Landscape Connectivity of Isolated Waters for Wildlife in the Sonoran Desert

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Executive Summary

We provide an analysis of Sonoran Desert water network connectivity to inform managers of current conditions for target wildlife and how the connectivity will change as the landscape becomes more water limited.

Climate change is expected to lead to fragmentation of the network, increasing coalescence distance by 8% and reducing the persistence and overall number of waters on the landscape. Identification of key water sites, ranked by network connectivity metrics, are presented in Appendix B. Wetland number under our scenario of water limitation will decline by 43% reducing network resilience.

Anurans and Caudates, although varying in ability to disperse, generally experienced reduced connectivity between water sites in current and future scenarios at both daily and longer dispersal distances.

Desert Bighorn, Mule Deer, and Sonoran Pronghorn all experienced reduced connectivity between individual waters in clusters and between clusters in their respective territories. Anthropogenic water sources may prove critical to maintaining network connectivity in the future.

Gambel's Quail also experience a reduction in connectivity within and between clusters of waters in the Sonoran Desert. Masked Bobwhite would also follow this trend if a wild population existed in its historical range in the Sonoran Desert.

Executive Summary Table: The Sonoran Desert isolated waters network percent change between modeled current scenario and future climate limited water scenario for the changes in total number of clusters present, changes in mean number of wetlands per cluster, and change in largest cluster size.

Species	Movement	Changes in # of clusters	Change in # wetlands/cluster	Change in max # wetlands/cluster
Colorado River Toad	Daily (0.4 km)	-38%	-5%	-64%
	Dispersal (6 km)	6%	-46%	-66%
American Bullfrog	Daily (2 km)	-22%	-28%	-33%
	Dispersal (15 km)	30%	-56%	-54%
Chiricahua Leopard Frog	Daily (3.5 km)	-9%	-38%	-69%
	Dispersal (12 km)	9%	-47%	-52%

Lowland Leopard Frog	Daily (0.9 km)	-33%	-14%	-39%
	Dispersal (6 km)	6%	-46%	-66%
Couch's Spadefoot	Daily (0.8 km)	-34%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Plains Spadefoot	Daily (0.8 km)	-34%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Mexican Spadefoot	Daily (0.8 km)	-34%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Great Plains Toad	Daily (0.7 km)	-35%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Red Spotted Toad	Daily (0.7 km)	-35%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Sonoran Green Toad	Daily (0.7 km)	-35%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Southwestern Woodhouse's Toad	Daily (0.7 km)	-35%	-15%	-44%
	Dispersal (2 km)	-22%	-28%	-33%
Lowland Burrowing Treefrog	Daily (0.6 km)	-36%	-10%	-61%
	Dispersal (2 km)	-22%	-28%	-33%
Western narrow-mouth Toad	Daily (0.6 km)	-36%	-10%	-61%
	Dispersal (2 km)	-22%	-28%	-33%
Arizona Tiger Salamander	Daily (0.4 km)	-38%	-5%	-64%
	Dispersal (2 km)	-22%	-28%	-33%
Sonoran Tiger Salamander	Daily (0.4 km)	-38%	-5%	-64%
	Dispersal (2 km)	-22%	-28%	-33%
Desert Bighorn	Daily (1.6 km)	-26%	-25%	-35%
	Dispersal (5 km)	1%	-43%	-45%
Mule Deer	Daily (3 km)	-11%	-36%	-55%
	Dispersal (10 km)	15%	-50%	-54%

Sonoran Pronghorn	Daily (1 km)	-32%	-14%	-33%
	Dispersal (10 km)	15%	-50%	-54%
Masked Bobwhite	Daily (0.2 km)	-40%	-4%	-71%
	Dispersal (2 km)	-22%	-28%	-33%
Gambel's Quail	Daily (0.5 km)	-37%	-12%	-72%
	Dispersal (2 km)	-22%	-28%	-33%

Table of Contents

Introduction

Purpose, Aims, & Goals

We provide analyses of desert wildlife waters network connectivity for Sonoran Desert wildlife of interest. The goal of this work is to enhance the Desert Landscape Conservation Cooperative (LCC) Stakeholders' abilities to manage isolated desert waters for various species of wildlife by evaluating landscape connectivity as a function of climate change and habitat quality. Specifically we project future water availability for wildlife communities as a function of climate change and water quality, and examine connectivity of the landscape for threatened and endangered (T&E) species, most game species, and amphibians as a function of water availability. Furthermore, this work expands the study of water resources management in desert ecosystems for the Bureau of Reclamation (BOR) and the Desert Landscape Conservation Cooperative (Desert LCC) to include isolated wildlife waters. This work directly enhances current initiatives by the BOR in the West-Wide Climate Risk Assessments project, which in part identifies risks to water supplies. Our project extends this estimate of risk to ephemeral waters and will directly inform managers of those waters of conservation concern.

This project covers 20 species of wildlife over the Sonoran Desert Ecoregion of the United States. A quantitative and predictive analysis has been conducted based on water type and climate change to explore the connectedness of isolated water resources for the focal species. These focal species were selected by the Desert LCC based on their vulnerability to change in water availability (amphibians) and interest by managers (invasive species, game species, and T&E species).

This work will enhance the ability of natural resource professionals to manage water resources that are affected by a changing climate within the Desert LCC by identifying areas of low connectivity, areas where connectivity could threaten the persistence of T&E species, and areas where connectivity is threatened by climate change. This work will identify opportunities for improving the management of desert wildlife, from large mammals through amphibians.

The Sonoran Desert

The Sonoran Desert extends from Southern Arizona and California into much of the state of Sonora, Mexico, as well as most of the peninsula of Baja California and covers approximately 260,000 square kilometers of land. The majority of the Sonoran Desert is classified as a rain-shadow desert and receives between 3 to 15 inches (7.62 to 38.1 cm) of rain annually depending on location (Phillips & Comus 2000). Rain is generally found to occur in localized storms that are extremely variable in precipitation amount and duration. These storms generally occur during a summer monsoon season from July through early December (Adams & Comrie 1997). There is a winter rainy season as well that occurs in December and January.

Yuma, Arizona sits in the Lower Colorado River Valley section of the Sonoran Desert (Figure 1). This section is the hottest and driest and Yuma receives approximately 3 inches (7.62 cm) of rain on average annually (BMGR-INRMP 2012) but some years may receive less than this or no rain at all. Moving east from Yuma towards the Arizona Upland region of the Sonoran Desert near Tucson, rains increase to approximately 12 inches (30.48 cm) annually. Temperatures can rival the Mohave Desert of California and often exceed 120°F (49°C) during the summer (Phillips & Comus 2000).

Even with these extreme conditions the Sonoran Desert is a biological hotspot that is different from other North American Deserts because of its much milder winters (Phillips & Comus 2000). It is also home to tall columnar cacti such as the *saguaro* and *organ pipes* which rarely occur in other North American Deserts. The Sonoran Desert is thought to be home to over 2000 species of native plants, 130 species of mammals, 500 kinds of birds, 20 amphibians, 100 reptiles, and possibly as many as 30 native freshwater fish species (Phillips & Comus 2000).

The Sonoran Desert is also host to a wide variety of geodiversity. In a special section of the journal *Conservation Biology*, Hjort *et al*. (2015) discuss areas important to conserve based on environmental and cultural services provided. The Sonoran Desert is home to many of the listed examples including caves (e.g. Kartchner Caverns), cliffs (e.g. Superstition Mountains), talus (e.g. Santa Rita Mountains), tufa (e.g. Mono Lake), sand dunes (e.g. Pinta Sand Dunes), waterfalls (e.g. Winn Falls), temporary pools (e.g. White Tank), and desert springs (e.g. Bender Springs). These features are often important sites of biodiversity and conserving them will help biodiversity be able to adapt and move as climate changes shifts home ranges and habitat availability (Hjort et al. 2015). This report focuses on the temporary pools, springs, and other water sources of the Sonoran Desert.

Isolated Desert Waters

Biodiversity is often concentrated around wet areas in arid lands, even if the waters are ephemeral (Souza et al. 2006). Often the biodiversity of these arid land ephemeral waters is driven by the presence of rare and endemic species (Hendrickson & Minckley 1985). These wetlands also provide the foundation for much of the faunal diversity and are critically limiting to desert wildlife (Rosenstock et al. 1999).

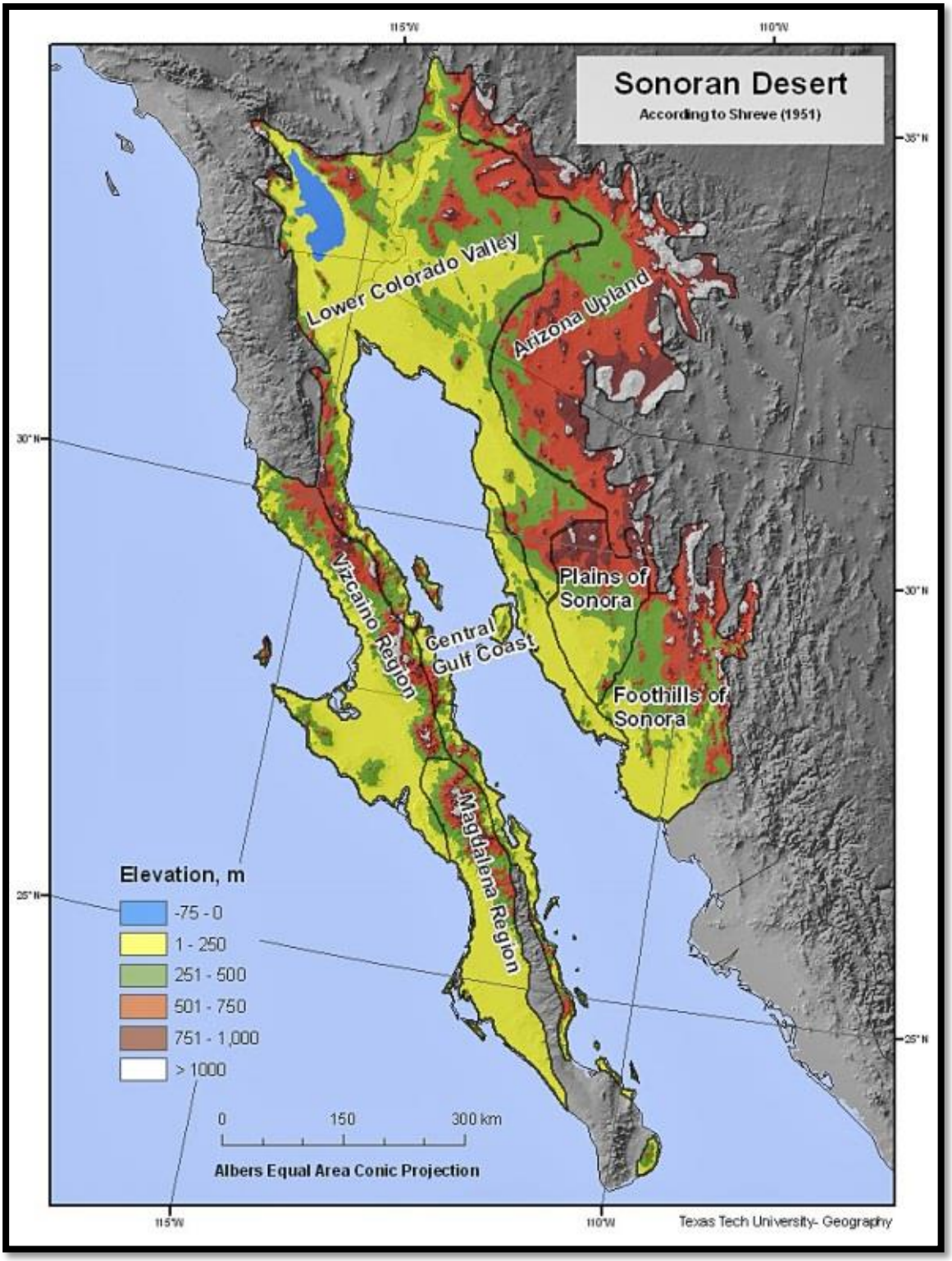


Figure 1. Sonoran Desert biomes adapted from Shreve (1951).

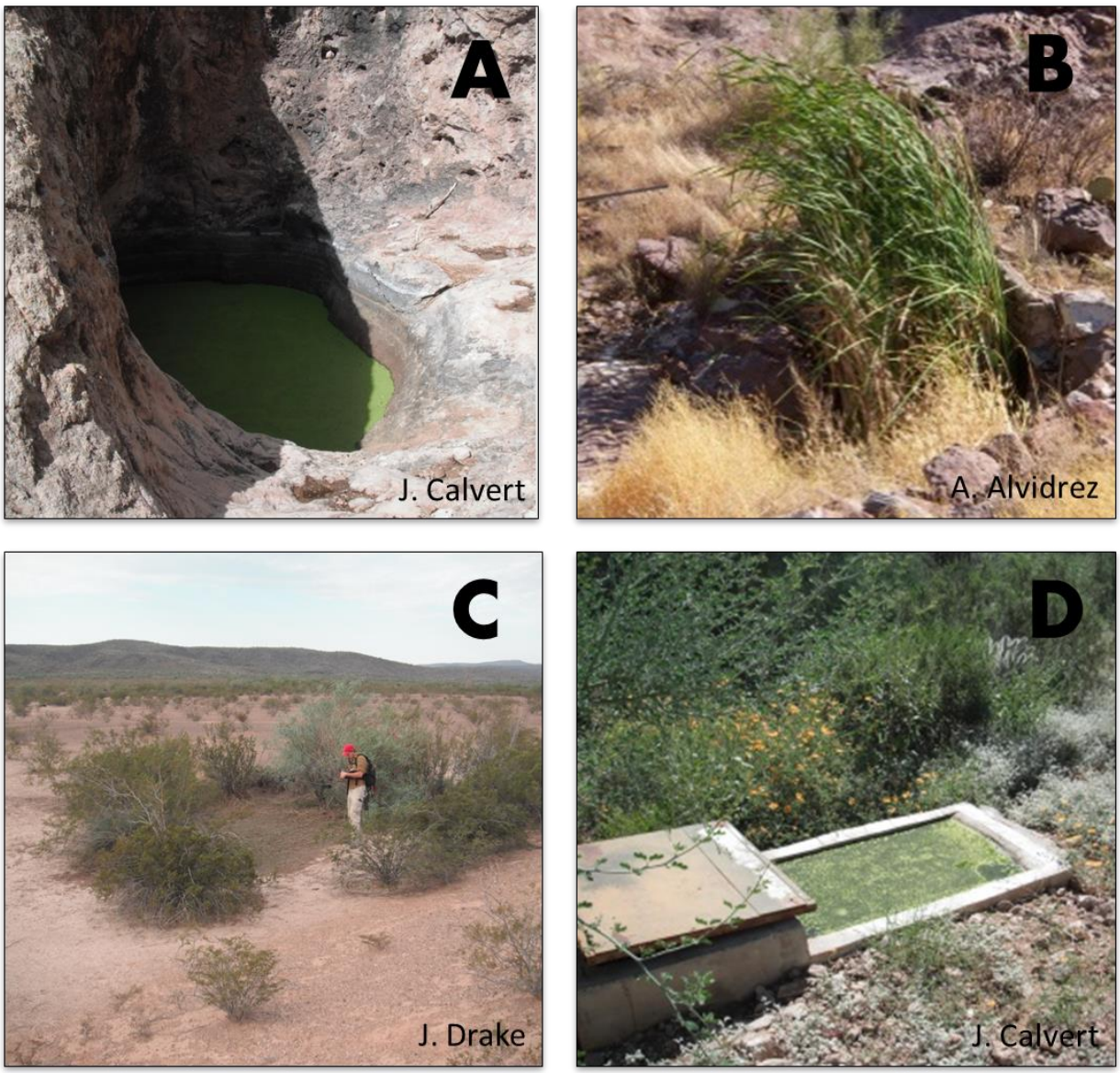


Figure 2. Common types of Sonoran Desert isolated waters: (A) tinaja or plunge pool; (B) spring with obscuring emergent vegetation; (C) recently dried charco and (D) artificial catchment (also known as guzzler).

In the Sonoran Desert, water often is limited to isolated and ephemeral sources. These can include springs, ephemeral streams, tinajas (rock pools), and charcos (extremely small and short lived puddles similar in appearance to the playa lakes of the south plains region of northern Texas; Figure 2). Spring flow is often dependent on the tradeoff between groundwater withdrawal and rainfall. Sometimes a spring that has been dormant will flow after changes in environmental circumstances such as increased rainfall in the watershed. Ephemeral streams, tinajas, and charcos are even more dependent on rainfall. These water sites are available only after rainfall and until percolation, evaporation and wildlife use depletes them of water.

The water sources are not limited to natural sources. Anthropogenic water locations, known as catchments, have been installed by federal and state agencies to help supplement the limited permanent natural water available for game species. The Arizona Game and Fish Department started installing theses anthropogenic water catchments (also called guzzlers) in the 1940's to help augment waters to help increase the numbers of game species such as Gambel's quail and desert bighorn sheep (Rosenstock et al. 2004; Wright 1959). There have been suggestions that non-target species, such as amphibians, can also benefit from the development catchments which provide more reliable wet habitat.

There are also studies that show the structural differences of catchments opposed to natural waters can lead to problems for wildlife. Recent work has shown that some of the isolated waters in the Sonoran Desert have extremely high ammonia concentrations (Figure 3), exceeding the EPA's Criteria for Aquatic Life for ammonia concentration. Over 70% percent of the catchments surveyed exceeded these criteria by a factor of 10 (Griffis-Kyle & Jenness 2013; Hermosillo 2013) and had ammonia levels that are toxic to amphibians and most species of aquatic invertebrates tested (Camargo & Alonso 2006). Ammonia levels may be high enough to impact terrestrial wildlife (Griffis-Kyle et al. 2014; WHO 2003), especially those individuals most dependent on water, such as pregnant and lactating females, who consume 40 to 50% more water than others in the population (Cain et al. 2006). However, little is known about this relationship.

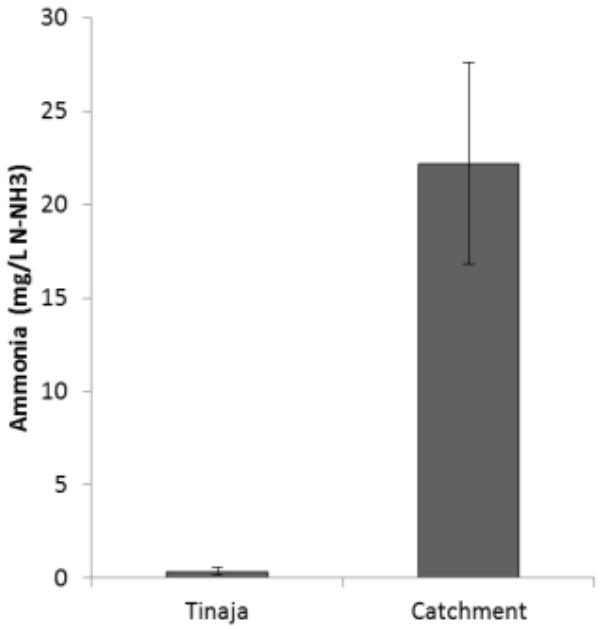


Figure 3. Ammonia concentrations in catchments (average ($\bar{x}$) = 22.2, Standard Error (SE) = 5.4; n = 16) were much higher than levels in tinajas ($\bar{x}$ = 0.3; SE = 0.2; n=5). Error bars represent SE (from Griffis-Kyle and Jenness 2013).

Ammonia accumulates from the decomposition of organic matter. Natural tinajas and springs are flushed of accumulated debris during rain events, but there is no natural mechanism to remove organic material from catchments. This issue will be exacerbated with climate change for two reasons: (1) the toxicity of the ammonia increases with temperature, and (2) evaporation of waters concentrates the ammonia even further. Consequently, constructed water catchments, some of which may be viable waters currently will harbor harmful concentrations of ammonia in the future, exacerbated by climate change. This is a problem for managers as one of the activities to alleviate water limitation caused by climate change is to develop constructed waters in the desert.

Isolated desert waters are highly sensitive to intra- and inter-seasonal variation in precipitation and air temperature in terms of both water quantity and water quality. These waters can exhibit dramatic variation in hydroperiod over relatively short timespans, creating a dynamic system of unpredictable and ephemeral resources for wildlife. Changes in rainfall and temperature from climate change can impact water quality by altering temperatures for chemical reactions and increasing concentrations of ions as a result of evaporation. Given our knowledge of how ammonia affects the suitability of individual water sites for organisms, the analysis of habitat connectivity becomes more challenging. Such differences in water quality, combined with their inherent isolation, mean that management of these waters and their associated wildlife will not be effective without quantifying connectivity routes between them now and in in the future with projected changes in climate. This study addresses these issues by exploring the connectivity between natural and anthropogenic waters under current conditions and future climate scenarios.

Importance of Connectivity

Movement is critical to the survival of animal populations - "connectivity is a vital element of landscape structure" (Taylor et al. 1993). Variance in habitat connectivity is a key determinant of extinction risk for many species (Fahrig & Merriam 1985) as well as a factor in the success of invasive species (Crooks & Suarez 2006). Habitat connectivity is a primary aim of many conservation activities (Taylor et al. 1993). Therefore connectivity is a key attribute for evaluating conservation value of a network of isolated waters. Many conservation activities focus on identification and management of habitat patches with specific functions (Metzger & Décamps 1997; Minor & Urban 2008).

Connectivity may not be desirable in all situations when it facilitates the invasion of exotic species or pathogens (Drake 2016); consequently, constructing corridors to facilitate movement between habitat patches such as wetlands can be counter-productive to wildlife management. Quantitative assessments of connectivity that include priority species for conservation and species to exclude and identifying areas to enhance movement of priority species as well as areas to restrict potential invasive pathways.

At the landscape scale, the spatial configuration of wetlands, species dispersal abilities, the quality of the waters, and the overall quality of the habitat are important to wildlife abundance and diversity. We project the impacts of climate change focusing on habitat requirements for organisms at the level of individual wetlands (patch scale) and incorporate projected wetland losses from climate change. To do so, we will use approaches from graph theory, weighting the importance of each water and its contribution to connectivity by water type based on field data (Griffis-Kyle & Jenness 2013).

There are specific forms of connectivity that have been identified: structural connectivity and functional connectivity (Tischendorf & Fahrig 2000). Structural connectivity is the physical description of the how the landscape is connected (Andersson & Bodin 2009). This is in the form of Euclidian (straight line) distances between habitat patches (in this case, waters).

To quantify structural connectivity, we used graph theory. Graph theory (network theory) can be highly effective at identifying conservation targets for habitat networks composed of numerous, discrete patches (Bunn et al. 2000; Fall et al. 2007). A habitat network is described as a graph of nodes (habitat patches, i.e., wetlands) connected by actual or potential dispersal routes termed "links," which we approximated as straight-line distances between wetland centroids. The wetlands of the Sonoran Desert are particularly well-suited to a graph-theoretic treatment because they are discrete patches. The tinajas and catchments form the nodes of a graph, and potential dispersal routes between the waterbodies represent linkages.

Graph theory is an efficient tool for conservation planning because it is used with occurrence data rather than detailed demographic data that most conservation prioritization methods require, but that are lacking for most species and take time and resources to acquire (Minor & Urban 2007). Moreover, graph-theoretic methods allow for a quantitative assessment of the role of each wetland. Thus, in ranking wetland habitat patches with respect to conservation importance, graph-theoretic metrics are effective surrogates for more complicated models that require key demographic rates as inputs. A graph-theoretic approach provides a relatively rapid assessment of the habitat connectivity in wetland landscapes and how that capacity varies as a function of land use/land cover change and climatic change. Such speed and efficiency in quantifying connectivity are critical given the pace and magnitude of wetland losses due to projected climate change in the southwestern U.S.

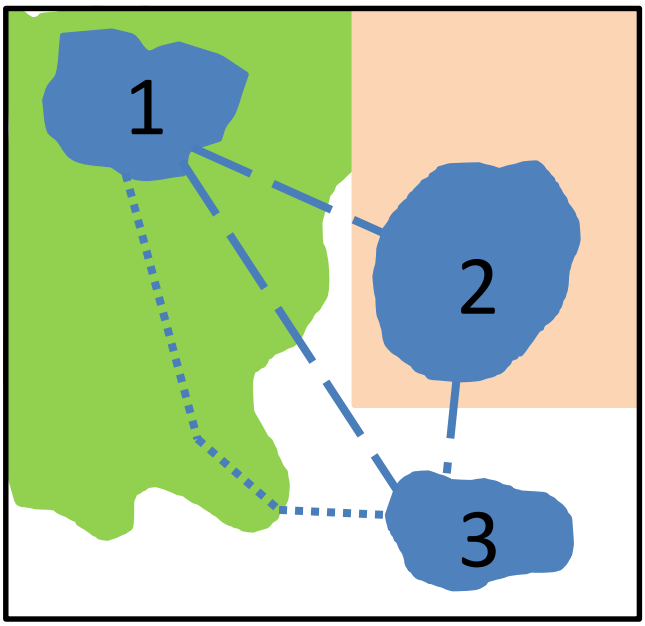


Figure 4. The figure shows three wetlands (blue polygons) embedded within three surrounding matrix habitats (green, tan, white). If an animal had to move from wetland 1 to 3 and all habitats were equally permeable (as might be the case to a bird flying overhead), it could choose to use wetland 2 as a stepping stone (stopover site), making relatively short movements (dashed lines), or make a longer, direct path between 1 and 3 (dashed line). But if the green habitat is the most readily traversable, followed by white and then tan (as might be the case to an overland disperser like an amphibian), then a longer path might be taken that minimizes distance in habitats that impede movement (dotted line). Structural connectivity can thus be assessed by simple Euclidian distance among wetlands (dashed lines), and functional connectivity can be assessed by weighting each matrix habitat type according to its resistance to movement (dotted line).

Graph theory can be highly effective at quantifying structural connectivity through use of Euclidian distances among nodes (habitat patches). Such an approach provides a strong null model, but real organisms seldom move in straight lines, being affected by differences in the permeability of different land use/land cover types (with movement impeded by some forms of land use/land cover, and facilitated by other forms). However, connectivity has two components: structural (spatial) and functional (biotic response) (Figure 4).

An assessment of functional connectivity (i.e., how organisms actually move through the landscape) is therefore comprised of a least-cost path rather than Euclidian shortest-distance paths. There are several methods in calculating least-cost paths or the functional connectivity of an environment. Cost weighted distance measures have been used to calculate least-distances for paths and corridors that can help in conservation planning (Adriaensen et al. 2003; Zeller et al. 2012). There are limitations with these methods as they calculate the single corridor most likely to represent possible movement scenarios (Cushman et al. 2013). A newer method of calculating paths uses circuit theory (McRae et al. 2008; McRae 2006) to calculate all possible dispersal routes between habitat patches. We propose to identify the most likely routes for movement among wetlands now and under future climatic conditions, critical information for effective conservation.

Climate Change Impacts

As the climate changes and the American Southwest faces increased temperatures and reduced precipitation (Seager et al. 2007; IPCC 2014; Karl et al. 2009), the importance of managing and maintaining the scarce water resources available for wildlife will increase. Many models suggest that the rainfall that does occur will be more violent and less frequent causing an overall reduction in water availability. The natural waters of the desert, and the wildlife that depend on them are threatened by anthropogenically driven shifts in the climate (Unmack & Minckley 2008). Many species of amphibians and invertebrates rely on the isolated waters of the Southwest for reproduction, making them extremely vulnerable to habitat loss via climate change. It is becoming much clearer that the landscapes must be managed in ways that can increase adaptability to climate change and land use change (Vos et al. 2008). Hence, management and maintenance of these waters will increase in importance with increased climatic variability. Given some of the recent discoveries of water quality issues with catchments, it is important to know how important artificial catchments are to wildlife and how important they will be in the future as natural resources continue to decline.

Study Approach

Approach Summary

Our goal is to model how the presence of waters, both natural and artificial, impact the ability of a wide range of animals to move through the ecoregion. Identifying habitat patches and how organisms will or will *not* move between these patches can provide important information for managers. This analysis is carried out at the regional/landscape level to model the basic characteristics of the isolated water resources within the context of the United States portion of the Sonoran Desert. How the habitat patches and other landscape features influence the movement of different species are considered in terms of a regional context. The approach of this study is summarized here:

- **Study Area:** Designation of extent of study area for use in geo-spatial calculations.

- **Focal Species Selection:** Select species based on various criteria including dependence on water, legal mandates for conservation, and management interest. These species will constitute a wide variety of dispersal capabilities, functional guilds, and taxonomic groups.

- **Wetland Database Collection:** Compile a geospatial database of wetlands and water sites using data from ground-truthing; remote sensing; and federal, state, and non-profit conservation organizations databases.

- **Structural Landscape Analysis:** Identify water sites important to connectivity based on graph theory analysis and metrics based on focal species dispersal and movement capabilities.

- **Functional Landscape Analysis:** Explore functional connectivity of the Sonoran Desert landscape using resistance mapping based on circuit theory analysis.

- **Climate Change Scenarios:** Examine potential connectivity disruptions by culling wetlands based on various climate change scenarios. Some culling scenarios will be based on sensitivity to climate change and some scenarios will be based on management scenarios.

- **Areas of Importance:** Throughout the analyses, areas of conservation and connectivity importance will be identified through structural and functional connectivity analyses.

Methodology

Study Area

The study area is the United States portion of the Sonoran Desert as delineated by the outer boundary of the 5th level hydrological units (HUCs) that overlaid the Environmental Protection Agency's Level III Ecoregion boundary assessment for the Sonoran Desert Ecoregion (Strittholt et al. 2012). In addition to this area delineated by watershed boundaries, we have included a 32.2 km (20 mile) buffer around the designated boundary. This additional border was included in the study area to help prevent boundary effects (Koen et al. 2010) which could skew spatial calculations by not including important elements that occur just outside the area of interest.

Focal Species

We targeted 20 species in the Sonoran Desert Ecoregion that have legal mandates for conservation and are of management interest (Table 1). Movement information is key to connectivity studies. Here we used two main different measures for species movement for our connectivity analyses.

For non-amphibian species, we used average distances from water sites and daily movement distances. These larger animals are opportunistically drinking from water sites as the move through the landscape. Although some species might not necessarily need to consume water, animals will opportunistically drink available water. The need for water will only increase as the species that do occur in the Sonoran are already near the edge of their physiological tolerances. Climate shifts and habitat loss are very likely to push many animals past their tolerance for disturbances, heat stress, and water needs.

For amphibians, known maximum distances traveled or known distances away from water were used as measures for connectivity analyses. We are using these max distances because we are looking at wetlands and isolated waters for these species as breeding habitat. These max distances used are good surrogates for effective dispersal distances. The risk of desiccation aboveground is relatively high in much of the Sonoran Desert for most of the year causes amphibian movement to be costly. Many amphibian species are not known to move much more than 2 kilometers for dispersal (Smith & Green 2005), but this information is anecdotal at best and based on related species found in more mesic environments at the least.

Table 1. Target species for landscape connectivity analysis. We use the maximum distance moved for amphibians because we are looking at connectivity between breeding sites, and we use average distance from water site for game species, as these species use water sites for drinking.

Species	Distance from water (km)	Notes
Colorado River toad (*Incilius alverius*)	6[1]	Based on lowland leopard frog
American bullfrog (*Lithobates catesbeianus*)	8[2]	Manage for isolation as this is a threat to the Chiricahua Leopard Frog
Chiricahua leopard frog (*Lithobates chiricahuensis*)	3.5[3]	Maximum unidirectional distance moved
Lowland leopard frog (*Lithobates yavapaiensis*)	6[1]	Based on Rio Grande and plains leopard frog
Couch's spadefoot (*Scaphiopus couchii*)	0.8[1]	Based on eastern spadefoot
Plains spadefoot (*Spea bombifrons*)	0.8[1]	Based on eastern spadefoot
Mexican spadefoot (*Spea multiplicata*)	0.8[1]	Based on eastern spadefoot
Great Plains toad (*Anaxyrus cognatus*)	0.7[4]	
Red-spotted toad (*Anaxyrus punctatus*)	0.7[1]	
Sonoran green toad (*Anaxyrus retiformis*)	0.7[1]	Based on red-spotted toad
Southwestern Woodhouse's toad (*Anaxyrus woodhousii australis*)	0.7[1]	Based on red-spotted toad
Lowland burrowing treefrog (*Smilisca fodiens*)	0.6[1]	Based on western narrow-mouth toad
Western narrow-mouth toad (*Gastrophryne olivacea*)	0.6[1]	
Arizona tiger salamander (*Ambystoma mavortium nebulosum*)	0.4[1]	Based on tiger salamander
Sonoran tiger salamander (*Ambystoma mavortium stebbinsi*)	0.4[1]	Based on tiger salamander
Desert bighorn (*Ovis canadensis mexicana*)	3[5]	Average distance to water site for females
Mule deer (*Odocoileus hemionus crooki*)	3[6] 5[7]	Average of females and males Average for summer dry season
Sonoran pronghorn (*Antilocapra americana sonoriensis*)	10[8]	Highest use within 1 km, use within 10 Federally Endangered
Masked bobwhite (*Colinus virginianus ridgwayi*)	Unk	Unknown, but most core ranges < 3 ha[9] Federally Endangered
Gambel's quail (*Callipepla gambelii*)	Unk	See masked bobwhite

[1]Average of max distance moved reviewed in (Smith & Green 2005), [2](Schwalbe & Rosen 1999), [3](Sredl & Jennings 2005),[4](Ewert 1969), [5](Cain et al. 2008), [6](Krausman & Etchberger 1995), [7](Rautenstrauch & Krausman 1989), [8](deVos Jr & Miller 2005), and [9](Kuvlesky Jr. & Dobrott 1995).

These target species (Table 1) use isolated waters for part of their life cycle or use surface water for drinking. The 14 amphibian species are dependent on isolated waters and are, as a taxa, extremely vulnerable to changes in hydrology and landscape connectivity of ephemeral water sites. These species are also likely to be very vulnerable to elevated ammonia concentrations (Camargo & Alonso 2006) found in artificial catchments (Griffis-Kyle et al. 2014, Hermosillo 2013). The American bullfrog, an invasive species, is included because it is a threat to the threatened Chiricahua leopard frog and other native fauna (Rosen & Schwalbe 2002; Rosen & Schwalbe 1994). There are two species of big game, one species of small game, and two species that are federally endangered (Table 1).

We have broken the 14 amphibian species down into groups and subgroups. These groups are based on the ability to disperse and how the landscape matrix impacts those dispersal capabilities. More specific information about grouping, life history, occurrence, habitat use, and water dependence will be covered in each species specific section.

Wetlands

Identification of isolated waters, i.e. habitat patches , was necessary as there are currently no complete archives of isolated waters of the Sonoran Desert. There are, however, attempts at rectifying this. Federal databases such as the National Wetland Inventory (http://www.fws.gov/wetlands/), the National Hydrological Dataset (http://nhd.usgs.gov/), and the United States Geological Survey's (USGS) Geographic Names Information System (http://nhd.usgs.gov/gnis.html) all have many of the more permanent springs and wetland water features mapped. Of the waters that are mapped, many federal databases may be based off of decades old USGS topographic maps that do not currently reflect the available habitat.

Regionally, waters such as ephemeral springs, tinajas, charcos, and other isolated or ephemeral waters are not remotely mapped easily due to small sizes, ephemeral nature, and rugged topographical locals, or sometimes unknown altogether (Drake et al. 2015), and thus are often omitted from such federal databases. Non-governmental organizations (NGO's) working in tandem with state and federal agencies are working to map out the current state of affairs for waters in the Sonoran Desert. Besides knowing accurate locations for current waters, the efforts are extending to include rapid biological surveys for plant and animal species occurrences. With this data they are building more comprehensive databases for the Sonoran Desert. Two of the main organizations working on this are Springs Stewardship Institute (SSI; Flagstaff, AZ) and Sky Island Alliance (SIA; Tucson, AZ).

These efforts are much needed and are still in their nascent stages. Although the information is being compiled, ground-truthed, and curated, the databases are often only accessible by the parent organization or with select permission thereof. Often, the early stages of these initiatives are geographically limited. SIA efforts are based primarily in the Madrean Archipelago near the Tucson area (although they are slowly expanding).

Other resources included state and federal land management agencies. The Arizona Game and Fish Department (AZGFD) manage nearly a thousand wildlife waters in AZ including but not

limited to: guzzlers, modified tinajas, windmill pumps, and cattle tanks. They maintain a geospatial database of these waters in Arizona. For sections of the Sonoran Desert inside California, the BLM's Rapid Ecological assessment (REA) has a geospatial collection of water sites within the Sonoran Desert Ecoregion and we used these data points to identify artificial isolated waters in the California portion of the Sonoran Desert.

We compiled all available waters from knowledgeable sources (Table 2) and our own field research. This information we compiled into a large geospatial database to use as focal nodes in our analyses using ArcMap 10.2.2 (unless otherwise noted ArcMap is the program used for geospatial analysis; ESRI 2014). Data were converted from their native projections and coordinate systems to North American Datum 1983, Universal Transverse Mercator Zone 12 North.

Table 2. Isolated water locations provided by state and federal agencies; non-governmental organizations; and publically available databases.

Source	Description	URL	Date Accessed
AZGFD	Waters managed by the AZGFD for the benefit of wildlife. Includes, but not limited to, artificial catchments, modified tinajas, springs, and stock tanks.	Unavailable publically for download - Provided by agency; habimap.org for online viewing	3/11/2014
56th Range Office - Luke Air Force Base	Known natural and artificial isolated waters on the Barry M. Goldwater Air Force Range.	Unavailable Publically - Provided by agency	4/28/2014
NMSU Faculty	Natural and artificial isolated waters.	Unavailable Publically - Provided by agency	1/7/2015
Sky Island Alliance	Springs and other natural waters in the Santa Cruz Study Area and Sky Island Region.	Unavailable Publically - Provided by agency; curated database under development	4/26/2014
Springs Stewardship Institute	Springs and other natural waters in the Sonoran Desert Ecoregion.	http://springsdata.org/	7/7/2014
Bureau of Land Management's Sonoran Desert Rapid Ecological Assessment	Sonoran Desert "guzzlers" (artificial catchments) and modified/managed natural waters within the SOD REA boundaries.	http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas/sonoran.html ; http://consbio.org/products/projects/blm-rapid-ecological-assessment-rea-sonoran-desert	3/13/2014

Water site locations were often redundant between databases. These redundancies were accounted for by manually removing isolated water locations from the geospatial database. Waters were categorized when possible between natural and artificial provenances so that anthropogenic water influence on system connectivity could be distinguished during the structural analysis. Two different sets of water sites were used. The first encompasses the

entire constructed geospatial database of isolated waters. The second is a subset of waters for a climate limited scenario which includes springs and managed waters which are the most likely to survive into the future as functional water sites.

Structural Landscape Analysis

The mapping of the Sonoran Desert's isolated waters allows these waters to be analyzed using graph theory for a better understanding of the Sonoran Desert's structural connectivity. These waters serve as *focal nodes* and are connected by *links*. To quantify the connectivity of the Sonoran Desert Ecoregion clusters of wetlands, hubs, and stepping-stones have been identified (Table 3).

Table 3. Important metrics for evaluating connectivity of a landscape and other graph-related terms (adapted from (Urban & Keitt 2001; Proulx et al. 2005; Clauset et al. 2004)

Node:	A wetland
Link:	Actual or potential dispersal route between wetlands
Stepping- stones:	Wetlands that that facilitate connectivity through the landscape as a whole
Cutpoints:	Wetlands whose loss would result in a disproportionately high degree of landscape fragmentation
Hubs:	Wetlands that are connected to many other wetlands
Coalescence:	When the entire landscape can be crossed by an animal moving from wetland to wetland (i.e., wetlands are within the animal's dispersal capacity)
Diameter:	The shortest path across the entire graph
Modularity:	A measure of community structure. The number of paths between grouped wetlands within and between them. When the modularity is high there are many edges within communities and only a few between them.

These metrics, along with path length and numbers, can quantify the connectivity within and across the Sonoran Desert Ecoregion. Stepping-stones and hubs are essential features for identifying connected areas. To understand the critical threshold of when an entire landscape is connected by all its component parts, the property of *coalescence* is examined. This defines if a landscape is traversable or not depending on any given species, vagility, dispersal capabilities, and the distribution of habitat.

Structural connectivity metrics will be calculated using the package *igraph* (Csardi & Nepusz 2006) in R version 3.1.3 (R Core Team 2015). Although the dispersal capabilities of each species may be unique, we can group species together based on similar vagility. Based on biological data (dispersal distances and movement distances that our focal species represent; Table 1) we used a range of dispersal distances to quantify the connectivity of the landscape (0.5, 1, 3, 5, 10, and 15 km). We will also explore the maximum distance needed to travel the entire network of waters to determine coalescence and system wide, *global*, metrics.

At each individual connectivity distance, we calculated the number of wetlands clusters present. Along with this measure, we also ranked individual wetlands according to their

importance to the entire system. This connectivity ranking of habitat patches according to how important they are for overall connectivity in the global network is common (Bodin & Saura 2010), but rankings are influenced by the metric used (Laita et al. 2011). Because ranks can be influenced by the metric used, we have used three conceptually and computationally different measures of connectivity. We have identified the habitat patches as stepping-stones, cutpoints, and/or hubs (Table 3).

These graph metrics are important for connectivity and can represent biologically relevant ideas:

- *Stepping-stones* will be determined via betweenness centrality, a standard (and recommended: Bodin & Saura 2010) network metric that identifies the number of shortest paths through each node within the network, with a stepping-stone being a node through which most of the shortest paths pass (Csardi & Nepusz 2006). These nodes represent the waters that serve as the "backbone" of the network and are potentially important pathways for the landscape.

- A *cutpoint* (or articulation point) is a node that, if removed, causes the network to become fragmented (i.e., increases the number of clusters present) (Csardi & Nepusz 2006) and will be identified as either a cutpoint or not. These cutpoints are biologically crucial, representing areas that could serve as choke points for movement in the environment.

- *Kleinberg's hub scores* are proportional to the number of links from a node, with a node that is connected to a large number of other nodes (within each of our specified dispersal distances) receiving a high hub score (Csardi & Nepusz 2006). These represent wetlands that can be especially useful for dispersal as they are well connected to other wetlands and potential provide easy access to more resources and habitat.

We will rank wetlands according to their betweenness centrality scores and their hub score, for each of the focal dispersal distances. Designation as a cutpoint is Boolean (yes/no) rather than a score and so will not be ranked, only identified.

Given the number of waters available across the landscape, we have tables available for each scenario run (Appendix C). The top ten percent of each scenario will be compared to examine if any waters occur frequently between scenarios. In this way we identify waters that are important across a wide variety of scenarios for various metrics. These waters would be considered of special interest for connectivity and conservation purposes.

Functional Landscape Analysis

Animals respond to the environment and do not treat all landscape features equally. Up to this point, the structural analysis has not incorporated the impacts of the landscape on wildlife movement. Functional connectivity builds on the ideas of structural connectivity by including how the animals respond and therefore move through a landscape (Taylor et al. 2006; Crooks &

Sanjayan 2006). Functional connectivity can be assessed using GIS techniques like resistance surfaces and least-cost paths (Adriaensen et al. 2003; Theobald 2006). Least-cost paths represent the path across the landscape that provide the theoretical least resistance to an animal moving across the surface based on that specie's habitat preferences and physical capabilities. This method allows different resistance values to be assigned to the landscape matrix between designated habitat patches in the study area. In this way a "cost" is determined for traveling between any two given habitat patches.

Cost of travel, as quantified by resistance values, is different for each habitat characteristic for each species. Common habitat characteristics that were considered included: land cover and land use, elevation, topography, road density, and species occurrence (Table 4). For each of these characteristics, a value of relative resistance was assigned to reflect current knowledge based on available literature of habitat use. Where the literature was lacking, experts on the study area and the species in question were asked to give expert opinion on how a habitat characteristic would impact the focal species. To assign resistance values to spatial data layers representing different habitat characteristics, we used the GIS program ArcMap 10.2.2 (ESRI 2014) to manage geospatial databases. The data was accessed from government-controlled, publically-accessible databases (Table 4). Several spatial data layers needed to be calculated into a new format to be more easily interpreted and biologically relevant as resistance values.

Because species respond to the landscape differently, not all layers were used to calculate resistance values for a given species. Additionally, data layers may be weighted to account for the various impacts each landscape feature on a particular species (Equation 1). Species specific resistance values and layer weights for each will be provided in the next section dedicated to species specific results. A complete list of all resistance values will be provided in the appendices to compare values side by side (Appendix A).

$$R_L W_L + R_E W_E + R_T W_T + R_P W_P$$

Equation 1. Equation describing total resistance value being weighted by multiple topological factors (Adapted from Beier et al. 2009). *R*=resistance value; *W*=weight value; *L, E, T, P,* all represent various landscape variables.

The purpose of this analysis is to gauge all movement possibilities between isolated water sources to better understand a region's connectivity for multiple species of animals. LCPs and corridors based off of LCPs are limited in that they only represent the single best path between designated habitat patches. This may reflect the best potential route, but wildlife will not always pick the "best" route because of imperfect knowledge of the area or other proximal factors (Adriaensen et al. 2003; Theobald 2006).

A method that is increasingly being used to gauge connectivity is circuit theory which calculated ecological resistance (McRae 2006). These analyses can stand independently of LCP analyses or can be used in compliment with them (McRae et al. 2008; McRae et al. 2014) and Linkage Mapper (McRae & Kavanagh 2011). Circuit theory analyses are better suited to regional analyses of connectivity as the method identifies all possible routes available between habitat patches (McRae et al. 2008). There are limitations to circuit theory just as with LCPs: (1) It is a

model and does not cover every feature of the landscape, and (2) there is uncertainty in model parameters and estimations (Zeller et al. 2012).

Table 4. Table of spatial layers used as inputs for resistance value calculations.

Item	Source	Description	URL
Land cover	National Land Cover Dataset 2011	Derived from the National Land Cover Dataset (Jin et al. 2013). This represents land cover (e.g. highly developed, agricultural) and vegetation classes that represent habitat characteristics important to almost all organisms.	http://www.mrlc.gov/nlcd2011.php
Climate scenario land cover	USGS Fore-SCE data	Derived from the Fore-SCE land cover projections for the year 2050 under the emissions scenario A1B (Sohl et al. 2014). This represents land cover (e.g. highly developed, agricultural) and vegetation classes that represent habitat characteristics important to almost all organisms projected into the future.	http://landcover-modeling.cr.usgs.gov/projects.php
Elevation	USGS National Elevation Dataset	Digital elevation models (DEMs) data from the National Elevation Data Set (Gesch et al. 2002; Gesch 2007) stitched together to encompass the entire study area. Elevation was broken down into categories to represent the range of elevations available in study area. Elevation influences habitat and can be an important characteristic that can limit species occurrence. Also used for calculating elevation, slope and, TPI.	http://ned.usgs.gov/
Slope	Derived from Elevation dataset	This layer was derived from elevation data layer using slope calculator in ArcMap 10.2.2 (ESRI 2014). Slope is an important characteristic in determining the ruggedness of a terrain and the species that will use a given area. Slope was designated into categories to represent slope classes that would influence wildlife movement.	
Topographic Position Index	Derived from slope and elevation	This data type is derived from the slope and elevation dataset using Corridor Design Toolbox (Majka et al. 2007) for ArcMap. Topographic position relates the relative position in the landscape of a specific point. Four classes were designated: canyon bottoms, slopes, ridgetops, and flats (Weiss 2001).	
Roads	U.S. Census Bureau TIGER Products	Road density is calculated from the TIGER/Line 2010 Census (U.S.C.B. 2010) and is represented as kilometers of road per square kilometer. Roads impact wildlife to various degrees but often have negative impacts.	https://www.census.gov/geo/maps-data/data/tiger.html

Table 5. Raster grain size for connectivity analyses.	
Grain Size (meters)	Species
120	Arizona Tiger Salamander
	Sonoran Tiger Salamander
	Couch's Spadefoot
	Plain's Spadefoot
	Mexican Spadefoot
	Sonoran Green Toad
	Red-Spotted Toad
	Southern Woodhouse's Toad
	Lowland Burrowing Treefrog
	Western Narrow Mouth Toad
150	American Bullfrog
	Lowland Leopard Frog
	Chiricahua Leopard Frog
	Colorado River Toad
	Masked bobwhite
	Gambel's Quail
240	Desert Bighorn
	Mule Deer
	Sonoran Pronghorn

One of the most important model parameters to consider is the scale used to calculate resistance value landscapes, *i.e.* the grain of the resistance surface. Spatial layers are kept in native (often 30 meter) grid cells during resistance value assignments, but not all species will experience the environment on this scale. Consequently, It is important to conduct analyses at the spatial extent that animals experience the environment, lest information is lost at too large a grain (Wiens & Bachelet 2010; Wiens 1989). This need, to maintain the smallest grain size necessary, must be weighed against computational limitations. Although algorithms are fairly efficient for raster landscapes in circuit theory, there are still computational roadblocks (McRae et al. 2014). Circuitscape can calculate all possible combinations of possible pathways but as extent increase, so does the number of calculations needed to be executed. Our system of habitat patches is quite large and we have many paths to calculate between patches, so some of our simulations took weeks to complete. To speed computations we increased the grain size by a factor of 10 as detailed in, McRae *et al.* (2008), which has been shown to provide results analogous to finer grain sizes. We grouped species during resistance calculations based on minimum grain size that reflect species' interaction with the landscape (Table 5). The increases in grain size were in effort to allow the models to run without crashing the research computers due to memory limitations. We perform these calculations using Spatial Analyst extension in ArcMap (ESRI 2014) and with the Gnarly Landscape Utilities (McRae et al. 2013). All species will be modeled at 250 meter grain for the functional climate scenario as that is the grain size of the FORE-SCE land cover datasets.

Climate Change Scenarios

The climate change scenarios were modelled using both structural analyses and functional analyses described above. Given the projections of drier and hotter conditions (Seager et al. 2007; Melillo et al. 2014), we assume a loss of isolated waters in the system such that those that are not managed for wildlife (e.g. guzzlers) or known springs were removed from the analysis. This realistic scenario will reflect the reduction in surface water availability based on climatic forecasts. Spring flow in arid systems can often be tied to rainfall (Unmack & Minckley 2008), but are also some of the most reliable waters in the desert. Managed waters such as anthropogenic water catchments will continue to be managed and filled by state and federal conservation agencies.

With the climate scenario version of isolated waters, a functional connectivity analysis will also be carried out. For current scenarios, the latest edition of the National Land Cover Dataset was used to calculate patch resistance values, and for future scenarios we used USGS simulated land cover data that models human population change, economic growth, agricultural production, and environmental stability (Sohl & Sayler 2008; Sohl et al. 2014). We used the land cover projection that follows the SRES A1B emission models (IPCC 2014) for the year 2050. These models resistance values will be assigned to correlating land cover types and resistance surfaces will be recalculated using these land cover resistance values. These scenarios will be used with the new climate model isolated waters dataset to explore likely changes in connectivity for the different species.

Areas of Importance

From these four described connectivity scenarios (1. Structural analysis with all waters, 2. Structural analysis without climate vulnerable waters, 3. Functional analysis with all waters, and 4. Functional analysis without climate vulnerable waters), we assessed areas of conservation importance. These areas include current and future probable dispersal routes and habitat corridors, and areas of weak linkages in landscape for the focal species. The identification of those waters that will be diminished or lost altogether will be an important step to understanding climate change impacts.

Using these connectivity scenarios we will identified and prioritized:

- Waters that are important for current management or future restoration of connectivity
- Waters that are important for maintaining overall system connectivity
- Current probable dispersal routes and weak linkages
- Vulnerable corridors that may be diminished or lost altogether
- Waters that may contribute to the spread of invasive species

Regional Results

The Sonoran Desert network of isolated waters for the all waters scenario coalesced at 29.1 km with a total number of 6,214 waters contributing to system connectivity. Under the climate limited waters scenario, the coalescence distance (the farthest distanced needed to travel between any 2 points) increased by about 8% to 31.4 km while the total number of waters decreased to 3,558 (Table 6). Wetland numbers decreased in the climate limited waters scenario, and as a result, the longest path through the graph decreased. The average number of links between each isolated water also decreased by approximately a fifth throughout the system. Graph density and network modulatory increased from the all waters scenario to the climate limited waters scenario.

Table 6. Global connectivity metrics of the Sonoran Desert's network of isolated waters for two different scenarios: a*ll waters scenario* (all known isolated waters in the Sonoran Desert) and *climate limited waters scenario* (only isolated waters that are actively managed or identified as springs which may survive the increased temperatures and decreased precipitation forecasted for the Sonoran Desert in the coming decades).

Metric	All Waters Scenario	Climate Limited Waters Scenario
Coalescence Distance (meters)	29,100	31,400
Number of Wetlands	6,214	3,558
Longest Path (Diameter – meters)	837,609.2	816,068.3
Graph Density (number of links/possible links)	0.02884889	0.03550449
Average Path Length (average number of edges between vertices)	11.76776	9.636085
Network Modularity	-0.0002135	-0.00041572

These patterns reflect an increase in fragmentation from the current condition (all waters scenario) to the climate limited waters scenario. The increase of network modularity suggests that the decrease in wetland numbers and the resulting topology caused a minor increase in between-group connections. The small modularities overall suggest that there is a large number of alternative routes through the system. Although there may be a large number of alternative routes possible, the structure and graph density of the system suggest that the majority of the possible links through the system would not be plausible routes for wildlife at such long distances as 29.1 km (the coalescence distance of the graph). The network of isolated waters is too spread out to provide realistic links. The shape, topology, and metrics of the all waters scenario compared to the climate limited waters scenario show a reduction of whole landscape connectivity between wetland patches in the Sonoran Desert.

At distances below coalescence, subgraphs emerged from the system representing clusters of wetlands. At any given category of dispersal distance, we used the number of clusters to understand the fragmentation of the system. Between 3 and 5 km, the number of clusters

reduced dramatically and cluster size increased as the system began to shift from more fragmented to more connected. The mean cluster size was larger for the all waters scenario, representing a habitat network where more waters are available for animals to use (Figure 5) under current conditions than those modelled under climate limited waters scenario.

These results indicate that species with low vagility have very few areas that have habitat redundancy as defined by the number of water sites in a cluster, and this decreases further in the climate limited water scenarios. Localized extirpations may increase as an already limited redundancy is further limited by climate and land use changes. As dispersal and movement capabilities increase, structural connectivity limitations decrease. The functional connectivity of the landscape becomes more important to access resources as the amount of land traversed by an individual increases. Species-specific analyses must incorporate both structural and functional connectivity results to fully understand habitat distribution, habitat connectivity, and the ability of an organism to move through the landscape.

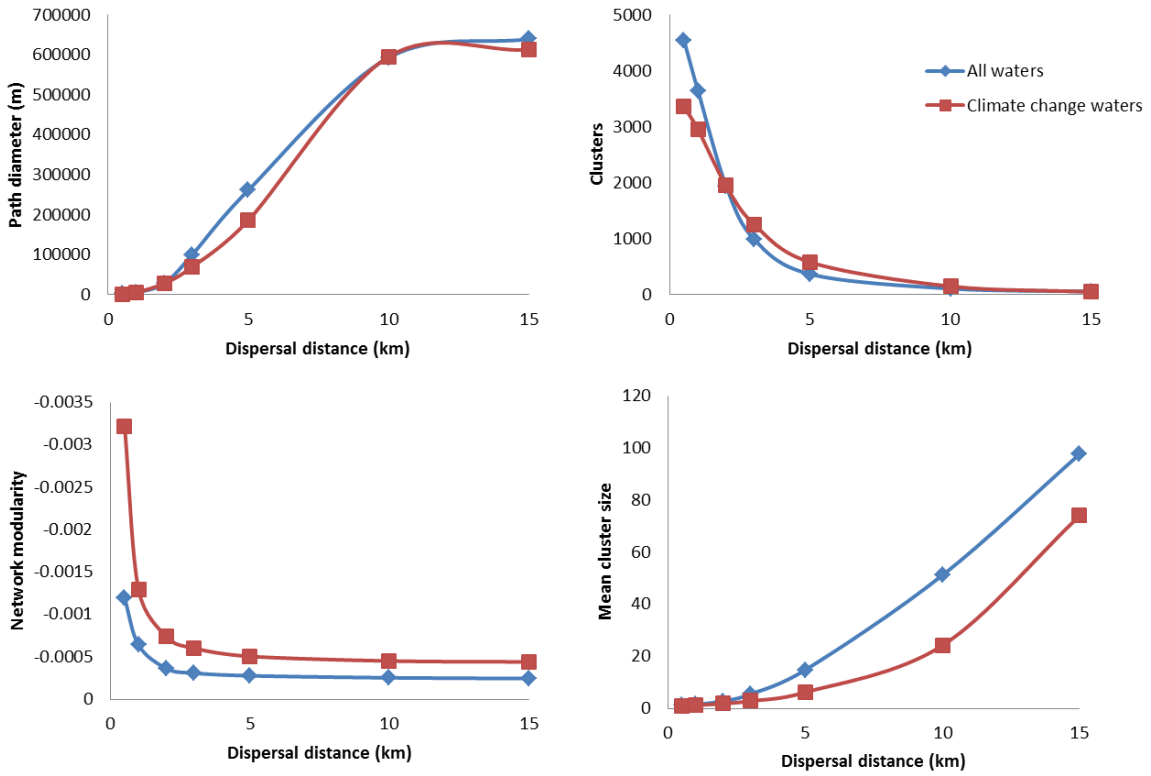


Figure 5. Graph of diameters, clusters, mean cluster size, and network modularity (clockwise from top left) set against dispersal distances from scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario ("All waters") reflect all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario ("Climate change waters") reflects a future based on climate projections that predict less rain and higher temperatures for the American Southwest where only spring fed isolated waters may survive and be augmented by managed game waters. The climate limited waters scenario shows reduced connectivity metrics: shorter path diameters at all distances; fewer clusters at shorter distances and more at high distances because of increased fragmentation of the network; higher network modularity; and smaller mean clusters sizes at all dispersal distances.

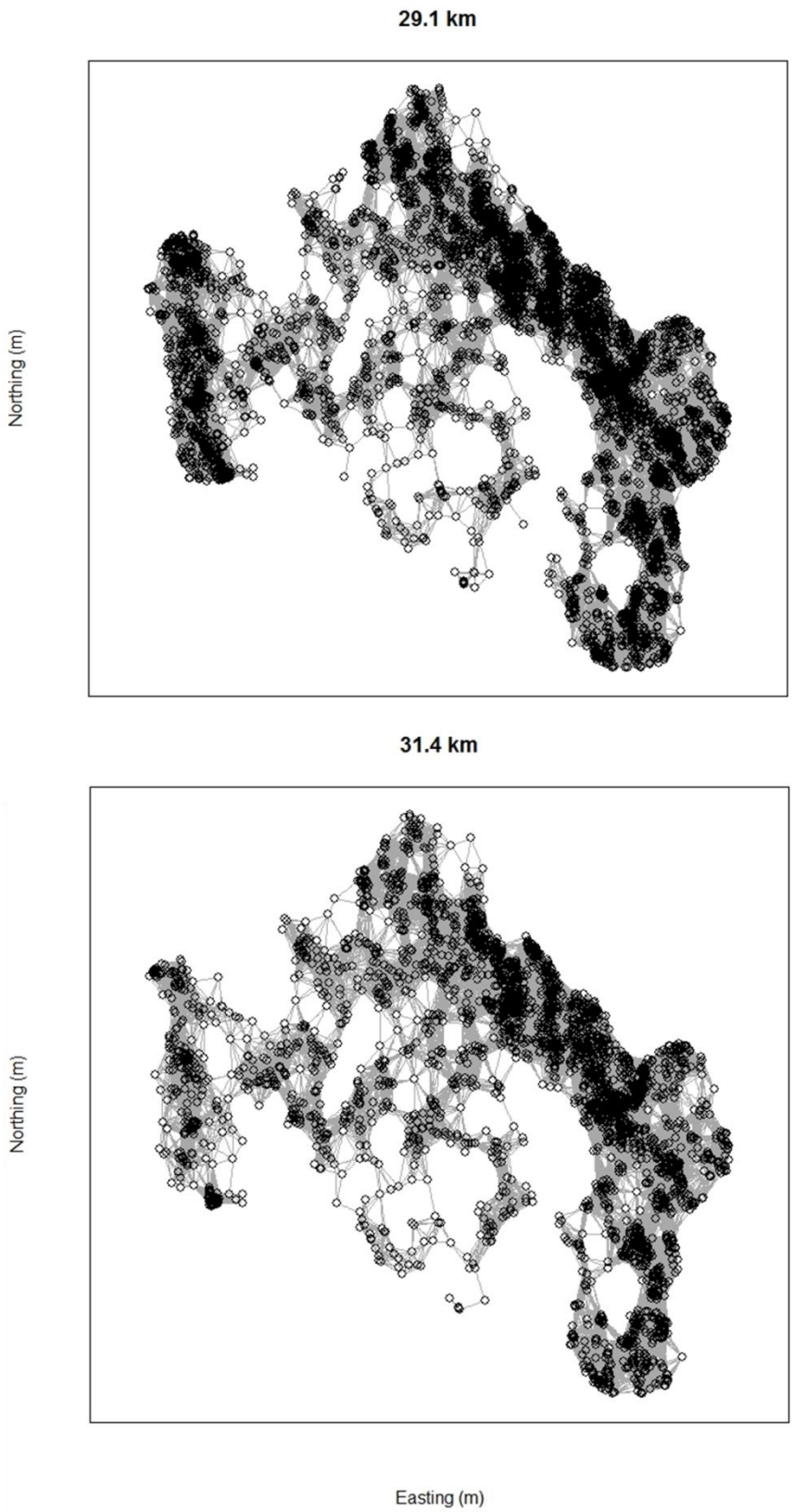


Figure 6. Critical distance of Sonoran Desert (29.1 km) at present day for all waters and for limited waters under a climate limited water site scenario (31.4 km). These scenarios are from graph theory cluster analysis of the U.S. Sonoran Desert. The current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters.

Current Condition Model

- Number of waters: 6214
- Critical distance: 29,100m
- Average path length: 11.76776 (average number of paths between waters)
- Graph density: 0.02884889
- Network modularity: –0.0002135

Climate Limited Waters Scenario

- Number of waters: 3558
- Critical distance: 31,400m
- Average path length: 9.636085 (average number of paths between waters)
- Graph density: 0.03550449
- Network modularity: –0.00041572

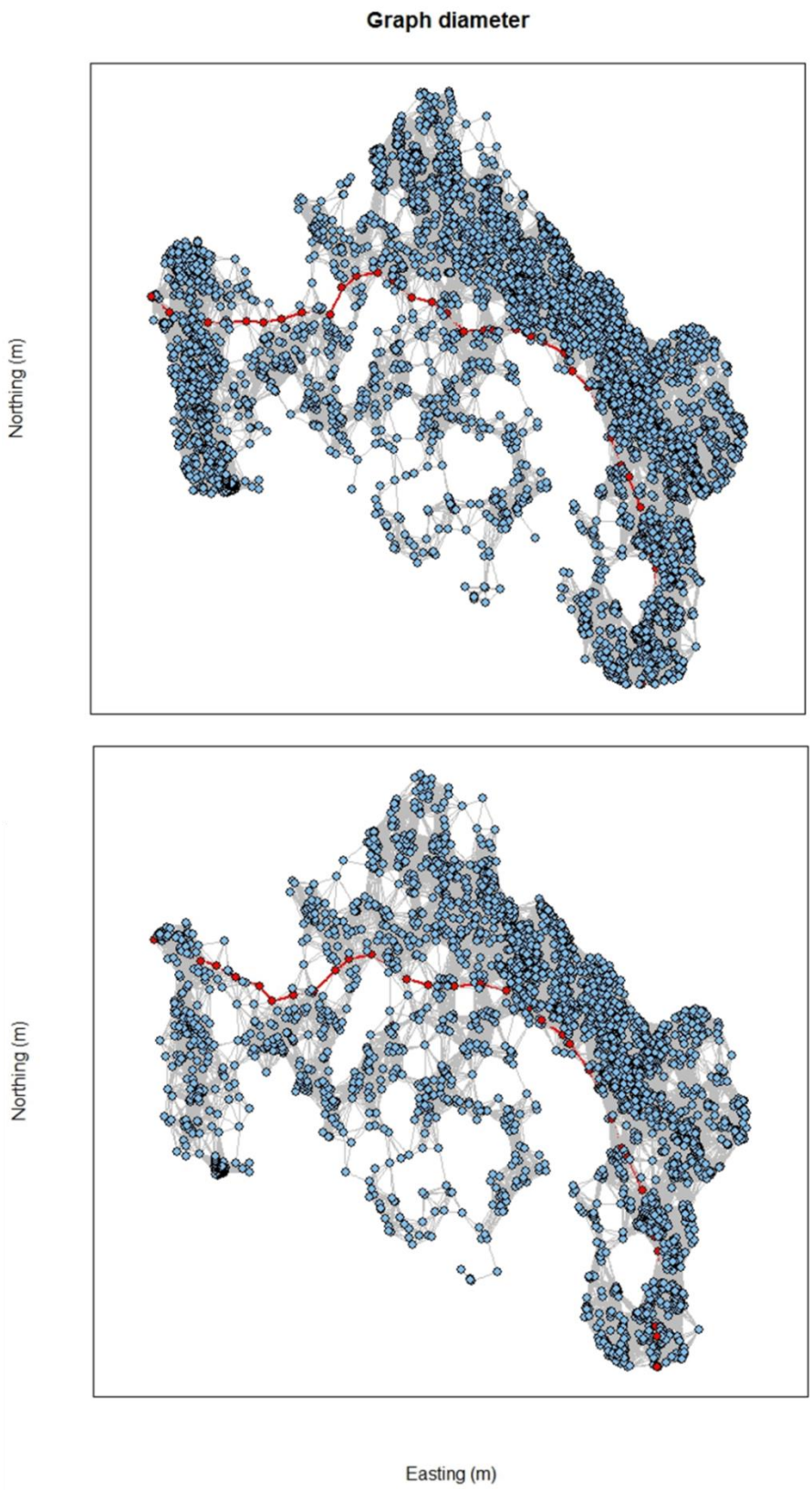


Figure 7. Graph diameter—which represents the longest direct path across the system—of the Sonoran Desert under current water site distribution (top) and under climate limited water site distribution scenarios (bottom) for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters.

Current Condition Scenario

- Graph diameter: 837,609.2 m

Climate Limited Waters Scenario

- Graph diameter: 816,068.3 m

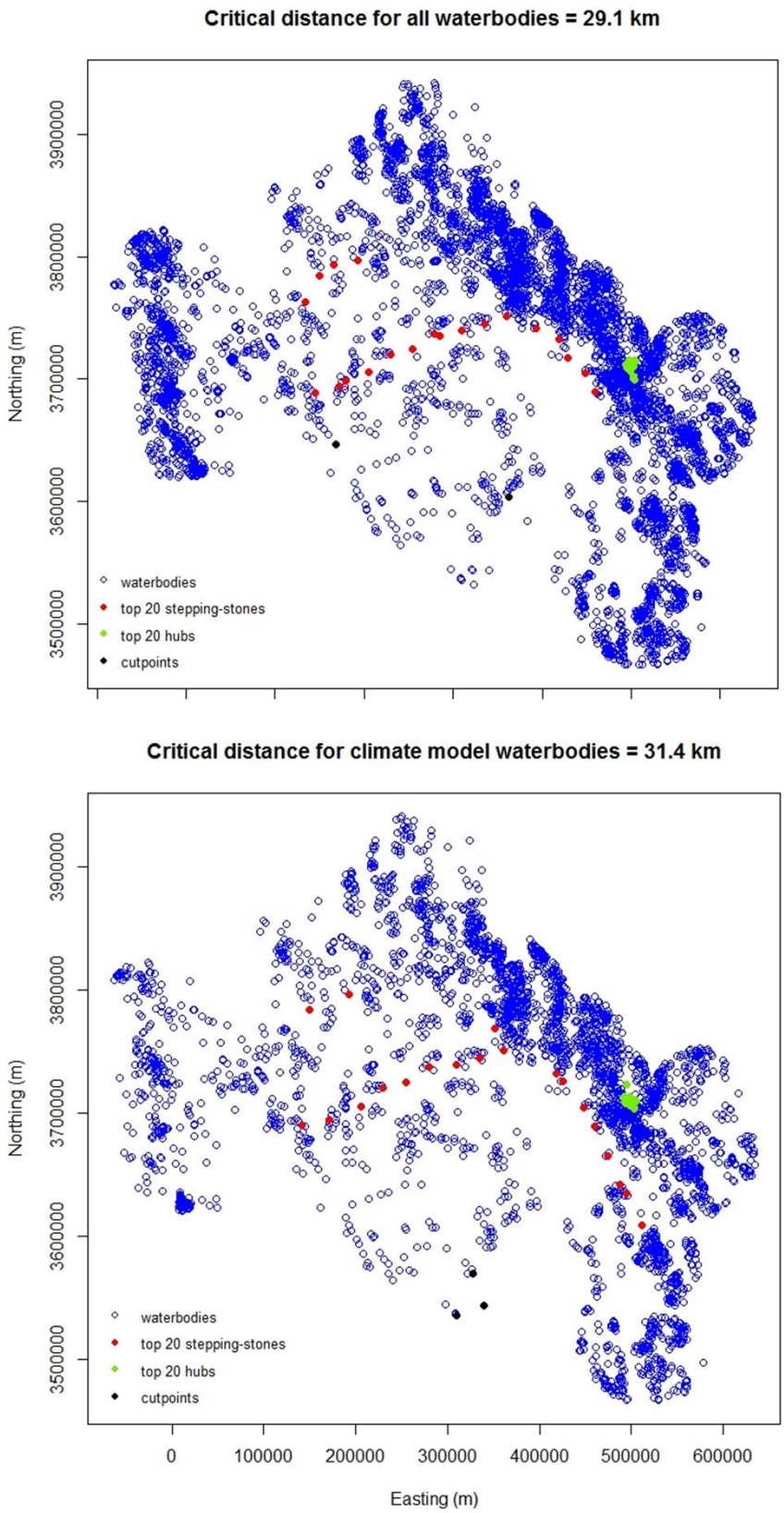


Figure 8. Top 20 stepping stones, top 20 hubs, and cutpoints for the Sonoran Desert Region for current conditions (top) and climate limited waters scenario (bottom). These scenarios are from graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters.

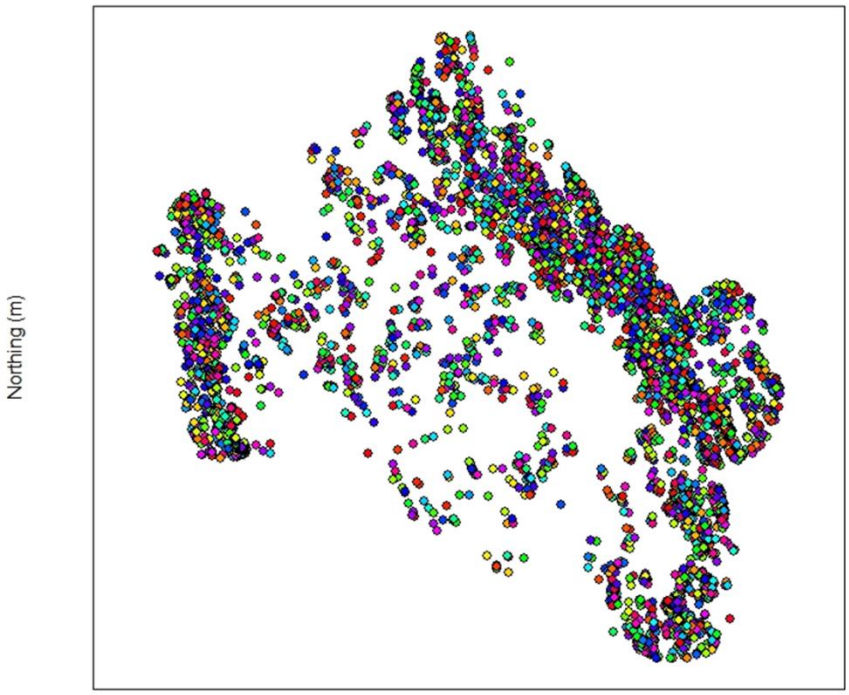
Current Condition Scenario

- See Appendix B for ranked list of stepping stones
- See Appendix B for ranked list of hubs
- See Appendix B for list of cutpoints

Climate Limited Waters Scenario

- See Appendix B for ranked list of stepping stones
- See Appendix B for ranked list of hubs
- See Appendix B for list of cutpoints

0.5 km



Climate limited waters scenario - 0.5 km

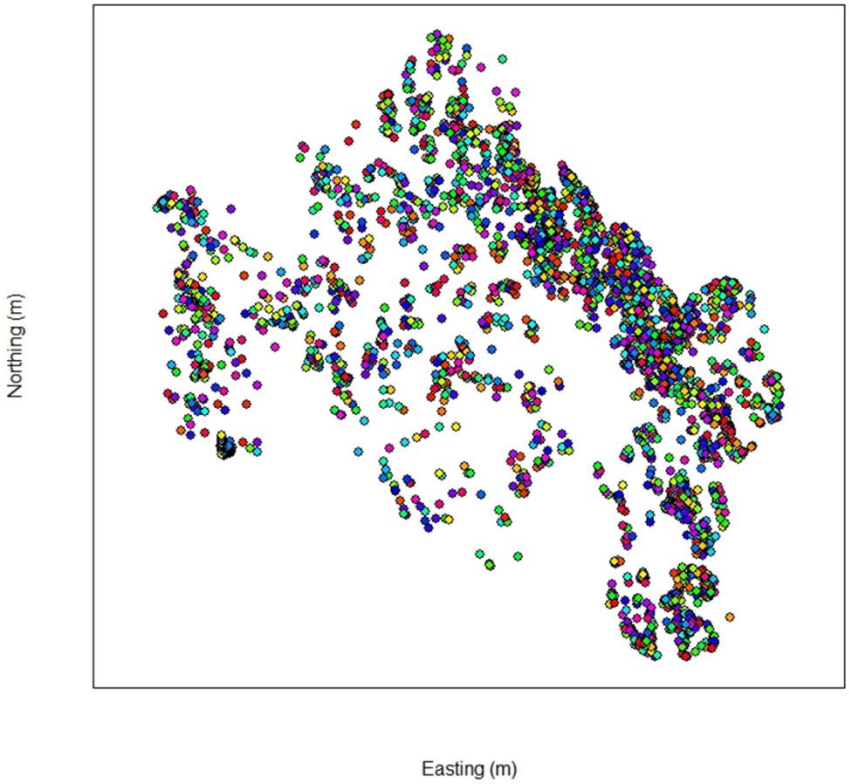


Figure 9. 0.5 km dispersal distance cluster graphs current (top) and climate limited water (bottom) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters. Colors represent clusters of connected waters and may be repeated.

Current Condition Scenario

- Total number of waters: 6214
- Number of clusters: 4547
- Mean Cluster Size: 1.182758
- Network Modularity: -0.00119273
- Longest Path: 1481.549m

Climate Limited Waters Scenario

- Total number of waters: 3558
- Number of clusters: 3353
- Mean Cluster Size: 1.061139
- Network Modularity: -0.00321867
- Longest Path: 1188.732m

1 km

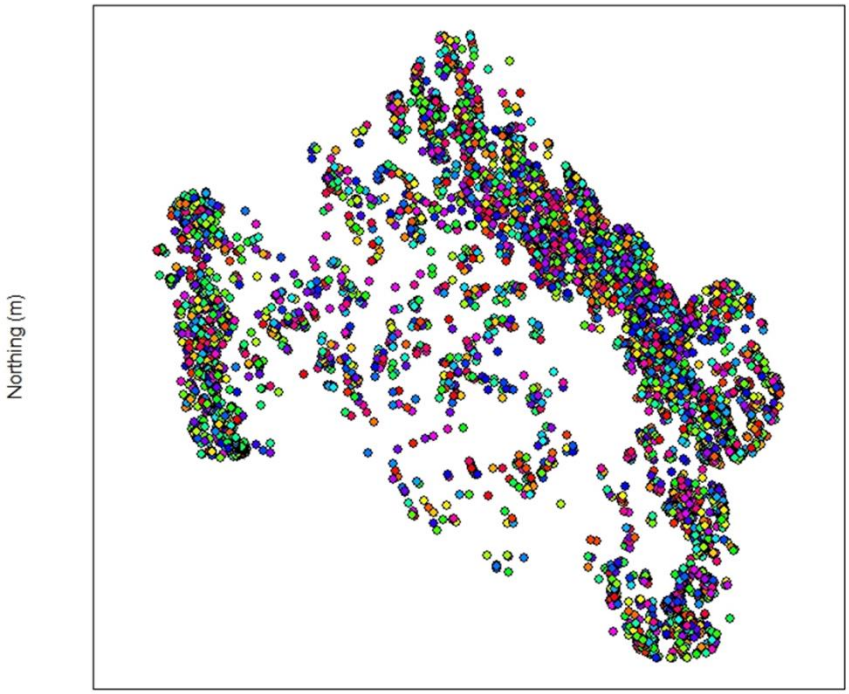
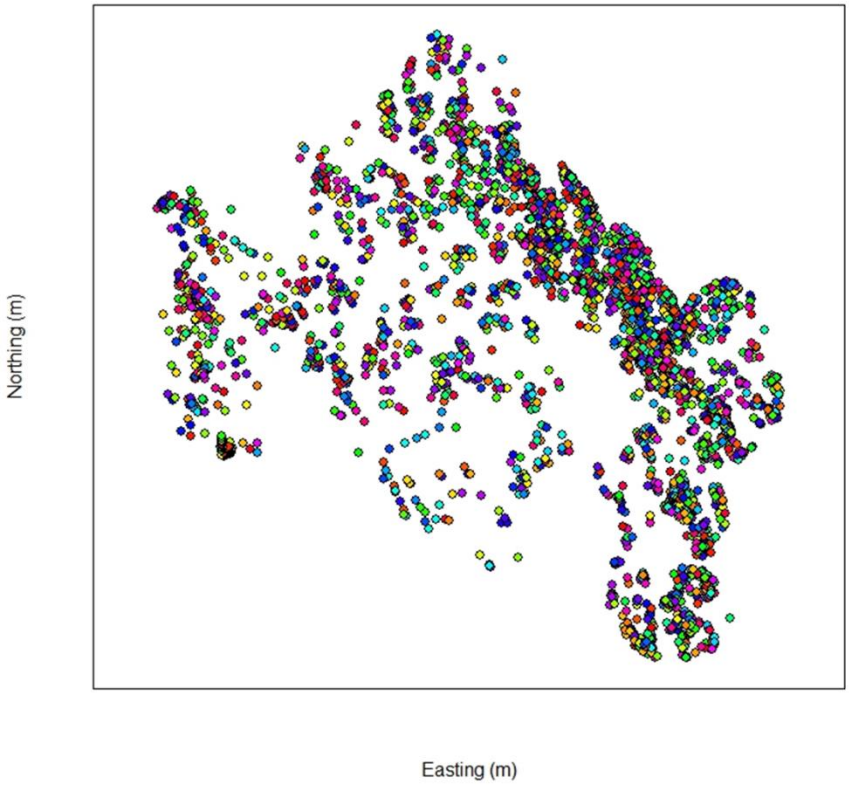


Figure 10. 1.0 km dispersal distance cluster graphs current (top) and climate limited water (bottom) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters. Colors represent clusters of connected waters and may be repeated.

Climate limited waters scenario - 1 km



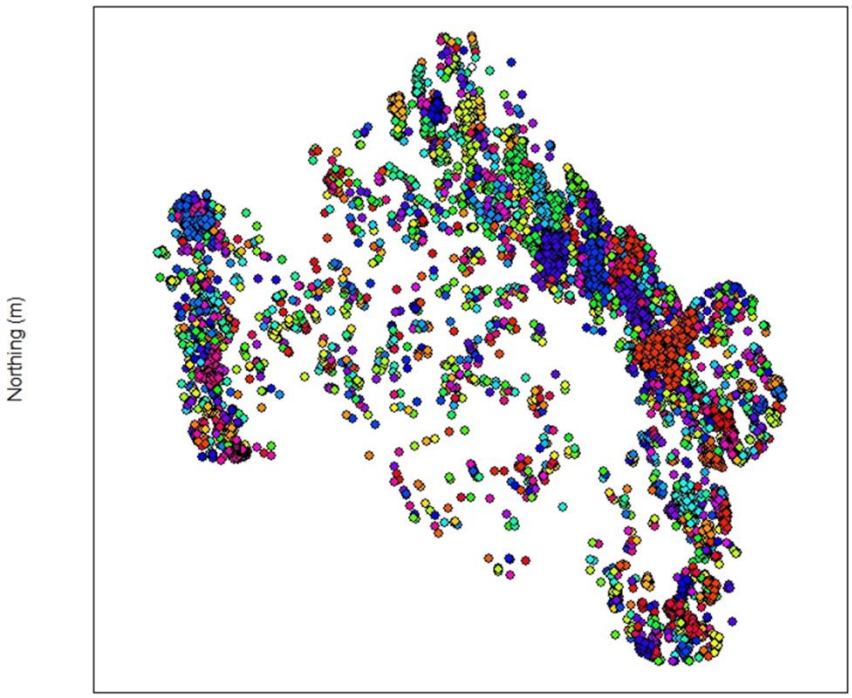
Current Condition Scenario

- Total number of waters: 6214
- Number of clusters: 3643
- Mean Cluster Size: 1.476256
- Network Modularity: -0.000640421
- Longest Path: 5216.304m

Climate Limited Waters Scenario

- Total number of waters: 3558
- Number of clusters: 2948
- Mean Cluster Size: 1.20692
- Network Modularity: -0.001293829
- Longest Path: 5588.711m

3 km



Climate limited waters scenario - 3 km

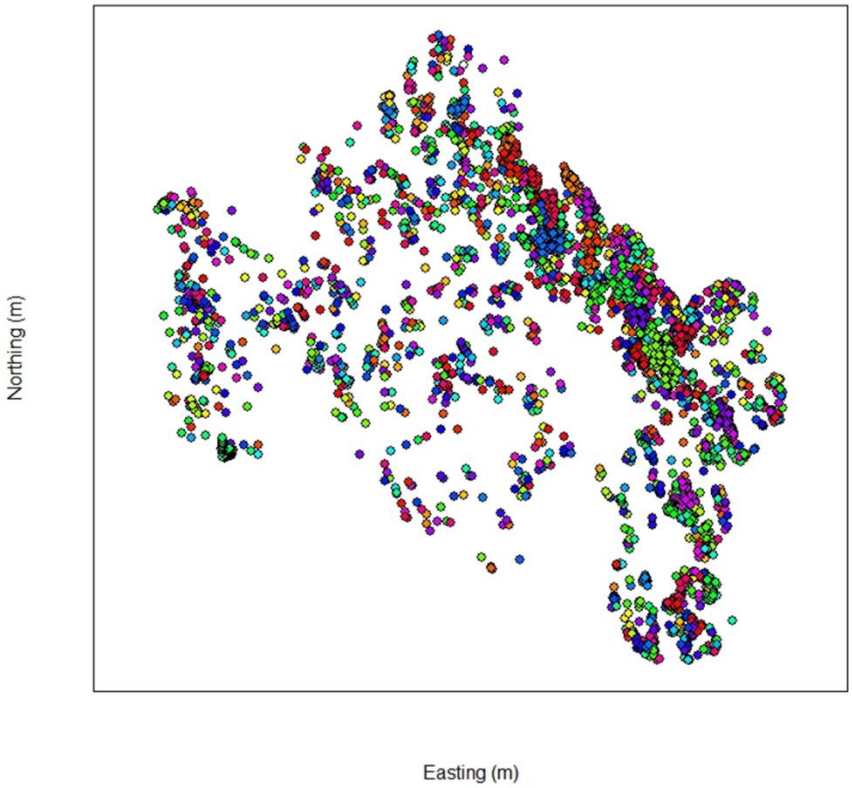


Figure 11. 3.0 km dispersal distance cluster graphs current (top) and climate limited water (bottom) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters. Colors represent clusters of connected waters and may be repeated.

Current Condition Scenario

- Total number of waters: 6214
- Number of clusters: 986
- Mean Cluster Size: 5.454361
- Network Modularity: -0.000308612
- Longest Path: 99465.26m

Climate Limited Waters Scenario

- Total number of waters: 3558
- Number of clusters: 1254
- Mean Cluster Size: 2.837321
- Network Modularity: -0.000602188
- Longest Path: 69028.52m

5 km

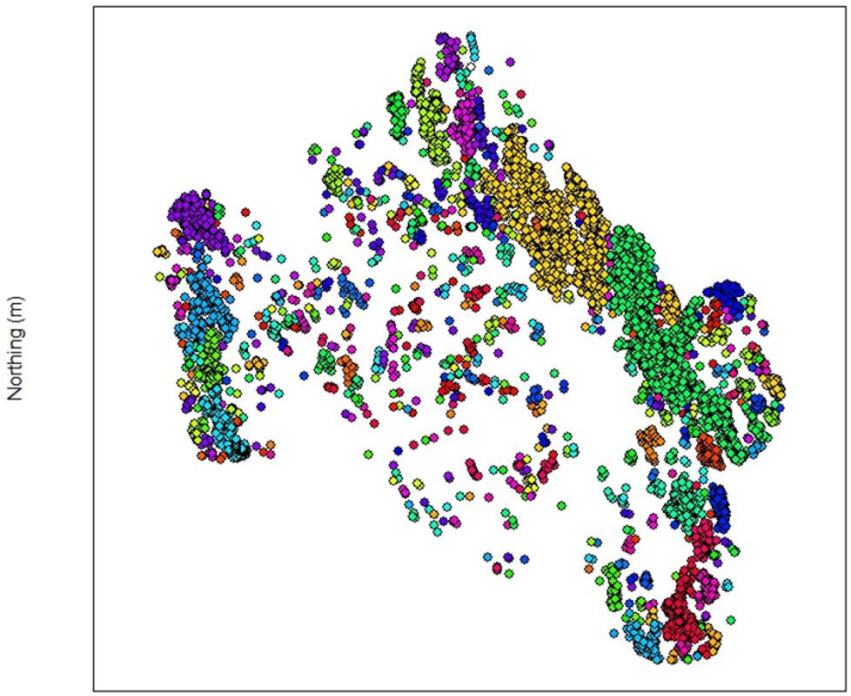
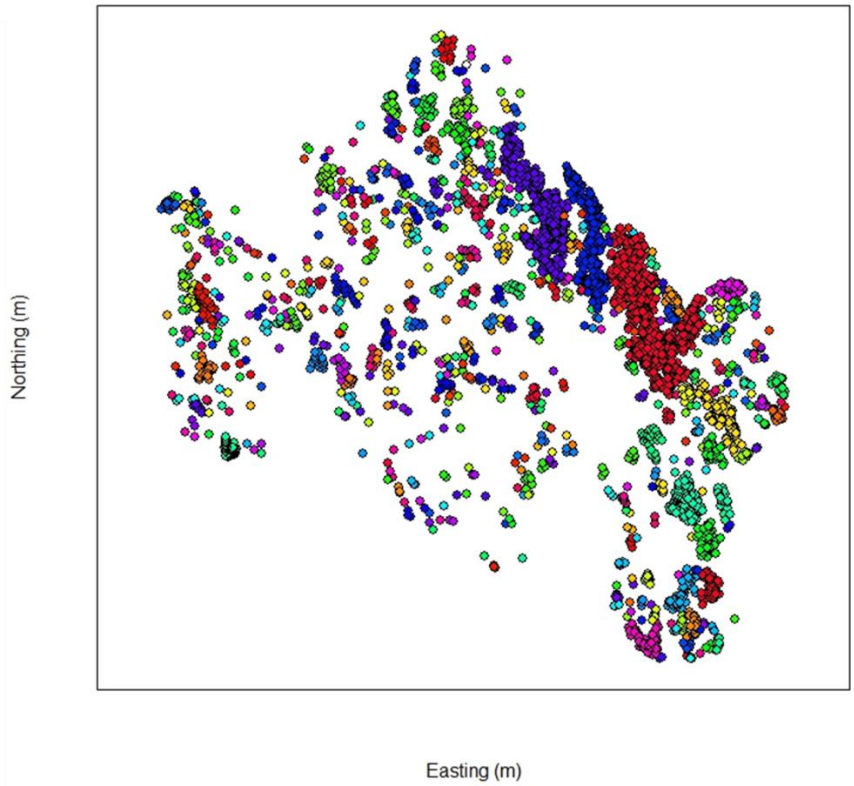


Figure 12. 5.0 km dispersal distance cluster graphs current (top) and climate limited water (bottom) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters. Colors represent clusters of connected waters and may be repeated.

Current Condition Scenario

- Total number of waters: 6214
- Number of clusters: 364
- Mean Cluster Size: 14.77473
- Network Modularity: -0.000277405
- Longest Path: 261,104.8m

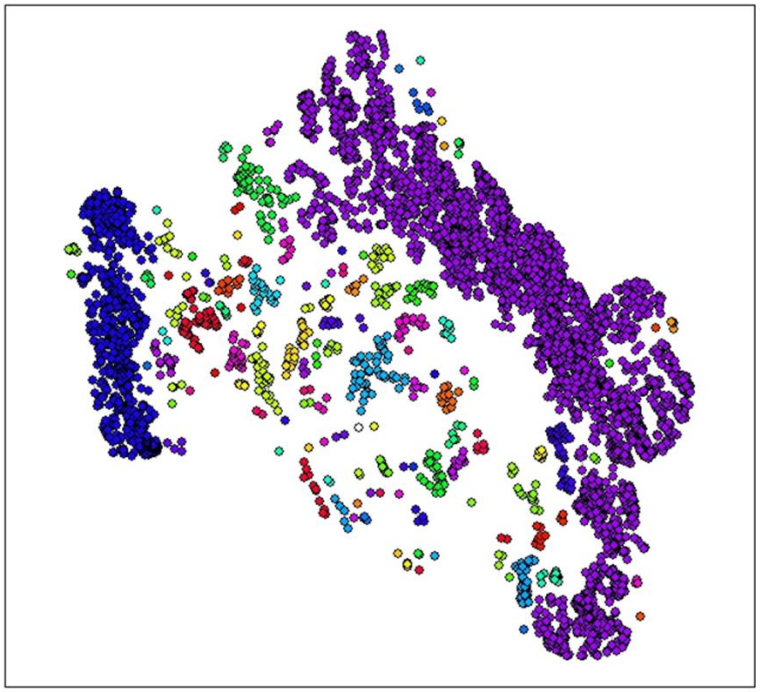
Climate limited waters scenario - 5 km



Climate Limited Waters Scenario

- Total number of waters: 3558
- Number of clusters: 577
- Mean Cluster Size: 6.166378
- Network Modularity: -0.000506115
- Longest Path: 185,676.4m

10 km



Climate limited waters scenario - 10 km

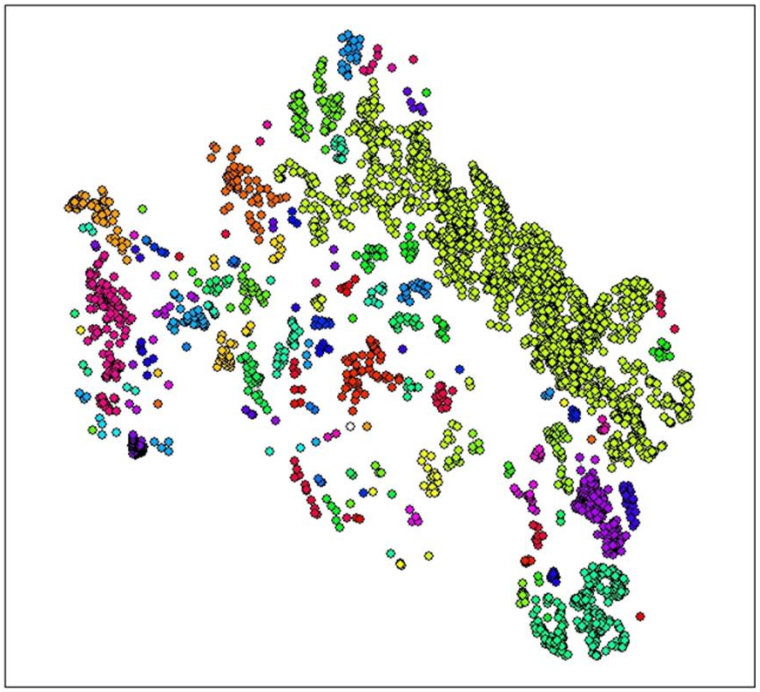


Figure 13. 10 km dispersal distance cluster graphs current (top) and climate limited water (bottom) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Current scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters. Colors represent clusters of connected waters and may be repeated.

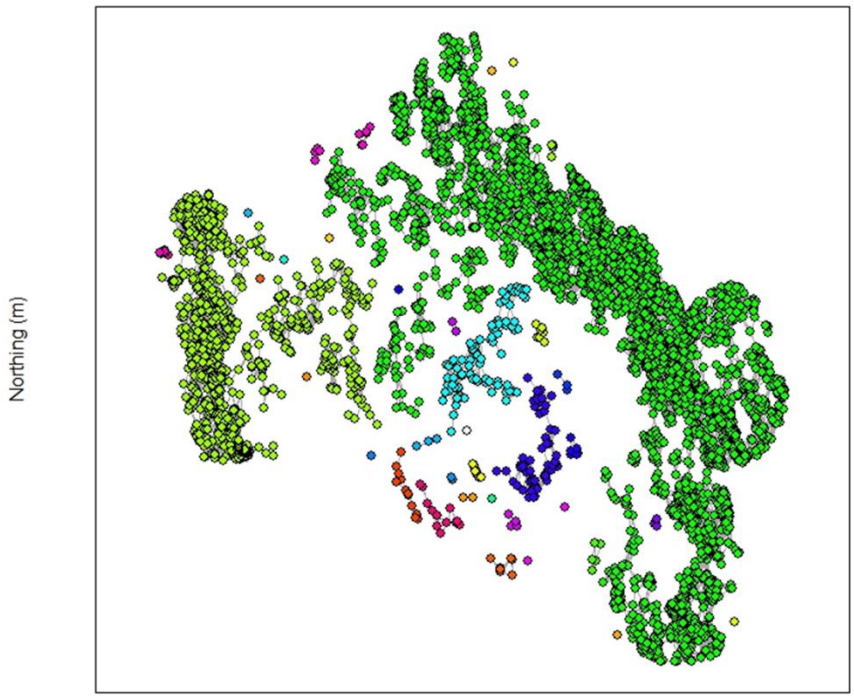
Current Condition Scenario

- Total number of waters: 6214
- Number of clusters: 105
- Mean Cluster Size: 51.21906
- Network Modularity: -000253635
- Longest Path: 592,328.1m

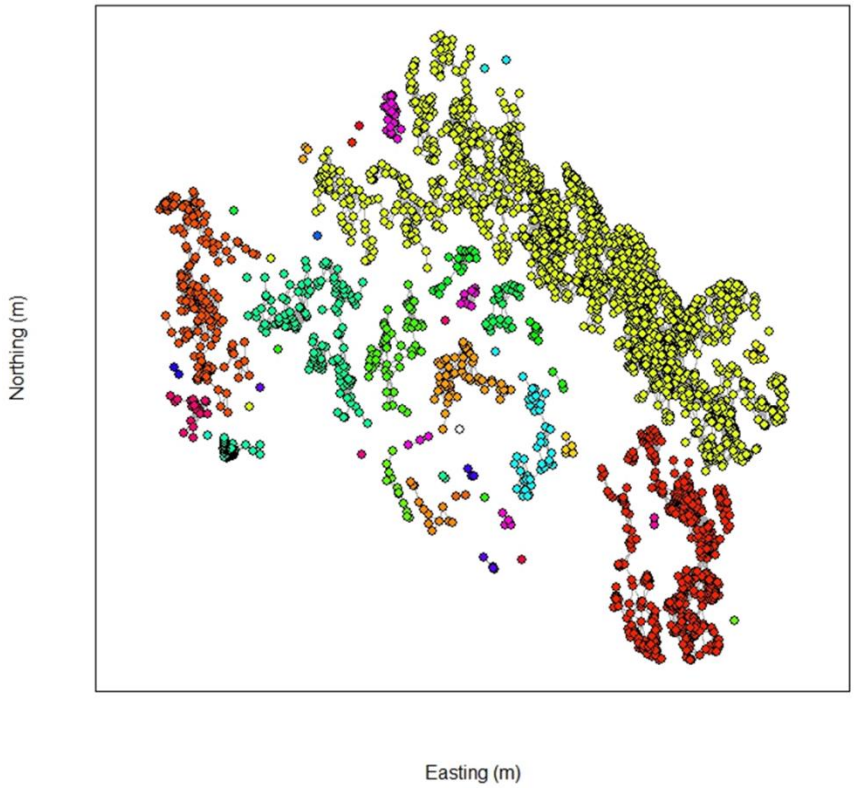
Climate Limited Waters Scenario

- Total number of waters: 3558
- Number of clusters: 147
- Mean Cluster Size: 24.20408
- Network Modularity: -000451552
- Longest Path: 594,767.4

15 km



Climate limited waters scenario - 15 km



- Network Modularity: -0.000441413
- Longest Path: 611,769.2m

Species Specific Results

Species specific results include a description of each species' distribution, habitat use, and spatial ecology information to help interpret connectivity results. Any notes on the special legal or population status known to the authors for the region are also listed. These brief notes on natural history and spatial patterns helps put the models in a biologically pertinent framework and the results into an understandable context. After these sections, the basis of each model will be discussed. Finally, the results of both structural analysis and functional analysis will be provided. These will consist mostly of figures derived from their respective analysis.

Graphs of structural results represent clusters of water sources available and connected to each other at a given dispersal distance. Results of current waters will be displayed alongside a future climate change scenario set of waters. Functional analysis results will be displayed as a resistance graph in context of geophysical location. Darker colors will represent areas that have more resistance for animal movement and lighter colors will represent the opposite. The resistance graph will be clipped to the extent of the Sonoran Desert as outlined by the BLM Sonoran Desert REA (Strittholt et al. 2012).

During analysis, a 32.2 km buffer was added around the spatial extent of the Sonoran Desert so that final figures could show results with the artifacts of edge effects from the analysis process. Even so, some edge effects appear around the edges of the Sonoran Desert even post clipping. These edge effects have been attempted to be rectified and when impossible to prevent, have been noted in the results.

A current functional resistance graph followed by the climate change scenario will be presented. The current functional graph will use the full suite of waters available with the land cover from the most recent National Land Cover Dataset (Jin et al. 2013). The climate change scenario will use the restricted list of waters from the structural waters climate scenario as well as a projected land cover dataset from the year 2050 for the IPCC emissions scenario A1B (Sohl & Sayler 2008; Sohl et al. 2014).

Colorado River Toad (*Incilius alverius*)

Distribution & Status: The Colorado River toad is distributed from the southwest corner of New Mexico across Southern Arizona into southeastern California and south into Mexico the state of Sinaloa Mexico and are known to occur from sea level to 1,600 m (Cole 1962) In New Mexico the toad is listed as threatened (Degenhardt et al. 1996), a *Species of Special Concern* (CDFW 2015), but is considered to have a healthy population in Arizona.

Figure 15. Colorado River Toad found during chorus on the Barry M. Goldwater Air Force Range. Photo credit: Jordan Calvert

Habitat & Spatial Ecology: This species inhabits primarily desert habitat, but can also be found in arid grasslands and woody riparian areas (Degenhardt et al. 1996). It is a semi-aquatic toad that uses temporary pools, seasonal wetlands, and anthropogenic waters such as stock tanks for breeding habitat. Little is known on home ranges; however, movements of up to 400 m during a single day have been recorded (Lannoo 2005), and with overland movement to breeding sites during rainy periods. An average of known maximum movement distances has been calculate to be approximately 6 km by Smith and Green (Smith & Green 2005).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.4, 3.0, and 6.0 km
- These represent daily movement, intermediate dispersal, and max known dispersal distances respectively.

Functional Model:

- These animals prefer desert and arid grassland lowlands when water is available.
- A heavy weight was given to the topographic position as the wet areas they prefer are more likely to occur in canyon bottoms
- The weighted equation also accounted for impacts of impermeable surfaces as a result of human development and roads
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.4 km) modeled for this species resulted in 38% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (6 km), the number of clusters increase by 6% under the climate limited water scenario
- The average number of waters per cluster decreased by 5% and 46% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Few clusters have more than 1 water within 0.4 km, a distance a toad would be expected to move to a breeding site.
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Colorado River Toads for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 5%; at maximum modeled dispersal distances the mean cluster size decreased by 46%. Under the climate limited water scenarios the max cluster size is nearly a third of the current size (Table 7), suggesting isolation of populations. Circuit theory results show that current resistances for the Colorado River Toad are lowest along river drainages and in the wetter areas of the Sonoran Desert near the arid grasslands to the northeast and slowly becoming more resistant as streams, waters, and high quality habitat becomes more scarce toward drier regions of the desert. The projected resistances for the year 2050 show that areas around the Gila River, the Santa Cruz River, the Salt River and even the Colorado River will have much increased resistances between water bodies in addition to fewer waters within clusters, making longer distance dispersal events less likely. At the max known dispersal distance of 6 km, mean cluster size under the climate limited water scenario is reduced to just over half of current mean cluster size and max cluster size is reduced to nearly a third of original size (Table 7).

Table 7. Colorado River Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.4 km	3 km	6 km	0.4 km	3 km	6 km

Diameter (meters)	910.9	99465.3	455236.8	910.9	69028.5	265549.8
Clusters	5516	1414	407	3420	1254	433
Mean Cluster Size	1.1	4.4	15.3	1.04	2.837	8.2
Max Cluster Size	14	432	2678	5	193	907
Network Modularity	-0.0013	-0.00029	-0.00025	-0.0045	-0.000602	-0.00049

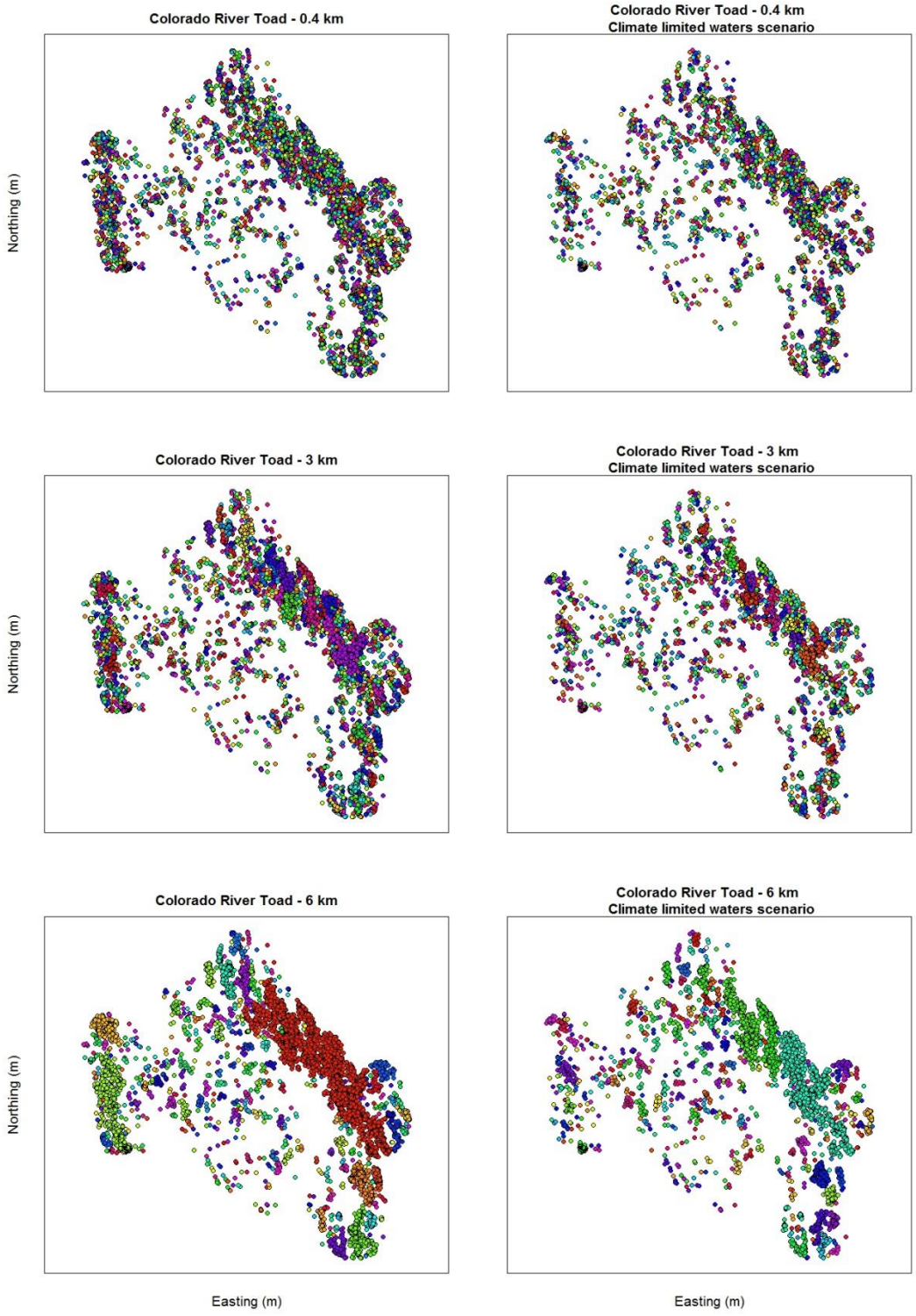


Figure 16. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Colorado River Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

Potential Resistances for the Colorado River Toad

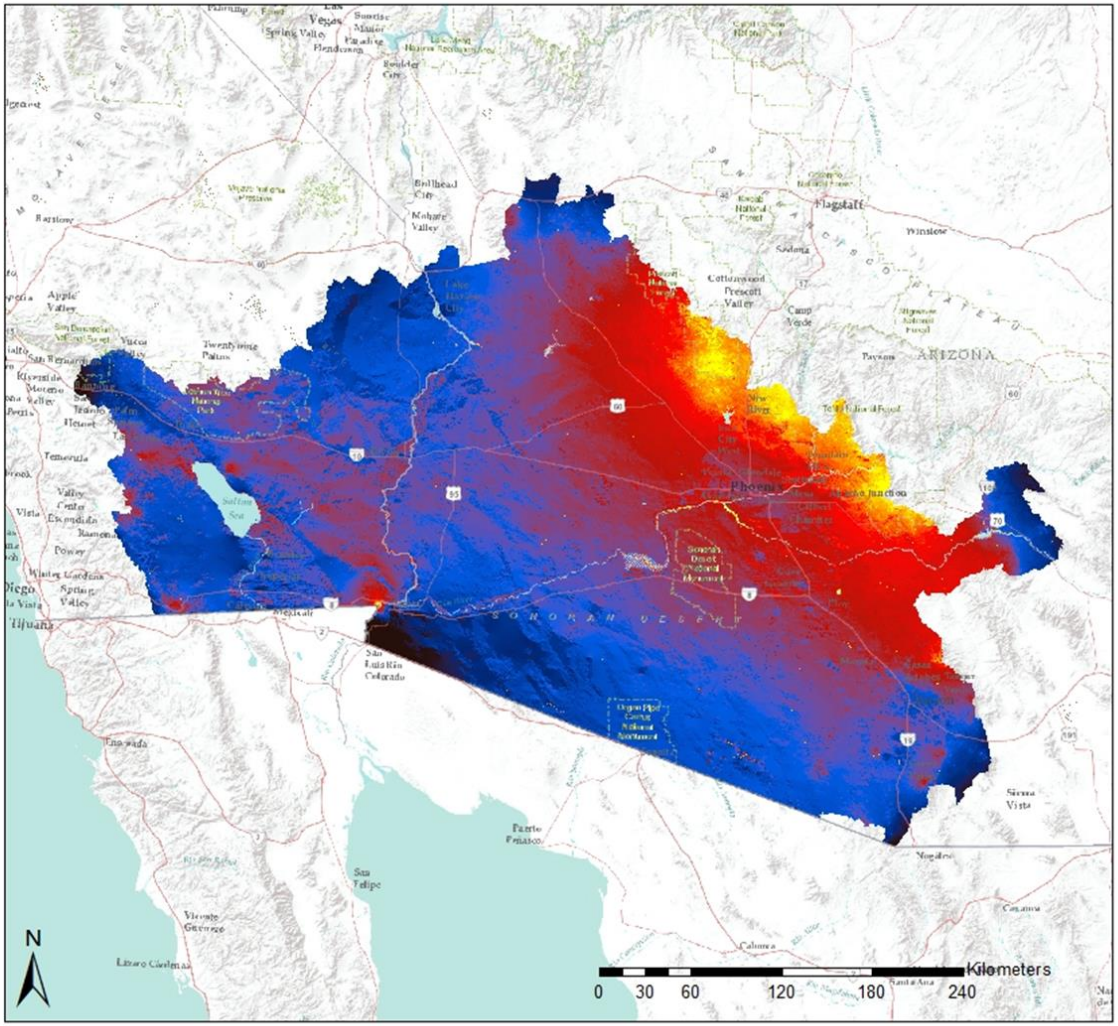


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Figure 17. Potential resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Note the reduced resistances around higher elevation areas and river valleys as well as a gradual increase of resistances as you move into the drier reaches of the Sonoran Desert in the southwestern section near the Mexican border.

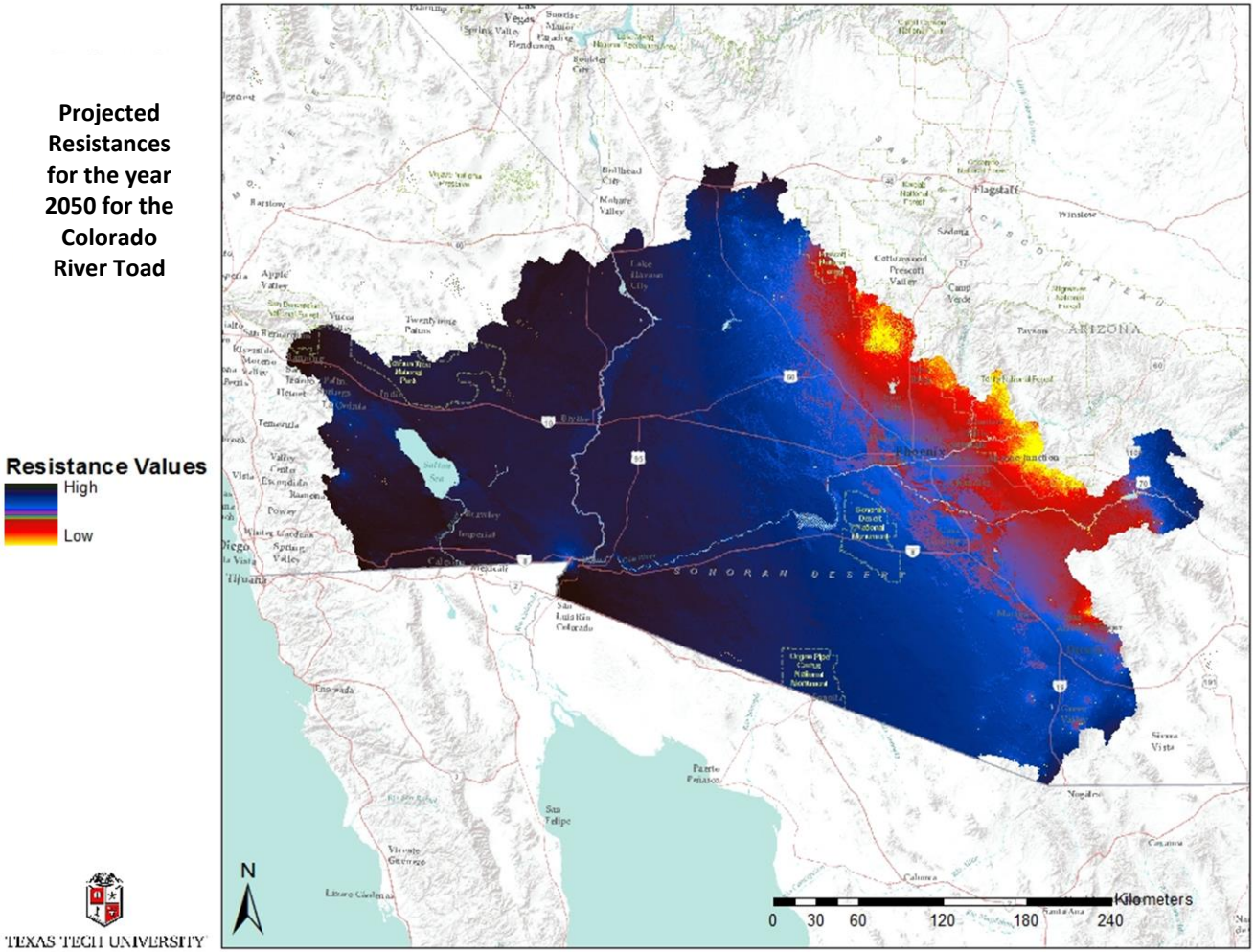

Figure 18. Projected resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Lower resistance areas much reduced compared to current land use scenarios as vegetation regimes shift northward and natural waters are reduced in number across the desert.

American Bullfrog (*Lithobates catesbeianus*)

Figure 19. American Bullfrog. Photo by: Carl D. Howe, Stow, MA, USA CC BY-SA 2.5

Distribution & Status: Native to the eastern United States, the American Bullfrog has now spread or been introduced to at least 4 continents (Ficetola et al. 2007). Non-native to the southwestern states, the bullfrog was introduced to the Sonoran region in the early 20th century by state agencies to provide recreational and hunting opportunities (Tellman 2002). Now considered an invasive species (Schwalbe & Rosen 1999), it has been implicated in the decline of several animals (Rosen & Schwalbe 1994; Schwalbe & Rosen 1988) including a federally listed species, the threatened Chiricahua leopard frog (USFWS 2002a). Areas of introduction have seen large increases in bullfrog density (Lannoo 2005). They are known to occur from sea level upwards to 2,740 m (9,000 ft) (Stebbins 2003). This species is also considered to be a vector of *Batrachochtrium dendrobatidis*, a fungus lethal to many native amphibians (Daszak et al. 2004; Hanselmann et al. 2004).

Habitat & Spatial Ecology: Adult bullfrogs prefer warmer and more lentic permanent waters (Wang & Li 2009). They are able to inhabit anthropogenic waters in the Sonoran Desert as they tend to more resemble bullfrog's native habitat than available natural waters in the Sonoran Desert (Hayes & Jennings 1986). Occupying shorelines of streams and lakes, backwaters, ponds and marshes, and reservoirs adults will breed in vegetation in permanent waters (Lannoo 2005). Bullfrogs will move during rainy nights for breeding (Lannoo 2005) and during drought (Jameson 1956) and their movements tend to be considerably larger than that traveled by the average amphibian (Smith & Green 2005). Records of bullfrog movement of a variety of distances across a variety terrain are available (Table 8). There is evidence to suggest that they can disperse upwards of 10 km across arid grasslands (Kahrs 2006).

Model Basis:

Structural Model:

- Modeled dispersal distances of 2.0 km, 10.0 km, and 15.0 km
- These represent daily movement capabilities, maximum known dispersal distances, and a probable beyond maximum known dispersal scenario to use for conservation purposes.

Functional Model:

- These animals are habitat generalists but only establish in areas with permanent water.
- Can use temporary waters for dispersal
- A heavy weight was also given to the topographic position as the wet areas they prefer are more likely to occur in canyon bottoms and in flats
- The weighted equation included lower negative impacts of human developments that potentially provide habitat.
- See Appendix A for weighted resistance equation and resistance values

Table 8. The various distances of American bullfrogs (*Lithobates catesbeianus*) have been found away from water sources or the distance of observed travel for bullfrogs.

Study Distance	Meters	Type
6.8 miles[1]	10,944	Across open grassland
5 miles[2]	8047	Anecdotal dispersal
2 miles[2]	3219	From home pond
2 km[3]	2000	Distance from known population
5250 feet[4]	1600	Along water corridor
1 km[5]	1000	Overland travel

[1](Kahrs 2006); [2](Schwalbe & Rosen 1999); [3](Rosen & Schwalbe 1994); [4](Ingram & Raney 1943); [5](Snow & Witmer 2010)

Results & Discussion:

Synopsis**:**

- Daily movement distance (2 km) modeled for this species resulted in 22% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (15 km), the number of clusters increased fragmentation by 30% under the climate limited water scenario
- The average number of waters per cluster decreased by 28% and 56% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- The American Bullfrog is much more capable of long distance movements than most if not all native species of the Sonoran Desert.
- At longest known dispersal distance (10 km), bullfrogs could access nearly 72% of the water sites in the Sonoran Desert based on currently known locations
- The mean cluster size per dispersal distance is smaller in the climate limited waters scenario than the current scenario, possibly limiting spread of bullfrog.

- Anthropogenically added waters could allow the bullfrog dispersal to isolated clusters of wetlands.
- The bullfrog is most likely to remain in perennial waters at mid to higher elevations and near suburban, agricultural, and light urban developments due to lower resistances in these areas.

Being a habitat generalist, the bullfrog has the capacity to use many types of waters and habitat for dispersal. At the 2 km distance for daily movement, bullfrogs have a 28% reduction of mean cluster size in the climate limited water scenario (Table 9). The bullfrog is able to disperse successfully across a variety of habitats and has been documented moving up to 10 km. In the current waters scenario the bullfrog has access to almost 72% of the isolated waters across the Sonoran Desert as they are already present in this large cluster of wetlands. Accidently placing a new anthropogenic catchment in the wrong place can provide new dispersal routes into currently isolated clusters of water sites. Bullfrogs need perennial water for successful reproduction and catchments could provide this habitat in otherwise unsuitable terrain. Our functional analysis shows a heavy reliance on perennial reservoirs and rivers. These types of waters are often stocked with non-native sport fish which avoid bullfrog tadpoles because of toxins excreted by their skin in favor of native species. As land cover changes and water sites are reduced due to climatic factors, the bullfrog has more resistance to movement in much of the Sonoran Desert, particularly in the driest sections in the southwestern part of the desert. However, cities and surrounding agricultural areas can still provide favorable habitat with low resistance to movement. The lowest projected landscape resistance is found in areas where spring density is highest, northeast towards the Mogollon Rim and higher elevations. As climate change removes more waters for native species, it is also removing possible dispersal routes for the bullfrog. This is not a solution to bullfrog invasion as native species are not as well equipped for dispersal as the bullfrog.

Table 9. American Bullfrog structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed isolated waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	2 km	10 km	15 km	2 km	10 km	15 km
Diameter (meters)	27538.1	700614	866368.2	27691.2	594767.4	611769.2
Clusters	2502	128	37	1944	147	48
Mean Cluster Size	2.5	48.6	167.9	1.8	24.2	74.1
Max Cluster Size	88	4454	4796	59	2035	2228
Network Modularity	-0.00034	-0.00023	-0.00022	-0.00074	-0.00045	-0.00044

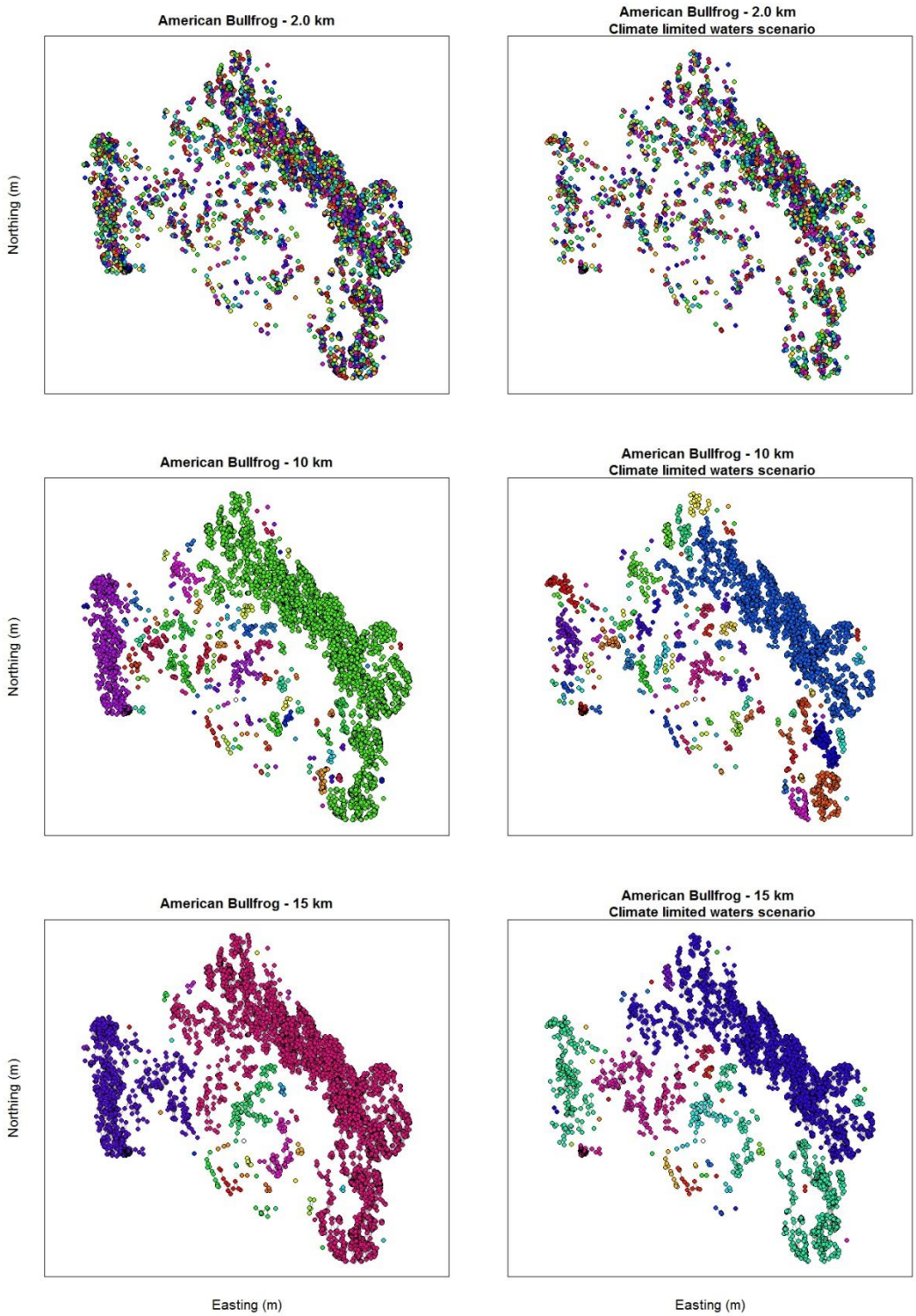

Figure 20. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for American Bullfrog. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the outer sections of the graph where the majority of historic bullfrog observations have occurred.

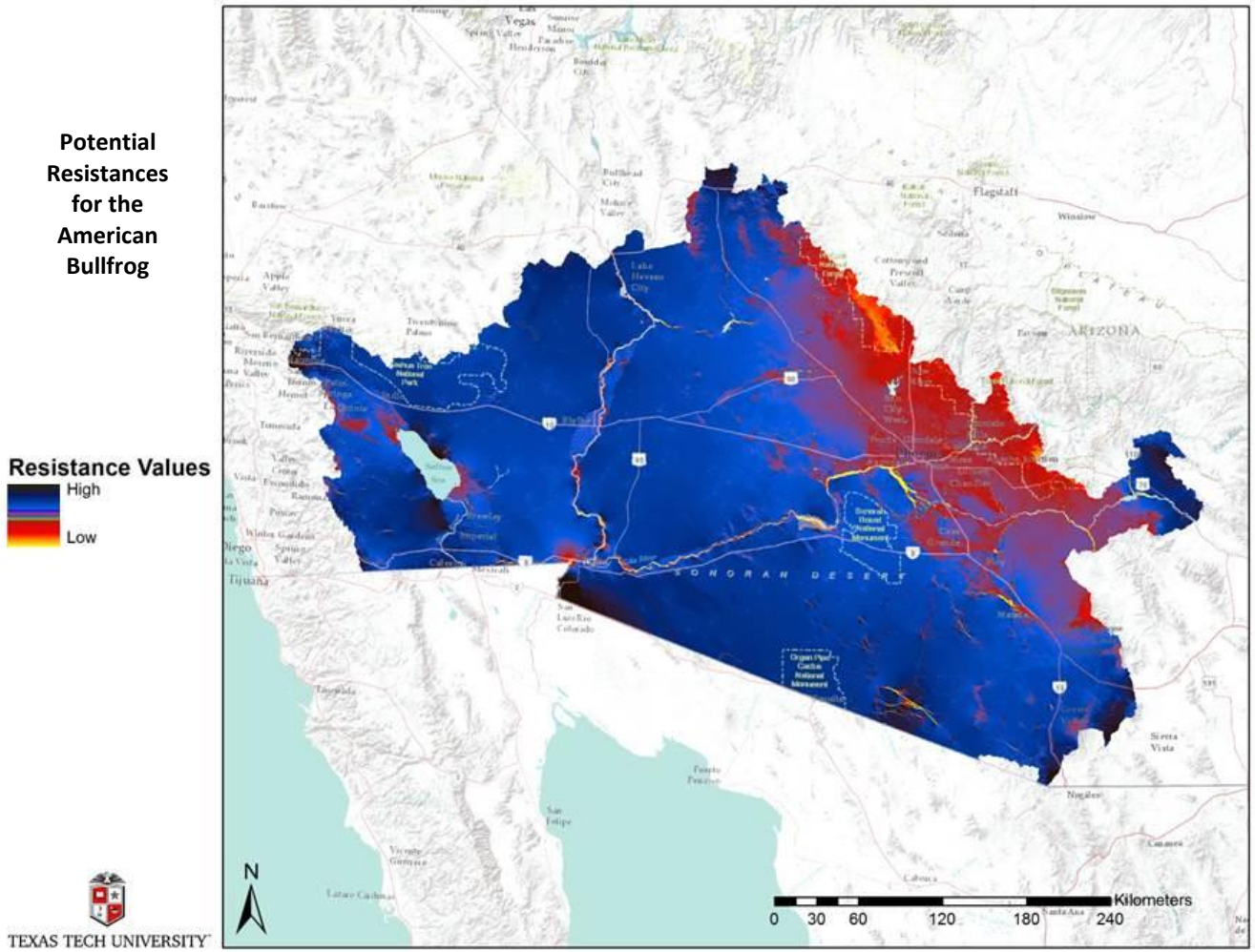

Figure 21. Potential resistances for the American Bullfrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Lowest resistances occur most frequently in the Colorado River, Gila River, and Salt River as well as near the northeastern border of the map because of the density of water sites.

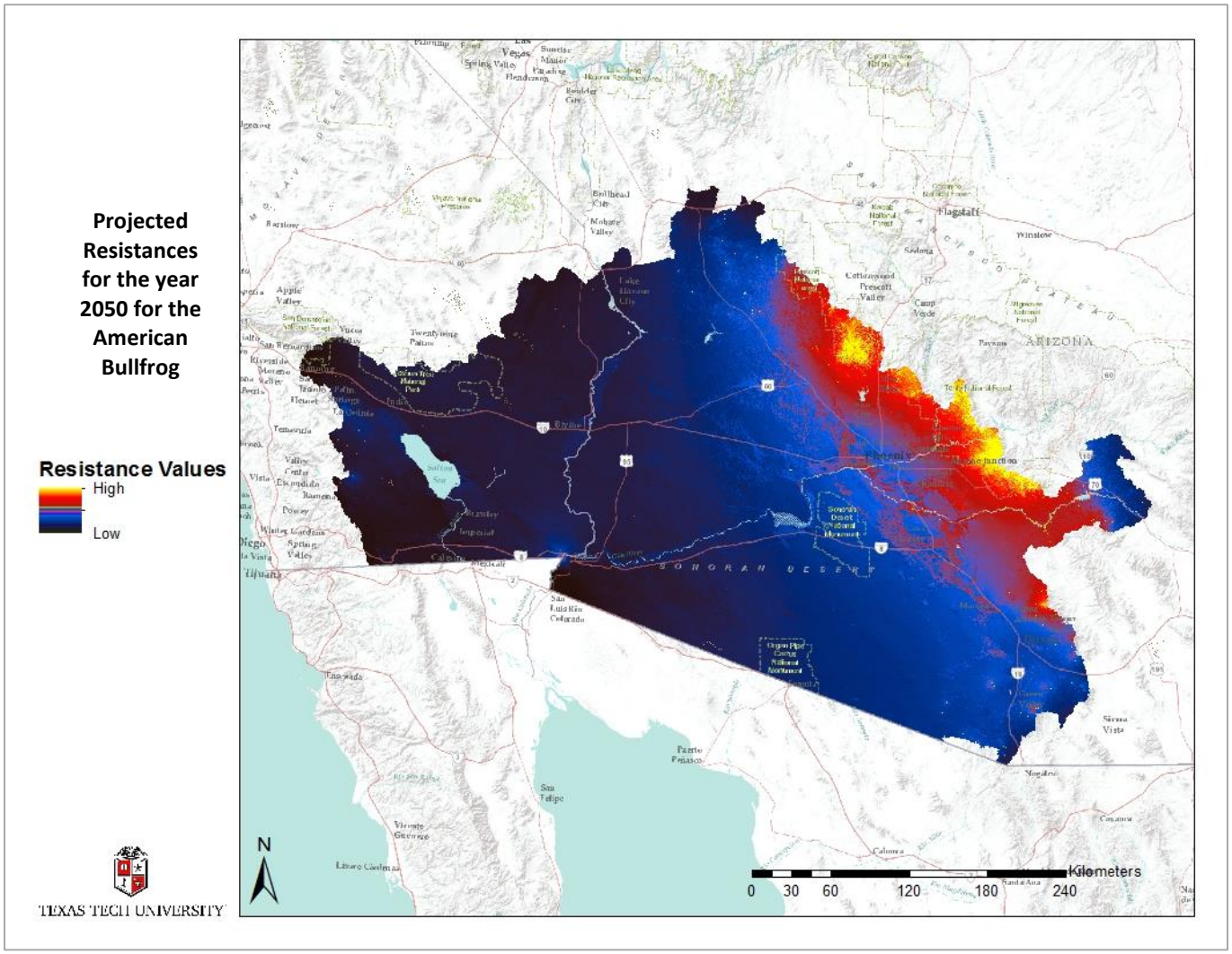

Figure 22. Projected resistances for American Bullfrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Agricultural lands, suburban developments, and perennial waters (springs, rivers, and reservoirs) have the lowest projected resistance values. The areas near the Mogollon Rim and near agricultural lands will be the most likely to support bullfrog populations.

Chiricahua Leopard Frog (*Lithobates chiricahuensis*)

Figure 23. Chiricahua Leopard Frog in the Coconino National Forest, AZ. Photo by: Jim Rorabaugh/USFWS CC BY 2.0

Distribution & Status: Known to occur in Arizona, New Mexico, and Mexico, the Chiricahua Leopard Frog's range is generally divided into two areas: a southern group in the Gila River drainages and sky islands of southeastern Arizona, southwestern New Mexico, and northern Mexico (Lannoo 2005) and a northern group along the Mogollon Rim (Degenhardt et al. 1996) at elevations between 1,000 m and 2,700 m (Platz & Mecham 1979). The species is in decline across its known territory (Degenhardt et al. 1996; Lannoo 2005) and has been federally listed as threatened (USFWS 2002a). It is now limited in the United States to springs, stock tanks, and other headwater areas free of invasive bullfrogs and other invasive predators (Rosen & Schwalbe 1994; Schwalbe & Rosen 1988; USFWS 2012).

Habitat & Spatial Ecology: The Chiricahua Leopard Frog is a habitat generalist and is often in a wide variety of aquatic habitats including seeps, springs, stock tanks, intermittent creeks, and perennial streams (Degenhardt et al. 1996). This species breeds aquatically in a wide variety of natural and anthropogenic waters (Lannoo 2005), although It prefer waters that do not contain fish. The species can move distances of 3.5 km over short time periods (Sredl & Jennings 2005) and have expanded ranges as far as 12 km per year (Rosen & Schwalbe 1995)., but it is not known if migrations occur for breeding (Lannoo 2005).

Model Basis:

Structural Model:

- Modeled dispersal distances of 3.5, 5.0, and 12.0 km
- These represent maximum unidirectional movement, movement over intermittent wet terrain, and max known yearly dispersal distances for leopard frogs respectively.

Functional Model:

- This species is a habitat generalist using available waters devoid of non-native predators
- More weight was given to land cover variables to account for preferences towards areas with emergent and herbaceous wetlands

- The weighted equation accounted for negative impacts of human developments that can remove habitat or hold non-native aquatic predators
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (3.5 km) modeled for this species resulted in 9% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (12 km), the number of clusters increased by 9% under the climate limited water scenario
- The average number of waters per cluster decreased by 38% and 47% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Managed waters could be important for species persistence in the southern population as reduced precipitation deprives the sky islands of snow melt and rain to feed streams.
- The Chiricahua Leopard Frog is one of the most capable native dispersers in the Sonoran Desert, but much of its range has been restricted by invasive species and habitat loss
- Resistance to movement between water sites and known habitat will increase in the future

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Chiricahua Leopard Frog for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 38%; at maximum modeled dispersal distances the mean cluster size decreased by 47%. The Chiricahua Leopard Frog should be able to access much of its historic habitat, but is limited by invasive species like the American Bullfrog. At its known maximum unidirectional movement (3.5 km), under climate limited water scenario, maximum cluster size reduced 31%. By the year 2050, the Chiricahua leopard frog will have a harder time dispersing. At intermediate dispersal distances (5 km), this species could access much of its original habitat given favorable circumstances and removal of invasive species, but climate change will make that harder to do as waters become limited and resistance of the landscape increase between isolated waters. The Chiricahua Leopard Frog has lowest resistances where densities of waters are highest, such as areas near the Mogollon Rim area and in areas near sky islands. Bullfrog occurrence effectively prevents the species from using the terrain, thus increasing landscape resistance in those areas. Functional connectivity is reduced in the 2050 projected scenario as

water sites are limited and vegetation shifts upslope and northward (Figure 26). The areas of lowest resistance will still be in areas of high spring density near the Mogollon Rim populations.

Table 10. Chiricahua Leopard Frog structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	3.5 km	5 km	12 km	3.5 km	5 km	12 km
Diameter (meters)	202922.4	257111.4	669308.7	86187.2	185676.4	569012.4
Clusters	1105	572	87	1009	577	95
Mean Cluster Size	5.6	10.9	71.4	3.5	6.2	37.5
Max Cluster Size	789	1238	4463	244	680	2141
Network Modularity	-0.00028	-0.00026	-0.00023	-0.00057	-0.00051	-0.00045

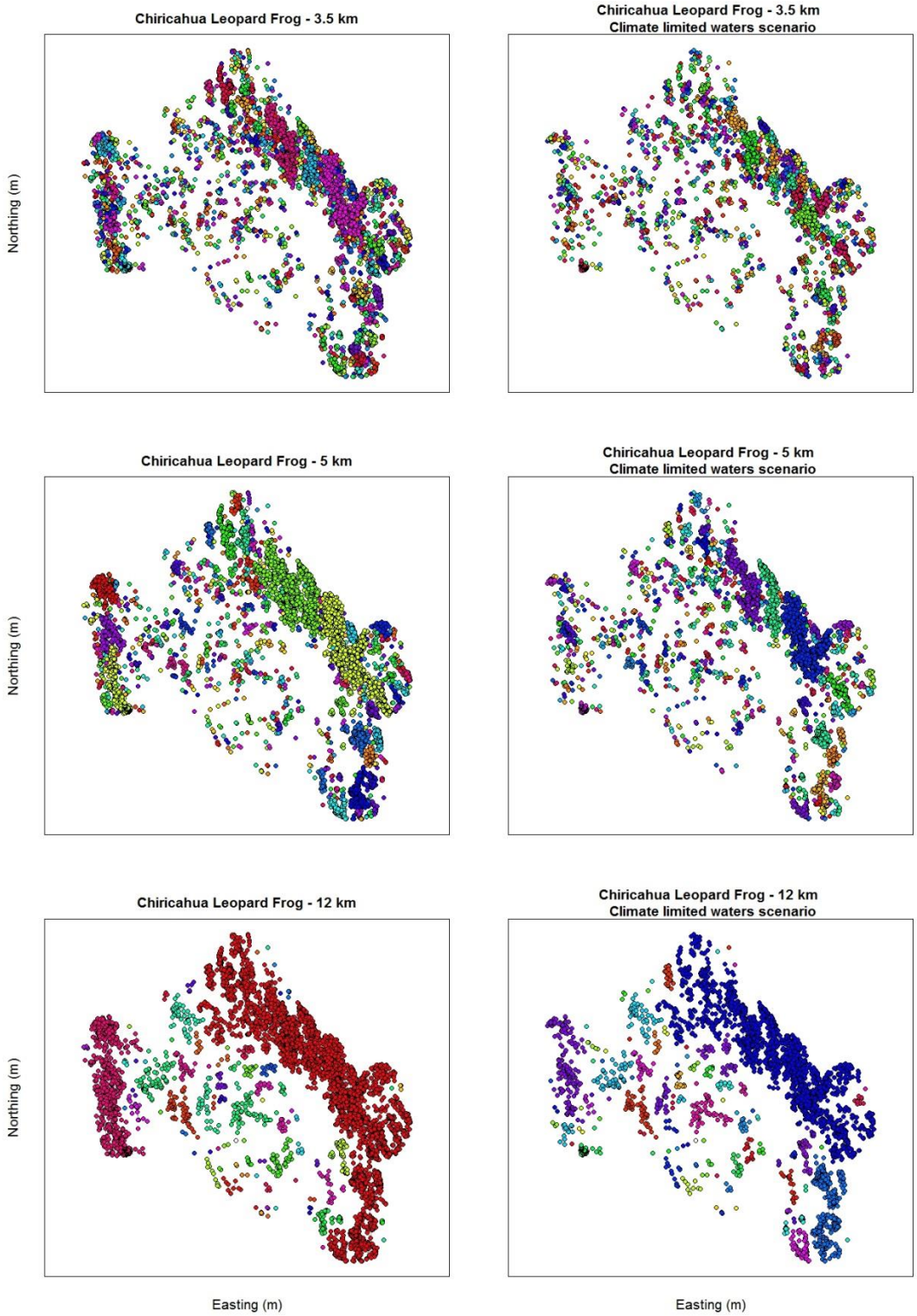

Figure 24. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Chiricahua Leopard Frog. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

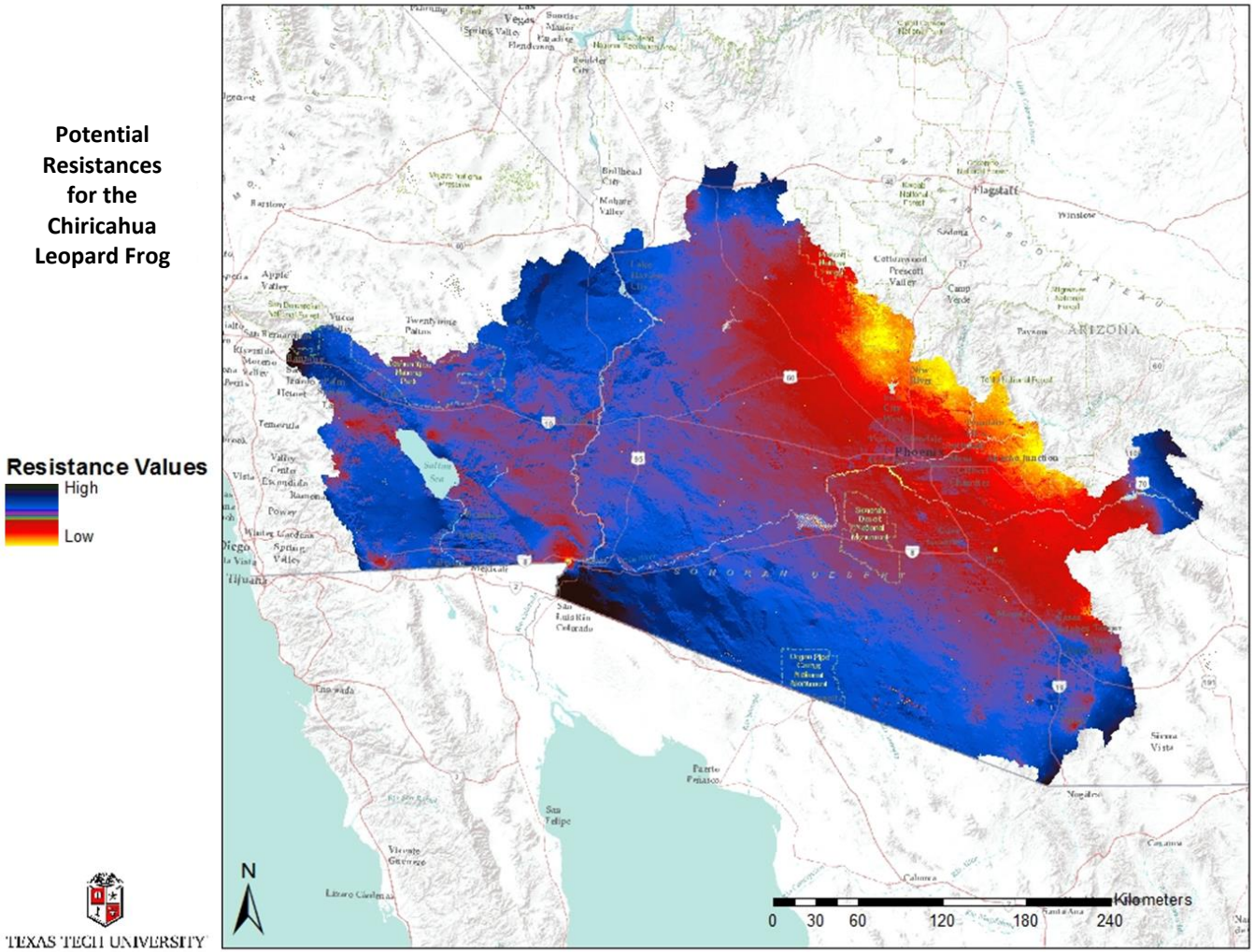

Figure 25. Potential resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area. There are still increased resistance to movement around urban centers.

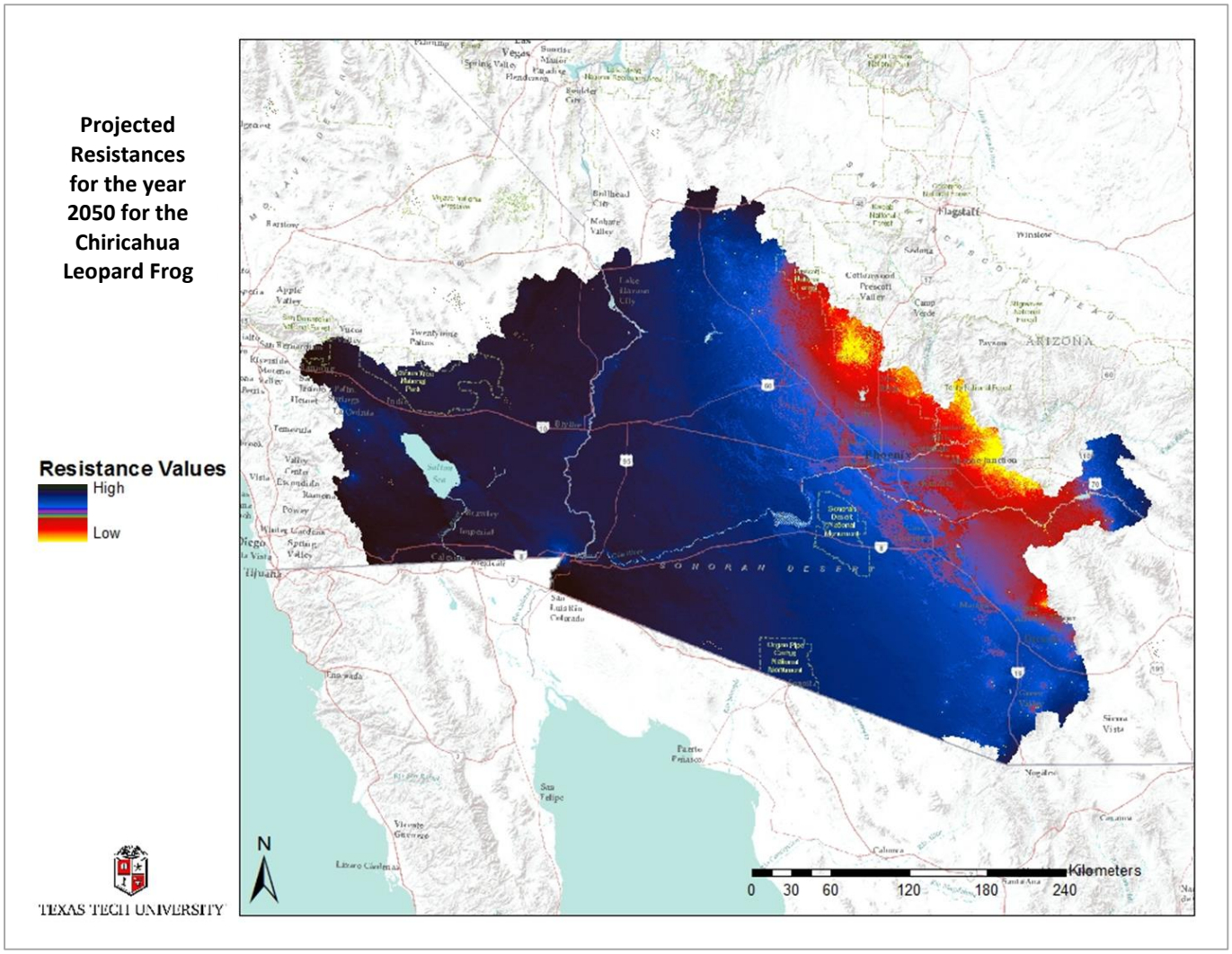

Figure 26. Projected resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Lowland Leopard Frog (*Lithobates yavapaiensis)*

Distribution & Status: Lowland Leopard Frogs are found in southwestern New Mexico and Southern Arizona generally south of the Mogollon Rim with possible populations in southeastern Nevada and California (Degenhardt et al. 1996; Lannoo 2005), and Sonora, Mexico (Platz & Frost 1984). It is listed as endangered by New Mexico Department Game and Fish (NMGF 2014), and is thought to be missing from large parts of its historical range (Clarkson & Rorabaugh 1989). It is found from sea level to 1460 m across its range (Goldberg et al. 1998), and up to 1700 m in New Mexico (Degenhardt et al. 1996).

Figure 27. Lowland leopard frog in Burro Creek, Arizona.
Photo by: reptilist - CC BY-NC-ND 2.0

Habitat & Spatial Ecology: The Lowland Leopard Frog uses a variety of permanent and semi-permanent, natural or manmade, waters occurring from desert scrub to pinyon-juniper (Platz & Frost 1984). Inhabited natural waters include rivers, streams, pools in intermittent streams, springs, and wetlands; anthropogenic waters include cattle tanks, irrigation works, and artificial wildlife catchments (Lannoo 2005). Heterogeneity of shoreline vegetation, refugia availablity, and canopy cover appear to be important factors for determining lowland leopard frog occurrence (Wallace et al. 2010). Migrations for breeding have not been observed (Lannoo 2005), but other movements of almost 1 km have been observed to move from pools that had dried to those still retaining water (Sredl 1996; as cited in Lannoo 2005). A review of general leopard frog movement and dispersal information shows a possible upward dispersal capability of 6 km (Smith & Green 2005).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.9 km, 3.0 km, and 6 km
- These represent known maximum unidirectional movement, movement over intermittent wet terrain, and averaged known yearly dispersal distances for leopard frogs respectively.

Functional Model:

- These animals are habitat generalists that can use many types of waters that lack predatory invasive species.

- A heavy weight was given to the topographic position as the wet areas they prefer are more likely to occur in canyon bottoms
- The weighted equation accounted for impacts of human developments that might remove habitat or hold non-native aquatic predators
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.9 km) modeled for this species resulted in 33% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (6 km), the number of clusters increased by 6% under the climate limited water scenario
- The average number of waters per cluster decreased by 14% and 46% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- At yearly dispersal distances (6 km), this species can maintain connectivity with much of its Mogollon Rim territory.
- In the climate limited water scenarios the species will have less and more disconnected waters available for dispersal.
- At unidirectional movement distances (0.9 km) under the climate limited waters scenario, the Lowland Leopard Frog will have access to 1.2 waters at any given time with a maximum cluster size reduced to 11 water sites, only 61% of the current scenario.
- The mean cluster size is smaller at each distance in climate limited waters scenario limiting species access to water sites.
- Future projected resistances are going to be lowest in areas of high spring density near the Mogollon Rim populations.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Lowland Leopard Frog for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 14%; at maximum modeled dispersal distances the mean cluster size decreased by 46%. The Lowland Leopard Frog is capable of dispersing between much of its current habitat in the Mogollon Rim, but is limited from historic reaches in southeastern Arizona along the Gila and Colorado Rivers by invasive species like the American Bullfrog. At its known maximum

unidirectional movement (0.9 km), the Lowland Leopard Frog under climate limited water scenario, maximum cluster size reduced 61%. By the year 2050 the Chiricahua leopard frog will have a harder time dispersing from its core habitat in the northeastern section of the Sonoran Desert and areas of the Mogollon Rim. At yearly dispersal distances (6 km), this species could access much of its original habitat given favorable circumstances and removal of invasive species, but climate change will make that harder to do as waters become limited and resistance of the landscape increase between isolated waters. In the current waters scenario, many of the waters in the Mogollon Rim section of its range are found in a single large cluster that has 2678 waters in it. In the climate limited waters scenario, those waters in the same area are in 3 large unconnected clusters with the largest containing only 907 isolated waters. Functional connectivity is reduced in the 2050 projected scenario as water sites are limited and vegetation shifts upslope and northward (Figure 30). The areas of lowest resistance will still be near the Mogollon Rim.

Table 11. Lowland Leopard Frog structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.9 km	3 km	6 km	0.9 km	3 km	6 km
Diameter (meters)	5400.9	99465.3	455236.8	3943.2	69028.5	265549.8
Clusters	4563	1414	407	3051	1254	433
Mean Cluster Size	1.4	4.4	15.3	1.2	2.837	8.2
Max Cluster Size	18	432	2678	11	193	907
Network Modularity	-0.00067	-0.00029	-0.00025	-0.0015	-0.000602	-0.00049

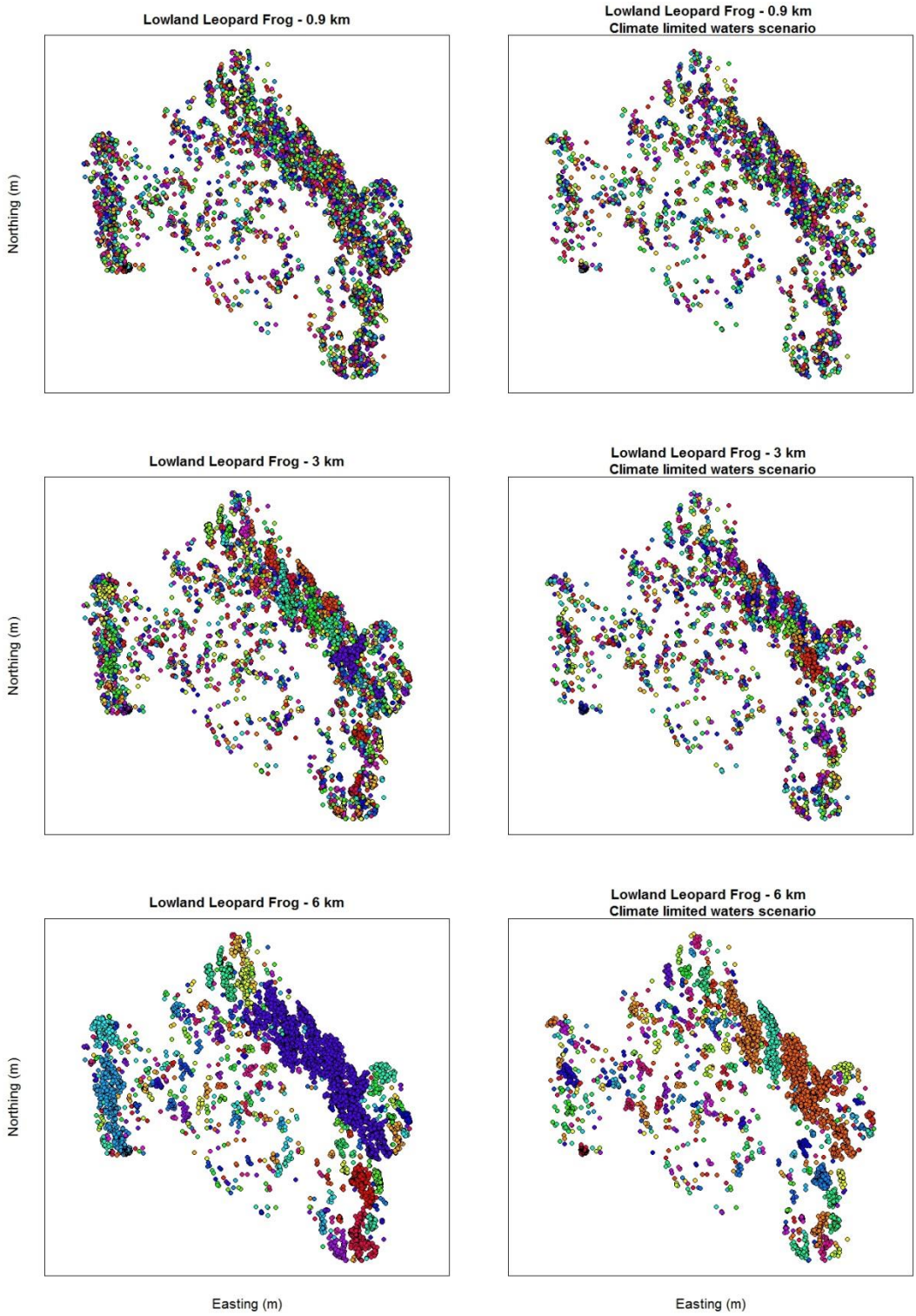

Figure 28. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Lowland Leopard Frog. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

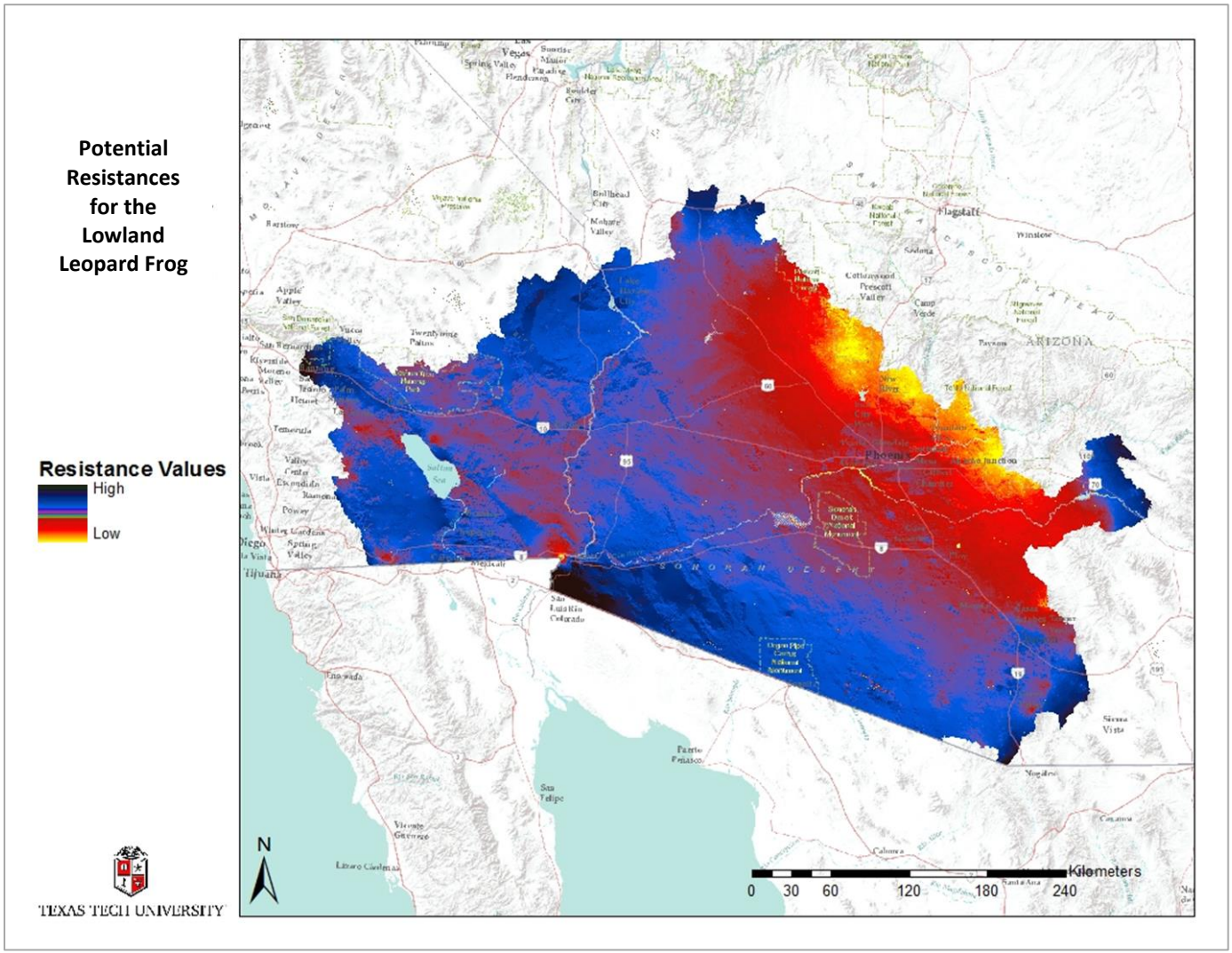

Figure 29. Potential resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area. There are increased resistances to movement in and around urban centers.

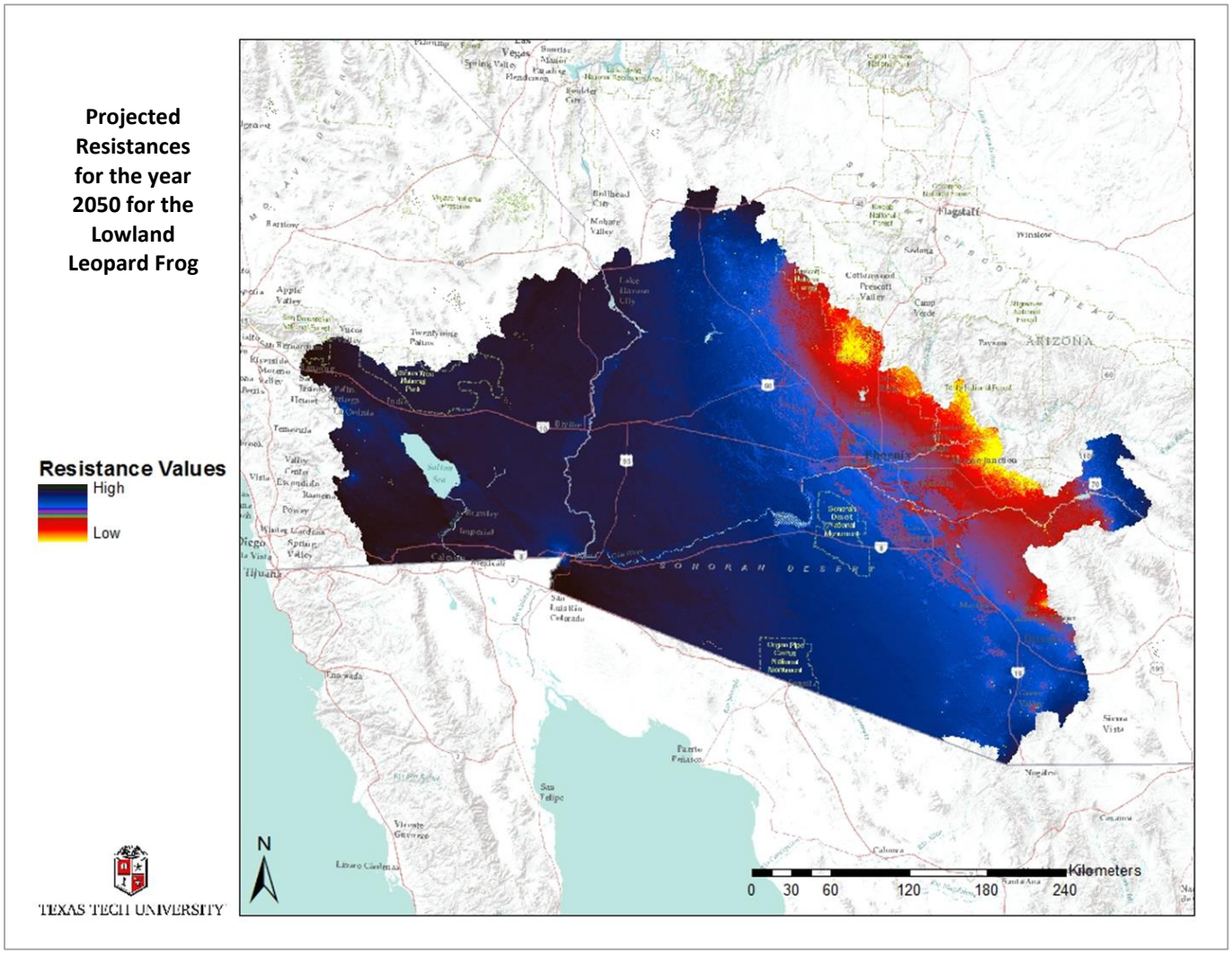

Figure 30. Projected resistances for the Colorado River Toad, Lowland Leopard Frog, and Chiricahua Leopard Frog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Couch's Spadefoot (*Scaphiopus couchii*)

Distribution & Status: Couch's Spadefoots are known to occur from central Texas and Oklahoma west across central and southern Arizona and New Mexico. The westward limit of their range appears to be southeastern California (Lannoo 2005). They occur in bordering Mexican regions and into Baja California (Degenhardt et al. 1996). The species occurs at elevations between 900 m and 1800 m in New Mexico (Degenhardt et al. 1996) and between 600 m to 1200 m in the Big Bend Region of Texas (Dayton & Fitzgerald 2006). It is listed as a species of *Special Concern* in Colorado (CPW 2015).

Figure 31. Couch's spadefoot mate during chorus. Photo by Jim Rorabaugh

Habitat & Spatial Ecology: This species is considered to be among the most well adapted for xeric conditions (Degenhardt et al. 1996). They occur in mesquite, arid grasslands, and creosote deserts (Lannoo 2005). The species makes breeding migrations as long as summer rains provide temporary pools for breeding (B. Sullivan 1989; Woodward 1983; McClanahan et al. 1994). These waters include playas, charcos, tinajas, pools in streambeds or arroyos, and stock tanks or other artificial pools. These spadefoots seem to disappear around areas of intense urban and agricultural development (Lannoo 2005). A possible reason being their need for soils soft enough to burrow into during most of the year to avoid desiccation (Creusere & Whitford 1976; McClanahan et al. 1994). There is little known about the extent of the migrations in *S. couchii*, but movements of 0.8 km have been documented for the eastern relative, *S. holbrookii* (Smith & Green 2005).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.8 km, 1 km, and 2 km
- These represent known daily movement distances, possible daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Adapted for xeric conditions
- Weighted land cover model for occurrences in grasslands and arid shrubby/herbaceous vegetation types

- Urban areas and densely roaded areas coded to show impacts of impervious surfaces on species
- Seem to prefer flatter terrain and canyon bottoms where rain filled waters occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.8 km) modeled for this species resulted in 34% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields—like those near the Yuma.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Couch's Spadefoot for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km— which is an unlikely long dispersal distance for Couch's Spadefoot) the mean cluster size decreased by 28%. The Couch's Spadefoot is presumed to have a fairly low vagility like the Eastern Spadefoots, although the xeric environment might reduce potential dispersal capabilities. At 0.8 km the Couch's Spadefoot, under climate limited water scenario, the max cluster size decreases by a third. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters appear in the northeast section of the Sonoran Desert north and east of the city of Phoenix. Under current conditions much of the flat lands—river valleys, arid-grasslands, and agricultural lands— across the entire region are good areas of movement for the spadefoot. Small patches of low resistance are found in otherwise high resistance areas in the southern and driest sections of the Sonoran (Figure 33). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to the spadefoot movement. Many of the former flat lands areas that provided lower resistance refuges have been lost (Figure 34). Agricultural lands (like those around Yuma, Phoenix, and Tucson) and small patches around managed waters provide low resistance pockets. If the majority of the

Sonoran Desert appears to have high resistances to movement, it is because the species also has low vagility. Although the desert is not conducive to movements, the xeric adapted Couch's Spadefoot might not experience the landscape like other, more vagile animals. The spadefoot stays underground or in concealed until rain comes. Projected rainfall will be less often but at higher intensities. The Couch's Spadefoot is one of the fastest metamorphosing amphibian species, being able to go from egg to metamorph in as little as 8 days (Newman 1988) with adaptive plasticity to reduced water availability. The adults breed in choruses, emerging with summer rains to meet in temporary pools that will continue to form after rains. As long as enough rain falls for ephemeral pools to survive between 10 and 14 days, Couch's may not experience the increase in movement resistance like other species, emerging near the temporary pools when the form.

Table 12. Couch's Spadefoot structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.8 km	1 km	2 km	0.8 km	1 km	2 km
Diameter (meters)	4605.3	6467.5	27538.1	2534.01	5588.7	27691.2
Clusters	4746	4351	2502	3129	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00071	-0.00059	-0.00034	-0.0017	-0.0013	-0.00074

Figure 32. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Couch's Spadefoot. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

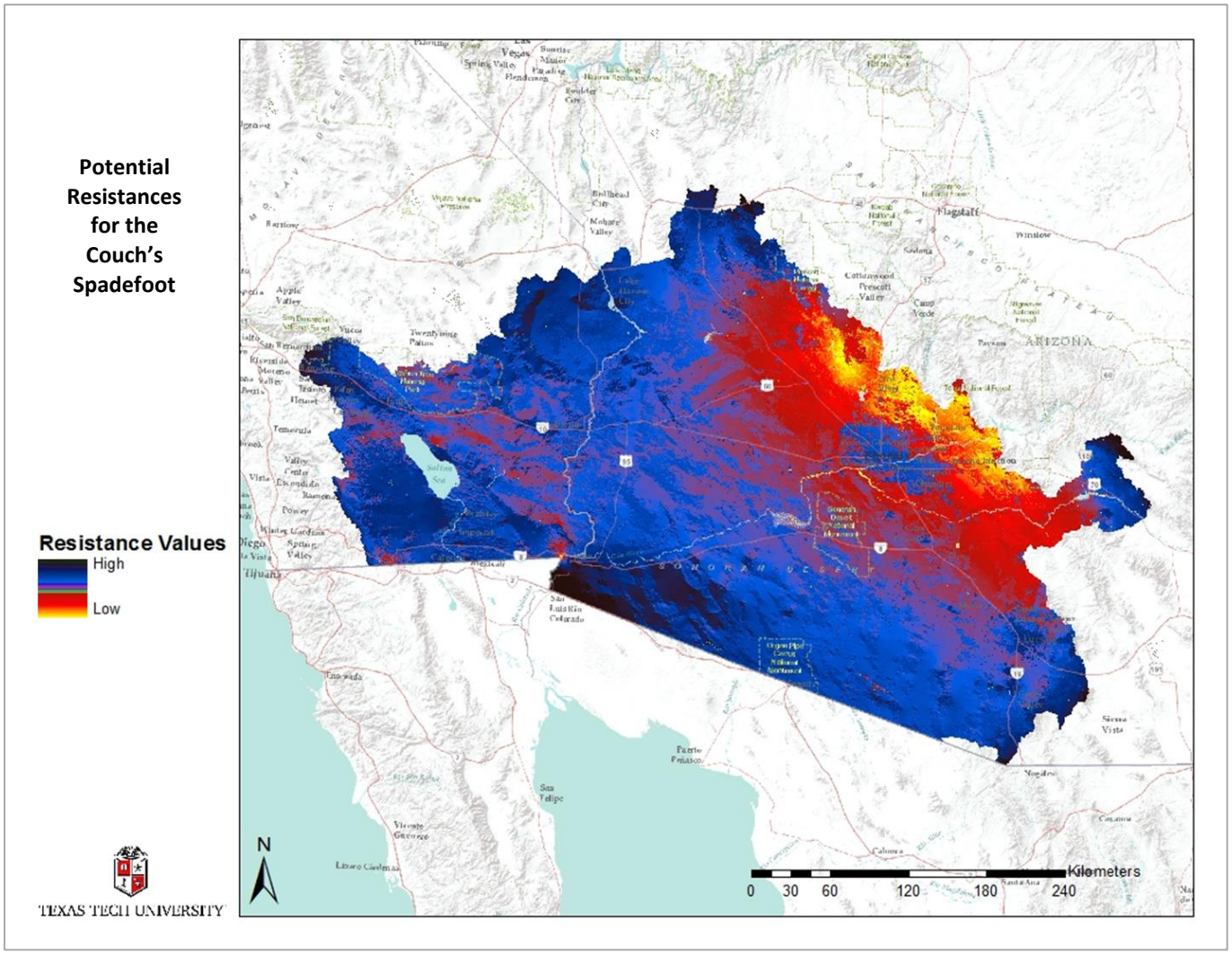

Figure 33. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

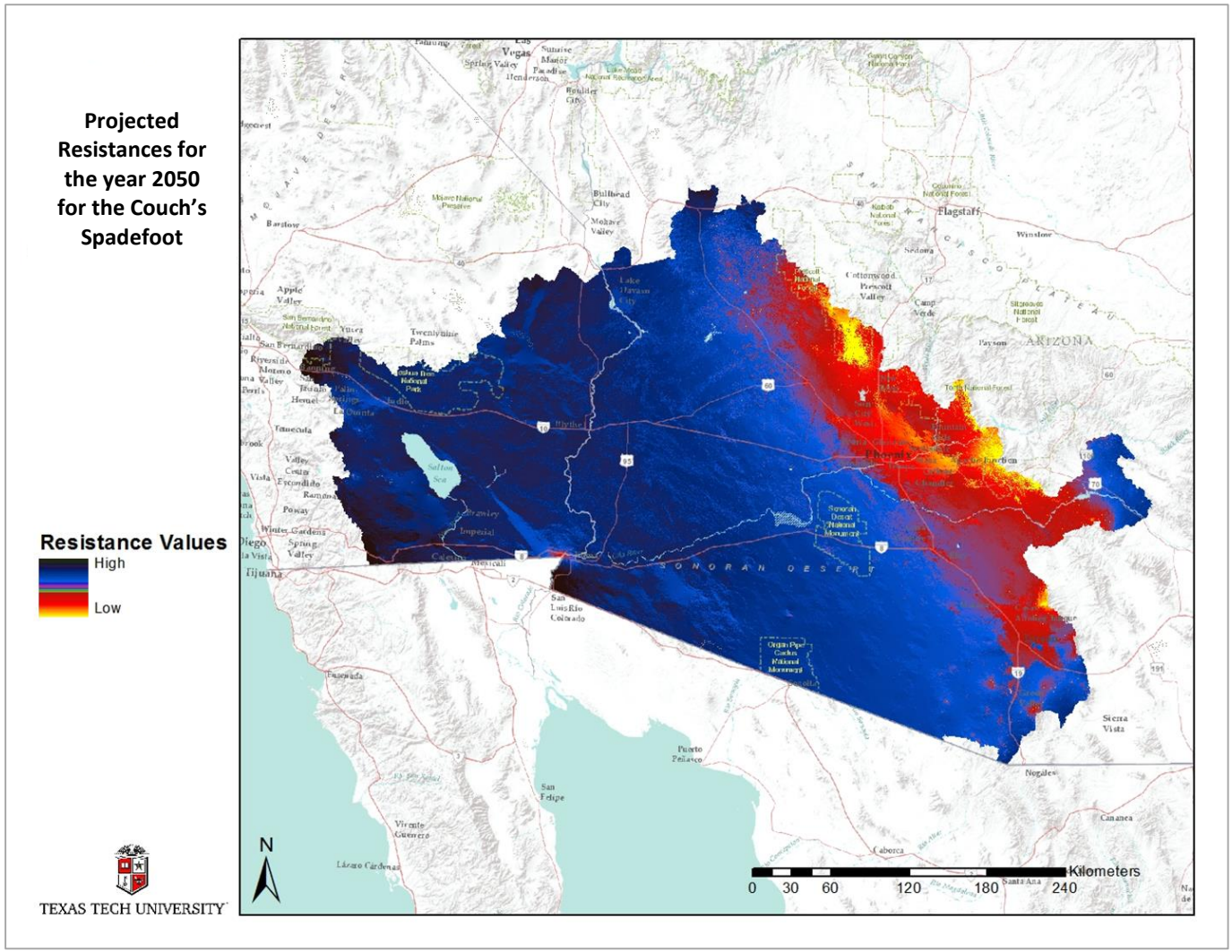

Figure 34. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Plains Spadefoot (*Spea bombifrons*)

Distribution & Status: The Plains Spadefoot occurs from northern Mexico in the south to southern Alberta in the north. They are as far west as northeastern and southeastern Arizona; east as far as western Iowa, Missouri, and into sections of Arkansas and much of western Texas (Lannoo 2005). It is known to occur from elevations of 900 m to as high as 2,200 m as favorable conditions allow (Degenhardt et al. 1996).

Figure 35. Plains spadefoot. Photo by: Andy Teucher. CC BY-NC 2.0

Habitat & Spatial Ecology: This species is found in similar habitat to the Couch's Spadefoot's, including arid grasslands, desert scrublands, semi-desert shrubs, riparian areas and sandy soils (Bragg 1965) where it relies on well-drained, loose soils for burrowing either shallow summer burrows or winter burrows (Bragg 1944; Lannoo 2005). When it emerges from burrows to take of advantage of summer rains, it breeds almost exclusively in temporary waters like stock tanks, playa pools, and tinajas (Lannoo 2005). *S. bombifrons* has been recorded moving at least 1 km during a night to reach breeding sites (Landreth & Christensen 1971). Other migrations events are unknown.

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.8 km, 1 km, and 2 km
- These represent known daily movement distances of eastern cognate, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Similar to Couch's Spadefoot
- Weighted land cover model for occurrences in arid grasslands and arid shrubby/herbaceous vegetation types
- Urban areas and densely roaded areas coded to show impacts of impervious surfaces on species
- Modeled preference for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.8km) modeled for this species resulted in 34% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields—like those near the Yuma, Phoenix, and—most importantly for the Plains Spadefoot—near Tucson.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Plains Spadefoot for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Plains Spadefoot) the mean cluster size decreased by 28%. Similar to the Couch's Spadefoot, The Plains Spadefoot is presumed to have a fairly low vagility like its eastern cognates, although the xeric environment might further reduce potential dispersal capabilities. At 0.8 km the Plains Spadefoot, under climate limited water scenario, the max cluster size decreases by a third. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters appears in the northeast section of the Sonoran Desert north and east of the city of Phoenix, although is to far south of the population that occurs in the northeast section of Arizona. Small patches of low resistance are found in otherwise high resistance areas in the southeastern section of the state (Figure 37). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to the spadefoot movement overall but there may be a localized decrease in resistance if agricultural lands expand as seen in the model. Many of the former flat lands areas that provided lower resistance refuges have been lost (Figure 38). Agricultural lands (like those around Yuma, Phoenix, and Tucson) and small patches around managed waters provide low resistance pockets across the Sonoran Desert.

Table 13. Plains Spadefoot structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.8 km	1 km	2 km	0.8 km	1 km	2 km
Diameter (meters)	4605.3	6467.5	27538.1	2534.01	5588.7	27691.2
Clusters	4746	4351	2502	3129	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00071	-0.00059	-0.00034	-0.0017	-0.0013	-0.00074

Figure 36. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Plains Spadefoot. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

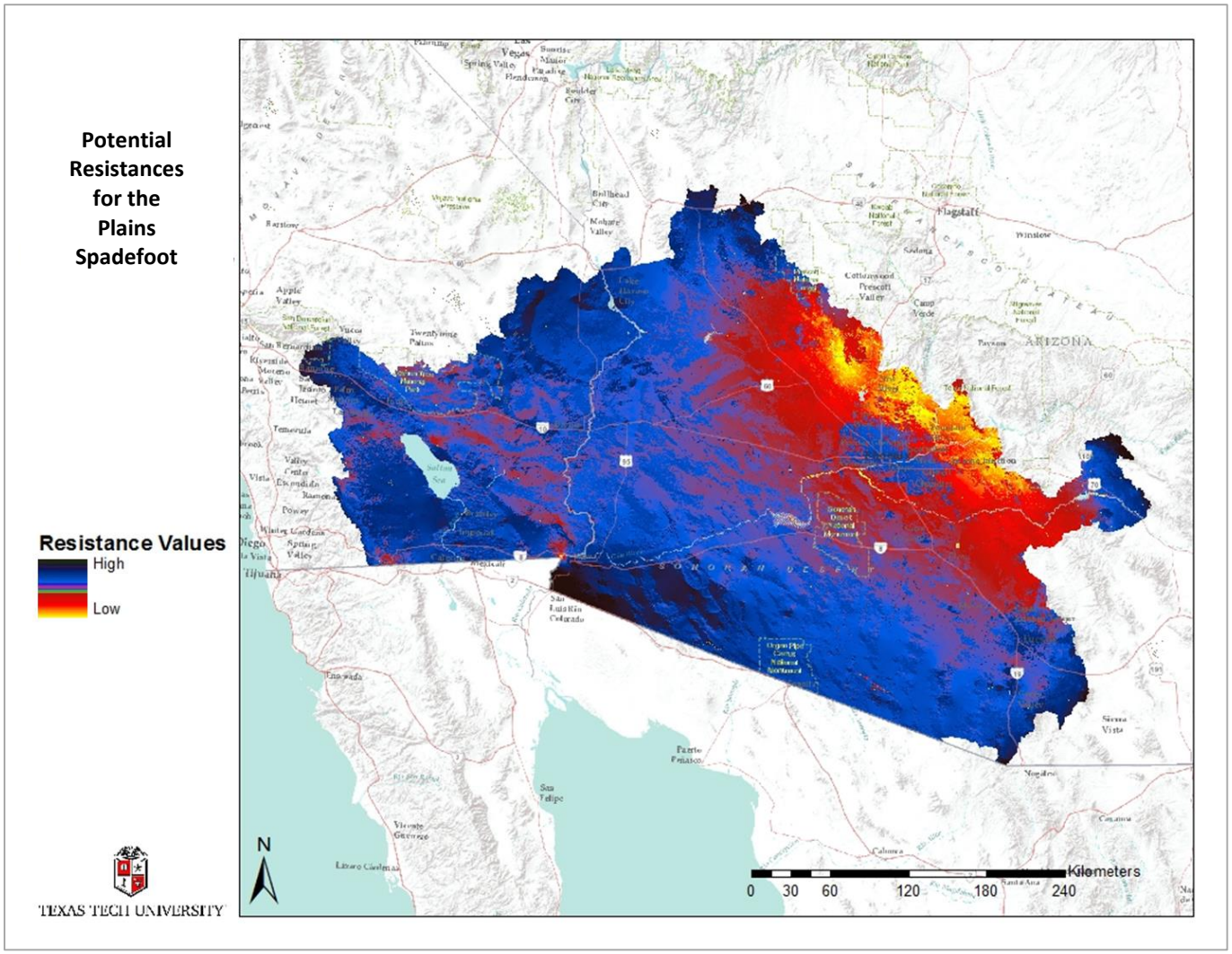

Figure 37. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

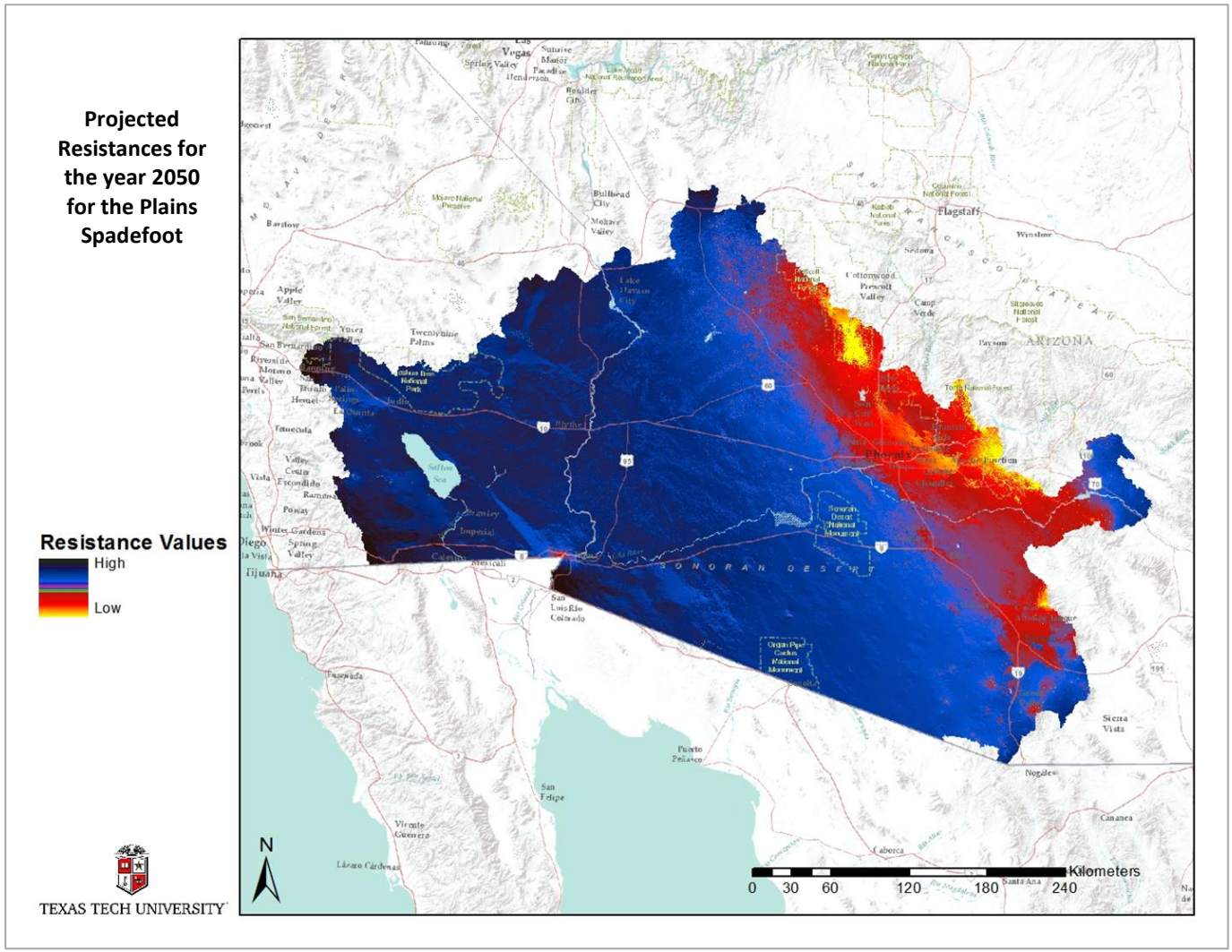

Figure 38. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Mexican Spadefoot (*Spea multiplicata*)

Distribution & Status: The Mexican Spadefoot is widespread across much of the southwest and into Mexico. It is known to occur from central Texas to south-central Arizona and from northwestern Oklahoma to southeastern Utah (Lannoo 2005). It occurs at elevations between 900 m and 2600 m (Degenhardt et al. 1996).

Figure 39. Mexican spadefoot Cochise County, AZ.
Photo by: squamatologist 2010 CC BY-NC-ND 2.0

Habitat & Spatial Ecology: Mexican Spadefoot toads use grasslands, sagebrush flats, semi-arid shrublands, and a wide range of arid to semi-arid habitats (Lannoo 2005). They inhabit these areas as long as breeding pools exist during rainy seasons. This species is similar to other spadefoots and breeds mostly in ephemeral pools and is known to readily use artificial sources of water for breeding. They are known to move to find breeding sites but there is little known about the migration (Lannoo 2005). After breeding, Mexican Spadefoots will burrow underground to avoid desiccation (Ruibal et al. 1969). Although little is known about the Mexican Spadefoot's movements, similar eastern spadefoot toads are known to disperse around 0.8 km (Smith & Green 2005) and the Plains Spadefoot is known to travel up to 1 km a night during breeding events (Landreth & Christensen 1971).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.8 km, 1 km, and 2 km
- These represent known daily movement distances of eastern cognate, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Similar to Couch's Spadefoot, Plains Spadefoot, and Great Plains Toad
- Weighted land cover model for occurrences in semi-arid grasslands and arid shrubby/herbaceous vegetation types
- Urban areas and densely roaded areas coded to show impacts of impervious surfaces on species

- Modeled preference for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.8 km) modeled for this species resulted in 34% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields.
- Areas east of Organ Pipe Cactus National Monument and south of Phoenix will experience an increase in resistance for the known ranges of the Mexican Spadefoot.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Mexican Spadefoot for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Plains Spadefoot) the mean cluster size decreased by 28%. Similar to the Couch's and Plains Spadefoot, the Mexican Spadefoot is presumed to have a fairly low vagility like its eastern cognates, although the xeric environment might further reduce potential dispersal capabilities. At 0.8 km the Plains Spadefoot, under climate limited water scenario, the max cluster size decreases by a third. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters are in the northeast section of the Sonoran Desert north and east of the city of Phoenix. Occurring in the eastern half of the Sonoran Desert, the spadefoot has access to many of the high density water locals around Phoenix. This reduced resistance to movement is partially due to water density and partially to higher densities of agricultural land (Figure 41). With projected climate and land use

change for the year 2050, the Sonoran Desert has an increased resistance to the spadefoot movement overall but much of Sonoran Desert—especially to the north and east of Phoenix is still low in resistance to movement. Many of the former flat lands areas that provided lower resistance south of the city may be lost (Figure 42). Managed waters and agricultural land may provide many refuges for the species in the future.

Table 14. Mexican Spadefoot structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.8 km	1 km	2 km	0.8 km	1 km	2 km
Diameter (meters)	4605.3	6467.5	27538.1	2534.01	5588.7	27691.2
Clusters	4746	4351	2502	3129	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00071	-0.00059	-0.00034	-0.0017	-0.0013	-0.00074

Figure 40. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Mexican Spadefoot. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

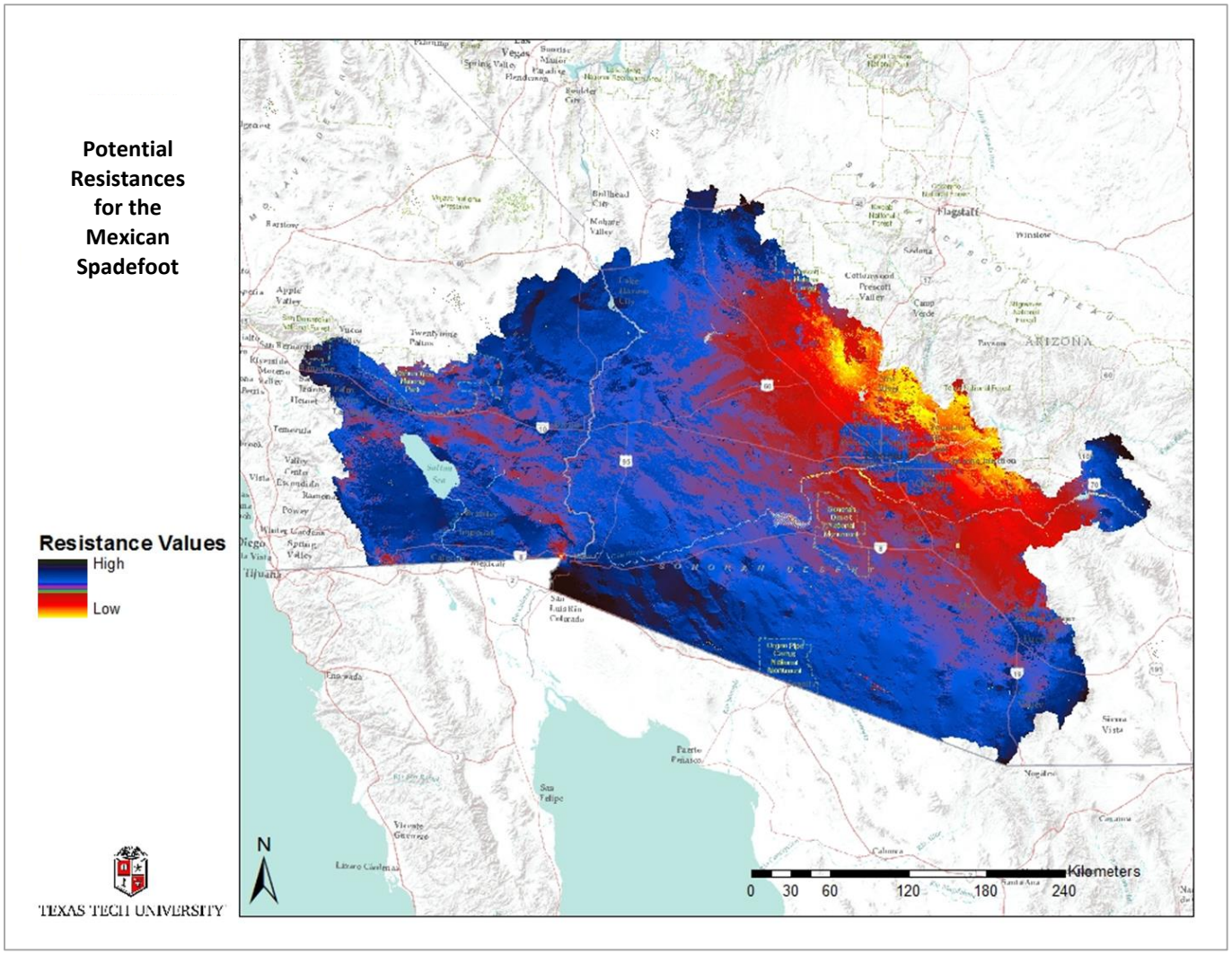

Figure 41. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

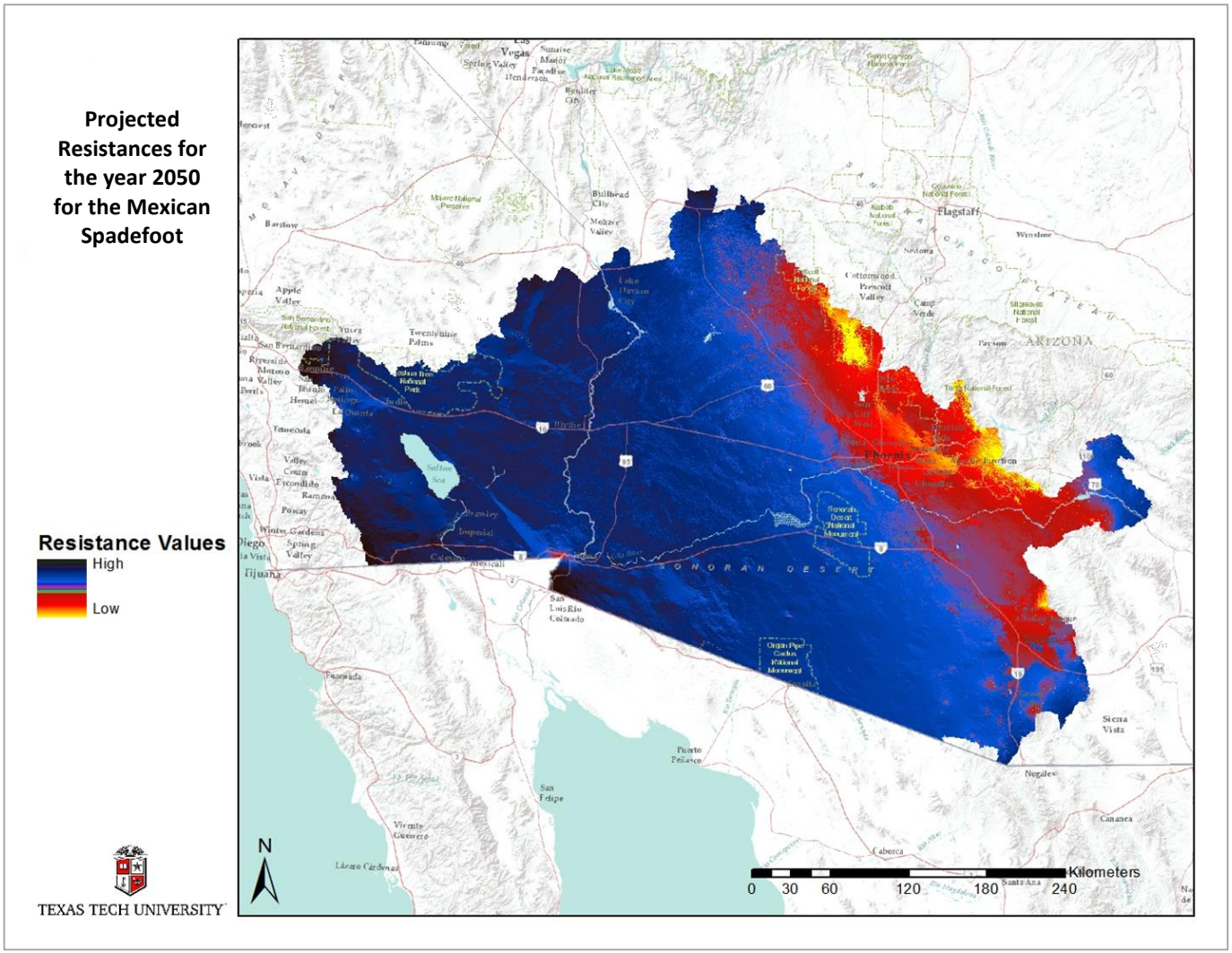

Figure 42. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Great Plains Toad (*Anaxyrus cognatus*)

Figure 43. Great plains toad on the road in Pima County, AZ. Photo by squamatologist 2010 CC BY-NC-ND 2.0

Distribution & Status: The Great Plains Toad is one of the most common toads of the Southwest (King 1932). It has a wide distribution that spans the Great Plains from Alberta and Manitoba in Canada and south into Mexico (Degenhardt et al. 1996). It occurs in the arid southwest including Arizona and southeastern Nevada, Utah, and California. It occurs eastward into Texas, Oklahoma and northwards into western Minnesota (Lannoo 2005). This species is thought to occur below 1900 m (Degenhardt et al. 1996). Although the Great Plains toad has a wide distribution it can be locally abundant or rare.

Habitat & Spatial Ecology: *A. cognatus* is found in grassland habitats, sandhills, mesquite and creosote scrublands and desert scrubs (Lannoo 2005; Stebbins 2003; Ewert 1969), and is found in agricultural (Degenhardt et al. 1996) and urban (Krupa 1994) areas. This species tolerates human alteration of the landscape better than other toads, but because these toads breed aquatically, areas of intense urbanization may still be detrimental. Breeding occurs in both artificial and natural permanent and temporary waters with a preference for fishless aquatic environments (Krupa 1994; Krupa 1989; Lannoo 2005). Migrations to and from temporary pools resulted in an observed maximum movements of approximately 1,300 m (Ewert 1969). They generally avoid freezing and desiccation by seeking refuge in underground burrows from which they will emerge and travel to breeding and feeding areas (Ewert 1969; Degenhardt et al. 1996; Lannoo 2005).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.7 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Similar to Couch's Spadefoot and Red Spotted Toad

- Weighted land cover model for occurrences in arid grasslands and arid shrubby/herbaceous vegetation types
- Urban areas and densely roaded areas coded to show impacts of impervious surfaces on species
- Exists throughout much of the Sonoran except in the most mountainous and driest sections
- Modeled preference for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.7 km) modeled for this species resulted in 35% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields throughout the Sonoran Desert
- Areas east of Organ Pipe Cactus National Monument and south of Phoenix will experience an increase in resistance for the known ranges of the Great Plains Toad.
- Areas of light disturbance that promote temporary pool formation may be accessible for the Great Plains Toads—agricultural lands and road sides may provide moderate resistance refuges in otherwise high resistance areas.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Great Plains Toad for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Great Plains Toads) the mean cluster size decreased by 28%. Similar to the Red Spotted Toad, The Great Plains Toad is presumed to have a similar low vagility and

the xeric environment might reduce potential dispersal capabilities. At 0.7 km the Great Plains Toad, under climate limited water scenario, the max cluster size decreases by 44%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters appears in the northeast section of the Sonoran Desert north and east of the city of Phoenix. Occurring in the eastern half of the Sonoran Desert, the spadefoot has access to many of the high density water locals around Phoenix. This reduced resistance to movement is partially due to water density and partially to higher densities of agricultural land (Figure 45). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to amphibian movement. Much of Sonoran Desert—especially to the north and east of Phoenix is still low in resistance. Many of the former flat lands areas that provided lower resistance south of the city may be lost (Figure 46), but managed waters, temporary pools formed near road works, and agricultural land may provide many refuges for the species in the future.

Table 15. Great Plains Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters

	All waters			Climate limited waters		
	0.7 km	1 km	2 km	0.7 km	1 km	2 km
Diameter (meters)	3295.2	6467.5	27538.1	2728.6	5588.7	27691.2
Clusters	4957	4351	2502	3219	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00082	-0.00059	-0.00034	-0.00203	-0.0013	-0.00074

Figure 44. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Great Plains Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

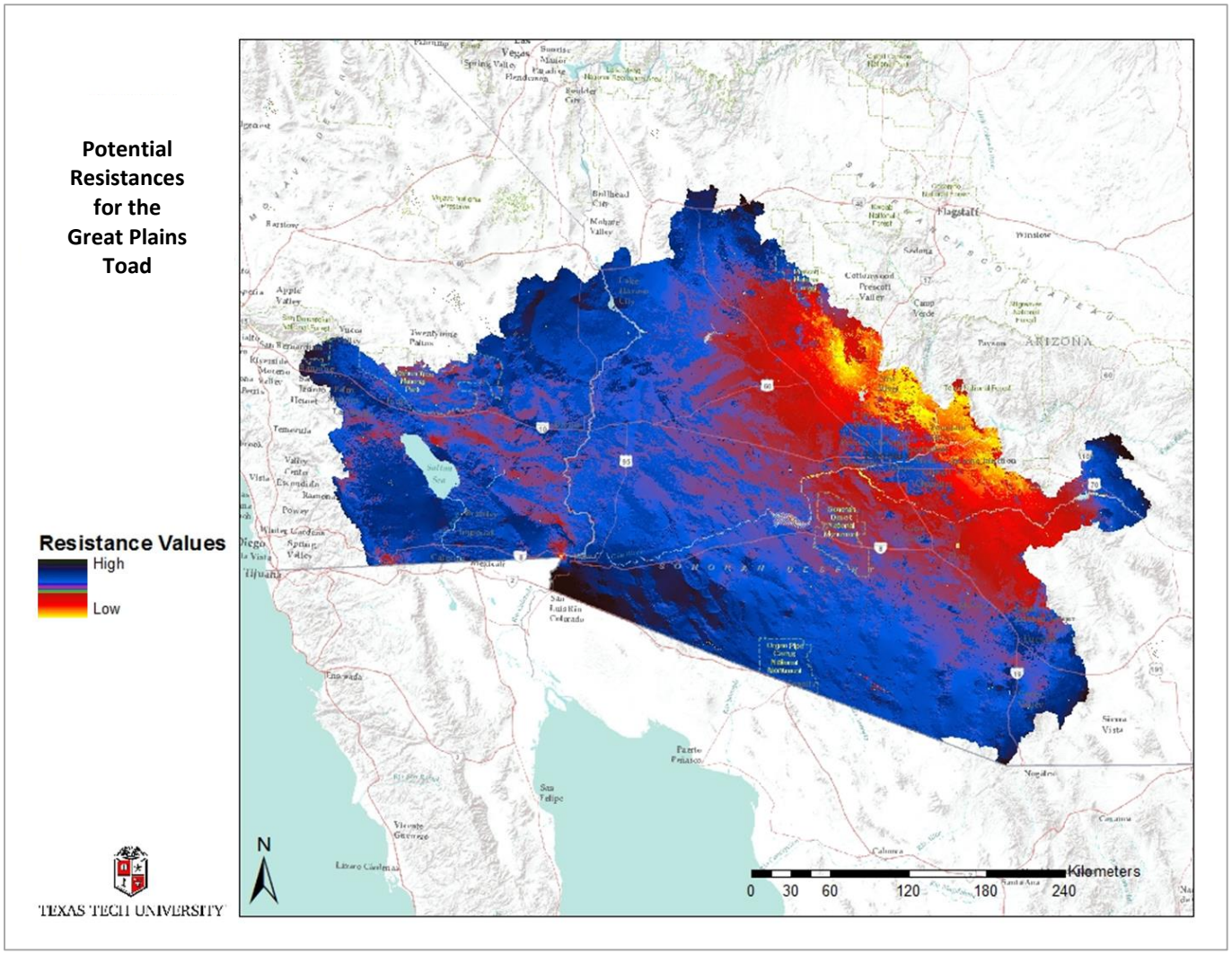

Figure 45. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

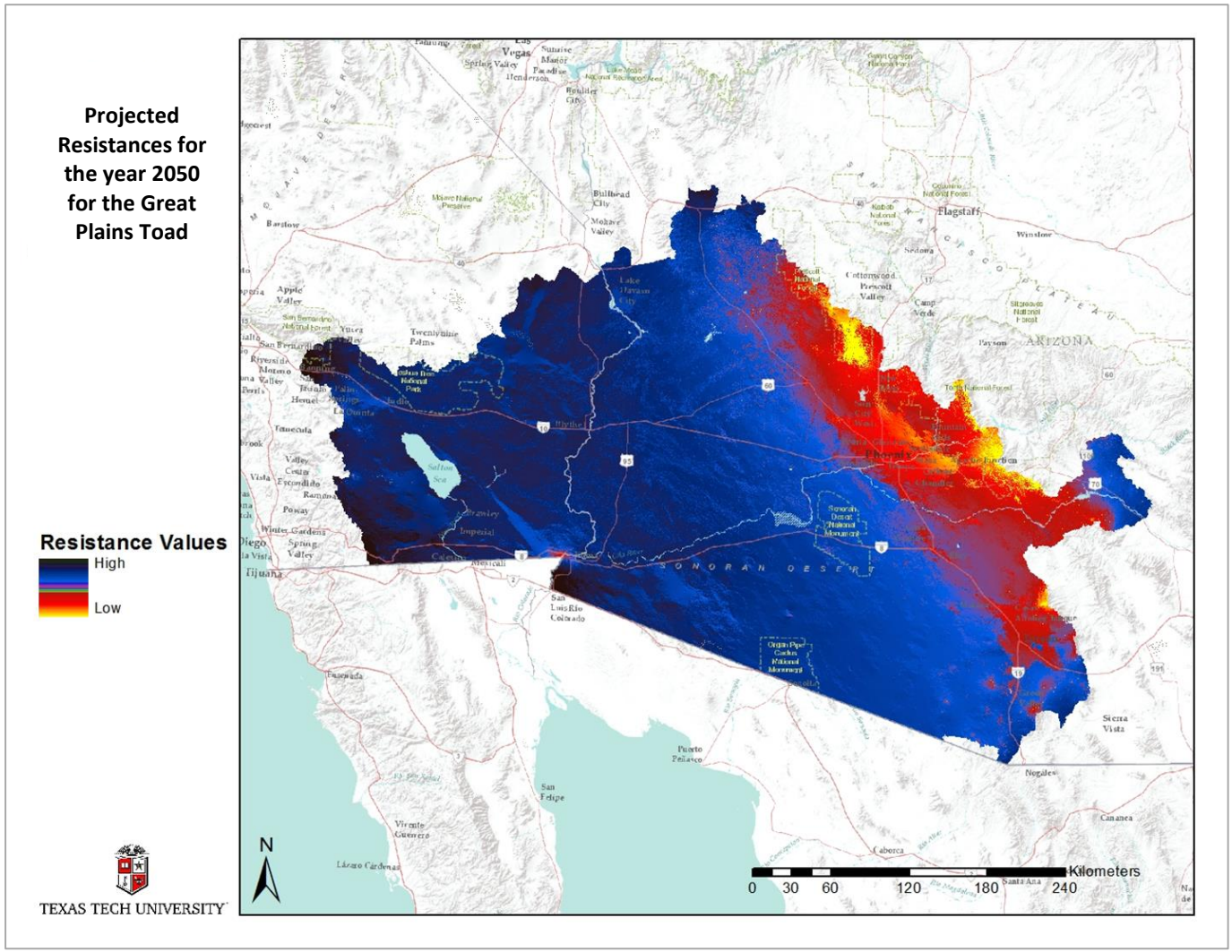

Figure 46. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Red Spotted Toad (*Anaxyrus punctatus)*

Distribution & Status: Red Spotted Toads occur from central Texas and Oklahoma westward to south-central California. The range reaches into southeastern Utah, parts of Colorado, and down into Mexico (Lannoo 2005; Degenhardt et al. 1996). The species is patchily distributed based on elevation, latitude, terrain, flood events and ephemeral water availability (Bradford et al. 2003). The species occurs below 2200 m (Degenhardt et al. 1996).

Figure 47. Red Spotted Toad in the Barry M. Goldwater Air Force Range, AZ. Photo by: Joe Drake

Habitat & Spatial Ecology: These toads will breed, depending on water availability and locality, in small desert springs and streams and in ephemeral desert pools (Tevis Jr 1966; Lannoo 2005). Adults generally are associated with rocky areas, streams, arroyos, upland areas, and drainages (Tevis Jr 1966). It is well adapted for arid environments but appears to stay closer to riparian areas but will inhabit grasslands when waters are available (Ferguson et al. 1969). It is also will sometimes use anthropogenic waters like stock tanks (Degenhardt et al. 1996). Adults are assumed to aestivate in the Sonoran Desert during periods of prolonged drought and are thought to hibernate during dryer and cooler months in winters (Lannoo 2005). They will inhabit cracks in mud and under rocks and possibly burrow as well (Tevis Jr 1966; Ferguson et al. 1969). Migrations are not thought to be large, as an average of recorded movements is thought to be approximately 0.7 km (Smith & Green 2005). There have been recorded movements of nearly 1km for a displaced individual returning to its known area (Weintraub 1974).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.7 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Similar to Couch's Spadefoot and Great Plains Toad

- Weighted land cover model for occurrences in arid grasslands and arid shrubby/herbaceous vegetation types
- Urban areas and densely roaded areas coded to show impacts of impervious surfaces on species
- Modeled preferences for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur but also occur in rocky rugged terrain where waters exist
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.7 km) modeled for this species resulted in 35% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields throughout the Sonoran Desert.
- The toadless reaches of the Sonoran Desert near Yuma may expand to the north and east as conditions become hotter and drier—resistances increase in these areas.
- Areas of light disturbance that promote temporary pool formation may be accessible for the Red Spotted Toads—agricultural lands and road side pools may provide moderate resistance refuges in otherwise high resistance areas.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Red Spotted Toad for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Red Spotted Toad) the mean cluster size decreased by 28%. Similar to the Great Plains Toad, the Red Spotted Toad is presumed to have a similar low vagility and the xeric environment might reduce potential dispersal capabilities. At 0.7 km the Red Spotted Toad, under climate limited water scenario, the max cluster size decreases by 44%. At 2 km

dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters appears in the northeast section of the Sonoran Desert north and east of the city of Phoenix. Occurring in the eastern half of the Sonoran Desert, the toad has access to many of the high density water locals around Phoenix. This reduced resistance to movement is partially due to water density and partially to higher densities of agricultural land (Figure 49). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to amphibian movement. Much of Sonoran Desert—especially to the north and east of Phoenix is still low in resistance. Many of the former flat land areas that provided lower resistance south and west of the city, however, may be lost (Figure 50). Managed waters, temporary pools formed near road works, and agricultural land may provide many refuges for the species in the future. This toad occurs locally where small ephemeral pools develop, but artificial catchments may provide the only refuge in the driest and hottest parts of the future landscape, if rainfall does not sustain temporary pools long enough for metamorphosis to occur. Increased evaporation and reduced rainfall may pose a serious threat to these ephemerally breeding species in much of the western Sonoran Desert. The area near Yuma that historically lacks these toads may expand north and east as conditions become more variable in the future.

Table 16. Red Spotted Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters

	All waters			Climate limited waters		
	0.7 km	1 km	2 km	0.7 km	1 km	2 km
Diameter (meters)	3295.2	6467.5	27538.1	2728.6	5588.7	27691.2
Clusters	4957	4351	2502	3219	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00082	-0.00059	-0.00034	-0.00203	-0.0013	-0.00074

Figure 48. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Red Spotted Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

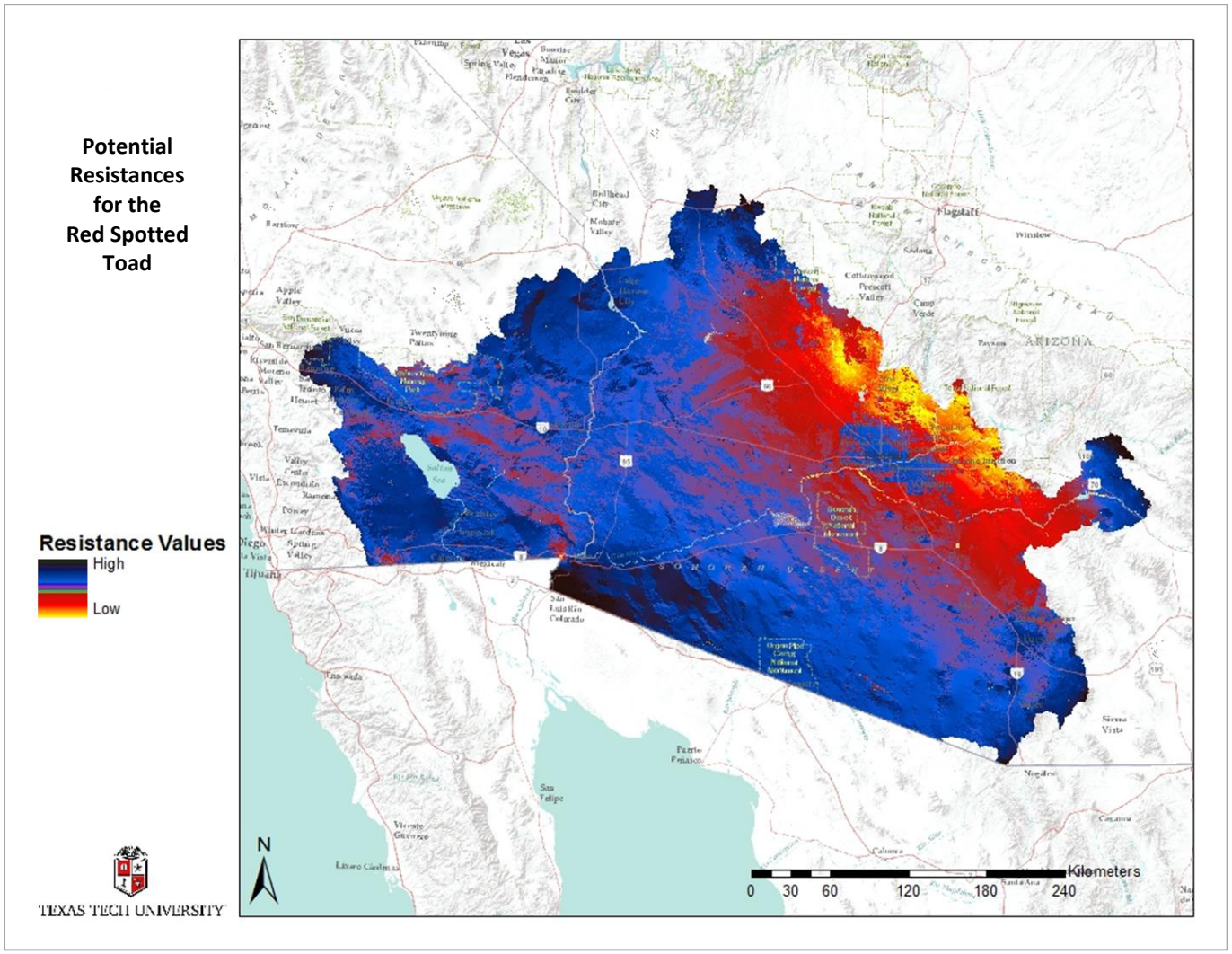

Figure 49. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

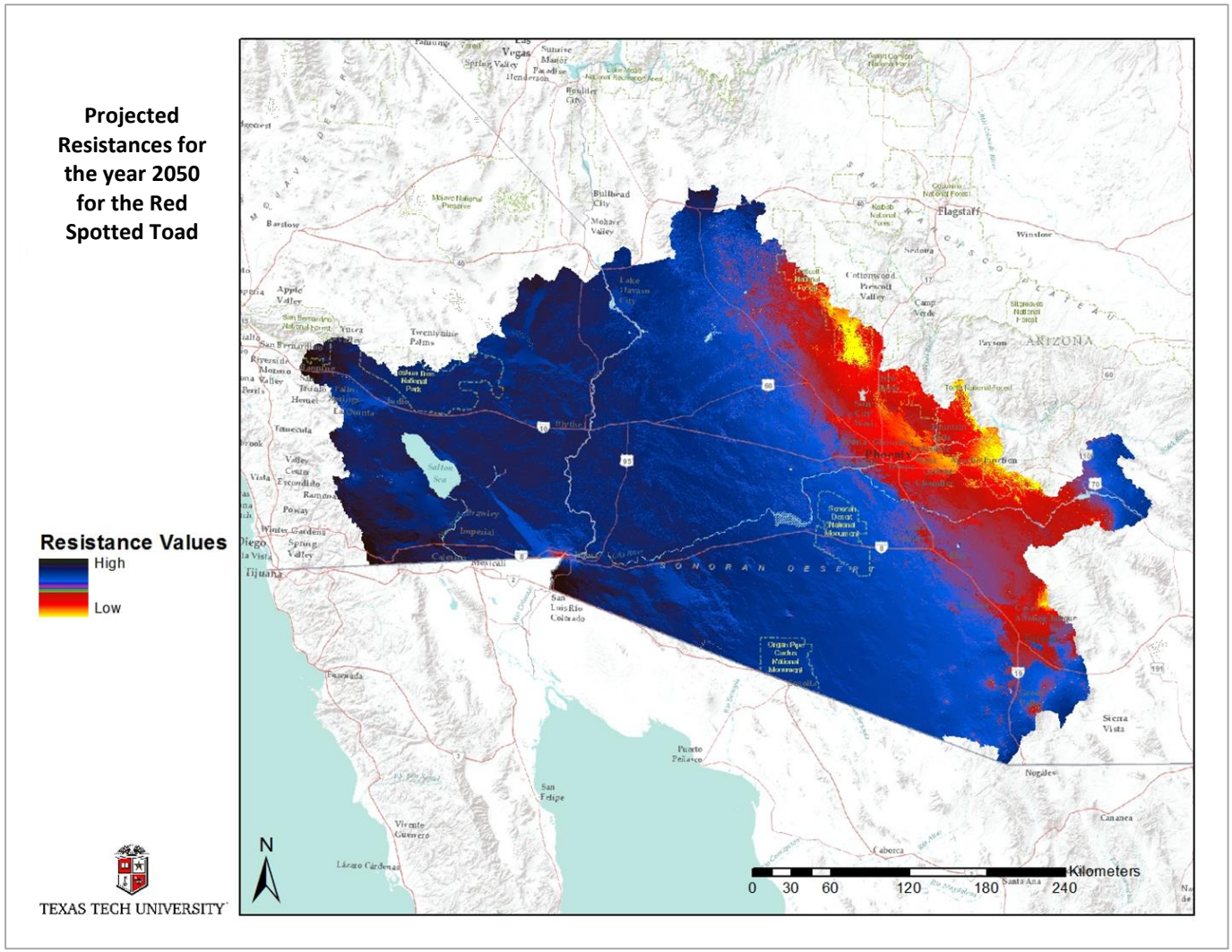

Figure 50. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Sonoran Green Toad (*Anaxyrus retiformis*)

Figure 51. Sonoran green toad. Photo by Josh More 2013 CC BY-NC-ND 2.0

Distribution & Status: The Sonoran Green Toads have a limited distribution in the United States. They are only known from San Cristobol Wash and Organ Pipe National Monument to San Xavier Mission to the East. Northern extent in the United States is thought to be Mobile, Arizona. This species exists south into Sonora, Mexico (Stebbins 2003; Rosen & Lowe 1996; Sullivan et al. 1996; Lannoo 2005). They are a low elevation species, occuring occuring between 150 m and 900 m (Lannoo 2005; Sullivan et al. 1996; Stebbins 2003). This species is limited in range and is considered a *Species of Greatest Conservation Need* by the state of Arizona (AZGFD 2012). It is not listed federally in the United States.

Habitat & Spatial Ecology: This species is thought to be limited to semi-arid habitats (Bogert 1962) and found in creosote flats, mesquite grasslands, upland saguaro-palo verde associations (Bogert 1962; Stebbins 2003; Sullivan et al. 1996; Lannoo 2005). These toads use rain pools, wash bottoms and other waters for breeding explosively after rains (AZGFD 2005). Little else is known about the habitat (Lannoo 2005). Migrations to breeding pools occurs after rains (Bogert 1962) but the extent and distance of movements are unknown.

Model Basis: Because of the lack of natural history and movement/spatial ecology data available, it would be hazardous to propose a resistance model for this species. However, because graph theory can work with limited population data (Bunn et al. 2000), we suggest using the dispersal distance of the similar Red Spotted Toad, *A. punctatus*, to simulate *A. retiformis* dispersal during graph theory simulations.

Structural Model:

- Modeled dispersal distances of 0.7 km, 1 km, and 2 km
- These represent known daily movement distances of the Red Spotted Toad, possible max daily movement distance, and an unlikely maximum dispersal scenario

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.7 km) modeled for this species resulted in 35% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- The limited range of the Sonoran Green Toad is in the south-central section of the Sonoran Desert—an area that may become reliant on artificial catchments for permanent waters.

Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Sonoran Green Toad) the mean cluster size decreased by 28%. The Sonoran Green Toad is presumed to have a similar low vagility as other toads and the xeric environment might reduce potential dispersal capabilities. At 0.7 km the Sonoran Green Toad, under climate limited water scenario, the max cluster size decreases by 44%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The known range of the Sonoran Green Toad in the south-central section of the graph has fewer waters in the climate limited waters scenario (Figure 52). We chose not to model the species in a functional connectivity scenario, because of a lack of movement and habitat use data. They are, however, similar enough to interbreed with Red Spotted Toads—some insight could be gained from Red Spotted Toad circuit theory analysis.

Table 17. Sonoran Green Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20 mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.7 km	1 km	2 km	0.7 km	1 km	2 km
Diameter (meters)	3295.2	6467.5	27538.1	2728.6	5588.7	27691.2
Clusters	4957	4351	2502	3219	2948	1944
Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00082	-0.00059	-0.00034	-0.00203	-0.0013	-0.00074

Figure 52. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Sonoran Green Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

Southwestern Woodhouse's Toad (*Anaxyrus woodhousii australis*)

Figure 53. Woodhouse's Toad found near northeastern Imperial County, California. Photo by: squamatologist 2007 CC BY-NC-ND 2.0

Distribution & Status: The Southwestern Woodhouse's Toad occurs from extreme southeastern California to southwestern Texas and reaches into the adjacent Mexico. It is thought to be distinctly isolated from *A. woodhousii woodhousii* by the Mogollon Rim which runs east-west across much of Arizona and New Mexico (Shannon & Lowe 1955). They are found near sea level by the Salton Sea in California and other subspecies are known to occupy elevations as high as 2500 m (Lannoo 2005). There have been some declines in populations locally (near Tucson) but are not federally listed (Lannoo 2005).

Habitat & Spatial Ecology: *A. w. australis* uses standing water (*e.g.* stock tanks, artificial ponds, pools in rivers, and ephemeral natural pools such as charcos, playas, and tinajas) for breeding habitat (Sullivan 1982; B. K. Sullivan 1989; Lannoo 2005). They are associated with water features and larger riparian areas in low elevations and are also found in other disturbed areas with water such as irrigation fields and urban parks with ponds (Lannoo 2005). Migrations to breeding ponds and streams has not been observed in large numbers (Lannoo 2005), but the closely related Fowler's toad, *A. fowleri*, has been observed to travel up to 1.3 km back to home ranges when displaced (R.J. Nichols, quoted in Oliver 1955).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.7 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Similar to Couch's Spadefoot and Great Plains Toad
- Weighted land cover model for occurrences in arid grasslands and arid shrubby/herbaceous vegetation types

- Urban areas and densely roaded areas modeled to show impacts of impervious surfaces on species
- Modeled preference for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.7 km) modeled for this species resulted in 35% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 15% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields throughout the Sonoran Desert.
- The toadless reaches of the Sonoran Desert near Yuma may expand to the north and east as conditions become hotter and drier—resistances increase in these areas.
- Areas of light disturbance that promote temporary pool formation may be accessible for the Red Spotted Toads—agricultural lands and road side pools may provide moderate resistance refuges in otherwise high resistance areas.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Southwestern Woodhouse's Toad for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements (using Red Spotted Toad information), the mean cluster size reduced by 15%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Southwestern Woodhouse's Toad) the mean cluster size decreased by 28%. Southwestern Woodhouse's Toad is presumed to have low vagility and the xeric environment might reduce potential dispersal capabilities. At

0.7 km the Southwestern Woodhouse's Toad, under climate limited water scenario, the max cluster size decreases by 44%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The highest density of waters appears in the northeast section of the Sonoran Desert north and east of the city of Phoenix. Occurring in the eastern half of the Sonoran Desert, the spadefoot has access to many of the high density water locals around Phoenix. This reduced resistance to movement is partially due to water density and partially to higher densities of agricultural land (Figure 55). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to amphibian movement. Much of Sonoran Desert—especially to the north and east of Phoenix is still low in resistance. Many of the former flat land areas that provided lower resistance south and west of the city, however, may be lost (Figure 56). Riparian areas may decline, but managed waters, urban areas with water, temporary pools formed near road works, and agricultural land may provide many refuges for the species in the future. This toad occurs locally where small ephemeral pools develop, but artificial catchments may provide the only refuge in the driest and hottest parts of the future landscape, if rainfall does not sustain temporary pools. Increased evaporation and reduced rainfall may pose a serious threat to these ephemerally breeding species in much of the western Sonoran Desert.

Table 18. Southwestern Woodhouse's Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.7 km	1 km	2 km	0.7 km	1 km	2 km
Diameter (meters)	3295.2	6467.5	27538.1	2728.6	5588.7	27691.2
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Mean Cluster Size	1.3	1.4	2.5	1.1	1.2	1.8
Max Cluster Size	18	18	88	10	12	59
Network Modularity	-0.00082	-0.00059	-0.00034	-0.00203	-0.0013	-0.00074

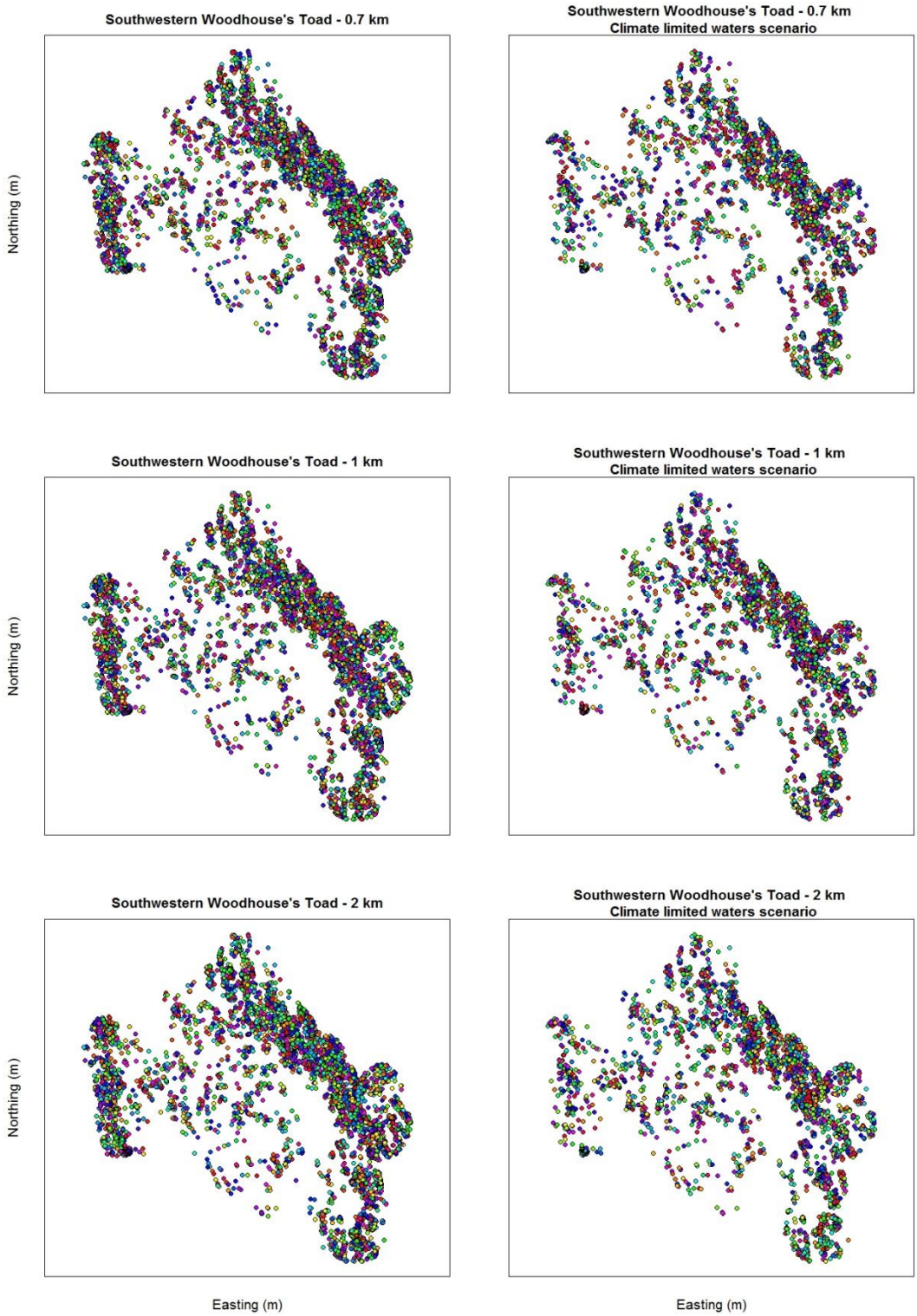


Figure 54. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Southwestern Woodhouse's Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

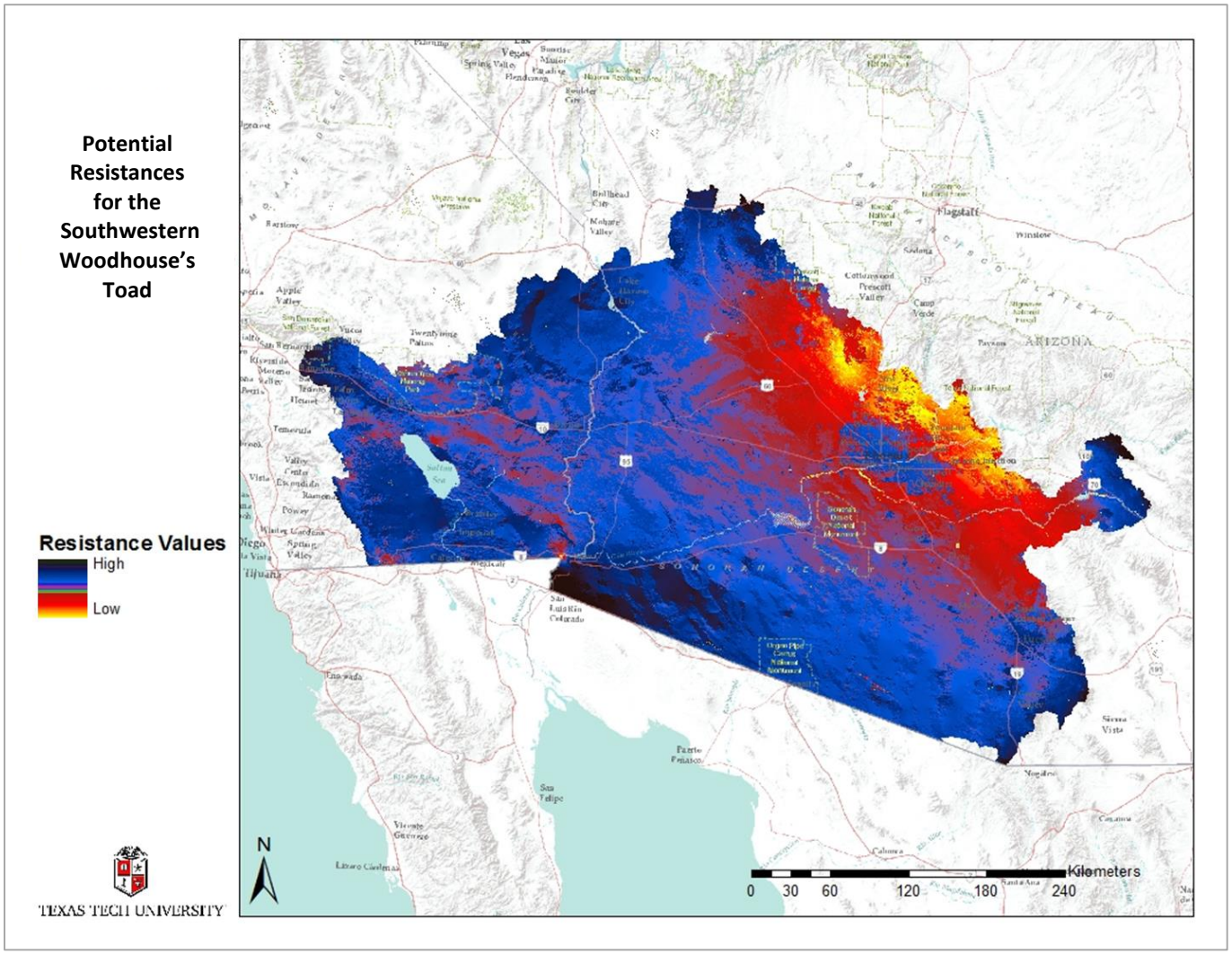


Figure 55. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

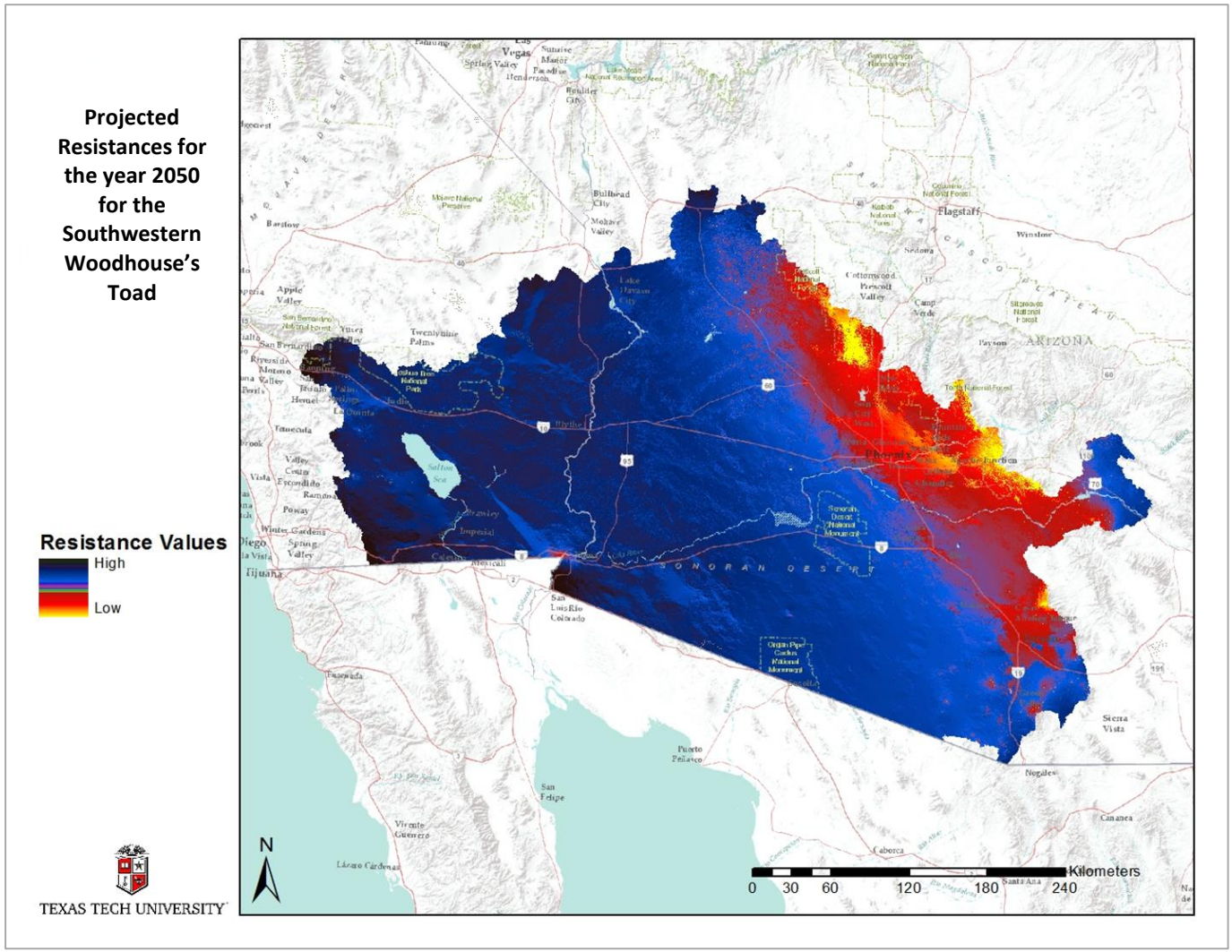


Figure 56. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.

Lowland Burrowing Treefrog (*Smilisca fodiens*)

Figure 57. Lowland burrowing treefrog in Maricopa County, AZ. Photo by: Thomas Brennan, © 2008.

Distribution & Status: The Lowland Burrowing Treefrog is limited to south-central Arizona in the United States but is thought to be common south into Mexico throughout the state of Sonora at elevations from sea level to nearly 1500 m (Stebbins 2003; Lannoo 2005). They may be limited to areas where soil temperatures do not drop below freezing (Ruibal & Hillman 1981). These frogs were only discovered in the United States in 1957 (Chrapliwy & Williams 1957), and known distributions are extremely limited to washes within Pima, Pinal, and Maricopa Counties of Arizona (Enderson & Bezy 2000; Sullivan et al. 1996). It is considered a *Species of Greatest Conservation Need* by the state of Arizona (AZGFD 2012).

Habitat & Spatial Ecology: Like many other amphibian species residing in the Sonoran Desert, this species is an explosive breeder (Sullivan et al. 1996) that uses temporary pools of washes and those that form along roads and in stock tanks for breeding (Chrapliwy & Williams 1957; Sullivan et al. 1996; Lannoo 2005). *S. fodiens* is adapted for a fossorial existence (Lannoo 2005), although there is debate about whether they dig their own burrows or use existing openings (Lannoo 2005). They migrate between breeding and nonbreeding habitats and adults are thought to use semi-arid mesquite grasslands with associated mesquite bosques (AZGFD 2003). There is little else known about the spatial ecology or habitat use by *S. fodiens* (Lannoo 2005)

Model Basis: Because of the lack of natural history and movement/spatial ecology data available, it would be hazardous to propose a resistance model for this species. However, because graph theory can work with limited population data (Bunn et al. 2000), we suggest using the dispersal distance of the Western Narrow-mouth Toad, *Gastrophryne olivacea*, to simulate *A. retiformis* dispersal during graph theory simulations. *G. olicacea* has an average max distance of 0.6 km (Smith & Green 2005) but as with many other amphibians, this might be underestimated.

Structural Model:

- Modeled dispersal distances of 0.6 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.6 km) modeled for this species resulted in 36% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 10% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- The limited range of the Lowland Burrowing Treefrog is in the south-central section of the Sonoran Desert—an area that may become reliant on artificial catchments for permanent waters as climate becomes hotter and drier.

Structural results showed a general decrease in available waters in any given cluster for this frog when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 10%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Lowland Burrowing Treefrog) the mean cluster size decreased by 28%. The Lowland Burrowing Treefrog has the lowest modeled vagility along with the Western Narrow-mouthed Toad, and the xeric environment might reduce potential dispersal capabilities. At 0.6 km the Lowland Burrowing Treefrog, under climate limited water scenario, the max cluster size decreases by 61%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The known range of the Lowland Burrowing Treefrog in the south-central section of the graph has fewer waters in the climate limited waters scenario (Figure 58). This species appears to use and rely on single water clusters at the conservative edge of modeled dispersal distance. We chose not to model the species in a functional connectivity scenario, because of a lack of movement and habitat use data. They do, however, have some similarities in breeding and behavior to other fossorial desert amphibians.

Table 19. Lowland Burrowing Treefrog structural model graph analysis results. All waters scenario reflects all available waters in the U.S. portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.6 km	1 km	2 km	0.6 km	1 km	2 km
Diameter (meters)	2649.2	6467.5	27538.1	2058.3	5588.7	27691.2
Clusters	5141	4351	2502	3287	2948	1944
Mean Cluster Size	1.2	1.4	2.5	1.08	1.2	1.8
Max Cluster Size	18	18	88	7	12	59
Network Modularity	-0.00095	-0.00059	-0.00034	-0.0025	-0.0013	-0.00074

Figure 58. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Lowland Burrowing Treefrog. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

Western Narrow-mouth Toad (*Gastrophryne olivacea*)

Distribution & Status: The Western Narrow-mouth Toad ranges across much of central southern United States such as Texas Oklahoma, and Kansas and into Mexico. There are disjunct populations that exist in the Sonoran Desert in southwestern New Mexico and extreme south-central Arizona (Lannoo 2005). It is found from sea level to approximately 1400 m (AZGFD 2013b). The state of New Mexico has listed the species as endangered (NMGF 2014) and Arizona has the species listed as one of special concern because of a lack of information about the species (AZGFD 2012).

Figure 59. Western Narrow-mouth Toad near Dolan Falls in West Texas. Photo by: Fernando Mateos-González 2015 CC BY-SA 2.0

Habitat & Spatial Ecology: This species is found in variety of habitats as long as there is water in the vicinity. In Arizona, they are known to use semi-desert grasslands, desert scrub, and oak woodlands (AZGFD 2013b). This species is generally thought to be nocturnal and has been described as "secretive" (Lannoo 2005). They breed in rain-fed ephemeral pools (natural and artificial), springs, flooded fields, and roadside ditches. *G. olivacea* migrates to these breeding pools overland and can travel over 600 m (Fitch 1956). Adults inhabit moist retreats and burrows during the day (Fitch 1956; Lannoo 2005) and likely hibernate during winter months (Fitch 1956).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.6 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Weighted land cover model for occurrences in arid grasslands and arid shrubby/scrubby vegetation types
- Urban areas and densely roaded areas modeled to show impacts of impervious surfaces on species

- Modeled preference for flatter terrain to slightly rolling hills and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.6 km) modeled for this species resulted in 36% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 10% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- The limited range of the Western Narrow-mouth Toad is in the south-central section of the Sonoran Desert—an area that may become reliant on artificial catchments for permanent waters as climate becomes hotter and drier reducing rain fed streams, springs, and other ephemeral waters.
- Future projected resistances are going to be lowest in areas of high spring density northeast of Phoenix and near agricultural fields throughout the Sonoran Desert—well out of the Western Narrow-mouth Toad's known range.
- Areas of light disturbance that promote temporary pool formation may be accessible for the Western Narrow-mouth Toad—agricultural lands, stock ponds, artificial catchments, and road side pools may provide moderate resistance refuges in otherwise high resistance areas (Figure 63).

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Western Narrow-mouth Toad for much of the study area. Habitat used by this toad will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the toad when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 10%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for Western Narrow-mouth Toad) the mean cluster size decreased by 28%. The Western Narrow-mouth Toad is presumed to have a relatively low vagility. At known average movement distances of 0.6 km, this amphibian has the lowest modeled dispersal distance of any anuran modeled in this report (Smith & Green 2005), and the xeric environment might reduce potential dispersal capabilities. At 0.6 km the Western Narrow-mouth Toad, under climate limited water scenario, the max cluster size decreases by 61%. At 2 km dispersal

distance, the climate limited waters scenario max cluster size decreases 33%. The least resistant areas in the range of the Western Narrow-mouth Toad are near riparian areas and in some of the flatter lands in its range (Figure 61). Many of the former suitable habitats that provided lower resistance in flat land areas, however, may be lost (Figure 62). Riparian areas may decline, but this species has been known to use ephemeral waters in its range. Riparian areas may decline, but this species has been known to use ephemeral waters in its range. Managed waters, stock ponds, temporary pools formed near road works, and agricultural land may provide many refuges for the species in the future. This toad occurs locally where small ephemeral pools develop, but artificial catchments may provide the only refuge in the driest and hottest parts of the future landscape, if rainfall does not sustain temporary pools. Increased evaporation and reduced rainfall may pose a serious threat to the ephemerally springs and streams that it uses in the uplands parts of its range.

Table 20. Western narrow-mouth Toad structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.6 km	1 km	2 km	0.6 km	1 km	2 km
Diameter (meters)	2649.2	6467.5	27538.1	2058.3	5588.7	27691.2
Clusters	5141	4351	2502	3287	2948	1944
Mean Cluster Size	1.2	1.4	2.5	1.08	1.2	1.8
Max Cluster Size	18	18	88	7	12	59
Network Modularity	-0.00095	-0.00059	-0.00034	-0.0025	-0.0013	-0.00074

Figure 60. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Western narrow-mouth Toad. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

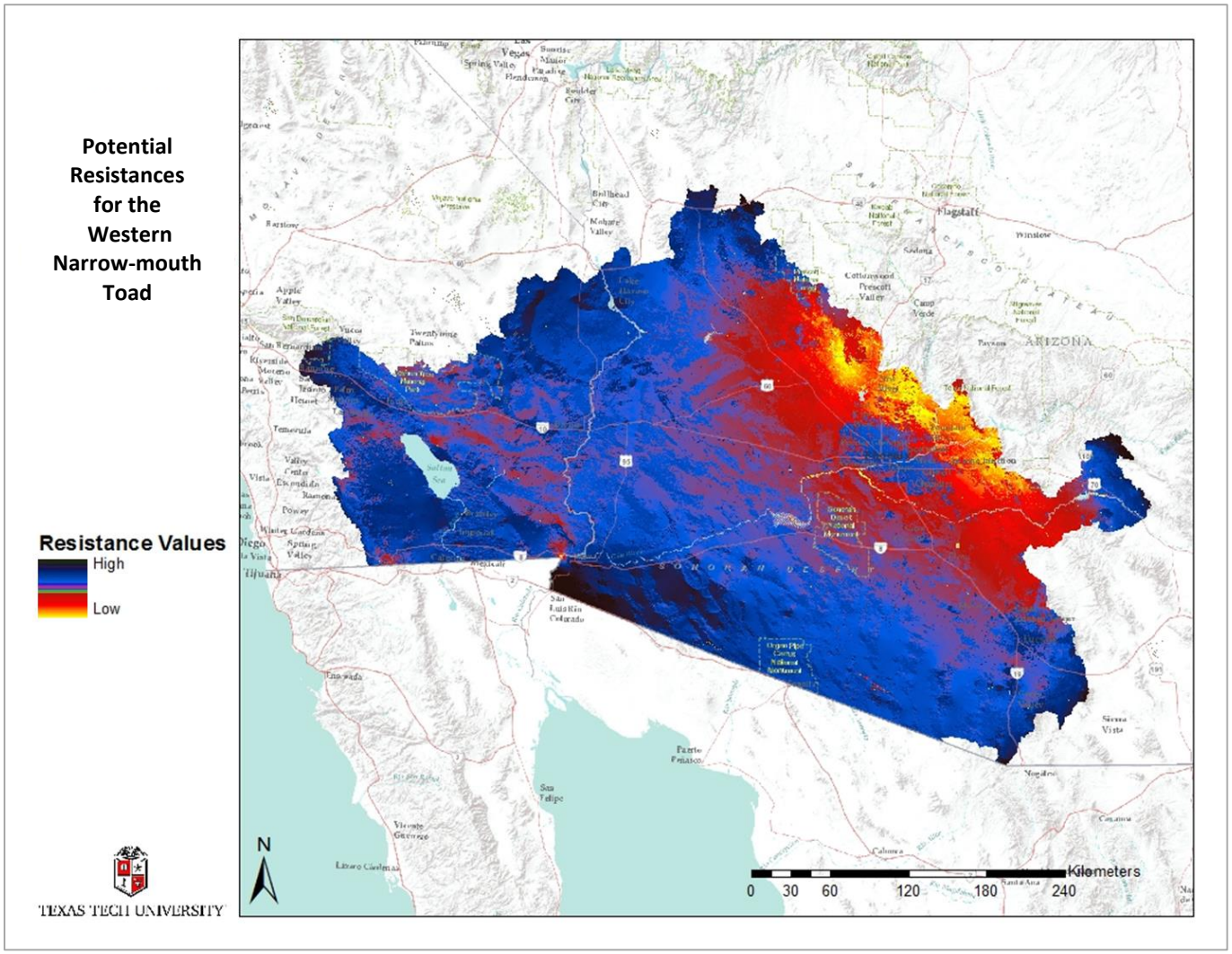


Figure 61. Potential resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert.

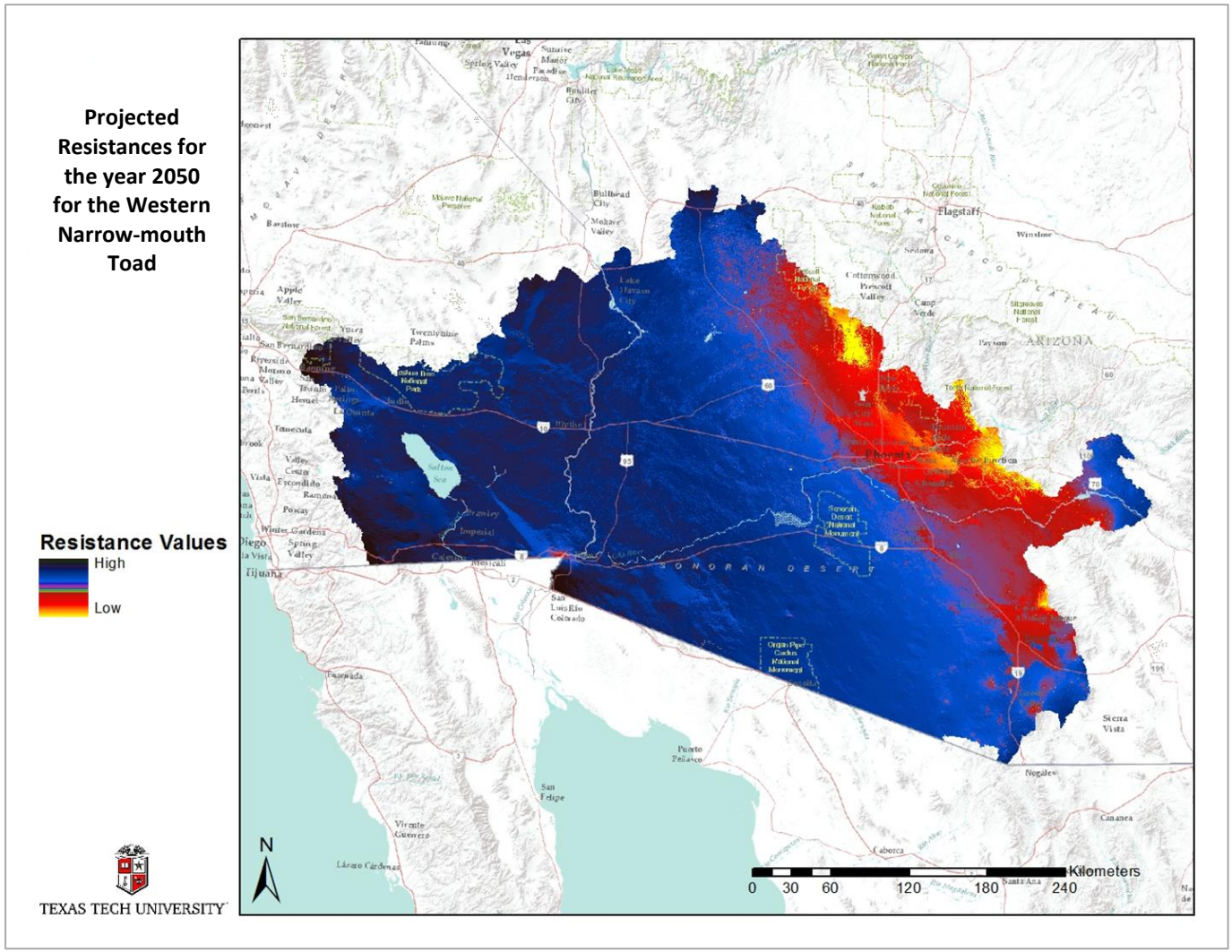
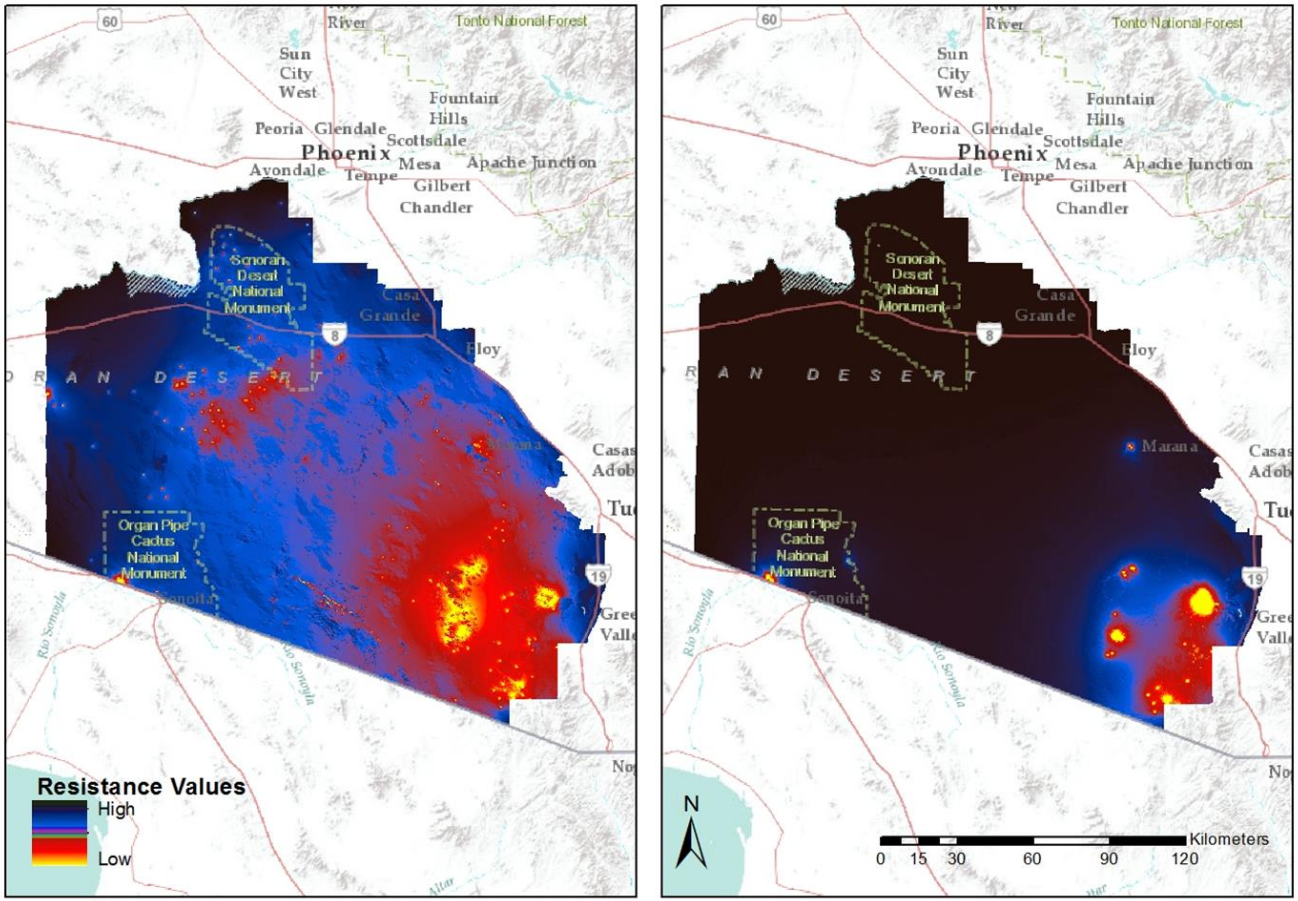


Figure 62. Projected resistances for the Couch's Spadefoot, Great Plains Toad, Red Spotted Toad, Sonoran Green Toad, Western Narrow-mouthed Toad, Southwestern Woodhouse's Toad, Plains Spadefoot, Mexican Spadefoot, and Lowland Burrowing Treefrog modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Reduced water availability occurs as movements across the landscape become harder due to increased resistances across much of the landscape. The Mogollon Rim area in the northeastern section of the graph will be the easiest area for animals to continue to disperse.



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Potential Resistances Subset for Current Conditions and Projected Resistances for the year 2050 for Sonoran Green Toad, Western Narrow-mouth Toad, and Lowland Burrowing Treefrog

Figure 63. Current potential resistances and projected resistances for the year 2050 for an area of the Sonoran Desert that reflects the known ranges of the Sonoran Green Toad, Western Narrow-mouthed Toad, and Lowland Burrowing Treefrog modeled using all known waters with current land cover and topographic conditions and climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B respectively. Relative resistances increase for this area of the Sonoran Desert under climate limited waters scenarios. Areas west of Interstate 19 have retained some connectivity; however, many of the waters become much more isolated. Little connectivity is maintained between the Organ Pipe Cactus National Monument, the Sonoran Desert National Monument, and the Buenos Aires National Wildlife Refuges and the San Miguel River has lost much of its corridor value due to land cover changes for the year 2050.

Arizona Tiger Salamander (*Ambystoma mavortium nebulosum*)

Figure 64. Arizona Tiger Salamander near Wasatch Utah. Photo by: Bryant Olsen 2008 CC BY-NC 2.0

Distribution & Status: Tiger salamanders are widespread across much of the United States. The subspecies *A. m. nebulosum* is known to occur in higher elevations, above 1,500 m, in Arizona as far south as Hannagan Meadows near the White Mountains (Collins 1981). It also occurs in other areas of the Colorado Plateau around the Four Corners region (Stebbins 1985).

Habitat & Spatial Ecology: This subspecies will use lotic and lentic fish-free waters, both natural and constructed, in middle to high-elevation subalpine grasslands, conifer forests/woodlands, and chaparral (Collins 1981). They breed aquatically and use mammal burrows and other cover during non-breeding periods (Stebbins 2003). Arizona Tiger Salamanders have been found up to 2 km away from last season's observations and 2 tiger salamanders were found between 3 and 4 km away from the nearest known source population (USFWS 2002b). California Tiger Salamanders were observed moving 600 m from a pre-existing pond to a newly created mitigation pond (Pechmann et al. 2001). Another study found a maximum observed movement of California Tiger Salamanders to be 248 m (Trenham 2001). The USFWS considered a new finding about California Tiger Salamanders being found in burrows up to 500 m away from natal ponds (Pitman 2005; USFWS 2007).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.4 km, 1 km, and 2 km
- These represent likely daily movement distances, possible max daily movement distance, and an seasonal dispersal scenario

Functional Model:

- Positively weighted land cover model for occurrences in arid grasslands and arid shrubby/scrubby vegetation types
- Urban areas and densely roaded areas modeled to show impacts of impervious surfaces on species

- Modeled preference for flatter terrain and canyon bottoms where rain filled waters and riparian areas occur but known to occur in rugged terrain as well
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.4 km) modeled for this species resulted in 38% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 5% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in riparian areas, areas of high spring density, and near agricultural fields northeast of Phoenix.
- Western and southern areas of the Sonoran Desert that have traditionally been too arid for tiger salamanders will reflect the conditions that will extend across more of the desert in the 2050 scenario.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Arizona Tiger Salamander for much of the study area. Habitat used by this salamander will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the salamander when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 5%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for the Arizona Tiger Salamander) the mean cluster size decreased by 28%. The Arizona Tiger Salamander is presumed to have a relatively low vagility. Tiger salamanders have average movement distances of 0.4 km, and this is the lowest dispersal modeled for amphibians this report, and the xeric environment might reduce potential dispersal capabilities. At 0.4 km the Arizona Tiger Salamander, under climate limited water scenario, the max cluster size decreases by 64%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The least resistant areas are in the current range of the Arizona Tiger Salamander that fall along the least dry sections of the edges of the Sonoran Desert Ecoregion; specifically in the northeastern and riparian corridor sections of the

graph (Figure 66). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to amphibian movement. Many of the former suitable habitats that provided lower resistance in may be lost (Figure 67). Increased urban growth and impervious surface density have reduced the habitat around cities and drier climates will reduce the number of permanent and ephemeral fishless waters that tiger salamanders use. Western and southern areas of the Sonoran Desert that have traditionally been too arid for tiger salamanders will reflect the conditions that will extend across more of the desert in the 2050 scenario.

Table 21. Arizona Tiger Salamander structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.4 km	1 km	2 km	0.4 km	1 km	2 km
Diameter (meters)	910.9	6467.5	27538.1	910.9	5588.7	27691.2
Clusters	5516	4351	2502	3420	2948	1944
Mean Cluster Size	1.1	1.4	2.5	1.04	1.2	1.8
Max Cluster Size	14	18	88	5	12	59
Network Modularity	-0.0013	-0.00059	-0.00034	-0.0045	-0.0013	-0.00074

Figure 65. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Arizona Tiger Salamander. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

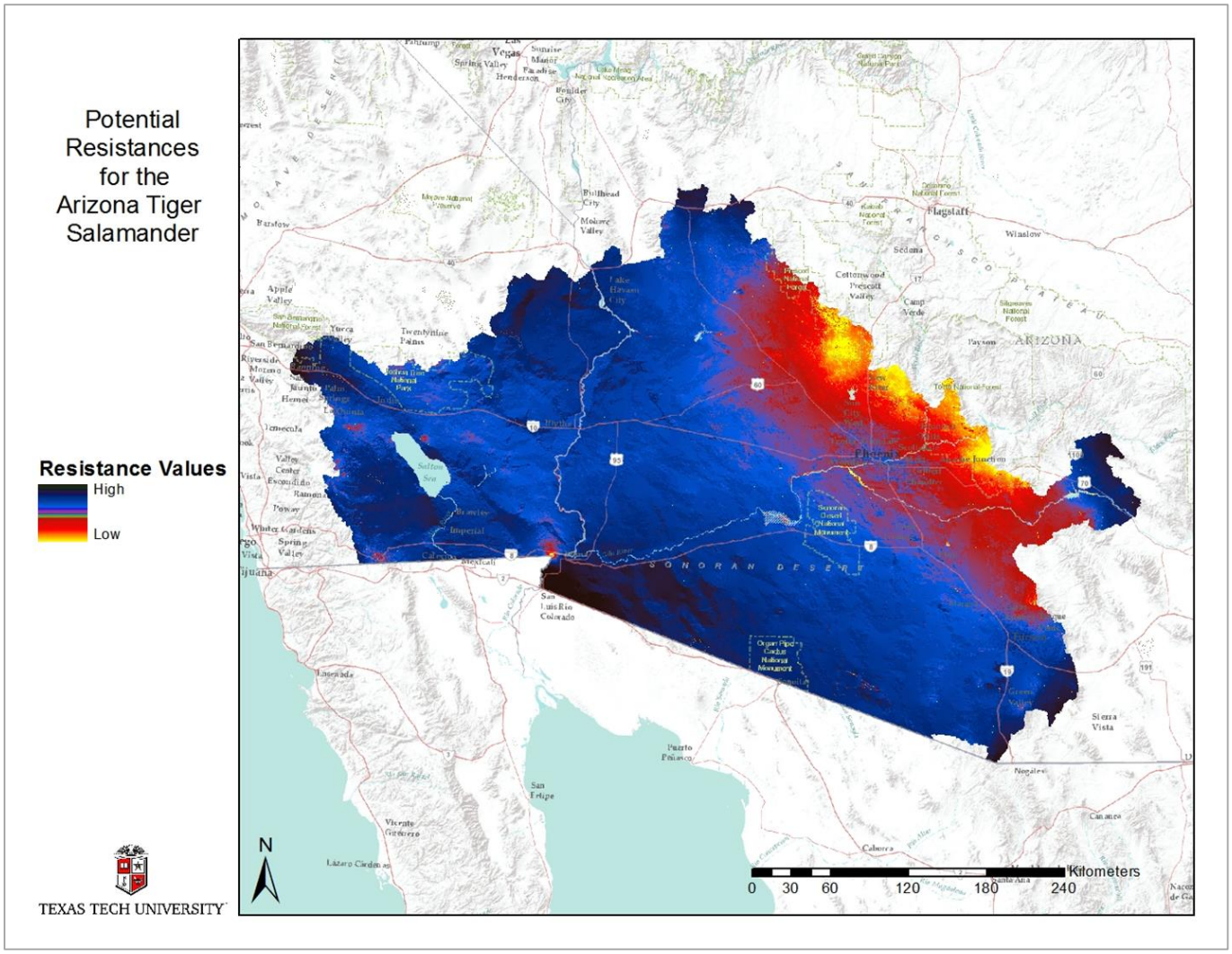

Figure 66.. Potential resistances for the Arizona Tiger Salamander under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Animal movement most facilitated by the density of waters in the northeastern section of the Sonoran Desert nearest the Mogollon Rim area and many small pockets of low resistance near isolated waters throughout the Sonoran Desert. This has traditionally been an area of Arizona Tiger Salamanders habitat where isolated waters like springs limit have historically limited native aquatic predators.

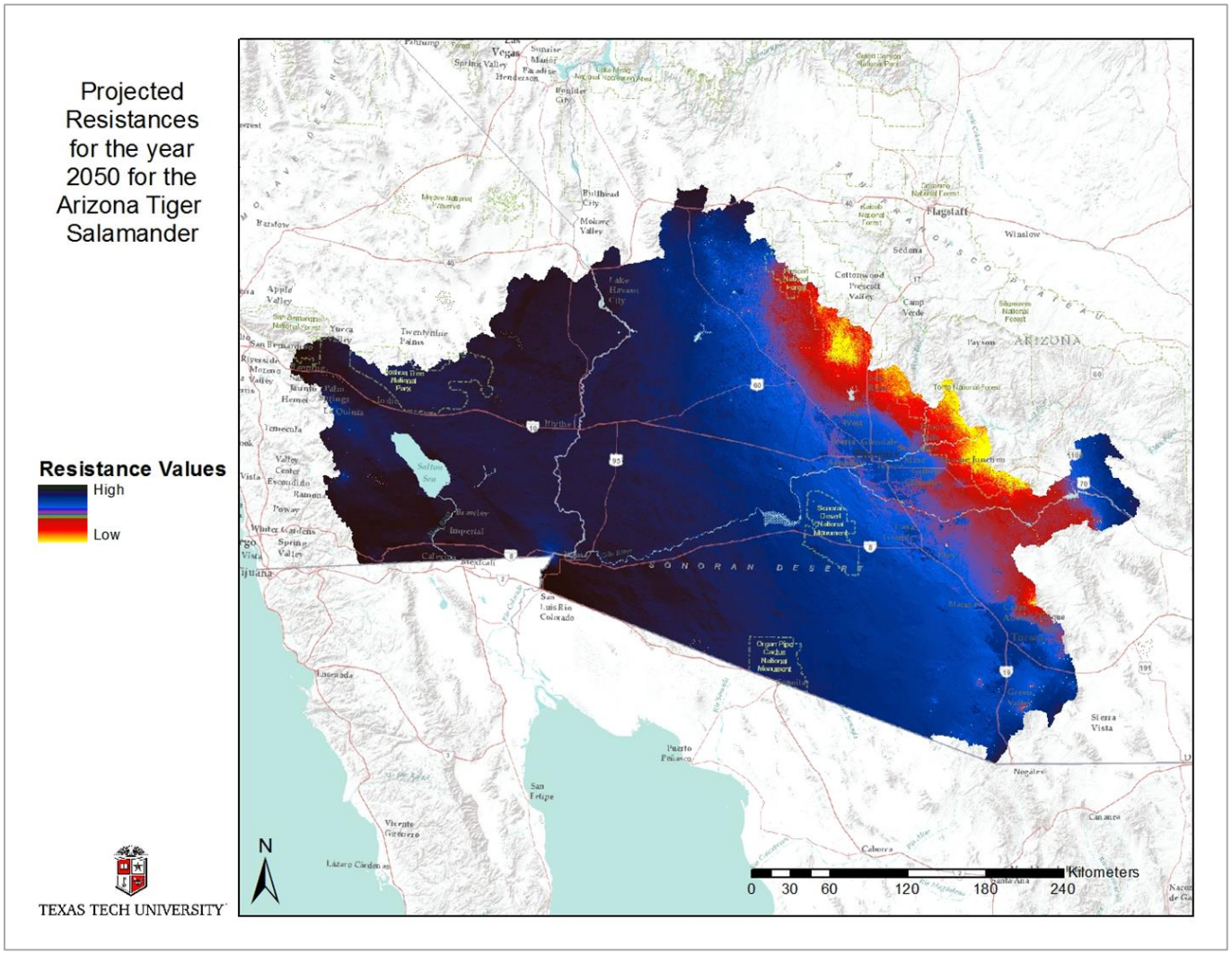

Figure 67. Projected resistances for the Arizona Tiger Salamander modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. With climate limited waters the Sonoran desert becomes much more resistant to amphibian movements. Managed waters and springs in the western section of the resistance graph act as islands in the landscape that have much lower connectivity potential. Areas to the northeast which have a high density of springs may retain low resistance.

Sonoran Tiger Salamander (*Ambystoma mavortium stebbinsi*)

Distribution & Status: The Sonoran Tiger Salamander subspecies is limited to the San Rafael Valley of Cochise and Santa Cruz counties in extreme southern Arizona with their range extending into Sonora, Mexico (AZGFD 2013a; USFWS 2002b). This species occurs in this area at elevations from approximately 1200 m to 1900 m (AZGFD 2013a). This subspecies has been federally listed as endangered since the beginning of 1997 (USFWS 2002b).

Figure 68. Sonoran Tiger Salamander in Santa Cruz County, AZ. Photo by: Thomas Brennan, © 2008.

Habitat & Spatial Ecology: The most important habitat characteristic for this subspecies is the availability of water from January through June for breeding (USFWS 2002b). Although earthen cattle tanks are the main suitable source of reliable water in this area (USFWS 2002b) due to the drying of the valley from human activity (Hendrickson & Minckley 1985), this subspecies used fishless semi-permanent and permanent waters such as springs, streams and ponds for breeding (Jones et al. 1988; AZGFD 2013a; USFWS 2002b). The San Rafael Valley where this species is found is mostly comprised of desert grassland with some oak and juniper woodlands appearing near the foothills of the mountains that delineate the valley (AZGFD 2013a).

Although the movements of this subspecies have been little studied, other species of *Ambystoma* have. Arizona Tiger Salamanders have been found up to 2 km away from last season's observations and 2 tiger salamanders were found between 3 and 4 km away from the nearest known source population (USFWS 2002b). California Tiger Salamanders were observed moving 600m from a pre-existing pond to a newly created mitigation pond (Pechmann et al. 2001). Another study found a maximum observed movement of California Tiger Salamanders to be 248m (Trenham 2001). The USFWS considered a new finding about California Tiger Salamanders being found in burrows up to 500m away from natal ponds Pitman 2005;USFWS 2007).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.4 km, 1 km, and 2 km
- These represent likely daily movement distances, possible max daily movement distance, and an seasonal dispersal scenario

Functional Model:

- Weighted land cover model for occurrences in arid grasslands and arid shrubby/scrubby vegetation types
- Urban areas and densely roaded areas modeled to show impacts of impervious surfaces on species
- Modeled for preference of flatter terrain and canyon bottoms where rain filled waters and riparian areas occur
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.4 km) modeled for this species resulted in 38% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 5% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Future projected resistances are going to be lowest in areas of high spring density and near agricultural fields around the San Rafael Valley.
- Projected models show reduced connectivity between waters in the year 2050 as land cover changes. Three distinct patches emerge, separated by Highway 89 and Route 82.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Sonoran Tiger Salamander for much of the study area. Habitat used by this salamander will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the salamander when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements modeled for this species, the mean cluster size reduced by 5%; at maximum modeled dispersal distances (2 km—which may be an unlikely long dispersal distance for the Sonoran Tiger Salamander) the mean cluster size decreased by 28%. The Arizona Tiger Salamander is presumed to have a relatively low vagility. Tiger salamanders have average movement distances of 0.4 km, and this is the lowest dispersal modeled for amphibians this report, and the xeric environment might reduce potential dispersal capabilities. At 0.4 km the Sonoran Tiger Salamander, under climate limited water scenario, the max cluster size decreases by 64%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33%. The least resistant areas in the range of the

Sonoran Tiger Salamander are near riparian areas and in some of the flatter lands in its range (Figure 70). With projected climate and land use change for the year 2050, the Sonoran Desert has an increased resistance to amphibian movement. Many of the former suitable habitats that provided lower resistance in flat land areas, however, may be lost (Figure 70). Under current conditions, there appears to be low resistance corridors between habitat west of Highway 89 and patches east of Highway 89. Projected conditions using the climate limited waters scenarios reduces the connectivity between these patches. Increased isolation occurs between habitat patches resulting in 3 distinct areas: clusters of connected waters east of Route 82, a reduced cluster of waters between Route 82 and Highway 89, and an almost completely separated cluster west of Highway 89 (Figure 70).

Table 22. Sonoran Tiger Salamander structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.4 km	1 km	2 km	0.4 km	1 km	2 km
Diameter (meters)	910.9	6467.5	27538.1	910.9	5588.7	27691.2
Clusters	5516	4351	2502	3420	2948	1944
Mean Cluster Size	1.1	1.4	2.5	1.04	1.2	1.8
Max Cluster Size	14	18	88	5	12	59
Network Modularity	-0.0013	-0.00059	-0.00034	-0.0045	-0.0013	-0.00074

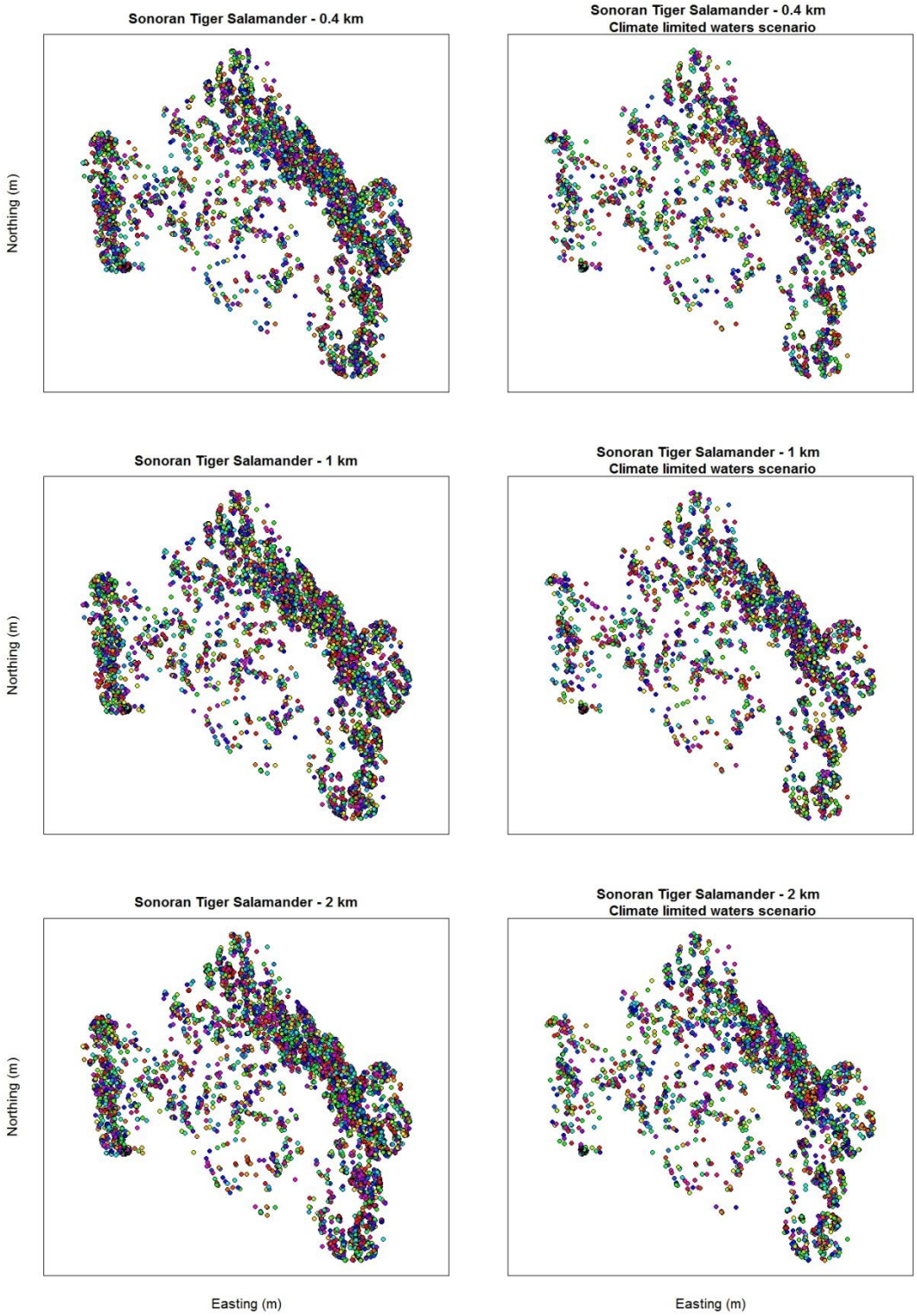

Figure 69. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Sonoran Tiger Salamander. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

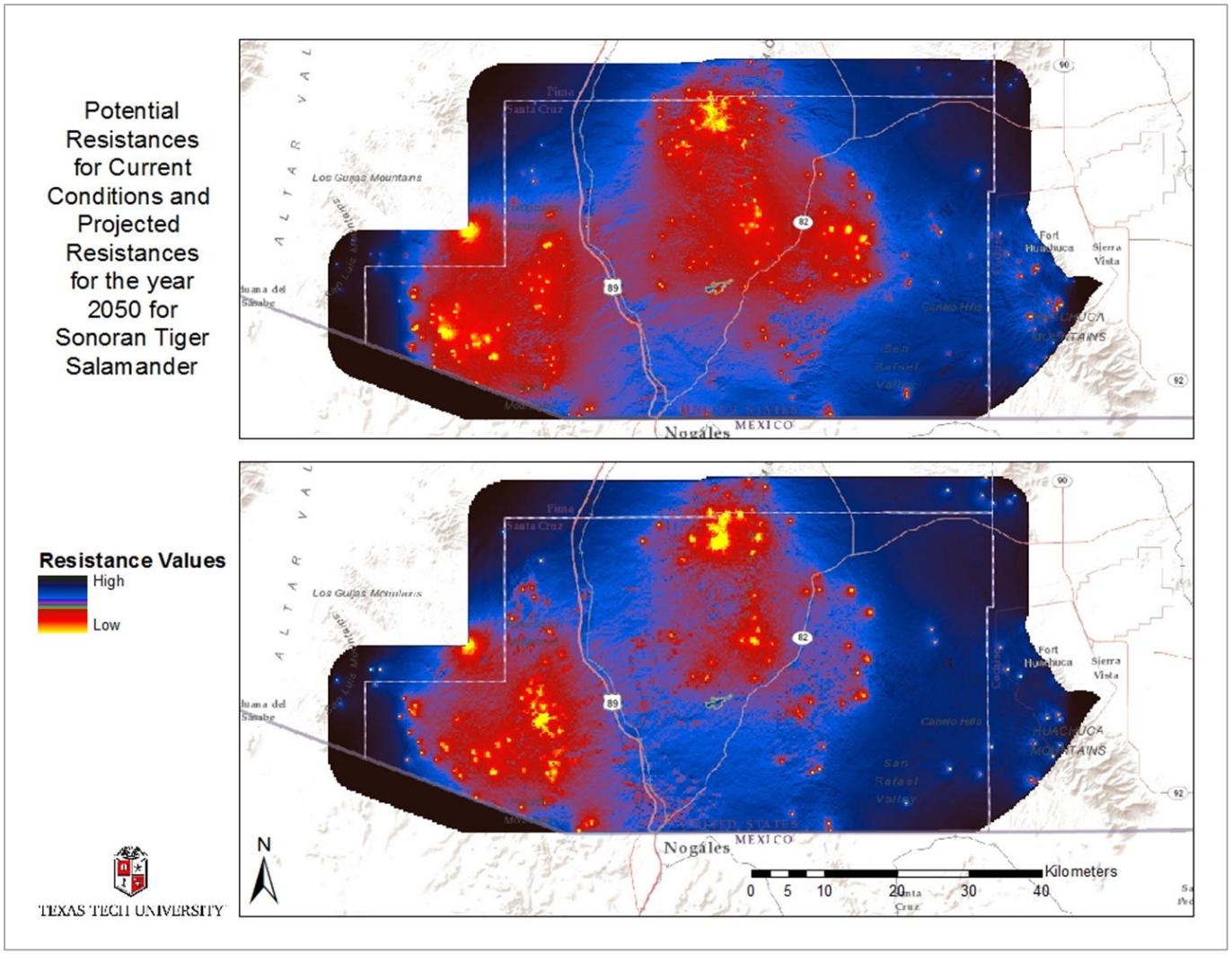

Figure 70. Potential resistances for the Sonoran Tiger Salamander under current conditions and all known isolated waters (top) and modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B (bottom). Circuit theory based resistance maps produced using Circuitscape for and around Santa Cruz County, AZ. Under climate scenarios with limited waters, the resistance to salamander movement is increased. Fewer waters and unfavorable climate conditions show a reduced connectivity between areas on each side of the Route 82 and Highway 89 corridors in the future.

Desert (Mexican) Bighorn (*Ovis canadensis mexicana*)

Figure 71. Desert Bighorn at a natural tinaja in the Barry M. Goldwater Air Force Range.

Distribution & Status: Bighorn sheep are found throughout the intermountain west ranging from high elevation alpine meadows in the Sierra Nevadas and Rocky Mountains to the desert mountain ranges of the southwestern United States and Mexico (Shackleton 1985). *O. c. mexicana* is found in the Sonoran Desert in the United States in Arizona, New Mexico and their range pushes into western Texas (Shackleton 1985; Hoffmeister 1986; ADBSS 2004). It is possibly separated from *O. c. cremneobates* and *O. c. nelsoni* by the Colorado River (Shackleton 1985). Anthropogenic activities such as losses to and changes in habitat have caused population declines (Johnson & Swift 2000; Krausman 2000) resulting in fragmented populations across the southwest (Singer, Bleich, et al. 2000; Singer, Papouchis, et al. 2000; Bleich et al. 1990; Epps et al. 2005). Because of population declines, local extinctions, and continuing threats to the species Arizona has listed it as a species of special concern (AZGFD 2012).

Habitat & Spatial Ecology: Bighorn sheep use semi-arid to arid grasslands (Shackleton 1985) in the Sonoran Desert in areas with access to steep rocky terrain (Van Dyke et al. 1983). The use of rocky terrain and other areas near sloped terrain between 40% and 80% grades are preferred by bighorn sheep (Alvarez-Cardenas et al. 2001; Van Dyke et al. 1983). Bighorn also prefer being near escape terrain like steep, rocky slopes (Van Dyke et al. 1983; Zeigenfuss et al. 2000; Calvert 2015). Water may be a limiting factor for bighorn sheep (Rubin et al. 2002), although this is controversial (Broyles 1995; Rosenstock et al. 2001) . Potentially if more water was available, more high quality habitat would be accessible in the Sonoran Desert (Bleich et al. 2010). In a habitat modelling study for bighorn sheep, Zeigenfuss *et al.* (2000) removed from core areas any land further than 3.2 km from known perennial water sources. During the summer months in desert environments, habitat use and distribution has been noted to gravitate around available water (Leslie & Douglas 1979). Cain *et al.* (2008) describe the average distance of females from water sites to be 3 km during a study in the Cabeza Prieta National Wildlife Refuge. Another study found that sheep did not move farther than 3.5 km away from water during summer movements (Longshore et al. 2009) while Monson (1965) noted that bighorn will be found 5 km away from perennial waters (As cited in: ADBSS 2004). Intramountane movements near the border with Mexico in south central Arizona showed

bighorn females moving an average of 1.6 km with a maximum distance of 4.9 km (Flesch et al. 2010).

Model Basis:

Structural Model:

- Modeled dispersal distances of 1.6 km, 3.0 km, and 5 km
- These represent known average daily intramontane movements, average female distance to water sites, and a max distance away from perennial waters scenario respectively

Functional Model:

- These animals are generally found in semi-arid to arid grasslands in rocky terrain
- More weight was given to land cover variables to account for preferences
- A heavy weight was also given to the topographic position and slope as the terrain they prefer is thought on grades between 40% and 80%
- The weighted equation also accounted for impacts of human developments that might remove habitat and for roads that might be a disturbance
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (1.6 km) modeled for this species resulted in 26% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (5 km), the number of clusters increased by 1% under the climate limited water scenario
- The average number of waters per cluster decreased by 25% and 43% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Areas like the northeastern section of the graph will continue to provide resilient movement capabilities for Bighorn, but managed waters will act as water “islands” across much of the southern and western sections of the U.S. Sonoran Desert.
- Large roads and rivers increased resistances for intermontaine as well as intramontane movements in both scenarios.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Desert Bighorn for much of the study area. Habitat used

by bighorn will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the bighorn when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species, the mean cluster size reduced by 25%; at maximum modeled dispersal distances (which represents the max distance a bighorn was found away from a perennial water source: 5 km) the mean cluster size decreased by 43%. At 1.6 km the Desert Bighorn, under climate limited water scenario, the max cluster size decreases by 35%. At 5 km dispersal distance, the climate limited waters scenario max cluster size decreases 45%. Waters across the western and southern sections of the Sonoran Desert have moderate connectivity and low to moderate resistances under current scenarios (Figure 73). Mountain ranges in and near urban centers provide only moderate to low resistance compared to the urban areas that are adjacent to them. This however can be a problem as large roads, rivers, and developments can isolate these mountains and sheep that inhabit them–the small ranges to the south of Phoenix are a good example and that isolation is clearly seen in Figure 73. The lowest resistances to movement appear in the northeastern sections of the graph just the northeast of the Phoenix urban area because of the density of waters in this region. Under climate limited water scenarios in the year 2050, this area still provides the lowest resistance to movements, although it has a slightly higher resistance to movements. In the 2050 graph (Figure 74), the urban centers of Phoenix and Tucson have expanded and become more dense; mountain ranges in and near these areas are more developed and much more resistant to bighorn movements. Moving into the Lower Colorado River Valley and surrounding areas of the western and southern parts of the Sonoran Desert, waters become “islands” with high resistance to movement between them. Populations of bighorns in these areas will have more resistance to intermontane movements. As climate change increases temperatures and decreases precipitation, bighorns will become more reliant on managed waters. Managed waters may provide the moisture that they might need to help offset thermoregulatory stresses and may have received from vegetation under normal conditions.

Table 23. Desert Bighorn structural model graph analysis results. All waters scenario reflect all available isolated waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited waters scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	1.6 km	3 km	5 km	1.6 km	3 km	5 km
Diameter (meters)	21851.6	99465.3	257111.4	12685.1	69028.5	185676.4
Clusters	3116	1414	572	2309	1254	577
Mean Cluster Size	2.0	4.4	10.86	1.5	2.837	6.2
Max Cluster Size	55	432	1238	36	193	680
Network Modularity	-0.00039	-0.00029	-0.00026	-0.00084	-0.000602	-0.000506

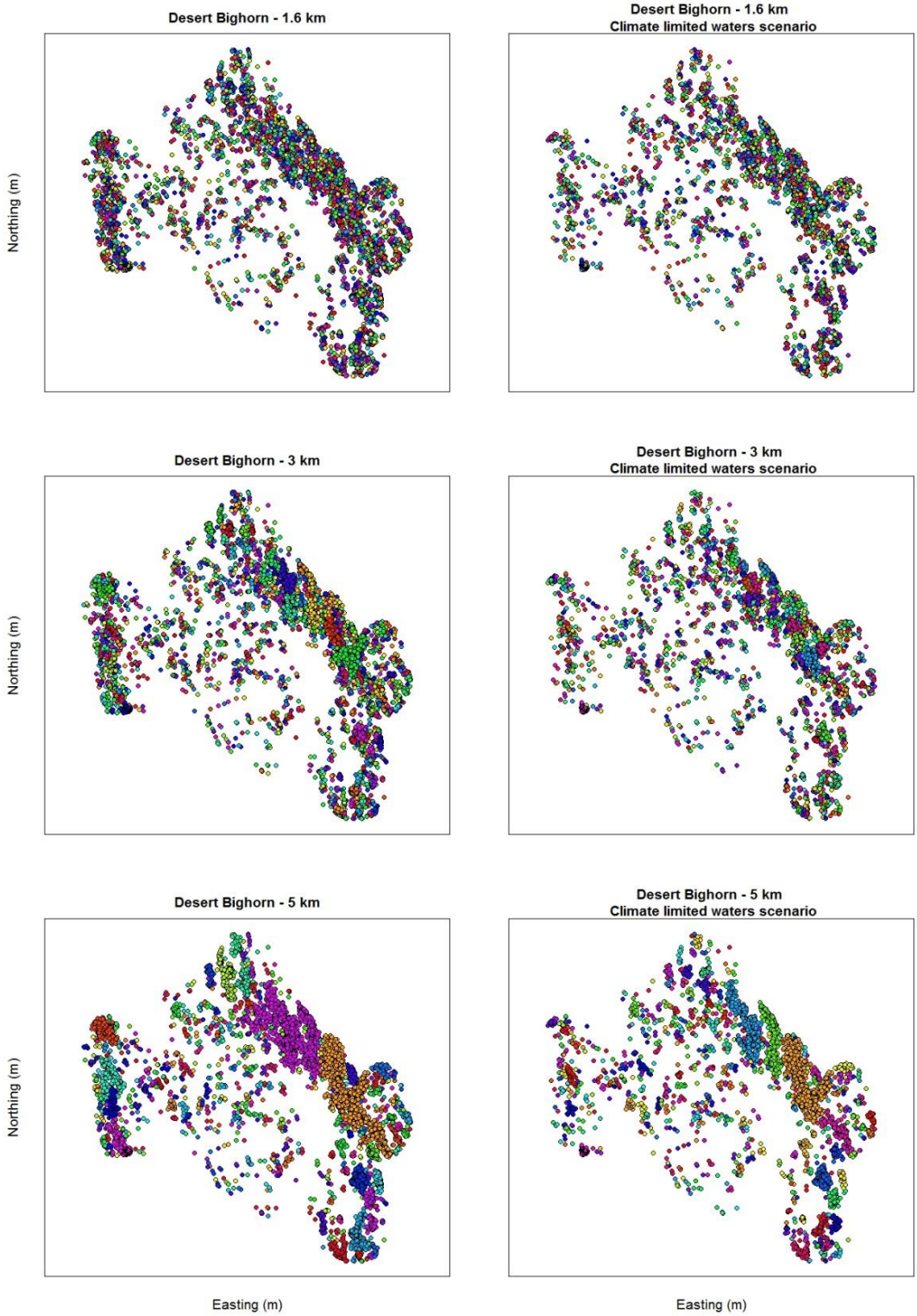

Figure 72. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Desert Bighorn. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

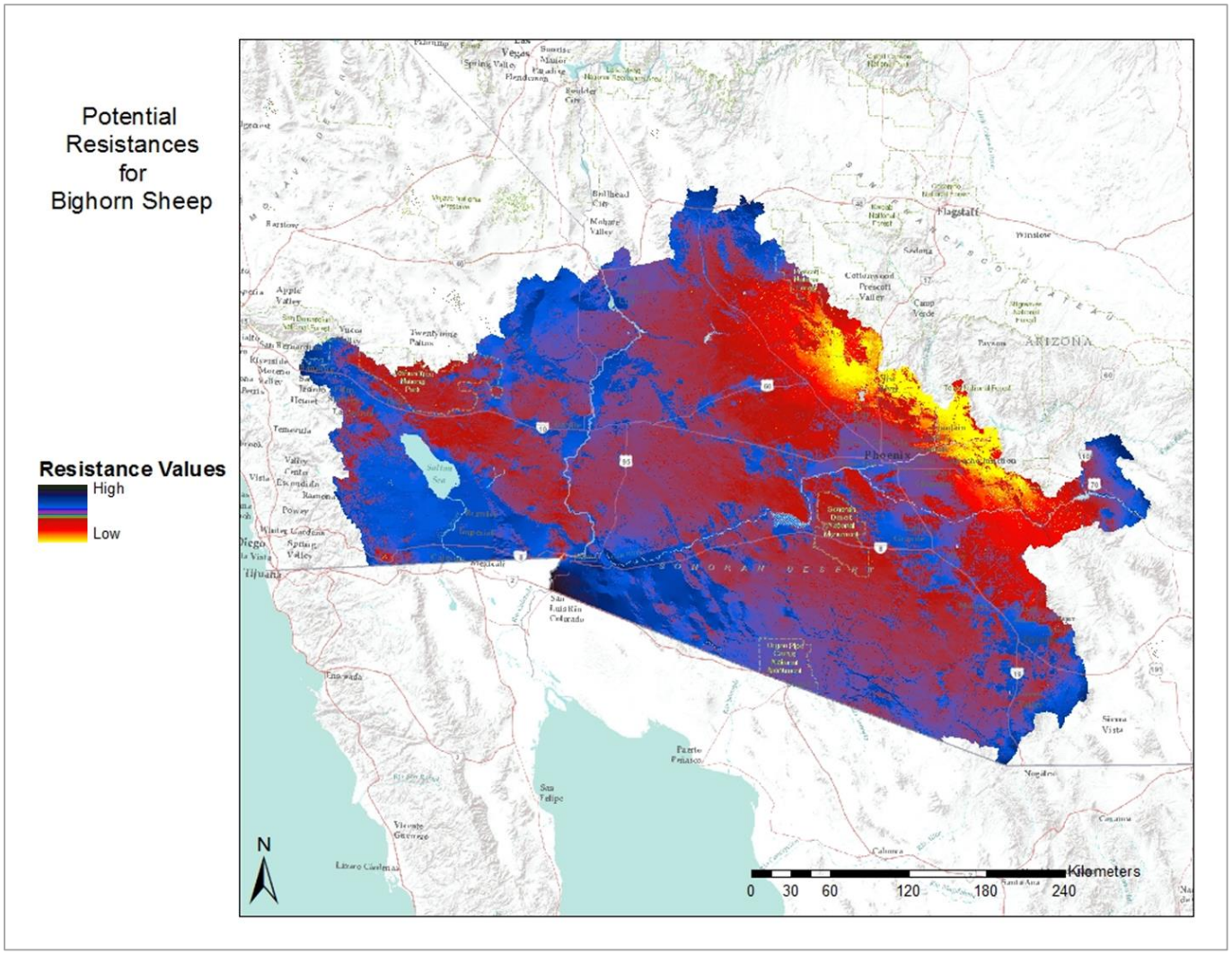

Figure 73. Potential resistances for the Desert Bighorn under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Due to high densities of water sites in the northeastern section of the map, resistance appears lowest there. Many of the mountain ranges in close proximity of urban areas are also lower resistance areas. Areas that might facilitate intramontane movements appear to have low to moderate resistances across much of the Sonoran Desert provided no large roads or rivers move through these areas.

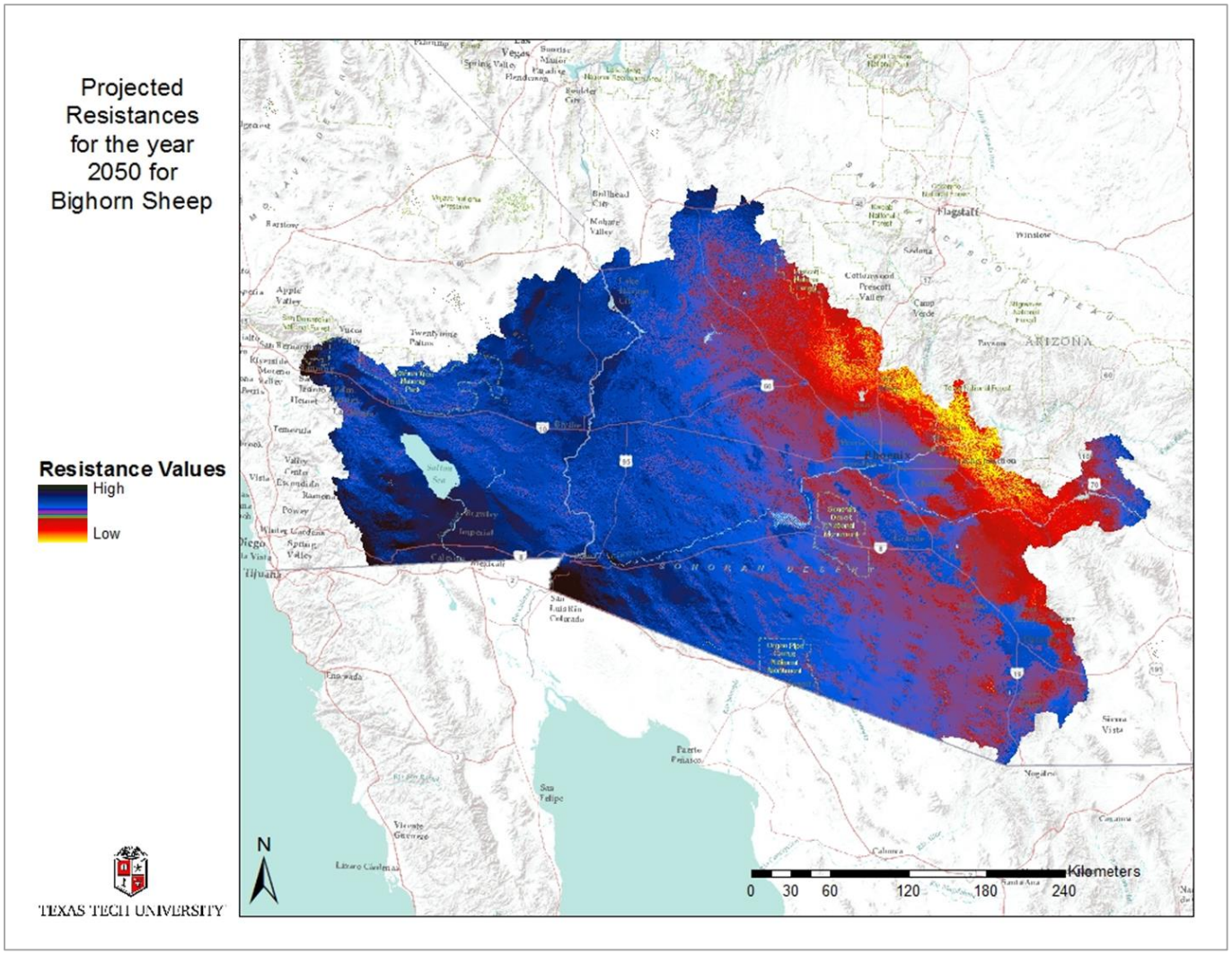

Figure 74. Projected resistances for Desert Bighorn modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. With climate limited waters the Sonoran desert becomes much more resistant to Bighorn movements. Managed waters and springs in the western section of the resistance graph act as islands in the landscape that have much lower connectivity potential. Areas to the northeast which have a high density of springs may retain low resistance to animal movements.

Mule Deer (*Odocoileus hemionus*)

Distribution & Status: Mule Deer are widespread across the United States including Arizona. The subspecies *O. h. crooki*, is located in central and southern Arizona (Hoffmeister 1986). It is thought that the deer might be absent in the driest reaches of the Sonoran Desert in the southwest corner of the state (Anderson & Wallmo 1984; Hoffmeister 1986). They generally are found below 1400 m but range from 60 m to 2225 m in elevation (Heffelfinger 2006; Krausman 1978; Mcculloch 1972).

Figure 75. Mule deer at an artificial catchment on the Barry M. Goldwater Air Force Range

Habitat & Spatial Ecology: Mule Deer are found in semi-desert grasslands and chaparral and shrub vegetation types (Heffelfinger 2006). Although able to use a variety of habitats, Sonoran Desert mule deer appear to prefer slight rocky and mountainous open terrain with slight slopes (Ordway & Krausman 1986) as long as sufficient forage and water are available. They are most likely to use browse shrub and shrub fruits, supplemented by forbs, succulents, and cactus fruits (Heffelfinger 2006). They use slopes and washes throughout creosote flats and avoid areas devoid of browse (Ordway & Krausman 1986; Heffelfinger 2006). Habitat use varies seasonally by sex - does tend to stay in foothills and mountains all year while bucks will travel to and from rugged areas and flats (Ordway & Krausman 1986). They will also use desert riparian areas to stay closer to reliable water sources (Heffelfinger 2006).

In a study at the Santa Rita Experimental Range, deer made daily movements of less than 1.8 km (Rodgers 1977), but will alter habitat use and movements according to water distribution , (Ordway & Krausman 1986) Seasonal migrations of Mule Deer can be as far as 14 km to move to seasonal water (Truett 1987; Rautenstrauch & Krausman 1989). The average distance to catchments for Mule Deer was 3 km, but during the driest seasons (spring and early summer before rains), Mule Deer tend to stay closer to waters (Krausman & Etchberger 1995). Another study found the same trend to stay closer to waters but found that deer would range up to 5km for water as it became scarcer (Rautenstrauch & Krausman 1989).

Model Basis:

Structural Model:

- Modeled dispersal distances of 3 km, 5 km, and 10 km

- These represent known average distances from catchments, scarce water ranging movements, and a max dry season movement to reach water.

Functional Model:

- These animals are generally found in semi-arid grasslands to chaparral and shrub vegetation regimes
- More weight was given to land cover variables to account for preferences of terrain that provided open habitat but avoidance of barren areas.
- Topographic position influences mule deer landscape resistance as they seem to prefer light slopes and open terrain
- The weighted equation also accounted for impacts of roads that might be a disturbance although
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (3 km) modeled for this species resulted in 11% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (10 km), the number of clusters increased by 15% under the climate limited water scenario
- The average number of waters per cluster decreased by 25% and 43% at daily and maximum modeled dispersal distances for climate limited water scenarios
- The northeastern section of the resistance graph shows lowest resistance to movement because of the high densities of waters.
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Suburban areas of Phoenix and Tucson as well as agricultural lands—especially those in and around the Lower Colorado River Valley—will serve as refuge for this adaptable species.
- Areas like the northeastern section of the graph will continue to provide resilient movement capabilities for Mule Deer, but managed waters will act as water “islands” across much of the southern and western sections of the U.S. Sonoran Desert.
- Mule Deer are known to change movement behavior to respond to water availability and as waters become less common in much of the Sonoran Desert, it is very likely they will follow suite.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Mule Deer for much of the study area. Habitat used by this deer will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the deer when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species (3 km, a known average distance from artificial catchments and good proxy for daily movement capabilities), the mean cluster size reduced by 36%; at maximum modeled dispersal distances (10 km – the upper limit of distances traveled to access water) the mean cluster size decreased by 50%. At 3 km the Mule Deer, under climate limited water scenario, the max cluster size decreases by 55%. At 10 km dispersal distance, the climate limited waters scenario max cluster size decreases 54% (Table 24). Large clusters emerge in the northeastern section of the Sonoran Desert (Figure 76), which partly because of the density of these waters, is one of the least resistant areas to Mule Deer movement (Figures 77 & 78). This coupled with rocky open terrain with slight slopes and a variety of vegetation allows the adaptable Mule Deer low resistance to movement. Under current resistance scenarios, landscape has moderate resistances in all but the most developed urban areas, the most barren desert, and the steepest terrains. In the farthest reaches of the U.S. Sonoran Desert, in the southern sections typified of sand dunes and volcanic rocks the Mule Deer has high resistance to movement. In the 2050 scenario (Figure 78), the Mule Deer also has high resistances near the southwestern sections of the Sonoran Desert. It also has much more resistance to movement than current scenario through the central areas of the Sonoran Desert to the west of the Phoenix metro area. Throughout the Sonoran however are agricultural areas that may act as corridors or refuges—especially along rivers like the Colorado, Gila, and Salt. Managed waters may be necessary to facilitate dispersal or migratory movements between dry and wet seasons. Phoenix metro area has an unusually low resistance in the future scenario, but Mule Deer are known to be habitat generalists which can readily survive on urban greenery. Lack of predation, abundant water sources, and plenty of forage often help them survive, thrive, and become urban pests. As habitat degrades in the surrounding area, human-wildlife conflicts may have a potential for increasing if Phoenix becomes a haven for thirsty Mule Deer.

Table 24. Mule Deer structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	3 km	5 km	10 km	3 km	5 km	10 km
Diameter (meters)	99465.3	257111.4	700614	69028.5	185676.4	594767.4
Clusters	1414	572	128	1254	577	147
Mean Cluster Size	4.4	10.86	48.6	2.8	6.2	24.2
Max Cluster Size	432	1238	4454	193	680	2035
Network Modularity	-0.00029	-0.00026	-0.00023	-0.000602	-0.000506	-0.00045

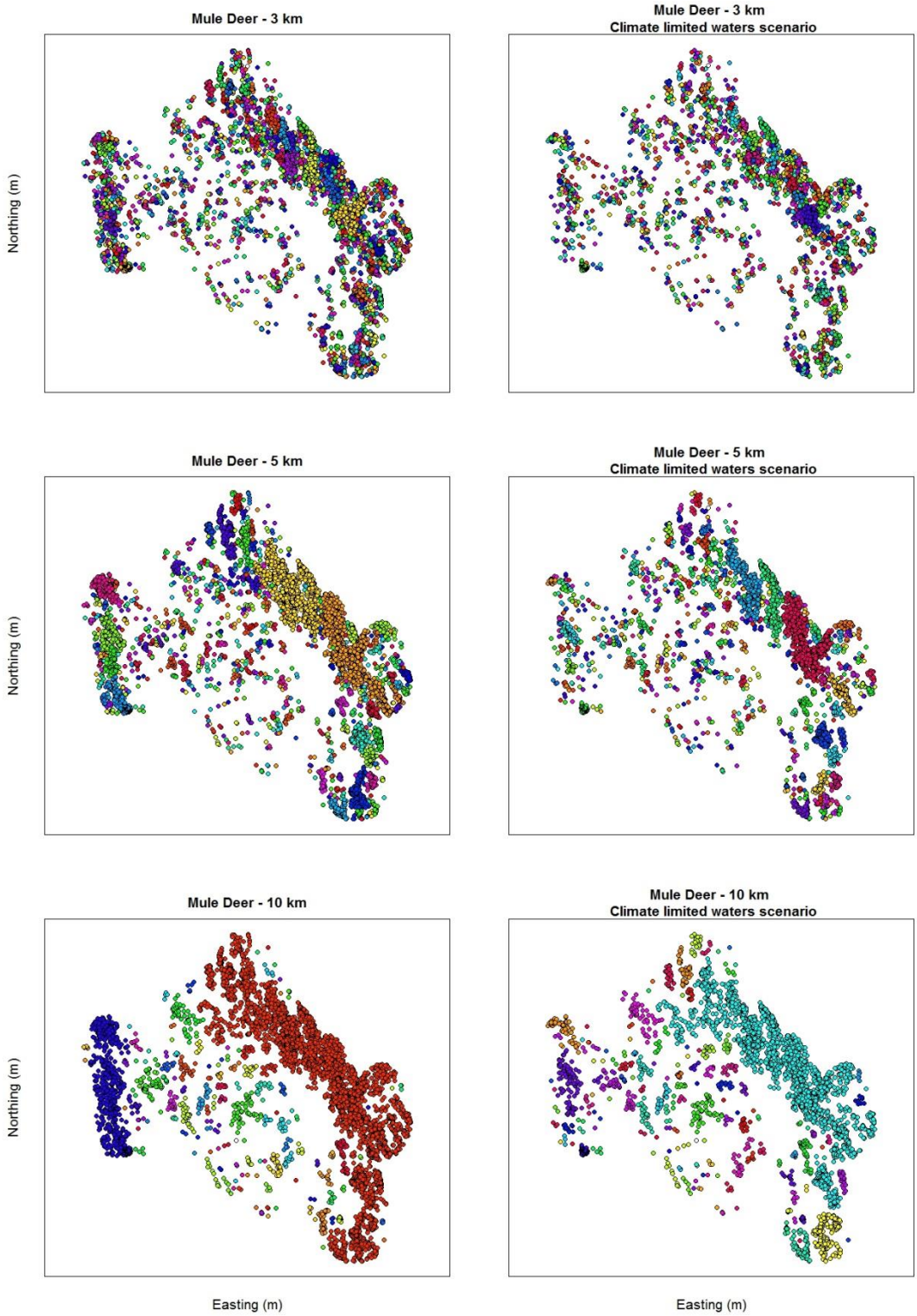

Figure 76. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Mule Deer. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

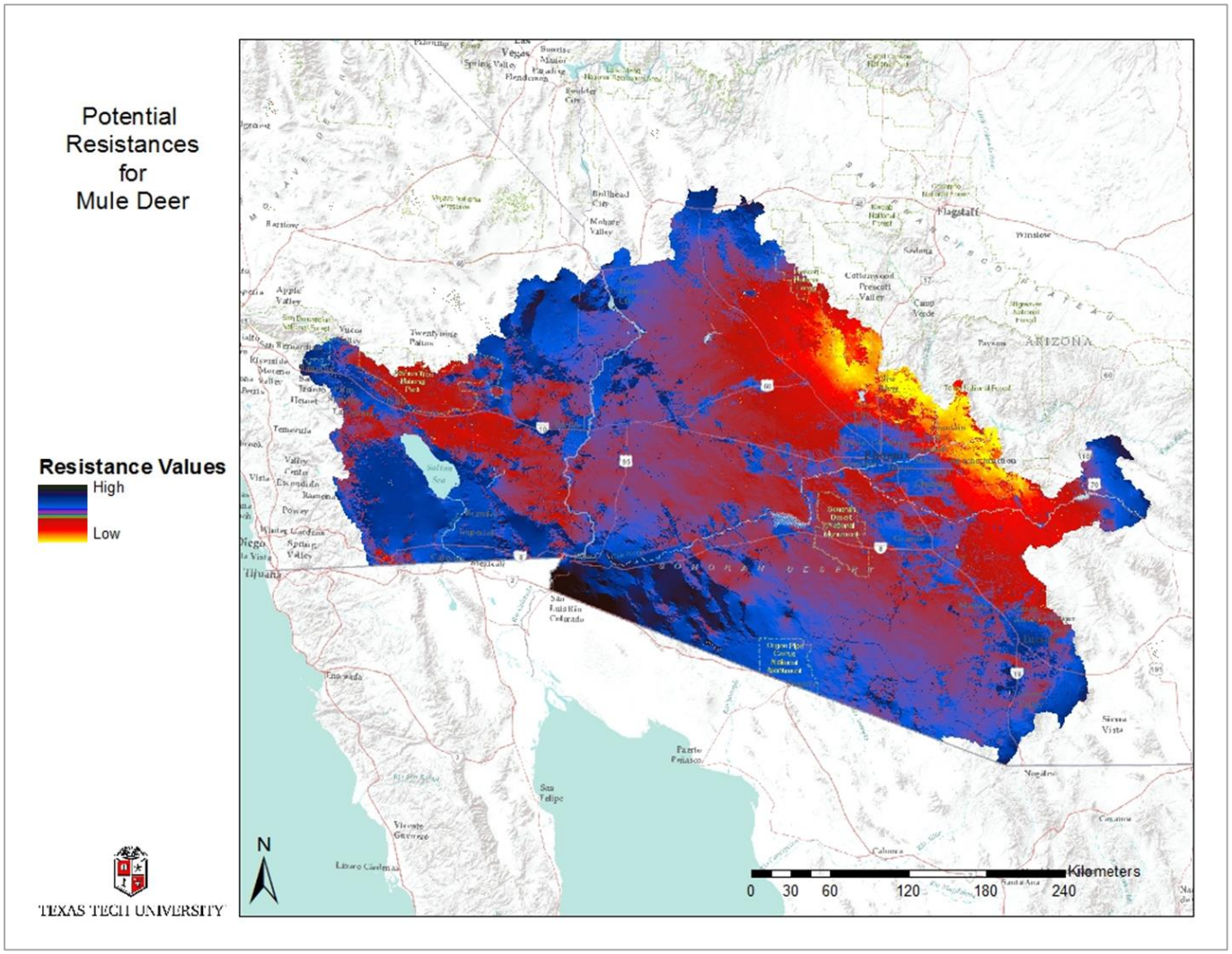

Figure 77. Potential resistances for the Mule Deer (Sonoran Desert subpopulation) under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. The area northeast of Phoenix has the lowest resistance to animal movement but much of the Sonoran Desert is accessible to mule deer. The densest and most developed areas of Phoenix have high resistance to mule deer but outlying suburbs and exurbs that are near agricultural land have low resistances. Resistances become highest near the Vidrios area and north of El Pinacante and Gran Desierto de Altar Sonora, Mexico.

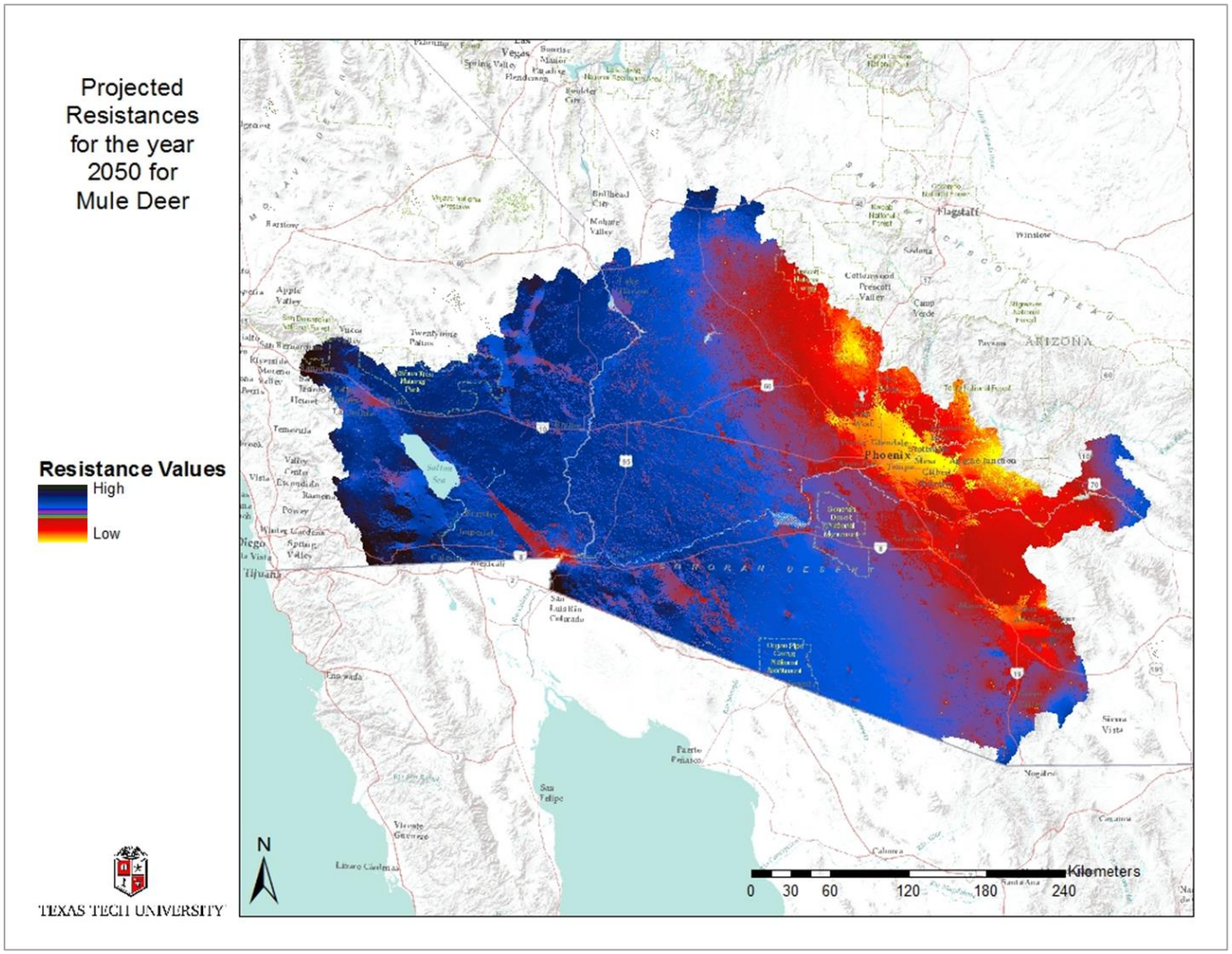

Figure 78. Projected resistances for Mule Deer (Sonoran Desert subpopulation) modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Phoenix and the areas northeast thereof are the least resistant to mule deer movement. Surrounding areas also have a low resistance measures as do agricultural lands in the other sections of the Sonoran in and around the Lower Colorado River Valley.

Sonoran Pronghorn (*Antilocapra americana sonoriensis*)

Distribution & Status: Pronghorn antelope are found across much of Arizona in grasslands (Hoffmeister 1986). *A. americana sonoriensis* is located in the southwestern section of the state of Arizona and into Sonora, Mexico (Thompson-Olais 1998) and is found from approximately 120 m to 500 m in elevation (AZGFD 2002). Much of the United States range is in the southwest region of the desert in the Cabeza Prieta Wildlife Refuge and the Barry M. Goldwater Air Force Range (AZGFD 2002). This species was listed as endangered in 1967 and continues to have a small population in the United States (Thompson-Olais 1998).

Figure 79. Sonoran Pronghorn on the Barry M. Goldwater Air Force Range. Photo by: Aaron Alvidrez

Habitat & Spatial Ecology: This subspecies of pronghorn inhabit broad alluvial valleys (Thompson-Olais 1998) and areas with low stable sand dunes that retain meadow-like conditions at or in near proximity (Hoffmeister 1986). Sonoran Pronghorn prefer flat land but will sometimes use gentle slopes and washes, and they rarely venture into rugged terrain (Hervert et al. 2005; O'Brien et al. 2005; Thompson-Olais 1998; AZGFD 2002). The species selects creosote-bursage, paloverde-saguaro, or desert short grasses assemblages (Hoffmeister 1986; AZGFD 2002), and it is suggested that areas with the presence of chain fruit cholla cactus might be extremely important to the animal (Hervert et al. 2005). These areas might however have a low density of vegetation (deVos Jr & Miller 2005) and provide long site lines for predator identification and evasion. There is conflicting evidence on how they select habitat based on water access and road proximity (deVos Jr & Miller 2005). Hoffmeister (1986) suggests that the availability of free water is important to the presence of the pronghorn; most animals are found within 1 km of water, but will commonly range up to 10 km for water (deVos Jr & Miller 2005; Hughes 1991). Even if it is not a necessity, the Sonoran Pronghorn is known to be an opportunistic drinker (AZGFD 1986).

Model Basis:

Structural Model:

- Modeled dispersal distances of 1.0 km, 5.0 km, and 10 km
- These represent known highest daily use of water, conservative average distance from waters for wet/dry seasons, and max observed distances from water used, respectively.

Functional Model:

- These animals are primarily found in areas of flat terrain with little cover.
- More weight was given to land cover variables to account for preferences away from dense vegetation
- A heavy weight was also given to slopes as the areas they prefer are more likely to occur in flats and outside of rugged areas
- The weighted equation also accounted for impacts of human developments that might contribute to habitat degradation and animal sensitivity to human activity
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (1 km) modeled for this species resulted in 32% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (10 km), the number of clusters increased by 15% under the climate limited water scenario
- The average number of waters per cluster decreased by 14% and 50% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Human development and loss of waters will decrease available usable habitat in certain areas but resistance of movement between waters may decrease in some areas as (such as the area around the Colorado River, woody vegetation is lost to hotter and drier climate

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Sonoran Pronghorn for much of the study area. Habitat used by this animal will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the antelope when comparing current and climate limited water scenarios. This is important to consider because at the average daily movements known for this species (1 km), the mean cluster size reduced by 14%; at maximum modeled distances (10 km – maximum known distance for water use) the mean cluster size decreased by 50%. At 1 km the antelope, under climate limited water scenario, the max cluster size decreases by 33%. At 10 km dispersal distance, the climate limited waters scenario max cluster size decreases 54% (Table 25). The entire system of water sites has a reduced redundancy in future scenarios. This can be seen in

reduced network modularity, smaller average clusters size, smaller maximum cluster sizes, and larger number of clusters for climate limited water scenarios. However, the majority of waters this will occur to in the Sonoran Desert will be outside of the current range of the Sonoran Pronghorn. Many of the waters that will likely be lost inside the current range are located in rocky habitat that the animals do not generally use. Sonoran Pronghorns, which are known opportunistic water drinkers, will most likely need more "permanent" waters to be available to continue to survive in its current range as these conditions push the species to the edge of their physiological tolerance. Additionally, current water management for the pronghorn includes waters that are actively filled and moved by managers, so they were not mapped and will not be affected by declining waters unless funding for management declines (USFWS 2015). Resistances graphs (Figure 81) have noticeable reductions of connectivity between current conditions and future projections. The current conditions reflect known ranges on the Barry M. Goldwater Airforce Range with corridors leading into the Cabeza Prieta National Wildlife Preserve and Organ Pipe National Monument. These connectivity corridors of low resistance areas disappear in the 2050 scenario, increasing movement costs between habitat patches. This could cause problems for low genetic diversity in an already limited population.

Table 25. Sonoran Pronghorn structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	1 km	5 km	10 km	1 km	5 km	10 km
Diameter (meters)	6467.5	257111.4	7000614	5588.7	185676.4	594767.4
Clusters	4351	572	128	2948	577	147
Mean Cluster Size	1.4	10.9	48.5	1.2	6.2	24.2
Max Cluster Size	18	1238	4454	12	680	2035
Network Modularity	-0.00059	-0.00026	-0.0032	-0.0013	-0.0051	-0.00045

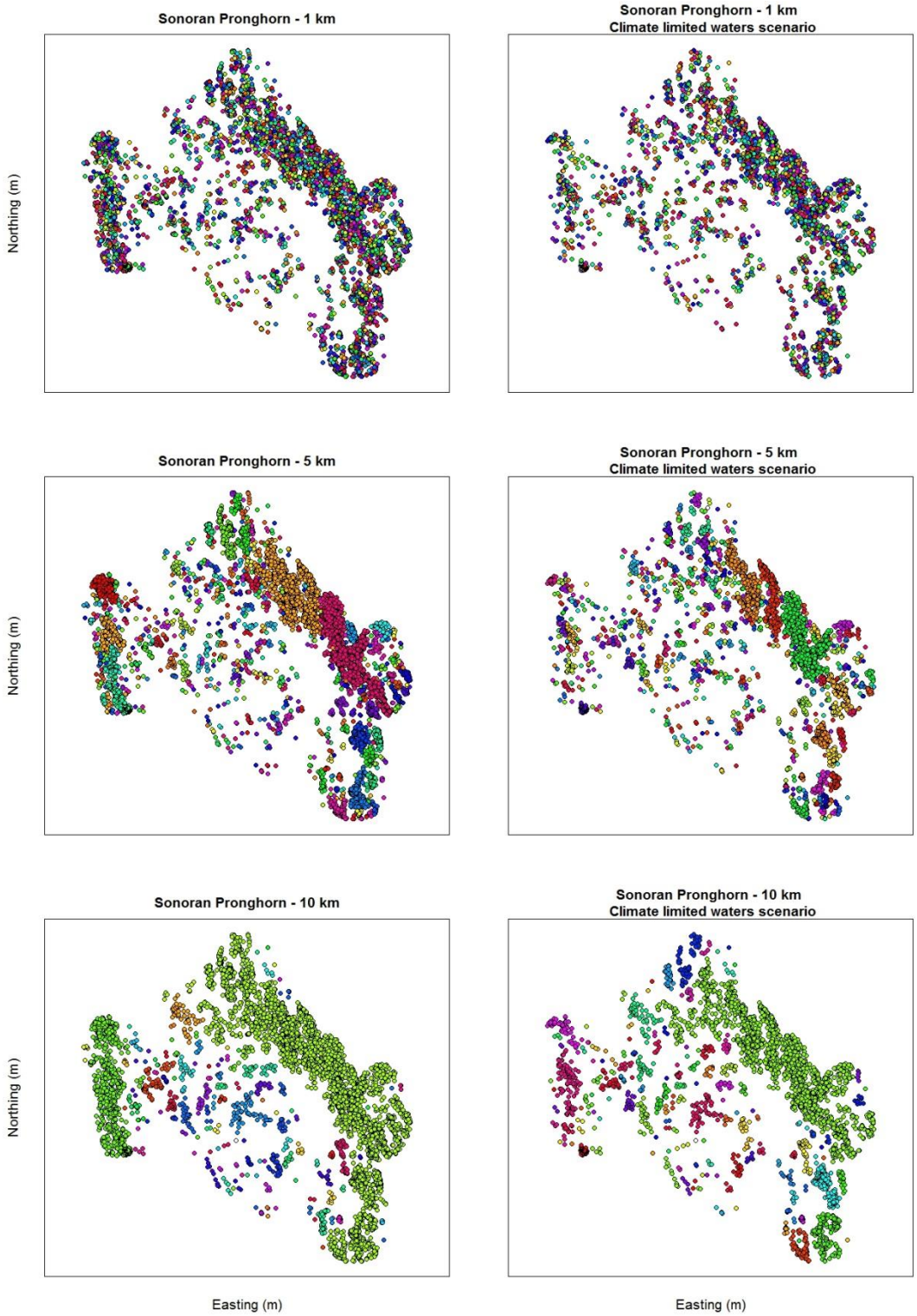

Figure 80. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Sonoran Pronghorn. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and in the southern section of the graph.

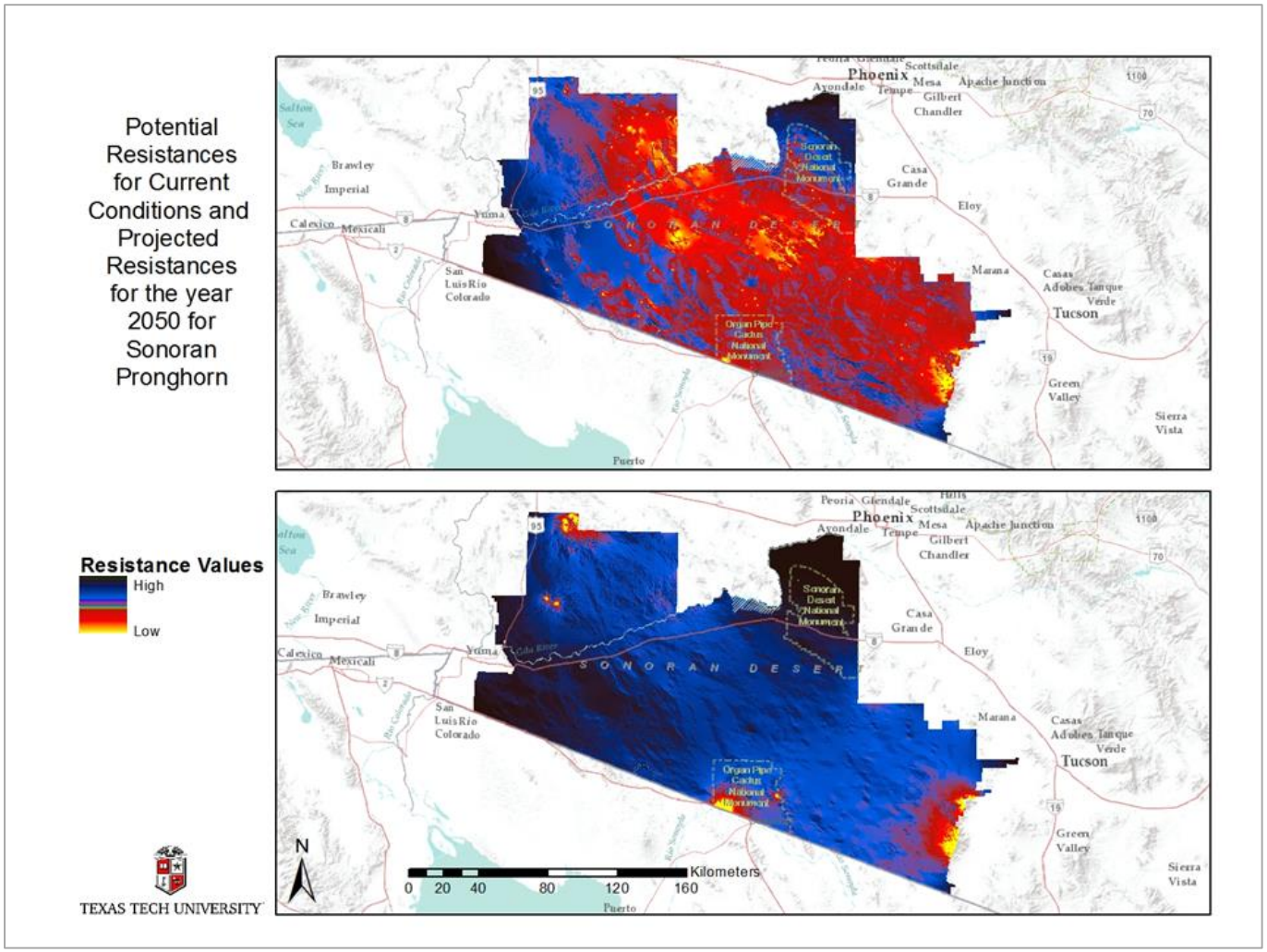

Figure 81. Potential resistances for the Sonoran Pronghorn under current conditions and all known isolated waters (top) and modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B (bottom). Circuit theory based resistance maps produced using Circuitscape and clipped to portions of Yuma, Maricopa, Pinal, and Pima counties in Arizona. Under climate scenarios with limited waters, the resistance to pronghorn movement is increased. Fewer waters and unfavorable climate conditions show a reduced connectivity over historic ranges like the Barry M. Goldwater Airforce Range.

Masked Bobwhite (*Colinus virginianus ridgwayi*)

Figure 82. Captive male masked bobwhite.
Photo by: Bryant Olsen 2011 CC BY-NC 2.0

Distribution & Status: Historically the Masked Bobwhite has existed in the Altar and Santa Cruz Valleys in Southern Arizona and across much of Sonora, Mexico at elevations between 150 m and 1200 m (Kuvlesky Jr. & Dobrott 1995). As of the early 2000's the Masked Bobwhite was only found on private lands in areas of northcentral Sonora, Mexico, and as a reintroduced population on the Buenos Aires National Wildlife Refuge (BANWR) in southern Arizona (Hernández et al. 2006; Kuvlesky Jr. et al. 2000). Recent estimates show that wild populations are non-existent in the United States and possibly Mexico and that most birds are now held in a captive flock in the BANWR or other captive breeding programs (USFWS 2014). The species was listed as endangered in The United States in 1967 (USFWS 2014).

Habitat & Spatial Ecology: Limited information exists on Masked Bobwhite habitat, but it is thought to include semi-arid grasslands, desert grasslands, and savannah grasslands with surrounding areas of brushy or woody vegetation with plenty of forbs (Hernández et al. 2006; Kuvlesky Jr. & Dobrott 1995; Brown et al. 2012). Guthery (2000) suggests that the habitat ecology of masked bobwhites in Arizona were similar to Northern Bobwhites in Texas with an emphasis on herbaceous cover and canopy cover compared to their Texan relatives. They are thought to use grassy river bottoms, flat and open valleys, and plains (Kuvlesky Jr. & Dobrott 1995). The Masked Bobwhite generally exhibits low movement habits; moving less than 1 km appears to be the normal distance traveled from a trap site to the original release site (Simms 1989; Kuvlesky Jr. & Dobrott 1995). They are found range from 64 m to 23.7 km with an average of 3.1 km distance between release sites and established home range centers when movement is necessary (Simms 1989).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.2 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an extreme daily dispersal scenario

Functional Model:

- Preference for grassland and savannah habitats reflected in land cover variables
- Urban areas highly resistant to masked bobwhite because of impacts to grasses and cover
- Topographic index weight reflects preference for flats and mesas but the avoidance of canyons
- Slope resistances reflect preference for flatter terrain
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.2 km) modeled for this species resulted in 40% reduction of clusters in the climate limited waters scenario
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario
- The average number of waters per cluster decreased by 4% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios
- Much of the historic range of the Masked Bobwhite will increase in resistance to potential movements for reintroduced individuals as waters disappear and vegetation changes. Permanent waters and active vegetation management will help maintain connectivity in the historic ranges.
- Managed waters will act as water "islands" across much of the historic ranges and other sections of the U.S. Sonoran Desert in the future if reintroduction continues for the Masked Bobwhite.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for Masked Bobwhite for much of the study area. Habitat theoretically available to this bird will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for the bird when comparing current and climate limited water scenarios, and indicate a disconnected system of waters that Masked Bobwhite would have available for use if it still inhabited its native range. This is important to consider because at the average daily movements modeled for this species (0.2 km – a known average daily distance movement capability), the mean cluster size reduced by 4%; at maximum modeled dispersal distances (2 km) the mean cluster size decreased by 28%. At 0.2 km the Masked Bobwhite, under climate limited water scenario, the max cluster size decreases by 71%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreased 33% (Table 26). Reintroduction events have occurred but the number of Masked Bobwhite in the wild is very low and not well known. Land covers of scrubland and arid grasslands with topographically flatter areas provide

the least resistance to movement between waters (Figure 84). As the landscape moves west through the Tohono O'Odham Nation Reservation, the resistance to movement increases as waters become scarcer and vegetation changes from grassland to desert scrub. The Quinlan Mountains also act as a strong barrier to movement and connectivity for the Masked Bobwhite. In the 2050 scenario, this trend is amplified by vegetation change and loss of waters. Tucson, under current conditions, has an unlikely moderate resistance to movement because of agricultural areas, urban green spaces, and high levels of waters surrounding it; this combination of factors, however, does not account for the sensitivity of the bird to development and loss of grasses. The projected scenario for the year 2050 has a much more accurate representation of the urban area in terms of resistance; increasing density of urban development, loss of grasslands and other suitable habitat structure, and the impacts of roads reduce the connectivity in the region.

Table 26. Masked Bobwhite structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.2 km	1 km	2 km	0.2 km	1 km	2 km
Diameter (meters)	787.9	6467.5	27538.1	422.8	5588.7	27691.2
Clusters	5859	4351	2502	3498	2948	1944
Mean Cluster Size	1.06	1.4	2.5	1.02	1.2	1.8
Max Cluster Size	14	18	88	4	12	59
Network Modularity	-0.0022	-0.00059	-0.00034	-0.0092	-0.0013	-0.00074

Figure 83. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Masked Bobwhite. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

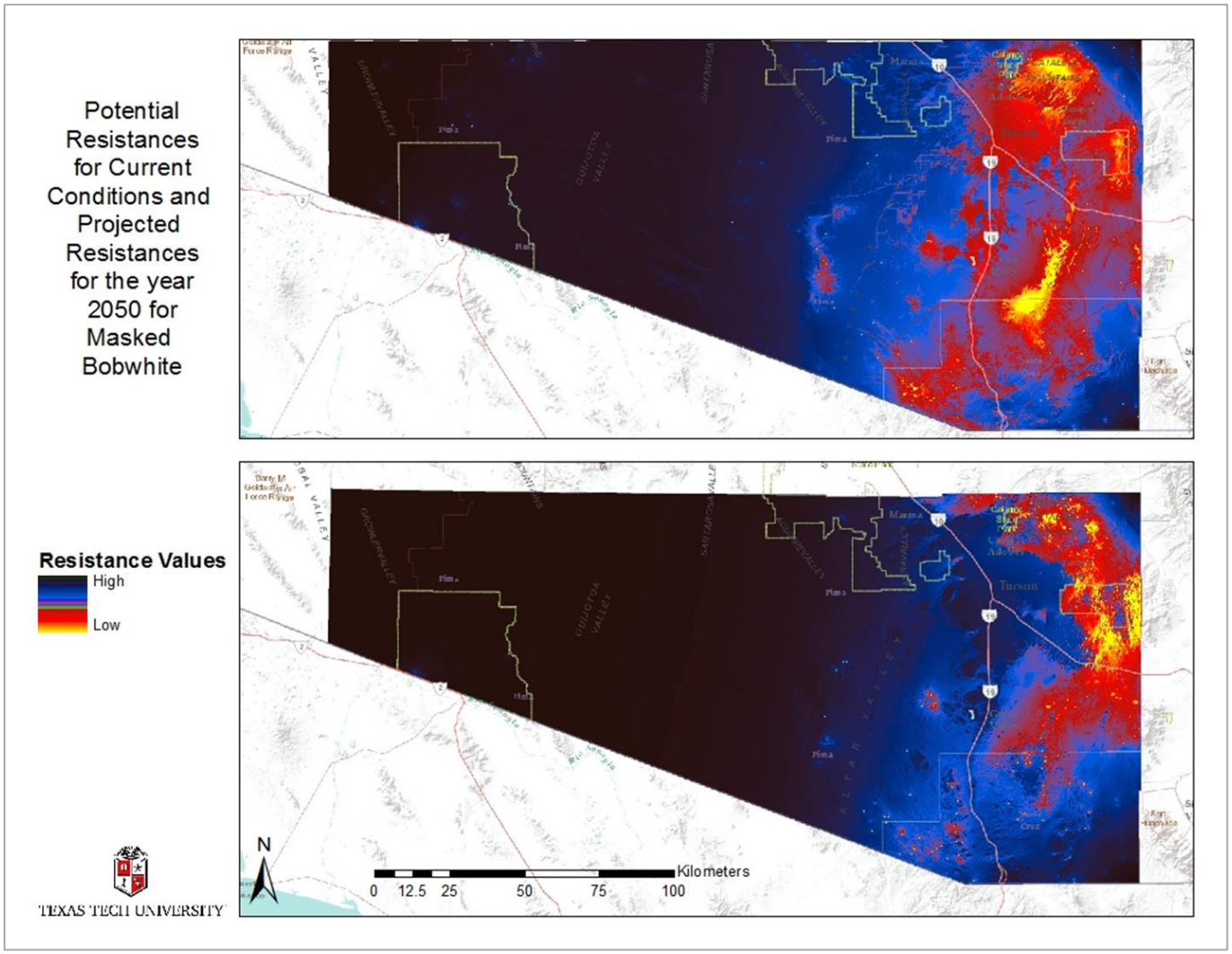

Figure 84. Potential resistances for the Masked Bobwhite under current conditions and all known isolated waters (top) and modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B (bottom). Circuit theory based resistance maps produced using Circuitscape and clipped to Pima County, AZ. Under climate scenarios with limited waters, the resistance to Bobwhite movement is increased. Fewer waters, unfavorable climate conditions, and changes in land cover show a reduced connectivity over historic ranges like the Buenos Aires National Wildlife Refuge.

Gambel's Quail (*Callipepla gambelii*)

Distribution & Status: Gambel's Quail are found in the American Southwest across the Sonoran Desert. The species inhabits southern Arizona, adjoining areas of California, Nevada, and New Mexico, and Sonora, Mexico (Brown et al. 1998). The species is most commonly found at elevations below 1,650 m but can be found as high as 3350 m (Gullion 1960).

Figure 85. Gambel's quail at a modified tinaja in the Barry M. Goldwater Air Force Range

Habitat & Spatial Ecology: This bird likes to inhabit warm-desert habitats that have shrubby and/or succulent vegetation present to provide roosts and forage (Brennan 2007; Brown 1989). They use a variety of vegetation including mesquite, saguaro, paloverde, jojoba, ocotillo, ironwood, acacia, prickly pear cactus, chollas, scrub oak and semi-arid grasslands that have been over taken by these and similar shrubby vegetation (Brown 1989; Brown et al. 1998). They are often found in desert washes, riparian areas and bajadas (Brown 1989) which have a good availability of brush for cover, food, and roost sites, and their distribution might be limited by suitable roost sites (Goodwin Jr. & Hungerford 1977). These birds survive well in desert metropolises including Phoenix and Tucson (Emlen 1974; Engel-Wilson & Jr 2002; Kuvlesky Jr. et al. 2002), and are found near agricultural areas (Gullion 1960). Evidence suggests they can survive using only metabolic water for hydration (Gorsuch 1934), but they will drink from water if its available (Gorsuch 1934; Cutler & Morrison 1998; O'Brien et al. 2006). Gambel's Quail will concentrate around game waters (Smith & Gallizioli 1963 as cited in Brown et al. 1998)(Gorsuch 1934). Their daily movement is between 500 m and 1 km (Gorsuch 1934; Brennan 2007) if not disturbed, but individual birds sometimes travel upwards of 1.3 km (Gorsuch 1934). Annual movements include movements from known home ranges up to 2 km (Gullion 1962; Greenwalt 1955).

Model Basis:

Structural Model:

- Modeled dispersal distances of 0.5 km, 1 km, and 2 km
- These represent known daily movement distances, possible max daily movement distance, and an unlikely maximum dispersal scenario

Functional Model:

- Preference for semi-arid grasslands and shrubby habitats with mesquite reflected in land cover variables
- Development that is not extremely dense is only modelled to be moderately resistant to Gambel's Quail because of known urban populations
- Topographic index weight reflects preference for canyon bottoms and to a lesser extent, flats
- See Appendix A for weighted resistance equation and resistance values

Results & Discussion:

Synopsis**:**

- Daily movement distance (0.5 km) modeled for this species resulted in 37% reduction of clusters in the climate limited waters scenario.
- At longest modeled dispersal distance (2 km), the number of clusters reduced by 22% under the climate limited water scenario.
- The average number of waters per cluster decreased by 12% and 28% at daily and maximum modeled dispersal distances for climate limited water scenarios.
- The northeastern section of the resistance graph shows lowest resistance to movement under current conditions because of the high densities of waters.
- Gambel's Quail are known to congregate around waters but movement behavior in response to water availability is not thoroughly understood.
- Much of the Sonoran Desert will increase in resistance to the Gambel's Quail as waters disappear and vegetation changes. Suburban areas of Phoenix and Tucson as well as agricultural lands and managed water sites—especially those in and around the Lower Colorado River Valley—will serve as refuge for this species.
- Loss of waters, changes in projected land cover, and climate changes for the year 2050 will result in more difficult dispersal and subsequent population isolation.
- Managed waters will likely become more important to this species as conditions and landscape connectivity declines.
- Areas like the northeastern section of the graph will continue to provide resilient movement capabilities for Gambel's Quail, but managed waters will act as water "islands" across much of the southern and western sections of the U.S. Sonoran Desert.

Our model depicts the Sonoran Desert increasing in overall resistance with climate change and modeled land cover changes for the Gambel's Quail for much of the study area. Habitat used by this bird will continue to change into the future as water resources become scarcer. Structural results showed a general decrease in available waters in any given cluster for this bird when comparing current and climate limited water scenarios results show a generally disconnected system of waters that Gambel's Quail have available for use. Quail will most likely have to stick to few to one waters in an average daily movement range. This is important to

consider because at the modeled daily movements known for this species, the mean cluster size reduced by 12%; at maximum modeled dispersal distances (2 km) the mean cluster size decreased by 28%. At 3 km the Gambel's Quail, under climate limited water scenario, the max cluster size decreases by 72%. At 2 km dispersal distance, the climate limited waters scenario max cluster size decreases 33% (Table 27). Although Gambel's Quail are thought to not need open water for survival in much of their range, they will use water when available and congregate near it. The highest density of these waters contributes to areas of least resistance in the landscape for Gambel's Quail movement (Figures 87 & 88). Under current resistance scenarios, landscape has moderate resistances in all but the most developed urban areas, the most barren desert, and the steepest terrains. In the farthest reaches of the U.S. Sonoran Desert, in the southern sections typified of sand dunes and volcanic rocks the Gambel's Quail has high resistance to movement. In the 2050 scenario (Figure 88), high resistances near the southwestern sections of the Sonoran Desert limit Gambel's Quail movement. It also has much more resistance to movement than current scenario through the central areas of the Sonoran Desert to the west of the Phoenix metro area. Throughout the Sonoran however are agricultural areas that may act as corridors or refuges—especially along rivers like the Colorado, Gila, and Salt. Managed waters may be necessary to facilitate dispersal or migratory movements between dry and wet seasons. Gambel's Quail are known to be habitat generalists that can readily survive in lightly urbanized areas. Lack of predation, abundant water sources, and plenty of forage often help them survive, thrive, and become urban pests. As habitat degrades in the surrounding area, human-wildlife conflicts may have a potential for increasing in urban areas as this adaptable birds uses any and all sources of forage and water.

Table 27. Gambel's Quail structural model graph analysis results. All waters scenario reflect all available waters in the U.S. Portion of the Sonoran Desert as outline by EPA watershed boundary with a 32.2km (20mi) spatial buffer. Climate limited scenario reflects a future based on current climate projections that predict less rain and higher temperatures in which only spring fed waters may survive and be augmented by managed game waters.

	All waters			Climate limited waters		
	0.5 km	1 km	2 km	0.5 km	1 km	2 km
Diameter (meters)	1481.5	6467.5	27538.1	1188.7	5588.7	27691.2
Clusters	5328	4351	2502	3353	2948	1944
Mean Cluster Size	1.2	1.4	2.5	1.06	1.2	1.8
Max Cluster Size	18	18	88	5	12	59
Network Modularity	-0.0011	-0.00059	-0.00034	-0.0032	-0.0013	-0.00074

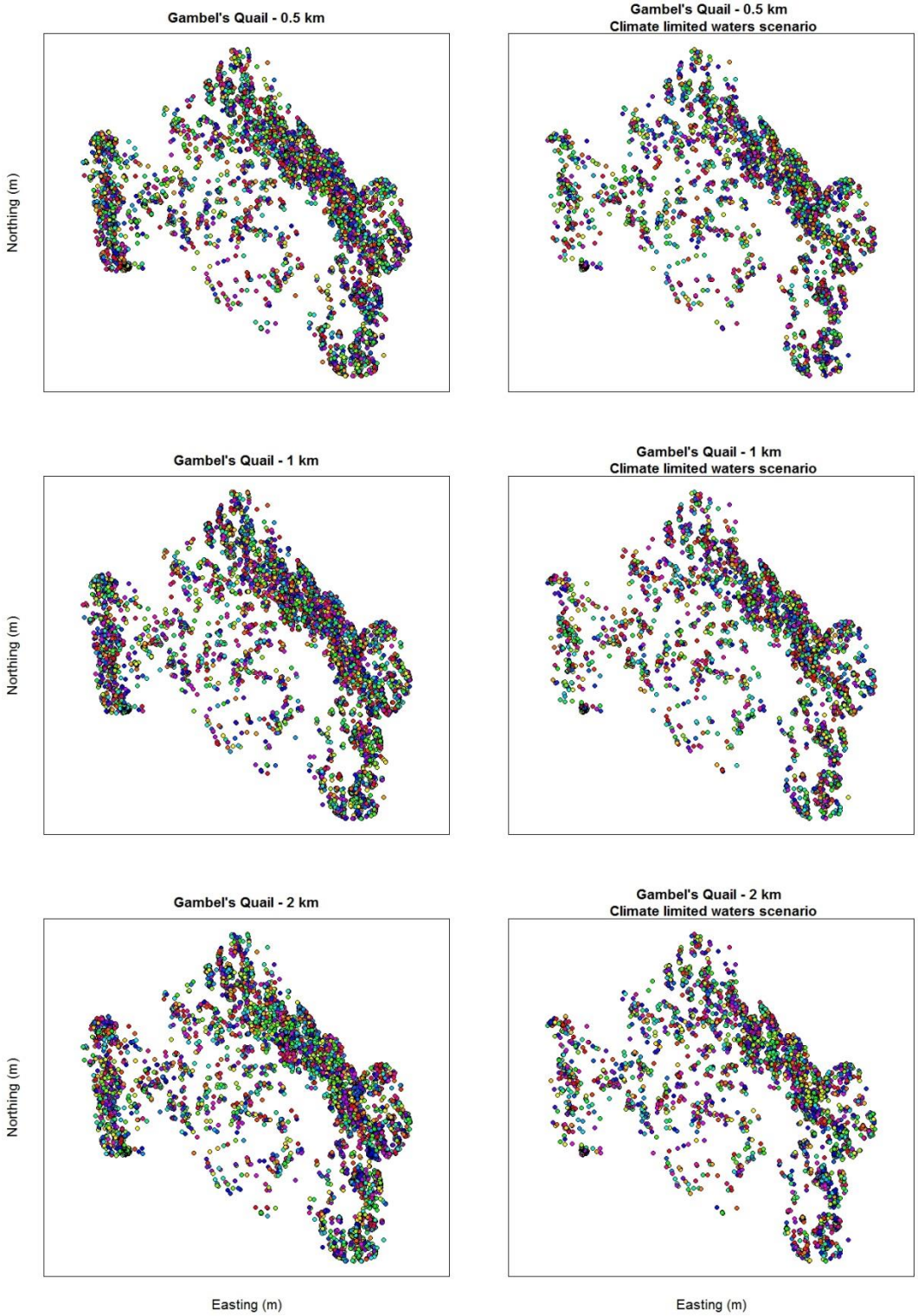

Figure 86. Current (left column) and climate limited water (right column) scenarios for graph theory cluster analysis of the U.S. Sonoran Desert. Distances represent different water-use availability scenarios for Gambel's Quail. Notice the reduced amounts of available waters and connectivity as evidence of increased number of clusters in the climate limited water scenario. There are noticeable decreases in the entire network and particularly in the left section of the graph.

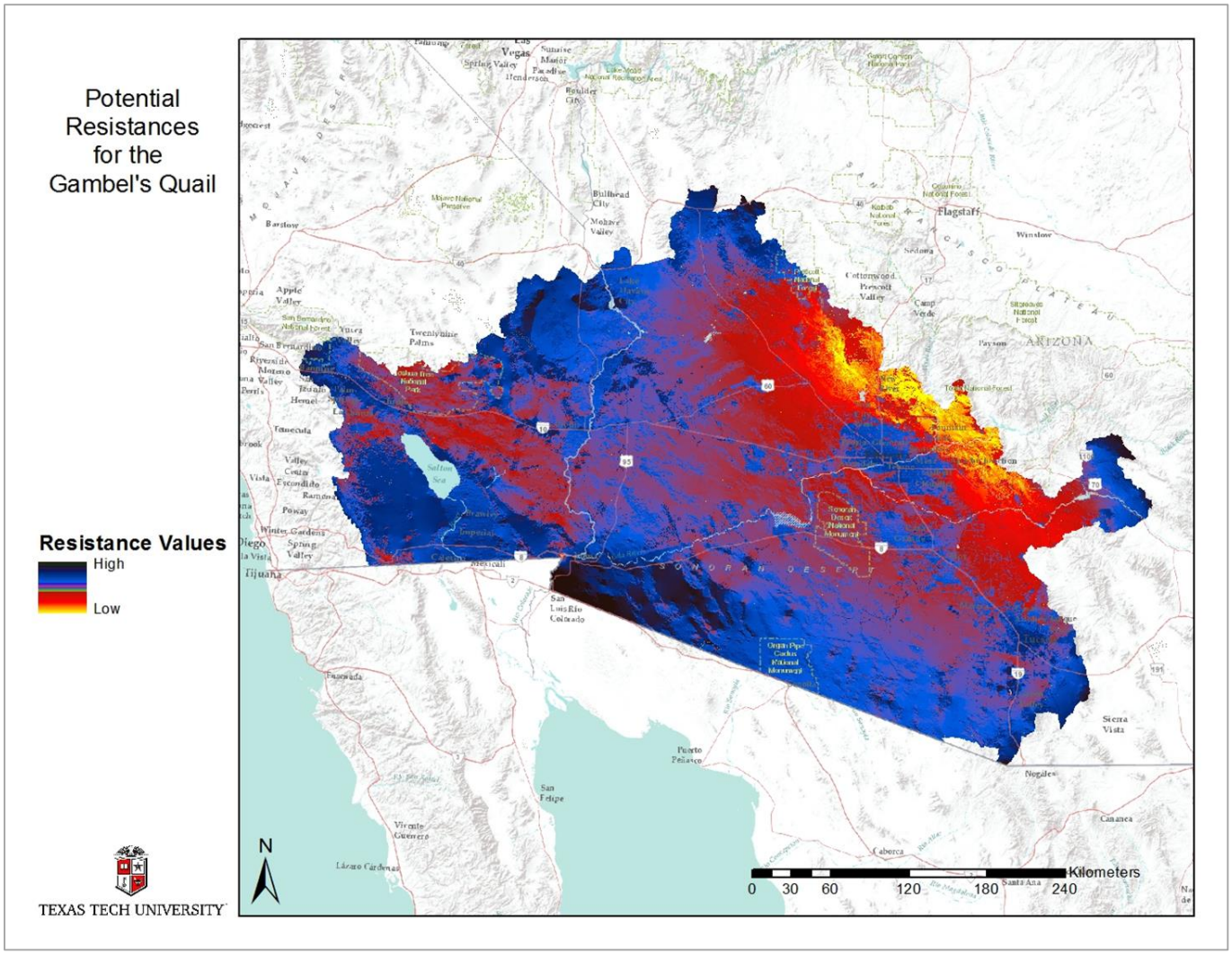

Figure 87. Potential resistances for Gambel's Quail under current conditions and all known isolated waters. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. Lowest resistances occur most frequently to the northeast of Phoenix. Many of the arid grasslands and river valleys also have lower resistances. The highest resistance values occur in southern section of the desert near Yuma. This area is one of the driest and warmest sections of the Sonoran Desert. There are islands of lower resistance around manmade waters in otherwise resistant areas.

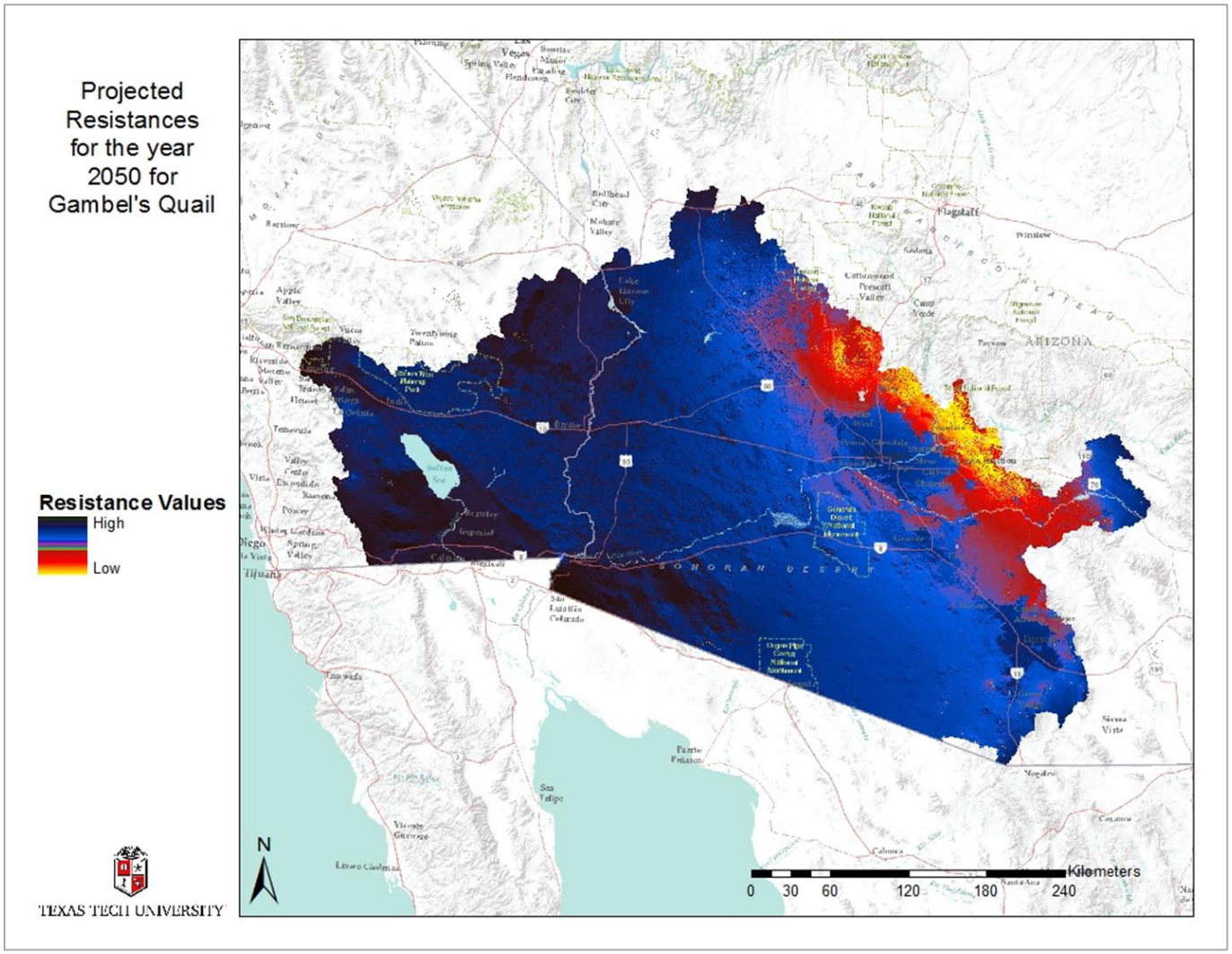

Figure 88. Projected resistances for Gambel's Quail modeled for the year 2050 using climate limited water availability and U.S.G.S. land cover projections for the year 2050 under the IPCC emissions scenario A1B. Circuit theory based resistance maps produced using Circuitscape and clipped to the U.S. Sonoran Desert. With climate limited waters the Sonoran Desert becomes much more resistant to quail movements. Managed waters and springs in the western section of the resistance graph act as islands in the landscape that have much lower connectivity potential. Areas to the northeast which have a high density of springs and may retain grasslands characteristics have low resistance.

Conclusion

The Sonoran Desert is likely to experience a decrease in connectivity between waters in the future as a result of changing land use and climate change. The structural connectivity will be impacted by the loss of waters from reduced precipitation and increased temperatures, loss of waters from human development, and from the loss of springs from groundwater overdraft. Although many of the waters that are important for structural connectivity under current conditions will remain so with climate change, more waters will act as cutpoints, meaning that the network will be more prone to fragmentation. This will impact species that can only move shorter distances more harshly than those species that can move and will have access to more water sites. Species like the Red Spotted Toad and Couch's Spadefoot, whose life cycles in part depend on the presence of isolated waters in the desert, will be impacted as their ability to access more than one water source in much of the Sonoran Desert is already limited to less than 2 water sites under current conditions. For many of these species, a decline in water availability will likely lead to declines in populations.

Desert anurans will have a limited access to resource patches in the future, but are known to opportunistically use very ephemeral waters. The tiger salamanders of the Sonoran Desert can use ephemeral waters in a limited capacity, but they seem to prefer at least semi-permanent waters. This dependence, coupled with a low vagility, means that the loss of resources is even more isolating for these salamanders. Forty-three percent of the waters modeled under current conditions were lost under the climate limited water scenario. These waters were the most likely to be rain dependent and lost to changing climate conditions. Species whose movement is less than 3 to 5 km will have the most reduction in resource access in the future based on structural connectivity metrics.

Functional connectivity analysis also shows that climate change and land use change will result in lost connectivity between habitat patches like isolated waters. Human development of natural areas, loss of habitat patches, changing vegetation in response to climate, and invasion of pest species will all contribute to loss of resource access. Areas of dense waters, like those to the northeast of the city of Phoenix, AZ, will have the lowest resistance for a variety of species including Mule Deer, Gambel's Quail, and the Lowland and Chiricahua Leopard Frogs. This area will also remain resilient to climate changes as it has the most alternative paths and habitat patches for organisms to use in close proximity. Areas farther to the south and to the west of the Sonoran Desert will experience the most fragmentation.

Critically endangered species like the Masked Bobwhite face a continuing struggle to be successfully re-established that will only get harder. Much of their historic range was impacted by human land use change. The trend of converting land to urban, agriculture, and ranching will likely continue throughout the southwest, including in Arizona, and specifically in the Sonoran Desert. Climate change impacts such as reduced waters and changing vegetation will continue to reduce the connectivity between resource patches. This in turn limits access to those resources and the benefits that a highly permeable landscape allows native species.

While land use change may impact native species detrimentally, it often facilitates the introduction or expansion of invasive species—which can further harm natives. Species like the American Bullfrog are contributing to the decline of native herpetofauna and are known predators and competitors with a wide range of native fauna. Bullfrogs are excellent at using manmade waters like reservoirs and anthropogenic water catchments that resemble their home habitat and would rarely be found in the Sonoran Desert naturally. These structurally different waters are more lentic and permanent than the natural tinajas and spring fed streams. These waters, however, are important tools for human water needs and wildlife resource augmentation and will be continued to be used. Understanding how they will impact connectivity is important (Drake 2016) and developing techniques that address landscape connectivity and management decisions in regards to invasive species is essential to preventing further unnecessary invasions and may lead to restoration of landscapes to native species (Drake 2016).

Land use change and climate change will have serious impacts to the Sonoran Desert and the ability of many different types of animals to access water resources. Maintaining connectivity between habitat patches into the future—be they isolated waters, stands of old growth pines, or arid grasslands—will be essential to local populations for resource access, migration, and genetic diversity. This report has studied the connectivity of the Sonoran Desert landscape and how that impacts movements between waters. Although circuit theory and graph theory have limitations, they do provide a solid basis for understanding how the landscape may influence animal movement between resource patches. Connectivity, an essential component of the landscape, should be understood for specific species requirements at regional scales. In this way managers can show how endangered species have access to resources when reintroduced, how invasive species may invade new territories, and how management decisions have impact at regional and local scales.

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Works Cited

Adams, D.K. & Comrie, A.C., 1997. The North American Monsoon. *Bulletin of the American Meteorological Society*, 78(10), pp.2197–2213.

ADBSS, 2004. *Wildlife Water Developments and Desert Bighorn Sheep in the Southwestern United States*, Mesa. Available at: http://www.adbss.org/adbss_water_just2005.pdf.

Adriaensen, F. et al., 2003. The application of "least-cost" modelling as a functional landscape model. *Landscape and Urban Planning*, 64(4), pp.233–247.

Alvarez-Cardenas, S. et al., 2001. The variables of physical habitat selection by the desert bighorn sheep (*Ovis canadensis weemsi*) in the Sierra del Mechudo, Baja California Sur, Mexico. *Journal of Arid Environments*, 49(2), pp.357–374.

Anderson, A.E. & Wallmo, O.C., 1984. *Odocoileus hemionus*. Mammalian Species, 219, pp.1–9.

Andersson, E. & Bodin, Ö., 2009. Practical tool for landscape planning? An empirical investigation of network based models of habitat fragmentation. *Ecography*, 32(1), pp.123–132.

AZGFD, 2002. *Antilocapra americana sonoriensis*. Unpublished abstract compiled and edited by the Heritage Data Management System, p.7.

AZGFD, 2003. *Smilisca fodiens*. Unpublished abstract compiled and edited by the Heritage Data Management System, p.5.

AZGFD, 2005. *Anaxyrus retiformis*. Unpublished abstract compiled and edited by the Heritage Data Management System, p.6.

AZGFD, 2012. Arizona's State Wildlife Action Plan: 2012-2022.

AZGFD, 2013a. *Ambystoma mavortium stebbinsi* (*Ambystoma tigrinum stebbinsi*). Unpublished abstract compiled and edited by the Heritage Data Management System, p.8.

AZGFD, 2013b. *Gastrophryne olivacea*. Unpublished abstract compiled and edited by the Heritage Data Management System, p.6.

Beier, P., Majka, D.R. & Newell, S.L., 2009. Uncertainty analysis of least-cost modeling for designing wildlife linkages. *Ecological Applications*, 19(8), pp.2067–77.

Bleich, V.C., Marshal, J.P. & Andrew, N.G., 2010. Habitat use by a desert ungulate: Predicting effects of water availability on mountain sheep. *Journal of Arid Environments*, 74(6), pp.638–645.

Bleich, V.C., Wehausen, J.D. & Holl, S.A., 1990. Desert-dwelling Mountain Sheep: Conservation Implications of a Naturally Fragmented Distribution. *Conservation Biology*, 4(4), pp.383–390.

BMGR-INRMP, 2012. Barry M. Goldwater Range integrated natural resources management plan 2012 update, Barry M. Goldwater Range. Available at: http://www.luke.af.mil/shared/media/document/AFD-130823-073.pdf.

Bodin, Ö. & Saura, S., 2010. Ranking individual habitat patches as connectivity providers: Integrating network analysis and patch removal experiments. *Ecological Modelling*, 221(19), pp.2393–2405.

Bogert, C.M., 1962. Isolation Mechanisms in Toads of the *Bufo debilis* Group in Arizona and Western Mexico. American Museum Novitates. pp.1-38

Bradford, D.F. et al., 2003. Habitat patch occupancy by toads (*Bufo punctatus*) in a naturally fragmented desert landscape. *Ecology*, 84(4), pp.1012–1023.

Bragg, A.N., 1965. *Gnomes of the Night*, Philadelphia, Pennsylvannia: University of Pennslvannia Press.

Bragg, A.N., 1944. The Spadefoot Toads in Oklahoma with a Summary of Our Knowledge of the Group. *The American Naturalist*, 78(779), pp.517–533.

Brennan, L.A. ed., 2007. *Texas Quails: Ecology and Management*. Texas A&M University Press, College Station, TX.

Brown, D.E. et al., 2012. An analysis of masked bobwhite collection locales and habitat characteristics. In *Proceedings of the National Quail Symposium*. pp. 7:305–328.

Brown, D.E., 1989. *Arizona game birds*, Tucson, AZ: University of Arizona Press & Arizona Game and Fish Department.

Brown, D.E. et al., 1998. Gambel's Quail. In A. Poole & F. Gill, eds. *The Birds of North America*.

Broyles, B. 1995. Desert wildlife water developments: questioning use in the Southwest. Wildlife Society Bulletin 23:663–675.

Bunn, A.G., Urban, D.L. & Keitt, T.H., 2000. Landscape connectivity: A conservation application of graph theory. *Journal of Environmental Management*, 59(4), pp.265–278.

Cain, J.W. et al., 2006. Mechanisms of Thermoregulation and Water Balance in Desert Ungulates. *Wildlife Society Bulletin*, 34(3), pp.570–581.

Cain, J.W. et al., 2008. Responses of Desert Bighorn Sheep to Removal of Water Sources.

Wildlife Monographs, 171(171), pp.1–32.

Calvert, J., 2015. *Large Mammal Water Use on the Barry M. Goldwater Range-East in Southwestern Arizona*. M.S. Thesis: Texas Tech University.

Camargo, J. A. & Alonso, Á., 2006. Ecological and toxicological effects of inorganic nitrogen pollution in aquatic ecosystems: A global assessment. *Environment International*, 32(6), pp.831–849.

CDFW, 2015. *Special Animals List*. California Department of Fish and Wildlife, Sacramento

Chrapliwy, P.S. & Williams, K.L., 1957. A species of frog new to the fauna of the United States: *Pternohyla fodiens Boulenger*. *Smith II*.

Clarkson, R. & Rorabaugh, J., 1989. Status of Leopard Frogs (*Rana pipiens* Complex: *Ranidae*) in Arizona and Southeastern California. *The Southwestern Naturalist*, 34(4), pp.531–538.

Clauset, A., Newman, M. & Moore, C., 2004. Finding community structure in very large networks. *Physical review. E, Statistical physics, plasmas, fluids, and related interdisciplinary topics*, 70(6 Pt 2), p.066111.

Cole, C.J., 1962. Notes on the distribution and food habits of *Bufo alvarius* at the eastern edge of its range. *Herpetologica*, 18(3), pp.172–175.

Collins, J., 1981. Distribution, habitats and life history variation in the tiger salamander, *Ambystoma tigrinum*, in east-central and southeast Arizona. *Copeia*, 1981(3), pp.666–675.

CPW, 2015. Threatened and Endangered List. *Colorado Parks & Wildlife*. Available at: http://cpw.state.co.us/learn/Pages/SOC-ThreatenedEndangeredList.aspx [Accessed August 17, 2015].

Creusere, M. & Whitford, W.G., 1976. Ecological Relationships in a Desert Anuran Community. *Herpetologica*, 32(1), pp.7–18.

Crooks, K. & Sanjayan, M., 2006. Connectivity conservation: maintaining connections for nature. In K. Crooks & M. Sanjayan, eds. *Connectivity Conservation*. Cambridge: Cambridge University Press, pp. 1–19.

Crooks, K. & Suarez, A., 2006. Hyperconnectivity, invasive species, and the breakdown of barriers to dispersal In K. Crooks & M. Sanjayan, eds. *Connectivity Conservation*. Cambridge: Cambridge University Press, pp. 451–478.

Csardi, C.N. & Nepusz, T., 2006. The igraph software package for complex network research. *Interjournal Complex Systems*, p.1695. Available at: http://igraph.sourceforge.net/.

Cushman, S.A. et al., 2013. Biological corridors and connectivity. *Key Topics in Conservation Biology 2*, (August), pp.384–404.

Cutler, T. & Morrison, M., 1998. Habitat use by small vertebrates at two water developments in southwestern Arizona. *The Southwestern Naturalist*, 43(2), pp.155–162.

Daszak, P. et al., 2004. Experimental evidence that the bullfrog (*Rana catesbeiana*) is a potential carrier of *chytridiomycosis*, an emerging fungal disease of amphibians. *Herpetological Journal*, 14, pp.201–207.

Dayton, G.H. & Fitzgerald, L. A., 2006. Habitat suitability models for desert amphibians. *Biological Conservation*, 132(1), pp.40–49.

Degenhardt, W.G., Painter, C.W. & Price, A.H., 1996. *Amphibians and Reptiles of New Mexico*, Albuquerque, NM: University of New Mexico Press.

deVos Jr, J. & Miller, W.H., 2005. Habitat Use and Survival of Sonoran Pronghorn in Years with Above-Average Rainfall. *Wildlife Society Bulletin*, 33(1), pp.35–42.

Drake, J.C. 2016. *The role of isolation in Sonoran Desert water site connectivity based conservation strategies*. Master's Thesis. Dept. of Natural Resources Management, Texas Tech University

Drake, J.C. et al., 2015. Testing a model for the prediction of isolated waters in the Sonoran Desert. *Journal of Arid Environments*, 118, pp.1–8.

Drake, J.C., McIntyre, N.E. Griffis-Kyle, K.L. 2016. Graph theory as an invasive species management tool: Case study in the Sonoran Desert. *In Review* A

Drake, J.C., McIntyre, N.E. Griffis-Kyle, K.L. 2016. Nesting connectivity models to resolve management conflicts of isolated water networks in the Sonoran Desert. *In Review* B

van Dyke, W.A. et al., 1983. *Wildlife habitat in management rangelands – bighorn sheep. U.S. Forest Service General Technical Report, PNW-159.*, Portland, OR.

Emlen, J.T., 1974. An Urban Bird Community in Tucson, Arizona: Derivation, Structure, Regulation. *The Condor*, 76(2), pp.184–197.

Enderson, E.F. & Bezy, R.L., 2000. Geographic Distribution: *Pternohyla fodiens*. *Herpetological Review*, 31, pp.251–252.

Engel-Wilson, R. & Jr, W.K., 2002. Arizona quail: species in jeopardy. *Quail V: Proceedings of the Fifth National Quail Symposium*. Austin, TX.

Epps, C.W. et al., 2005. Highways block gene flow and cause a rapid decline in genetic diversity

of desert bighorn sheep. *Ecology Letters*, 8(10), pp.1029–1038.

ESRI, 2014. *ArcGIS Desktop 10.2*, Redlands, CA: Environmental Systems Research Institute.

Ewert, M., 1969. *Seasonal movements of the toads* Bufo americanus *and* B. cognatus *in northwestern Minnesota*. Ph.D. Dissertation. Minneapolis, MN.

Fahrig, L. & Merriam, G., 1985. Habitat patch connectivity and population survival. *Ecology,* 66(6), pp. 1762–1768.

Fall, A. et al., 2007. Spatial graphs: Principles and applications for habitat connectivity. *Ecosystems*, 10(3), pp.448–461.

Ferguson, J.H., Lowe, C.H. & Fergusoni, J.H., 1969. Evolutionary Relationships in the Bufo punctatus Group. *American Midland Naturalist*, 81(2), pp.435–466.

Ficetola, G.F., Thuiller, W. & Miaud, C., 2007. Prediction and validation of the potential global distribution of a problematic alien invasive species - the American bullfrog. *Diversity and Distributions*, 13(4), pp.476–485.

Fitch, H.S., 1956. A field study of the Kansas ant-eating frog, *Gastrophryne olivacea*. *University of Kansas Publication of the Museum of Natural History*, 8, pp.275–306.

Flesch, A.D. et al., 2010. Potential effects of the United States-Mexico border fence on wildlife: Contributed paper. *Conservation Biology*, 24(1), pp.171–181.

Gesch, D.B. et al., 2002. The National Elevation Dataset. *Photogrammetric Engineering & Remote Sensing*, 68(1), pp.5–32.

Gesch, D.B., 2007. The National Elevation Dataset. In D. F. Maune, ed. *Digital Elevation Model Technologies and Applications: The DEM Users Manual.* American Society for Photogrammetry and Remote Sensing, pp. 99–118.

Goldberg, S.R., Bursey, C.R. & Cheam, H., 1998. Helminths of two native frog species (*Rana chiricahuensis, Rana yavapaiensis*) and one introduced frog species (*Rana catesbeiana*) (*Ranidae*) from Arizona. *The Journal of parasitology*, 84(1), pp.175–177.

Goodwin Jr., J.G. & Hungerford, C.R., 1977. *Habitat use by native Gambel's and scaled quail and released masked bobwhite quail in southern Arizona.* USFS Research Paper RM-197. Tucson, AZ.

Gorsuch, D.M., 1934. *Life History of the Gambel Quail*. University of Arizona Bulletin Biological Science Bulletin. Tucson, AZ.

Greenwalt, L.A., 1955. *Mobility of Gambel's quail (Lophortyx gambeli gambeli) in a desert-*

grassland -- oak-woodland area in southeastern Arizona. M.S. Thesis. University of Arizona.

Griffis-Kyle, K.L. & Jenness, J., 2013. Amphibian and dragonfly biodiversity in isolated wildlife waters of the USAF, BMGR. *Annual Report submitted to Luke Air Force Base 56 RMO/ESM, July through October 2012, Arizona.*

Griffis-Kyle, K.L., Kovatch, J.J. & Bradatan, C., 2014. Water quality: A hidden danger in anthropogenic desert catchments. *Wildlife Society Bulletin*, 38(1), pp.148–151.

Gullion, G.W., 1962. Organization and Movements of Coveys of a Gambel Quail Population. *The Condor*, 64(5), pp.402–415.

Gullion, G.W., 1960. The ecology of Gambel's quail in Nevada and the arid southwest. *Ecology*, 41(3), pp.518–536.

Guthery, F., King, N. & Nolte, K., 2000. Comparative habitat ecology of Texas and masked bobwhites. *The Journal of Wildlife Management*, 64(2), pp.407–420.

Hanselmann, R. et al., 2004. Presence of an emerging pathogen of amphibians in introduced bullfrogs *Rana catesbeiana* in Venezuela. *Biological Conservation*, 120(1), pp.115–119.

Hayes, M. & Jennings, M., 1986. Decline of ranid frog species in western North America: are bullfrogs (*Rana catesbeiana*) responsible? *Journal of Herpetology*, 20(4), pp.490–509.

Heffelfinger, J., 2006. *Deer of the Southwest*, Texas A&M University Press. College Station, TX.

Hendrickson, D. & Minckley, W., 1985. Cienegas: Vanishing climax communities of the American Southwest. *Desert plants (USA)*, 6(August), pp.130–176.

Hermosillo, E. 2013. Barry M. Goldwater Range East report FY 2013, USGS. Yuma, AZ, pp. 1-2.

Hernández, F. et al., 2006. Recovery of Rare Species : Case Study of the Masked Bobwhite. *The Journal of Wildlife Management*, 70(3), pp.617–631.

Hervert, J.J. et al., 2005. Home-Range and Habitat-Use Patterns of Sonoran Pronghorn in Arizona. *Wildlife Society Bulletin*, 33(1), pp.8–15.

Hjort, J. et al., 2015. Why geodiversity matters in valuing nature's stage. *Conservation Biology*, 29(3), pp.630–639.

Hoffmeister, D.F., 1986. *Mammals of Arizona*, Tucson, AZ: The University of Arizona Press and the Arizona Game and Fish Department.

Hughes, K.S., 1991. *Sonoran Pronghorn use of Habitat in Southwest Arizona*. M.S. Thesis. University of Arizona.

Ingram, W. & Raney, E., 1943. Additional studies on the movement of tagged bullfrogs, *Rana catesbeiana* Shaw. *American Midland Naturalist*, 29(1), pp.239–241.

IPCC, 2014. North America. In V. R. Barros et al., eds. *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B. Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, United Kingdom and New York, NY USA: Cambridge University Press.

Jameson, D.L., 1956. Survival of Some Central Texas Frogs under Natural Conditions. *Copeia*, 1956(1), p.55.

Jin, S. et al., 2013. A comprehensive change detection method for updating the National Land Cover Database to circa 2011. *Remote Sensing of Environment*, 132, pp.159–175.

Johnson, T.L. & Swift, D.M., 2000. A test of a habitat evaluation procedure for rocky mountain bighorn sheep. *Restoration Ecology*, 8(4S), pp.47–56.

Jones, T.R. et al., 1988. Systematic status and distribution of *Ambystoma tigrinum stebbinsi* Lowe (Amphibia: *Caudata*). *Copeia*, 1988(3), pp.621–635.

Kahrs, D., 2006. American bullfrog eradication in Sycamore Canyon, Arizona, a natural open aquatic system. *Sonoran Herpetologist*, 19(7), pp.74–77.

Karl, T., Melillo, J. & Peterson, T. eds., 2009. *Global climate change impacts in the United States*, Cambridge: Cambridge University Press.

King, F.W., 1932. Records and notes from the vicinity herpetological of Tucson , Arizona , July and August , I930. *Copeia*, 1932(4), pp.175–177.

Koen, E.L. et al., 2010. The effect of map boundary on estimates of landscape resistance to animal movement. *PLoS ONE*, 5(7), p.e11785.

Krausman, P. & Etchberger, R., 1995. Response of desert ungulates to a water project in Arizona. *The Journal of Wildlife Management*, 59(2), pp.292–300.

Krausman, P.R., 2000. An Introduction to the Restoration of Bighorn Sheep. *Restoration Ecology*, 8(4), pp.3–5.

Krausman, P.R., 1978. Forage relationships between two deer species in Big Bend National Park, Texas. *The Journal of Wildlife Management*, 42(1), pp.101–107.

Krupa, J.J., 1989. Alternative mating tactics in the Great Plains toad. *Animal Behaviour*, 37,

pp.1035–1043.

Krupa, J.J., 1994. Breeding biology of the Great Plains Toad in Oklahoma. *Journal of Herpetology*, 28(2), pp.217–224.

Kuvlesky Jr., W. et al., 2000. The status of masked bobwhite recovery in the United States and Mexico. In *Quail IV: proceedings of the Fourth National Quail Symposium, May 6-9, 1997*. Tall Timbers Research Station. Tallahassee, FL.

Kuvlesky Jr., W. & Dobrott, S., 1995. *Masked bobwhite Recovery Plan*, United States Fish and Wildlife Service. Albuquerque, NM.

Kuvlesky Jr., W.P., Fulbright, T.E. & Engel-Wilson, R., 2002. The impact of invasive exotic grasses on quail in the southwestern United States. *Quail V: The Fifth National Quail Symposium*. Austin, TX.

Laita, A., Kotiaho, J.S. & Mönkkönen, M., 2011. Graph-theoretic connectivity measures: what do they tell us about connectivity? *Landscape Ecology*, 26(7), pp.951–967.

Landreth, H. & Christensen, M., 1971. Orientation of the plains spadefoot toad, *Scaphiopus bombifrons*, to solar cues. *Herpetologica*, 27(4), pp.454–461.

Lannoo, M. ed., 2005. *Amphibian Declines: The Conservation Status of United States Species*, University of California Press.

Leslie, D.M. & Douglas, C.L., 1979. Desert Bighorn Sheep of the River Mountains, Nevada. *Wildlife Monographs*, (66), pp.3–56.

Longshore, K.M., Lowrey, C. & Thompson, D.B., 2009. Compensating for diminishing natural water: Predicting the impacts of water development on summer habitat of desert bighorn sheep. *Journal of Arid Environments*, 73(3), pp.280–286.

Majka, D., Jenness, J. & Beier, P., 2007. CorridorDesigner: ArcGIS tools for designing and evaluating corridors. Available at: http://corridordesign.org.

McClanahan, L.L., Ruibal, R. & Shoemaker, V.H., 1994. Frogs and toads in deserts. *Scientific American*, 270(3), pp.82–88.

Mcculloch, C.Y., 1972. Deer foods and brush control in southern Arizona. *Journal of the Arizona Academy of Sciences*, 7(3), pp.113–119.

McRae, B., 2006. Isolation by resistance. *Evolution*, 60(8), pp.1551–1561.

McRae, B. et al., 2008. Using circuit theory to model connectivity in ecology, evolution, and conservation. *Ecology*, 89(10), pp.2712–2724.

McRae, B. & Kavanagh, D., 2011. Linkage Mapper Connectivity Analysis Software. Available at: http://www.circuitscape.org/linkagemapper.

McRae, B., Shah, V. & Mohapatra, T., 2014. CIRCUITSCAPE User Guide. *The Nature Conservancy*. Available at: http://docs.circuitscape.org/circuitscape_4_0_user_guide.html?&id=gsite.

McRae, B., Shirk, A.J. & Platt, J.T., 2013. *Gnarly Landscape Utilities: Resistance and Habitat Calculator User Guide*, Seattle WA. Available at: http://www.circuitscape.org/gnarly-landscape-utilities.

Melillo, J., Richmond, T., & Yohe, G. 2014. *Climate change impacts in the United States: the third national climate assessment.* National Climate Assessment and Development Advisory Committee, U.S. Global Change Research Program, Subcommittee on Global Change Research

Metzger, J.P. & Décamps, H., 1997. The structural connectivity threshold: an hypothesis in conservation biology at the landscape scale. *Acta Oecologica*, 18(1), pp.1–12.

Minor, E.S. & Urban, D.L., 2008. A graph-theory framework for evaluating landscape connectivity and conservation planning. *Conservation Biology*, 22(2), pp.297–307.

Minor, E.S. & Urban, D.L., 2007. Graph theory as a proxy for spatially explicit population models in conservation planning. *Ecological Applications*, 17(6), pp.1771–1782.

Newman, R.A., 1988. Adaptive plasticity in development of *Scaphiopus couchii* tadpoles in desert ponds. *Evolution*, 42(4), pp.774–783.

NMGF, 2014. *Threatened and Endangered Species of New Mexico Biennial Review and Recommendations.* New Mexico Game and Fish. Santa Fe, NM.

O'Brien, C.S. et al., 2005. Landscape-level models of potential habitat for Sonoran pronghorn. *Wildlife Society Bulletin*, 33(1), pp.24–34.

O'Brien, C.S. et al., 2006. Wildlife use of water catchments in southwestern Arizona. *Wildlife Society Bulletin*, 34(3), pp.582–591.

Oliver, J.A., 1955. *The natural history of North American amphibians and reptiles.* Van Norstrand Company. Princeton, NJ

Ordway, L.L. & Krausman, P.R., 1986. Habitat use by desert mule deer. *Journal of Wildlife Management*, 50(4), pp.677–683.

Pechmann, J. et al., 2001. Amphibian colonization and use of ponds created for trial mitigation of wetland loss. *Wetlands*, 21(1), pp.93–111.

Phillips, S.J. & Comus, P.W. eds., 2000. *A Natural History of the Sonoran Desert*, Tucson, AZ: Arizona-Sonora Desert Museum Press.

Pitman, B.T., 2005. Observations of upland habitat use by California tiger salamanders based on burrow excavations. In *Transactions - Western Section of the Wildlife Society 41*. pp. 26–30.

Platz, J. & Mecham, J., 1979. *Rana chiricahuensis*, a new species of leopard frog (*Rana pipiens* Complex) from Arizona. *Copeia*, 1979(3), pp.383–390.

Platz, J.E. & Frost, J.S., 1984. *Rana yavapaiensis*, a new species of leopard frog (*Rana pipiens* complex) from Arizona. *Copeia*, 1984(3), pp.940–948.

Proulx, S.R., Promislow, D.E.L. & Phillips, P.C., 2005. Network thinking in ecology and evolution. *Trends in Ecology and Evolution*, 20(6), pp.345–53.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. Available at: http://www.r-project.org/.

Rautenstrauch, K. & Krausman, P., 1989. Influence of water availability and rainfall on movements of desert mule deer. *Journal of Mammalogy*, 70(1), pp.197–201.

Rodgers, K.J., 1977. *Season Movement of Mule Deer on the Santa Rita Experimental Range*. M.S. Thesis. University of Arizona.

Rosen, P.C. & Lowe, C.H., 1996. Ecology of the amphibians and reptiles at Organ Pipe Cactus National Monument, Arizona. *Technical Report No. 53*. Cooperative Park Resources Studies Unit, University of Arizona, Tucson, AZ

Rosen, P. & Schwalbe, C., 1994. Introduced aquatic vertebrates in the Chiricahua region: Effects of declining native ranid frogs. *RM-GTR-264: Biodiversity and Management of the Madrean Archipelago: the Sky Islands of Southwestern United States and Northwestern Mexico*, pp.251–261.

Rosen, P. & Schwalbe, C., 1995. Bullfrogs: introduced predators in southwestern wetlands. In *Our Living Resources*. pp. 452–454.

Rosen, P. & Schwalbe, C., 2002. Widespread Effects of Introduced Species on Reptiles and Amphibians in the Sonoran Desert Region. In B. Tellman, ed. *Invasive Exotic Species in the Sonoran Region*. Tucson: The University of Arizona Press, pp. 220–240.

Rosenstock, S., Ballard, W.B. & Devos, J.C., 1999. Viewpoint: benefits and impacts of wildlife water developments. *Journal of Range Management*, 52(4), pp.302–311.

Rosenstock, S. et al., 2001. Muddying the water with poor science: a reply to Broyles and Cutler. Wildlife Society Bulletin 29:734–738.

Rosenstock, S. et al., 2004. Studies of Wildlife Water Developments in Southwestern Arizona: Wildlife Use, Water Quality, Wildlife Diseases, Wildlife Mortalities, and Influences on Native Pollinators. *Technical Guidance Bulletin No. 8*.

Rubin, E.S. et al., 2002. Bighorn sheep habitat use and selection near an urban environment. *Biological Conservation*, 104(2), pp.251–263.

Ruibal, R. & Hillman, S., 1981. Cocoon structure and function in the Burrowing Hylid Frog, *Pternohyla fodiens*. *Journal of Herpetology*, 15(4), p.403.

Ruibal, R., Jr, L.T. & Roig, V., 1969. The terrestrial ecology of the spadefoot toad *Scaphiopus hammondii*. *Copeia*, 1969(3), pp.571–584.

Schwalbe, C. & Rosen, P., 1988. Preliminary report on effect of bullfrogs on wetland herpetofaunas in southeastern Arizona. *RM-GTR-166: Management of amphibians, reptiles, and small mammals in North America: Proceedings of the symposium*, pp.166–173.

Schwalbe, C. & Rosen, P., 1999. Bullfrogs–the dinner guests we're sorry we invited. *Sonorensis*, 19(1), pp.8–10.

Seager, R. et al., 2007. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science*, 316(5828), pp.1181–1184.

Shackleton, D.M., 1985. *Ovis canadensis*. Mammalian Species, pp.1–9.

Shannon, F. & Lowe, C.H.J., 1955. A New Subspecies of *Bufo woodhousei* from the Inland Southwest. *Herpetologica*, 11(3), pp.185–190.

Simms, K.M., 1989. *Home range, habitat use, and movements of reintroduced masked bobwhite*. M.S. Thesis. University of Arizona, Tucson.

Singer, F.J., Bleich, V.C. & Gudorf, M.A., 2000. Restoration of bighorn sheep metapopulations in and near western national parks. *Restoration Ecology*, 8(4), pp.14–24.

Singer, F.J., Papouchis, C.M. & Symonds, K.K., 2000. Translocations as a tool for restoring populations of bighorn sheep. *Restoration Ecology*, 8(4S), pp.6–13.

Smith, H.R. & Gallizioli, S., 1963. *Gambel Quail population trend techniques.* F.S. Proj. W 7-78-R. Phoenix, AZ.

Smith, M.A. & Green, D.M., 2005. Dispersal and the metapopulation paradigm in amphibian

ecology: Are all amphibian conservation populations metapopulations? *Ecography*, 28(1), pp.110–128.

Snow, N. & Witmer, G., 2010. *American Bullfrogs as invasive species: a review of the introduction, subsequent problems, management options, and future directions*, USDA - APHIS.

Sohl, T. & Sayler, K., 2008. Using the FORE-SCE model to project land-cover change in the southeastern United States. *Ecological Modelling*, 219(1-2), pp.49–65.

Sohl, T., Sayler, K. & Bouchard, M., 2014. Spatially explicit modeling of 1992 to 2100 land cover and forest stand age for the conterminous United States. *Ecological Applications*, 24(5), pp.1015–1036.

Souza, V. et al., 2006. An endangered oasis of aquatic microbial biodiversity in the Chihuahuan desert. *Proceedings of the National Academy of Sciences of the United States of America*, 103(17), pp.6565–6570.

Sredl, M. & Jennings, R., 2005. *Rana chiricahuensis*: Platz and Mecham, 1979, Chiricahua leopard frogs. In *Amphibian Declines: The Conservation Status of United States Species.* Berkeley: University of California Press, pp. 546–549.

Sredl, M.J., 1996. From Rags to Riches: evolution of ranid frog conservation and management in Arizona. In *Annual Meeting of the Wildlife Society, Western Section*. Sparks, Nevada.

Stebbins, R.C., 1985. *A field guide to western reptiles and amphibians*. Boston: Houghton Mifflin Company.

Stebbins, R.C., 2003. *A field guide to western reptiles and amphibians*. New York, NY: Houghton Mifflin Harcourt.

Strittholt, J.R. et al., 2012. *Sonoran Desert Rapid Ecoregional Assessment Report*, Denver. Available at: http://www.blm.gov/wo/st/en/prog/more/Landscape_Approach/reas/sonoran.html#memo.

Sullivan, B., 1989. Desert environments and the structure of anuran mating systems. *Journal of Arid Environments*, 17(2), pp.175–183.

Sullivan, B.K. et al., 1996. Arizona distribution of three Sonoran Desert anurans: *Bufo retiformis, Gastrophryne olivacea,* and *Pternohyla fodiens*. *Great Basin Naturalist*, 56(1), pp.38–47.

Sullivan, B.K., 1989. Mating system variation in Woodhouse's Toad (*Bufo woodhousii*). *Ethology*, 83, pp.60–68.

Sullivan, B.K., 1982. Sexual selection in Woodhouse's toad (*Bufo woodhousei*) I. Chorus organization. *Animal Behaviour*, 30(3), pp.680–686.

Taylor, P. et al., 1993. Connectivity is a vital element of landscape structure. *Oikos*, 68, pp.571–573.

Taylor, P., Fahrig, L. & With, K.A., 2006. Landscape connectivity: a return to basics. In K. Crooks & M. Sanjayan, eds. *Connectivity Conservation*. Cambridge: Cambridge University Press, pp. 29–43.

Tellman, B., 2002. Human Introduction of Exotic Species in the Sonoran Region. In B. Tellman, ed. *Invasive Exotic Species in the Sonoran Region*. Tucson: The University of Arizona Press, pp. 25–46.

Tevis Jr, L., 1966. Unsuccessful breeding by desert toads (*Bufo punctatus*) at the limit of their ecological tolerance. *Ecology*, 47(5), pp.766–775.

Theobald, D., 2006. Exploring the functional connectivity of landscapes using landscape networks. In K. Crooks & M. Sanjayan, eds. *Connectivity Conservation*. Cambridge: Cambridge University Press, pp. 416–443.

Thompson-Olais, L.A., 1998. *Final revised Sonoran Pronghorn recovery plan (*Antilocapra americana sonoriensis*)*, United States Fish and Wildlife Service. Ajo, AZ.

Tischendorf, L. & Fahrig, L., 2000. On the usage and measurement of landscape connectivity. *Oikos*, 90, pp.7–19.

Trenham, P., 2001. Terrestrial habitat use by adult California tiger salamanders. *Journal of Herpetology*, 35(2), pp.343–346.

Truett, J.C., 1987. *Ecology of the Desert Mule Deer,* Odocoileus hemionus crooki *Mearns, in southeastern Arizona*. Ph.D. Dissertation. University of Arizona, Tucson.

U.S.C.B., 2010. TIGER/Line 2010 Census, Census Tract national-based. Available at: http://www.census.gov/geo/www/tiger.

Unmack, P.J. & Minckley, W., 2008. The Demise of Desert Springs. In L. E. Stevens & V. J. Meretsky, eds. *Aridland Springs in North America*. Tucson: University of Arizona Press, pp. 11–34.

Urban, D. & Keitt, T., 2001. Landscape connectivity: a graph-theoretic perspective. *Ecology*, 82(5), pp.1205–1218.

USFWS, 2014. *5-Year Review: Summary and Evaluation* U.S. Fish and Wildlife Service Buenos

Aires National Wildlife Refuge, Sasabe, AZ.

USFWS, 2012. Endangered and Threatened Wildlife and Plants; Listing and Designation of Critical Habitat for the Chiricahua Leopard Frog; Final Rule. *Federal Register*, 77(54), pp.16324–16424.

USFWS, 2002a. Endangered and Threatened Wildlife and Plants; Listing of the Chiricahua Leopard Frog (*Rana chiricahuensis*); Final Rule. *Federal Register*, 67(114), pp.40790–40811.

USFWS, 2015. *Recovery Plan for the Sonoran pronghorn (*Antilocapra americana sonoriensis*), Second Revision*, U.S. Fish and Wildlife Service. Albuquerque, NM.

USFWS, 2007. *Sonora tiger salamander (*Ambystoma tigrinum stebbinsi*) 5-year review: summary and evaluation*, U.S. Fish and Wildlife Service. Phoenix, AZ.

USFWS, 2002b. *Sonora tiger salamander (*Ambystoma tigrinum stebbinsi*) recovery plan*, U.S. Fish and Wildlife Service.Phoenix, AZ.

Vos, C. et al., 2008. Adapting Landscapes to climate change: examples of climate-proof ecosystem networks and priority adaptation zones. *Journal of Applied Ecology*, 45, pp.1722–1731.

Wallace, J.E., Steidl, R.J. & Swann, D.E., 2010. Habitat Characteristics of Lowland Leopard Frogs in Mountain Canyons of Southeastern Arizona. *Journal of Wildlife Management*, 74(4), pp.808–815.

Wang, Y. & Li, Y., 2009. Habitat selection by the introduced American bullfrog (*Lithobates catesbeianus*) on Daishan Island, China. *Journal of Herpetology*, 43(2), pp.205–211.

Weintraub, J., 1974. Movement patterns of the red-spotted toad, *Bufo punctatus*. *Herpetologica*, 30(2), pp.212–215.

Weiss, A., 2001. Topographic position and landforms analysis. *Poster presentation, ESRI User Conference, San Diego, CA*, 64, pp.227 – 245.

WHO, 2003. *Ammonia in drinking-water. Background document for development of WHO guidelines for drinking–water quality.*, World Health Organization, Geneva.

Wiens, J.A., 1989. Spatial scaling in ecology. *Functional Ecology*, 3(4), pp.385–397.

Wiens, J.A. & Bachelet, D., 2010. Matching the multiple scales of conservation with the multiple scales of climate change. *Conservation Biology*, 24(1), pp.51–62.

Woodward, B., 1983. Predator-prey interactions and breeding-pond use of temporary-pond species in a desert anuran community. *Ecology*, 64(6), pp.1549–1555.

Wright, J.T., 1959. *Desert Wildlife - Wildlife Bulletin No. 6*, Arizona Game and Fish Department. Phoenix.

Zeigenfuss, L.C., Singer, F.J. & Gudorf, M. a., 2000. Test of a modified habitat suitability model for bighorn sheep. *Restoration Ecology*, 8(4S), pp.38–46.

Zeller, K.A., McGarigal, K. & Whiteley, A.R., 2012. Estimating landscape resistance to movement: a review. *Landscape Ecology*, 27(6), pp.777–797.