Final Report

# Desert Tortoise Population Connectivity Modeling

# in the Vicinity of the Proposed Bonanza Solar Project

February 2023

Prepared for the Bureau of Land Management

Prepared by: Ken Nussear

Department of Geography

University of Nevada, Reno

1664 N. Virginia Street

Reno, NV 89557

# Table of Contents

# 1.0 - Introduction

## *1.1 - Desert Tortoise Connectivity*

The Mojave desert tortoise (*Gopherus agassizii*) is listed as threatened and is afforded protection under Federal and State endangered species provisions throughout its range in the Mojave Desert and parts of the Sonoran Desert in Nevada, California, Utah, and Arizona (USFWS 1994 and 2011). One of the recovery actions listed in the 2011 Revised Recovery Plan for the Mojave Population of the Desert Tortoise is to determine the importance of corridors and physical barriers to desert tortoise distribution and gene flow (Recovery Action 5.5). In areas subject to anthropogenic pressures, corridors improve opportunities for individual contact and gene flow. It is important then to determine attributes of corridor suitability (e.g. size in the context of suitable habitat and disturbance levels), and to examine how linear barriers may impede otherwise connected habitat. Corridors are needed to allow movement between habitat patches, prevent genetic isolation, and ultimately to ensure persistence of the species.

High levels of gene flow and isolation-by-distance (IBD) play an important role in genetic connectivity for tortoises across their range (Hagerty and Tracy 2010; Murphy et al. 2007). However, IBD does not account for landscape features (e.g. mountains, playas, anthropogenic disturbance) that may influence population connectivity and gene flow. Support for alternative models acting in conjunction with IBD, such as isolation-by-resistance (IBR) has been found on a broad scale with mountains and valleys limiting gene flow (Hagerty et al. 2010; Sanchez-Ramirez et al. 2018), and at a finer spatial scale with roads acting as barriers (Dutcher et al. 2020; Latch et al. 2011). Roads are associated with high tortoise mortality and reduced abundance ranging from 0.2 – 4 km from the road, depending on traffic volume (Boarman and Sazaki 2006; Nafus et al. 2013; Peaden et al. 2015; von Seckendorff Hoff and Marlow 2002). Tortoise persistence may rely heavily on the ability to disperse across the landscape (Edwards et al. 2004), and road fencing tied in with underground hydrological culverts may ease mortality rates and allow for gains in connectivity (Berry 1986; Boarman et al. 1997; Boarman and Sazaki 2006; Ruby et al. 1994).

Because landscape changes that impact populations, positively or negatively, are associated with a time lag measured in generations (Landguth et al. 2010) and tortoises are long lived, detection of demographic and genetic shifts often occurs well after the landscape has been altered. Long-term monitoring has revealed that tortoise populations continue to decline even within most protected areas, likely influenced by anthropogenic habitat use (Allison and McLuckie 2018; Averill-Murray et al. 2021). Declines in large tortoises may reflect human disturbance (Corn 1994) and are potentially problematic as survival of large adults, especially females, strongly impacts population growth (Doak et al. 1994). Increasing development pressures across tortoise habitat continue to increase habitat loss and fragmentation while highlighting the need to maintain connected habitat (Averill-Murray et al. 2013).

The University of Nevada, Reno (UNR) recently completed a project looking at the 17 most crucial areas in Clark County for desert tortoise connectivity and determined that seven of those areas currently have a low connectivity potential or fail to maintain connectivity into the future based on future development projections (Dutcher et al. 2019). The project used available software applications to simulate tortoise population genetics through time, but the models were limited in scope and realism due to memory and parameter limitations. Two important limiting features were the inability to model overlapping generations, which is important toward understanding the potential for demographic and genetic impacts through time, and modeling populations at the scale of the likely habitat patches, but with sufficient resolution to represent realistic barriers to movement.

This project builds on a follow up project that uses individual based (aka agent-based) modeling to attempt to provide a more realistic approach to understanding the potential for tortoises to maintain connectivity in light of disturbance on landscapes associated with urbanization and other anthropogenic impacts and features. These types of models are used among many species to evaluate connectivity under more realistic conditions of movement, demographic, and live history parameters (e.g. Werner et al. 2007; Landguth et al. 2010; McLane et al. 2011; Kanalgaraj et al. 2013; Coulon et al. 2015; Allen et al. 2016; Day et al. 2020). UNR seeks to address these questions by modeling connectivity of tortoise populations among areas in fragmented habitat to better understand the possible influences of anthropogenic disturbance on population connectivity and demographics of tortoises in areas differentially impacted by anthropogenic activities and barriers to movement by modeling movement, mating and demographics. These simulations were intended to evaluate the relative effects of different proposed solar build out alternatives, and these were compared to static scenarios that reflect current habitat conditions. The model parameters that were chosen were based on empirical data, and resulted in stable conditions for current day conditions, which was useful toward evaluating the relative effects of different build out scenarios on connectivity and predicted demographics. It should be noted that there have been reported declines in desert tortoise populations throughout much of their range, and our modeling effort was not intended to capture nor simulate the causes of declines. Thus, these simulations are by no means intended to reflect predicted tortoise population numbers, nor potential effects of climate change on tortoise populations, or habitat, but rather to model the potential differences in connectivity among areas in and around a proposed solar facility.

This report supports the Bureau of Land Management (BLM) requirements under the 2012 Solar Programmatic Environmental Impact Statement and Record of Decision for solar projects proposed in Variance areas. This report was not prepared for compliance with Section 7 of the Endangered Species Act.

## 2.0 - Materials and Methods

### *2.1 - Study Areas and Digital Habitat Representation*

The study area for this analysis was derived from areas of connected habitat using a combination of a habitat model (Nussear and Simandle 2019), and one watershed unit delineated as part of the Watershed Boundary Dataset produced by the U.S. Geological Survey (USGS 2021) that encompassed the proposed development area (Figure 1). The study area extends from just east of the Creech Air Force Base at Indian Springs, Nevada to approximately 10 miles east of the junction of US 95 and Highway 160 extending north from Pahrump, Nevada.

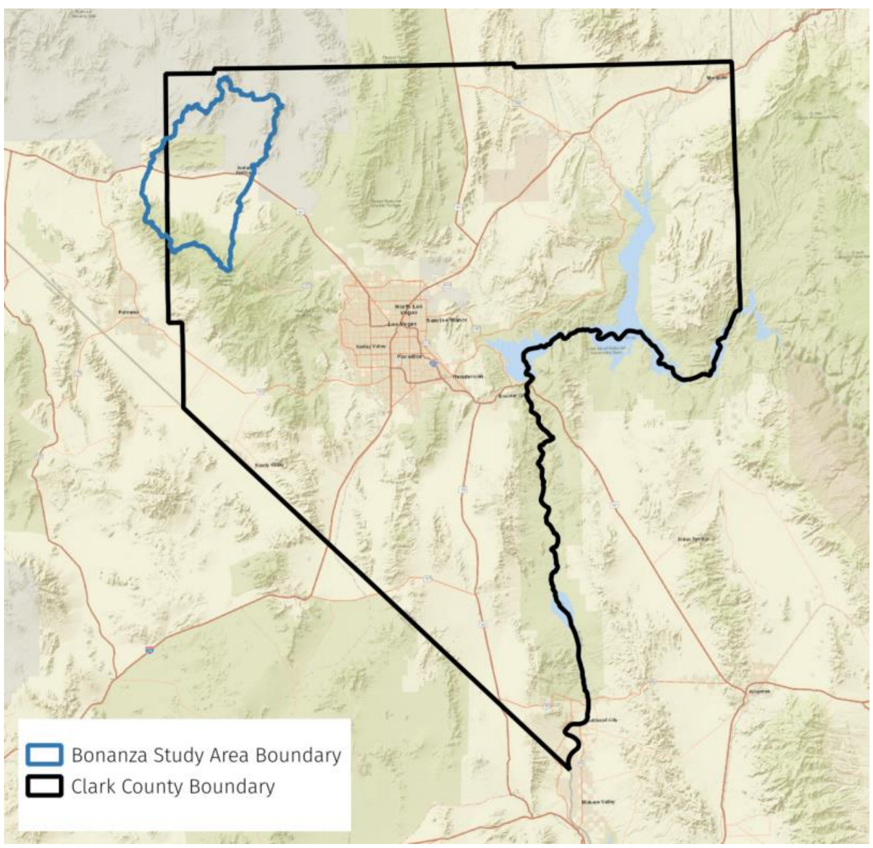


Figure 1 - Study area used in our analyses shown with Clark County, NV as a reference.

Given the accelerated pace of habitat disturbance in Mojave desert tortoise habitat and long generation times for the species, real time field studies of current and planned impacts is challenging. Using resistance surfaces from large areas across the study area in Clark County, and parts of Nye County, Nevada (Figure 1), UNR simulated connectivity of tortoise populations across complex landscapes to evaluate multiple alternative scenarios of solar development, while including barriers to movement and habitat conditions on the landscape. These scenarios are based on three potential build-out scenarios provided by the developer. All three of these scenarios are located west of Indian Springs and Creech Air Force base, and just south of US 95 – which in the study area is a divided highway with two lanes in each direction, with some culverts across both road sections to provide water drainage, and potentially provide an opportunity for tortoises to move through to provide connectivity between areas divided by these barriers (Figure 2).

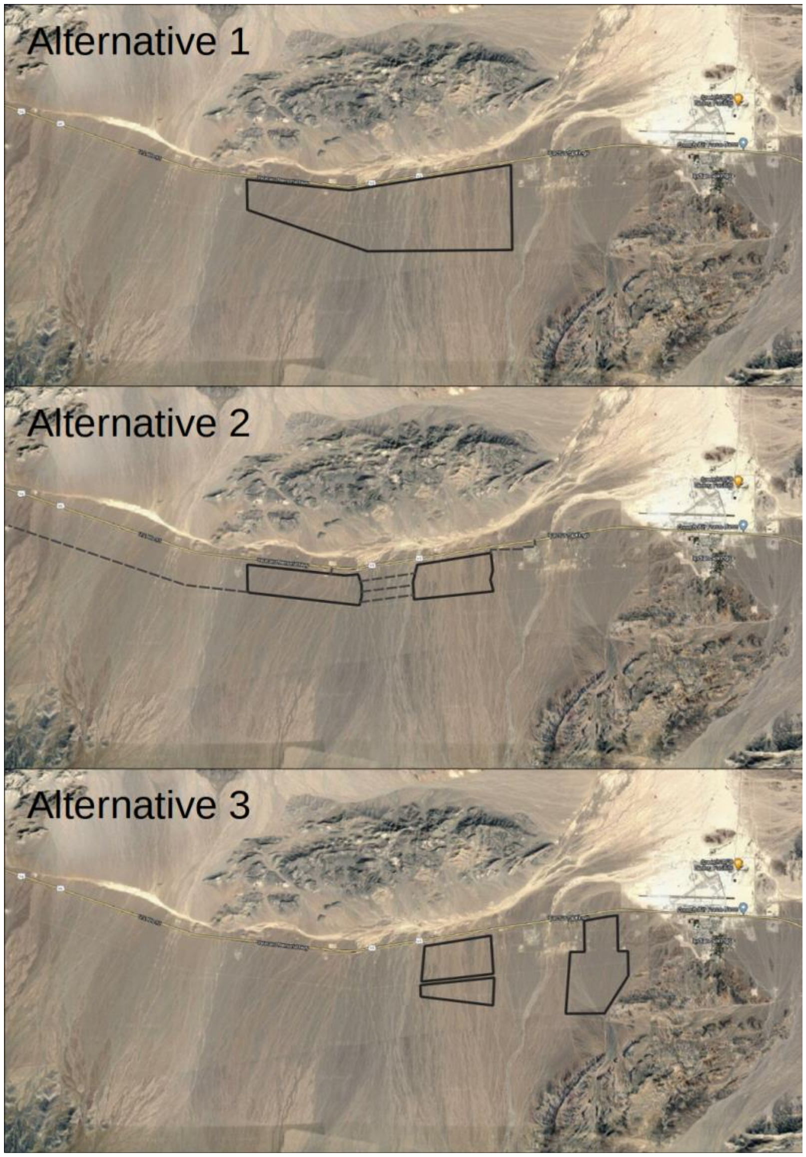

Figure 2 – Overview of the three solar alternative scenarios.

Alternative 1 is the largest of the proposed solar configurations – with one large development block proposed that has an estimated area of 20.76 km$^2$ (8 mi$^2$) (Figure 2, Table 1). Alternative 2 has a split configuration, with connecting roads implemented for transmission infrastructure, and has an estimated area of the two combined sections of 7.72 km$^2$ (2.9 mi$^2$$_)$ (Figure 2, Table 1). Alternative 3 has 3 segments – located closer to Indian Springs, and has an estimated area of 10.75 km$^2$ (4.15 mi$^{2)}$ (Figure 2, Table 1).

Simulations were run forward-in-time for 100 years using realistic parameters for movement, mating, and mortality derived from empirical studies (Dutcher et al. 2019; Mitchell et al. 2021; Hromada et al. 2020). The 100-year time frame was chosen to match current modeling predictions of urban growth within Clark County Nevada that UNR is using for a current project (Nussear et al. 2022), as well as a time frame that has revealed genetic differences in tortoise population genetics due to barriers on the landscape (Dutcher et al. 2020). Demographic patterns were predicted from simulation output to better understand the potential impacts of the different development scenarios.

Road and railroad GIS data layers were obtained from the U.S. data repository (catalog.data.gov) which originated from Tiger/Line files at the U.S. Census Bureau for all of Clark County. Roads were classified as primary, secondary, or local by road name (e.g. US 95) and the average annual daily traffic (AADT) volumes for primary roads were assigned using the Nevada Department of Transportation's Trina dataset. Primary roads were also assigned a permeability value based on their AADT values with heavily trafficked roads (i.e. I-15) considered not passable, moderately trafficked roads – with reduced passability where no fencing occurs (e.g. US 95), and minor roads considered the most passable with only minor reduction of tortoise movement (although none of these occur in the reduced study area used in this study). Fencing layers were obtained that represent tortoise proof fencing throughout Clark County, and these were treated as full barriers to movement. Culverts under primary roads were included with attribute information indicating tortoise ability to use each culvert as a crossing structure (provided by Clark County, Nevada). Each culvert was assigned a value ranging from 1 to 5, from the most passable culverts to the least: 80% passable (1), 60% passable (2), 40% passable (3), 20% passable (4), not passable (5). This considered the current culvert passability, and excluded passage where many of the culverts are not tied into the tortoise fencing, and thus cannot be used by tortoises – despite their otherwise sufficient condition. UNR modeled reductions in habitat quality attributed to existing dirt roads by rasterizing a minor roads layer which included dirt roads and trails from the USGS national Transportation Dataset (NTD) to a resolution of 30 m. The number of 30 m pixels in the 250 m was then summed and scaled between 0 and 1 to represent the degree of road incursion in each modeling pixel. This value was then multiplied by 0.5 to represent 50% habitat degradation and subtracted from the tortoise habitat suitability score for that pixel.

A least-cost path algorithm was used to simulate movement on landscape surfaces (Dijkstra 1959). Modeling movement across landscapes can be a computationally expensive process. Using agent-based models adds to the expense because the least-cost path algorithm runs for each individual at each time step in the simulation. Computational intensity also depends on the resolution of the raster representing the landscape, with smaller cell sizes increasing computation time, and RAM (random access memory) needed to store raster layers. This results in a trade-off between run time, performance, and landscape detail. To minimize this trade-off, UNR developed a quadtree data structure and created an R package (*quadtree* package v.0.1.6, Friend 2022a) to allow simulations to remain computationally tractable with fine-scale spatial details. Unlike rasters, quadtrees can have variable cell sizes, with a minimum of 30 m in UNR simulations (Figure 3). This allowed heterogeneous areas to be represented by smaller cells and homogeneous areas by larger cells (Samet 1984; Friend 2022b). Necessary landscape information was retained by being represented at a fine-scale (such as areas along major roads that may contain culverts) while only causing a small increase in overall computation time (van Bemmelen et al. 1993).

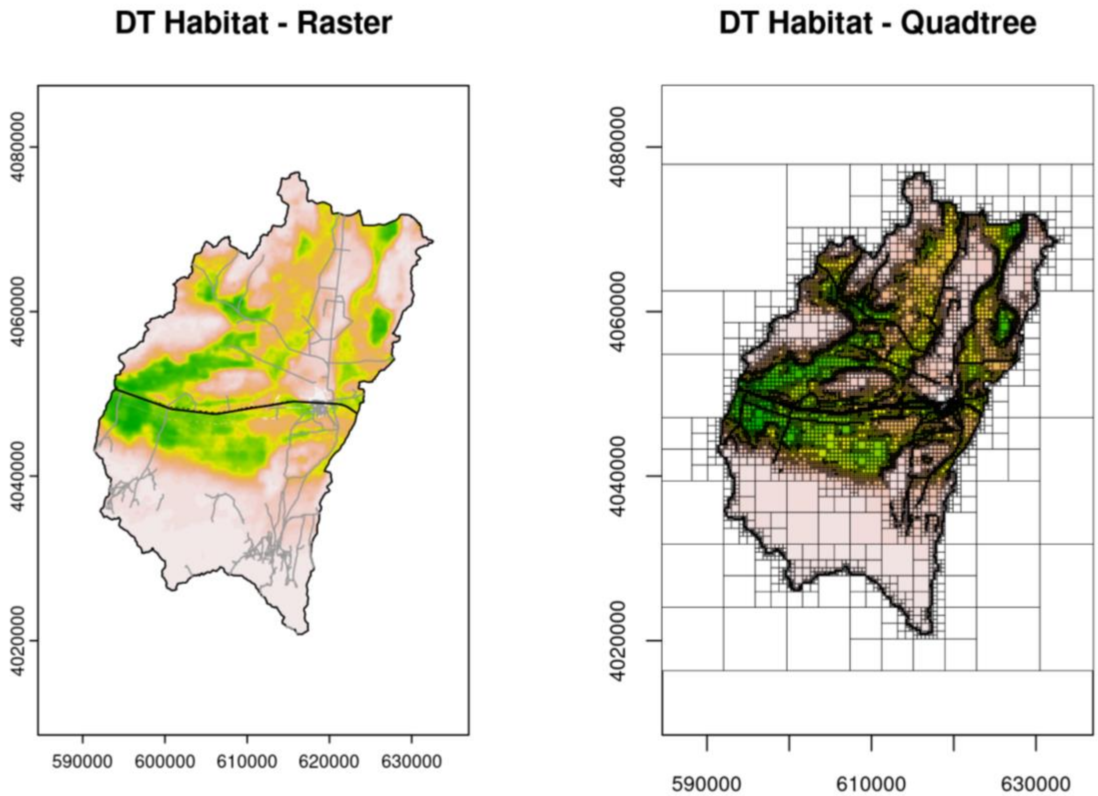


Figure 3 - The raster and quadtree representations of the habitat model for the study area.

### *2.2 - Forward-in-time Simulation Framework*

An individually-based forward-in-time modeling framework was created in R 4.1.2 (R Core Team 2022) to construct simulations accounting for variable barrier and scenario configurations. This consisted of generating an initial random population of tortoises for the study area, that were then established using a burn-in run of 5,000 years with a simulated "habitat only" cost landscape (1 - habitat values) to allow for the population density to adjust to the influences of local habitat condition and spatial habitat arrangement. Simulations were then run for 100 annual cycles for each scenario, and included dispersal, breeding, and mortality for each year. Each tortoise was tracked individually throughout its lifetime. Movements, matings, and demographic parameters were recorded for each year of the simulation.

Movements were simulated to represent an annual displacement for each tortoise. These dispersal movements were based on the yearly home range shift of resident radio-telemetered tortoises tracked for multiple years at eight sites in the Mojave Desert in Nevada (previously reported in Nussear et al. 2012; Drake et al. 2012 and 2015; Sah et al. 2016; Hromada et al. 2020): Bird Spring Valley (n=120), Coyote Springs (n=118), Halfway Wash (n=47), Lake Mead (n=9), McCullough Pass (n=20), Piute Valley (n=129), Stateline Pass (n=11), and California: Fort Irwin (n=263). While some of these studies included translocated animals, no movements of translocated animals were included in the data used for this modeling effort. For each iteration of annual dispersal, a random bearing for direction of movement was drawn, and a random number between 0 and 1 was used to find the closest corresponding home range shift distance from a probability distribution function derived from the movement dataset (Figure 4).

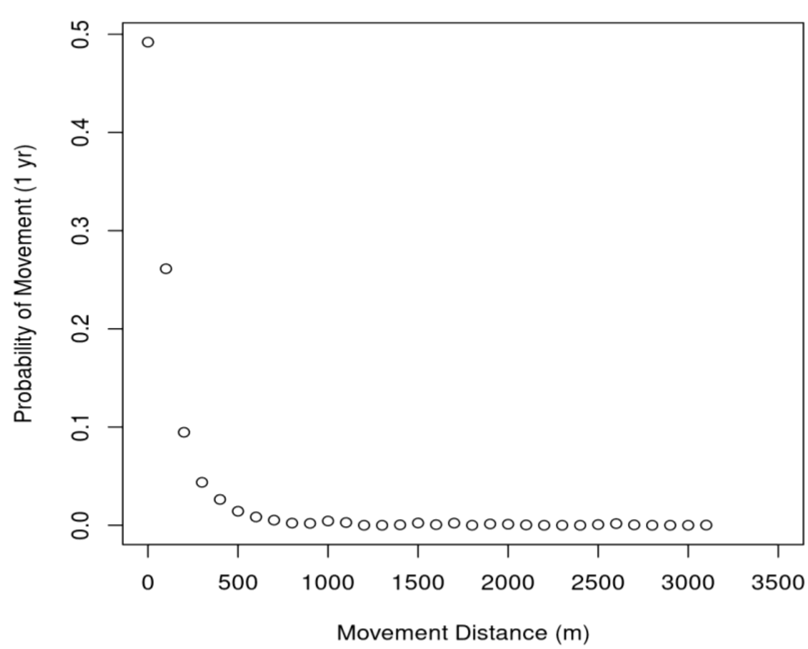


Figure 4 - Probability of annual movement distances calculated from annual kernel home range centroid shifts for 717 resident tortoises at eight Mojave desert sites.

UNR used “least cost paths” to identify potential movement pathways that minimized the accumulated cost of movement across a cost surface that considers habitat, habitat degradation (due to roadways, barriers, etc.), restrictions of movement due to roadways and fencing, while allowing the use of differential culvert passability. Moving across this cost surface allows the consideration that movement through low quality, rugged terrain, or and degraded habitat with barriers will be less likely than open high quality undisturbed habitat. Movement cost was considered to be the inverse of habitat suitability (in the absence of anthropogenic disturbance), such that areas of high suitability were "easier" for tortoises to move through than those of lower suitability (e.g. rough mountainous areas or vast dry lakes that are not typically considered habitat). A new destination point was calculated using the randomly generated bearing and distance from the distribution discussed above. A movement path was then calculated from the animal's current location to the new location using a least cost path using the *lcp_finder* and *find_lcp* functions in the *quadtree* package (Friend 2022a). Due to irregularities on the landscape (e.g. the least cost path traces around an obstacle), it was possible that the least cost path was longer than the desired displacement distance, as the movement path varied to avoid obstacles or poor habitat (Figure 5). An accumulation cost was calculated to stop movement at the location where the selected cost adjusted displacement distance was achieved. As the movement model placed all tortoises in the center of the cost surface quadtree grid cell, all final locations were selected at random within an ellipse formed between the last two points (note - this had the potential to inadvertently create a small number of unintended barrier crossovers of full barriers). Tortoises that dispersed into completely unsuitable habitat (e.g. somehow ending up on a road or off the edge of the map) were considered mortalities for that year.

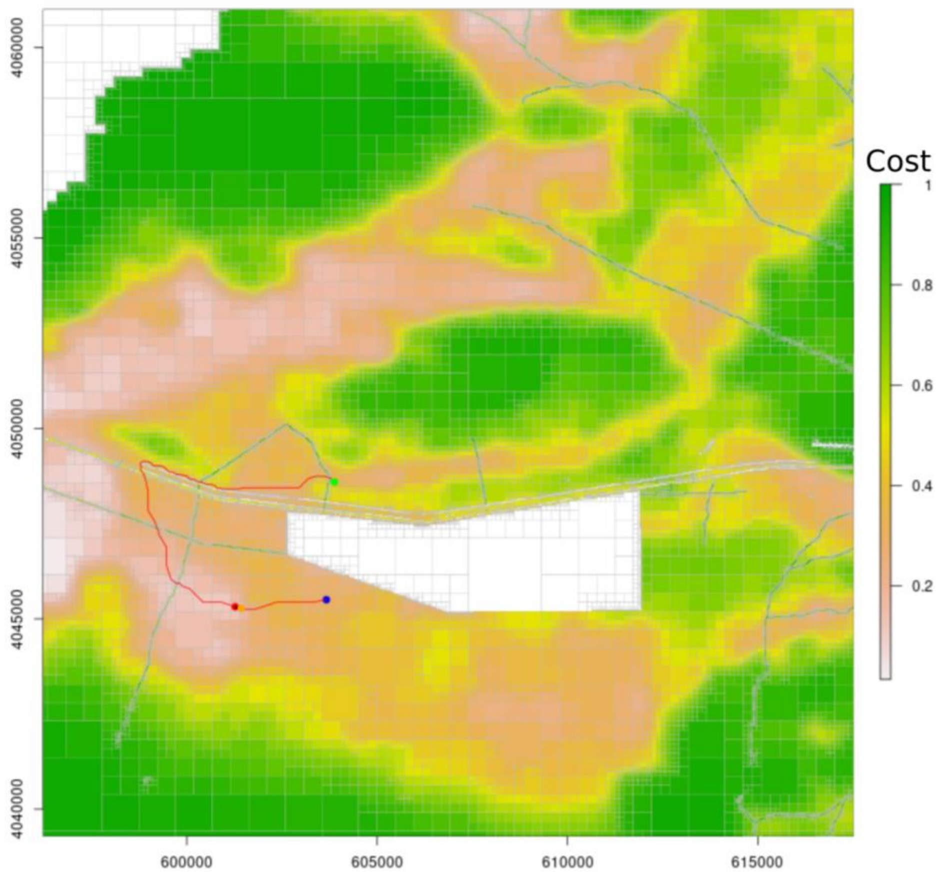


Figure 5 –Least Cost Movement Example from the Alt1 Scenario. The coloring in the image represents the cost to movement, where green indicates the highest cost, and earth colors indicate lower cost. White indicates full barriers to movement. The black dot shows the origin of the tortoise. The green dot is the random destination, the red line indicates the least cost path across the cost surface to get there given the habitat surface and available culverts. The red dot indicates the maximum cost distance equivalent as the cost across the surface is accumulated, and the orange dot indicates the adjusted end point to avoid end points landing in a pixel center each time.

In each year reproduction was modeled by creating a list of all males within a given radius (1,000 m for the simulations in this report) that could reach each female through a least cost path movement (as described above). The number of eggs per female in each year was drawn from a Poisson distribution (characterizes discrete events with a low probability of occurrence) with lambda = 6 (parameter of the Poisson distribution similar to the mean), as this approximates the average number of eggs laid per year by Mojave desert tortoises (Mitchell et al. 2021). Since tortoises are known to have multiple paternity, each male within the mating radius had the ability to be the father to one or more eggs, and was selected at random (with replacement) for each egg. The genetic makeup of the offspring was assigned randomly (one allele at each locus drawn from the mother and the father) for each of 20 alleles. Offspring were produced with an equal sex ratio (USFWS 2011) and their initial spatial locations were set as the location of the mother. The mother and father were recorded along with the local habitat value and zone (areas within landscapes predetermined by major roads and the railway). Each offspring was then assigned an age of 0 and a start year.

After movement and mating, tortoises were subject to mortality. For each tortoise a mortality risk score was calculated that considered individual age, habitat suitability, and the local tortoise density. The baseline mortality was set at 4% per year to represent high survivorship and low overall annual mortality of adults for this species (Turner et al. 1984; Congdon et al. 1993; Doak et al. 1994; Longshore et al. 2003). Elevated risk relative to age was assessed for juveniles < 10 years old, as these tortoises were assumed to be approaching 100 mm in size (Medica et al. 2012) and at a higher risk of predation and other factors (e.g. susceptibility to climate extremes, predation, and dietary deficiencies (Doak et al. 1994; USFWS 1994; Bjurlin and Bissonette 2004; Tracy et al. 2004; USFWS 2011; Segura et al. 2020). The partial risk score for elevated risk juveniles was calculated using a sigmoidal function (e.g. Caglar et al. 2018) where baseline mortality (4%) was increased for very young animals (by 15% to 19% per year, Doak et al. 1994; Bjurlin and Bissonette 2004), and decreased back to the baseline as animals reached ages of 10 years old, corresponding with larger sizes (Figure 6). Mortality was maintained at the baseline for mid aged animals (Doak et al. 1994). Older tortoises were also considered to have higher mortality risk (Doak et al. 1994; Tracy et al. 2004; Medica et al. 2012). Starting at age 60, mortality risk increased above the baseline adult mortality (by 6% to 10%, Figure 6, Doak et al. 1994). The inverse of habitat suitability was used in calculations of mortality risk, such that low quality habitat (1) had a higher risk, while higher quality habitat (0) had no added risk. Finally, localized density was calculated for each year using a Poisson point process density estimator of all tortoise locations with a bandwidth of 1,000 m using the *density* function within the *spatstat.core* package (v.2.30, Baddeley and Turner 2005). The localized density per cell was calculated and an increased mortality risk was assigned to cells exceeding a density of 20 tortoises/km$^2$ using a sigmoidal function where risk at densities higher than this were assumed to be highest - adding up to 10% more risk (Figure 7). This number was selected based on density estimates for the local area conducted in prior surveys (Ironwood 2022). Given that these surveys occurred in proximity to the existing highway, any current impacts due to this roadway are likely reflected in these densities. The three partial risk scores (Age, Habitat, and Density based) were then summed to create the total additional mortality risk for each individual. For each tortoise in each year the mortality was determined using a random Poisson draw using the risk score as lambda, and a random uniform number draw between 0 and 100. If the random uniform number was less than the risk score the tortoise was considered to have died during this year. For example, if a tortoise had an additive risk score of 10%, and the random number drawn was any of 1 to 10, the tortoise was considered to have died, while any number drawn from 11 to 100 resulted in the tortoise surviving for another year.

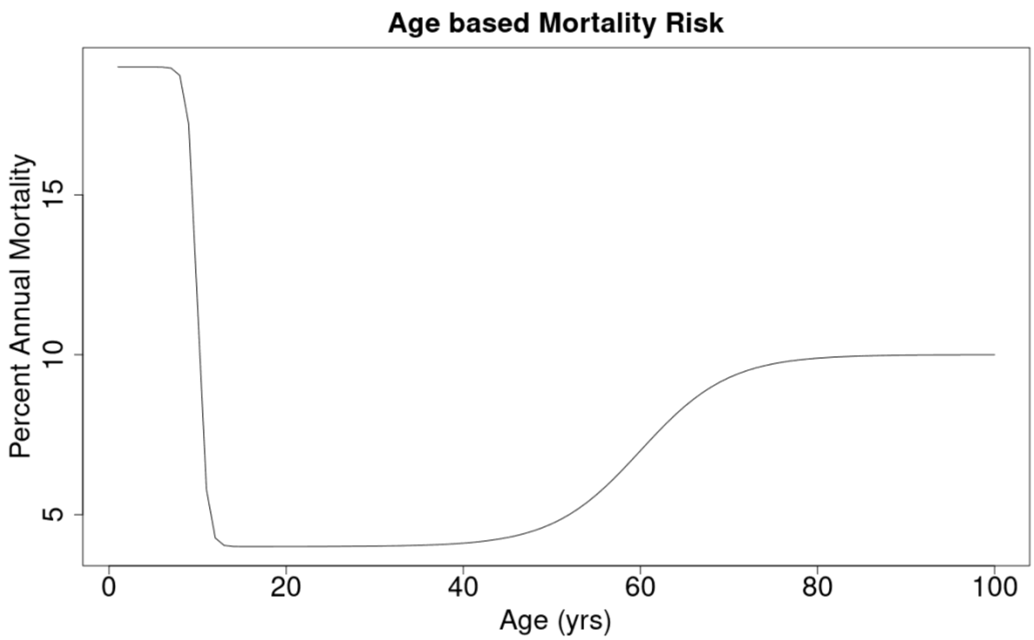


Figure 6 - Function used to assess mortality risk as a function of tortoise age.

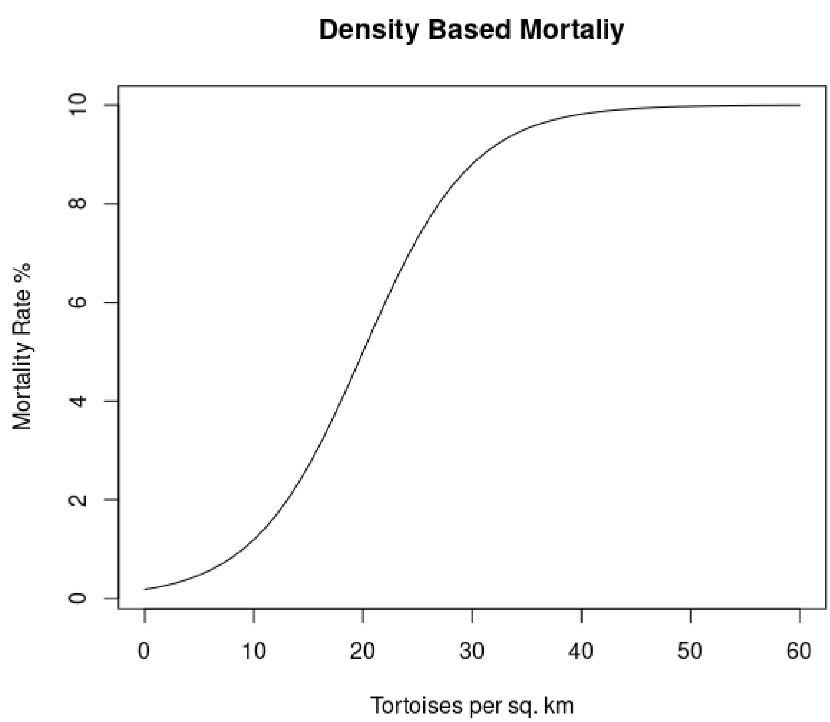


Figure 7 - Density based mortality risk used for simulations.

The following simulation scenarios were evaluated for each of the study areas:

1. No Barrier – landscape with no anthropogenic disturbance based only on the habitat model/cost was run to create a 100 year baseline for an unimpeded landscape.
2. Simple Barrier – major roadways and railways, and existing urbanized areas were considered to be barriers to movement with all available culverts closed.
3. Culvert 3 – roadways and railways, and existing urbanized areas were considered barriers relative to traffic loads with culverts assigned values from 0% – 80% passable (provided by Clark County), as described above. Culverts not tied into fencing were treated as full barriers.

Three scenarios were then run for each of the proposed solar alternatives which were added to the Culvert 3 scenario above.

a. The proposed area was considered fenced and uninhabitable for the 100-year simulation – Alternative 1, Alternative 2 and Alternative 3.
b. The proposed area was considered fenced for 2 years and then habitat was considered 25% recovered -Alternative 1_25, Alternative 2_25 and Alternative 3_25.
c. The proposed area was considered fenced for 2 years and then habitat was considered 50% recovered -Alternative 1_50, Alternative 2_50 and Alternative 3_50
d. The proposed area was considered fenced for 2 years and then habitat was considered 75% recovered -Alternative 1_75, Alternative 2_75 and Alternative 3_75.

## 3.0 - Results

### *3.1 - Population Demographics*

In order to assess the results of the simulations, UNR examined demographic metrics like population size, mortality rate, reproduction rate, and annual displacement distance. By comparing metrics across scenarios, the relative consequences of the different landscape configurations on tortoise populations can be inferred.

As connectivity is a key focus of this project, metrics related to movement of tortoises between zones were calculated. Due to the nature of the simulation, there are both explicit and implicit movements between populations. Explicit movements are defined as a movement of a tortoise from one zone to another. However, movement can also occur implicitly – females are allowed to mate with males so long as they are within 1,000 m and are not separated by a barrier, which means that tortoises in two different zones can mate so long as they are reachable. While this does not register as an "explicit" movement, it clearly implies the movement of a tortoise from one zone to another in the production of offspring with parents residing in two adjacent areas. Therefore, to analyze the movement between zones both the explicit and implicit movements were evaluated.

For explicit movement, UNR recorded the movement of tortoises between zones and then used this to analyze the number of immigrants and emigrants for each zone in each year. This information was also used to keep track of the pairwise movement between the zones – that is, the number of tortoises that moved between a pair of zones (regardless of direction).

To identify implicit movements, the number of tortoises born each year whose parents were in different zones was calculated. For each pair of zones, the number of new-born tortoises with parents from those two zones was recorded.

Analyzing movement metrics across simulations can indicate whether some scenarios allow more movement than others. In addition, by examining these yearly values over time for a single simulation, changes in connectivity over time can be identified – this is particularly useful for examining how future development may impact connectivity. The three alternative solar build-out scenarios with landscape habitat representations (including barriers and current impacts) are shown in Figure 9 below.

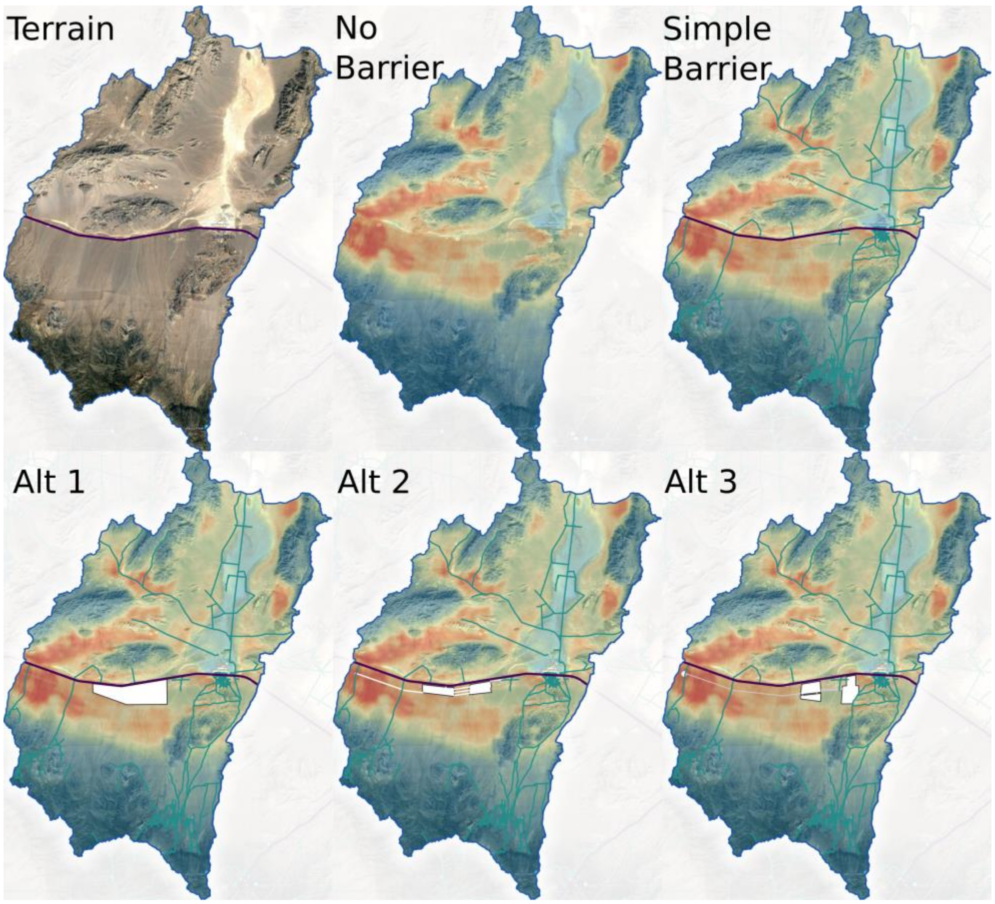


Figure 9- Terrain map of the study area, and No Barrier and Simple Barrier Scenarios. Map coloration indicates a range of tortoise habitat values from highest (red) to lowest (blue). Degradation due to roads, proposed solar facilities, urban areas, and urbanization for the Simple barrier is shown in each of the panels, and (Bottom Row) Alternative 1, Alternative 2 and Alternative 3 Scenarios are indicated in white.

The study area was divided into five primary zones for analysis (Figure 10). Although several other very small isolated patches existed, they were largely fragments segregated by the parallel highways, and urban areas near Indian Springs. The zones are separated by key barriers in the region (US 95) as well as discontinuous patches of habitat that created isolated areas – e.g. at the northern edge between Zones 1 and 3. Zone 2 was the zone most directly impacted by potential solar development, and connectivity among adjacent zones was monitored using the methods described above. The three scenarios were expected to reduce the habitat area in Zone 2 between 7 $km^2$ (Alternative 2) and 20 $km^2$ (Alternative 1) (Table 1).

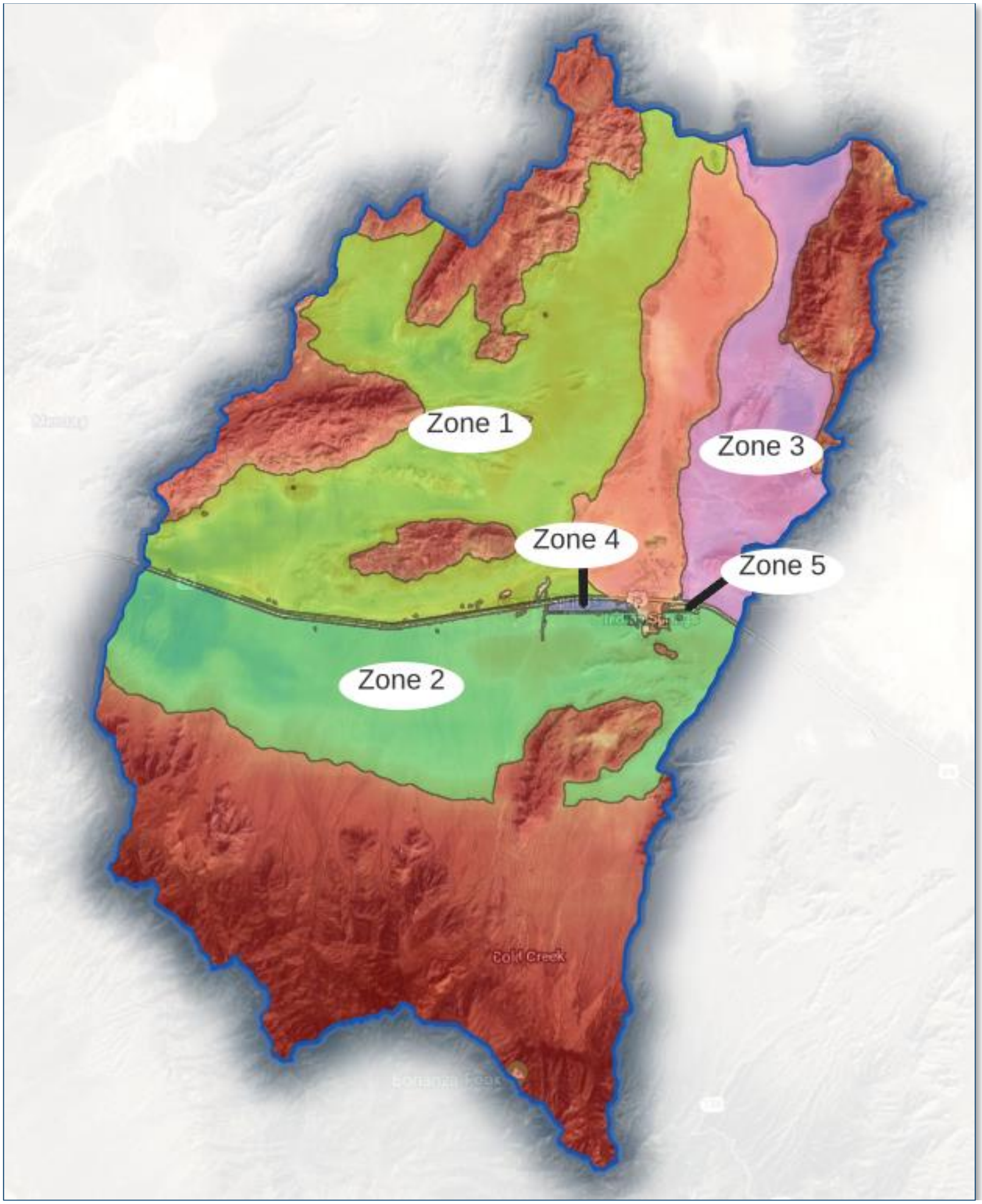


Figure 10 - Zones in the Northwest Corridor study area that were used for the analyses. The three primary zones tracked were zones 1, 2, and 3 – with Zones 4 and 5 capturing the area surrounding Indian Springs.

| Zone # | Description | Area (km2) |
|---|---|---|
| 1 | NW | 288.5 |
| 2 | South | 200.32 |
| 3 | NE | 98.4 |
| 4 | IS West | 2.01 |
| 5 | IS East | 0.34 |
| **Scenario** | | **Area (km2)** |
| Alt 1 | | 20.76 |
| Alt 2 | | 7.72 |
| Alt 3 | | 10.75 |

Table 1 – Zone areas, and Scenario Areas – Note Scenarios subtract habitat from Zone 2.

### *3.2 - Demographics*

Changes in area and habitat due to the different sizes of proposed solar alternatives, and the different levels of proposed restoration resulted in few to no changes in modeled tortoise demographics over time generally, and across all three of the density scenarios.

#### *3.2.1 - Mortality Rates*

Adult mortality rates largely remained between 7% and 10% overall with underlying random fluctuations due to the random nature of the simulations, but without pattern relative to the zone, the solar Alternatives (1-3) or the simulation relative to complete exclusion, or phased in tortoise inclusion after the build-out with some habitat degradation (Figures 11, 12, 13, 14). Mortality rates for the simple and no barrier simulations were also similar to those of the development scenarios (Figures 11, 12, 13, 14). General linear models were examined for mortality rates as a function of year, by zone, and build-out scenario, as well as examining Zone 2 alone, and mortality rates did not indicate a significant difference over time for any condition. For the most pessimistic scenario (100% habitat loss on the alternative designation for the length of the simulation) – and focusing on Zone 2 – where development occurred, there were no differences in mortality rates among sim scenarios (p values 0.19 - 0.93), nor were there trends in mortality rates over time for any sim (year:sim pvalues 0.35 - 0.82) (Table 2). This was the case for each of the phased restoration simulations as well (25%, 50% and 75%).

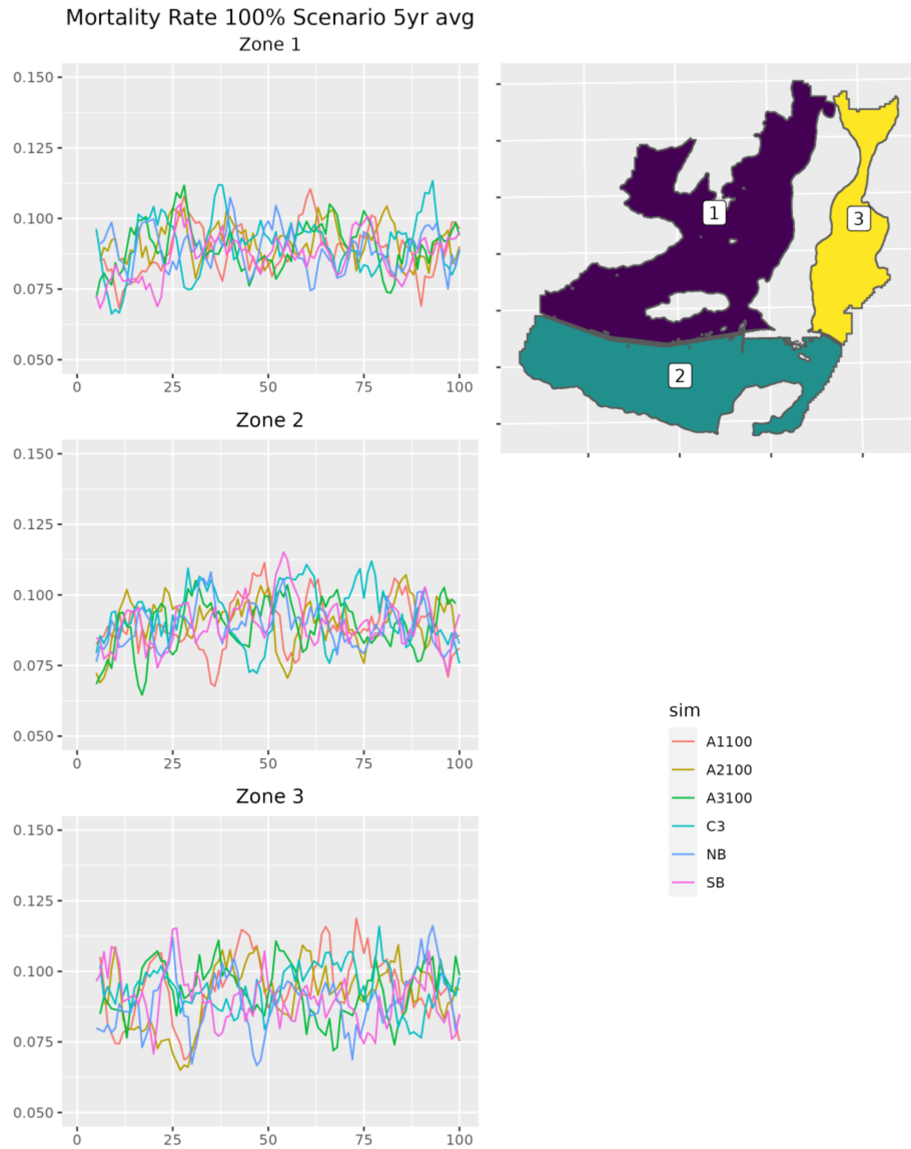


Figure 11 - Adult mortality rates by zone for the full exclusion scenarios. Proportion of the adult tortoise population dying over time in each zone – where the Alternatives (1-3), and Simple Barrier (SB), No Barrier (NB), and Culverted highway (C3) are included for comparison, as indicated by different colors as shown in the plot legend.

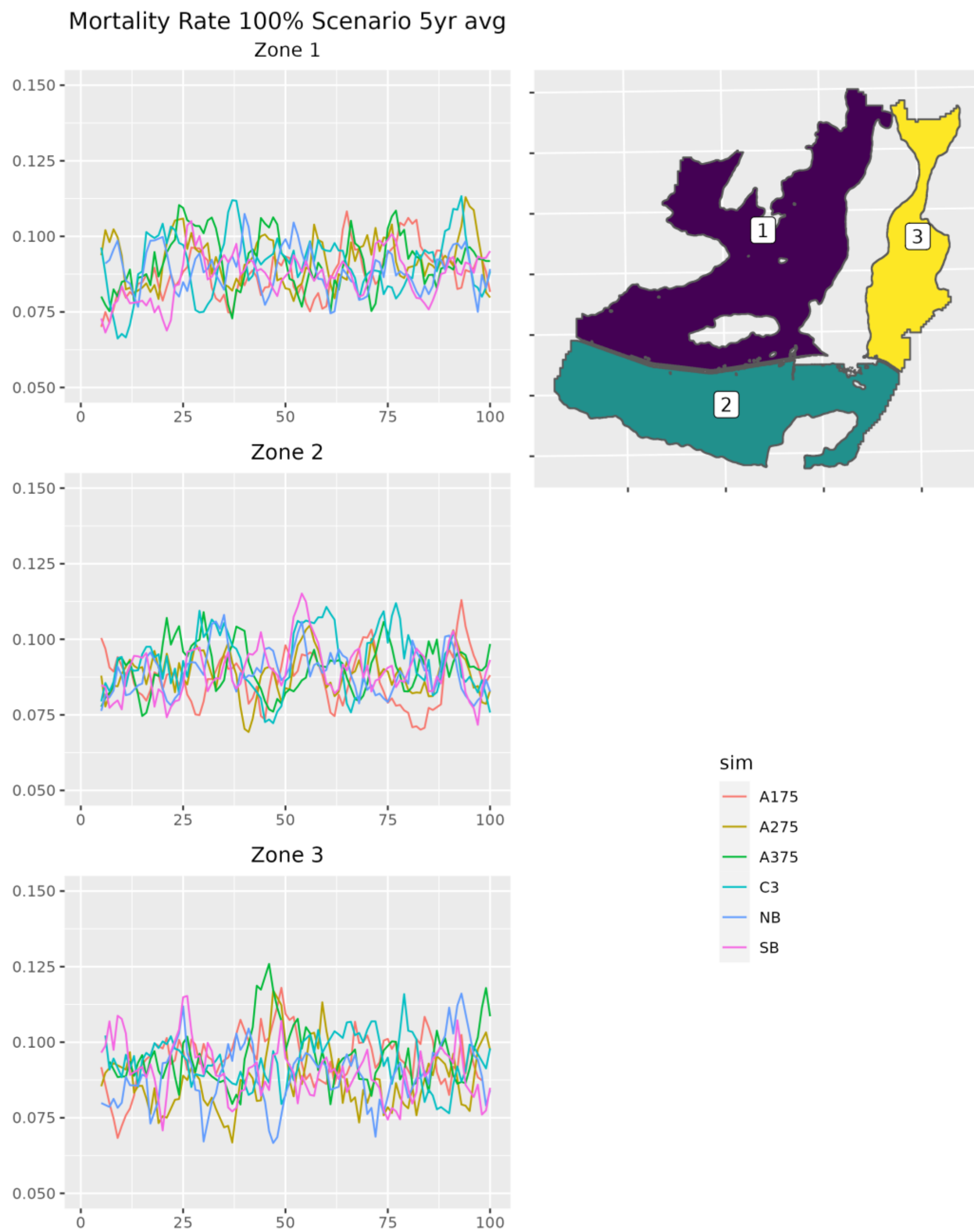


Figure 12 - Adult mortality rates by zone for the 75% restoration scenarios. Proportion of the adult tortoise population dying over time in each zone – where the Alternatives (1-3), and Simple Barrier (SB), No Barrier (NB), and Culverted highway (C3) are included for comparison, as indicated by different colors as shown in the plot legend.

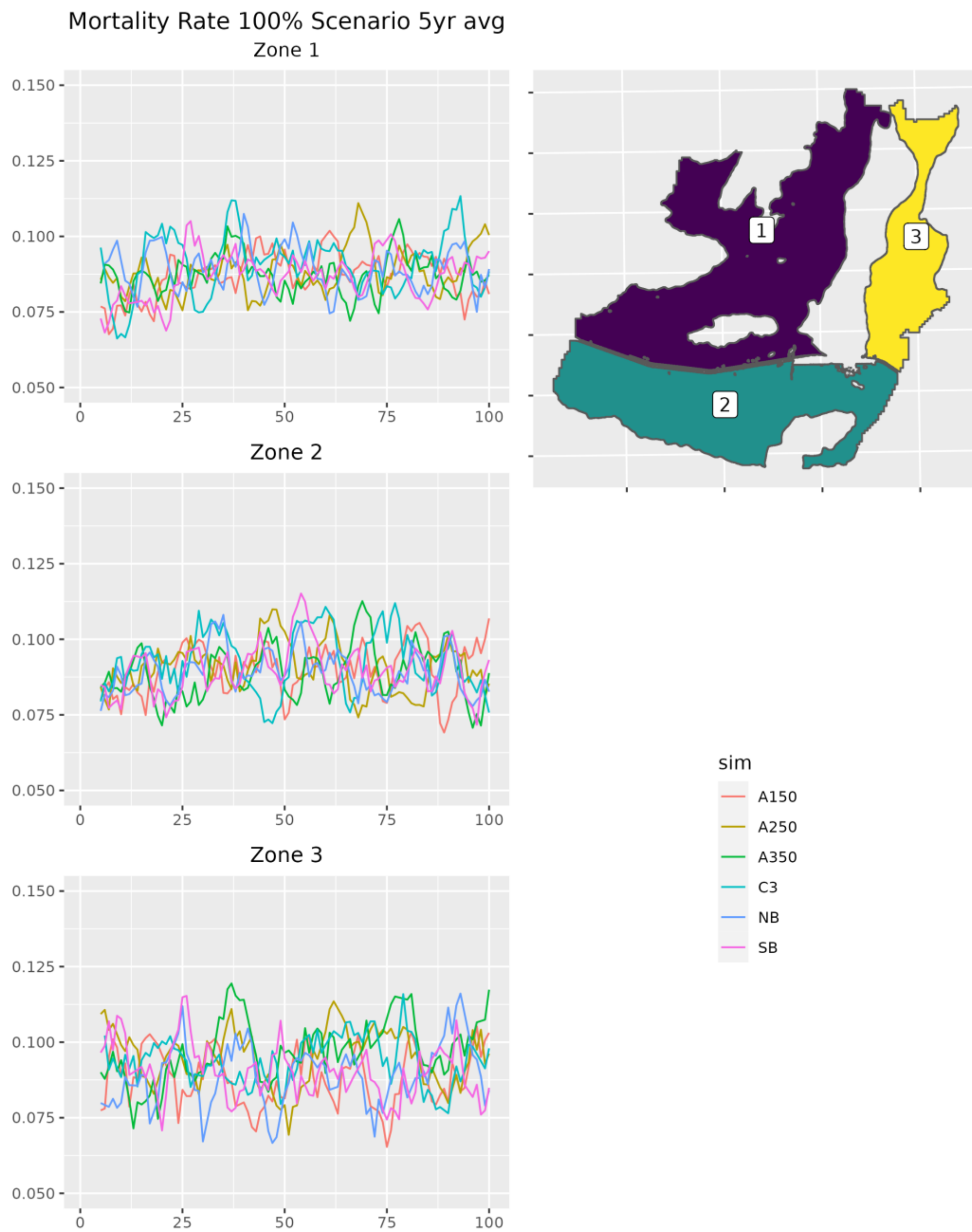


Figure 13 - Adult mortality rates by zone for the 50% restoration scenarios. Proportion of the adult tortoise population dying over time in each zone – where the Alternatives (1-3), and Simple Barrier (SB), No Barrier (NB), and Culverted highway (C3) are included for comparison, as indicated by different colors as shown in the plot legend.

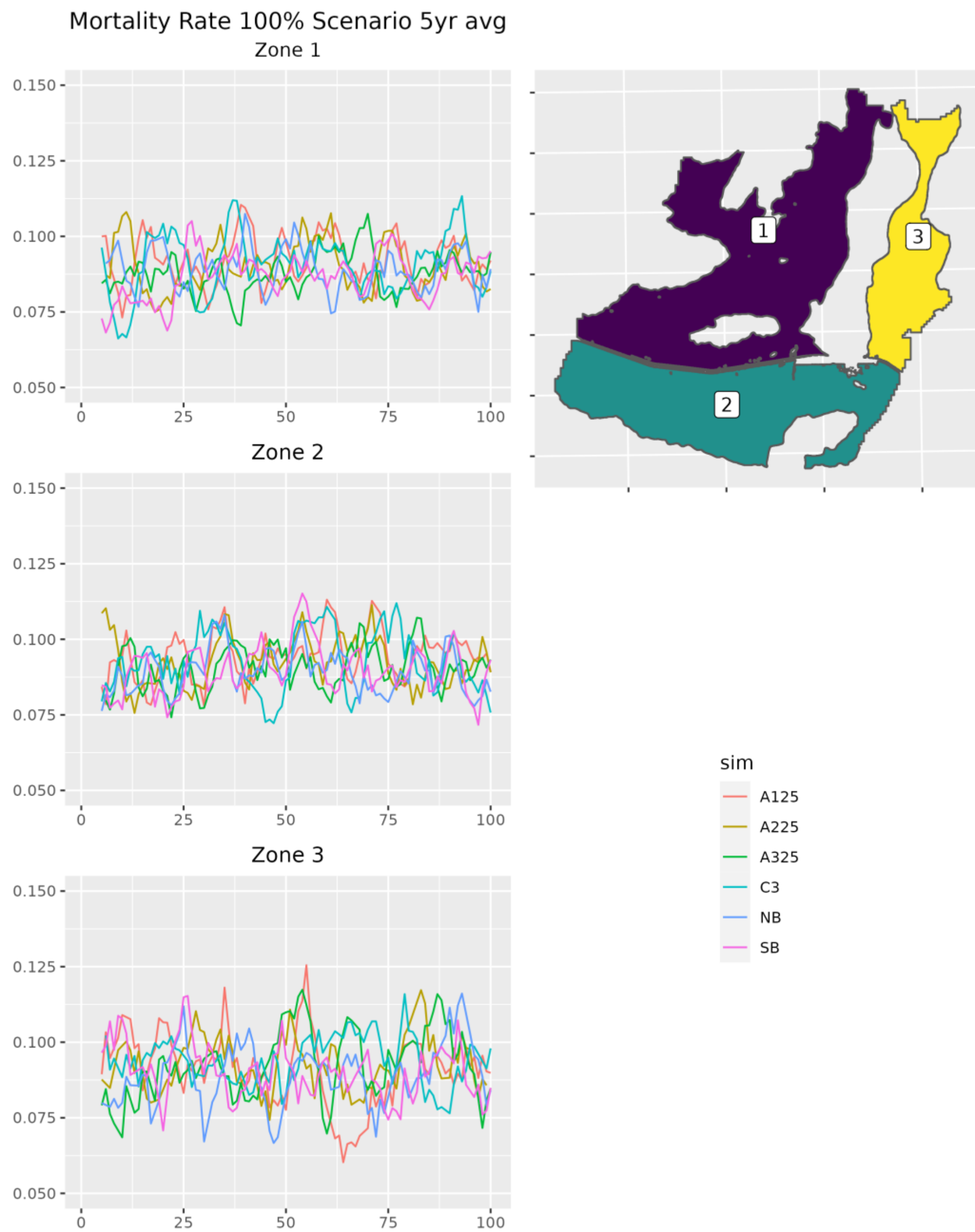


Figure 14 - Adult mortality rates by zone for the 25% restoration scenarios. Proportion of the adult tortoise population dying over time in each zone – where the Alternatives (1-3), and Simple Barrier (SB), No Barrier (NB), and Culverted highway (C3) are included for comparison, as indicated by different colors as shown in the plot legend.

| Parameter | Coefficient | Std. Error | t value | Pr(>\|t\|) |
|---|---|---|---|---|
| (Intercept) | 0.0841 | 0.0040 | 21.1360 | <2e-16 *** |
| year | 0.0001 | 0.0001 | 1.1660 | 0.24 |
| simC3 | 0.0074 | 0.0056 | 1.3070 | 0.19 |
| simA1100 | 0.0024 | 0.0056 | 0.4240 | 0.67 |
| simA2100 | 0.0049 | 0.0056 | 0.8720 | 0.38 |
| simA3100 | 0.0005 | 0.0056 | 0.0870 | 0.93 |
| year:simC3 | -0.0001 | 0.0001 | -0.9370 | 0.35 |
| year:simA1100 | 0.0000 | 0.0001 | -0.2760 | 0.78 |
| year:simA2100 | -0.0001 | 0.0001 | -0.5340 | 0.59 |
| year:simA3100 | 0.0000 | 0.0001 | -0.2280 | 0.82 |

Table 2. Analysis of the 100% habitat reduction scenario for mortality rates in Zone 2. Each "sim" coefficient is relative to a simple (full) barrier scenario.

Aside from modeled mortality rates over time, there were initial losses that would be expected as a result of the initial build-out. Whether these result in mortalities or removal of individuals for later translocation, the result is a displacement of individuals from their natural habitat. Translocations of tortoises that may occur in the future were not within the scope of this modeling effort. Using tortoise locations from the "Culvert 3" or current conditions across the 100-year simulation, the means of the number of each animals within each year that were located within the Alternative 1, Alternative 2, and Alternative 3 boundaries were calculated. This resulted in an estimated loss of 20, 6, and 6 tortoises (respectively) in the three scenario footprints (Figure 15).

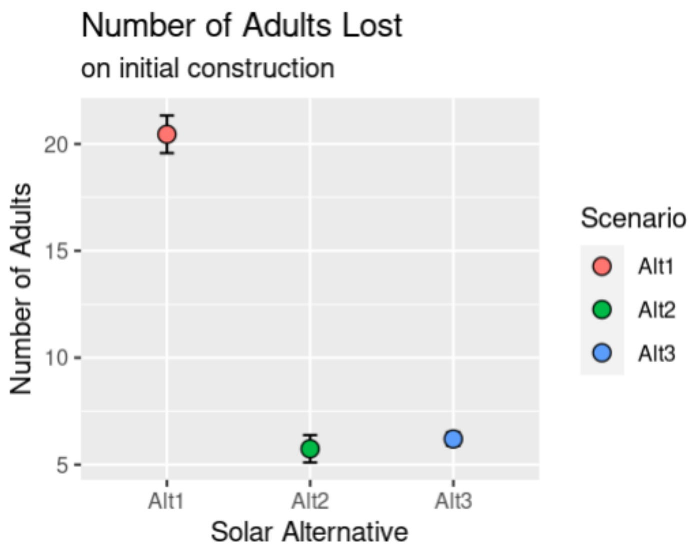


Figure 15 – Number of adult individuals located within the footprint of the developed areas for the Alt1, Alt2, and Alt3 scenarios. Numbers of adults were derived by intercepting the 100 annual tortoise locations with each boundary, and are presented as means with 95% confidence intervals.

### *3.2.2 - Number of Individuals*

The number of adult animals over time was stable – or even slightly increasing relative to zone, scenario, or build-out type in some cases (Figures 16 - 19). There was a generally increasing trend over time in all three of the build-out alternatives, and across most of the alternatives/barrier scenarios – although the alternative solar scenarios really only had the potential to directly affect Zone 2. Detailed analysis of Zone 2 alone indicated a slightly positive trend in the numbers of adult individuals over time for each of the simulations relative to the simple barrier scenario (p values $< 0.05$ for each of the year: sim analyses for the 100% habitat loss scenario) (Table 3). In addition – each of the alternatives had fewer tortoises on average than the simple barrier scenario – although this number averaged between 16 and 20 animals per year (Table 3). The absolute number of animals in each zone was proportional to zone area.

| Parameter | Coefficient | Std. Error | t value | Pr(>\|t\|) |
|---|---|---|---|---|
| (Intercept) | 214.4588 | 2.6189 | 81.8900 | < 2e-16 *** |
| year | 0.0565 | 0.0450 | 1.2540 | 0.210431 |
| simC3 | -16.3206 | 3.7037 | -4.4070 | 1.29e-05 *** |
| simA1100 | -20.9485 | 3.7037 | -5.6560 | 2.63e-08 *** |
| simA2100 | -16.9194 | 3.7037 | -4.5680 | 6.23e-06 *** |
| simA3100 | -12.8261 | 3.7037 | -3.4630 | 0.000581 *** |
| year:simC3 | 0.2469 | 0.0637 | 3.8780 | 0.000120 *** |
| year:simA1100 | 0.1538 | 0.0637 | 2.4160 | 0.016057 * |
| year:simA2100 | 0.1630 | 0.0637 | 2.5590 | 0.010786 * |
| year:simA3100 | 0.1467 | 0.0637 | 2.3030 | 0.021680 * |

(Table 1) – where Zone 1 had the most animals, followed by Zones 2 and 3 (Figures 16-19). Table 3. Analysis of the 100% habitat reduction scenario for the number of tortoises in Zone 2 over time. Each “sim” coefficient is relative to a simple (full) barrier scenario.

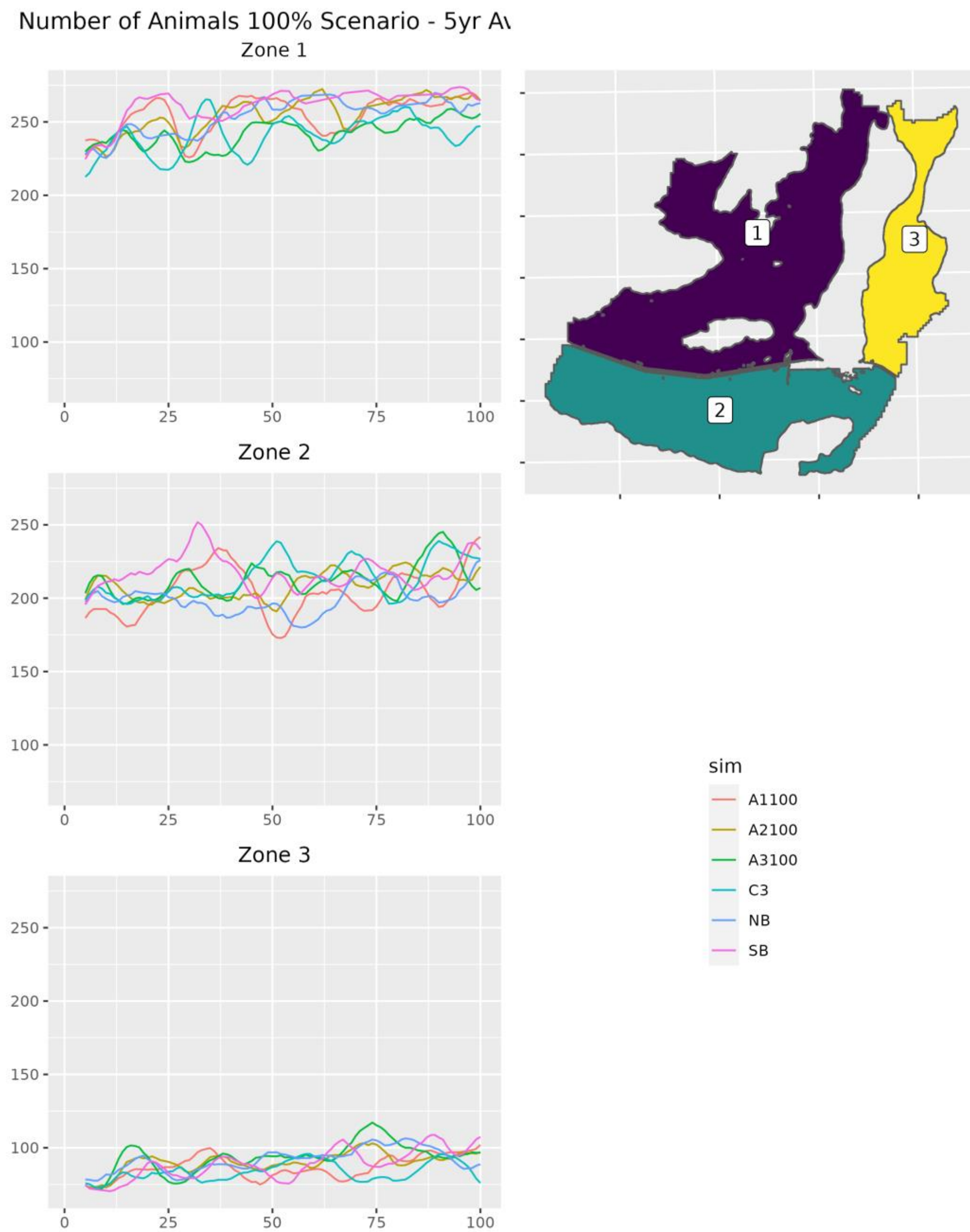


Figure 16 – Five year moving average of the number of tortoises alive over time for each zone for the 100% restoration scenarios, graphed by each scenario, and proposed solar alternative (represented by different colors).

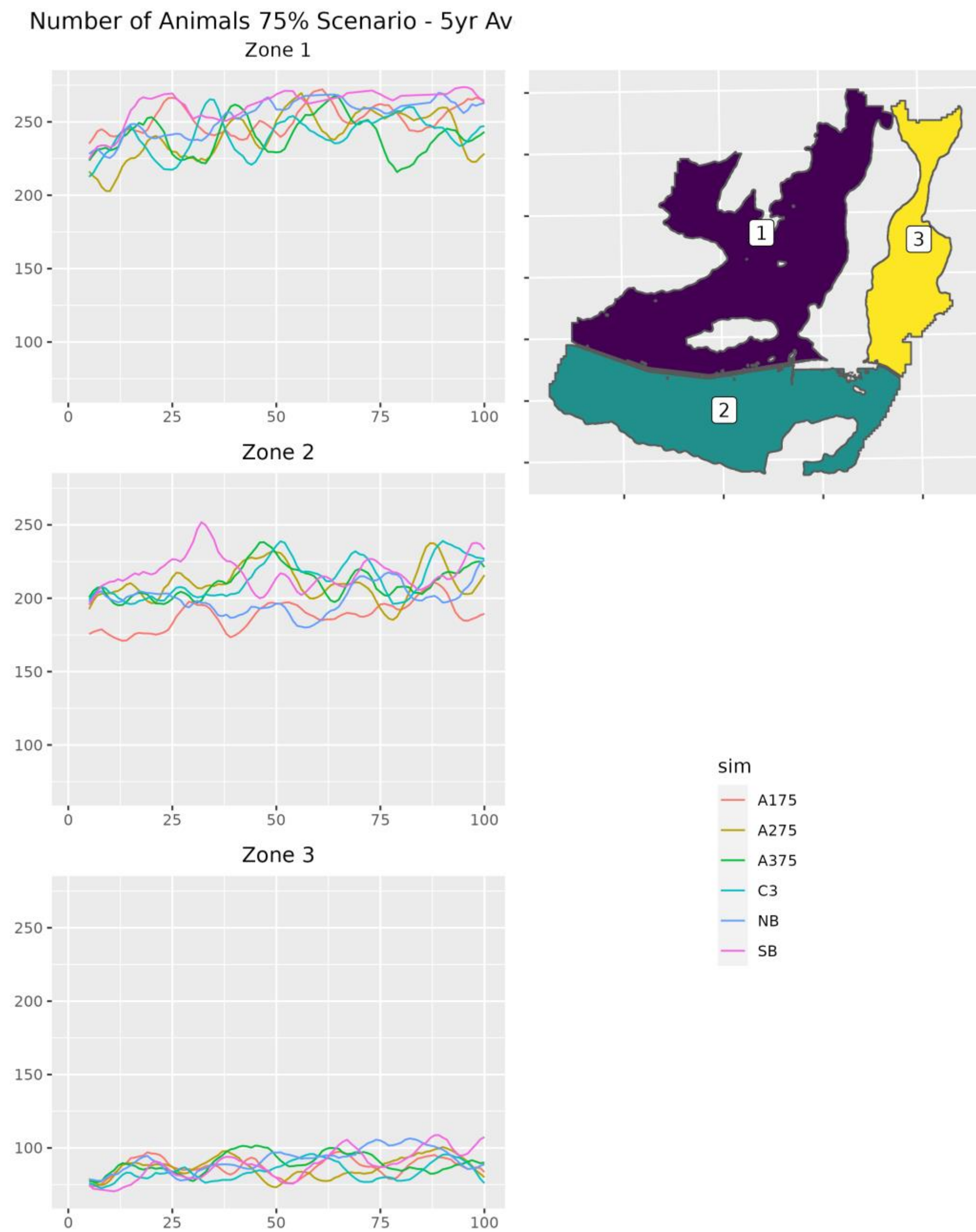


Figure 17 - Five year moving average of the number of tortoises alive over time for each zone for the 75% restoration scenarios, graphed by each scenario, and proposed solar alternative (represented by different colors).

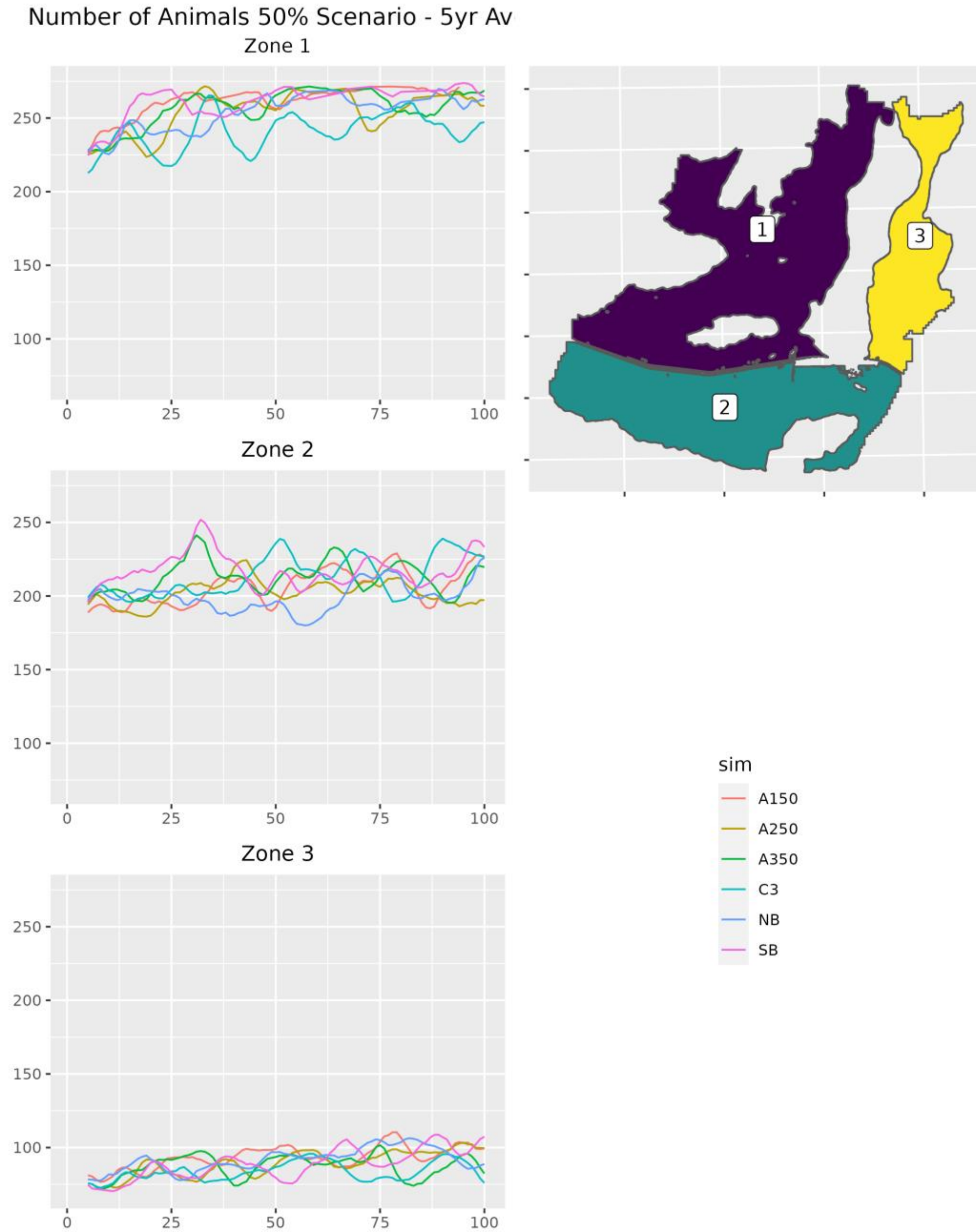


Figure 18 - Five year moving average of the number of tortoises alive over time for each zone for the 50% restoration scenarios, graphed by each scenario, and proposed solar alternative (represented by different colors).

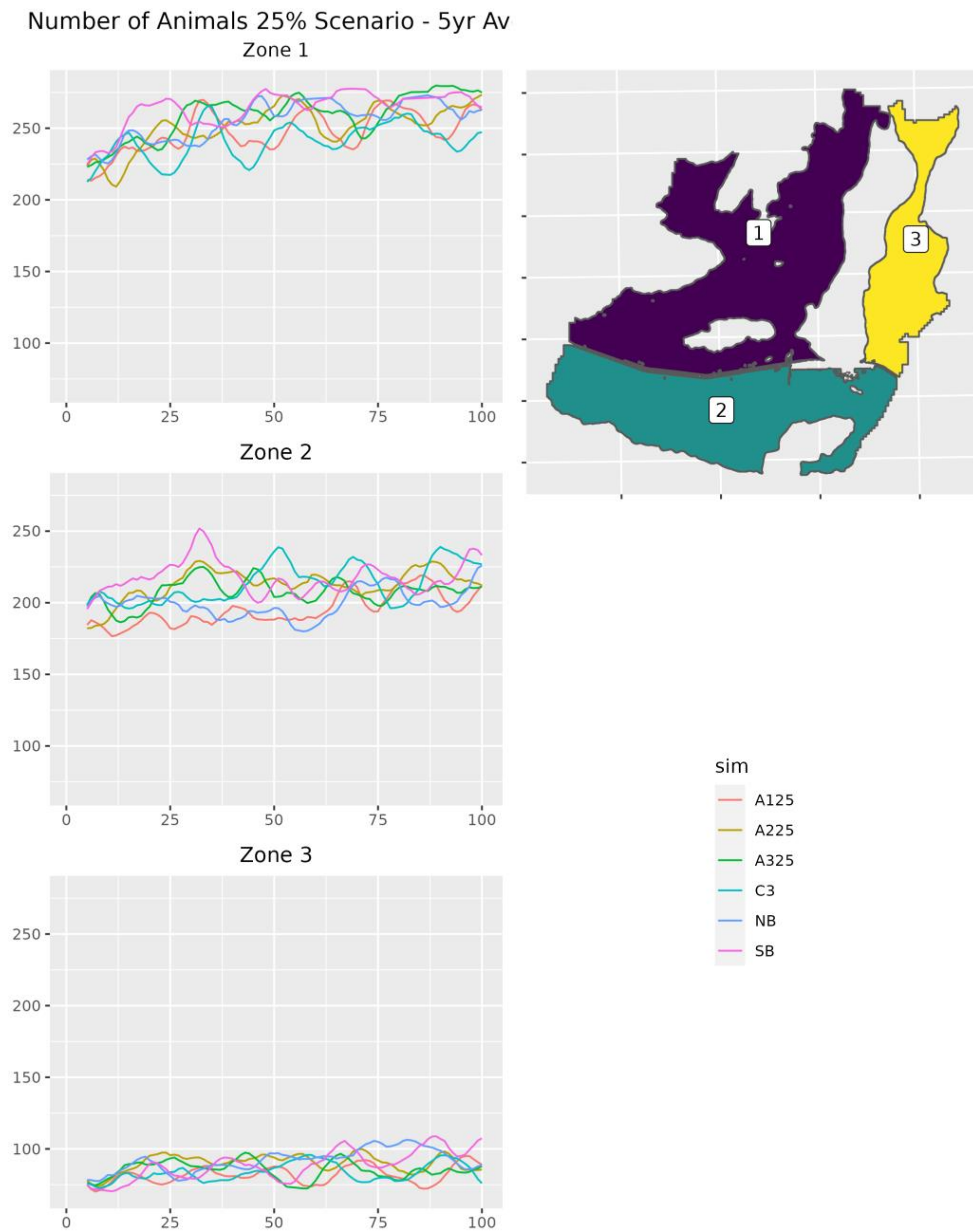


Figure 19 - Five year moving average of the number of tortoises alive over time for each zone for the 25% restoration scenarios, graphed by each scenario, and proposed solar alternative (represented by different colors).

*3.2.3 - Cross Zone Movement Rates*

The number of individuals moving between adjacent zones are shown for the 4 different habitat exclusion scenarios (100%, 75%, 50%, and 25% habitat exclusion by the buildouts) in Figures 20-23. The scenarios did not exhibit markedly different numbers among the different buildout or exclusion scenarios (Table 4). While the “No Barrier” simulation had higher exchange rates between Zones 1 and 2 than other scenarios, the exchanges for the other scenarios were similar to what was projected by the “Culvert” scenario – depicting the current state of the habitat with barriers (Table 4). It should be noted that these numbers represent a single 100-year scenario – and would be expected to vary among different iterations, however movement of individuals does not appear to be drastically reduced above that already imposed by the existing roadway and build-out (Culvert 3), which is already lower in general than the hypothetical “No Barrier” simulation – which had higher exchange rates between Zones 1 and 2, Zones 2 and 3, Zones 1 and 4, and Zones 5 and 3 – all of which represent crossings of US 95 (Table 4).

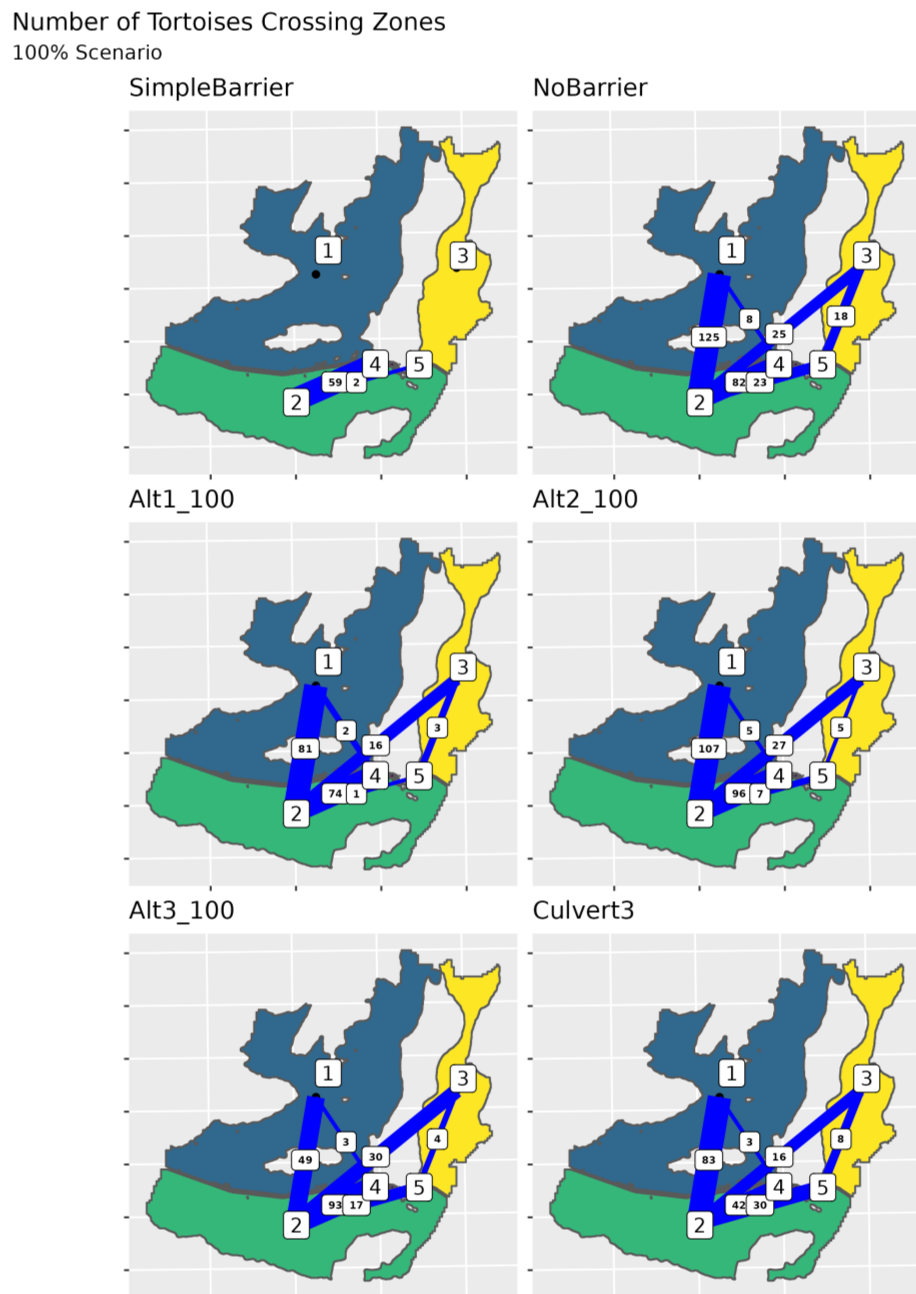


Figure 20 - The number of tortoises moving between zones in the study area among years for the 100% exclusion scenario. Large lines indicate the cumulative movements between the larger zones – with numbers on the lines indicating numbers of animals – and larger numbers indicating zones.

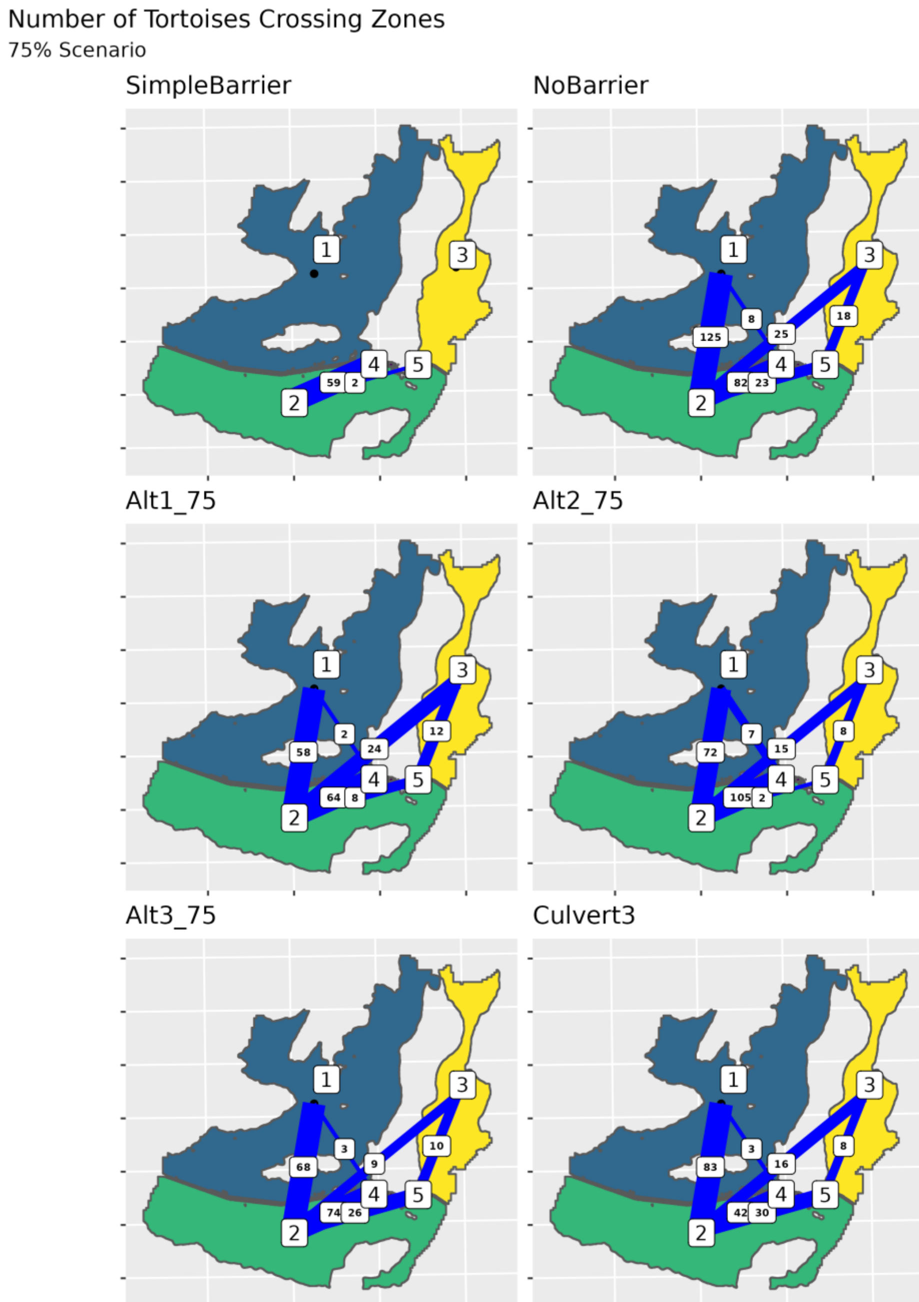


Figure 21 - The number of tortoises moving between zones in the study area among years for the 75% restoration scenario. Large lines indicate the cumulative movements between the larger zones – with numbers on the lines indicating numbers of animals – and larger numbers indicating zones.

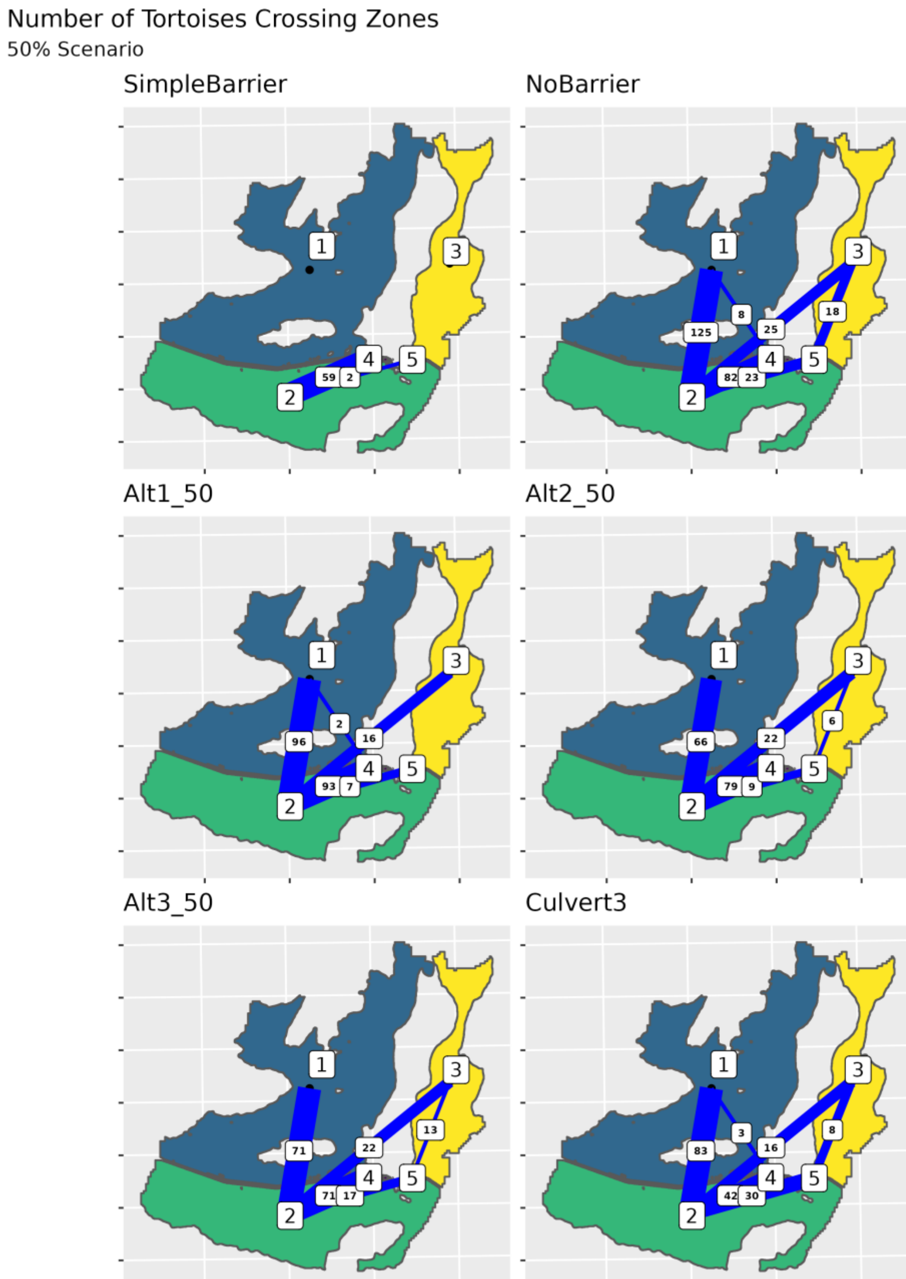


Figure 22 - The number of tortoises moving between zones in the study area among years for the 50% restoration scenario. Large lines indicate the cumulative movements between the larger zones – with numbers on the lines indicating numbers of animals – and larger numbers indicating zones.

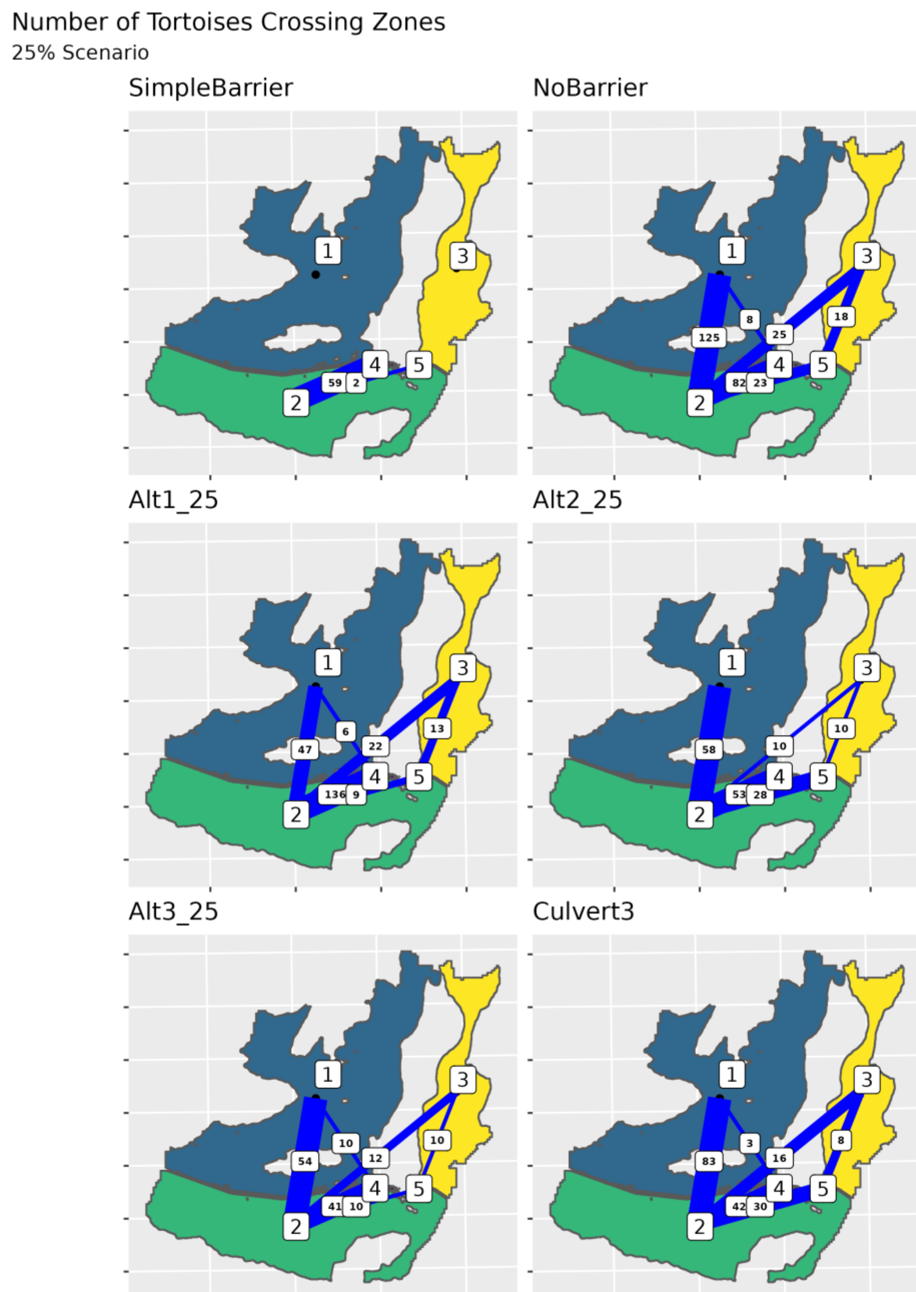


Figure 23 - The number of tortoises moving between zones in the study area among years for the 25% restoration scenario. Large lines indicate the cumulative movements between the larger zones – with numbers on the lines indicating numbers of animals – and larger numbers indicating zones.

| | Zones Connected | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Scenario* | 1-2 | 2-3 | 1-3 | 1-4 | 1-5 | 2-4 | 2-5 | 3-4 | 3-5 | 4-5 |
| *Simple Barrier* | 0 | 0 | 0 | 0 | 0 | 59 | 2 | 0 | 0 | 0 |
| *No Barrier* | 125 | 25 | 0 | 8 | 0 | 82 | 23 | 0 | 18 | 0 |
| *Culvert 3* | 83 | 16 | 0 | 3 | 0 | 42 | 30 | 0 | 8 | 0 |
| *100% Scenario* | | | | | | | | | | |
| *Alt 1* | 81 | 16 | 0 | 2 | 0 | 74 | 1 | 0 | 3 | 0 |
| *Alt 2* | 107 | 27 | 0 | 5 | 0 | 96 | 7 | 0 | 5 | 0 |
| *Alt 3* | 49 | 30 | 0 | 3 | 0 | 93 | 17 | 0 | 4 | 0 |
| *75% Scenario* | | | | | | | | | | |
| *Alt 1* | 58 | 24 | 0 | 2 | 0 | 64 | 8 | 0 | 12 | 0 |
| *Alt 2* | 72 | 15 | 0 | 7 | 0 | 105 | 2 | 0 | 8 | 0 |
| *Alt 3* | 68 | 9 | 0 | 3 | 0 | 74 | 26 | 0 | 10 | 0 |
| *50% Scenario* | | | | | | | | | | |
| *Alt 1* | 96 | 16 | 0 | 2 | 0 | 93 | 7 | 0 | 0 | 0 |
| *Alt 2* | 66 | 22 | 0 | 0 | 0 | 79 | 9 | 0 | 6 | 0 |
| *Alt 3* | 71 | 22 | 0 | 0 | 0 | 71 | 17 | 0 | 13 | 0 |
| *25% Scenario* | | | | | | | | | | |
| *Alt 1* | 47 | 22 | 0 | 6 | 0 | 136 | 9 | 0 | 13 | 0 |
| *Alt 2* | 58 | 10 | 0 | 0 | 0 | 53 | 28 | 0 | 10 | 0 |
| *Alt 3* | 54 | 12 | 0 | 10 | 0 | 41 | 10 | 0 | 10 | 0 |

Table 4 Numbers of animals moving between major zones over the 100-year simulation by habitat exclusion and build-out scenarios.

### *3.2.4 - Birthrates*

Per capita birth rates were calculated for all four exclusion scenarios, and across all three alternative scenarios. Birth rates were consistently between 3.5 and 4 tortoises produced per capita across all zones, and among all scenarios. Random fluctuations were stronger than any discernible pattern, and none of the scenarios appeared to differ significantly from no barrier and simple or culvert-based scenarios (Figures 24 -

27).

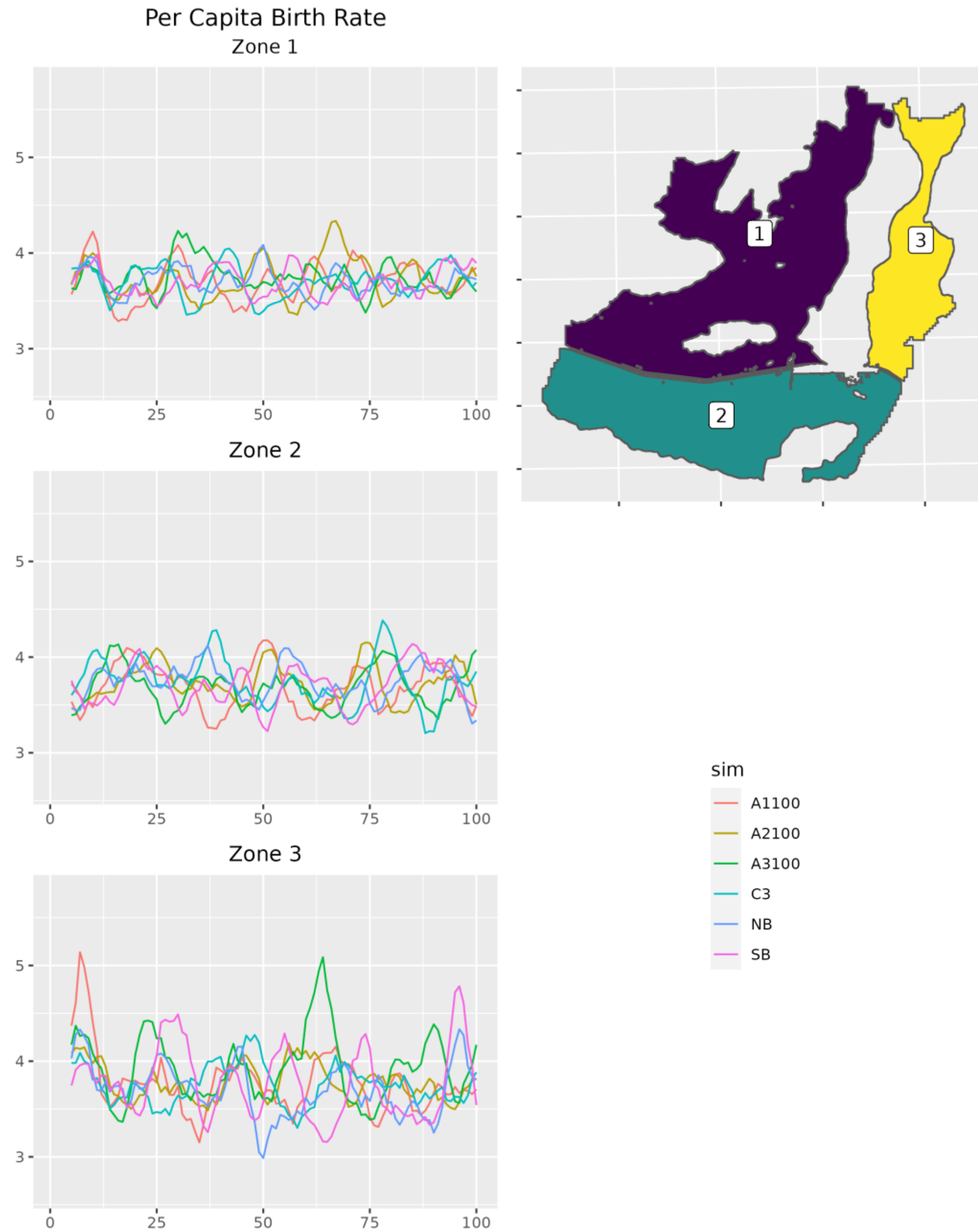


Figure 24. Per-capita birth rates for the three major zones for the 100% exclusion scenario, across all barrier simulations.

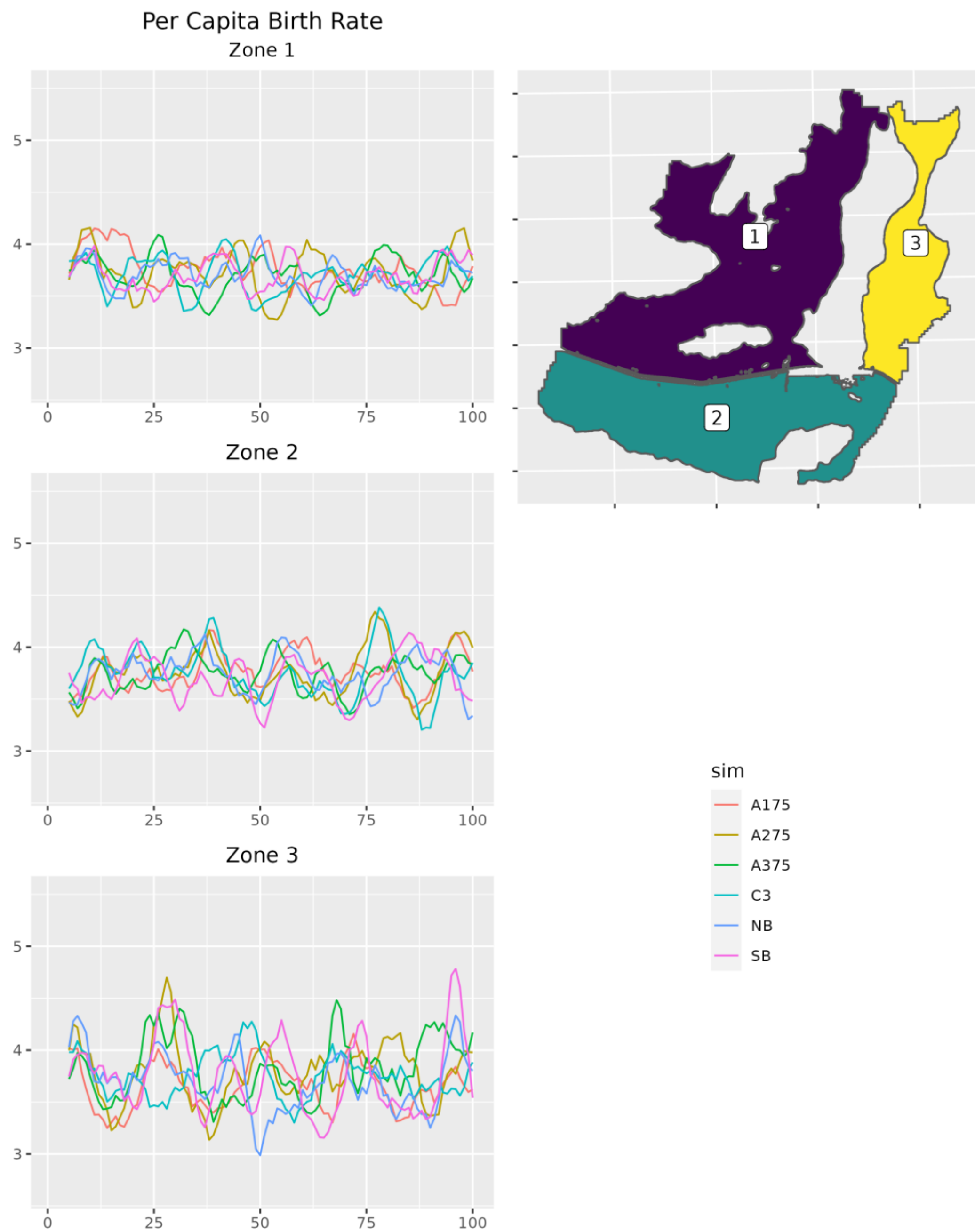


Figure 25. Per-capita birth rates for the three major zones for the 75% restoration scenario, across all barrier simulations.

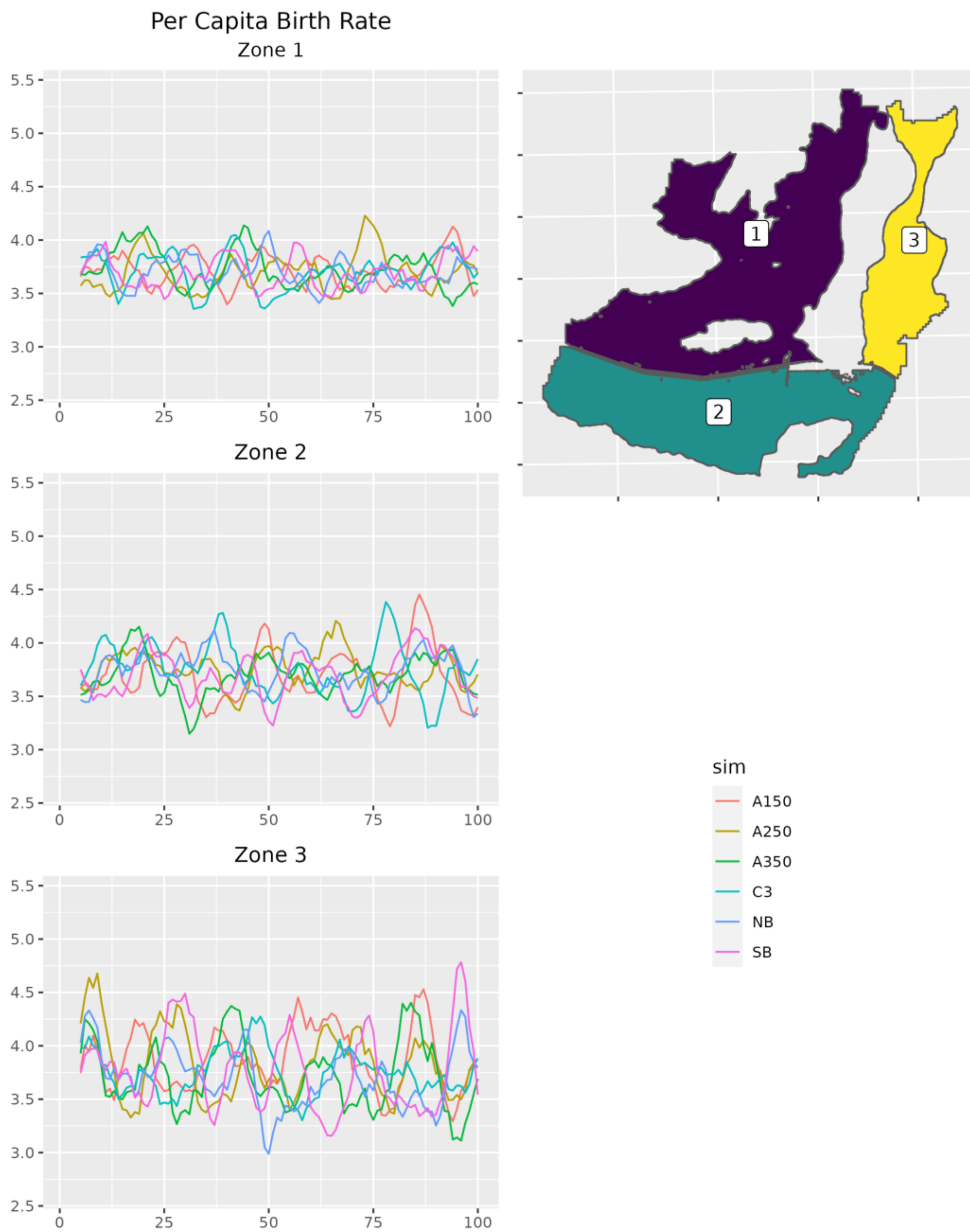


Figure 26. Per-capita birth rates for the three major zones for the 50% restoration scenario, across all barrier simulations.

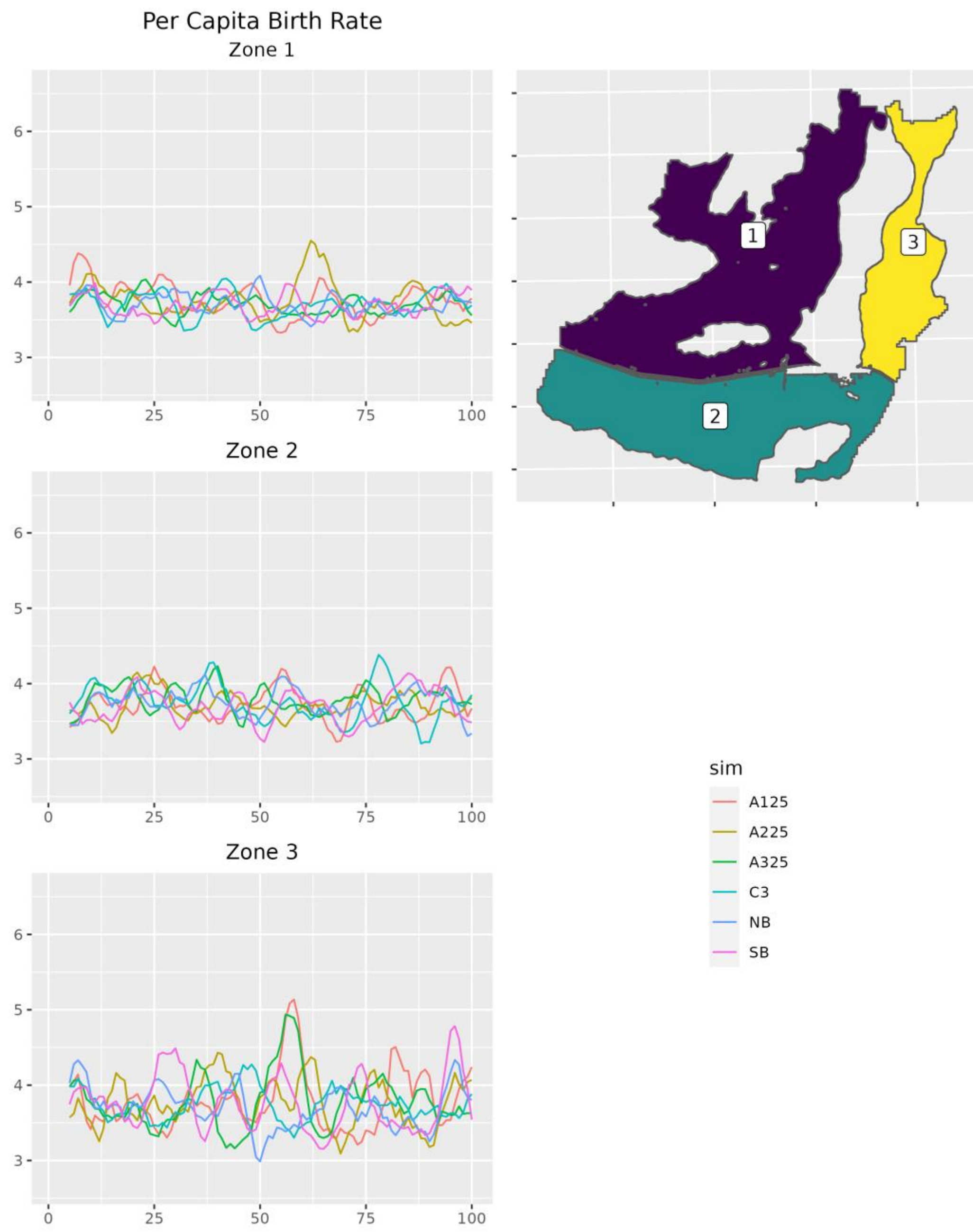


Figure 27. Per-capita birth rates for the three major zones for the 25% restoration scenario, across all barrier simulations.

## 4.0 - Discussion

Simulations for this study area were conducted over a 100-year simulation period. Simulations were included for scenarios that had no barriers to movements; simulations where the roads acted as full barriers;

and simulations where existing culverts and barriers were considered. These were intended to provide comparative baselines from which the relative effects of the proposed solar development alternatives could be compared. In addition, the effects of three solar alternatives were simulated with the full exclusion of tortoises for the 100-year period, as well as allowing tortoises back into the build areas with 25%, 50% and 75% habitat restoration after solar build-out. Birth rates, mortality rates, numbers of individuals, and movement rates by tortoises among zones were monitored given the different habitat configurations. There were no discernible effects on connectivity or demographics in our simulations that were above the random fluctuations for these parameters modeled by the simulations.

It should be noted that the population sizes themselves within the modeled zones are small. This was due to the reduction in the "carrying capacity" imposed on the simulations to more closely reflect recent surveys on the ground, and the limited area in which the simulations were conducted. For example, the average number of adult tortoises in the three scenario runs without solar development ("No Barrier", "Simple Barrier" and "Culvert 3") that were located in the "Protocol Survey Area" was 30 with a confidence interval of +/- 2.5, while the surveyed number of adult tortoises was 23 (Ironwood 2022). Given the fact that tortoises would be likely be lost for any of the alternative solar scenarios, it would be expected that associated losses of tortoises within these areas would occur, but there were not significant differences among the scenarios compared with either the simple barrier or no barrier simulations that had no solar developments. This is likely due to the fact that mortality in the development footprints is limited because there were very few tortoises located in the proposed development areas– per the field surveys that were used to set the density with which the scenarios were modeled. For example, only 20 adult animals were located in the Alternative 1 boundary area, while the other two alternatives contained 6 adults each (Figure 15). The simulations indicated predictions of slightly increasing number of tortoises through time in some cases. This may have been due to the low densities with which the model was initiated relative to the predicted habitat suitability of the sites given the county wide model that was used, which does not reflect the potential degradation due to the existing roadways. The surveys that informed these densities were taken relatively close to the highways that have likely impacted tortoise habitat and adjacent populations for decades (von Seckendorf Hoff and Marlow 2002; Boarman and Sazaki 2006; Nafus et al. 2013; Peaden et al. 2015), and thus while habitat condition may appear unaffected, tortoise densities may be lower due to these impacts. There was no density information provided to populate starting densities throughout the rest of the presumably less disturbed habitat areas other than the 2022 Ironwood survey. It is likely that adjacent areas further from the highway have higher tortoise densities due to the lack of a road effect, and while habitat degradation due to dirt roads and routes was included, the slight increase in numbers may reflect adjustment to the lower starting density in less impacted areas, and it was certainly not attributable to the proposed buildout scenarios.

The habitat configuration in the greater study area (Figure 1) is largely devoid of barriers – except US 95 bisecting the area from east to west. The configuration of tortoise habitat near the proposed solar build-out areas tends to be of lower suitability to the east as it approaches Indian Springs, Nevada (Figure 9). The habitat to the north of the proposed development areas across US 95 has very little suitable area on the eastern extent, which provides little opportunity for tortoise movement, as populations there are of limited size. In addition, there is steep terrain to the north of US 95 that likely limits tortoise densities. Habitat transitions to larger more suitable areas to the west both south and north of US 95 (Figure 9). One of the consequences not modeled here are genetic effects. In other simulation modeling efforts, UNR has found that populations with fewer than 5,000 individuals tended to show changes in genetic diversity and heterozygosity over time (Dutcher 2020; Nussear et al. 2022). Longer term effects have been shown to reflect increased genetic distances, even in landscapes divided approximately 100 years (Dutcher et al. 2020), and maintenance of connectivity is critical toward maintaining population genetic structure (Edwards et al. 2004). In the simulations provided here there was clearly sufficient exchange of individuals – such that gene flow would likely be sufficient to provide connections between the depicted zones. For example, Edwards et al. (2004) estimated 5 migrants per generation between populations using genetic markers, and our interchange between the area south of US 95 and the two zones to the north was in the hundreds over the 100-year simulation for each of the alternative solar scenarios.

The configuration of the solar build-out scenarios is such that they are generally concentrated along US 95 – just west of the existing Creech Air Force Base at Indian Springs. This area is already affected by the barriers to movement introduced by the divided US 95 highway, and tortoise fencing – with few culverts tied into the existing fencing, which is known to restrict tortoise movement (Boarman et al. 1997). Thus, the build-out alternatives did little to impede movements between the northern and southern zones beyond that of the existing barriers. Tortoises are known to use culverts (Berry 1986; Ruby et al. 1994; Boarman et al. 1998) and have recently used the larger box type culverts on US 95 (Ecocentric 2021). Each of the solar alternative scenarios results in the potential loss of culverts for crossing. Alternative 3 results in the loss of 9 crossings facilitated by 13 culverts, 3 of which are tied in with the exclusion fencing (Scott Cambrin pers comm. 2022). Alternative 2 results in the loss of- 12 crossings created by 24 culverts, 6 of which are tied in with the exclusion fencing (Scott Cambrin pers comm. 2022). Alternative 1 results in the loss of 15 crossings facilitated by 28 culverts, 8 of which are tied in with the exclusion fencing (Scott Cambrin pers comm. 2022). Collectively there are an estimated 52 culverts along highway 95 that could be used for tortoise connectivity. Thirty-seven of these were considered passable during recent BLM surveys, but the data given to UNR by Clark County indicated that only 12 of these are tied into tortoise fencing, and 14 were considered impassable.

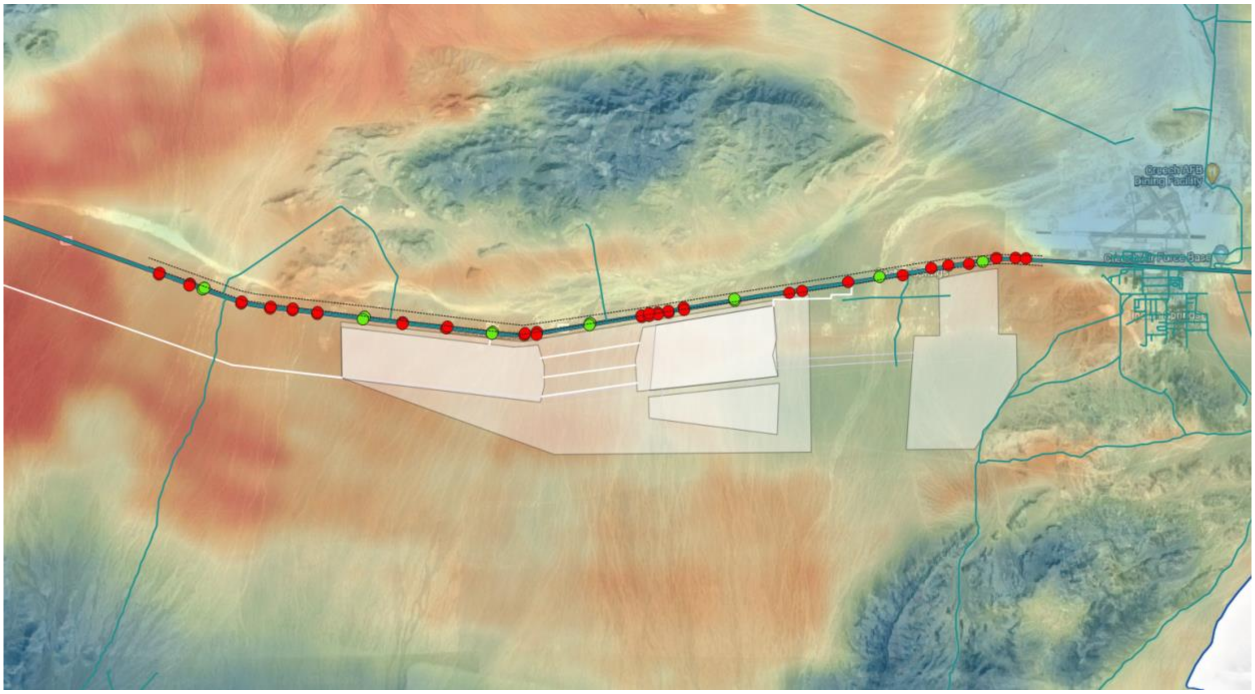

Figure 28. A map of the three solar alternative scenarios with culverts indicated in red, and culverts tied in with fencing per data from Clark Count shown in green.

One UNR recommendation might be to improve connectivity by allowing the existing culverts to tie into the fencing as solar construction is conducted, and to ensure that culverts are properly maintained to ensure safe passage so that they do not contribute to mortality (Lovich et al. 2011; Ecocentric 2021). While tortoises are known to use culverts, they are less likely to do so if the culverts are occluded (Ruby et al. 1994). The confirmation that culverts are passable, tied in with fencing, and maintained will be important toward connectivity in this area. This is likely to have the effect of improving connectivity over current conditions and can contribute toward maintaining genetic and demographic connectivity (Averill-Murray et al. 2021).

Finally, it is important to recognize the scope of this modeling effort, and what it is and is not intended to accomplish. These simulations were designed to compare the effects of proposed solar alternative to the conditions imposed by current habitat configurations, and to more extreme barriers (full barrier), and non-existent ideal habitat (no barrier), which were meant to bound the range of possible tortoise movements and demographics. It should be noted that these are simulations of the relative effects, of the proposed solar facilities, and not of the current or future conditions of the tortoise populations in these areas that may be influenced by climate change, disease, wildfire, expanded OHV use, or similar real world problems causing declines in tortoise populations.

These models were populated using limited information of tortoise densities in the project area, and thus actual tortoise densities in the larger modeled area may be different. In addition, UNR used modeled anthropogenic development projections from the Nussear (2022) modeling effort for Clark County. These projections did not include, nor was UNR provided information on the future expansions of US 95 to an interstate (although this is rumored to be the case), other proposed developments in the area for transmission corridors etc., and thus these were outside of the scope of this project. Similarly, UNR was not provided information on the potential release of individuals (i.e. translocation) back into the development footprint, nor any adjacent areas, and thus any effects of those actions were not modeled as they are outside the scope of this project.

## 5.0 - References


Allen, C. H., L Parrott, and C Kyle. 2016. An individual-based modelling approach to estimate landscape connectivity for bighorn sheep (*Ovis canadensis*). Peer J, 4, e2001.

Allison, LJ and AM McLuckie. 2018. Population trends in Mojave desert tortoises (*Gopherus agassizii*). *Herpetological Conservation and Biology,* 13(2):433-452.

Averill-Murray, RC, CR Darst, N Strout and M Wong. 2013. Conserving population linkages for the Mojave desert tortoise (*Gopherus agassizii*). *Herpetological Conservation and Biology* 8(1):1-15.

Averill-Murray, RC, TC Esque, LJ Allison, S Bassett, SK Carter, KE Dutcher, SJ Hromada, KE Nussear and KT Shoemaker. 2021. Connectivity of Mojave desert tortoise populations – Management implications for maintaining a viable recovery network. U.S. Geological Survey 2021-1033.

Baddeley, A and R Turner. 2005. Spatstat: an R package for analyzing spatial point patterns. *Journal of Statistical Software*. 12:1-42.

Berry, K.H. 1986. Desert tortoise (*Gopherus agassizii*) research in California, 1976-1985. *Herpetologica*, pp. 62-67.

Bjurlin, CD and JA Bissonette. 2004. Survival during early life stages of the desert tortoise (*Gopherus agassizii*) in the south-central Mojave Desert. *Journal of Herpetology*, pp. 527-535.

Boarman, WI, ML Beigel, GC Goodlett and M Sazaki. 1998. A passive integrated transponder system for tracking animal movements. *Wildlife Society Bulletin*, 26, pp. 886-891.

Boarman WI and M Sazaki. 2006. A highway's road-effect zone for desert tortoises (*Gopherus agassizii*) *Journal of Arid Environments,* 65(1): 94-101.

Boarman WI, M Sazaki and WB Jennings. 1997. The effect of roads, barrier fences, and culverts on desert tortoise populations in California, USA. *Proceedings: Conservation, Restoration, and Management of Tortoises and Turtles.* pp. 54-58.

Caglar MU, AI Teufel and CO Wilke. 2018. Sicegar: R package for sigmoidal and double-sigmoidal curve fitting. PeerJ 6:e4251 https://doi.org/10.7717/peerj. 4251.

Cambrin, S. (2022). Personal communication [*March 8* Zoom meeting with K. Nussear, University of Nevada, Reno, Reno, Nevada. *RE*: Tortoise exclusion fencing related to U.S. 95 culverts in Indian Springs. Senior Biologist, Clark County, Las Vegas, Nevada.

Congdon, JD, AE Dunham and RVL Sels. 1993. Delayed Sexual Maturity and Demographics of Blanding's Turtles (*Emydoidea blandingii*): Implications for Conservation and Management of Long-Lived Organisms. Society for Conservation Biology. *Conservation Biology*, 7(4): 826-833.

Corn, PS. 1994. Recent trends of desert tortoise populations in the Mojave Desert. *Fish and Wildlife Research,* 13: 85-96.

Coulon, A, J Aben, S Palmer, V Stevens, T Callens, D Strubbe and J Travis. 2015. A stochastic movement simulator improves estimates of landscape connectivity. *Ecology*, 96(8), 2203-2213.

Day, CC., PA Zollner, JH Gilbert and NP McCann. 2020. Individual-based modeling highlights the importance of mortality and landscape structure in measures of functional connectivity. *Landscape Ecology*, 35(10), 2191-2208.

Dijkstra, EW. 1959. A note on two problems in connexion with graphs. *Numerische Mathematik* 1: 269–271.

Doak D, Kareiva P and Klepetka B. 1994. Modeling population viability for the desert tortoise in the western Mojave Desert. *Ecological Applications,* 4(3):446-460.

Drake, KK, TC Esque, KE Nussear, LA Defalco, SJ Scoles-Sciulla, AT Modlin and PA Medica. 2015. Desert tortoise use of burned habitat in the eastern Mojave Desert. *The Journal of Wildlife Management,* 79(4):618–629. issn: 0022541X. DOI: 10.1002/jwmg.874.

Drake, KK, KE Nussear , TC Esque, AM Barber, KM Vittum , PA Medica, CR Tracy, and KW Hunter. 2012. Does translocation influence physiological stress in the desert tortoise? *Animal Conservation,* 15.6:560–570. issn: 13679430. DOI: 10.1111/j.1469-1795.2012.00549.x.

Dutcher, KE. 2020. Connecting the Plots: Anthropogenic Disturbance and Mojave Desert Tortoise (*Gopherus agassizii*) Genetic Connectivity (Doctoral dissertation, University of Nevada, Reno).

Dutcher, KE, JS Heaton, and KE Nussear. 2019. Desert tortoise connectivity modeling. Technical Report 2015-UNR-1580A. Clark County Desert Conservation Program, 76 pp.

Dutcher, KE, AG Vandergast, TC Esque, A Mitelberg, MD Matocq, JS Heaton and KE Nussear. 2020. Genes in space: What Mojave desert tortoise genetics can tell us about landscape connectivity. *Conservation Genetics,* 2020:1-15. DOI: https://doi.org/10.1007/s10592-020-01251-z

Ecocentric. 2021. Desert tortoise connectivity across roadways. Project Number 2015-Ecocent-1508B. Technical Report to Clark County, Nevada Desert Conservation Program.

Edwards, T, CR Schwalbe, DE Swann and CS Goldberg. 2004. Implications of anthropogenic landscape change on inter-population movements of the desert tortoise (*Gopherus agassizii*). *Conservation Genetics* 5(4): 485-499.

Friend, D. 2022a. Package *quadtree* v.0.1.6: Region quadtrees for spatial data. https://dfriend21.github.io/quadtree/.

Friend, D. 2022b. Using Simulations to Predict the Genetic Connectivity of the Mojave Desert Tortoise. Dissertation, Department of Geography, University of Nevada Reno.

Hagerty, BE, KE Nussear, TC Esque and CR Tracy. 2010. Making molehills out of mountains: Landscape genetics of the Mojave desert tortoise. *Landscape Ecology,* 26(2):267-280.

Hagerty, BE and CR Tracy. 2010. Defining population structure for the Mojave desert tortoise. *Conservation Genetics*11(5):1795-1807.

Hromada, SJ, TC Esque, AG Vandergast, KE Dutcher, CI Mitchell, ME Gray, T Chang, BG Dickson and KE Nussear. 2020. Using movement to inform conservation corridor design for Mojave desert tortoise. *Movement Ecology,* 8:2051-3933. DOI: 10.1186/s40462-020-00224-8.

Ironwood Consulting (Ironwood). 2022. Desert Tortoise Survey Report, Bonanza Solar Project, Clark County, Nevada.

Kanagaraj, R, T Wiegand, S Kramer-Schadt and SP Goyal. 2013. Using individual-based movement models to assess inter-patch connectivity for large carnivores in fragmented landscapes. *Biological Conservation*, 167:298-309.

Landguth, EL, SA Cushman, MK Schwartz, KS McKelvey, M Murphy and G Luikart. 2010. Quantifying the lag time to detect barriers in landscape genetics. *Molecular Ecology,* 19(19): 4179-4191.

Latch, EK, WI Boarman, A Walde and RC Fleischer. 2011. Fine-scale analysis reveals cryptic landscape genetic structure in desert tortoises. *PLoSone,* 6(11):e27794.

Longshore, KM., JR Jaeger and JM Sappington. 2003. Desert tortoise (*Gopherus agassizii*) survival at two eastern Mojave Desert sites: death by short-term drought? *Journal of Herpetology*, 37(1):169-177.

Lovich, JE, JR Ennen, S Madrak and B Grover. 2011. Turtles and culverts, and alternative energy development: An unreported but potentially significant mortality threat to the Desert Tortoise (*Gopherus agassizii*). *Chelonian Conservation and Biology*, 10(1):124-129.

McLane, A. J., C Semeniuk, GJ McDermid and DJ Marceau. 2011. The role of agent-based models in wildlife ecology and management. *Ecological Modelling*, 222(8):1544-1556.

Medica, PA, KE Nussear, TC Esque and MB Saethre. 2012. Long-term growth of desert tortoises (*Gopherus agassizii*) in a southern Nevada population. in: *Journal of Herpetology,* 46.1, pp. 213–220. issn: 0022-1511. DOI: 10.1670/11-327.

Mitchell, CI, DA Friend, LT Phillips, EA Hunter, JE Lovich, M Agha, SR Puffer, KL Cummings, PA Medica, TC Esque and KE Nussear. 2021. Unscrambling the drivers of egg production in Agassiz's desert tortoise: Climate and individual attributes predict reproductive output. *Endangered Species Research*, 44:217-230.

Murphy, RW, KH Berry, T Edwards and AM McLuckie. 2007. A genetic assessment of the recovery units for the Mojave population of the desert tortoise, *Gopherus agassizii*. *Chelonian Conservation and Biology,* 6(2):229-251.

Nafus, MG, TD Tuberville, KA Buhlmann and BD Todd. 2013. Relative abundance and demographic structure of Agassiz's desert tortoise (*Gopherus agassizii*) along roads of varying size and traffic volume. *Biological Conservation* 162:100-106.

Nussear, KE, KE Dutcher, S Basset and D Friend. 2022. Desert Tortoise Connectivity Solutions Modeling. Technical Report for Project Number: 2015-UNR-1580C. Clark County Desert Conservation Program, 127 pp.

Nussear, KE, CR Tracy, PA Medica, DS Wilson, RW Marlow and PS Corn. 2012. Translocation as a conservation tool for Agassiz's desert tortoises: survivorship, reproduction, and movements. *Journal of Wildlife Management* 76.7, pp. 1341–1353. issn: 0022541X. DOI:10.1002/jwmg.390.

Nussear, KE and ET Simandle. 2019. Covered Species Analysis Support Phase II. 2013-UNR-1460E. Clark County Desert Conservation Program, p. 312.

Peaden, JM, TD Tuberville, KA Buhlmann, MG Nafus and BD Todd. 2015. Delimiting road-effect zones for threatened species: Implications for mitigation fencing. *Wildlife Research* 42:650-659.

R Core Team. 2022. R: A language and environment for statistical computing (version 1.3.1093). https://www.r-project.org.

Ruby, DE, JR Spotila, SK Martin, SJ Kemp. 1994. Behavioral responses to barriers by desert tortoises: Implications for wildlife management. *Herpetological Monographs* 8:144-160.

Sah, P, KE Nussear, TC Esque, CM Aiello, PF Hudson and S Bansal. 2016. Inferring social structure and its drivers from refuge use in the desert tortoise, a relatively solitary species. *Behavioral Ecology and Sociobiology* 70.8, pp. 1277–1289. issn: 0340-5443. DOI: 10.1101 025494.

Samet, H. 1984. The quadtree and related hierarchical data structures. *ACM Computing Surveys (CSUR)* 16(2):187–260.

Sanchez-Ramirez, S, Y Rico, KH Berry, T Edwards, AE Karl, BT Henen and RW Murphy. 2018. Landscape limits gene flow and drives population structure in Agassiz's desert tortoise (*Gopherus agassizii*). *Scientific Reports* 8(1):1-17.

Segura, A, J Jimenez and P Acevedo. 2020. Predation of young tortoises by ravens: The effect of habitat structure on tortoise detectability and abundance. *Scientific Reports*. 10:1-9.

Tracy, CR, R Averill-Murray, WI Boarman, D Delehanty, J Heaton, ED McCoy, DJ Morafka, KE Nussear, B Hagerty and PA Medica. 2004. Desert tortoise recovery plan assessment. U.S. Fish and Wildlife Service, Desert Tortoise Recovery Plan Assessment Committee.

Turner, FB, PA Medica and CL Lyons. 1984. Reproduction and survival of the desert tortoise (*Scaptochelys agassizii*) in Ivanpah Valley, California. *Copeia*, pp. 811-820.

U.S. Fish and Wildlife Service (USFWS). 1994. Desert tortoise (Mojave population) Recovery Plan. US Fish and Wildlife Service, Portland, Oregon. 73 pp plus Appendices.

USFWS. 2011. Revised recovery plan for the Mojave population of the desert tortoise (*Gopherus agassizii*). Pacific Southwest Region, Sacramento, California.

U.S. Geological Survey (USGS). 2021. Federal standards and procedures for the National Watershed Boundary Dataset (WBD) Techniques and Methods 11-A3. https://doi.org/10.3133/tm11A34

van Bemmelen, J, W Quak, M van Hekken and P van Oosterom. 1993. Vector vs. raster-based algorithms for cross country movement planning. Proceedings AutoCarto, *American Society for Photogrammetry.* pp. 304.

von Seckendorff Hoff K and Marlow RW. 2002. Impacts of vehicle road traffic on desert tortoise populations with consideration of conservation of tortoise habitat in southern Nevada. *Chelonian Conservation and Biology.* 4(2):449-456.

Werner, FE, RK Cowen and CB Paris. 2007. Coupled biological and physical models: present capabilities and necessary developments for future studies of population connectivity. *Oceanography*, 20(3):54-69.