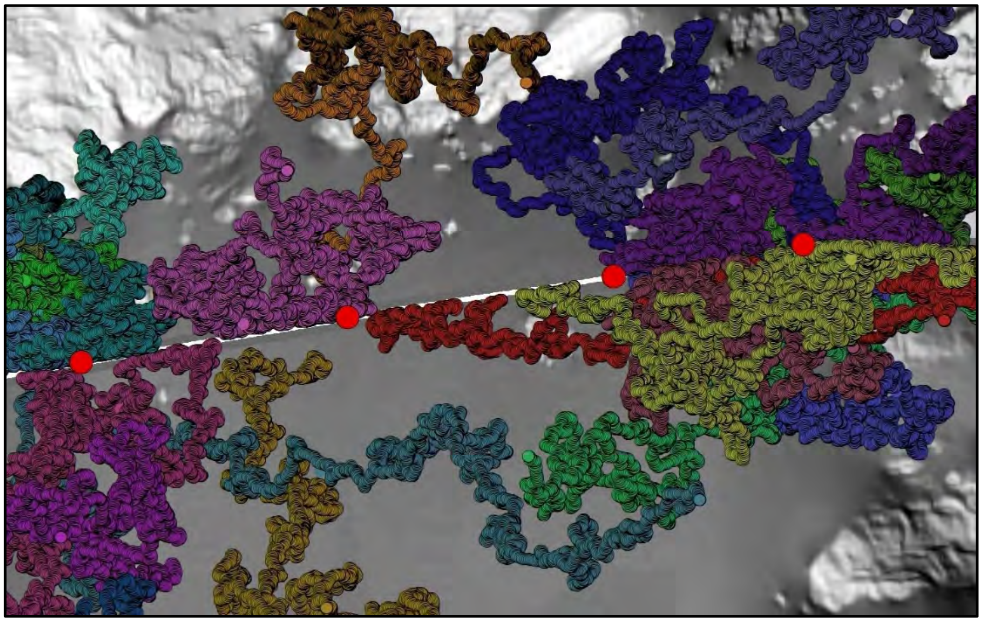
D03 – Final Project Report for MDT Connectivity Simulations



Prepared for:
Clark County, Nevada – Desert Conservation Program

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Prepared by:
Alta Science and Engineering, Inc.
1220 Big Creek Road, Suite A
Kellogg, Idaho 83837
alta-se.com

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Section 1 Introduction

Wildlife corridors have been identified as critical to sustaining a functional and genetic link between potentially isolated populations and where these habitat linkages can help buffer against stochastic events, climate change, habitat loss, edge effects, and genetic drift (Beier and Noss 1998, Lovich and Ennen 2011). Preserving connectivity across the desert landscape of the United States' southwest is especially critical for a variety of sensitive species. Yet, the desert habitat is increasingly fragmented by landscape-level disturbances, which include linear features like transportation and transmission line corridors, and larger habitat disturbances such as utility scale renewable energy projects, urbanization, or military expansion efforts (Hromada et al. 2020). These barriers to movement vary in size and scope, and the impacts may be temporary or permanent, wide-ranging, or local.

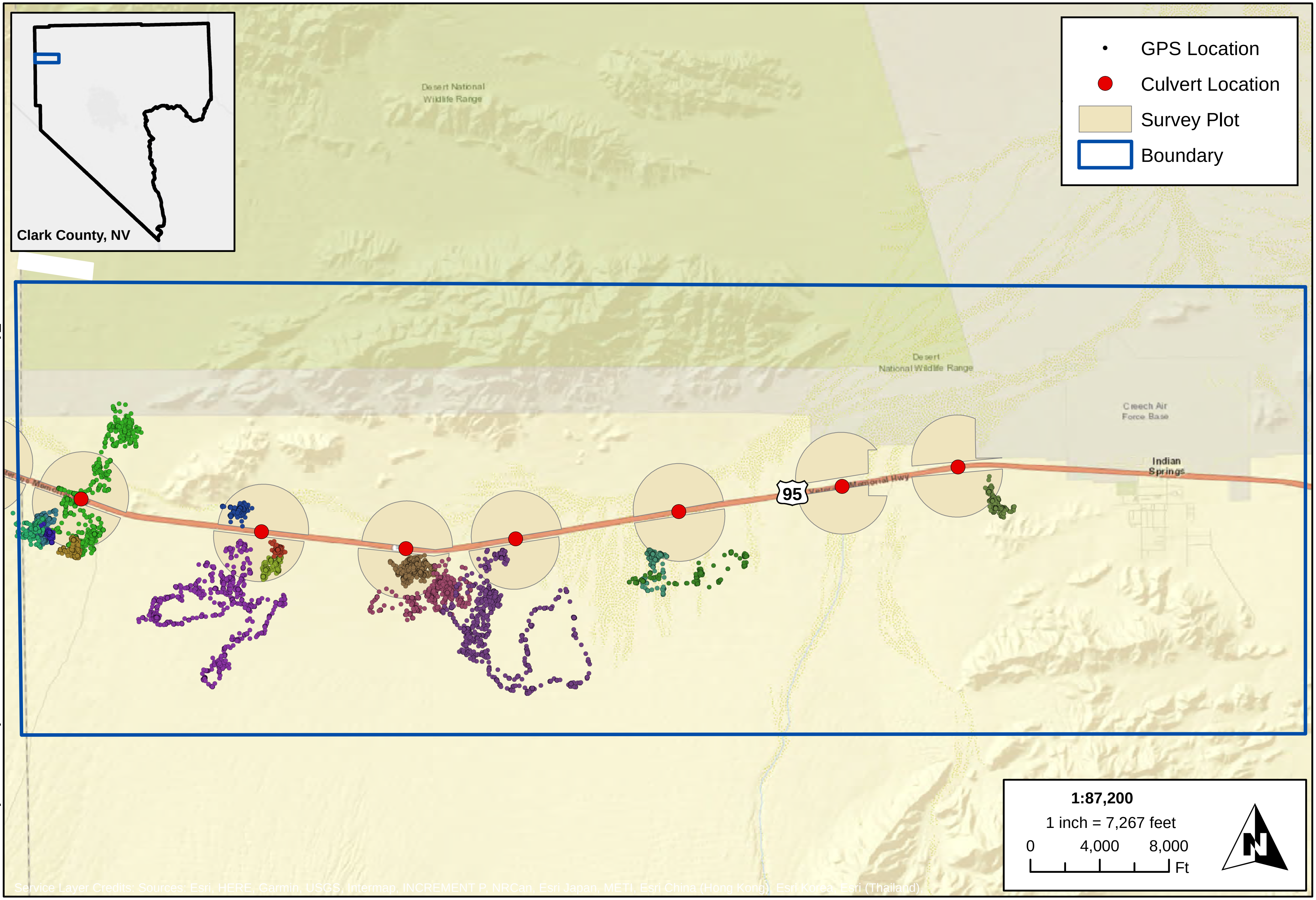
Many of these disturbances occur in the habitat of the federally- and state-protected Agassiz's desert tortoise (*Gopherus agassizii*). The tortoise was listed as threatened under the Federal Endangered Species Act in 1990 (USFWS 1990) with varied and persistent threats causing a rapid decline in the population across its range (USFWS 2011, Allison and McLuckie 2018) despite considerable conservation and management efforts. Desert tortoises exhibit a high degree of site fidelity, with home ranges averaging 16 hectares (ha) for females and 44 ha for males (Harless et al. 2009). Desert tortoises have a range-wide pattern of isolation-by-distance with gene flow (Dutcher 2020).

Recent and ongoing research has underscored the importance of connectivity corridors to aid in the recovery of desert tortoises (Dutcher et al. 2020, Hromada et al. 2020, Averill-Murray et al. 2021). A stated goal in the U. S. Fish and Wildlife Service's (USFWS) revised recovery plan is to 'connect functional habitat', noting the importance of culverts for smaller-scale connectivity across fenced roads and railroads (USFWS 2011, Rautsaw et al. 2018). Recovery Action 5.6 (USFWS 2011) calls for the determination of the importance of corridors and physical barriers to desert tortoise distribution and gene flow.

The current management practice along roadways in desert tortoise habitat is to install exclusion fencing to prevent these animals from crossing roads. This has been shown to be an effective method to reduce road mortality by more than 90% (Boarman and Sazaki 1996). Concomitantly, culverts under roadways are placed to maintain adequate connectivity between the landscape on both sides of a roadway. Desert tortoises are known to use culverts (Fusari 1985) and they are expected to maintain habitat connectivity (Boarman and Kristan 2006). However, the role that culverts play in maintaining functional connectivity is currently untested.

To test the functionality of culverts for desert tortoise connectivity, the Clark County Desert Conservation Program initiated a culvert study along two highways in Clark County, Nevada, USA. The study aimed to use mark-recapture sampling to estimate population densities on either side of 18 existing culverts. The study also entailed attaching GPS transmitters to resident desert tortoises to potentially observe individual tortoise movement through culverts. However, due to inherent limitations in capturing and monitoring free-ranging animals, including low sample sizes, natural mortality during the monitoring period, and a short monitoring window relative to the long lifespan of desert tortoises, any project may fail to observe use of culverts by desert tortoises even if such use is of sufficient prevalence to maintain population connectivity.

One promising option despite field challenges is computer simulations generated using realistic models based on movement of local free-ranging desert tortoises. This was the objective of the study described here. We used movement data from local GPS-tagged desert tortoises to populate multistate random walk models to approximate the movements of local desert tortoises. We then allowed simulated desert tortoises to move around the landscape in response to a heterogeneous surface reflecting landform connectivity for desert tortoises and monitored the rates at which simulated desert tortoises used culverts to cross the highway. A key novel component of the simulation was the inclusion of an impermeable barrier, the fenced highway. This meant that although simulation desert tortoises could approach the highway, they could only walk alongside it until they reached a culvert. We also varied the density of culverts in the simulated landscape to evaluate whether an increased culvert density would more effectively ensure functional connectivity of desert tortoise populations across the highway.



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Print Date: Jan 15, 2022	Projection: NAD83 UTM Zone 11N	Project Name	Figure 1	
Project Number: 21105-40	Project Manager: T. Harju	MDT Connectivity Simulations	Study Area	
	Cartographer: J. Berg			

Section 2 Methods

We leveraged data previously collected on GPS-tagged desert tortoises and connectivity layers as the basis for novel movement simulations to understand the potential for long-term use of culverts under U.S. Highway 95 by desert tortoises in northwestern Clark County, Nevada, USA. We simulated movement paths of hypothetical desert tortoises across a heterogeneous landscape resistant to movement and in relation to an impermeable (i.e., fenced) highway punctuated by fully permeable corridors (i.e., culverts). The exclusionary fencing along U.S. Highway 95 is relatively new (e.g., ~10 years), relative to the lifespan of resident desert tortoises (S. Cambrin, pers. comm.).

2.1 Field data collection

For the field portion of this study, contractors for the Clark County Desert Conservation Program radio-tagged wild resident desert tortoises near U.S. Highway 95. Biologists surveyed for desert tortoises within an 800meter (m) semi-circular plot surrounding existing culverts. Tortoises were captured, marked, and had a transmitter and GPS-logger attached, then were released at their capture location for monitoring. GPS units were programmed to record coordinates of desert tortoise locations approximately every 30 minutes. The cutoff of relocation data for this analysis was October 9th, 2021.

2.2 Data preparation

Step lengths and turning angles are common metrics used to discretize the continuous-time movement paths of free-ranging animals in order to parameterize movement simulations (Fortin et al. 2005, Thurfjell et al. 2014). We therefore summarized the GPS location data for the desert tortoises as a series of consecutive steps composed of the linear distances between successive locations. We also calculated turning angles as the difference in degrees between the direction aligned with the previous step and the direction aligned by the current step.

Desert tortoises exhibit a range of spatial behaviors, especially marked by switching between extremely localized behaviors (e.g., feeding, sunning, resting, aestivation during hot and dry weather, and seasonal brumation during cold weather) and more active behaviors, such as traveling, foraging, dispersal, and mate-seeking (Harless et al. 2009, Sadoti et al. 2017). Desert tortoise movements can also be modulated by environmental features, as their size and locomotive abilities can be constrained by rough topography and vertical features. Based on examination of the movement data and general knowledge of the ecology of established resident desert tortoises, we split the simulated location data into two types of movement behaviors, resting and moving, to more accurately capture this range of behaviors. We used the resting state to encompass multiple localized behaviors, including localized foraging (e.g., within ~ 1m) and true resting, and we used the moving state to encompass any of the larger locomotive behaviors. We parameterized the moving state using estimates of step length, correlations of turning angles, and transition rates from resting to moving and moving to resting from a hidden Markov model of movement states using the GPS locations from resident tortoises (S. Harju, unpublished data).

To reflect heterogeneous landscape resistance to movement for desert tortoises, we modified an existing model of connectivity (Gray et al. 2019, retrieved from Malcolm and Lacey 2019) to include impermeable roads bisected by the culverts through which tortoises could travel. We re-scaled the layer of connectivity from 0 (high connectivity, or low resistance) to 1 (no connectivity, or high resistance/impermeable) and merged the layer with layers of rasterized roads (classified as 1) and rasterized culverts (classification ranged from 0.05 inside the culvert to 0.25 just outside the culvert to reflect potential 'attractiveness' of the culvert as a burrow surrogate or as a way past the fenced highway).

2.3 Movement simulations

We simulated movement paths of hypothetical desert tortoises as modulated by a heterogeneous landscape movement surface and in relation to an impermeable highway with intermittent fully permeable corridors (i.e., culverts). We conducted the simulations within package 'SiMRiv' in Program R (v4.0), which allows for multi-state movement simulations in heterogeneous environments with barriers to movement (Quaglietta and Porto 2019).

We simulated desert tortoise movements using the two general movement states described above, between which tortoises were allowed to switch at any time. Thus, via simulation, we were solely interested in mimicking the movement patterns of resident tortoises and did not ascribe specific behaviors to either movement state. Each movement state had its own set of movement parameters. For the resting state, we used a true random walk model, with a 1-unit step length and random turning angles (the 1-unit step length was equal to the resistance raster grid cell resolution, i.e., 0.6 m). This was to encompass short, localized movements in addition to true stationarity as well as GPS error associated with true stationarity. For the moving state, we specified a correlated random walk with maximum step lengths of 37 raster cells and a correlation of turning angles between successive steps of 0.707. We defined the perceptual range of the simulated tortoises (i.e., the range via which they could perceive the underlying resistance surface and thus make shorter step lengths or avoid high resistance raster cells) as a Gaussian kernel centered on the current location with a standard deviation of 25 map units (e.g., 66% of the perceived resistance cells were within 25 map units). This reflected declining perception of movement limitations at farther distances (Hayes et al. 1988, Walton and Baxter 2019).

Having two movement states, simulated desert tortoises also needed estimates of transition rates between the two movement states. A hidden Markov model of movement states on the free-ranging tortoises found that tortoises switched from resting to moving states with a frequency of 0.098 and from moving to resting with a frequency of 0.228.

We used mark-recapture estimates to determine the number of simulated tortoises for each semi-circular survey plot on each side of the highway, for a total of 37 simulated tortoises (Table 1; S. Harju, unpublished data). To reflect the movements and potential encounters with culverts that free-ranging, GPS-tagged desert tortoises experience, the starting locations for simulated tortoises were randomly generated within the plots. For each simulation, the 37 tortoises were set to step at 30-minute intervals for 730 days (i.e., 2 years), ignoring the fact that desert tortoises spend the majority of the year aestivating or brumating underground (i.e., the ecological equivalent of simulated movements was greater than 2 years).

We repeated simulations 1000 times. Results were evaluated based on the number of times a tortoise crossed the road under two densities of culverts, the actual density existing on the landscape (0.65 culverts/mile, or 7 culverts total) and a higher density of 2.58 culverts/mile (or 28 culverts total), and two culvert widths: 24 inches (in; the smallest culvert size in the study area) and a wider culvert of 72 in (the most common width of box culverts used in the study area). The combinations of culvert density and width meant tortoises could cross under four different scenarios: 1) seven 24-in culverts, 2) seven culverts with an increased width of 72 in, 3) an increased number of culverts (28) with width of 24 in, and 4) an increased number of culverts (28) with increased widths (72 in).

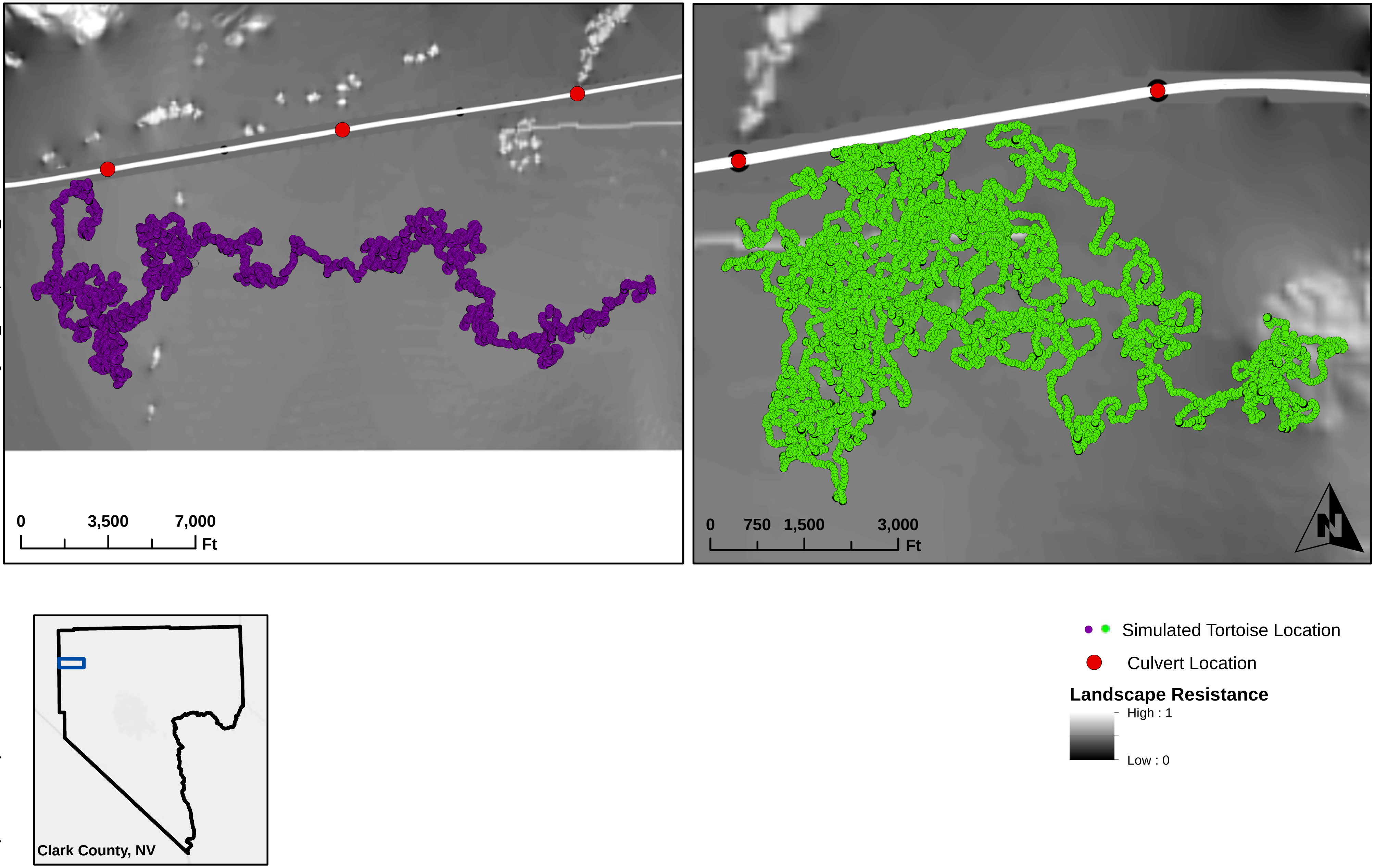
Table 1. Mark-recapture estimates that were used to determine the number of simulated desert tortoises per survey plot

Plot ID	Population Estimate
95-01S	3.34
95-02N	0.00
95-02S	0.00
95-03N	0.00
95-03S	2.02
95-04N	0.00
95-04S	3.34
95-05N	1.00
95-05S	8.57
95-06N	1.00
95-06S	7.26
95-07N	1.00
95-07S	9.87

Section 3 Results

Field crews captured and GPS-tagged 15 adult resident tortoises (nine males and six females) between April 3rd, 2021 and August 19th, 2021. At first capture, tortoises had midline carapace lengths ranging from 183 – 269 millimeters (mm; mean = 230.3 mm, SD = 23.7 mm). There was a mean number of GPS locations per tortoise of 2,740.3 (SD = 1,322.2, range 469 – 4,746).

Examination of free-ranging tortoise movement paths revealed two general behavioral types of resident tortoises, which we've termed locals and rangers, each with two types of movement states, resting and moving (Figure 2). All six females and four of the nine males were 'locals' and occupied smaller home ranges, regardless of the number of GPS locations. Five males were 'rangers' and exhibited long exploratory or ranging movements. For all simulated tortoises, movement states alternated between highly clustered GPS locations representing resting (e.g., resting, sunning, feeding, or aestivating) and larger step lengths along movement tracks representing a moving state (e.g., foraging, territory defense, mate seeking, etc.; Figure 3).



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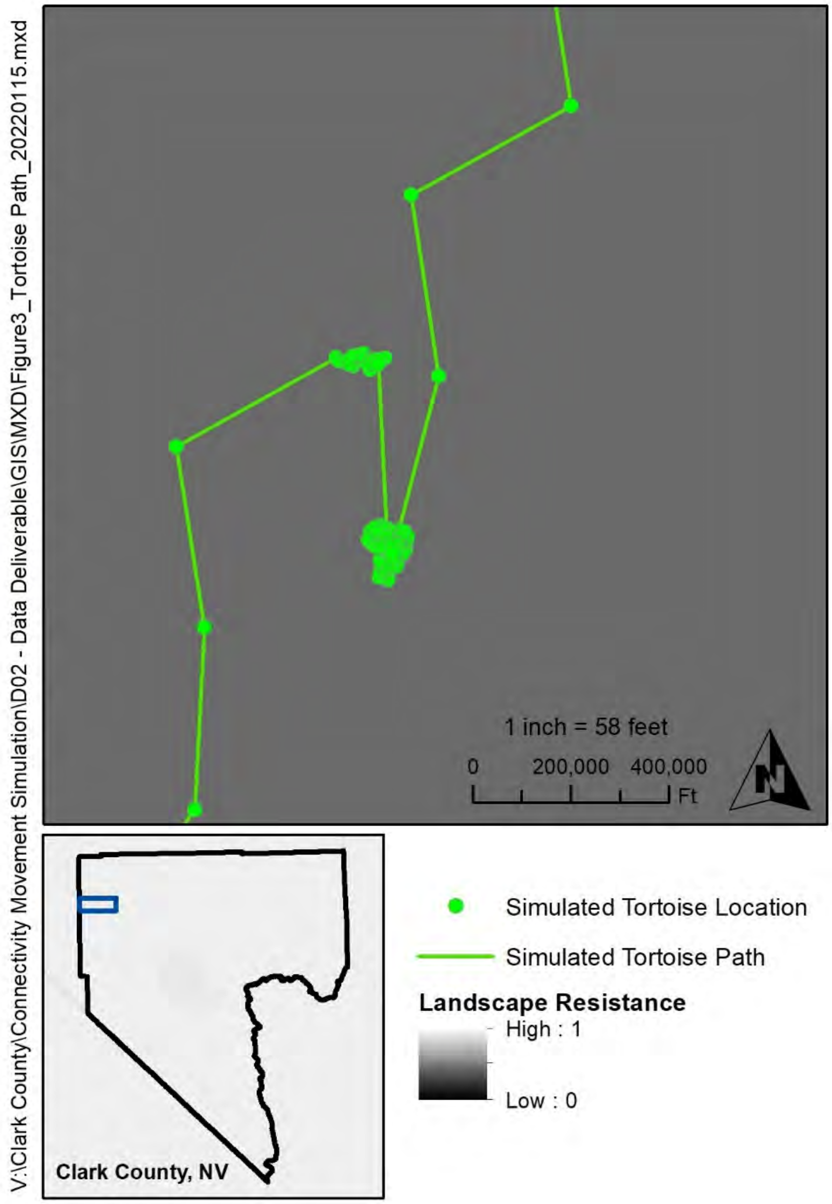
Print Date: Jan 15, 2022	Projection: NAD83 UTM Zone 11N	Project Name	Figure 2	
Project Number: 21105-40	Project Manager: T. Harju	**MDT Connectivity Simulations**	**Example Simulated Desert Tortoise Movement Paths**	
	Cartographer: J. Berg			

Figure 3. Illustration of clustered resting state and extended movement state for free-ranging desert tortoises



Free-ranging tortoise use of culverts to cross the highway was extremely rare. Only two out of 41,089 (0.005%) steps involved crossing the highway by a single individual male who crossed from north to south on April 14th, 2021, between 11:07-11:43 a.m. PDT, and back again from south to north on June 30th, 2021, between 11:05-11:36 a.m. PDT. Simulated tortoise use of culverts was even rarer than that of free-ranging tortoises, despite specifically enhancing the apparent attractiveness of the culverts to the simulated tortoises (e.g., lower resistance than all of the surrounding landscape). If simulated tortoises crossed the highway at the same rate as free-ranging tortoises, we would have expected ~64 crossings per simulation (i.e., 1,296,480 * 0.005 / 100%). Instead, simulated tortoises crossed at varying rates, depending on the combination of width and number of culverts. Crossing rates across tortoises and simulations increased with number of culverts and culvert width; the average crossing rate was 0.00002% (range: 0.0 – 0.0002) for seven 24-in culverts, 0.00006% (0.0 – 0.0003) for seven 72-in culverts, 0.00008% (0.0 – 0.0004) for 28 24-in culverts, and 0.0002% (0.0 – 0.0006) for 28 72-in culverts.

Section 4 Discussion

We documented a free-ranging resident male tortoise using a single culvert as a connectivity pathway across U.S. Highway 95, crossing once and then returning one and a half months later. Although all free-ranging tortoises were captured, GPS-tagged, and released within 800 m of a culvert, most tortoises did not approach within 500 m of a culvert. Those that were occasionally within 500 m of a culvert did not approach within 150 m.

Simulated tortoises, randomly starting within the same 800-m radius plots as captured tortoises, crossed the highway at lower rates compared to captured tortoises. This is perhaps surprising, given that the simulations each had an order of magnitude higher number of steps, the high-density culvert simulation had 200% more culverts to be encountered and used, and that we explicitly improved the attractiveness of the culverts to simulated tortoises to estimate a positive “burrow” effect of the culverts. That simulated tortoises crossed the combination of high-density, wide culverts 150% more times than the combinations of 28 24-in culverts, seven 72-in culverts, or low-density narrow culverts is to be expected, however, given there were more culverts to be encountered and used.

There are several possible explanations for both findings. First, free-ranging tortoises may have had territories that were established away from the highway well prior to the installation of exclusionary fencing to promote culvert use. These tortoises perhaps never will encounter a culvert because it is outside of their home range. New territories set up by dispersing tortoises may be required to observe frequent use of the culverts. Second, free-ranging tortoises may actively avoid the highway itself based on road noise and perceived danger, rendering any crossing structure largely ineffective as larger deterrents will always be present. Third, although clearly usable as crossing structures as evidenced in this and accompanying datasets of non-GPS-tagged tortoises (e.g., unpublished data, S. Cambrin pers. comm.), culverts may be too small and inconspicuous for free-ranging tortoises to encounter frequently. Evidence of this is that the one free-ranging tortoise that did use a culvert for crossing spent six days walking along the highway near the culvert before entering the culvert. It may have been searching for a direct path over the highway or may not have found the culvert until after six days. Similarly, Boarman et al. (1998) only observed five of 172 tagged tortoises crossing culverts a couple of times each in a period spanning over two years.

The observed less-frequent crossing of culverts by simulated tortoises also yielded interesting conclusions. The lack of crossings demonstrated that free-ranging tortoise use of culverts are not random events, as random wandering of simulated tortoises did not result in as many encounters or increased use of culverts, even though simulated tortoises wandered in relation to the underlying connectivity resistance surface and in patterns similar to free-ranging tortoises. This suggests that some free-ranging tortoises are using unidentified cues to detect and choose to use culverts, albeit very infrequently. It is unknown if free-ranging tortoises would have increased culvert use had more or wider culverts been available, but the simulations showed that increasing culvert density and/or width would increase culvert use under a random walk scenario.

Little research exists on the type and size of culverts that tortoises prefer, though there is indication that size, temperature, amount of light, and water flow can influence culvert use by other turtle species (Sievert and Yorks 2015). We originally thought that a small, dark culvert resembling a burrow would be attractive to desert tortoises. While we could not possibly include light as a factor in our simulations, Sievert and Yorks (Sievert and Yorks 2015) reported that brighter, more open tunnels received higher traffic by turtle species than did dark tunnels, and it is interesting to consider whether wider culverts would receive more light and further increase the crossing rates we observed. If light or other cues are used by free-ranging tortoises, it is possible that increased culvert density would increase connectivity.

We found that culverts under an exclusionary fenced highway can function for providing connectivity of individuals on either side of the highway. However, the functional impact of this connectivity is unknown as the sole traversing individual returned to the north side from where he was originally captured. We can reasonably conclude that desert tortoise use of culverts is likely related to other cues than simple random walking within a heterogeneous landscape. Random walking simulated tortoises did encounter culverts, whereas the crossing free-ranging tortoise appeared intent on crossing the highway several days before using the culvert. It is therefore possible that larger scale movement patterns (e.g., exploration, territory defense, or mate seeking) may drive encounters with the highway, and subsequent use of the culverts, beyond that which we captured in the local heterogeneous landscape.

Section 5 Management Implications

Roads and exclusionary fencing fragment habitat and impede functional connectivity for desert tortoises resulting in population loss and isolation. Our results indicate that when planning for infrastructure and conservation of desert tortoise populations, transportation planners and wildlife managers should consider the densities and widths of culverts used in road improvement projects. We found that both higher culvert densities (e.g., 2.58 vs. 0.65 culverts/mile) and wider culverts (e.g., 72 vs. 24 in) were associated with higher crossing rates of simulated desert tortoises. The implications are that connectivity across highways for desert tortoises would benefit from increasing the density and/or width of under-highway culverts. We did not identify a threshold of diminishing returns, and therefore recommend that transportation retrofits seek to maximize culvert densities and sizes wherever possible. Opportunities to retrofit or enhance existing culverts should include installing new culverts of increased size, placing additional culverts at key locations where good habitat for crossing occurs (e.g., along desert dry washes), or locating culverts at more frequent intervals based on the home range size of tortoises. More research to determine the optimum number and effective width of culverts from both an economic and a biological standpoint would facilitate safe, cost efficient crossings while minimizing the potential for habitat fragmentation and population isolation and loss.

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Appendix A

Program R Code for Simulations

```
# Clark County Mojave Desert Tortoise Connectivity Simulation
# Alta Science & Engineering and Heron Ecological
# 2022-02-15

# Set up ----------------------------------------------------------------------

setwd()

library(SiMRiv)
library(rgdal)
library(raster)
library(png)


# Source the needed function --------------------------------------------------

source(paste0(getwd(), "/Code Files/SiMRiv_2022-01-28.R"))


# Resistance layer - might need to compress ------------------------------------

culvert <- raster(paste0(getwd(), "/rds_7_final.tif"))
#culvert[] <- sapply(culvert, as.numeric)

tifoptions <- c("COMPRESS=DEFLATE", "PREDICTOR=2", "ZLEVEL=6")
writeRaster(orig, paste0(getwd(), "/GIS/SHP/Rast Rds 95_24in/rds_7_fin_comp.tiff"),
            options = tifoptions, overwrite = FALSE)
rm(orig, tifoptions)



# Create the model -------------------------------------------------------------

# Two-state: resting and CorrelatedRandomWalk. Transition rates based on frequency
# of GPS tortoises doubling or halving their consecutive step length. Perception
# of the landscape is limited to 25 m when walking (e.g., cannot see across the
# highway). When walking, step length is 38 m # (37+1). Looks pretty comparable to
# wild tortoises (wandering punctuated by resting).

# The definition of the movement behavior - two states: either 1-m step pure
# random walks or 38-m step correlated random walks

# Fully circular perceptual range (i.e. perceiving back is as easy as forward)
#twostate.walker <- species(state.RW() + state(0.48, perceptualRange(type = "circular",
25),
#                                              37, "CorrelatedRW"), trans =
transitionMatrix(0.017,0.08))

# Gaussian forward-facing perceptual range with sigma=8. With 50 map units width
# at 180 deg. from a 25-unit circular perceptive range, sigma = 8 should have
# forward-facing 99% perception of 48 map units wide at 180 deg
#twostate.walker <- species(state.RW() + state(0.48, perceptualRange(type = "gaussian",
8),
#                                              37, "CorrelatedRW"), trans =
transitionMatrix(0.017, 0.08))
```

```
#twostate.walker = species(state.RW() + state(0.80, perceptualRange(type = "gaussian",
25), 37, "CorrelatedRW"),
#                                  trans = transitionMatrix(0.017, 0.08))

# Replace two-state CRW movement parameters with best estimates from a two-state
# Hidden Markov Movement model
#twostate.walker <- species(state(0.71,4.5 ,"CorrelatedRW")  + state(0.48
,perceptualRange(type="gaussian",25 ), 43.7 ,"CorrelatedRW"), trans =
transitionMatrix(0.098,0.228 ))

twostate.walker <- species(state.RW() +
                             state(0.707, perceptualRange(type = "gaussian", 25), 43.7,
"CorrelatedRW"),
                           trans = transitionMatrix(0.098, 0.228))


#twostate.walkers.28 =
list(twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker,
#
twostate.walker,twostate.walker,twostate.walker,twostate.walker)


twostate.walkers.37 =
list(twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker,twostate.walker,twostate.walker,twostate.walker,
                           twostate.walker)


# Set starting locations ----------------------------------------------------

# 2 locations in each plot along Hwy 95
#simstart28 = matrix(c(615495, 615207, 611017, 610053, 607328, 607642, 606004, 604905,
#                    603321, 602727, 605579, 606206, 602819, 603301, 599260, 600057,
#                    599753, 600482, 615037, 615213, 613195, 613185, 613833, 613023,
#                    607921, 607097, 610190, 609878, 4048580, 4048775, 4048171, 4047824,
#                    4047270, 4046925, 4047177, 4047115, 4047148, 4047456, 4047872,
#                    4047973, 4048365, 4048074, 4048129, 4047924, 4048928, 4048658,
#                    4049230, 4049669, 4048887, 4049499, 4048116, 4048425, 4048423,
#                    4047842, 4048383, 4048509), nrow = 28, ncol = 2)
```

```
# Actual MDT numbers (37) and locations along Hwy 95
locs <- st_read(paste0(getwd(), "/GIS/SHP/Tortoise Data/Starts_95_Actual.shp"))
mat1 <- data.frame(locs$POINT_X, locs$POINT_Y)
simstart_actual <- data.matrix(mat1)
rm(locs, mat1)


# Conduct simulations using parallel processing --------------------------------
# *change number simulations, cores, time, input/output locations first*

sim_fx(resist_surf = raster(paste0(getwd(), "/GIS/SHP/Rast Rds 95_72in/
neut_28_95_72_comp.tif")),
       xing_ply = sf::st_read(paste0(getwd(), "/GIS/SHP/Altered Ply Rds/Rd_Dsslv.shp")),
       trials = seq(1, 30), numCores = 2,
       individuals = twostate.walkers.37,
       starting_locs = simstart_actual, time = 35040,
       out_crs = "+proj=utm +zone=11 +datum=NAD83 +units=m +no_defs",
       sims_out_fldr = paste0(getwd(), "/Code Files/Outputs/Hwy95/NeutralLandscape/
Culverts28_72in"))


#-------------------------------------------------------------------------------


# Function
sim_fx <- function(
  resist_surf = raster(paste0(getwd(), "/GIS/SHP/Trial/rds_trial2/rds_trial2.adf")),
  xing_ply = sf::st_read(paste0(getwd(), "/GIS/SHP/Altered Ply Rds/Rd_Dsslv.shp")),
  trials = seq(1, 10),
  numCores = 2,
  individuals = twostate.walkers.37,
  starting_locs = simstart_actual,
  time = 2880,
  out_crs = "+proj=utm +zone=11 +datum=NAD83 +units=m +no_defs",
  sims_out_fldr = paste0(getwd(), "/Code Files/Outputs/Trial")){

  # Manage packages
  if(all(c("snowfall", "SiMRiv", "raster", "rgdal", "png", "sf", "dplyr") %in%
installed.packages()[, 1]) == FALSE)
    stop("You must install the following packages: snowfall, SiMRiv, raster, rgdal, png,
sf, dplyr")
  require(snowfall)
  require(SiMRiv)
  require(raster)
  require(rgdal)
  require(png)
  require(sf)
  require(dplyr)
  require(terra)

  # Check the out folder exists
  if(dir.exists(sims_out_fldr) == FALSE){
    dir.create(sims_out_fldr)
  }

  print(paste0("Start time: ", Sys.time()))
```

```
  sfInit(parallel = T, cpus = ifelse(length(trials) < numCores, length(trials), numCores))
  sfExport("trials", "individuals", "time", "resist_surf", "starting_locs", "out_crs",
"sims_out_fldr")
  sfLibrary(dplyr)
  sfLibrary(sf)
  sfLibrary(terra)

  res_fx <- do.call(rbind, sfClusterApplyLB(1:length(trials), function(i){
    start.time <- Sys.time()

    # Create 28 tortoises, walking for 720 days
    sim.multiple.twostate <- SiMRiv::simulate(individuals = individuals, time = time,
                                              resist = resist_surf, coords =
starting_locs)

    # Extract and compile sim cords.not elegant, but needed the job done quickly
    simcoords.out <- cbind(c(sim.multiple.twostate[,1],sim.multiple.twostate[,4],
                             sim.multiple.twostate[,7],sim.multiple.twostate[,10],
                             sim.multiple.twostate[,13],sim.multiple.twostate[,16],
                             sim.multiple.twostate[,19], sim.multiple.twostate[,22],
                             sim.multiple.twostate[,25], sim.multiple.twostate[,28],
                             sim.multiple.twostate[,31], sim.multiple.twostate[,34],
                             sim.multiple.twostate[,37], sim.multiple.twostate[,40],
                             sim.multiple.twostate[,43], sim.multiple.twostate[,46],
                             sim.multiple.twostate[,49], sim.multiple.twostate[,52],
                             sim.multiple.twostate[,55], sim.multiple.twostate[,58],
                             sim.multiple.twostate[,61], sim.multiple.twostate[,64],
                             sim.multiple.twostate[,67], sim.multiple.twostate[,70],
                             sim.multiple.twostate[,73], sim.multiple.twostate[,76],
                             sim.multiple.twostate[,79], sim.multiple.twostate[,82],
                             sim.multiple.twostate[,85], sim.multiple.twostate[,88],
                             sim.multiple.twostate[,91], sim.multiple.twostate[,94],
                             sim.multiple.twostate[,97], sim.multiple.twostate[,100],
                             sim.multiple.twostate[,103], sim.multiple.twostate[,106],
                             sim.multiple.twostate[,109]),
                           c(sim.multiple.twostate[,2],sim.multiple.twostate[,5],
                             sim.multiple.twostate[,8],sim.multiple.twostate[,11],
                             sim.multiple.twostate[,14],sim.multiple.twostate[,17],
                             sim.multiple.twostate[,20] ,sim.multiple.twostate[,23],
                             sim.multiple.twostate[,26] ,sim.multiple.twostate[,29],
                             sim.multiple.twostate[,32] ,sim.multiple.twostate[,35],
                             sim.multiple.twostate[,38] ,sim.multiple.twostate[,41],
                             sim.multiple.twostate[,44] ,sim.multiple.twostate[,47],
                             sim.multiple.twostate[,50] ,sim.multiple.twostate[,53],
                             sim.multiple.twostate[,56] ,sim.multiple.twostate[,59],
                             sim.multiple.twostate[,62] ,sim.multiple.twostate[,65],
                             sim.multiple.twostate[,68] ,sim.multiple.twostate[,71],
                             sim.multiple.twostate[,74] ,sim.multiple.twostate[,77],
                             sim.multiple.twostate[,80] ,sim.multiple.twostate[,83],
                             sim.multiple.twostate[,86], sim.multiple.twostate[,89],
                             sim.multiple.twostate[,92], sim.multiple.twostate[,95],
                             sim.multiple.twostate[,98], sim.multiple.twostate[,101],
                             sim.multiple.twostate[,104], sim.multiple.twostate[,107],
                             sim.multiple.twostate[,110]))

    # Create points then connect with lines
```

```
    sp.sim.twostate <- data.frame(coords = simcoords.out, ID = rep(1:37, each = time),
order = rep(time)) %>%
      st_as_sf(coords = c("coords.1", "coords.2")) %>%
      st_set_crs(out_crs) %>%
      group_by(ID) %>%
      summarise(do_union = FALSE) %>%
      st_cast("LINESTRING")

    # If lines cross road, record a 1, else record a 0
    r1 <- trials[i]
    r2 <- ifelse(any(st_intersects(xing_ply, sp.sim.twostate, sparse = FALSE) == TRUE), 1,
0)
    #r3 <- length(unlist(sf::st_intersects(xing_ply, sp.sim.twostate, sparse = TRUE)))

    if(r2 == 1){
      st_write(sp.sim.twostate, paste0(sims_out_fldr, "/trial_", trials[i], ".shp"),
append = FALSE)

      v.rd <- vect(xing_ply)
      v.lines <- vect(sp.sim.twostate)
      x <- terra::intersect(v.lines, v.rd)
      r3 <- nrow(x)

    } else {
      r3 <- 0
    }

    return(rbind(data.frame(), cbind(sim = r1, cross = r2, num.cross = r3)))

  }))

  sfStop()
  print(paste0("End time: ", Sys.time()))
  write.csv(res_fx, paste0(sims_out_fldr, "/results.csv"), row.names = FALSE)

}
```