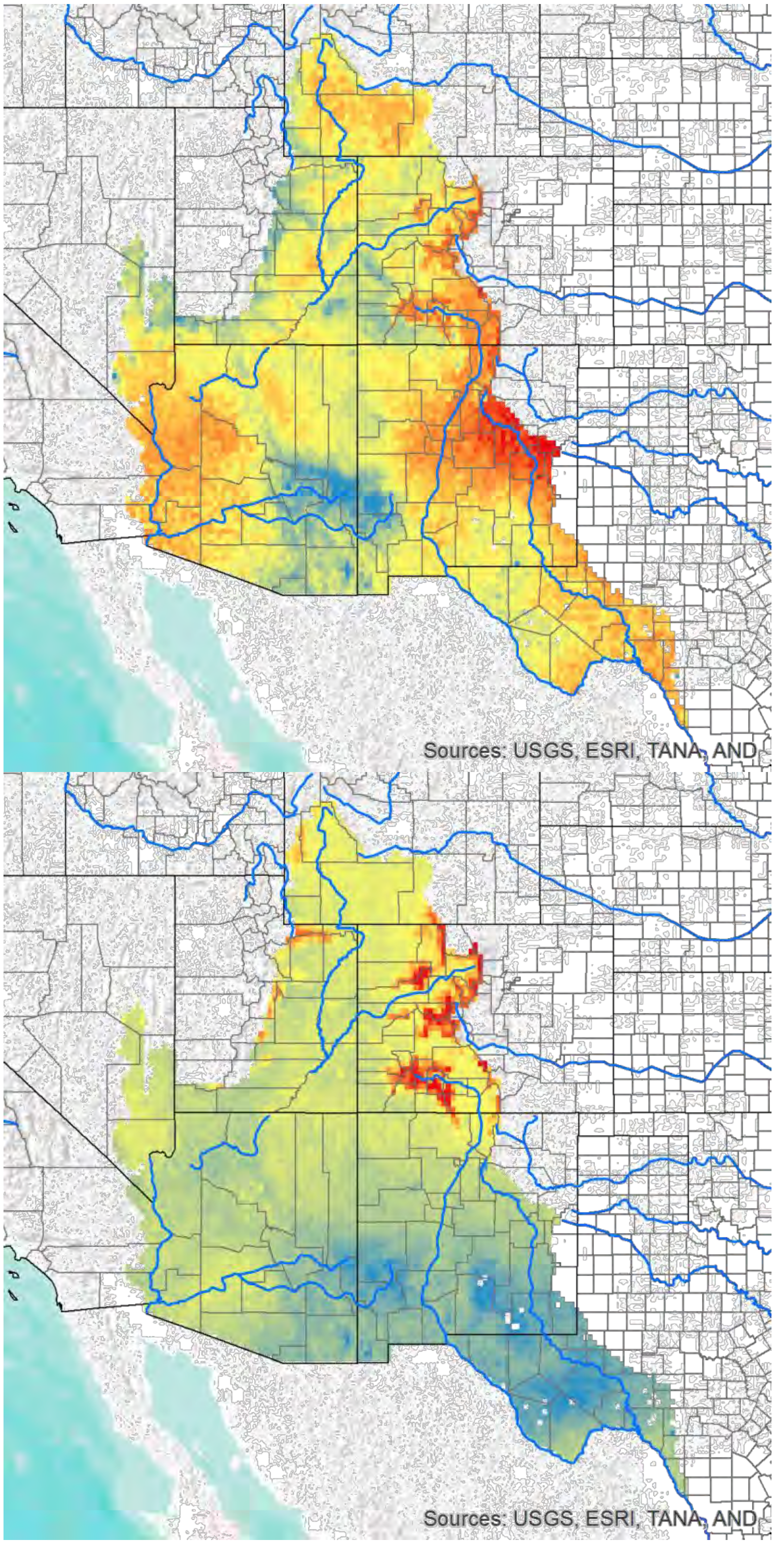


Figure 2. Modeled changes in riparian vegetation greenness (EVI) between current and short-term (2039; top) and long-term (2099; bottom) time horizons. Red indicates areas where index of riparian vegetation greenness is likely to increase while blue indicates areas where index of greenness is likely to decrease.

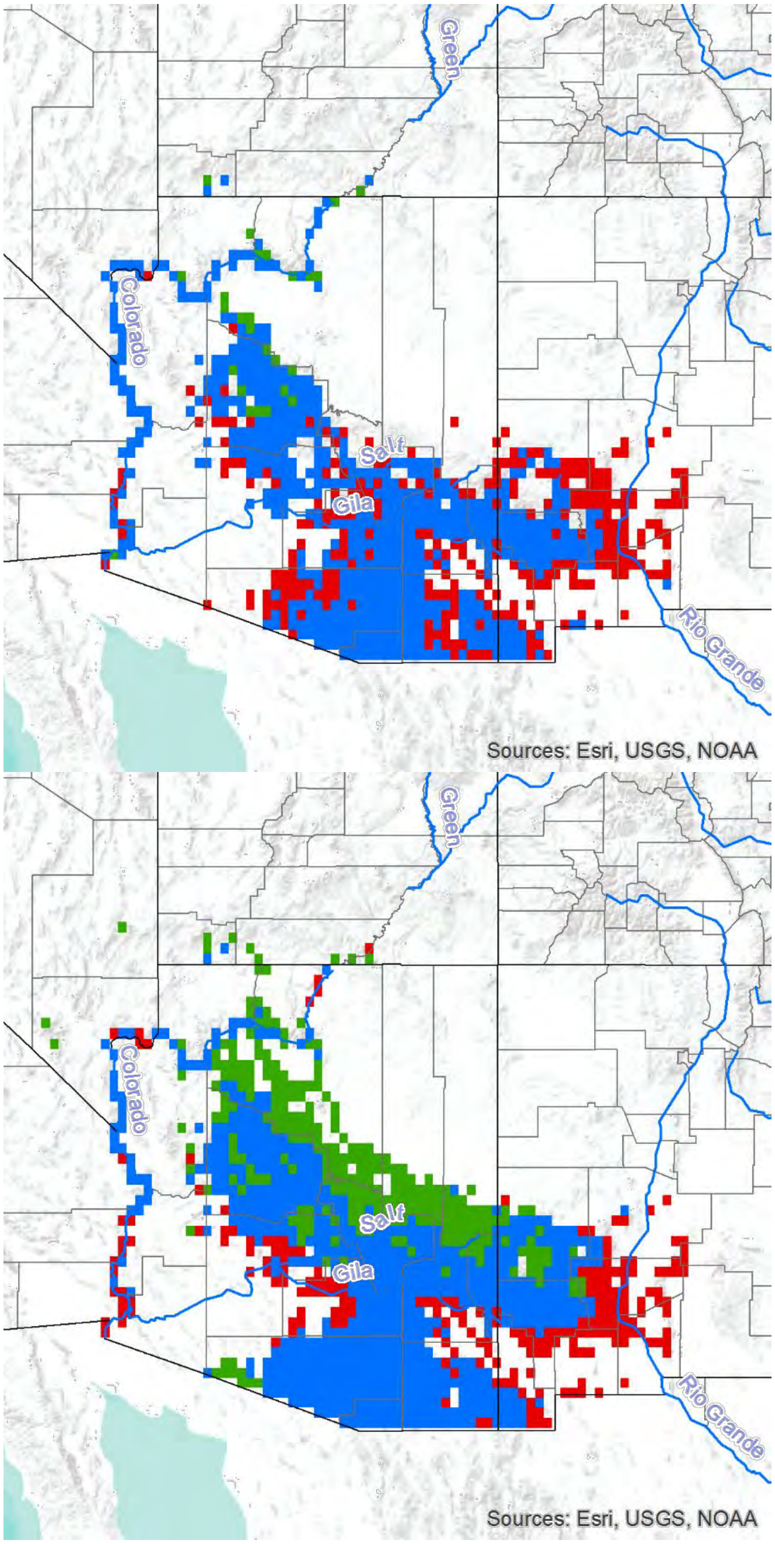
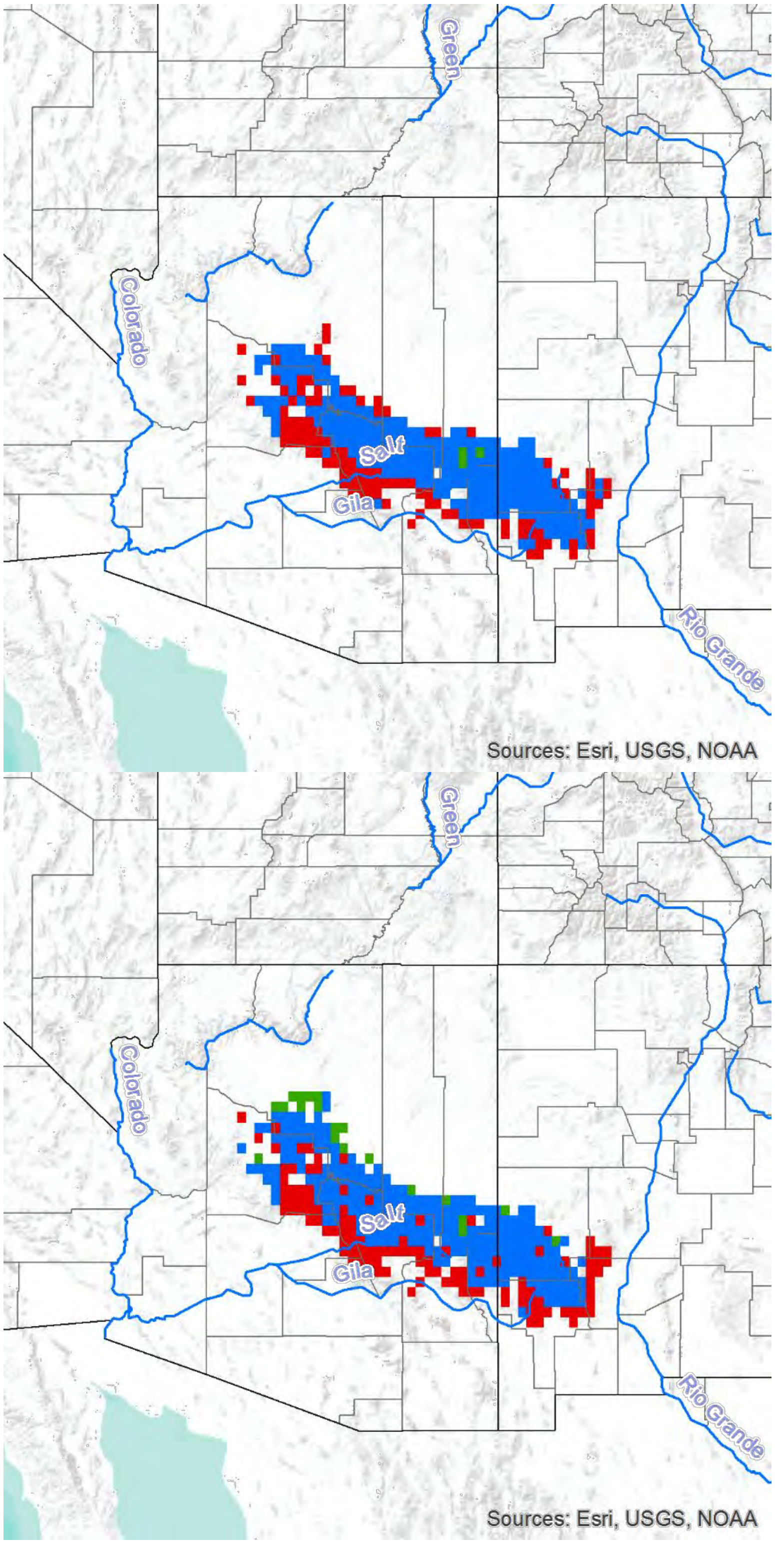


Figure 3. Projected changes in range for the Northern Mexican Gartersnake between current and short-term (2039; top) and long-term (2099; bottom) time horizons. Red indicates areas that become unsuitable; green represents newly suitable areas, while blue indicates areas where suitability persists during the period (refuge).



Green
Colorado
Salt
Gila
Rio Grande
Sources: Esri, USGS, NOAA

Figure 4. Projected changes in range for the Narrow-headed Gartersnake between current and short-term (2039; top) and long-term (2099; bottom) time horizons. Red indicates areas that become unsuitable; green represents newly suitable areas, while blue indicates areas where suitability persists during the period (refuge).

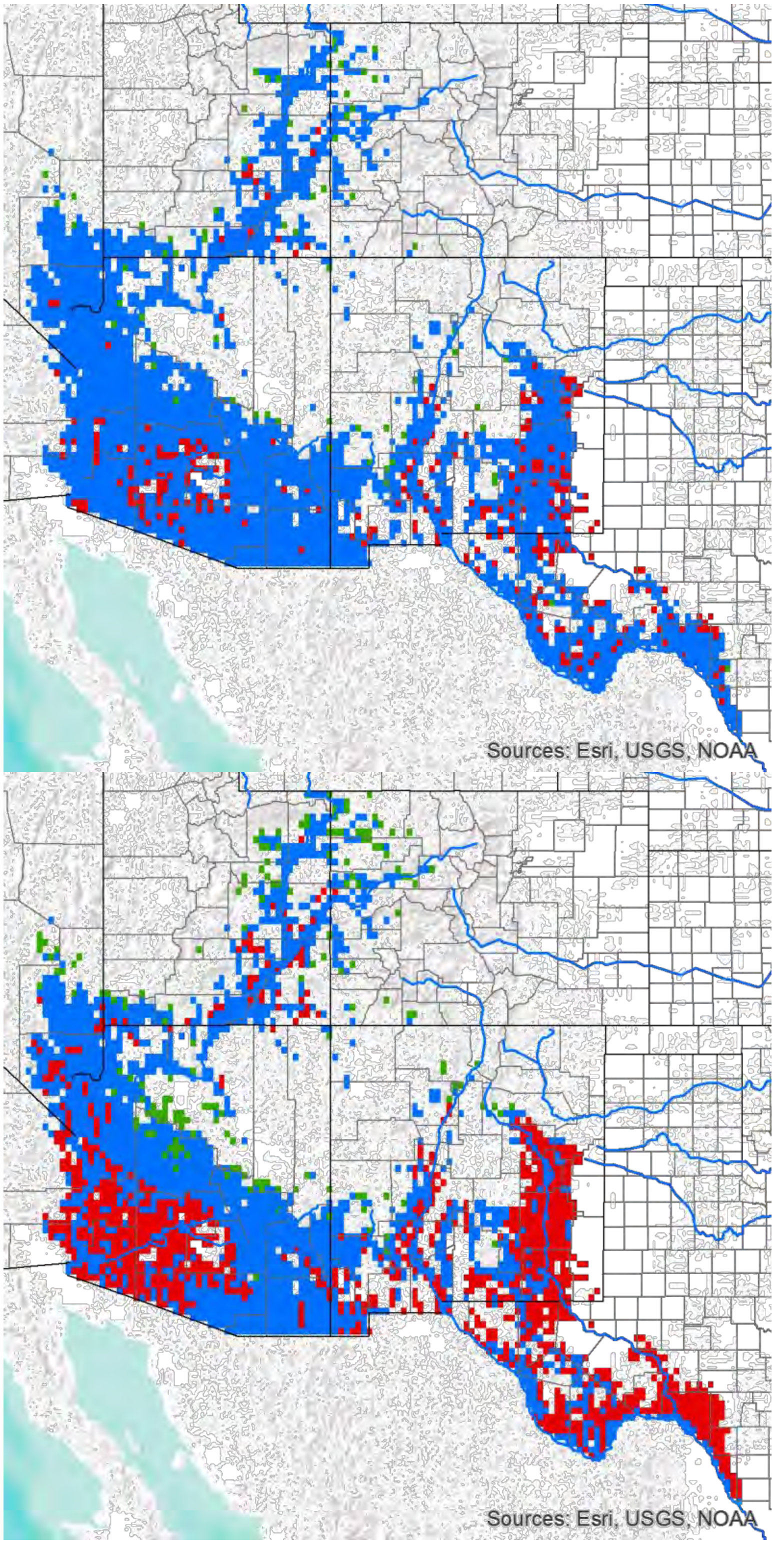


Figure 5. Projected changes in range for the Yellow-breasted Chat between current and short-term (2039; top) and long-term (2099; bottom) time horizons. Red indicates areas that become unsuitable; green represents newly suitable areas, while blue indicates areas where suitability persists during the period (refuge).

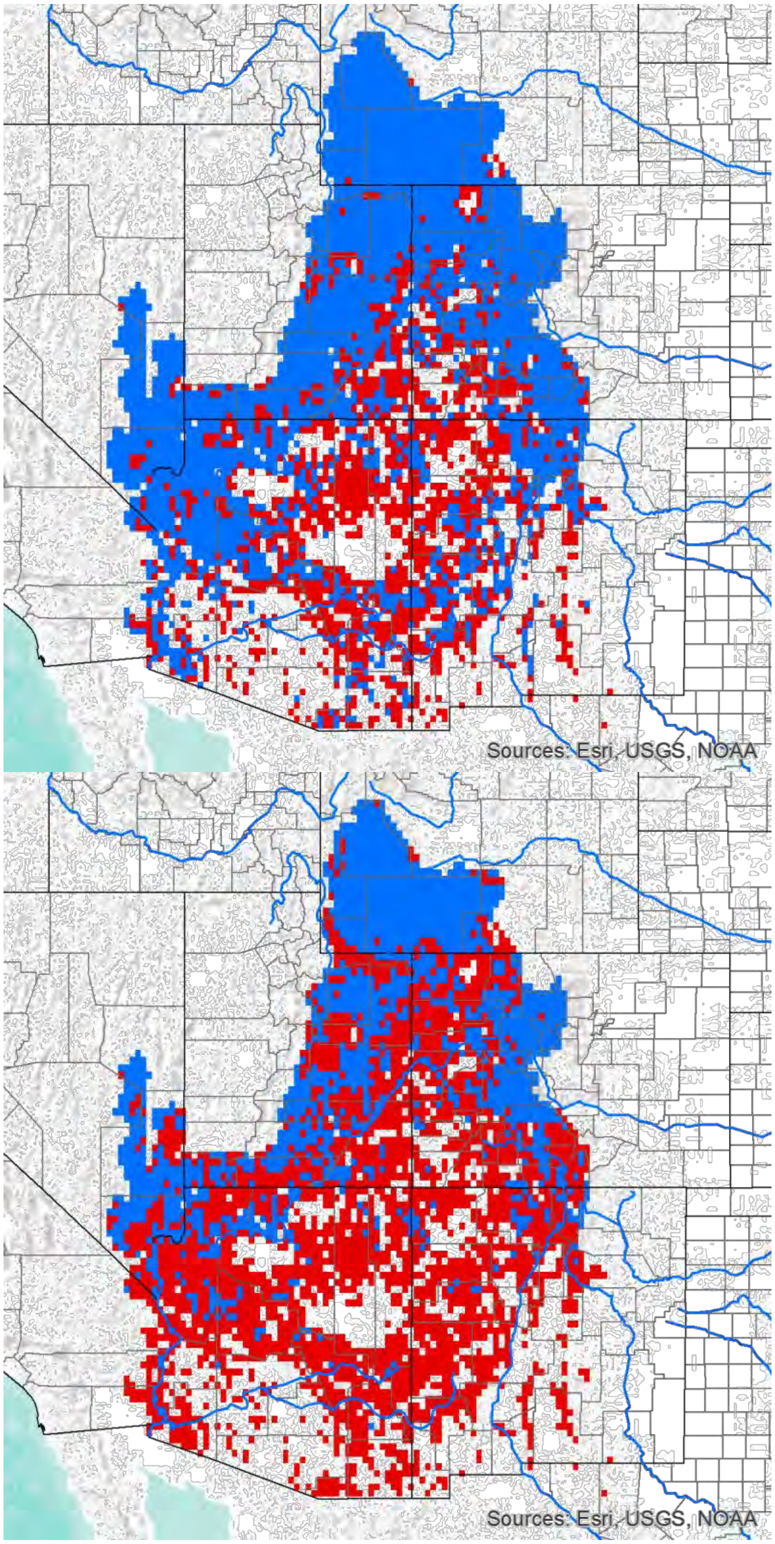


Figure 6. Projected changes in range for the Yellow Warbler between current and short-term (2039; top) and long-term (2099; bottom) time horizons. Red indicates areas that become unsuitable; green represents newly suitable areas, while blue indicates areas where suitability persists during the period (refuge).

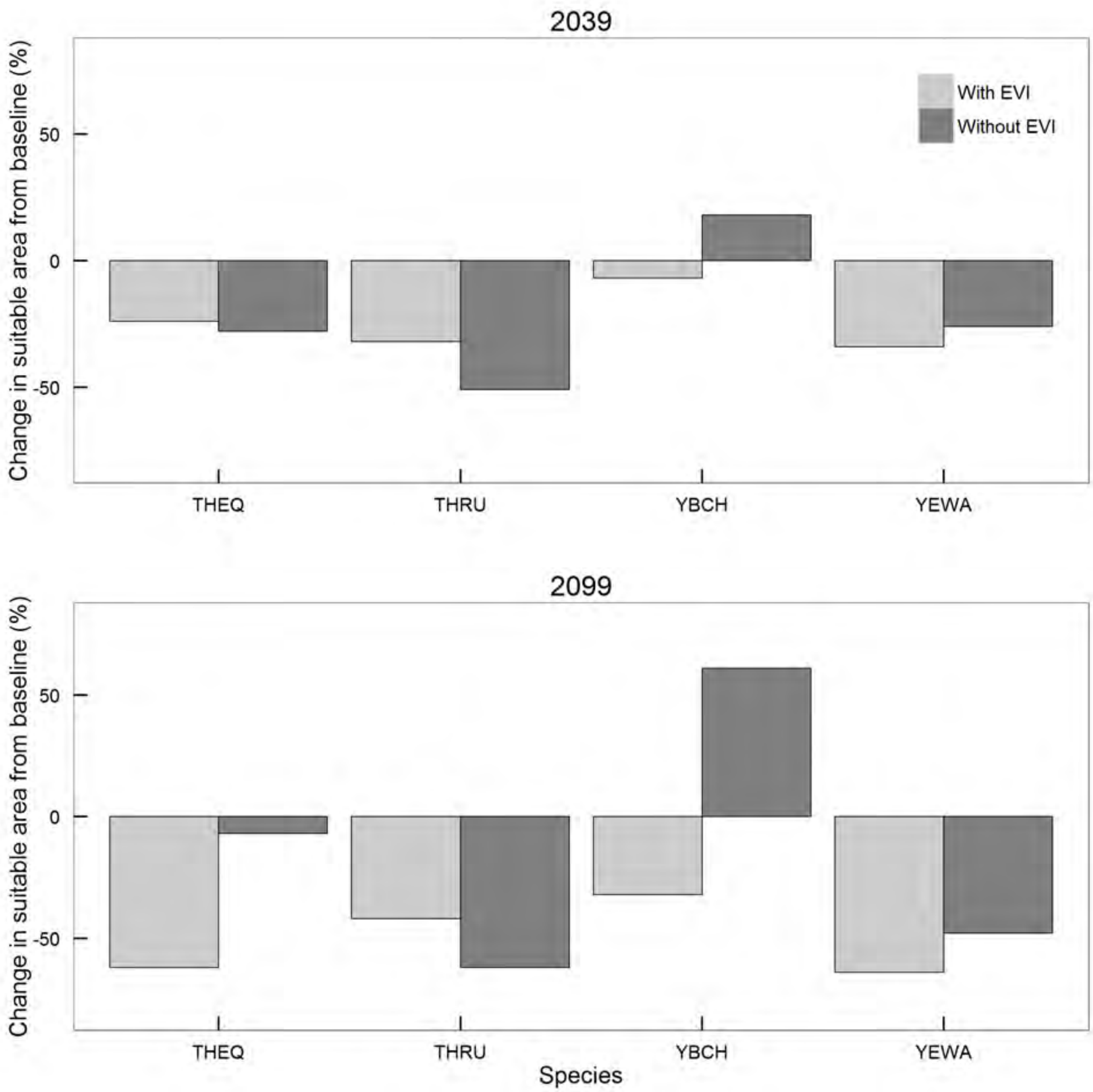
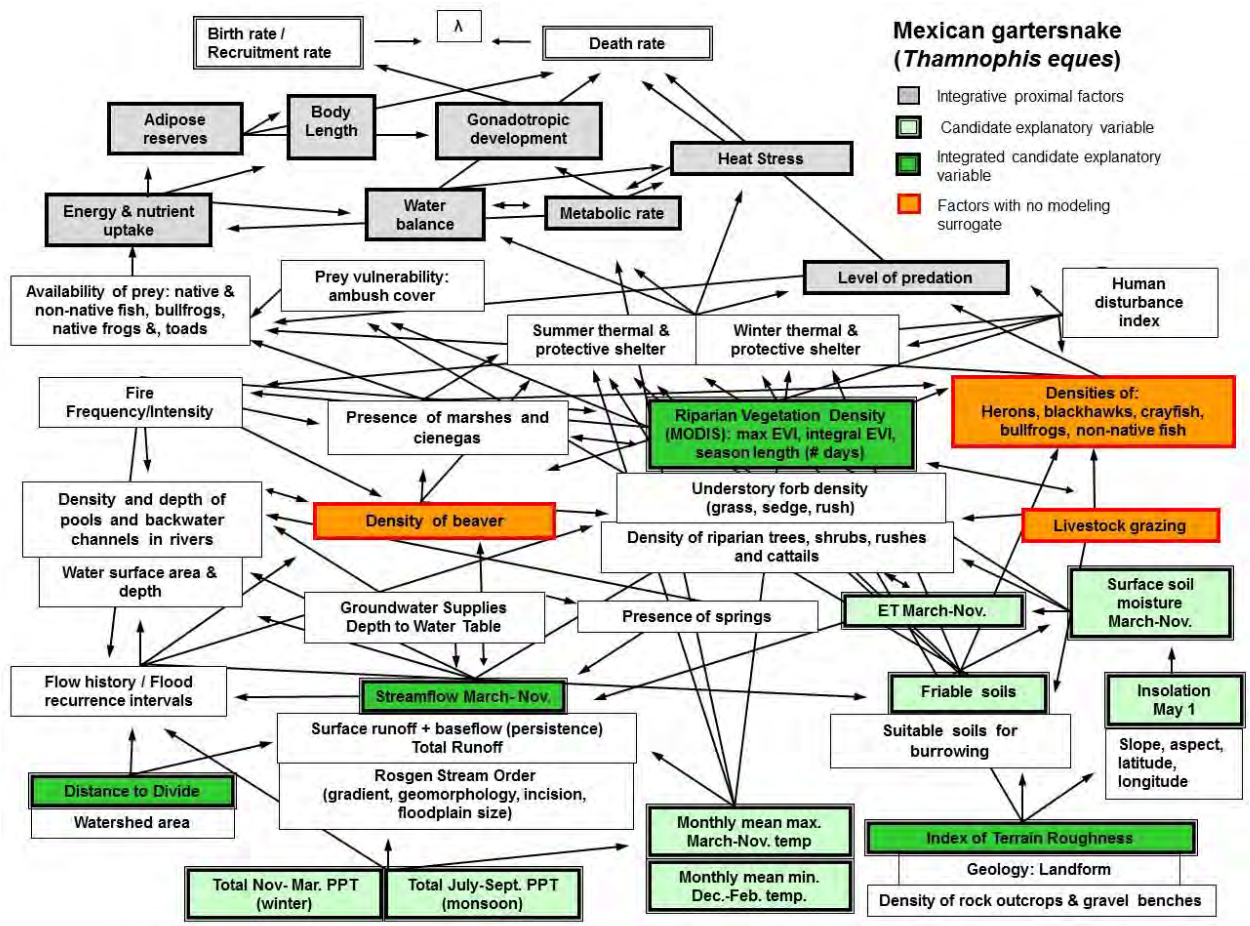


Figure 7. Comparison of future to baseline suitability of landscape for birds and reptiles, differentiated by models that include an index of riparian vegetation (with EVI) or not (without EVI).

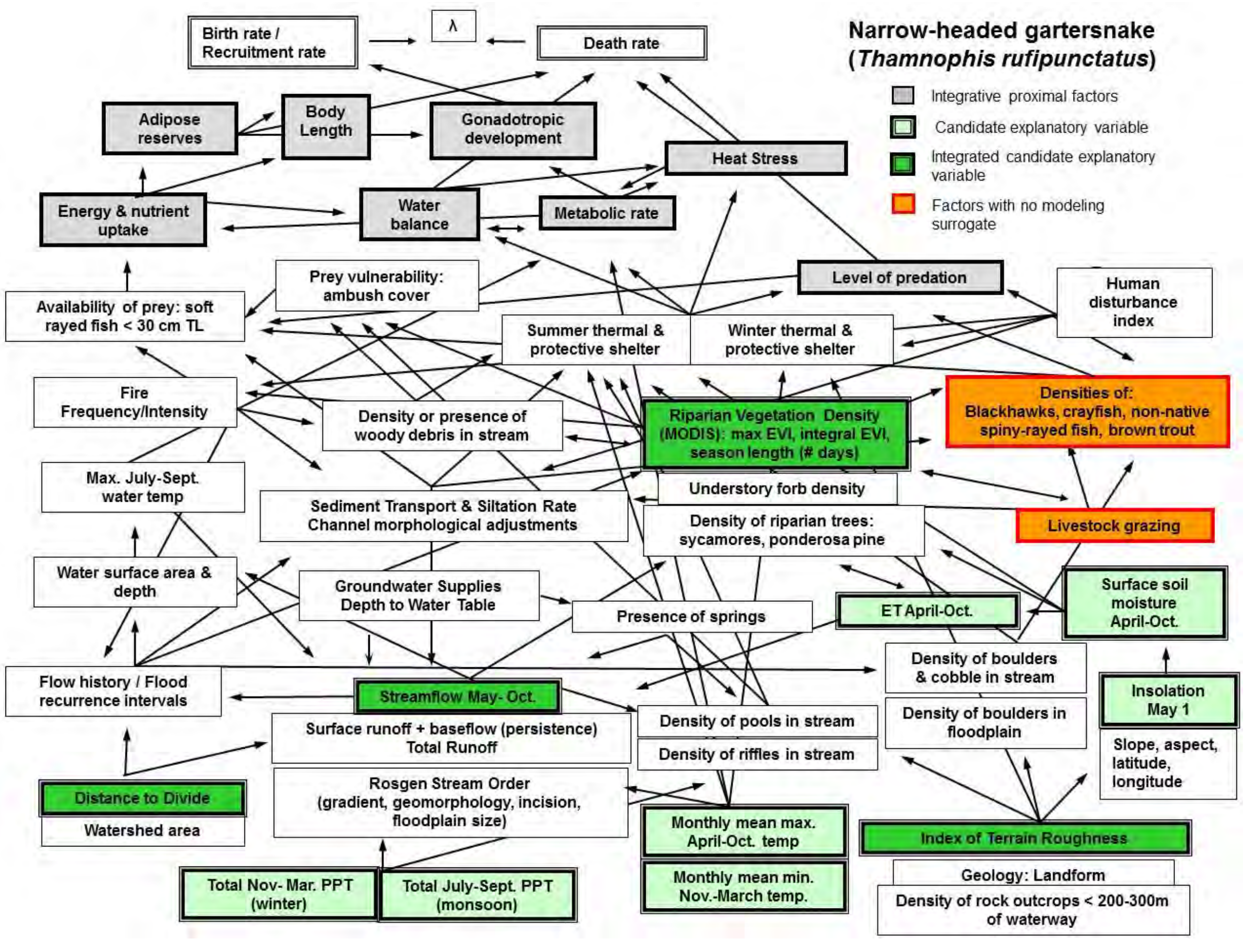
9 APPENDICES

9.1 CONCEPTUAL DIAGRAMS USED FOR VARIABLE SELECTION

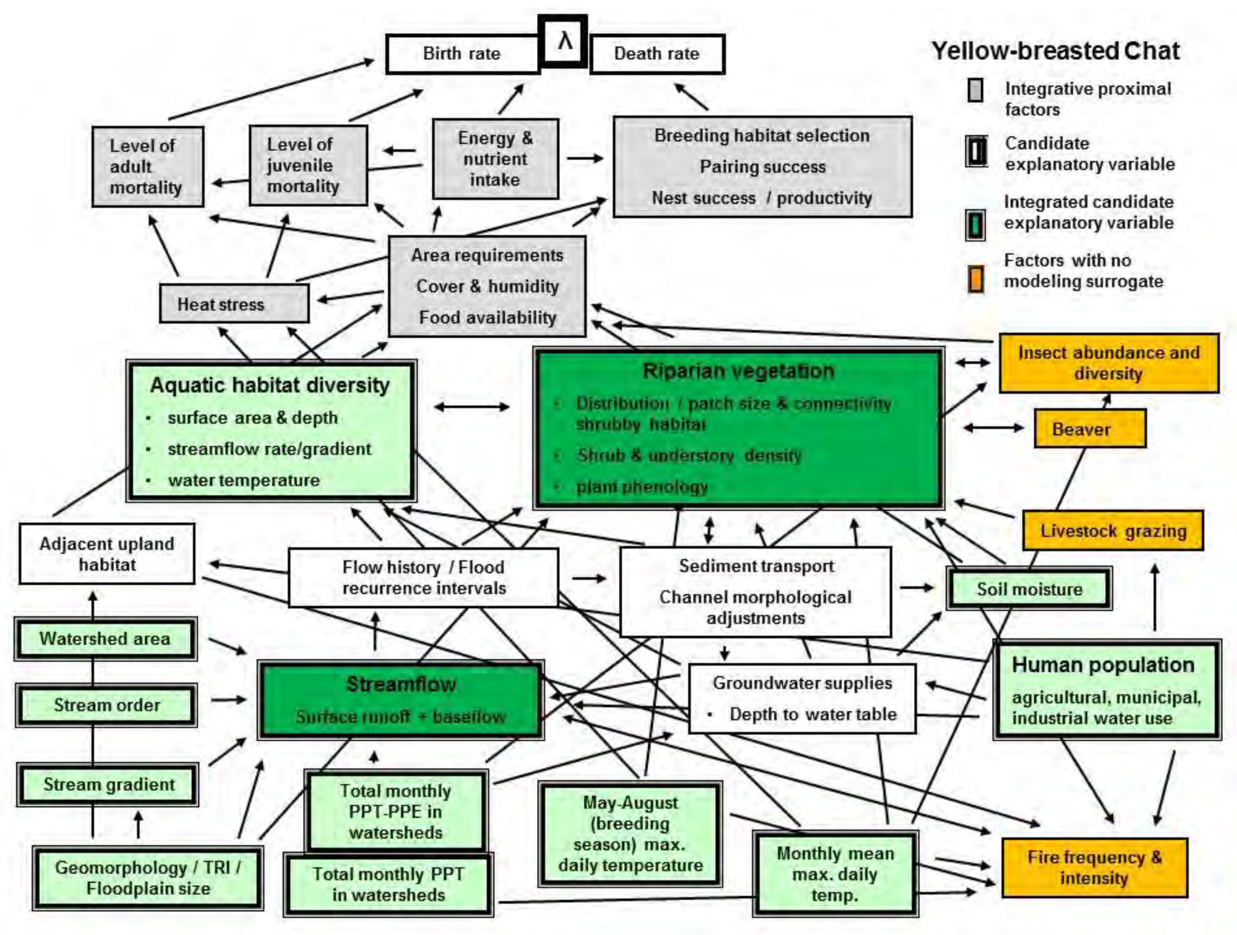
9.1.1 Mexican Gartersnake (THEQ)



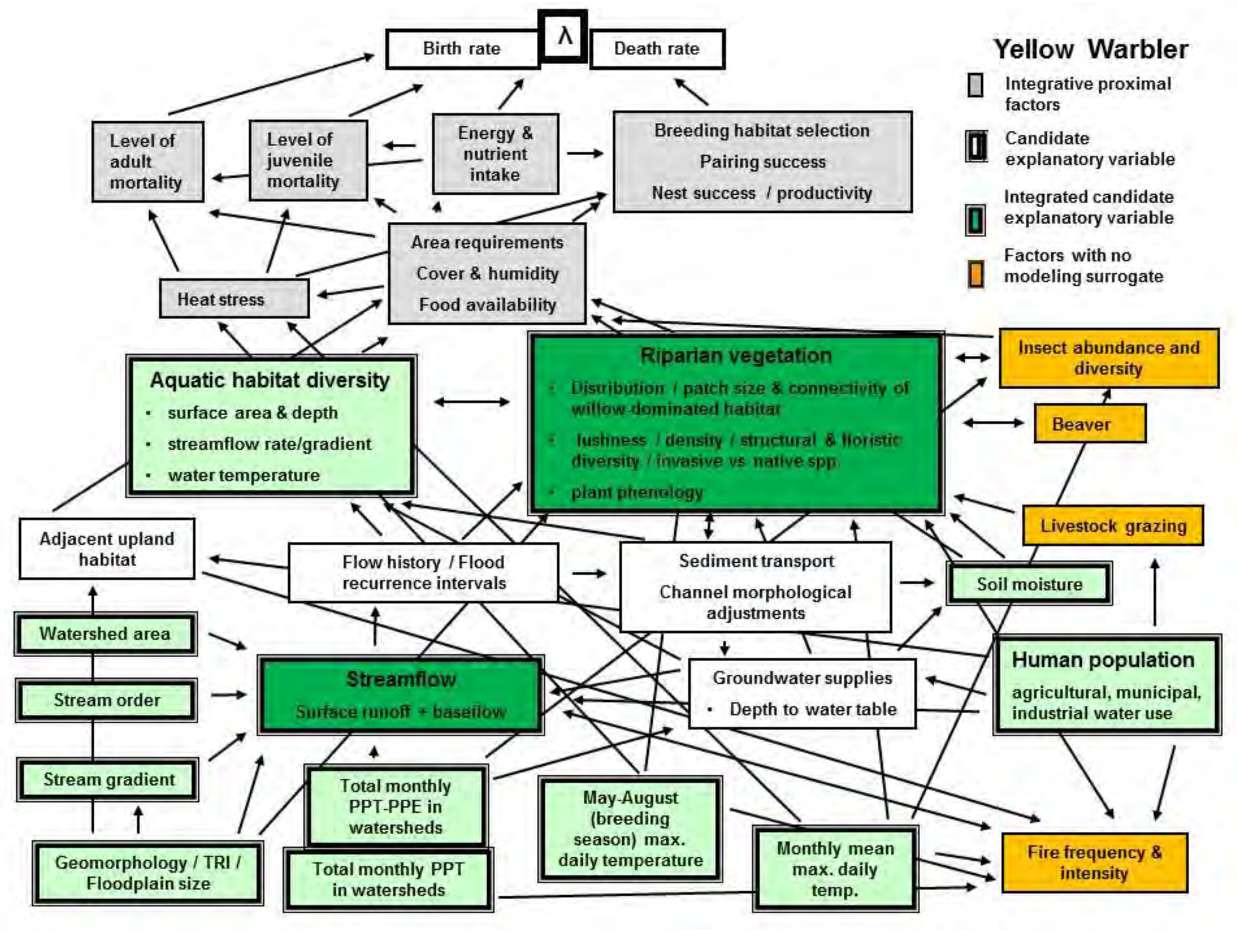
9.1.2 Narrow-headed Gartersnake (THRU)



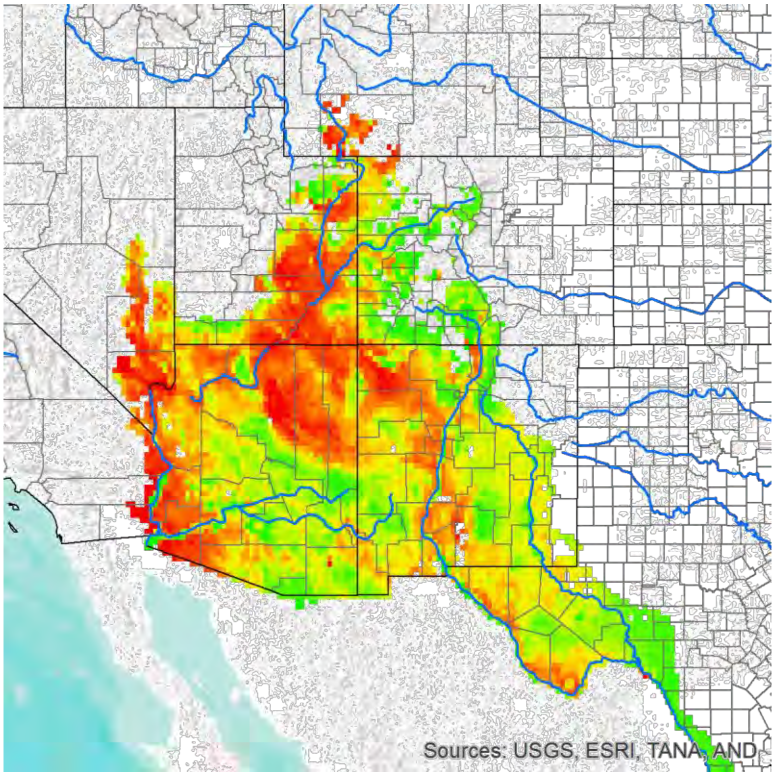
9.1.3 Yellow-breasted Chat (YBCH)

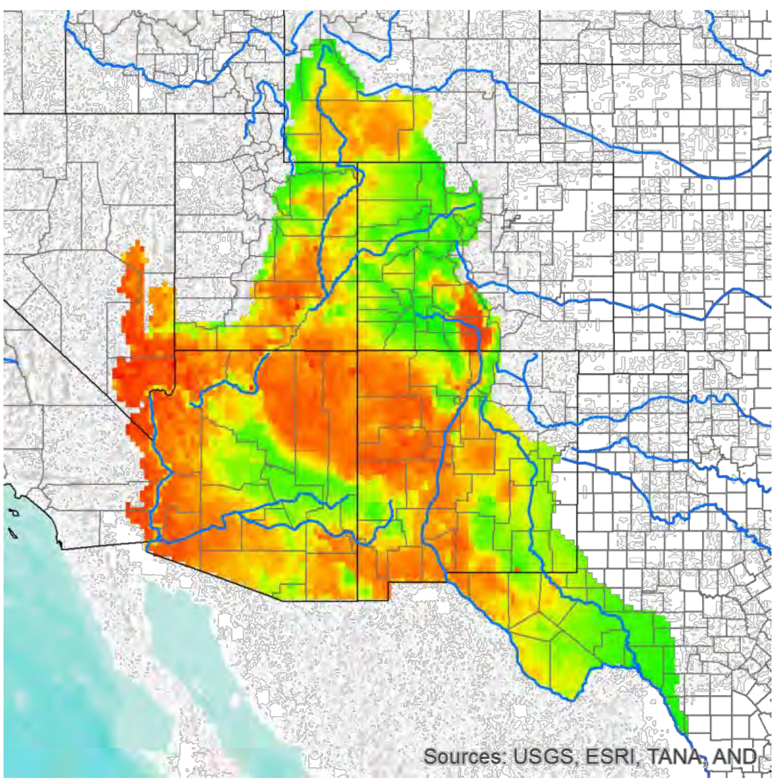


9.1.4 Yellow warbler (YEWA)



9.2 Prediction of riparian vegetation greenness





Actual (top) and modeled (bottom) index of riparian vegetation greenness (EVI) for the current time period based on a linear regression of several climate and landscape variables (see Section 2.5).