Best Practices for Managing Dunes Sagebrush Lizards in Texas

Adult male Dunes Sagebrush Lizard from Andrews County, Texas. Photo by Toby J. Hibbitts.

May 2016

Texas A&M University

Institute of Renewable Natural Resources, Department of Wildlife and Fisheries Sciences,
Biodiversity Research and Teaching Collections

College Station, Texas

This document was prepared by the Dunes Sagebrush Lizard Research Team (Wade Ryberg, Danielle Walkup, Megan Young, Lee Fitzgerald, and Toby Hibbitts) with assistance from Texas A&M Institute of Renewable Natural Resources' Geospatial Analysis Team (Brian Pierce, Lydia Cao, Kevin Skow, Amanda Dube, and Lauren Johnson) and Director, Roel Lopez.

For information contact (waryberg@tamu.edu)

Best Practices for Managing Dunes Sagebrush Lizards (*Sceloporus arenicolus*) in Texas

Prepared by the
Dunes Sagebrush Lizard Research Team

EXECUTIVE SUMMARY

The Texas Conservation Plan (TCP; Texas Comptroller of Public Accounts 2012) includes a significant role for research on the behavior, population dynamics, habitat, and geographic distribution of the Dunes Sagebrush Lizard (DSL) as it relates to conservation and management objectives outlined in the TCP (Fig. ES.1). Guided by those conservation and management objectives, we initiated a four-year study (2012-15) with the goal of increasing our understanding of the effects of land use, especially landscape fragmentation and disturbance resulting from oil and gas development, on DSL populations. This study was designed to build upon and enhance the long-term research program on the species, and consisted of three major research foci:

(1) **Behavior and Movement** – to understand how landscape configuration and patterns of land use influence DSL movements and behavior
(2) **Population Dynamics** – to quantify the dynamics of lizard populations across sites and assess the effects of human activities on DSL demography and immigration
(3) **Habitat Modeling** – to map suitable and potential habitat and identify critical areas for conservation, plan dispersal corridors, and classify threats to DSL persistence.

This report is organized into six chapters on the different components of research described above. First we provide a summary of research and a synthesis of the research program on the DSL. The chapters that follow are presented as manuscripts, each with its own introduction, methods, results and discussion. For this reason, some introductory material on the natural history of the DSL may be repeated in the introductory statements in each chapter. In Chapter 2 we present a study on home range and movements of the DSL in fragmented and unfragmented habitat using radio telemetry. Chapter 3 presents results from a landscape-scale, mark-recapture study on population dynamics and diffusion of the DSL in disturbed and undisturbed habitat. Chapter 4 is a study of the effects of roads on behavior and movement of the DSL. Chapter 5 presents results of distribution surveys throughout the range of the DSL in Texas, and Chapter 6 reports results of a habitat suitability model for the DSL in Texas.

Results from these chapters culminate in recommendations for updating knowledge about the species and habitat in Texas. Those research results and recommendations for Species and Habitat Updates are summarized below.

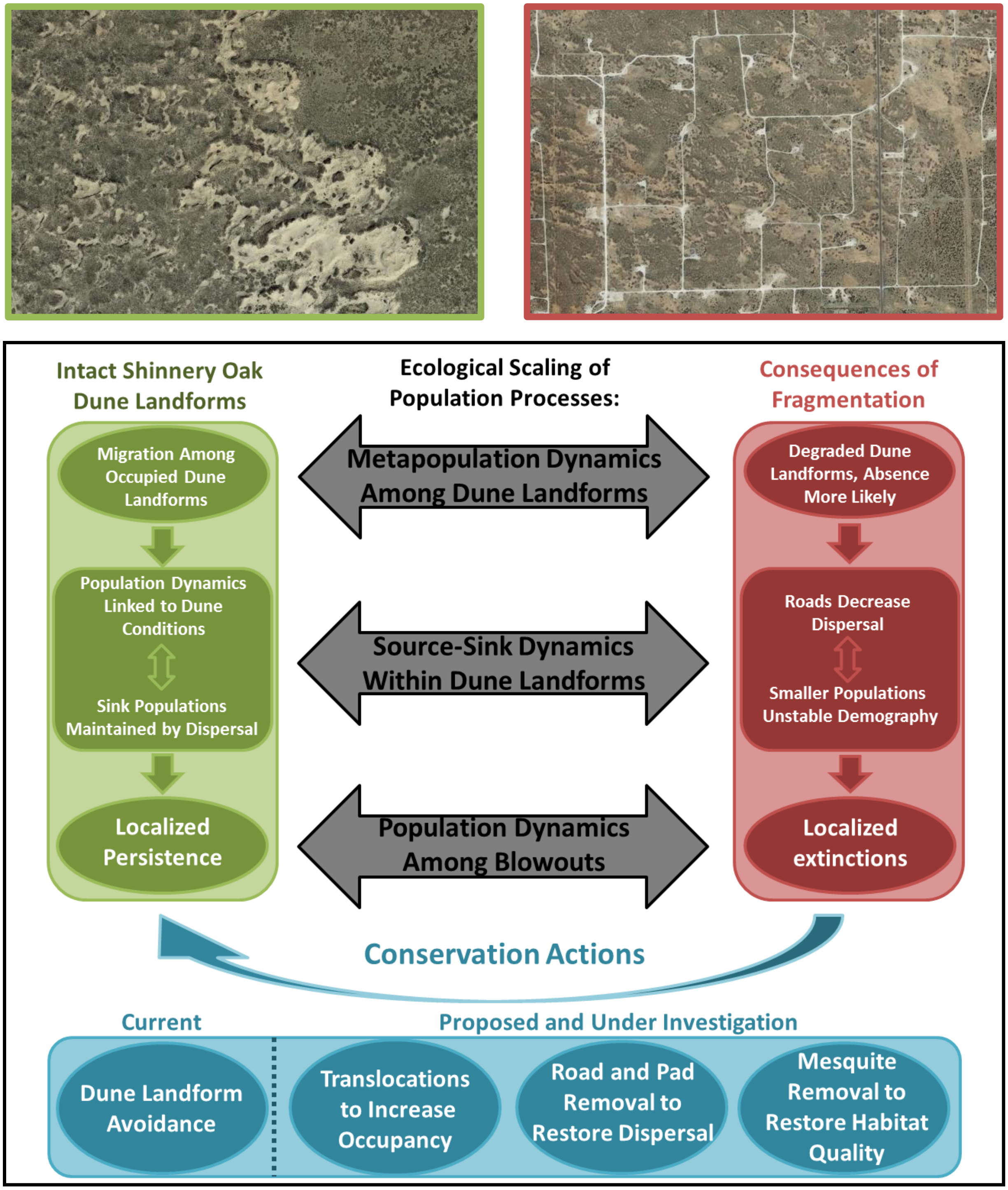


Figure ES.1. Summary of Dunes Sagebrush Lizard past and current research findings, and future research goals evaluating current and proposed conservation actions.

ES.1 Species Update

Consequences of Habitat Fragmentation and Disturbance for Dunes Sagebrush Lizard Movements and Population Dynamics

Fragmentation from oil and gas development had a significant effect on DSL home range size and length of daily movements (CHAPTER 2). In fragmented habitat, the DSL exhibited larger home ranges and moved longer distances each day presumably due to the abundance of open sand and lesser availability of Shinnery Oak cover relative to the unfragmented habitat. Open sand may leave DSL individuals vulnerable to predation and can reach surface temperatures greater than 40° C, making it an unhospitable substrate for long-term use. Additionally, similar to other species of *Sceloporus*, male DSLs had significantly larger core home ranges and moved significantly longer distances each day than females.

Only one individual DSL was observed crossing a caliche road during the course of this study. This individual only crossed the road in a place where sand had covered the caliche (CHAPTER 2). Although this does show that caliche roads are not an absolute barrier for the DSL, it is clear that this type of movement does not occur regularly and would not be sufficient to maintain spatial population structure. In many places throughout the Mescalero-Monahans Sandhills ecosystem, caliche roads are constructed in a grid like network. This network of roads appears to be the major source of fragmentation of the habitat utilized by the DSL. These barriers to dispersal can have a significant effect on populations (CHAPTER 3), and may increase the chances of localized extinctions through the effective isolation of populations within smaller and smaller habitat patches.

Although DSL abundance was greater in undisturbed habitat than disturbed habitat, the realized rate of population growth indicated that populations in both habitats were stable (neither increasing nor decreasing) during the course of this study (CHAPTER 3). However, the diffusion rate, a measure of population spread or dispersal, was more than 4 times higher in undisturbed habitat. This difference in diffusion rate was driven by more DSL individuals making relatively longer distance movements that covered a larger spatial extent in undisturbed habitat compared to disturbed habitat. Very few DSL individuals were observed crossing roads in disturbed habitat despite the fact that many individuals were captured immediately adjacent to roads. This observed low frequency of road crossings in disturbed habitat is consistent with the road acting as a barrier to DSL movements, which accounts for the observed differences in diffusion rates for disturbed and undisturbed habitats. These results suggest that while roads contribute less to overall habitat loss than well pads, they appear to be the main driver of habitat fragmentation and DSL population subdivision, because they limit diffusion and therefore reduce population connectivity.

The effect of roads on DSL movements appears to be caused by surface avoidance behavior in this species (CHAPTER 4). An experiment designed to identify the mechanism behind the observed effects of roads on DSL behavior and movements demonstrated that DSL individuals significantly altered their movement pattern to avoid hard, caliche road surfaces even when vehicle traffic and noise were excluded. The evidence of surface avoidance limiting DSL movement leads to several meaningful implications for the conservation of the DSL. The effects of roads on DSL populations must be considered long-term and persistent. This means that even if roads were simply closed and abandoned, the effects on populations could persist as long as caliche is present. Since noise and traffic related effects of roads were excluded in this experiment, it is unclear how the DSL might respond to these factors. Noise and traffic may also have a negative effect on DSL movements, which may make roads even greater barriers to movements than already observed.

A second experiment was designed to determine if a simple and inexpensive strategy such as constructing a sand-filled trench across a road (i.e., ecopassage) could mitigate the observed effects of caliche roads on DSL movements. The DSL did not use the sand-crossing structure, and the presence of the structure in the caliche road did not alter DSL movement patterns. Additional experiments with different road-crossing structures could provide meaningful insights into the plausibility of using road-crossing structures to facilitate movements of the DSL across roads in occupied habitat.

<u>Recommendation</u>: Evidence from this research (CHAPTER 2, CHAPTER 3) indicates that roads are the main source of fragmentation in DSL habitat. A growing body of research also demonstrates that fragmentation and habitat loss go hand-in-hand and cause decline in DSL populations (Leavitt and Fitzgerald 2013, Walkup et al. in review). Also, research consistently points to the quality and connectivity of large contiguous areas of suitable habitat as the main factor affecting DSL persistence. The best strategy to maintain the quality and connectivity of large contiguous areas of suitable habitat is avoidance of Shinnery Oak sand dunes when constructing new roads. When areas of occupied habitat are fragmented by existing roads, connectivity of habitat patches might be restored through road removal. Candidates for road removal can be selected in sites with road redundancy (multiple access roads to the same location) or roads that access areas that are no longer in use. Additional research into effective ecopassages for the DSL should continue in order to increase connectivity at sites where road removal or avoidance is not possible (CHAPTER 4).

ES.2 Habitat Update

Distribution Surveys and Habitat Suitability of the Dunes Sagebrush Lizard in Texas

During the entire 4-year study (2012-15), distribution surveys resulted in a number of new localities for the species in Texas, though some were geographically close to known localities (CHAPTER 5). All of the survey sites where the DSL was detected were located within areas of very high or high likelihood of occurrence (dark green or light green, respectively) on the TCP Permit Area/Likelihood of Occurrence Map. The DSL was not detected in areas of low or very low likelihood of occurrence (orange or red, respectively), or outside the predicted areas of occurrence (CHAPTER 1 – Fig. 1.1). These results validate our current perception of DSL habitat, corroborate the predicted likelihood of occurrence categories for these areas, and also imply that the current version of the TCP Permit Area/Likelihood of Occurrence Map is an accurate and effective tool for constructing and implementing conservation and management objectives included in the TCP.

Fine scale variation in DSL occurrence observed in areas of very high likelihood of occurrence suggest that the TCP Permit Area/Likelihood of Occurrence Map is conservative in its preservation of DSL habitat at landscape scales and that the current map might be improved with greater precision (i.e., fine scale resolution). However, the observed accuracy of the current TCP Permit Area/Likelihood of Occurrence Map over the last four years of surveys was very high and that accuracy should not be sacrificed for greater precision. As such, our criteria for evaluating the utility of a fine scale habitat suitability model for administering the TCP was based on model accuracy.

The DSL Habitat Suitability Map (Model) was more precise, but less accurate in predicting occupancy of the DSL than the current TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 6 – Fig. 6.2). Under the Habitat Suitability Map, 15% of DSL detections (*n* = 15) occur in sites predicted to have low and very low habitat suitability, whereas zero DSL detections occur in sites with low and very low likelihood of occurrence. This indicates that increasing precision in habitat suitability came at a cost of model accuracy in certain regions within the DSL distribution in Texas.

Despite its administrative limitations, the DSL Habitat Suitability Map can help identify areas where habitat conservation should be a priority and guide current and future research related to conservation and management objectives under the TCP, especially for habitats with very high suitability (dark green). For example, by overlaying roads on top of the Habitat Suitability Map, we can identify priority areas for road removal in southern Andrews and central Crane Counties, which contain the most habitat exhibiting very high suitability under the greatest threat from roads (Fig. 6.6). This approach has already been used to identify sites for research related to conservation and management objectives under the TCP in Crane County. Specifically, we are currently researching 1) the effects of road and well pad reclamation on DSL habitat suitability, and 2) the feasibility of re-establishing populations of the DSL in unoccupied but otherwise suitable habitats using translocation (Appendix A).

Recommendations: The observed accuracy of the current TCP Permit Area/Likelihood of Occurrence Map over the last four years of surveys indicates that it is more effective at preserving DSL habitat at landscape scales than the Habitat Suitability Map. No updates to the TCP Permit Area/Likelihood of Occurrence Map are needed at this time.

The trade-off between increased precision and accuracy exhibited by the DSL Habitat Suitability Map could be mitigated with additional custom imagery at specific locations where localized limitations in available imagery caused over and under-representation of habitat features during imagery classification and remote sensing steps.

Table of Contents

EXECUTIVE SUMMARY iii

Figure ES.1 Summary of Dunes Sagebrush Lizard research program iv

ES.1 Species Update v

ES.2 Habitat Update vi

CHAPTER 1 – INTRODUCTION TO THE RESEARCH PROGRAM ON THE DUNES SAGEBRUSH LIZARD 1

1.1 Background 1

1.2 Life History 2

1.2.1 Description 2

1.2.2 Reproduction and Nesting 2

1.2.3 Diet and Predators 2

1.3 Evolutionary History, Systematics, and Taxonomy 2

1.4 Geographic Distribution 3

1.5 Habitat 3

1.6 Population Ecology 3

1.6.1 Population Dynamics 3

1.6.2 Population Genetics 4

1.7 Effects of Fragmentation 4

1.8 Study Objectives 5

Figure 1.1 TCP Permit Area/Likelihood of Occurrence Map 6

CHAPTER 2 – EFFECTS OF FRAGMENTATION ON THE HOME RANGE AND MOVEMENTS OF THE DUNES SAGEBRUSH LIZARD 7

2.1 Background 7

2.2 Methods 8

2.2.1 Study Site 8

2.2.2 Radiotelemetry (Figures 2.1, 2.2, 2.3) 8

2.2.3 Data Analyses (Figure 2.4) 10

2.3 Results (Tables 2.1, 2.2 and Figures 2.5, 2.6, 2.7, 2.8, 2.9) 11

2.4 Discussion 16

CHAPTER 3 – EFFECTS OF HABITAT DISTURBANCE ON POPULATION DYNAMICS AND DIFFUSION OF THE DUNES SAGEBRUSH LIZARD 18

3.1 Background 18

3.2 Methods 19

3.2.1 Super-grids and Trapping (Figures 3.1, 3.2, 3.3) 19

3.2.2 Population Dynamics 21

3.2.3 Analysis of Movements 22

3.3 Results 22

3.3.1 Trapping Results (Figures 3.4, 3.5, 3.6, 3.7, 3.8) 22

3.3.2 Population Dynamics (Table 3.1 and Figure 3.9) 29

3.3.3 Analysis of Movements (Table 3.2 and Figure 3.10)........31
3.4 Discussion........34
3.4.1 Population Dynamics Summary........34
3.4.2. Analysis of Movements Summary........35
3.5 Conclusions........36
CHAPTER 4 – EFFECTS OF ROADS ON DUNES SAGEBRUSH LIZARD MOVEMENTS.37
4.1 Background........37
4.2 Methods........39
4.2.1 Study Site........39
4.2.2 Study Design (Figure 4.1)........39
4.2.3 Behavior Trials........40
4.2.4 Statistical Analyses........40
4.3 Results (Table 4.1)........41
4.4 Discussion........41
4.5 Conclusions........42
CHAPTER 5 – DISTRIBUTION SURVEYS........44
5.1 Background........44
5.2 Methods........44
5.3 Results and Discussion (Table 5.1)........45
5.3.1 Surveys by County........52
5.3.2 Surveys by Likelihood of Occurrence (Table 5.2)........52
5.3.3 Repeated Surveys........53
5.4 Conclusions........53
CHAPTER 6 – HABITAT SUITABILITY MODEL FOR THE DUNES SAGEBRUSH LIZARD IN TEXAS........54
6.1 Background........54
6.2 Methods........56
6.2.1 Study Area........56
6.2.2 Remote Sensing........56
6.2.3 Imagery Classification........57
6.2.4 Rugosity........57
6.2.5 Statistical Analyses (Tables 6.1, 6.2, 6.3, 6.4 and Figure 6.1)........58
6.3 Results and Discussion (Tables 6.5, 6.6 and Figure 6.2, 6.3, 6.4, 6.5)........62
6.4 Conclusions (Figure 6.6)........68
APPENDIX A – FUTURE RESEARCH ON THE DUNES SAGEBRUSH LIZARD IN TEXAS........70
A.1 Background........70
A.2 Translocation of the Dunes Sagebrush Lizards to Unoccupied Habitat in Texas........70
A.2.1 Research Approach........70
A.2.2 Conservation Implications........71

A.3 Effects of Road and Well Pad Reclamation on Dunes Sagebrush Lizard Habitat Suitability 71
A.3.1 Research Approach 71
A.3.2 Conservation Implications 71
A.4 Effects of Mesquite on Dunes Sagebrush Lizard Habitat Suitability and Occupancy 72
A.4.1 Research Approach (Figure A.1) 72
A.4.2 Conservation Implications 74
APPENDIX B – LITERATURE CITED 75

CHAPTER 1 – INTRODUCTION TO THE RESEARCH PROGRAM ON THE DUNES SAGEBRUSH LIZARD

1.1 Background

The Dunes Sagebrush Lizard (DSL, *Sceloporus arenicolus*) is a small dune-dwelling lizard endemic to southeastern New Mexico and adjacent west Texas (Degenhardt and Jones 1972, Axtell 1988, Degenhardt et al. 1996, Fitzgerald and Painter 2009, Fitzgerald et al. 2011). Specifically, the DSL is endemic to the Shinnery Oak sand dunes of the Mescalero-Monahans Sandhills ecosystem that forms a crescent-shaped arc of disjunct dunes through Andrews, Crane, Gaines, Ward and Winkler counties in Texas (Fitzgerald et al. 2011) and in Chaves, Eddy, Lea and Roosevelt counties in New Mexico (Laurencio and Fitzgerald 2010). The DSL is a habitat specialist. It only lives in sites characterized by bowl-shaped depression of sand (blowouts), and carries out its entire life cycle among interconnected blowouts and the vegetation around the perimeter of blowouts (Fitzgerald et al. 1997, Fitzgerald et al. 2005, Fitzgerald and Painter 2009, Hibbitts et al. 2013).

The DSL has been a species of conservation concern to government agencies and many stakeholder groups for at least two decades (Fitzgerald et al. 2012). It is of special interest to wildlife agencies in Texas and New Mexico because in addition to having a very restricted and naturally disjunct distribution, land use practices have contributed to fragmentation and loss of habitat (Smolensky and Fitzgerald 2011, Leavitt and Fitzgerald 2013, Ryberg et al. 2015). It was proposed for federal listing as endangered by the US Fish and Wildlife Service in December 2010 (Federal Register December 14, 2010). The proposed rule was centered on a number of threats to the species' habitat, with particular emphasis on the problems of Shinnery Oak removal by spraying of herbicides and habitat destruction and fragmentation caused by oil and gas development. In June 2012, the proposed rule was withdrawn, based on the US Fish and Wildlife Service assessment that the threats were being addressed by the implementation of the New Mexico Candidate Conservation Agreement (CCA) and Candidate Conservation Agreement with Assurances (CCAA), the Texas Conservation Plan (TCP), and the Bureau of Land Management's (BLM) Resource Management Plan Amendment (RMPA) (Federal Register June 19, 2012).

In Texas, the TCP includes a significant role for research on the behavior, population dynamics, habitat, and geographic distribution of the DSL. In 2011, a distribution study was carried out to add information on the extent of the species' range and its distribution in Texas (Fitzgerald et al. 2011), and a study of habitat selection enhanced knowledge of the species habitat requirements (Hibbitts et al. 2013). In 2012, a multi-pronged four-year study was initiated with the goal of increasing our understanding of the effects of land use, especially landscape fragmentation resulting from oil and gas development and other land uses on the DSL. The research project was designed to build upon and enhance the long-term research program on the species, and consisted of three major research foci: (1) *Behavior and Movement*, to understand how landscape configuration and patterns of land use influence lizard movements and behavior, (2) *Population Dynamics*, to quantify the dynamics of lizard populations across sites and assess the effects of human activities on lizard demography and immigration, (3) *Habitat Modeling*, to map suitable and potential habitat and identify critical areas for conservation, plan dispersal corridors, and classify threats to lizard persistence.

1.2 Life History

1.2.1 *Description*

The DSL is a small phrynosomatid lizard. Males average 54.5 mm SVL and females average 53.8 mm SVL (Degenhardt et al. 1996). The dorsal coloration is light brown with an ill-defined pair of longitudinal lighter stripes extending down the sides of the torso. Males have large paired blue belly patches and occasionally have scattered blue scales on the throat. Females develop orange markings on the sides of the face, neck, and body when they become gravid.

1.2.2 *Reproduction and Nesting*

The DSL can be found active throughout the year; however, the activity peaks in spring and summer. Like most lizards, onset of reproduction is cued by increasing temperatures and day length in spring. Courtship and mating occurs mostly during May and June, which also corresponds to the peak activity period for the species. Like other members of their genus and family, female DSLs migrate out of their core home range to nest (Hill and Fitzgerald 2007). During a 2007 radio-tracking study, 10 nesting sites were found and two nests were discovered with eggs. Females nested at night and dug their nest tunnels into the steep side of a blowout until they reached moist soil. Another nest was found in 2011 in a blowout (Ryberg et al. 2012). These observations, taken together, indicated females select nest sites close to the moisture horizon in the sandy soil and chose sites where sand grain size composition is relatively coarse compared to surrounding areas in their home range (Ryberg et al. 2012). Females may reproduce once or twice in a season, laying an average of 5 eggs per clutch in mid-June, and again in late July or early August (Fitzgerald and Painter 2009, Ryberg et al 2015). Hatchlings appear in early July and a portion will reach sexual maturity in their first spring (about 10 months of age). Individuals that hatch later or grow slower may not breed until their second spring. The lifespan of the DSL is 3-5 years.

1.2.3 *Diet and Predators*

The DSL is a sit-and-wait ambush forager and its diet is typical of small North American lizard species, consisting mostly of ants, grasshoppers and crickets, spiders, beetles, and other arthropods (Fitzgerald and Painter unpublished data). A number of predators prey on DSLs, including a variety of snake species, avian predators such as loggerhead shrikes (Hathcock and Hill 2012), and mammalian predators. One radio-tracking study found coachwhip snakes (*Coluber flagellum*) consumed 20% of radio-tagged gravid females (Hill and Fitzgerald 2007).

1.3 Evolutionary History, Systematics, and Taxonomy

When first discovered, the DSL was considered a disjunct population of *S. graciosus*, the Sagebrush Lizard. It was formally described as a new subspecies, *S. graciosus arenicolus* (Degenhardt and Jones 1972), but elevated to species status (*S. arenicolus*) by Collins (1991) because the DSL was identified as a morphologically distinct, allopatric subspecies. Later studies of phylogenetic systematics of lizards in the genus *Sceloporus* supported the identity of the DSL, but finer scale resolution of relationships among the sagebrush lizards, including the DSL was still lacking (Wiens and Reeder 1997, Wiens et al. 2010). A recent study by Chan et al. (2013) used modern phylogenetic analyses of DNA sequence data and reviewed taxonomic literature on the morphology of the DSL. Their study demonstrated the DSL is morphologically, behaviorally, and genetically distinct from its nearest relatives and should be considered a species. An estimate of divergence times showed the DSL, together with its most closely related Sagebrush Lizard populations, was about 2,330,000 years old, and the average age of DSL lineages was about 490,000 years old. It is believed that the DSL co-evolved with formation of the Mescalero-Monahans Sandhills ecosystem during the Pleistocene (Chan et al. 2009), presumably becoming specialized to live in the dune environment where it diverged in isolation from its Sagebrush Lizard ancestors.

1.4 Geographic Distribution

Since the description of the DSL, the known distribution of the species in Texas and New Mexico was restricted to only a few locations. A three year distribution study in New Mexico was the first effort to document the geographic range in that state (Fitzgerald et al.1997). The first survey efforts to better understand the distribution of DSL in Texas occurred in 2006 and 2007; however, DSL were only captured at 3 of 27 sites surveyed (Laurencio et al. 2007). In 2011, a major survey of the range of the DSL in Texas was undertaken (Fitzgerald et al. 2011). The 2011 study completed 51 surveys at 50 sites, and documented presence of the DSL at 28 of the 50 sites. Additionally, a map was produced that categorized areas of the species’ range in Texas ranging according to Very High, High, Low, or Very Low Likelihood of Occurrence (Fig. 1.1.). In their report on the range and distribution of the DSL in Texas, Fitzgerald et al. (2011) concluded that habitat quality and historical patterns of occurrence influenced the likelihood of occupancy or occurrence of the DSL in habitats distributed across the landscape. In Texas, the DSL is currently known to persist in Andrews, Gaines, Ward, and Winkler Counties. Populations have not been observed in Crane County since 1970 (Fitzgerald et al. 2011).

1.5 Habitat

The habitat requirements of the DSL have been studied in detail at several spatial scales ranging from microhabitat use (Hibbitts et al. 2013) to the characteristics of blowouts (Fitzgerald et al. 1997), and finally to regional landscape scale patterns of habitat configuration (Ryberg et al. 2013). The DSL is a habitat specialist, occurring only in Shinnery Oak sand dunes with blowouts. The DSL utilizes microhabitats with steeper slopes and more open sand than expected by chance (Hibbitts et al. 2013). The largest size classes of blowouts (those that were large in area and deep) were most often found to be occupied by the DSL (Fitzgerald et al. 1997). The size and configuration of the complexes of these blowouts on the landscape also are associated with larger populations of the DSL (Ryberg et al. 2013).

1.6 Population Ecology

1.6.1 *Population dynamics*

Previous studies in New Mexico have examined how population dynamics of the DSL are linked to the Shinnery Oak sand dune landscape. A five-year mark-recapture study in practically undisturbed habitat in New Mexico yielded much information on population dynamics of the DSL. The research showed that among six independent trapping grids in contiguous Shinnery Oak dune habitat, the lizard population could be conceived as living in neighborhoods of individuals that created source-sink dynamics across that landscape (Ryberg et al. 2013). Neighborhood size was associated with contiguity of the habitat, slope, and soil compaction, and larger neighborhoods acted as net exporters of individuals (sources) and smaller neighborhoods as net importers (sinks). Annual survival at the sites varied from 0.46 to 0.74 annually, recruitment ranged from 0.09 to 0.16 per site, but the realized rate of population growth was stable (indistinguishable from 1) at each site. With the same mark-recapture study, Ryberg et al. (2015) also examined the linkages between configuration of the blowout areas and survivorship of adults and juveniles, and fecundity of females (population vital rates). They showed that the landscape configuration influenced population dynamics with the population growth rate (λ) being sensitive to proportional changes to fecundity and juvenile survival in irregular blowouts with more edge, while in more regularly shaped blowouts with less edge, the population growth rate was more sensitive to proportional changes to adult survival (Ryberg et al. 2015). Finally, population estimates of the DSL were carried out at multiple sites in New Mexico during two field seasons by Smolensky and Fitzgerald (2010), using both distance sampling and total removal plots. DSL densities ranged from 4.6/ha using distance sampling methods to 30/ha using total removal plots.

1.6.2 *Population genetics*

A study of genetic population structure of the DSL (Chan et al. 2007, Chan et al. 2009) found three genetic clusters corresponding to north, central, and southern regions of the species' entire range across southeastern New Mexico and West Texas. The study also showed limited gene flow between two sites in the northern and central populations, as well as from the southern population to the western central population. Migration estimates between the genetic populations were low, although there is a suggestion of asymmetric migration from the north to the central region.

1.7 Effects of Fragmentation

Construction of networks of caliche well pads and roads for oil and gas development within the Shinnery Oak sand dune landscape results in the loss and fragmentation of Shinnery Oak sand dune habitat. Research on the DSL has identified potential correlates between oil and gas development and lizard abundance. Using data from visual transect surveys and measurements of oil pad density Sias and Snell (1998) found a significant, negative correlation between lizard abundance and oil pad density. Additionally, Smolensky and Fitzgerald (2011) identified a positive association between lizard abundances and the amount or extent of blowouts within the surrounding habitat, although they did not find a linear relationship between abundance of DSLs and total area of caliche well pads and roads. To more fully investigate the effects of fragmentation on populations of the DSL, a large mark-recapture study was undertaken near Loco Hills, NM. Populations in fragmented habitat had skewed demographic structure and very low abundance compared to populations in unfragmented habitat. Some populations completely disappeared from fragmented sites where they were historically documented. On fragmented grids, the yearly capture rate started at 0.0019 captures/trap-day in 2009 and 2010 and decreased every year until, in 2013, zero DSLs were captured on fragmented grids (Walkup et al. 2014, Walkup et al. in review). This disappearance of populations of the DSL contributes to community disassembly in fragmented habitats, likely due to changes in the landscape configuration in fragmented sites which had fewer large dune blowouts than unfragmented sites (Leavitt and Fitzgerald 2013).

1.8 Study objectives

We developed this four year study to address aspects of DSL biology that would fill knowledge gaps. Very little work has been done on movements and home range sizes of DSL; some movements have been inferred from mark-recapture studies (Ryberg et al. 2013) and home range sizes have been estimated for gravid females (Hill and Fitzgerald 2007). These initial studies indicated that DSL were comparable to other members of their genus in regards to female home range size and movements. However, previous work did not address the effects of habitat fragmentation on movements or home range, or even investigate the home range of male DSLs.

All previous population studies were conducted in New Mexico. No in depth population studies have been done in Texas, where the species' distribution is farther south and east than the New Mexico distribution, and Texas populations are genetically distinguishable from those in New Mexico (Chan et al. 2009, 2013). Additionally, previous mark-recapture studies focused on the population dynamics of the DSL in fragmented habitat have not attempted to estimate population vital rates such as survivorship due to extremely small population sizes and very low recapture rates in populations in fragmented areas. In this study, we selected a disturbed site that is becoming increasingly fragmented, with the aim of observing the effects of fragmentation on DSL movements and population dynamics before the population size is too small to study.

Currently the distribution of the DSL in Texas is based off of subject matter expert knowledge (Fig. 1.1), meaning that the map is not repeatable and the boundaries of the distribution and likelihood of occurrence categories are subjective. Additionally, the current map is not a habitat quality map but simply a likelihood of occurrence map. In this study, we explored whether a fine scale habitat suitability model using image classification and remote sensing techniques can be as or more accurate and effective at preserving DSL habitat at landscape scales than the current, subject-matter-expert-based, Permit Area/Likelihood of Occurrence Map (Fig. 1.1).

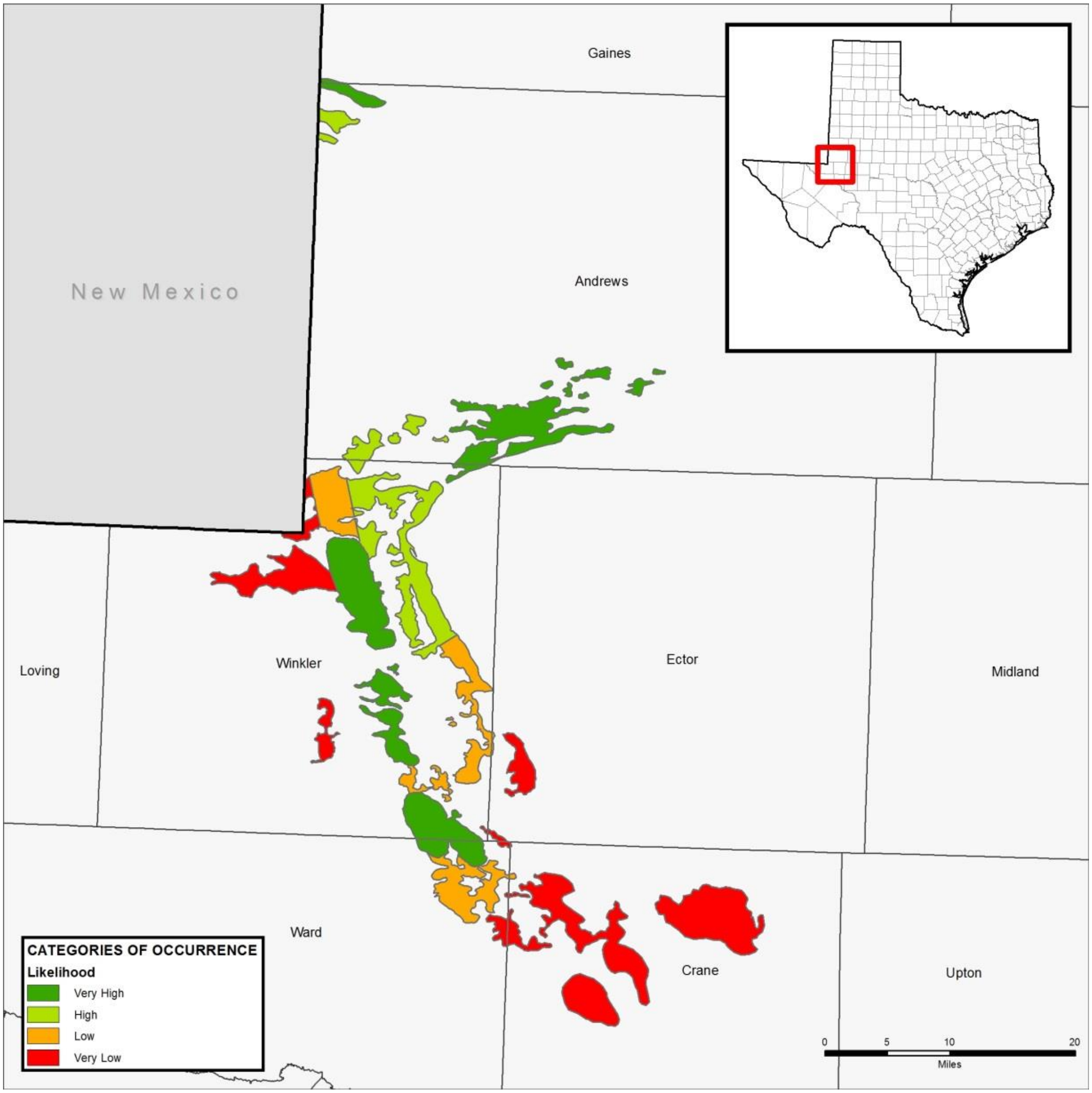


Figure 1.1. Texas Conservation Plan Permit Area/Likelihood of Occurrence Map created by Dr. Toby Hibbitts, TAMU Research. The colors in the legend and corresponding map represent Likelihood of Occurrence Class; red is Very Low (0-25 percent probability of DSL occurrence), orange is Low (25-50 percent probability of DSL occurrence), light green is High (50-75 percent probability of DSL occurrence), and dark green is Very High (75-100 percent probability of DSL occurrence).

CHAPTER 2 – EFFECTS OF FRAGMENTATION ON THE HOME RANGE AND MOVEMENTS OF THE DUNES SAGEBRUSH LIZARD

2.1 Background

Burt (1943) described the home range as the area used by an animal for its normal daily activities, such as locating food, mates, or shelter. In lizards, home range size can be influenced by myriad factors, including availability of food or mates, habitat quality, body size, sex, reproductive status or territoriality (Rose 1982, Ruby and Dunham 1987, Hews 1993, Perry and Garland 2002, Haenel et al. 2003, Manteuffel and Eblmaier 2008). Further, the size of an individual's home range is directly related to the local movement necessary to acquire food, mates, or habitat of sufficient quality and quantity. Elucidating patterns of movement and home range within a species can therefore provide insights into its ecological niche. In the case of threatened or imperiled species, like the Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*), this knowledge is crucial for making informed conservation decisions.

The DSL is a small phrynosomatid lizard endemic to the Mescalero-Monahans Sandhills ecosystem of southeastern New Mexico and adjacent west Texas (Degenhardt et al. 1996). The species is a psammophilic habitat specialist restricted to Shinnery Oak (*Quercus havardii*) sand-dune landforms, which consist of parabolic dunes and depressions called blowouts that are created from an interaction between wind, sand, and the dune-stabilizing Shinnery Oaks (Fitzgerald and Painter 2009, Laurencio and Fitzgerald 2010, Ryberg et al. 2015). Across these landforms, the spatial configuration of blowouts constrains or facilitates DSL movement, leading to local aggregations of lizards or neighborhoods of different sizes (Ryberg et al. 2013). Larger neighborhoods exhibit higher recruitment and population diffusion rates acting as sources for smaller neighborhood sinks with negligible recruitment. Thus, population persistence in this species depends on diffusion dispersal throughout interconnected habitat patches (Ryberg et al. 2013). Dispersal among isolated habitat patches is effectively zero (Chan et al. 2009, Leavitt 2012).

Habitat fragmentation is a process through which a landscape is broken into a number of smaller, more isolated patches, separated by unsuitable habitat and is always associated with habitat loss (Fahrig 2003). Fragmentation may also alter factors like solar radiation, wind, and hydrologic regimes, perpetually altering the landscape (Saunders et al. 1991). Fragmentation and loss of habitat are different phenomena, but together are a major driver of biodiversity loss (McGarigal and Cushman 2002). Among reptiles, habitat modification, including fragmentation, loss, and small-scale changes in microhabitat, has also contributed to species declines (Gibbons et al. 2000, Gardner et al. 2007, Whitfield et al. 2007). Specialist species are acutely susceptible to habitat alteration due in part to their dependence on one, or few, habitat types (Devictor et al. 2008, Hibbitts et al. 2009), and their adaptation to a relatively stable environment (Futuyma and Moreno 1988).

Within the Mescalero-Monahans Sandhills ecosystem, fragmentation from oil and gas development results in a landscape with fewer, smaller, and more isolated habitat patches (Leavitt and Fitzgerald 2013). In Texas, well pad density may reach 55 well pads per section (Hibbitts et al. 2013), connected by caliche roads. With an average well pad size of 13,620 m^2, there is potential for approximately 30% of native land cover to be converted to caliche well pads in the most densely altered areas. Although habitat fragmentation is a landscape-level process, it can affect processes at the community and population levels (Smolensky and Fitzgerald 2011, Leavitt and Fitzgerald 2013, Ryberg et al. 2013).

Our objectives for this study were threefold: first, analyze variation in movement and home range between male and female lizards. Second, analyze variation in movement and home range between lizards in fragmented and unfragmented habitats. Third, evaluate the role of caliche roads as barriers to localized movements.

2.2 Methods

2.2.1 *Study Site*

The study area was located within southern Andrews County, TX (975 m to 1010 m elevation). We chose sites known from previous surveys to contain the DSL (Hibbitts et al. 2013). We selected one fragmented site and two unfragmented sites, based on their proximity to or distance from caliche roads, in order to compare differences in home range and movements. The fragmented site was approximately 7 ha in area, bisected by a caliche road, and abutted three caliche well pads. It was located in a section (1 square mile) with 61 well pads, among the highest density in the area. One unfragmented site was approximately 4.5 ha in area. The site was 100 m from the nearest road, a small 2-track used primarily for ranching vehicles. The other unfragmented site was approximately 1 ha, within a larger chain of blowouts. The nearest road was another small 2-track, located 50 m away. These sites were located in a section with only 6 well pads, which is considered a relatively low degree of fragmentation based on other research on the species (Sias and Snell 1998, Painter et al. 1999, Leavitt and Fitzgerald 2013).

2.2.2 *Radiotelemetry*

Figure 2.1. Radio-Telemetry Equipment. In the left panel, researcher Megan Young is shown with antenna and receiver. The right panel shows a DSL with a radio on its back.

Figure 2.2. Telemetered female DSL found in shady refuge during an afternoon relocation.

Figure 2.3. Telemetered DSL found burrowed in the sand during an evening relocation. The radio and antenna remain above the sand surface. The lizard's eye can be seen below the radio and to the right of the Shinnery Oak leaf.

We captured 36 lizards by noose or pitfall trap for radio telemetry attachment (Fig. 2.1). Upon capture, we marked all lizards with a unique toe clip and affixed a 0.3 g radio transmitter (Model R614, Advanced Telemetry Systems) directly to the middle of the back of each lizard using cyanoacrylate glue, with the whip antenna extending posteriorly (Sabo 2003). We relocated lizards using a scanning receiver (Model R410, Advanced Telemetry Systems, Inc., Isanti, MN) and a 3-element Yagi antenna.

During June-August, 2012 and May-August, 2013, we tracked lizards three times per day for thirty days, or until transmitters were lost due to shedding or predation. We located lizards during their prime activity period (0900-1100), during the hottest part of the day (1400-1600) (Fig. 2.2), and in the evenings (1800-2000) (Fig. 2.3). During each relocation, we attempted to visually locate the lizard to confirm its position, and to record its behavior. We recorded locations in the field using a handheld GPS unit (Garmin Model) with an accuracy of ±3 m.

2.2.3 *Data Analyses*

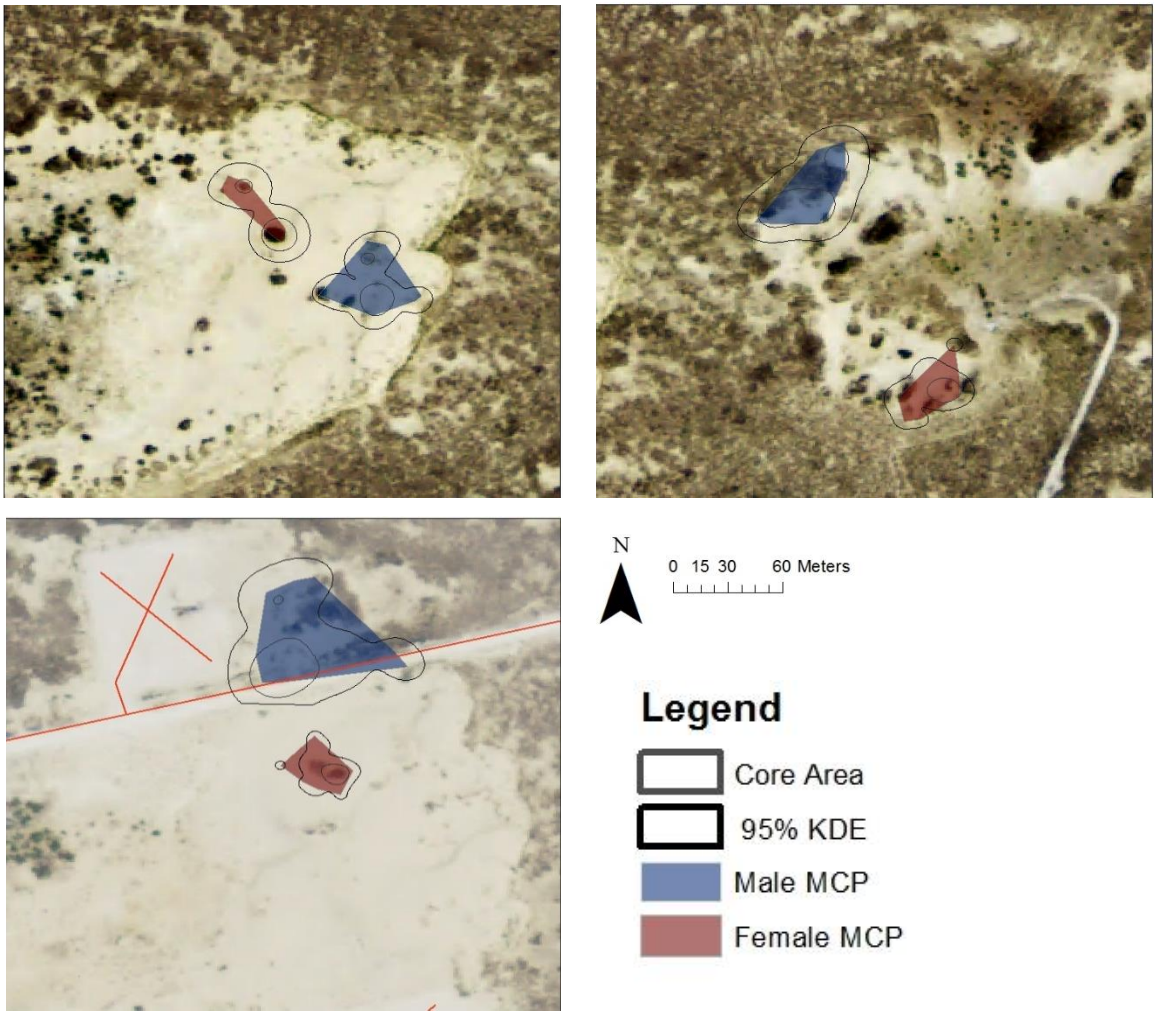


Figure 2.4. Representative home ranges at each of the three study sites: unfragmented (top panels) and fragmented (bottom panel). Minimum convex polygon home ranges are shown as colored polygons, with blue indicating male and red female. Black contour lines show 95% KDE and grey contour lines show 50% KDE or core area. Red lines in the fragmented image indicate roads and a well pad.

We used ESRI ArcInfo 10.1 (ESRI, Redlands, CA) and the adehabitatHR package in R v. 2.15.1 to calculate the following home range estimators and movement parameters: 100% minimum convex polygons (MCP), 50% and 95% fixed kernel density estimators (KDE), and mean distance moved per day (Fig. 2.4). Because home range estimators are sensitive to the number of relocations, we only included lizards with at least 25 locations in the analyses (Schoener 1981). The least-squares cross validation (LSCV) method of selecting the smoothing parameter, recommended by Seaman et al. (1999) failed to minimize the Mean Integrated Squared Error (MISE) for most lizards; therefore we used the reference bandwidth instead.

We conducted two-way ANOVA tests in R v 2.15.1 to assess the effects of sex and habitat type (fragmented vs. unfragmented) on each of the parameters listed above. To determine the effect of caliche roads and well pads on movements we used a chi-squared test (χ^2) with Yates correction. We calculated the amount of caliche versus non-caliche soil surface at our fragmented site and compared expected versus observed movements that crossed caliche or ended on caliche.

2.3 Results

We tracked lizards for an average of 28.0 days (range: 10-36) and collected an average of 60.2 relocations per lizard (range: 26-90) (Table 2.1). Over the course of the study, four of the 36 lizards were lost to snake predation (1 *Arizona elegans*, 3 *Coluber flagellum*) and 10 others shed their radios prior to the end of the 30-day tracking period. Throughout the duration of the study, we observed one lizard cross a road.

Means and standard deviations for MCP, 95% KDE, 50% KDE, and distance moved per day are given in Table 2.2. A two-factor ANOVA for MCP size showed a significant effect of habitat (fragmented vs. unfragmented) (Fig. 2.5; $F = 5.23$, $p = 0.028$), with individuals in fragmented habitat exhibiting larger home ranges than those in unfragmented habitat. Although male MCP sizes tended to be larger than those of females, the difference was not significant ($F = 2.05$, $p = 0.162$), nor was there any interaction between habitat and sex ($F = 0.52$, $p < 0.477$). We observed a nearly significant effect of sex on 95% KDE ($F = 3.89$, $p = 0.057$), with males exhibiting larger home ranges than females, but observed no effect of habitat ($F = 2.86$, $p = 0.100$) or interaction effect ($F = 1.70$, $p = 0.201$) on 95% KDE size. Males had significantly larger 50% KDE home ranges than females ($F = 9.07$, $p = 0.005$), but no effect of habitat ($F = 1.43$, $p =0.241$) or interaction effect ($F = 1.70$, $p = 0.201$) was observed (Fig. 2.6). Typical home ranges for a male and female at each site are given in Figure 2.4.

Males moved significantly longer distances per day than females ($F = 4.90$, $p = 0.03$), and lizards in fragmented habitat moved significantly longer distances per day than those in unfragmented habitat ($F = 6.34$, $p = 0.017$), but no interaction was observed between habitat type and sex ($F = 0.11$, $p = 0.746$) (Fig. 2.7).

We observed 3 movements on caliche roads out of the 799 total movements made by all lizards in the fragmented site. This was significantly less than the expected crossing rate based on the total percentage of available habitat that had a caliche substrate ($\chi^2 = 46.534$, $p < 0.0001$). Additionally all 3 movements on roads were made by the same individual (DSL 32) at the same location (Fig. 2.8). The road at the crossing location had a thin (approximately 5cm) covering of sand over the caliche (Fig. 2.9).

Table 2.1. Home range and distance metrics for all lizards in the study. Sites are identified as fragmented (F) or unfragmented (U).

ID	Sex	Site	Relocations	Mean Distance Moved (m/day)	100 % MCP (m^2)	95 % KDE (m^2)	50 % KDE (m^2)
1	F	U	90	18.72	451.91	514.57	95.57
2	F	U	63	9.50	392.47	1367.81	284.16
4	M	U	85	14.17	1153.85	1607.79	253.99
5	M	U	78	31.29	862.58	1514.72	402.71
11	M	U	26	23.45	451.82	1013.85	239.65
13	M	U	27	23.06	475.35	1130.14	286.80
14	F	U	60	7.65	283.70	418.79	51.90
15	M	U	90	21.97	1040.40	1630.92	318.18
16	F	U	63	17.18	208.43	330.00	74.74
17	M	U	55	25.40	1097.50	1985.16	497.12
18	F	U	56	22.59	816.09	2544.10	417.52
20	F	F	80	23.48	924.54	807.48	131.66
21	F	F	62	20.72	318.12	480.44	91.65
22	M	F	77	24.25	898.40	1198.26	189.10
23	M	F	74	45.18	2841.61	4106.59	936.55
24	M	U	26	24.44	444.86	883.39	212.42
25	M	U	81	23.51	116.66	569.96	137.75
27	M	U	80	28.65	884.96	1091.50	256.29
28	M	U	77	23.08	619.65	723.95	130.21
29	M	U	48	30.31	716.98	1327.26	366.34
31	M	F	70	25.53	431.66	579.00	144.50
32	M	F	66	30.19	3558.93	5998.81	998.54
35	F	U	28	30.74	575.16	1069.82	225.41
36	F	U	65	24.65	1303.12	1567.61	225.95
37	M	F	45	31.64	1905.60	5876.19	1204.28
38	M	F	56	20.99	433.77	1034.07	295.28
39	M	U	65	20.15	1432.92	2787.39	760.69
40	F	U	63	17.42	409.25	938.64	214.64
41	F	F	88	26.58	1072.09	1277.56	183.24
44	F	U	50	24.13	546.37	906.03	140.96
45	M	U	56	26.60	444.84	910.58	288.03
46	F	F	43	27.20	548.87	943.52	218.61
47	F	F	50	22.46	1320.64	1711.51	222.99
48	M	U	50	12.76	193.12	306.37	52.21
50	F	F	31	21.97	381.44	725.09	99.56
52	F	U	42	17.55	284.71	555.01	138.14

Table 2.2. Group means with standard deviations for all individuals in unfragmented habitat, all individuals in fragmented habitat, all males and all females.

	MCP	95%	50%	Distance
Unfragmented	633.6 (364.9)	1154.0 (646.2)	253.0 (159.3)	21.6 (6.3)
Fragmented	1219.6 (1044.4)	2061.5 (2046.7)	393.0 (402.5)	26.7 (6.7)
Females	614.8 (362.6)	1009.9 (580.1)	176.0 (93.2)	20.8 (6.1)
Males	100.3 (874.1)	1813.8 (1646.1)	398.5 (320.5)	25.3 (6.8)

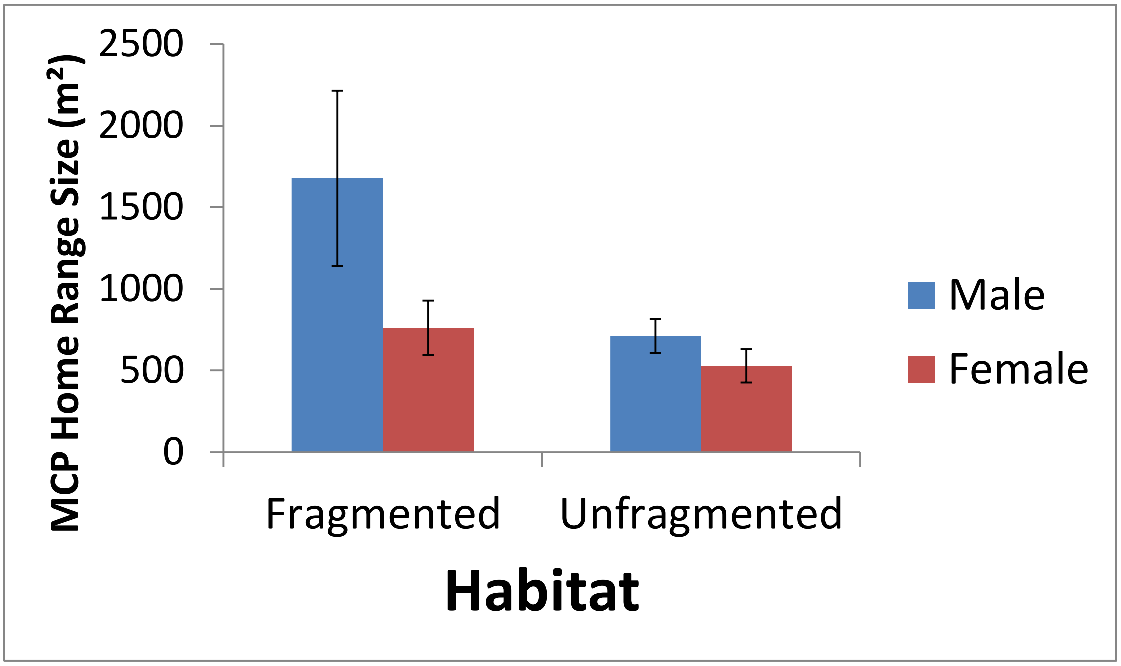


Figure 2.5. In fragmented habitat, the DSL had a significantly larger home range based on MCP than in unfragmented habitat. There was no significant difference between male and female MCP home range sizes, and there was no significant interaction between sex and habitat.

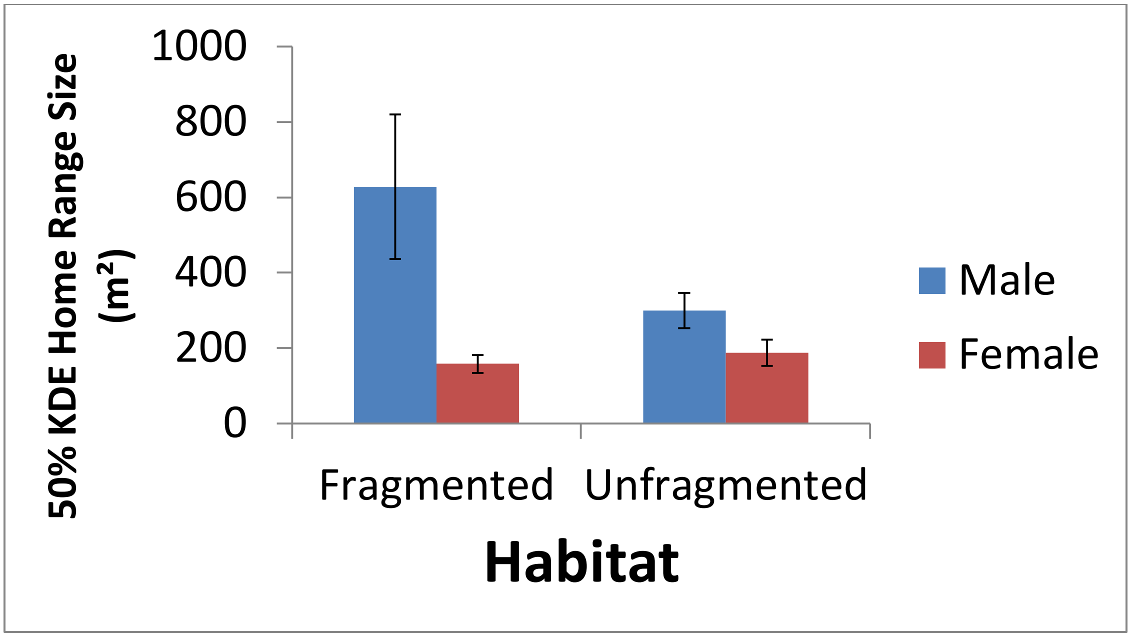


Figure 2.6. Male DSLs have significantly larger core area home ranges than females based on 50% KDE estimation. There was no significant effect of habitat on this relationship and no interaction effect.

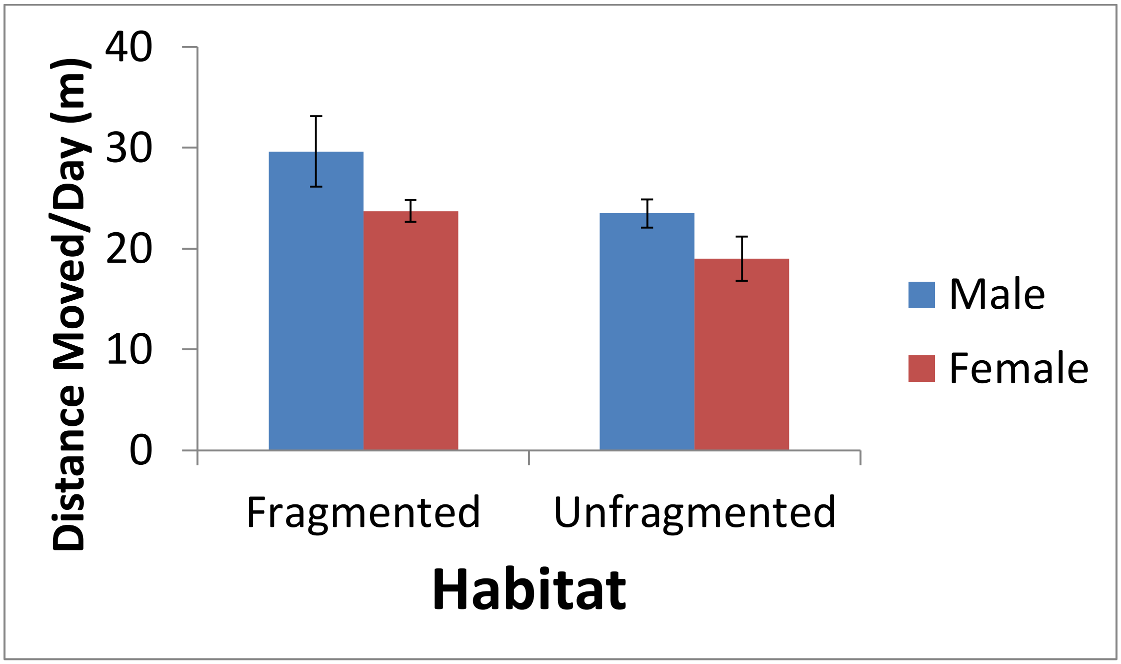


Figure 2.7. The DSL moved significantly longer distances per day in fragmented habitats, and males moved significantly longer distances than females. There was no significant interaction between habitat and sex.

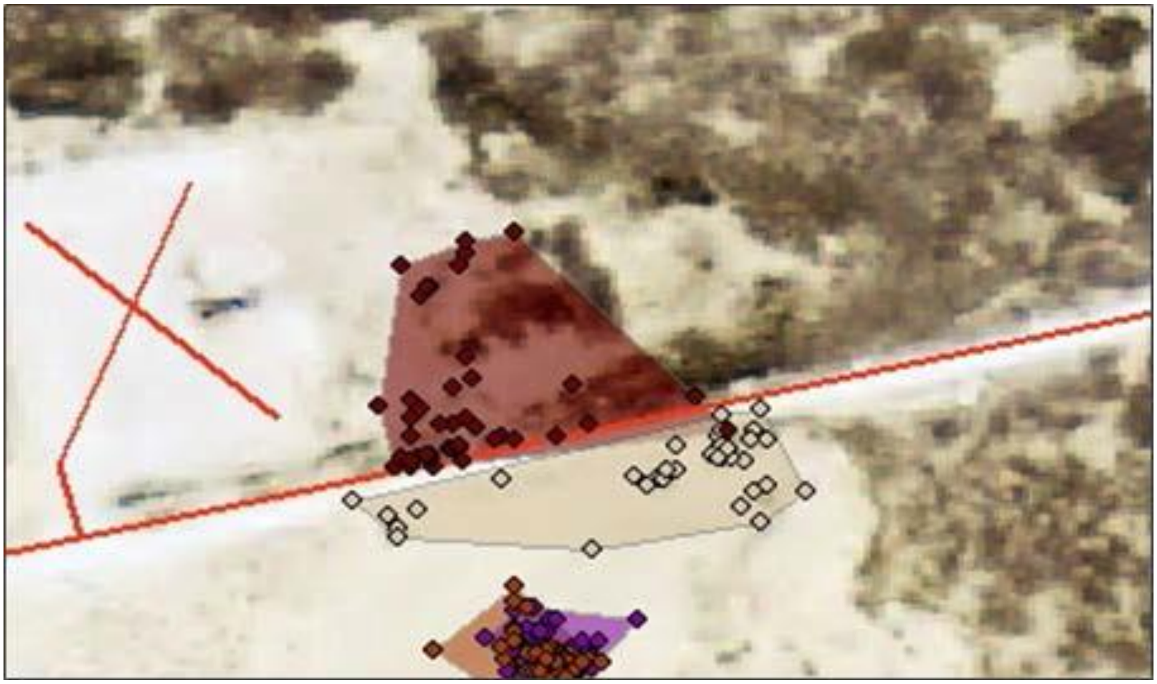


Figure 2.8. Home-range (MCP) of DSL individuals 32 (maroon) and 37 (beige). Individual 32 was the only DSL to cross a caliche road. This crossing was made at a sand-covered portion of the caliche road (Fig. 2.9). Individual 37 moved directly parallel to the road, but never crossed it. No individuals were observed on caliche surfaces.

Figure 2.9. Image on the left shows a standard caliche road surface immediately adjacent to the image on the right, which shows the sand-covered location where a lizard crossed the road.

2.4 Discussion

Our results illustrated that fragmentation from oil and gas development had a significant effect on DSL home range size and length of daily movements. Specifically, lizards in fragmented areas exhibited larger MCP home ranges and moved longer distances each day. Additionally, our study found differences between demographic groups, with males having significantly larger core home ranges and moving significantly longer distances than females.

At the 50% KDE level, which is representative of an individual's core area of use (White and Garrott 1990), males had significantly larger home ranges than females, regardless of the type of habitat in which they were found. The effect of sex was nearly significant ($p = 0.057$) at the 95% KDE level, as well. Among many lizard species, males have larger home ranges than females (Perry and Garland 2002). This is particularly true among species of the genus *Sceloporus* (Ferner 1974, Smith 1985, Abell 1999); Abell (1999) reported home ranges of male *Sceloporus virgatus* four times larger than those of females. Some authors have attributed this to the fact that female home ranges are primarily determined by energetic requirements, while male home ranges must additionally provide access to mates (Hews 1993, Perry and Garland 2002). Abell (1997) found that a male *S. virgatus* in close spatial proximity to a female was more likely to sire most, or all, of the female's clutch, therefore a larger male home range may correlate with greater reproductive success. Although we did not examine the specific reasons for larger male home ranges in the DSL, it is clear that this observation conforms to a larger pattern among *Sceloporus.*

Movements of the DSL also varied between sexes, with males moving significantly longer distances per day than females. This result might also be related to reproductive requirements. All of our observations took place during the breeding season, and we assumed that most, if not all, of the females were gravid at some point during the study. The added mass of eggs can hinder speed and mobility (Shine 2003) and affect behavior. Hill (pers. comm.) observed female DSLs basking more frequently as they approached time of nesting. In contrast, male lizards may move more to increase their likelihood of encountering a female mate or defend territory.

Home range sizes varied widely among individuals in our study, but appear to be consistent with the data available for this species. Minimum convex polygon home range sizes are often reported, allowing for comparisons to be made among populations of the same species or between species. Hill and Fitzgerald (2007) reported MCP home ranges of female DSL ranging from 46.4 m^2 to 2799.7 m^2, consistent with our MCP estimates for female lizards ranging from 208.4 m^2 to 1320.6 m^2.

Minimum convex polygon home range size was larger and movements were longer in fragmented habitat than in unfragmented habitat. We did not test for specific mechanisms that may explain this phenomenon; however, the literature points to density-dependent interactions, or resource availability. In many species, home range size is negatively correlated with lizard density (Whiting 1999, Haenel et al. 2003). However, no single factor adequately explained variation in home range size in those studies. Similarly, Manteuffel and Eblmaier (2008) experimentally manipulated density in *S. virgatus* populations and found smaller home ranges within the high density group. As DSL abundance has been shown to be lower in fragmented habitat than in unfragmented habitat (Leavitt and Fitzgerald 2013), it is possible that larger DSL home ranges at our fragmented site are related to the low lizard densities observed there.

Conversely, fewer resources or resources of lower quality may occur in fragmented habitat, forcing lizards to utilize larger home ranges or move longer distances to acquire adequate resources. Hews (1993) observed female *Uta palmeri* shifting their home ranges in response to supplemented food resources, suggesting that individual space use can be directly linked to resource availability. In this study, we believe the DSL may have had larger MCP home ranges in fragmented habitat due to the abundance of open sand and lesser availability of Shinnery Oak cover, relative to the unfragmented habitat. Open sand may leave individuals vulnerable to predation and can reach surface temperatures greater than 40° C, making it an unhospitable substrate for long-term use. This, coupled with the relative unavailability of Shinnery Oak cover in the fragmented habitat, may have forced individuals to cross large swaths of open sand in order to reach suitable microhabitats. By virtue of the fact that the MCP derives its shape from the outermost locations, this method can often include areas not actually used by an individual (Worton 1987). Thus, MCP estimates for fragmented habitat may be larger because lizards must cross open sand, but not spend substantial time on open sand. This is supported by the fact that lizards in fragmented habitat moved longer distances than those in unfragmented habitat.

We only observed one individual DSL crossing a caliche road during the course of this study, which included 799 relocations of 14 lizards in fragmented habitat. This individual appeared only to cross the road in a place where sand had covered the caliche. Although this does show that caliche roads are not an absolute barrier for the DSL it is clear that this type of movement does not occur regularly and would not be sufficient to maintain spatial population structure as described by Ryberg et al. (2013). In many cases caliche roads are constructed in a grid like network within the Mescalero-Monahans Sandhills ecosystem. This network of roads appears to be the major source of fragmentation of the habitat utilized by the DSL, and it has been demonstrated that populations are smaller and disrupted in areas fragmented by roads (Leavitt and Fitzgerald 2013, Walkup et al. in review). These barriers to dispersal appear to have a significant effect on populations, and may increase the chances of localized extinctions through the effective isolation of populations within smaller and smaller habitat patches.

CHAPTER 3 – EFFECTS OF HABITAT DISTURBANCE ON POPULATION DYNAMICS AND DIFFUSION OF THE DUNES SAGEBRUSH LIZARD

3.1 Background

Within Shinnery Oak (*Quercus havardii*) sand-dune landforms, subpopulations of the Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*) are made up of demographic units called "neighborhoods" (Ryberg et al. 2013). Neighborhoods are connected by diffusion (i.e., population spread) and exhibit source-sink population dynamics and spatial structure that are closely tied to the quality and configuration of blowouts at fine spatial scales and the quantity and connectivity of blowouts at landscape scales. Recent and ongoing research shows that human disturbances affecting the quality, configuration, quantity and connectivity of blowouts may affect DSL populations by disrupting the source-sink dynamics that maintain DSL persistence across the landscape (Smolensky and Fitzgerald 2011; Ryberg et al. 2013, 2015; Walkup et al. in review).

Building on the home range and movement study described above (CHAPTER 2), the multi-year, multi-site, mark-recapture study described below will help determine how lizard behaviors and movements scale-up to generate the variation in lizard demography and population diffusion that influences these source-sink dynamics and therefore DSL persistence in undisturbed and disturbed habitats. Specifically, we estimate DSL survivorship, recruitment, the realized rate of population growth, several movement parameters, and population diffusion rates in undisturbed and disturbed habitats.

Previous mark-recapture studies focused on the population dynamics of the DSL in fragmented habitat have not attempted to estimate population vital rates such as survivorship due to extremely small population sizes and very low recapture rates in populations in fragmented areas. In this study, we selected a disturbed site that is becoming increasingly fragmented, with the aim of observing the effects of fragmentation on DSL movements and population dynamics before the population size is too small to study. Previous studies established criteria for fragmentation based on the number of well pads per section (Sias and Snell 1998). Across some of those studies, the degree of fragmentation has ranged from 23 – 54 well pads per section in New Mexico (Walkup et al. 2014) to 61 well pads per section in the home range and movement study (CHAPTER 2). The disturbed site in this study was placed in a section with 12 well pads; so we considered the site disturbed but not as highly fragmented as in other parts of the Mescalero-Monahans Sandhills ecosystem.

Activities related to oil and gas extraction continued without obstruction during the four-year study (2012-15), and three additional well pads were constructed in that section during the course of the study. Thus populations in the disturbed habitat in this study were not yet experiencing the full effects of fragmentation that may emerge in the near future.

3.2 Methods

3.2.1 *Super-grids and Trapping*

To quantify DSL demographic and movement variation in undisturbed and disturbed habitats, two pitfall trap super-grids were constructed for a mark-recapture study. One of these super-grids was constructed in undisturbed habitat and the other in disturbed habitat (Fig. 3.1). The super-grid in disturbed habitat was bisected by a road and had well-pads in the southeast and northeast corners as well as one at the western edge. The undisturbed super-grid was approximately 500 meters from the nearest well-pad and caliche road of a comparable size to the disturbed super-grid. The super-grids were approximately 5.5 kilometers apart, and both were located in habitat classified as very-high likelihood of occurrence (CHAPTER 1 – Fig. 1.1). Each super-grid was designed with 36 sub-grids arranged in a 6 x 6 pattern with 50 meter spacing. Each sub-grid had nine pitfall traps arranged in a 3 x 3 pattern with 10 meter spacing. Thus, each super-grid contained a total of 324 pitfall traps (36 sub-grids x 9 traps each) that sampled a 136,900 m^2 area (370 x 370 m).

A pitfall trap consisted of a five-gallon bucket, and ply-wood cover-board to provide shade (16”x16” painted piece of 3/8” plywood). A pitfall trap was created by burying the five-gallon bucket in the sand up to the rim, making sure not to fill the bucket with sand (Fig. 3.2). When the super-grid was in operation and lizards were being sampled in pitfall traps, the buckets were open with the cover boards positioned 1-2 inches directly over the bucket opening. Lizards seeking refuge under the cover board moved through this 1-2 inch gap and fell into the open bucket below. The cover boards provided shade for trapped lizards. When the super-grid was not operational, buckets were sealed with tight-fitting plastic lids, covered with sand and covered with the boards.

Trapping intervals for each super-grid were eight days long in 2012 and six days long in 2013-2015. In 2012, most captures occurred in the first six days of trapping, dropping dramatically the last two days. Because of this the trapping interval was reduced, allowing more trapping intervals to occur each month. This slight adjustment to trapping methodology resulted in an increase in our trapping success rate for the DSL. On the first day of each trapping interval, all pitfall traps were opened and set, making the super-grid operational. Each day after opening and checking all traps, lizards were processed on-site, and traps were reset. On the final day of each interval, traps were checked, lizards were processed, and traps were closed. During processing, captured lizards were identified to species, given a unique mark (toe-clip) if not already marked (Fig. 3.3), weighed, measured (e.g., length), and sex was determined. After recording the specific trap locality, the captured lizard was released.

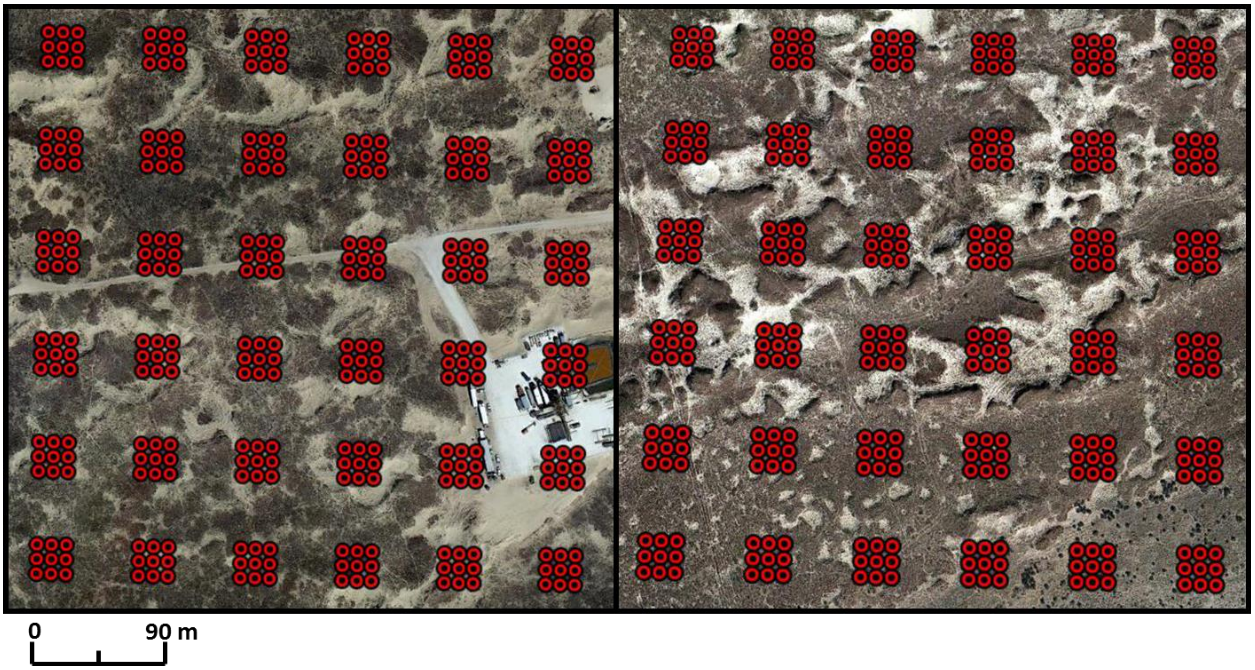


Figure 3.1. Super-grids constructed for a landscape scale mark-recapture study in disturbed (left) and undisturbed (right) habitats. Each red circle shows the location of a pitfall trap. Each super-grid is 370m x 370m, covering 136,900 m^2. Lighter shades depict blowouts embedded within the darker shaded Shinnery Oak sand dune landscape. On the disturbed grid (left) a caliche road bisects the super-grid, along with a shorter road and a well-pad in the bottom right corner of the super-grid.

Figure 3.2. Pitfall trap with cover board and a female DSL (left). Juvenile DSLs captured in pitfall trap (right).

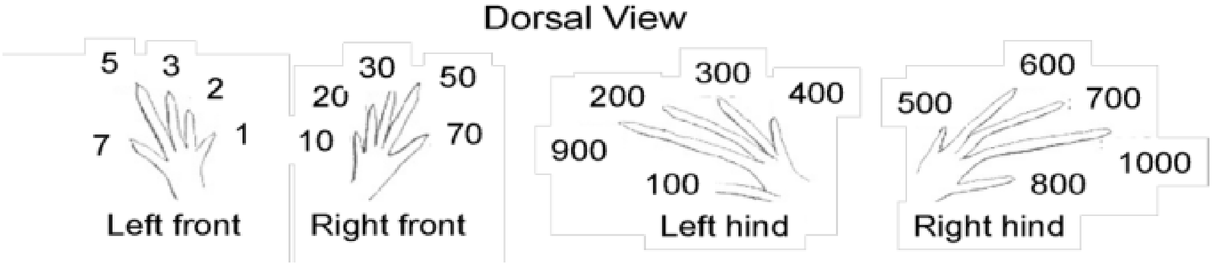


Figure 3.3. Marking scheme for the DSL. Toes can be clipped in combination to provide unique numbered marks for up to 1,999 lizards.

3.2.2 *Population Dynamics*

To estimate the population dynamic parameters, the mark-recapture data was organized into capture histories for each lizard. Capture histories consisted of a unique identifier (Super-grid-toeclip id, e.g. E-101), a vector of 1's (detected, i.e., captured in a trap) or 0's (not detected) for each trap session (1-41, corresponding to the sets of dates the traps were opened; multiple days were collapsed into one session – even if a lizard was captured more than once a session they still only had a 1), and two group covariates (super-grid – disturbed = E, undisturbed = W, and sex – male = M, female = F). These capture histories were analyzed using Program MARK, version 8.0 (White & Burnham 1999).

Preliminary analyses were conducted using the Cormack-Jolly-Seber (CJS) model, which estimates apparent survival and probability of encounter (Lebreton et al. 1992). This allowed us to test for the effects of multiple covariates on a small number of parameters, increasing the probability of modeling success while minimizing the variation around the estimated parameters. The preliminary analysis tested the *a priori* models we determined based on the effects of time (monthly), treatment (disturbed or undisturbed super-grid) and sex (male or female). Results supported apparent survival that varied across months and probability of detection based on an additive month and treatment. Since a difference in apparent survival across sex was unsupported in this basic model, it was not included in the final models.

For the final analysis, capture histories were analyzed using a Pradel model, which estimates apparent survival (ϕ), probability of encounter (p), recruitment (*f*; addition of immigrants and juveniles into the population), and the realized rate of population growth rate (λ; Pradel 1996). Again, *a priori* candidate models were developed to model the effects of treatment (disturbed vs. undisturbed, "g" in the models) and time (monthly time step, "m" in the models), as well as an additive effect (where the treatments were forced into a parallel structure) and an interaction effect (where each treatment effect was allowed to vary with time). The global model was ϕ(g*m) p(g*m) *f*(g*m). In the Pradel models, lambda (λ_i) for each sampling interval (i) can be derived based on apparent survival (ϕ_i) and recruitment (f_i) using the equation below (Pradel 1996):

$$\lambda_i = f_i + \phi_i$$

We tested for goodness of fit for the Pradel models using program RELEASE Tests 2 and 3, implemented in Program MARK (White and Burnham 1999). We used Akaike's Information

Criterion, corrected for small sample size (AIC_c) to identify the most parsimonious model from the set of *a priori* candidate models (Burnham and Anderson 1998).

3.2.3 *Analysis of Movements*

For each individual DSL with more than one capture, we calculated three movement parameters: step length (straight line distance (m) moved between each recapture), total step length (total distance (m) moved from initial capture to final recapture), and net displacement (straight line distance (m) from initial capture to each recapture), using Hawth's Tools for ArcGIS 9.2 (Beyer 2004). For individuals with three or more captures we were also able to calculate the spatial extent of movements (area covered within perimeter of traps (m^2)). The time between recaptures varied from 1 – 701 days (mean = 26.58 days) on the disturbed super-grid and 1 – 726 days (mean = 28.38 days) on the undisturbed super-grid. We compared movements across treatment (disturbed vs. undisturbed), sex (female vs. male), and the interaction of the two variables using a 2-way ANOVA. We log-transformed the data for each movement parameter to meet the assumptions of normality and homoscedasticity.

We also calculated diffusion rate based on recaptures on each super-grid. Diffusion rate quantifies the rate of population spread, combining both the mean and variance in the dispersal distance over time (Turchin 1998). We confirmed independence between subsequent movements by calculating the ratio d^2/s^2 [where d^2 is the mean square distance between successive displacements (only estimated for individuals with 4 or more captures), s^2 is the mean squared deviation of displacements, (X_i, Y_i) are the displacements (i.e., distance between the x-y coordinates of each successive movement; (x_{i+1} - x_i, $y_{i+1} - y_i$)), and $(\bar{X}, \bar{Y})$ are the means of (X_i, Y_i); Turchin 1998], as shown below:

$$d^2 = \frac{1}{m}\sum_{i=1}^{m}[(X_{i+1} - X_i)^2 + (Y_{i+1} - Y_i)^2]$$

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}[(X_i - \bar{X})^2 + (Y_i - \bar{Y})^2]$$

Swihart and Slade (1985) gave calculated critical values for the d^2/s^2 ratio to evaluate the null hypothesis that the movements were independent. We then calculated the diffusion rate ($\widehat{D}$) for the population on each super-grid using the equation below, where l_i is the step length in meters and t_i is the time interval in days:

$$\widehat{D} = \frac{\sum_{i=1}^{n} l_i^2}{4\sum_{i=1}^{n} t_i}$$

3.3 Results

3.3.1 *Trapping Results*

In 2012, the two super-grids were operational from May to September and again in November, yielding a total of 26,568 trap-days (41 days x 324 traps x 2 super-grids). In 2013, the two super-grids were operational February, April through September, and November, for a total of 33,048 trap-days (51 days x 324 traps x 2 super-grids). In 2014, the two super-grids were operational February, March through September, and November, for a total of 35,640 trap-days (55 days x 324 traps x 2 super-grids). In 2015, the two super-grids were operational February through August for a total of 30,456 trap-days (47 days x 324 traps x 2 super-grids). Over those four years combined (2012-15), the two super-grids were operational for a grand total of 125,712 trap-days. During this time 12,814 lizards were captured, of which 1,539 were DSLs. After creating initial capture histories for individual lizards, 726 individual DSLs were captured: 549 on the undisturbed super-grid and 177 on the disturbed super-grid. The other 815 captures were recaptures of some of these individuals.

To visualize trends in DSL activity and abundance, the capture data described above was adjusted by trapping effort to show mean daily captures by month for the six most common species of lizards observed in the mark-recapture study (Fig. 3.4; Three species were captured so rarely they were not included in the figure). Among all other species, the DSL (purple bars) maintained the third highest daily capture rate from May to September 2012, February 2013 to August 2013, May to August 2014, and May to July 2015 (excluding months in which traps were not operational). However, the DSL had the second highest daily capture rate in November 2012, September 2013 through April 2014, September and November 2014, and April and August 2015 (excluding months in which traps were not operational).

Capture rates of the DSL were slightly higher in 2013 than 2012 and 2014 (8.2 ± 3.7, 8.0 ± 4.2, 7.3 ± 4.3 captures/day, respectively; Fig. 3.5A). The capture rate for 2015 was lowest across the four years (6.4 ± 4.8 captures/day). When analyzed by treatment, capture rates in the undisturbed super-grid were driving the overall pattern of higher captures rates in 2013 than 2012 and 2014 and lower capture rates in 2015 (7.0 ± 3.1, 6.5 ± 3.7, 6.0 ± 3.5; 4.2 ± 3.1 captures/day, respectively; Fig. 3.5B). However, the capture rates in the disturbed super-grid did not follow this pattern; they were highest in 2015, followed by 2012, 2014, then 2013 (1.9 ± 1.5, 1.4 ± 0.7, 1.3 ± 1.1, 1.2 ± 0.8 captures/day, respectively; Fig. 3.5C).

Capture rates of the DSL varied throughout the year due to seasonal differences in temperature. More lizards were active in the summer months compared to the winter months. This seasonality was extreme in 2015. No DSLs were captured in February and March of that year, but they were captured during those months in previous years (2013-2014). Capture rates also varied during the breeding season (spring to early fall) with an activity peak earlier in the spring (April and May) and another peak later in the season (August to November) as hatchlings emerged.

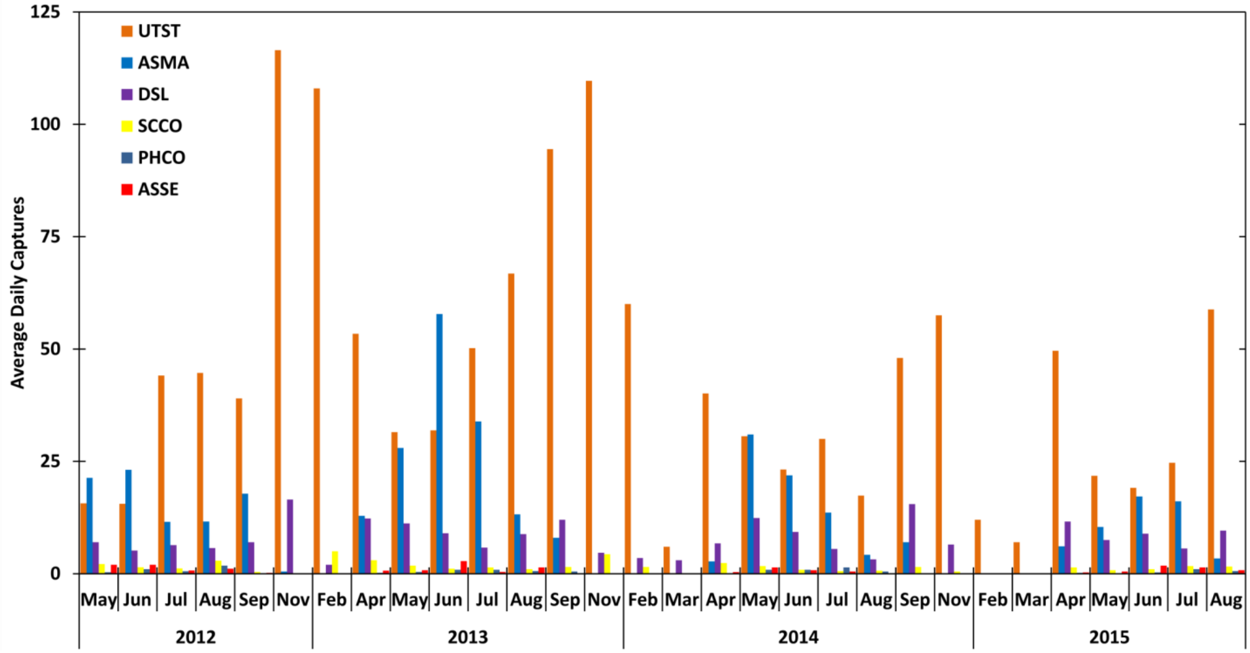


Figure 3.4. Average daily captures by month for six species of lizards from May 2012 to August 2015 (excluding months when no trapping occurred: October and December 2012; January, March, October and December 2013; January, October and December 2014; January 2015). Species listed are *Uta stansburiana* (UTST), *Aspidoscelis marmorata* (ASMA), *Sceloporus arenicolus* (SCAR/DSL), *S. consobrinus* (SCCO), *Phrynosoma cornutum* (PHCO) and *A. sexlineata* (ASSE).

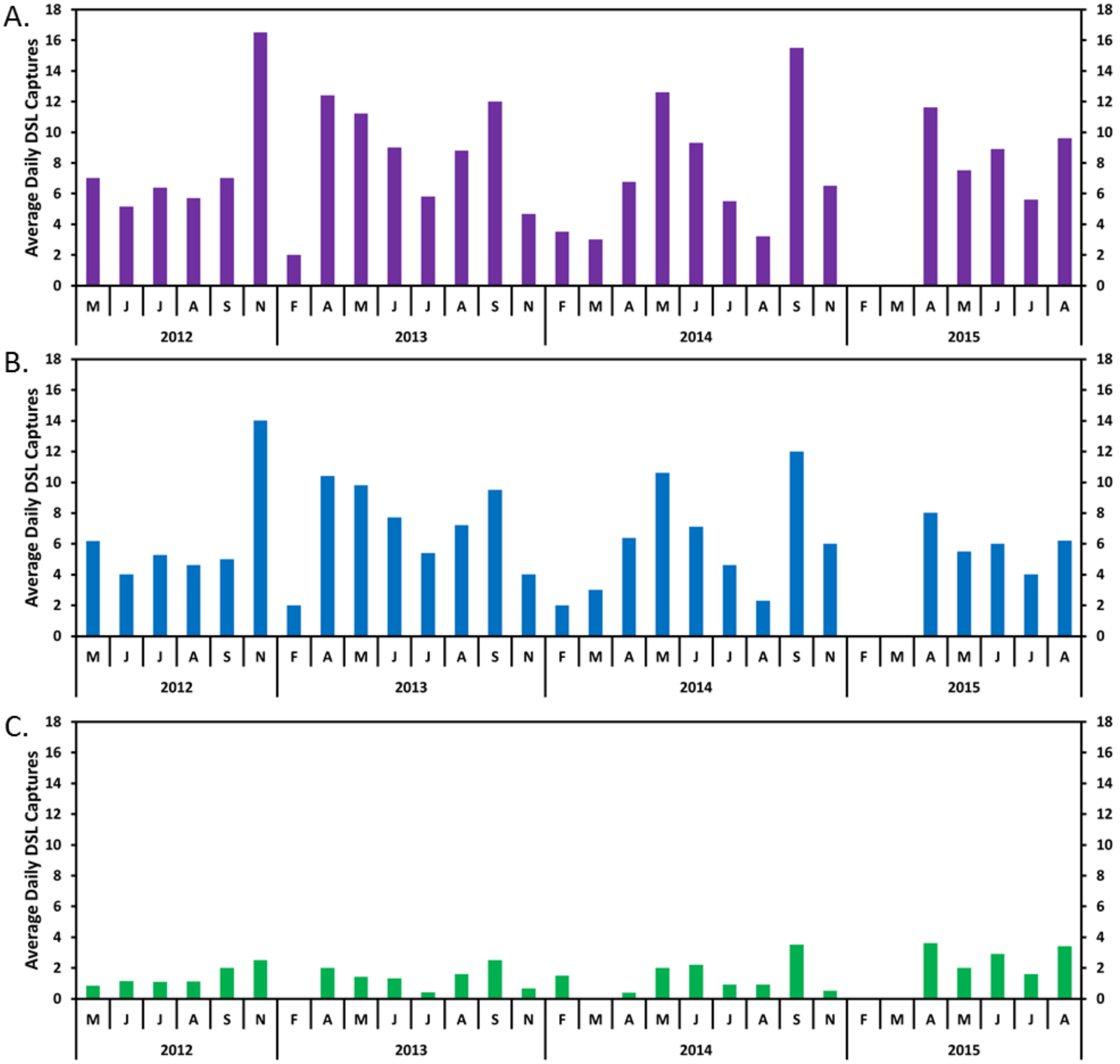


Figure 3.5. DSL average daily capture by month from May 2012 to August 2015 (excluding months when no trapping occurred: October and December 2012; January, March, October and December 2013; January, October and December 2014; January 2015). Panel A. All DSL captures in both the disturbed and undisturbed super-grids combined. Panel B. Capture rates for the DSL in the undisturbed super-grid. Panel C. Capture rates for the DSL in the disturbed super-grid.

To visualize this seasonal change in demographic structure within the DSL population, the capture data were partitioned into adult male (blue bars), adult female (purple bars) and hatchling/juvenile (orange bars) categories (Fig. 3.6). Across all years, captures early in the season generally consisted mostly of adults and a few juveniles from the previous breeding season that are still relatively small. By June, most of the juveniles have reached adult size. Hatchling DSLs began emerging in July and continued to emerge and grow into juveniles in August and September. As a result, during these months DSL captures were comprised of mostly hatchling and juvenile life-stage lizards. In November, this trend decreased as the juveniles grew into adult life-stages. Overall, these seasonal trends in capture rate and DSL abundance align with the results of previous mark-recapture studies on the DSL (Walkup et al. 2014; Walkup et al. in review).

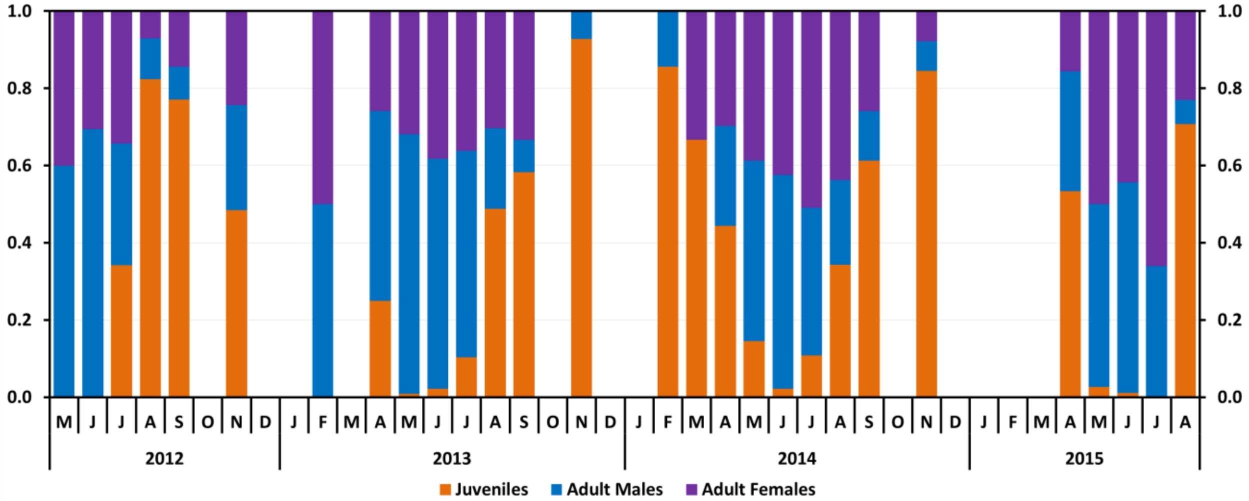


Figure 3.6. Proportion of captures for each life stage by month for all DSL captures from May 2012 to August 2015 (excluding months when no trapping occurred: October and December 2012; January, March, October and December 2013, January, October and December 2014; January 2015).

To further explore the differences in the DSL populations in the undisturbed and disturbed super-grids, we partitioned the captures by treatment to visualize the seasonal change in the demographic structure in each super-grid (Fig. 3.7). Again, the pattern observed in the undisturbed super-grid (Fig. 3.7A) was very similar to the overall pattern (Fig. 3.6). Although there were fewer captures, the proportions and seasonal trends were consistent, and likely drive the pattern we see in the overall structure. The pattern observed in the disturbed super-grid was similar to that in the undisturbed super-grid, and did not exhibit the demographic stochasticity or the breakdown in demographics observed in highly fragmented habitat in other studies (Walkup et al. in review). The largest difference in the disturbed super-grid occurred in May and June of 2013 and 2015 and March through June of 2014, when juveniles were not captured in the disturbed super-grid like in the undisturbed super-grid.

More DSL were captured around the larger blowouts in both the undisturbed and disturbed super-grids (Fig. 3.8). Captures in the undisturbed super-grid were concentrated in the northern half, where a chain of dunes runs east-west (Fig. 3.8A). When total captures were partitioned by adults (Fig. 3.8B) and juveniles (Fig. 3.8C), there was little difference between the capture locations of these different life stages. However, juveniles were found more often outside of higher quality habitat. For example, the majority of captures in the southeast corner of the undisturbed super-grid were juveniles. Juveniles and young adult male DSL were typically found at the edge of habitat where dunes transitioned to mesquite flats. Most of these individuals were captured only once, but one individual was recaptured as an adult in larger blowouts toward the middle of the undisturbed super-grid. Juveniles were also found more often outside of large blowout chains.

There were fewer DSL captures in the disturbed super-grid, and these captures were distributed sparsely (Fig. 3.8D). Captures of the DSL in the disturbed super-grid also occurred in relatively large blowouts, although there were fewer individuals captured in each blowout. Most adults were captured on the southern half of the disturbed super-grid (Fig. 3.8E), while juvenile captures were relatively more evenly dispersed throughout (Fig. 3.8F).

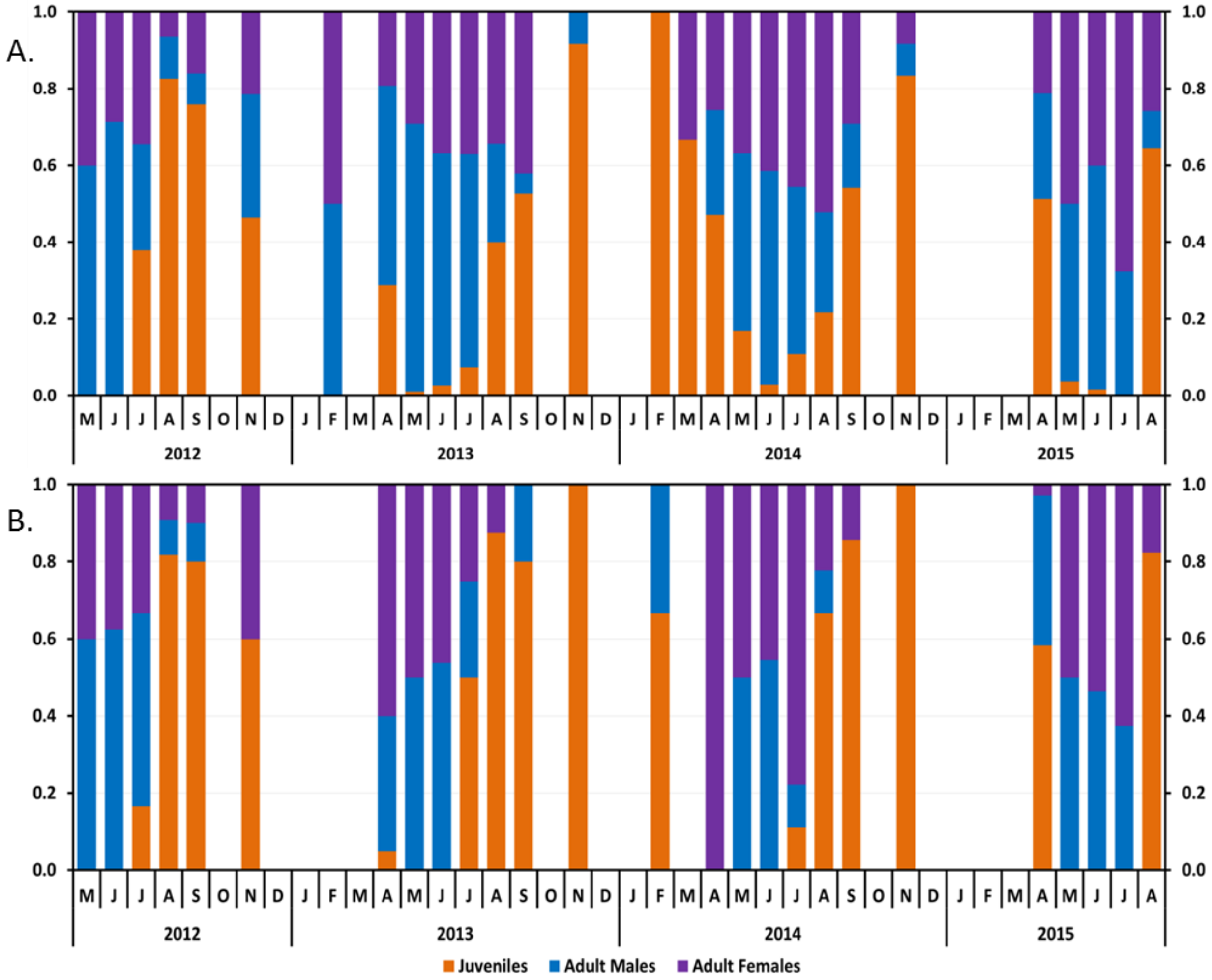


Figure 3.7. Proportion of captures for each life stage by month from May 2012 to August 2015 (excluding months when no trapping occurred: October and December 2012; January, March, October and December 2013, January, October and December 2014; January 2015). Panel A. Proportions of captures for each life stage by month for the DSL in the undisturbed super-grid. Panel B. Proportions of captures for each life stage by month for the DSL in the disturbed super-grid.

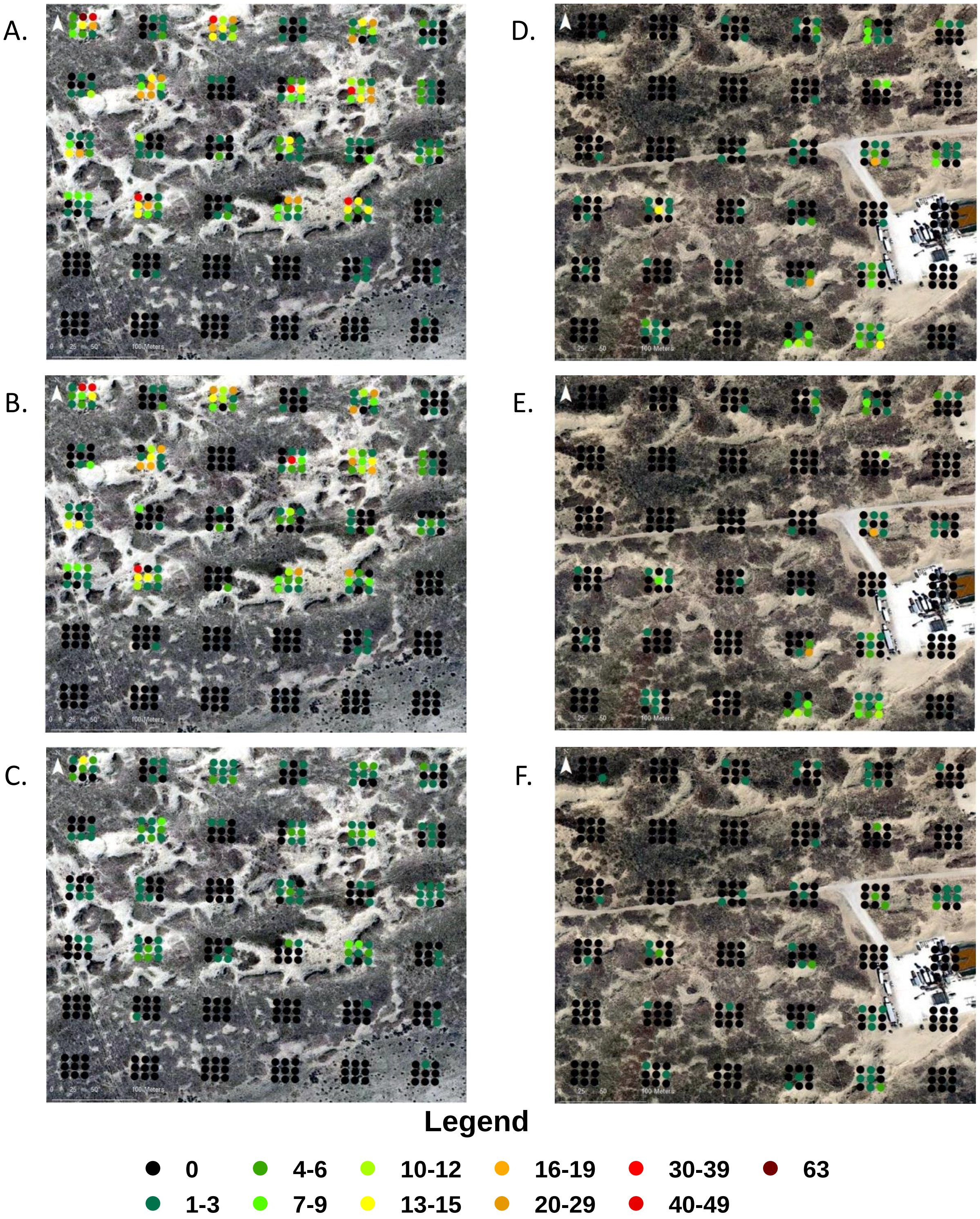


Figure 3.8. Frequency of DSL captures overlaid on trapping locations at each super-grid. Panel A. All captures from undisturbed super-grid. Panel B. Undisturbed super-grid adult captures. Panel C. Undisturbed super-grid juvenile captures, Panel D. All disturbed super-grid captures. Panel E. Disturbed super-grid adult captures. Panel F. Disturbed super-grid juvenile captures. Colored circles represent total numbers of captures at each trap.

3.3.2 *Population Dynamics*

Overall we had 1,539 DSL captures of 726 individuals, including 309 captures of 177 individuals in the disturbed super-grid and 1,230 captures of 549 individuals in the undisturbed super-grid. Thus we were able to use capture histories from 726 individuals to estimate population parameters.

The combined results of the goodness-of-fit Test 2 + Test 3 indicated the Pradel models fit the data well, although the data were a little underdispersed, so no adjustments were made using $\hat{c}$ (χ^2_{203} = 179.9, P = 0.88; $\hat{c}$ = 0.89). Of the 120 models tested, the "best" (most parsimonious) model, determined by $\mathrm{AIC_c}$ weight, assumed a time-varying apparent survival rate, an interaction effect of treatment and time on detection probability, and an interaction effect of treatment and time on recruitment (Table 3.1).

Estimates of apparent survival from the best model varied across months from 0.70 to 1.0 (95% CI – 0.64-0.76 and 1-1, respectively; Fig. 3.9A). While other models that had very low $\mathrm{AIC_c}$ weights showed a treatment effect (Table 3.1), the 95% confidence intervals (CI) had high overlap, indicating no real difference in apparent survival (Φ) across the treatments. For the best model, estimates of detection probability (p) ranged from 0.06 to 0.36 in the undisturbed super-grids (95% CI – 0.04-0.08 and 0.31-0.41, respectively) and from 0.02 to 0.28 (95% CI – 0.01-0.04 and 0.21-0.37, respectively) in the disturbed super-grid (Fig. 3.9B).

Recruitment for the best model varied across months, but was higher in the disturbed super-grid in July and August and higher in the undisturbed super-grid during the other months, both earlier and later in the year (September, November, February, April-June). Estimates of recruitment varied from 0 to 0.40 (95% CI – 0-0 and 0.25-0.56, respectively) in the undisturbed super-grid and from 0 to 1.13 in the disturbed super-grid (95% CI – 0-0 and 0.58-1.68, respectively; Fig. 3.9C).

The realized rate of population growth (λ) can be derived from apparent survival and recruitment. Derived estimates of population growth ranged from 0.80 to 1.40 (95% CI – 0.72-0.88 and 1.24-1.57) in the undisturbed super-grid and from 0.75 to 2.13 (95% CI – 0.62-0.91 and 1.65-2.74) in the disturbed super-grid (Fig. 3.9D). These population growth rate estimates were combined to a single yearly estimate of population growth of 1.03 in the undisturbed super-grid and 1.01 in the disturbed super-grid, essentially indistinguishable from 1.00. Although there was seasonal variation, the populations were stable and neither increasing nor decreasing over the duration of the study.

Table 3.1. Top 12 Pradel models with AIC$_c$ weights greater than zero. Model shows parameterization for apparent survival (ϕ), detection probability (p), and recruitment (_f_), with constant (.), treatment (g), or time (m) effects. Models sorted according to model likelihood, estimated from the AIC$_c$ weights.

Model	AICc	Delta AICc	AICc Weights	Model Likelihood	Number Parameters	Deviance	-2log(L)
Φ(m) p(g*m) _f_(g*m)	8814.68	0	0.9195	1	30	2082.603	8753.226
Φ(g*m) p(g+m) _f_(m)	8821.09	6.40	0.03731	0.0406	25	2099.455	8770.078
Φ(m) p(g+m) _f_(m)	8821.31	6.62	0.03345	0.0364	19	2112.098	8782.721
Φ(m) p(g*m) _f_(g*m)	8824.98	10.30	0.00533	0.0058	20	2113.71	8784.333
Φ(g*m) p(g*m) _f_(g*m)	8827.42	12.73	0.00158	0.0017	36	2082.701	8753.324
Φ(m) p(g*m) _f_(m)	8827.76	13.08	0.00133	0.0014	24	2108.208	8778.831
Φ(g*m) p(g+m) _f_(g+m)	8828.87	14.19	0.00076	0.0008	26	2105.155	8775.778
Φ(g+m) p(g+m) _f_(g+m)	8829.18	14.49	0.00065	0.0007	21	2115.839	8786.462
Φ(g*m) p(g*m) _f_(g+m)	8835.13	20.45	0.00003	0	31	2100.958	8771.581
Φ(g+m) p(m) _f_(g*m)	8836.45	21.77	0.00002	0	25	2114.821	8785.444
Φ(.) p(g*m) _f_(g*m)	8836.76	22.08	0.00001	0	25	2115.13	8785.752
Φ(g) p(g*m) _f_(g*m)	8837.69	23.00	0.00001	0	26	2113.971	8784.594

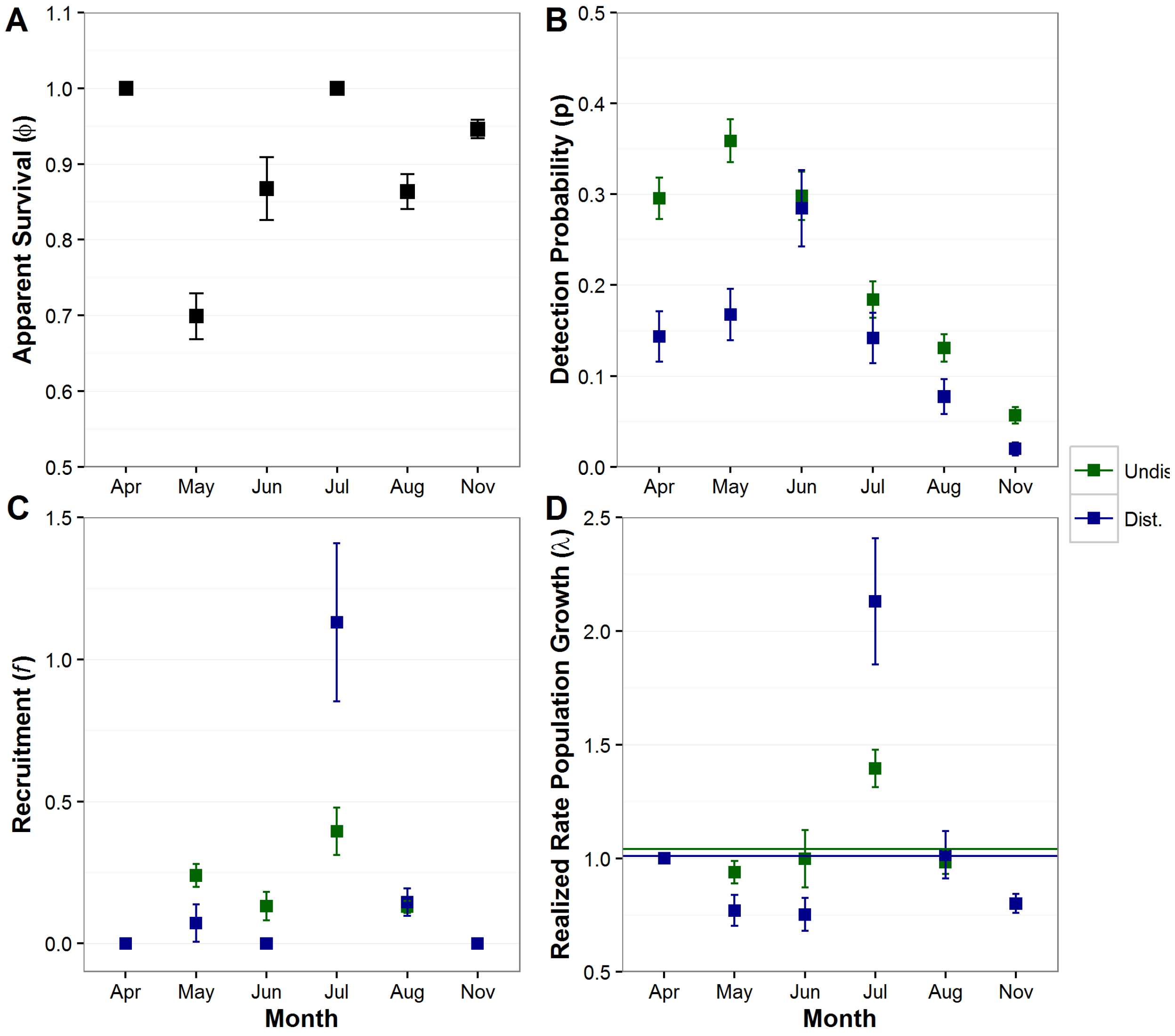


Figure 3.9. Parameter estimates from the top Pradel model. Panel A. Apparent survival estimates ± SE for both super-grids (no treatment affect). Panel B. Detection probability estimates ± SE for the undisturbed super-grid (green) and disturbed super-grid (blue). Panel C. Recruitment estimates ± SE for the undisturbed super-grid (green) and disturbed super-grid (blue). Panel D. Realized rate of population growth estimates ± SE for the undisturbed super-grid (green) and disturbed super-grid (blue); λ = 1 indicates a stable population; λ<1, a decreasing population, λ>1, an increasing population. Horizontal lines identify time-independent population growth rates for both super-grids labeled as above.

3.3.3 *Analysis of Movements*

Overall we had 1,539 DSL captures of 726 individuals: 309 captures of 177 individuals in the disturbed super-grid and 1,230 captures of 549 individuals in the undisturbed super-grid. Of the 177 individuals in the disturbed super-grid, 64 were captured more than once, for a total of 132 recorded movements for analysis. Of the 549 individuals in the undisturbed super-grid, 241 were captured more than once, for a total of 680 recorded movements for analysis. The number of recaptures ranged from 1 to 9 in the disturbed super-grid and 1 to 20 in the undisturbed super-grid.

All four movement parameters had a significant sex effect (Mean Step Length - $F_{1,790} = 52.05$, $P < 0.001$; Mean Total Step Length - $F_{1,289} = 25.25$, $P < 0.001$; Net Displacement - $F_{1,1075} = 6.31$, $P = 0.012$; Spatial Extent - $F_{1,293} = 5.75$, $P = 0.017$). Males were moving longer distances and covering larger areas, overall, than were females in both disturbed and undisturbed super-grids (Table 3.2, Fig. 3.10).

Only one parameter, spatial extent, showed a treatment effect where spatial extent of movements was larger in the undisturbed super-grid than in the disturbed super-grid ($F_{1,293} = 5.15$, $P = 0.024$; Table 3.2; Fig. 3.10C). All of the other movement parameters had non-significant treatment effects (Mean Step Length - $F_{1,790} = 0.39$, $P = 0.39$; Mean Total Step Length - $F_{1,289} = 0.83$ $P = 0.36$; Net Displacement - $F_{1,1075} = 1.54$, $P = 0.23$).

Finally, there was no interaction effect of sex and treatment for any of the movement parameters (Mean Step Length - $F_{1,790} = 0.21$, $P = 0.65$; Mean Total Step Length - $F_{1,289} = 3.67$, $P = 0.06$; Net Displacement - $F_{1,1075} = 1.34$, $P = 0.25$; Spatial Extent - $F_{1,293} = 1.87$, $P = 0.17$), indicating that there was the same effect of disturbance on male and female movement parameters.

Diffusion rate was much higher in the undisturbed super-grid (111.1 m^2/day) than in the disturbed super-grid (25.5 m^2/day). This suggests that the DSL population in undisturbed habitat was diffusing or spreading more than 4 times faster than the DSL population in disturbed habitat. Because diffusion rate was calculated using the sum of the squared step lengths, more long-distance movements in the undisturbed super-grid resulted in a higher diffusion rate than observed in the disturbed super-grid over similar times steps.

A caliche road bisecting the disturbed super-grid appeared to be a barrier to movements of the DSL. While the DSL was captured in traps immediately adjacent to the road, only three individuals were captured on both sides of the road. One adult male was captured north of the road and recaptured 3 weeks later south of the road. Two juvenile males, both captured initially south of the road were recaptured as adults 19 months and 7 months later, respectively, on the north side of the road. These three movements are the three longest movements (237.3, 280.3, and 264.6 m, respectively) recorded on the disturbed super-grid, and they accounted for 2.2% of the total number of movements recorded on the disturbed super-grid ($n = 132$).

Table 3.2. Summary statistics for the 2-way ANOVAs, showing the mean ± SE, range, and number for each main effect (sex and treatment) for each of the four movement parameters. Abbreviations are as follows: SL – step length, tSL – total step length, ND – net displacement, and SE – spatial extent.

	Main Effect	SL (m)	tSL (m)	ND (m)	SE (m^2)
Mean ± SE	Female	11.9 ± 1.5	35.3 ± 5.3	18.9 ± 2.2	70.9 ± 27.1
	Male	30.1 ± 2.9	75.2 ± 7.7	25.2 ± 2.3	232.7 ± 65.8
	Undisturbed	20.4 ± 1.8	58.9 ± 5.8	22.7 ± 1.8	185.1 ± 47.1
	Disturbed	23.6 ± 4.3	48.7 ± 8.7	19.3 ± 3.5	57.2 ± 29.8
Median	Female	7.6	12.5	0.0	68.6
	Male	10.4	29.9	8.5	127.4
	Undisturbed	9.3	23.8	7.3	112.8
	Disturbed	9.4	19.3	0.0	41.1
Range	Female	0 - 341.4	0 - 372.0	0 - 341.4	0 - 2865.0
	Male	0 - 343.5	0 - 461.3	0 - 343.5	0 - 7332.8
	Undisturbed	0 - 343.5	0 - 461.3	0 - 343.5	0 - 7332.8
	Disturbed	0 - 280.3	0 - 280.3	0 - 285.4	0 - 1402.1
N	Female	402	136	532	132
	Male	392	157	547	159
	Undisturbed	664	230	886	233
	Disturbed	130	63	193	64

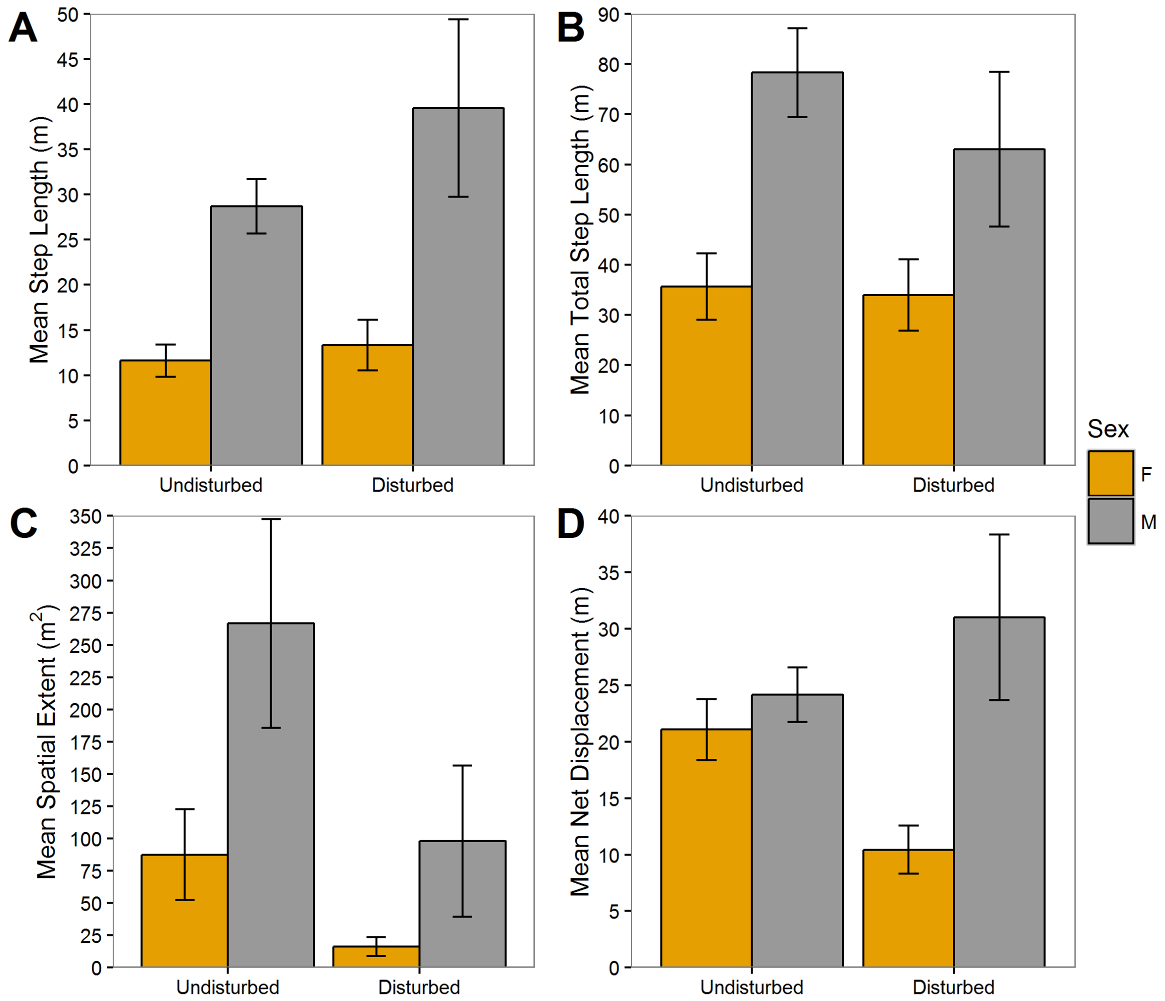


Figure 3.10. **Mean values and standard error for each estimated movement parameter by sex and treatment (undisturbed and disturbed super-grids). Panel A. Mean Step Length showed a significant difference between sexes, but no difference across treatment. Panel B. Mean Total Step Length showed a significant difference between sexes, but no difference across treatment. Panel C. Mean Spatial Extent showed a significant difference between sexes and between treatment. Panel D. Mean Net Displacement showed a significant difference across sexes, but no difference across treatment.**

3.4 Discussion

3.4.1 *Population Dynamics Summary*

The abundance of the DSL was greater in the undisturbed super-grid compared to the disturbed super-grid. This could be an effect of differences in the population parameters of each population. The parameters that could be influencing this include survival and recruitment, which make up the realized rate of population growth that describes how fast a population is growing (or declining) in a given time period. Using mark-recapture methods allowed us to correct survival and recruitment estimates based on the probability of detecting the DSL in the undisturbed and disturbed super-grids. Although it varied throughout the year, overall detection probability was higher in the undisturbed super-grid (Figure 3.9B), as expected given the higher abundance of the DSL in that super-grid.

There was no detectable difference in apparent survival between disturbed and undisturbed super-grids at the scale of and over the duration of the study. However, our best model indicated that recruitment varied over time and the pattern of recruitment varied between disturbed and undisturbed super-grids (as illustrated in Figure 3.9C). Specifically, recruitment in the disturbed super-grid was very low throughout the season but exhibited a large peak in July. Alternatively, recruitment in the undisturbed super-grid was elevated and steady throughout the season with a much smaller peak in July when compared to the disturbed super-grid.

While there was variation within the year for survival and recruitment, and between the disturbed and undisturbed super-grids for recruitment, the annual realized rate of population growth for both of these populations was indistinguishable from one (Fig. 3.9D), indicating that although the population was smaller on the disturbed super-grid, both populations were stable over the course of this study.

3.4.2 *Analysis of Movements Summary*

Analyses of movements showed males moved greater distances and covered more area over time on both undisturbed and disturbed super-grids. This result is also consistent with the results from the home range and movement study (CHAPTER 2).

No differences were detected in straight-line distance movement parameters in undisturbed and disturbed super-grids. The mean and median (used to describe movements made by the "average" DSL) were similar in both undisturbed and disturbed super-grids for step length (distance between consecutive captures), total step length (sum of all step lengths) and net displacement (distance between first capture and all following captures; Table 3.2).

While the "average" individual is moving the same in each habitat, there were fewer individuals making long-distance movements in the disturbed super-grid as compared to the undisturbed super-grid. In the tail of the distribution of step lengths, long-distance movements were defined as statistical outliers (> 2.0 SD of mean step lengths). These outliers represent movements greater than 113 meters (approximately one-third the width of the super-grid). There were 30 long-distance movements observed on the undisturbed super-grid and only 8 on the disturbed super-grid. Additionally, the maximum step length in the undisturbed super-grid was 343 meters (almost the width of the super-grid) compared to 280 meters (about three-quarters the width of the super-grid) in the disturbed super-grid. Thus many more individuals made relatively longer movements on the undisturbed super-grid, which helps to maintain population connectivity at the landscape level.

The spatial extent of lifetime DSL movements was different; lifetime DSL movements covered a larger area in the undisturbed super-grid compared to the disturbed super-grid, suggesting that lifetime DSL movements were restricted at the landscape scale in disturbed habitat. Given that the DSL perceives roads as a barrier to movements (CHAPTER 2, CHAPTER 4), this restricted spatial extent is most likely due to the presence of the caliche road bisecting the disturbed super-grid as well as the well pads located in and adjacent to the disturbed super-grid.

Diffusion rate was much higher in the undisturbed super-grid (111.1 m^2/day) than in the disturbed super-grid (25.5 m^2/day). This suggests that the DSL population in undisturbed habitat was diffusing or spreading more than 4 times faster than the DSL population in disturbed habitat. The diffusion rate can be scaled up to be on the same time scale as previous estimates (Ryberg et al. 2013). Assuming that individuals are actively moving about the landscape the entire year, the diffusion rate for the DSL population in undisturbed habitat is approximately 40,552 m^2/year compared to 9,306 m^2/year for the population in disturbed habitat. If that assumption is relaxed to a more realistic approximation of activity over half the year (Figs. 3.4-3.7), the diffusion rate for the DSL population in undisturbed habitat is approximately 20,276 m^2/year compared to 4,653 m^2/year for the population in disturbed habitat. These diffusion rates for populations in undisturbed and disturbed habitats are consistent with those observed previously for sources and sinks, respectively (Ryberg et al. 2013).

3.5 Conclusion

The abundance of the DSL was greater in the undisturbed super-grid (n = 549) compared to the disturbed super-grid (n = 177). Although DSL abundance was greater on the undisturbed super-grid, both populations were stable (neither increasing nor decreasing) during this four-year study. The diffusion rate, however, was more than 4 times higher in the undisturbed super-grid. This difference in diffusion rate was driven by more individuals making relatively longer distance movements that covered a larger spatial extent in the undisturbed super-grid compared to the disturbed super-grid. In addition, very few individual DSLs were observed crossing the road in the disturbed super-grid despite the fact that many individuals were captured immediately adjacent to the road. The low frequency of road crossings observed in the disturbed super-grid was consistent with the road acting as a barrier to DSL movements, which helps account for the observed differences in diffusion rates between disturbed and undisturbed super-grids. From these results, we conclude that while roads contribute less to overall habitat loss than well pads, they appear to be the main driver of habitat fragmentation and DSL population subdivision, because they limit diffusion and therefore reduce population connectivity.

CHAPTER 4 – EFFECTS OF ROADS ON DUNES SAGEBRUSH LIZARD MOVEMENTS

4.1 Background

Roads are ubiquitous in most landscapes around the world (Forman et al. 2003, Andrews et al. 2008, van der Ree et al. 2015). Ecological research has shown many negative effects of roads and traffic on native biodiversity, including the loss, fragmentation, and degradation of habitat (Taylor et al. 1993, Forman and Alexander 1998), subdivision of populations into smaller and more vulnerable fractions (Hanski 1999, Forman 2000, Lesbarreres and Fahrig 2012), increased rates of mortality from vehicular collisions (Fahrig et al. 1995, Hels and Buchwald 2001, Gibbs and Shriver 2002), alterations to light, moisture, and wind regimes (Delgado et al. 2007, Driscoll et al. 2013), and facilitation of the spread of invasive species (Crooks and Soulé 1999, Hulme 2009). The mechanisms through which roads and traffic harm different plant and animal populations often vary across taxa (Rytwinski and Fahrig 2012, van der Ree et al. 2015), which means reversing negative road effects will require mitigation efforts that are effective for many taxonomic groups (Fahrig and Rytwinski. 2009). However, in some cases, species-specific management techniques may need to be developed to mitigate the negative effects of roads (Peterson et al. 2003, Woltz et al. 2008, Lesbarreres and Fahrig 2012).

For terrestrial wildlife in particular, roads and traffic can create barriers to movement that result in population subdivision through demographic mechanisms (Noss et al. 1996, Clark et al. 2001). For example, traffic mortality can contribute to this population subdivision by reducing the flow of individuals between subpopulations (Swihart and Slade 1984, Gerlach and Musolf 2000). Habitat degradation can also contribute to population subdivision by reducing the quality of resources along roads and limiting reproduction and survival so that linear sink habitats reduce movements among subpopulations (Reijnen and Foppen 1994, Ortega and Capen 1999). At the individual level, animals can also exhibit a variety of road avoidance behaviors that ultimately constrain their movement patterns and lead to population subdivision (Jaeger et al. 2005). For example, animals with noise-avoidance behaviors (e.g., some birds; Reijnen et al. 1995, 1996, 1997) may stay away from areas where road-noise is audible, spatially extending the road effect zone. Typically the magnitude of this road effect depends on traffic volume rather than road size (Jaeger et al. 2005). Traffic emissions such as light and pollutants can create analogous situations, where the effect of the road is larger than the surface right-of-way (Forman 2000). Car-avoidance behaviors can also limit animal movements in proportion to traffic volume, but the extent of the road effect is limited to the road itself (Jaeger et al. 2005). A third type of road-avoidance behavior of particular importance to animals that exhibit strong habitat preferences or specializations is avoidance of the actual road itself, where individuals avoid the surface and edge of roads because of perceived inhospitable conditions (e.g., no shelter, different microclimate, lack of vegetation; Merriam et al. 1989; McGregor 2004). Road effects on the movements of species exhibiting these surface avoiding behaviors are continuous, even when traffic is not present (Jaeger et al. 2005).

By reducing or preventing movements, roads decrease landscape connectivity for animal populations (Taylor et al. 1993). Efforts to mitigate these road effects typically involve the construction of wildlife crossing structures, also called ecopassages, to increase landscape connectivity (van der Ree et al. 2007). Although many crossing structures have been installed, research evaluating their effectiveness at increasing landscape connectivity has accumulated slowly (Gilbert-Norton et al. 2010). Moreover, a review of the studies that currently exist has concluded that they contain little useful information for evaluating the efficacy of crossings for mitigating the effects of roads on connectivity (van der Ree et al. 2007). The reasons for these research failures are complex, but in most cases the failure occurs because road ecologists are not involved in the pre-construction, crossing study design. As a result, these studies often suffer from a lack of scientific rigor related to poor experimental design, low sample size, and absence of data before and after crossing construction. Alternatively, research shows the most successful crossing studies and mitigation projects are those aimed at minimizing the barrier effects of roads for individual species rather than more generic designs targeting effects on all wildlife (Lesbarreres and Fahrig 2012). Collectively, these studies indicate that taxon-specific needs should be better incorporated into road crossing research, design, and implementation.

Here, we investigate the behavioral mechanisms driving the observed negative effect of roads on Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*) movements (CHAPTER 2) and evaluate the effectiveness of proposed crossing structures designed to mitigate negative road effects. The DSL is a psammophilic, habitat specialist endemic to the Mescalero-Monahans Sandhills ecosystem of southeastern New Mexico and adjacent west Texas (Degenhardt et al. 1996). Within this ecosystem, the DSL resides only in Shinnery Oak (*Quercus havardii*) sand-dune landforms, which consist of parabolic dunes and depressions called blowouts that are created from an interaction between wind, sand, and the dune-stabilizing Shinnery Oaks (Fitzgerald and Painter 2009, Laurencio and Fitzgerald 2010, Ryberg et al. 2015). Within this landform, this species prefers large blowouts with steep slopes (Fitzgerald and Painter 2009, Ryberg et al. 2012, Hibbitts et al. 2013, Ryberg and Fitzgerald 2015). Across these landforms, the spatial configuration of blowouts constrains or facilitates DSL movement, leading to local aggregations of lizards or neighborhoods of different sizes (Ryberg et al. 2013). Larger neighborhoods exhibit higher recruitment and population diffusion rates acting as sources for smaller neighborhood sinks with negligible recruitment. Thus, population persistence in this species depends on diffusion dispersal throughout interconnected habitat patches (Ryberg et al. 2013). Dispersal among isolated habitat patches is effectively zero (Chan et al. 2009, Leavitt 2012).

Caliche roads fragment Shinnery Oak sand-dune landforms (Fitzgerald and Painter 2009, Smolensky and Fitzgerald 2010, Ryberg et al. 2015) and have been shown to restrict DSL movements (CHAPTER 2, CHAPTER 3), creating isolated populations that experience increased demographic stochasticity (Walkup et al. in review) and potentially localized extirpation (Leavitt and Fitzgerald 2013). Direct mortality from vehicular traffic has been documented only once for the DSL (pers. comm. A. L. Fitzgerald), and individuals frequently occupy suitable habitat directly adjacent to caliche roads (CHAPTER 2, CHAPTER 3). These observations suggest that restricted DSL movements are most likely driven by road surface avoidance, car avoidance, or noise avoidance behaviors. In this paper, we report results from an experiment designed to test the hypothesis that the caliche road surface is avoided by DSL thus restricting their movements. We also evaluated a proposed mitigation technique designed to minimize the effects of roads on movements of DSL by creating sandy crossing structures across caliche roads. This research is the first to explicitly test the effect of roads on behavior of this endemic species of conservation concern, and is an important first step leading to future research on the effects of roads in the

Mescalero-Monahans Sandhills ecosystem. Our findings can be applied to the development of conservation plans for the DSL, and to the effects of roads on squamate reptiles in general.

4.2 Methods

4.2.1 *Study Site*

Our study area was in the Mescalero-Monahans Sandhills ecosystem of southwest Andrews County, Texas, USA. Shinnery Oak sand-dune landforms throughout this ecosystem are dissected by roads of various sizes, ranging from unpaved jeep tracks to caliche roads to county state and federal highways. For this study, we selected a site situated within a large Shinnery Oak sand-dune landform known to be occupied by the DSL that was also partially bisected by a small caliche road. This particular road represents the smallest type of caliche road found within the ecosystem, a relatively narrow (5 m) flat track of caliche leading to an abandoned oil well pad that was being used far less than once per day. Because the effect of roads on wildlife and habitat should increase with the size of the road, this choice of a small caliche road allowed us to develop a null hypothesis, that the road would not affect DSL movements, which was difficult to reject. If the null hypothesis is rejected in this case of conducting trials with the smallest type of caliche road, then it stands to reason that much larger and more developed roads ranging up to asphalt-paved highways with roadside ditches should pose an even greater barrier to lizard movements.

4.2.2 *Study Design*

At the study site, we constructed two circular enclosures 15 m in diameter that were separated by 250 m (Fig. 4.1). We used circular enclosures for two important reasons. Circular enclosures in these behavioral trials avoid bias created by corners in a rectangular structure. Pilot studies indicated lizards tended to move toward the closest wall in a square enclosure. Circular enclosures also ensured the entire enclosure wall was equidistant from the central starting point. We used opaque plastic to form the 0.5 m high walls of the enclosure. Enclosure walls were also buried in sand to prevent lizards from escaping underneath the plastic. Vegetation was cleared from the enclosures, and we placed a small clump of live Shinnery Oak at each of the cardinal directions one meter away from the wall of the enclosure. At the center, we placed a 50 x 50 cm plywood board, which was covered with a thin layer of sand. This was the lizard release point for our trials.

The control enclosure was located in undisturbed occupied habitat where sand was the only substrate. The experimental enclosure also contained sand but was divided by the 5-meter wide caliche road running alongside the release point (Fig. 4.1A). To construct the enclosure for the second experiment, to test the hypothesis that the DSL would use a constructed sand crossing, we dug a one-meter wide trench across the caliche road, directly in front of the lizard release point, and filled it with sand from the occupied habitat (Fig. 4.1B).

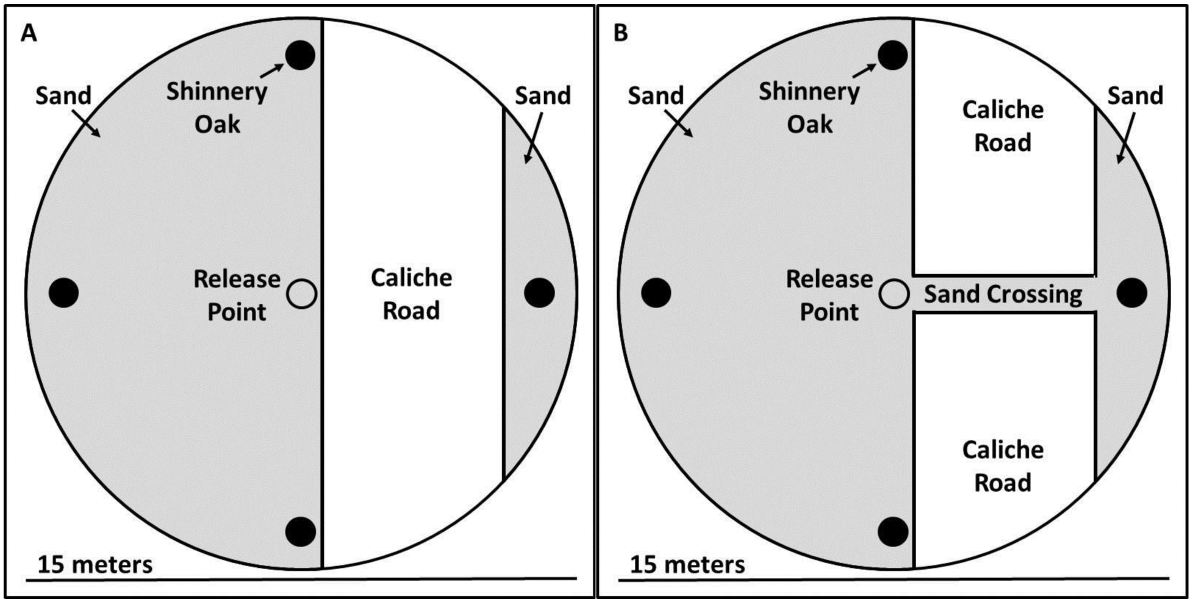


Figure 4.1. Diagram of road enclosure (A) and road enclosure with constructed sand crossing (B). The control enclosure (not pictured) was identically constructed but lacked the caliche road.

4.2.3 *Behavior Trials*

All trials were conducted on clear days in full sun from 6 to 10 August 2014. To minimize effects of time and weather, we conducted all trials during the peak activity period of the lizards (0830-1200 hrs) at air temperatures between 25 and 35ºC. Lizard subjects were captured from the surrounding habitat by pitfall trapping, noosing, and hand capture. Subjects were temporarily marked with permanent ink pens for individual identification and held in 20 L buckets with 15 cm of sand before trials were conducted. After the end of the each trial the lizard was removed from the enclosure and was later released at their point of capture.

Trials began by placing the subject on the center board under an opaque plastic container. One observer sat outside the enclosure 15 m from the release point, and used a string-and-pulley system to lift the container and start the trial. In cases where the lizard was startled by the lifting of the container, the trial was started again after 5 minutes. The observer, with the aid of binoculars, recorded the distance, direction, and time of each movement made by the lizard for 15 minutes. Trials were completed after 15 minutes or if the subject reached the enclosure wall and remained there. At the end of each trial, we recorded the subject's location in the enclosure. The same 22 subjects were used in all treatments, with two additional lizards used in the control enclosure. We conducted 22 trials in the road and experimental crossing enclosures, and 24 trials in the control enclosure.

4.2.4 *Statistical Analyses*

We used a circular statistical approach to test for uniformity of movements in each enclosure. Failing to reject the null hypothesis in the test of uniformity indicates that DSL movements were uniformly distributed or equally likely around the circular enclosure. Alternatively, rejection of the null hypothesis indicates that the distribution of DSL movements was significantly different from uniform.

For each treatment (control, road, crossing), we ran three tests of uniformity by grouping or binning the movement data in three different ways corresponding to halves, thirds, and quarters of the enclosures. By using multiple grouping arrangements, we can be certain that our results are not affected by the number and position of bins chosen for analysis. For each grouping arrangement, we totaled the number of times each trial ended in each bin of the enclosure for each treatment. We then compared that observed distribution of DSL movements to the expected uniform distribution of movements for each grouping arrangement using a chi-squared test (χ^2).

4.3 Results

A total of 24 adult DSL (13 females, 11 males) were used in these trials. Mean snout-vent-length was 57.91 mm (SD = 4.01 mm), mean tail length was 72.36 mm (SD = 21.11 mm), and mean mass was 5.44 g (SD = 1.30 g).

Use of space and movements within the control enclosure could not be differentiated from random, whether the enclosure was divided into halves, thirds, or quarters (Table 1). In both the road treatment and the crossing treatment, the null hypothesis in the test of uniformity was rejected under all three data grouping arrangements. Rejection of the null hypothesis indicates that the distribution of DSL movements was significantly different from uniform in the road and crossing treatments. In 44 trials, (22 in the road treatment and 22 in the sand crossing treatment) we observed a total of 8 road crossings. In the road treatment, 3 of 22 subjects either ran onto the road or crossed the road. In the sand crossing treatment, with the 1-meter sand-filled trench, zero of 22 lizards used the trench, and 5 subjects ran onto the road or crossed it. In all but these 8 trials, the lizards avoided the road and the sandy area across the road from the starting point. The sand-filled trench had no detectable effect on DSL use of space or movements.

Table 4.1. Statistical results of χ^2 test for each treatment and data grouping.

Treatment	**df**	**N**	χ^2	***p***
Control halves	1	24	0.17	0.700
Control thirds	2	24	3.25	0.200
Control quarters	3	24	7.00	0.100
Road halves	1	22	8.91	0.010
Road thirds	2	22	23.38	0.001
Road quarters	3	22	38.73	0.001
Sand crossing halves	1	22	14.73	0.001
Sand crossing thirds	2	22	32.97	0.001
Sand crossing quarters	3	22	38.00	0.001

4.4 Discussion

This experiment demonstrated that a small caliche road through DSL habitat affected movements of the DSL. In the control enclosure, DSL movements were uniformly distributed or equally likely around the circular enclosure, whereas in the road enclosure, the distribution of DSL movements was significantly different from uniform. In 82% of trials, the DSL completely avoided the road and sand-filled crossing. This road-effect on DSL movements was not influenced by vehicle traffic and noise because we excluded these factors during the experiment. It is important to also note that the road selected for this study was nearly abandoned, having been used far less than once per day for some time. With these other road avoidance mechanisms excluded, we conclude that deviation from uniformity in DSL movements is driven by avoidance of hard road surfaces such as caliche.

Evidence of surface avoidance limiting DSL movement leads to several other meaningful implications for the conservation of the DSL. First, the effects of roads on DSL populations must be considered long-term and persistent. This means that even if roads were simply closed and abandoned, the effects on populations will persist as long as caliche is present. Second, since we controlled for noise and traffic related effects of roads in this experiment, it is unclear how the DSL might respond to these factors. Noise and traffic may also have a negative effect on DSL movements, which may make roads even greater barriers to movement than already observed.

Third, we expect that larger caliche and paved roads, which make up the extensive checker-board network of roads in the Mescalero-Monahans Sandhills ecosystem, represent a much stronger effect on movements of the DSL. Because we rejected the null hypotheses that this small caliche road would not affect lizard movements, we are confident in the prediction that wider and more developed roads ranging up to asphalt-paved highways pose a greater barrier to movements in this species. Larger roads are usually elevated above-grade and have roadside ditches. The larger the road, the more pronounced the effect of ditches and the roadway, which represent a relatively broad swath of inhospitable habitat to the DSL. The trend of decreased crossing rate in association with increasing road-width has been shown in several other species that are not specialized on a particular habitat (Brehme et al. 2013).

We also observed that the sand crossing structure did not affect movement patterns or increase the rate of road crossings in the DSL. We designed this experiment to determine if a simple and inexpensive strategy such as constructing a sand-filled trench across a road could facilitate DSL road crossings (CHAPTER 2). The DSL has been observed using sandy pipelines, and observations exist of a few DSL individuals crossing a sand-covered section of a caliche road. The DSL subjects did not use the sand-crossing structure in our experiment. However, our observations in natural settings suggest that lizards can cross narrow (e.g. pipelines or sand roads), open areas with a sandy substrate when immediately adjacent to Shinnery Oak dunes. Additional experiments with road-crossing structures could provide meaningful insights into the plausibility of road-crossing structures designed to allow movements of DSL across roads in occupied habitat.

4.5 Conclusions

Evidence from our research (CHAPTER 2, CHAPTER 3) indicates that roads are the main source of fragmentation in DSL habitat. A growing body of research also demonstrates that fragmentation and habitat loss go hand-in-hand and cause decline in DSL populations (Leavitt and Fitzgerald 2013, Walkup et al. in review). Also, research consistently points to the quality and connectivity of large contiguous areas of suitable habitat as the main factor affecting DSL persistence. The best strategy to maintain the quality and connectivity of large contiguous areas of suitable habitat is avoidance of Shinnery Oak dunes when constructing new roads. When areas of occupied habitat are fragmented by existing roads, connectivity of habitat patches might be restored through road removal. Candidates for road removal can be selected in sites with road redundancy (multiple access roads to the same location) or roads that access areas that are no longer in use. Additional research into effective ecopassages for the DSL should continue in order to increase connectivity at sites where removal or avoidance is not possible.

CHAPTER 5 – DISTRIBUTION SURVEYS

5.1 Background

The scope and purpose of distribution surveys was guided by the results, conclusions and recommendations described in Fitzgerald et al. (2011). A major conclusion of this study was habitat quality influenced the likelihood of occurrence of the Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*) in habitats distributed across the landscape. Specifically, observations indicated the DSL was more likely to occur in suitable habitats where blowouts were open and free of encroaching grasses, Sand Sage (*Artemisia filifolia*) and Honey Mesquite (*Prosopis glandulosa*). These observations were consistent with studies of DSL habitat selection and range occupancy in New Mexico.

Another conclusion from Fitzgerald et al. (2011) was that DSL occupancy of suitable habitat can vary through time. Even though the DSL was known to occur in the Monahans Sandhills State Park since the 1960s, the species was undetected during surveys in 2006-09 and then detected again in 2010-15. Temporal variation in the abundance or occurrence of wildlife populations is frequently associated with fluctuating environmental conditions (e.g., drought), variable resources (e.g., food) and many other factors; but the exact causes of this temporal variation in abundance or occurrence is not known for the DSL. Guided by the conclusions described above, annual distribution surveys were designed to evaluate the status and trends of DSL occupancy and occurrence across different quality habitats through time.

The Fitzgerald et al. (2011) study, in addition to the landscape-scale DSL habitat delineation performed by Dr. Toby J. Hibbitts, also provided data for the TCP Permit Area/Likelihood of Occurrence Map in Texas (CHAPTER 1 - Fig. 1.1). This map directed research under the TCP by identifying areas that were best suited for specific research questions. Depending on the research topic, ranging from lizard behavior to population dynamics, sites were selected that vary in amount of habitat, connectedness of habitat and land-use. This map also identified areas where habitat conservation should be a priority and, therefore, served as the backbone for constructing and implementing conservation and management objectives included in the TCP. To validate the accuracy of this map and ensure that it was effective for this purpose, distribution surveys were conducted across each likelihood of DSL occurrence class and also outside the predicted area of occurrence. Results of distribution surveys were used to consider potential updates to the map and to monitor effectiveness of conservation and management activities outlined in the TCP.

5.2 Methods

Survey and monitoring efforts followed the methodology described in Fitzgerald et al. (1997, 2011). This methodology is designed to increase the probability of detecting the DSL if it is present and has been used in all recent surveys of the DSL in Texas and New Mexico. Under this methodology, the months of May through August are targeted for surveys, because they represent the months of peak lizard activity in the Mescalero-Monahans Sandhills ecosystem. During this period, lizards are establishing and defending territories, engaging in mate-seeking and nesting behaviors, and hatchlings are emerging.

During each survey, researchers walked slowly through habitat (16 hectares) searching for lizards. Observers did not walk a predetermined course; rather each observer carefully searched the area inspecting the habitat for all active lizards. When seen, lizards were identified to species and tabulated. Survey site locations and points where DSLs were observed were determined in the field with a hand-held Global Positioning System (GPS) unit (standard user precision only). Site locality data were recorded as decimal degrees using WGS84 as the GPS datum, but herein we report only site numbers to maintain compliance with landowner confidentiality agreements.

5.3 Results and Discussion

From June 2012 through August 2015, we conducted 272 DSL distribution surveys across 126 sites with crews made up of one to five observers (Table 5.1). Over these four years, more than 620 hours were spent surveying for the DSL between 8:32 AM and 2:45 PM. Most of these surveys occurred during the morning activity period of the lizards. Five surveys (1.8%) started after 12:00 PM due to unfavorable morning weather conditions.

Table 5.1. Surveys conducted for the DSL in Texas 2012-15. Survey times are in hours:minutes. Likelihood of occurrence classes are as follows: Dark Green (DG), Light Green (LG), Orange (O), Red (R), Outside (X).

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
1	1	1	12-Jun-12	Winkler	9:20	13:00	1	3:40	1	DG
2	2	1	13-Jun-12	Andrews	12:32	14:45	1	2:13	0	X
3	3	1	14-Jun-12	Andrews	10:40	12:30	1	1:50	0	X
4	4	1	15-Jun-12	Andrews	9:45	11:38	1	1:53	0	X
5	5	1	16-Jun-12	Andrews	9:40	11:40	1	2:00	0	X
6	6	1	19-Jun-12	Andrews	10:00	12:00	1	2:00	1	DG
7	6	2	22-Jun-13	Andrews	11:40	12:22	3	2:06	0	DG
8	7	1	21-Jun-12	Andrews-Gaines	9:20	10:15	2	1:50	1	DG
9	8	1	21-Jun-12	Andrews-Gaines	10:40	12:20	2	2:20	1	DG
10	9	1	23-Jun-12	Winkler	9:40	12:40	2	6:00	0	LG
11	9	2	21-Jun-13	Winkler	11:38	12:45	3	3:08	0	LG
12	10	1	24-Jun-12	Winkler	9:10	11:30	2	4:40	0	X
13	11	1	26-Jun-12	Crane	9:30	11:00	2	3:00	0	X
14	12	1	26-Jun-12	Crane	11:50	12:50	2	2:00	0	R
15	13	1	27-Jun-12	Winkler	10:15	12:00	2	3:30	1	DG
16	13	2	21-Jun-13	Winkler	9:25	10:05	3	1:10	1	DG
17	14	1	28-Jun-12	Winkler	10:30	11:40	1	1:10	0	DG
18	14	2	21-Jun-13	Winkler	10:55	11:57	3	3:02	1	DG
19	15	1	30-Jun-12	Winkler	8:50	10:30	3	5:00	1	LG
20	16	1	19-Jun-13	Crane	9:30	11:20	4	8:47	0	R
21	17	1	19-Jun-13	Crane	11:38	12:45	4	3:54	0	R
22	18	1	19-Jun-13	Crane	9:25	10:25	3	3:00	0	R

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
23	19	1	19-Jun-13	Crane	10:50	11:50	3	3:00	0	R
24	20	1	20-Jun-13	Andrews	10:15	11:31	5	5:46	0	LG
25	21	1	20-Jun-13	Andrews	11:47	13:06	5	5:19	1	LG
26	22	1	20-Jun-13	Winkler	9:15	10:20	4	4:20	0	R
27	23	1	20-Jun-13	Winkler	10:40	11:25	4	3:00	0	R
28	24	1	21-Jun-13	Winkler	9:24	11:07	3	4:41	0	LG
29	25	1	22-Jun-13	Andrews	9:50	10:55	3	3:10	0	DG
30	26	1	22-Jun-13	Andrews	9:55	11:00	3	3:05	1	DG
31	1a	1	3-Jul-14	Andrews	9:47	10:24	4	2:28	0	X
32	1a	2	21-Jul-14	Andrews	9:40	10:09	4	1:56	0	X
33	1a	3	11-Jun-15	Andrews	10:55	11:25	4	2:00	0	X
34	2a	1	19-Jun-14	Andrews	10:38	11:13	4	2:20	0	X
35	2a	2	4-Aug-14	Andrews	11:20	11:52	4	2:08	0	X
36	2a	3	21-Jun-15	Andrews	11:35	12:05	4	2:00	0	X
37	3a	1	19-Jun-14	Andrews	10:43	11:51	4	4:32	0	X
38	3a	2	4-Aug-14	Andrews	10:45	11:16	4	2:04	0	X
39	3a	3	20-Jun-15	Andrews	11:14	11:44	4	2:00	0	X
40	4a	1	26-Jun-14	Andrews	9:56	10:30	4	2:16	0	X
41	4a	2	4-Aug-14	Andrews	10:05	10:36	4	2:04	0	X
42	4a	3	4-Jul-15	Andrews	11:15	11:46	4	2:04	0	X
43	5a	1	26-Jun-14	Andrews	10:44	11:12	4	1:52	0	X
44	5a	2	6-Aug-14	Andrews	10:50	11:20	4	2:00	0	X
45	5a	3	19-Jun-15	Andrews	11:15	11:40	4	1:40	0	X
46	6a	1	2-Jun-14	Andrews	10:27	11:02	4	2:20	0	DG
47	6a	2	19-Jul-14	Andrews	10:30	11:07	4	2:28	1	DG
48	6a	3	24-Jul-15	Andrews	8:38	9:09	4	2:04	0	DG
49	7a	1	3-Jul-14	Andrews	10:37	11:11	4	2:16	0	X
50	7a	2	5-Aug-14	Andrews	9:59	10:29	4	2:00	0	X
51	7a	3	19-Jul-15	Andrews	11:40	12:09	4	1:54	0	X
52	8a	1	18-May-14	Andrews	9:56	10:33	4	2:28	0	X
53	8a	2	19-Jul-14	Andrews	12:06	12:36	4	2:00	0	X
54	8a	3	23-Jul-15	Andrews	9:46	10:15	4	1:54	0	X
55	12a	1	28-Jun-14	Andrews	11:21	11:53	4	2:08	0	DG
56	12a	2	30-Jul-14	Andrews	9:25	9:55	4	2:00	0	DG
57	12a	3	4-Jun-15	Andrews	11:49	12:20	5	2:35	1	DG
58	14a	1	3-Jun-14	Andrews	9:15	9:54	4	2:36	0	DG
59	14a	2	21-Jul-14	Andrews	11:23	11:58	4	2:20	0	DG
60	14a	3	24-Jul-15	Andrews	10:47	11:15	4	1:52	0	DG
61	16a	1	15-May-14	Andrews	11:09	11:50	4	2:44	0	DG

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
62	16a	2	21-Jul-14	Andrews	10:31	11:08	4	2:28	1	DG
63	16a	3	24-Jul-15	Andrews	10:00	10:30	4	2:00	0	DG
64	17a	1	18-Jun-14	Andrews	10:30	11:00	4	2:00	0	DG
65	17a	2	5-Aug-14	Andrews	10:42	11:12	4	2:00	0	DG
66	17a	3	5-Jul-15	Andrews	11:33	12:04	4	2:04	0	DG
67	18a	1	18-Jun-14	Andrews	9:44	10:19	4	2:20	0	DG
68	18a	2	5-Aug-14	Andrews	11:22	11:56	4	2:16	0	DG
69	18a	3	20-Jul-15	Andrews	11:34	12:01	4	1:48	0	DG
70	19a	1	10-Jun-14	Andrews	10:05	10:40	4	2:20	0	X
71	19a	2	30-Jul-14	Andrews	10:21	10:55	4	2:16	0	X
72	19a	3	25-Jul-15	Andrews	11:20	11:45	4	1:40	0	X
73	20a	1	12-Jun-14	Andrews	10:29	11:01	4	2:08	0	X
74	20a	2	28-Jul-14	Andrews	9:40	10:14	4	2:16	0	X
75	20a	3	8-Jun-15	Andrews	10:20	10:50	4	2:00	0	X
76	21a	1	3-Jun-14	Andrews	10:37	11:09	4	2:08	0	X
77	21a	2	28-Jul-14	Andrews	10:26	10:59	4	2:12	0	X
78	21a	3	8-Jun-15	Andrews	10:13	10:45	4	2:08	0	X
79	22a	1	31-May-14	Andrews	9:38	10:14	4	2:24	0	X
80	22a	2	22-Jul-14	Andrews	10:17	10:51	4	2:16	0	X
81	22a	3	23-Jul-15	Andrews	11:59	12:25	4	1:44	0	X
82	23a	1	31-May-14	Andrews	10:28	11:05	4	2:28	0	X
83	23a	2	22-Jul-14	Andrews	9:31	10:06	4	2:20	0	X
84	23a	3	23-Jul-15	Andrews	10:32	11:02	4	2:00	0	X
85	24a	1	12-Jun-14	Andrews	11:16	11:47	4	2:04	0	X
86	24a	2	31-Jul-14	Andrews	10:19	10:52	4	2:12	0	X
87	24a	3	10-Jun-15	Andrews	10:30	11:00	4	2:00	0	X
88	25a	1	2-Jun-14	Andrews	11:29	11:59	4	2:00	0	X
89	25a	2	28-Jul-14	Andrews	11:10	11:42	4	2:08	0	X
90	25a	3	8-Jun-15	Andrews	11:19	11:49	4	2:00	0	X
91	26a	1	11-Jun-14	Andrews	11:00	11:30	4	2:00	0	X
92	26a	2	16-Jul-14	Andrews	9:36	10:08	4	2:08	0	X
93	26a	3	9-Jun-15	Andrews	11:01	11:30	4	1:54	0	X
94	28a	1	28-Jun-14	Andrews	10:22	11:01	4	2:36	0	DG
95	28a	2	30-Jul-14	Andrews	11:17	11:50	4	2:12	0	DG
96	28a	3	5-Jun-15	Andrews	11:24	11:55	5	2:35	0	DG
97	29a	1	22-Jul-14	Andrews	11:07	11:40	4	2:12	0	DG
98	29a	2	25-Jul-15	Andrews	9:30	10:00	4	2:00	0	DG
99	31a	1	11-Jun-14	Andrews	9:37	10:14	4	2:28	0	X
100	31a	2	31-Jul-14	Andrews	11:05	11:34	4	1:56	0	X

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
101	31a	3	10-Jun-15	Andrews	11:29	11:59	4	2:00	0	X
102	32a	1	29-May-14	Andrews	9:40	10:16	4	2:24	0	X
103	32a	2	16-Jul-14	Andrews	10:17	10:52	4	2:20	0	X
104	32a	3	24-May-15	Andrews	11:22	11:55	4	2:12	0	X
105	33a	1	30-Jun-14	Andrews	10:00	10:40	4	2:40	0	DG
106	33a	2	6-Aug-14	Andrews	10:07	10:39	4	2:08	0	DG
107	33a	3	11-Jun-15	Andrews	9:42	10:13	4	2:04	0	DG
108	34a	1	29-May-14	Andrews	10:35	11:13	4	2:32	0	X
109	34a	2	16-Jul-14	Andrews	11:08	11:39	4	2:04	0	X
110	34a	3	24-May-15	Andrews	10:25	10:57	4	2:08	0	X
111	37a	1	17-Jun-14	Andrews	11:22	11:55	4	2:12	0	DG
112	37a	2	2-Jul-14	Andrews	9:52	10:26	4	2:16	0	DG
113	37a	3	25-Jun-15	Andrews	10:01	10:32	4	2:04	0	DG
114	38a	1	30-Jun-14	Andrews	10:58	11:30	4	2:08	0	X
115	38a	2	6-Aug-14	Andrews	9:23	9:54	4	2:04	0	X
116	38a	3	6-Jul-15	Andrews	10:56	11:27	4	2:04	0	X
117	39a	1	13-Jun-14	Andrews	9:44	10:16	4	2:08	0	X
118	39a	2	3-Jul-14	Andrews	11:46	12:19	4	2:12	0	X
119	39a	3	23-Jul-15	Andrews	11:15	11:45	4	2:00	0	X
120	43a	1	2-Jul-14	Andrews	10:40	11:11	4	2:04	0	X
121	43a	2	20-Jul-14	Andrews	9:41	10:15	4	2:16	0	X
122	43a	3	25-Jun-15	Andrews	10:52	11:22	4	2:00	0	X
123	44a	1	2-Jul-14	Andrews	11:23	12:01	4	2:32	0	DG
124	44a	2	20-Jul-14	Andrews	10:24	10:58	4	2:16	0	DG
125	44a	3	25-Jun-15	Andrews	11:45	12:14	4	1:54	0	DG
126	45a	1	15-Jun-14	Andrews	10:12	10:48	4	2:24	0	X
127	45a	2	1-Aug-14	Andrews	9:40	10:11	4	2:04	0	X
128	45a	3	23-Jun-15	Andrews	11:55	12:26	4	2:04	0	X
129	46a	1	26-May-14	Andrews	11:17	11:52	4	2:20	0	DG
130	46a	2	29-Jul-14	Andrews	11:25	11:55	4	2:00	0	DG
131	46a	3	24-Jun-15	Andrews	11:04	11:33	4	1:54	0	DG
132	47a	1	15-Jun-14	Andrews	11:06	11:35	4	1:56	0	X
133	47a	2	1-Aug-14	Andrews	10:23	10:53	4	2:00	0	X
134	47a	3	23-Jun-15	Andrews	11:15	11:45	4	2:00	0	X
135	49a	1	28-May-14	Andrews	9:48	10:22	4	2:16	0	X
136	49a	2	12-Jul-14	Andrews	9:49	10:25	4	2:24	0	X
137	49a	3	26-Jun-15	Andrews	9:30	10:01	4	2:04	0	X
138	50a	1	28-May-14	Andrews	10:39	11:14	4	2:20	0	X
139	50a	2	12-Jul-14	Andrews	10:41	11:11	4	2:00	0	X

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
140	50a	3	26-Jun-15	Andrews	10:19	10:45	4	1:44	0	X
141	52a	1	30-May-14	Andrews	11:21	11:59	4	2:32	1	DG
142	52a	2	20-Jul-14	Andrews	11:21	11:58	4	2:28	0	DG
143	52a	3	21-Jul-15	Andrews	11:21	11:53	4	2:08	1	DG
144	53a	1	30-May-14	Andrews	10:25	11:01	4	2:24	0	DG
145	53a	2	12-Jul-14	Andrews	11:21	11:59	4	2:32	0	DG
146	53a	3	27-May-15	Andrews	11:57	12:33	4	2:24	0	DG
147	54a	1	29-Jun-14	Andrews	9:45	10:19	4	2:16	0	DG
148	54a	2	7-Aug-14	Andrews	9:26	9:56	4	2:00	0	DG
149	54a	3	27-May-15	Andrews	11:03	11:39	4	2:24	0	DG
150	55a	1	29-Jun-14	Andrews	10:29	11:04	4	2:20	0	DG
151	55a	2	7-Aug-14	Andrews	10:04	10:33	4	1:56	0	DG
152	55a	3	27-May-15	Andrews	10:15	10:48	4	2:12	0	DG
153	58a	1	17-May-14	Andrews	11:27	12:13	5	3:50	1	DG
154	58a	2	14-Jul-14	Andrews	9:41	10:17	4	2:24	1	DG
155	58a	3	10-Jul-15	Andrews	11:25	11:55	4	2:00	1	DG
156	60a	1	13-Jun-14	Andrews	10:45	11:17	4	2:08	0	X
157	60a	2	13-Jul-14	Andrews	9:56	10:30	4	2:16	0	X
158	60a	3	8-Jul-15	Andrews	10:58	11:29	4	2:04	0	X
159	61a	1	1-Jun-14	Andrews	10:25	11:03	4	2:32	1	DG
160	61a	2	14-Jul-14	Andrews	10:41	11:15	4	2:16	1	DG
161	61a	3	10-Jul-15	Andrews	10:19	10:55	4	2:24	1	DG
162	63a	1	1-Jun-14	Andrews	9:38	10:13	4	2:20	0	DG
163	63a	2	10-Jul-15	Andrews	9:27	9:57	4	2:00	0	DG
164	64a	1	28-Jun-14	Andrews	9:47	10:25	4	2:32	0	DG
165	64a	2	29-Jul-14	Andrews	9:41	10:15	4	2:16	0	DG
166	64a	3	9-Jul-15	Andrews	11:20	11:48	4	1:52	0	DG
167	65a	1	28-Jun-14	Andrews	10:46	11:16	4	2:00	0	DG
168	65a	2	29-Jul-14	Andrews	10:35	11:04	4	1:56	0	DG
169	65a	3	9-Jul-15	Andrews	10:24	10:55	4	2:04	0	DG
170	66a	1	27-May-14	Andrews	11:32	12:06	4	2:16	0	X
171	66a	2	1-Aug-14	Andrews	11:16	11:47	4	2:04	0	X
172	66a	3	26-May-15	Andrews	10:46	11:23	4	2:28	0	X
173	67a	1	17-Jun-14	Andrews	10:07	10:41	4	2:16	0	X
174	67a	2	13-Jul-14	Andrews	10:58	11:30	4	2:08	0	X
175	67a	3	8-Jul-15	Andrews	11:55	12:38	4	2:12	0	X
176	70a	1	27-May-14	Andrews	10:33	11:04	4	2:04	0	X
177	70a	2	13-Jul-14	Andrews	12:00	12:31	4	2:04	0	X
178	70a	3	9-Jul-15	Andrews	9:29	10:00	4	2:04	0	X

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
179	1	1	24-Jun-15	Crane	11:13	11:46	4	2:12	0	X
180	1	2	23-Jul-15	Crane	9:42	10:42	4	2:00	0	X
181	8	1	24-Jun-15	Crane	10:08	10:43	4	2:20	0	X
182	8	2	23-Jul-15	Crane	10:37	11:07	4	2:00	0	X
183	25	1	17-Jun-15	Crane	11:09	11:39	4	2:00	0	X
184	25	2	3-Aug-15	Crane	10:24	10:52	4	1:52	0	X
185	34	1	19-Jul-15	Crane	9:14	9:46	4	2:08	0	X
186	34	2	1-Aug-15	Crane	8:59	9:28	4	1:54	0	X
187	59	1	5-Jun-15	Crane	11:29	12:01	4	2:08	0	X
188	59	2	3-Aug-15	Crane	9:25	9:55	4	2:00	0	X
189	74	1	17-Jun-15	Crane	10:10	10:40	4	2:00	0	X
190	74	2	3-Aug-15	Crane	11:13	11:43	4	2:00	0	X
191	79	1	5-Jun-15	Crane	10:34	11:05	4	2:04	0	X
192	79	2	3-Aug-15	Crane	8:36	9:05	4	1:54	0	X
193	84	1	9-Jun-15	Crane	10:13	10:46	4	2:12	0	X
194	84	2	23-Jul-15	Crane	8:45	9:16	4	2:04	0	X
195	87	1	9-Jun-15	Crane	11:16	11:47	4	2:04	0	X
196	87	2	1-Aug-15	Crane	9:55	10:25	4	2:00	0	X
197	105	1	7-Jun-15	Crane	10:24	10:57	4	2:12	0	X
198	105	2	20-Jul-15	Crane	9:00	9:30	4	2:00	0	X
199	106	1	7-Jun-15	Crane	11:14	11:46	4	2:08	0	X
200	106	2	20-Jul-15	Crane	9:50	10:20	4	2:00	0	X
201	109	1	19-Jul-15	Crane	10:12	10:42	4	2:00	0	R
202	109	2	20-Jul-15	Crane	10:38	11:11	4	2:12	0	R
203	110	1	20-Jun-15	Crane	10:21	10:53	4	2:08	0	R
204	110	2	19-Jul-15	Crane	11:03	11:34	4	2:04	0	R
205	117	1	20-Jun-15	Crane	11:45	12:15	4	2:00	0	R
206	117	2	2-Aug-15	Crane	9:35	10:05	4	2:00	0	R
207	120	1	21-Jun-15	Crane	10:51	11:23	4	2:08	0	R
208	120	2	2-Aug-15	Crane	8:32	9:03	4	2:04	0	R
209	147	1	20-Jun-15	Crane	11:18	11:48	4	2:00	0	R
210	147	2	1-Aug-15	Crane	10:52	11:20	4	1:52	0	R
211	163	1	4-Jun-15	Crane	11:25	11:58	4	2:12	0	R
212	163	2	4-Jul-15	Crane	9:58	10:28	4	2:00	0	R
213	175	1	4-Jun-15	Crane	10:40	11:10	4	2:00	0	R
214	175	2	4-Jul-15	Crane	9:10	9:40	4	2:00	0	R
215	225	1	25-May-15	Crane	11:20	11:50	4	2:00	0	R
216	225	2	7-Aug-15	Crane	10:55	11:25	4	2:00	0	R
217	240	1	3-Jun-15	Crane	10:24	10:55	4	2:04	0	X

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
218	240	2	2-Aug-15	Crane	10:36	11:07	4	2:04	0	X
219	17	1	8-Jul-15	Ward	10:38	11:07	4	1:54	0	X
220	20	1	8-Jul-15	Ward	11:51	12:25	4	2:16	0	X
221	28	1	8-Jul-15	Ward	9:42	10:12	4	2:00	0	X
222	71	1	5-Jul-15	Ward	9:56	10:30	4	2:16	0	O
223	71	2	21-Jul-15	Ward	8:52	9:23	4	2:04	0	O
224	102	1	26-May-15	Ward	12:24	12:55	4	2:04	0	O
225	102	2	7-Aug-15	Ward	9:16	9:45	4	1:54	0	O
226	182	1	19-Jun-15	Ward	11:33	11:53	4	2:00	0	X
227	182	2	22-Jul-15	Ward	11:28	11:58	4	2:00	0	X
228	188	1	2-Jul-15	Ward	10:50	11:22	4	2:08	0	DG
229	188	2	21-Jul-15	Ward	9:53	10:23	4	2:00	0	DG
230	201	1	8-Aug-15	Ward	8:45	9:15	4	2:00	1	DG
231	203	1	25-May-15	Ward	10:07	10:36	4	1:54	0	DG
232	203	2	7-Aug-15	Ward	10:49	11:16	4	1:48	0	DG
233	213	1	5-Jul-15	Ward	11:04	11:37	4	2:12	0	DG
234	213	2	21-Jul-15	Ward	10:40	11:12	4	2:08	0	DG
235	229	1	3-Jun-15	Ward	10:18	10:53	4	2:20	0	X
236	229	2	22-Jul-15	Ward	8:50	9:20	4	2:00	0	X
237	235	1	19-Jun-15	Ward	10:40	11:12	4	2:08	0	DG
238	235	2	22-Jul-15	Ward	10:35	11:06	4	2:04	0	DG
239	256	1	3-Jun-15	Ward	11:26	11:58	4	2:08	0	X
240	256	2	22-Jul-15	Ward	9:42	10:12	4	2:00	0	X
241	315	1	5-Jul-15	Winkler	12:16	12:46	4	2:00	1	DG
242	315	2	17-Jul-15	Winkler	11:48	12:18	4	2:00	0	DG
243	376	1	18-Jun-15	Winkler	10:17	10:47	4	2:00	0	X
244	376	2	26-Jul-15	Winkler	8:55	9:24	4	1:54	0	X
245	415	1	17-Jul-15	Winkler	10:20	10:50	4	2:00	0	DG
246	415	2	8-Aug-15	Winkler	8:51	9:22	4	2:04	0	DG
247	434	1	25-Jun-15	Winkler	11:08	11:46	4	2:32	0	DG
248	434	2	26-Jul-15	Winkler	10:53	11:23	4	2:00	0	DG
249	455	1	25-Jun-15	Winkler	9:54	10:35	4	2:44	0	DG
250	455	2	26-Jul-15	Winkler	9:58	10:30	4	2:08	0	DG
251	551	1	6-Jul-15	Winkler	11:56	12:26	4	2:00	0	X
252	564	1	9-Jul-15	Winkler	10:05	10:42	4	2:28	0	DG
253	564	2	5-Aug-15	Winkler	9:08	9:39	4	2:04	0	DG
254	565	1	9-Jul-15	Winkler	11:06	11:39	4	2:12	0	DG
255	565	2	5-Aug-15	Winkler	9:57	10:27	4	2:00	0	DG
256	639	1	26-May-15	Winkler	10:20	10:52	4	2:08	0	X

Number	Site	Survey	Date	County	Start	End	Observers	Survey Time	DSL Present	Likelihood
257	639	2	7-Aug-15	Winkler	8:57	9:27	4	2:00	0	X
258	731	1	11-Jul-15	Winkler	9:55	10:26	4	2:04	0	O
259	731	2	25-Jul-15	Winkler	9:00	9:31	4	2:04	0	O
260	743	1	10-Jul-15	Winkler	11:38	12:08	4	2:00	0	O
261	748	1	6-Jul-15	Winkler	10:50	11:20	4	2:00	0	X
262	748	2	24-Jul-15	Winkler	10:43	11:14	4	2:04	0	X
263	805	1	11-Jul-15	Winkler	11:15	11:45	4	2:00	0	O
264	805	2	25-Jul-15	Winkler	10:12	10:43	4	2:04	0	O
265	828	1	6-Jul-15	Winkler	10:01	10:32	4	2:04	0	X
266	828	2	24-Jul-15	Winkler	9:48	10:17	4	1:54	0	X
267	904	1	10-Jul-15	Winkler	9:45	10:18	4	2:12	0	DG
268	904	2	24-Jul-15	Winkler	8:49	9:20	4	2:04	0	DG
269	910	1	10-Jul-15	Winkler	10:37	11:08	4	2:04	0	X
270	910	2	7-Aug-15	Winkler	10:49	11:20	4	2:04	0	X
271	932	1	26-Jun-15	Winkler	10:36	11:06	4	2:00	0	X
272	932	2	7-Aug-15	Winkler	10:00	10:30	4	2:00	0	X

5.3.1 *Surveys by County*

The distribution of surveys included all known counties where the DSL historically occurred. Andrews County had the most surveys at 158, followed by Crane at 46, Winkler at 44, and Ward at 22. Two more surveys were conducted on the border of Andrews and Gaines Counties.

The DSL was detected on 23 total surveys (8.5%). In Andrews County, the DSL was detected on 14 surveys (8.9%). Ward and Winkler Counties had one (4.5%) and six (13.6%) positive DSL surveys, respectively. The two surveys on the border of Andrews and Gaines Counties were both positive, but the DSL was not detected in any of the Crane County surveys.

5.3.2 *Surveys by Likelihood of Occurrence*

Table 5.2. Surveys conducted for the DSL in Texas 2012-15 by likelihood of occurrence class. Surveys conducted outside the predicted areas of occurrence are also included.

	2012	2013	2014	2015	Total	Proportion	DSL Present
Dark Green (DG)	6	5	40	44	95	35.0%	21
Light Green (LG)	2	4	0	0	6	2.2%	2
Orange (O)	0	0	0	9	9	3.3%	0
Red (R)	1	6	0	16	23	8.5%	0
Outside (X)	6	0	58	75	139	51.0%	0
Total	15	15	98	144	272	100%	23

All 23 surveys where the DSL was detected were located within the dark or light green areas on the TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Figure 1.1, Table 5.2). The dark and light green areas reflect DSL habitats where the likelihood of DSL occurrence is very high or high, respectively. The DSL was not detected in any surveys located within orange or red areas, which reflect DSL habitats where the likelihood of DSL occurrence is low or very low, respectively. Additionally, the DSL was never detected on surveys located outside the predicted areas of occurrence.

5.3.3 *Repeated Surveys*

Over the four-year survey period, 50 sites were surveyed twice and 48 sites were surveyed three times. The DSL was detected on 16 of these surveys at 10 different sites within dark green areas of very high likelihood of occurrence only. At 3 of these sites (2 Andrews, 1 Winkler), the DSL was detected on every visit. At another site (Andrews), the DSL was detected in May 2014, not detected in July 2014, and then detected again in July 2015. At the remaining six sites (4 Andrews, 2 Winkler) the DSL was detected only once. The number of sites with single detections on the first, second, or third visits were two, three, and one, respectively.

These data indicate that detectability of the DSL is variable across the landscape, even in dark green areas where the likelihood of DSL occurrence is very high. Indeed, on many surveys in dark green areas, DSL was not detected at all, which could indicate that the likelihood of occurrence varies according to quality of habitat at a small scale within the established habitat classes identified in the TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Fig. 1.1.). That is, even within the broad categories of likelihood of occurrence, there is variation in quality of habitat that influences DSL occurrence and numbers at a given location. To evaluate this hypothesis, we created a model of DSL habitat suitability at fine spatial scales with established habitat classes (CHAPTER 6).

5.4 Conclusions

During the entire 4-year study (2012-15), surveys resulted in a number of new localities for the species in Texas, though some were geographically close to known localities. All of the survey sites where the DSL was detected were located within the dark or light green areas on the TCP Permit Area/Likelihood of Occurrence Map, corresponding to areas of very high or high likelihood of occurrence (CHAPTER 1 – Fig. 1.1). No DSL detections were made in orange or red areas or outside the predicted areas of occurrence.

These results validate our current perception of DSL habitat, corroborate the predicted likelihood of occurrence categories for these areas, and also imply that the current version of the TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Fig. 1.1) is an accurate and effective tool for constructing and implementing conservation and management objectives included in the TCP. The fine scale variation in DSL occurrence observed in predicted dark green areas over the last four years of surveys suggests that the TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Fig. 1.1) is conservative in its preservation of DSL habitat at landscape scales.

CHAPTER 6 – HABITAT SUITABILITY MODEL FOR THE DUNES SAGEBRUSH LIZARD IN TEXAS

6.1 Background

The first description of the Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*) distribution in Texas was done by Axtell (1988). In his atlas of Texas lizards, Axtell (1988) predicted the occurrence of the DSL based on historical localities from preserved specimens, map patterns, published literature, and knowledge of the environments in the Permian Basin region. He identified a five-county expanse of semixeric, eolian sands that were presumably derived during drier periods of active "blow-off" from the Pecos River Valley and adjacent eastern uplands in the late Pleistocene to mid-Holocene time period (16000-6000 ybp; Machenberg 1984). This sandy area extends from northeastern Ward County east into Ector and Crane Counties and also north into Winkler County. The eastern edge of this sandy area is formed by what Axtell refers to as the Concho Bluff, which diverts blown sand north and then eastward at its termination covering much of southern Andrews County. Axtell also noted that southern Gaines County contained eolian habitats similar to those occupied by the DSL in Andrews County, but no DSL had ever been observed there. Similarly, the DSL had never been observed in Ector County. Axtell recommended that future surveys target the range boundaries identified for the DSL in Texas and also monitor temporal changes in population status at known localities.

In 2006-07, Laurencio et al. (2007) conducted the next study of the DSL distribution in Texas. Prior to conducting field work, Laurencio et al. (2007) created an updated atlas of potential habitat for the DSL using general vegetation classes for Shinnery Oak (*Quercus havardii*) and Shinnery Oak-Mesquite Brush. Using the atlas to guide reconnaissance in field vehicles and after doing several surveys, Laurencio et al. (2007) determined that the areas in Lynn, Terry, Yoakum, Dawson, Howard, and most of Gaines counties were not suitable for the DSL. They selected 27 sites spread across 6 counties (Andrews, Cochran, Crane, Gaines, Ward, and Winkler) covering the known range of the DSL in Texas at the time and also sites near historical localities listed in Axtell (1988). Another county, Cochran, was included in the survey effort, because DSL habitat is found nearby in New Mexico. A total of 32 surveys at those 27 sites yielded 3 sites, one each in Andrews, Winkler, and Gaines counties where the DSL was detected. Two of these sites (one each in Andrews and Winkler Counties) fell between historic localities and helped fill in gaps in the known distribution of the species. The other site in Gaines County was near a historical locality for the species. Laurencio et al. (2007) concluded that the DSL was probably absent, rather than not detected, from most sites surveyed in Texas during those years.

In 2011, a major survey of the range of the DSL in Texas was conducted in order to better define the distribution of habitat for the species and to establish a baseline of the species' occurrence in Texas (Fitzgerald et al. 2011). This information was needed to inform public and private interests, and state and federal agencies interested in formulating conservation plans for the DSL. Survey areas in potential DSL habitat were delineated prior to field work. The survey areas also included sites with potential habitat outside the known distribution of the DSL. The 2011 study completed 51 surveys at 50 sites, and documented presence of the DSL at 28 of the 50 sites. These 28 localities helped fill in gaps within the known distribution in Texas, although several were near historical records in contiguous habitat. None of the 28 sites were located outside the known distribution in Texas. Fitzgerald et al. (2011) concluded that habitat quality and historical patterns of occupancy influenced the likelihood of occurrence of the DSL in habitats distributed across the landscape. They also observed that the DSL was more likely to occur in suitable habitats where blowouts were open and free of encroaching grasses, Sand Sage (*Artemisia filifolia*), and Honey Mesquite (*Prosopis glandulosa*).

By combining the DSL habitat delineation with survey data, a map was created that divided up the known species' range in Texas according to Very High, High, Low, or Very Low likelihood of occurrence (CHAPTER 1 – Fig. 1.1). This map is identified as the TCP Permit Area/Likelihood of Occurrence Map. In addition to guiding the current and future research described here, this map identified areas where habitat conservation should be a priority and therefore served as the backbone for constructing and implementing conservation and management objectives under the TCP. To insure that this map continued to be effective at this task, distribution surveys (CHAPTER 5) were designed to provide science-based updates to the map and therefore support conservation and management of the DSL through the adaptive management process described in the TCP.

As reported above, all of the survey sites where the DSL was detected were located within the dark or light green areas on the TCP Permit Area/Likelihood of Occurrence Map, corresponding to areas of very high or high likelihood of occurrence (CHAPTER 1 – Fig. 1.1). In the recent distribution surveys, no DSL detections were made in orange or red areas or outside the predicted areas of occurrence. These results validated our current perception of DSL habitat, corroborated the predicted likelihood of occurrence categories for the DSL, and demonstrated that the current version of the TCP Permit Area/Likelihood of Occurrence Map is an accurate and effective tool for constructing and implementing conservation and management objectives included in the TCP (CHAPTER 5).

These distribution surveys also indicated that detectability of the DSL was variable across the landscape, even in dark green areas where the likelihood of DSL occurrence is very high. Indeed, on many surveys in dark green areas, the DSL was not detected at all, which could indicate that the likelihood of occurrence varies according to quality of habitat at a small scale within the established habitat classes identified in the TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Fig. 1.1). That is, even within the broad categories of likelihood of occurrence, variation exists in quality of habitat that influences DSL occurrence and numbers at a given location.

The fine scale variation in DSL occurrence observed in predicted dark green areas over the last four years of surveys suggests that the current TCP Permit Area/Likelihood of Occurrence Map (CHAPTER 1 – Fig. 1.1) is actually conservative in its preservation of DSL habitat at landscape scales. It also suggests that the current map might be improved with greater precision (i.e., fine scale resolution), although the observed accuracy of the current TCP Permit Area/Likelihood of Occurrence Map over the last four years of surveys sets a high bar for replacement by any fine scale models of habitat suitability. As such, our criteria for evaluating the utility of a fine scale habitat suitability model for administering the TCP is based on model accuracy: Is the new model at least as accurate as the current TCP Permit Area/Likelihood of Occurrence Map? Increased precision is important, but only if it does not sacrifice model accuracy, which could lead to further habitat loss and fragmentation. Below, we explore whether a fine scale habitat suitability model for the DSL can be as or more accurate and effective at preserving DSL habitat at landscape scales than the current Permit Area/Likelihood of Occurrence Map.

6.2 Methods

Persistence of DSL populations depends on the conservation of intact Shinnery Oak sand-dune landforms, which are characterized by rugose topography and open patches of wind-blown sand, stabilized by Shinnery Oak. As such, the focal variables used in our landscape model of DSL habitat suitability included the distribution of sand and Shinnery Oak as well as terrain rugosity (i.e., roughness of the topography). We used both Remote Sensing (RS) and Geographic Information System (GIS) processing methods to identify, characterize, and analyze these variables (Fig. 6.1).

6.2.1 *Study Area*

To identify the extent of the study area and the distribution of Shinnery Oak sand-dune landforms in Texas, we used soil type and parent material data from the Soil Survey Geographic Database (SSURGO 2.2, http://soils.usda.gov/survey/ geography/ssurgo/) and surface geology from Geologic Atlas of Texas (GAT). The SSURGO database stores a variety of soil information collected by the National Cooperative Soil Survey (NCSS) dating back more than 100 years. It consists of both georeferenced spatial and tabular soil data. The spatial units are linked to attributes in the tabular data in the Map Unit Interpretations Record relational data base. The tabular attribute data contains estimates of physical and chemical soil properties, soil interpretations for each soil, and static and dynamic metadata. The digital raster format surface geology maps come from GAT, which was created by scanning and geo referencing the original University of Texas, Bureau of Economic Geology Geologic Atlas of Texas map sheets. GAT data provided subsurface geologic information for the entire state at the scale of 1:250,000.

6.2.2 *Remote Sensing*

We identified sand and Shinnery Oak land cover types in the study area using RS classification of the 1-meter resolution color infrared (false-color) National Agriculture Imagery Program (NAIP) imagery in 4-bands (Red, Green, Blue, and near infrared) from 2014 (Retrieved in January 2015; http://gis.apfo.usda.gov/arcgis/ services/). The NAIP program is administered by the United States Department of Agriculture’s (USDA) Farm Service Agency (FSA). The aerial photography NAIP imagery meets the FSA standards and is used to support FSA environmental conservation programs. Remote sensing classification of this imagery is the process of converting spectral information in remotely sensed images from satellite or aircraft into a finite set of land cover classes or themes. We used the Environment for Visualizing Images (ENVI) RS software application to process and analyze geospatial imagery. It is widely used by professionals and image analysts in the RS field.

6.2.3 *Imagery Classification*

The ENVI platform provides two RS imagery types of classification: Unsupervised and Supervised. Each type of classification can be made with a broad range of different classification methods (e.g., Al-Ahmadi and Hames 2008). Unsupervised classification is an approach that examines unknown pixels and categorizes them into a number of classes based on spectral response patterns within an image. It is performed to classify land cover types in RS imagery without providing training data. Its basic rule is that pixels from the same land cover type should be close together in the spectral measurement space (multivariate domain of the imagery defined by the number of spectral bands used), while pixels from different land cover types should be relatively well separated in spectral space. Classes generated from unsupervised classification are referred to as spectral classes, because they are entirely based on image spectral information (pixel values). The supervised classification technique requires user pre-defined training classes (delineation of areas within the image where the landcover type is known), and is used to cluster pixels into classes based on spectral similarity to the training data provided by the user. It has various classification algorithms including maximum likelihood, minimum distance, Mahalanobis distance, Spectral Angle Mapper (SAM), Parallelepiped, Binary Encoding, etc.

We first applied the unsupervised Iterative Self-Organizing Data Analysis Technique (ISODATA) and K-mean classification methods to determine the number of characteristics of the natural groupings of cells in NAIP imagery. We found that the NAIP imagery can be divided into five main classes, meaning the image classification results do not change much when specifying the numbers of classes more than five (i.e., spectral discrimination did not improve above $n = 5$ classes). The imagery classification classes included sand, Shinnery Oak, caliche (well pads and roads), mesquite, and grass land cover types.

Seven supervised classification methods were tested; these were Mahalanobis distance, maximum likelihood, minimum distance, parallelepiped, binary encoding, SAM, and spectral Information Divergence (SID). Regardless of methodology, the supervised classification enhanced the extraction of sand and Shinnery Oak compared to the unsupervised classification results. Overall, Mahalanobis distance classifiers produced the best results. As such, an iterative algorithm of supervised classification and extraction was used to identify and isolate each feature class with maximum discrimination (i.e., sand, caliche, Shinnery Oak, grass, mesquite).

6.2.4 *Rugosity*

To calculate the terrain rugosity (a measure of small-scale variation in surface elevation), we used the digital elevation map from National Elevation Database (NED) and the Shuttle Radar Topography Mission (SRTM) data as the source elevation data (e.g., Sappington et al. 2007). The NED, developed by U.S. Geological Survey (USGS), is a seamless mosaic of best-available elevation data. We used the 10-meter NED data (2013 version, retrieved from http://nationalmap.gov/elevation.html). The NED data worked well throughout most of the known DSL distribution in Texas. However, it was imprecise in several large, discrete areas of open sand dunes without vegetation. In these areas, we used SRTM data to calculate terrain rugosity. SRTM technology uses radar interferometry to generate terrain elevation information by comparing two radar signals that are taken at slightly different locations. Therefore, the accuracy of SRTM is not affected in the areas of open sand dunes without vegetation. We used the 30-meter resolution SRTM data to calculate rugosity in those particular areas to compensate for the low accuracy of NED data.

The most commonly used terrain rugosity calculation tools are Benthic Terrain Modeler (BTM; Wright et al. 2012) and Arc-Chord Ratio (ACR; Du Preez 2015). The BTM toolbox for ArcGIS contains a set of tools that allow users to calculate the terrain characteristics such as bathymetric position index (BPI), aspect, slope, and terrain ruggedness (i.e., vector ruggedness measure, VRM) from a spatial input data set. VRM measures terrain rugosity using vector analysis to quantify the dispersion of vectors, orthogonal to the terrain surface in a three-dimensional orientation, within a window of specified grid cell size. By using the vector analysis in BTM toolbox, the variability in slope and aspect is effectively captured into a single measured value. The VRM values can be from 0 (no terrain variation at all) to 1 (complete terrain variation). However, the typical values for real world terrains usually range from 0 to around 0.4. The ACR rugosity index is calculated from the contoured area of the surface divided by the area of the surface orthogonally projected onto a plane of best fit (POBF), where the POBF is a function (interpolation) of the boundary data only. We tested both BTM and ACR rugosity calculation results and found BTM decoupled the slope and generated better output than the ACR (i.e., BTM was less affected by elevational anisotropy).

6.2.5 *Statistical Analyses*

We used DSL survey locations (i.e., 2011-2015; Fitzgerald et al. 2011, CHAPTER 5) to extract congruent habitat variables (i.e., Caliche, Grass, Mesquite, Sand, Shinnery, Rugosity Area, Rugosity Mean, and Rugosity Standard Deviation) from the land cover classification and rugosity maps using GIS (400m x 400m cell size to match the DSL survey experimental design). The extracted variables and DSL survey results (i.e., DSL presence/absence) were exported and combined into one DSL survey modeling data set (DSLS) for statistical modeling of the probability of occurrence using binary logistic regression (i.e., species distribution modeling). The DSLS consisted of GridID (i.e., a unique identifier for the sample location), Latitude, Longitude, DSL survey result (i.e., binary; present or absent), and the 8 habitat variables spatially congruent to each surveyed sample location (n = 175; for 12 total variables).

We created a DSL regional habitat data set (DSLR) by extracting habitat variables (i.e., Caliche, Grass, Mesquite, Sand, Shinnery, Rugosity Area, Rugosity Mean, and Rugosity Standard Deviation) from the land cover classification and rugosity maps for the DSL region of Texas using GIS (400m x 400m cell size to match the DSL survey experimental design). The extracted variables were exported and combined into one DSLR data set for subsequent mapping of the probability of occurrence using ArcGIS (i.e., mapping the probability of occurrence using parameter estimates from the binary logistic regression of the DSLS data set). The DSLR data set consisted of GridID (i.e., a unique identifier for the sample location) and the 8 habitat variables for each grid location within the DSL region (n = 11,466; for 9 total variables).

We evaluated the variables for collinearity using pairwise correlation (Table 6.1) and plotted the results as a matrix plot. Rugosity mean and Rugosity standard deviation are highly correlated. We therefore dropped rugosity standard deviation from consideration in all future models.

Next we evaluated a binomial logistic regression model containing all habitat variables (i.e., the full model). There were 4 variables within the full model that were significant at an alpha = 0.05 level: Caliche, Sand, Shinnery, and Mean Rugosity (Table 6.2). Though not significant in the full model, it is noteworthy that the presence of Mesquite was negatively related to DSL presence. It is also noteworthy that Caliche was positively associated with DSL presence. This positive association is most likely driven by 1) a positive correlation between Caliche and Sand (i.e., lack of spectral separation between these two land cover types), which is also positively correlated with DSL presence, 2) confusion in remote sensing image classification between Caliche and Sand, and 3) the fact that many suitable habitats occupied by the DSL contain caliche roads and well pads (see 6.4 Conclusions).

Using this information we constructed a set of candidate models and performed model selection using Akaike's Information Criteria, corrected for small sample size (AICc). Table 6.3 summarizes model selection results for each model including K (number of parameters), AICc, Delta AICc, AICc Weight, and Log-Likelihood, with models sorted by AICc Weight.

Models 8, 9, and 10 were similar in Log Likelihood and AICc value. Model 8 had the lowest AICc value and highest AICc Weight, and was selected as the best overall model containing Caliche, Sand, Shinnery, and Mean Rugosity as predictor variables (Table 6.4).

We used parameter estimates from the selected model (i.e., model 8) to generate predicted probability of occurrence values for the DSLR data set. The DSLR data set was then imported into ArcGIS and used to generate a map of the probability of occurrence for the DSL region in Texas. We note this analysis and subsequent maps are predictive, and only on-the-ground field surveys can confirm actual DSL presence at a particular place and time. As such, future survey efforts will be needed to assess the accuracy of the predictive probability of occurrence map (i.e., verification of presence/absence in new sample locations).

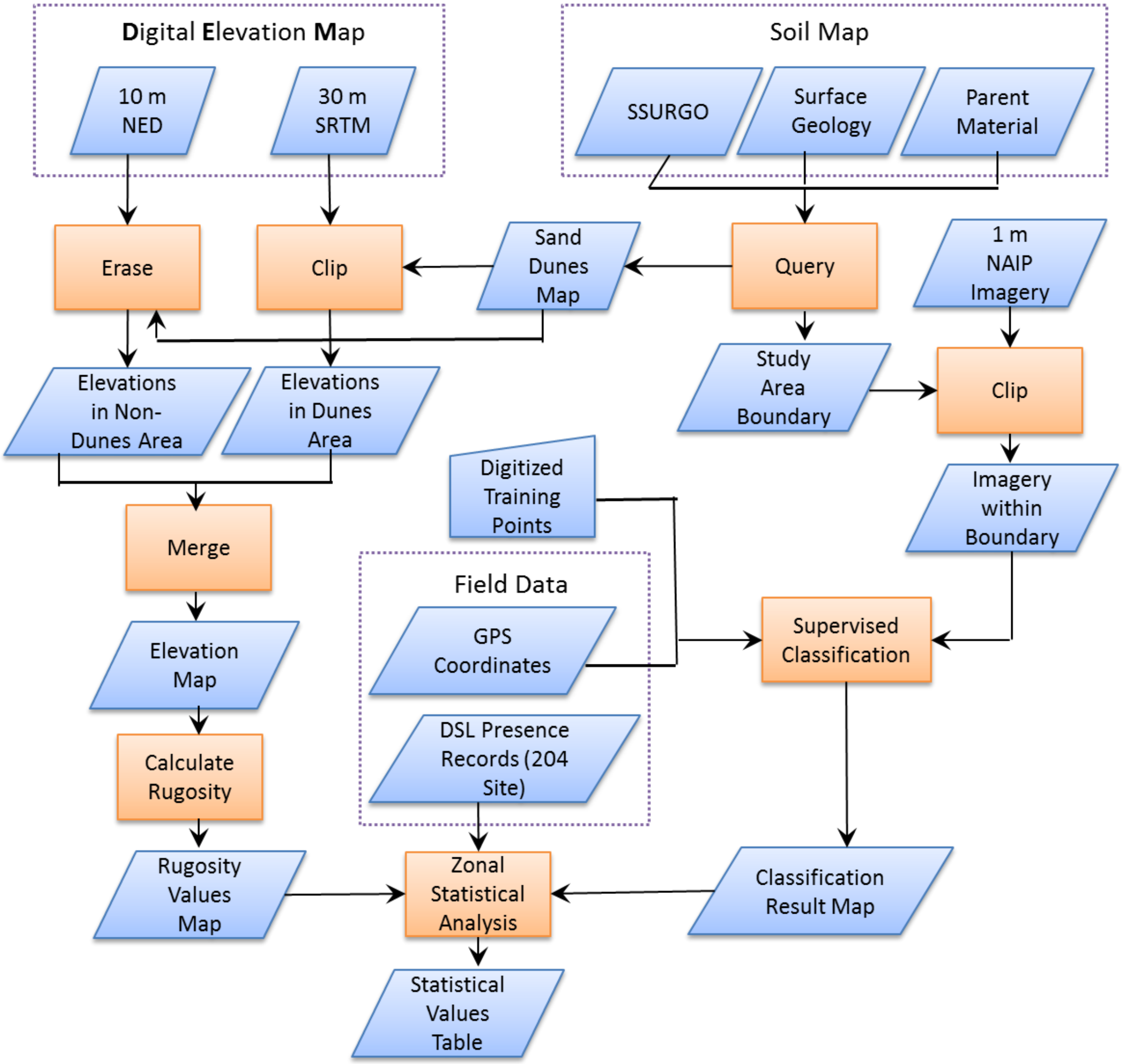


Figure 6.1. Workflow chart of remote sensing (RS) and geographic information system (GIS) processing.

Table 6.1. Correlation among habitat variables defining DSL habitat suitability model in Texas. SD = Standard Deviation.

	Caliche	Grass	Mesquite	Sand	Shinnery	Rugosity Mean	Rugosity SD
Caliche	1.000	-0.061	-0.155	0.416	-0.057	0.170	0.166
Grass	-0.061	1.000	0.201	-0.002	-0.043	-0.132	-0.080
Mesquite	-0.155	0.201	1.000	-0.041	0.125	-0.044	-0.010
Sand	0.416	-0.002	-0.041	1.000	-0.223	0.429	0.437
Shinnery	-0.057	-0.043	0.125	-0.223	1.000	-0.063	-0.039
Rugosity Mean	0.170	-0.132	-0.044	0.429	-0.063	1.000	0.831
Rugosity SD	0.166	-0.080	-0.010	0.437	-0.039	0.831	1.000

Table 6.2. Coefficient estimate, standard error, critical value, and *P*-value for all six variables included in the full model. Significance values at *P* < 0.001, 0.01, or 0.05 are coded as *, **, or *, respectively.**

	Coefficient Estimate	Standard Error	Critical Value (*z*)	*P*-value	Significance Value
(Intercept)	-4.271	1.447	-2.952	0.003	**
Caliche	1.082e-04	3.956e-05	2.735	0.006	**
Grass	-8.545e-06	1.085e-05	-0.788	0.431	
Mesquite	-4.650e-05	4.821e-05	-0.965	0.335	
Sand	1.166e-04	3.104e-05	3.756	<0.001	***
Shinnery	3.656e-05	1.008e-05	3.628	<0.001	***
Rugosity Mean	3.838e+03	1.393e+03	2.754	0.006	**

Table 6.3. Model selection for defining DSL habitat suitability in Texas.

Model	K	AICc	Delta AICc	AICc weight	Log-Likelihood
Model 8	5.00	119.32	0.00	0.48	-54.48
Model 10	6.00	120.82	1.51	0.22	-54.16
Model 9	6.00	128.39	9.07	0.01	-57.94
Model 7	4.00	129.96	10.65	0.00	-60.86
Model 6	3.00	157.70	38.38	0.00	-75.78
Model 3	2.00	166.30	46.99	0.00	-81.12
Model 5	2.00	193.27	73.95	0.00	-94.60
Model 2	2.00	200.21	80.89	0.00	-98.07
Model 1	1.00	241.04	121.72	0.00	-119.51
Model 4	2.00	242.18	122.86	0.00	-119.06

Table 6.4. Coefficient estimate, standard error, critical value, and *P*-value for four variables included in the best overall model (8) identified using AICc. Significance values at *P* < 0.001, 0.01, or 0.05 are coded as *, **, or *, respectively.**

	Coefficient Estimate	Standard Error	Critical Value (*z*)	*P*-value	Significance Value
(Intercept)	-5.550	9.952e-01	-5.576	<0.001	***
Caliche	1.260e-04	3.825e-05	3.294	<0.001	***
Sand	1.188e-04	3.083e-05	3.853	<0.001	***
Shinnery	4.268e-05	9.267e-06	4.605	<0.001	***
Rugosity Mean	4.000e+03	1.246e+03	3.209	0.001	**

6.3 Results and Discussion

Overall, the current TCP Permit Area/Likelihood of Occurrence Map and the DSL Habitat Suitability Map are very similar (Fig. 6.2). This indicates that the likelihood of DSL occurrence in Texas corresponds well with predicted habitat suitability. This is especially true for habitats with very high suitability and a very high likelihood of occurrence (dark green in both maps). For example, in Winkler County, which contains the most DSL habitat overall and the most dark green habitat in both maps, almost perfect agreement is present between the largest contiguous habitats with very high suitability and very high likelihood of occurrence. This strong relationship can also be seen in Ward and Andrews Counties to the south and north, respectively.

A major exception to this relationship can be seen in Crane County, where the DSL has not been detected in over four decades and therefore has a very low likelihood of occurrence (red). Reasons for the apparent disappearance of the DSL from historical localities in Crane County are completely unknown; however, the habitat suitability map for this area suggests that it is not due to a lack of habitat with very high suitability (dark green).

Agreement between the lower categories of occurrence and habitat suitability is much weaker throughout the species' range in Texas (Fig. 6.2). Most notably, habitats with a high likelihood of occurrence (light green) in northeastern Winkler County exhibit predominantly very low (red) habitat suitability for reasons discussed below. Additionally, almost all habitats with a low likelihood of occurrence (orange) in Texas exhibit very low (red) habitat suitability. The latter mismatch (orange occurrence vs. red suitability) is less concerning, because our distribution surveys failed to detect the DSL in low and very low likelihood habitats (CHAPTER 5). In other words, low and very low likelihood habitats are indistinguishable in terms of DSL detectability (=zero), and the zero observed detections for each is consistent with a very low habitat suitability ranking.

The mismatch in northeastern Winkler County is largely driven by a very localized under-representation of sand in the imagery classification and remote sensing steps of our analysis. The result is an under-representation of suitable habitat (dark or light green) in that area. This is not due to limitations in our approach, but rather reflects limitations in the available imagery for this particular geographic space. This mismatch is concerning, because several habitats where the DSL was detected during surveys are incorrectly predicted to exhibit very low habitat suitability. This example reflects a trade-off between increased precision and accuracy in the habitat suitability map caused by limitations in available imagery. It is possible that this trade-off between increased precision and accuracy can be mitigated with additional custom imagery at this location.

In general, both maps exhibit similar habitat boundaries, although the extent of the habitat suitability map is larger than that of the TCP Permit Area/Likelihood of Occurrence Map (Figs. 6.3 and 6.4). Once again, Winkler County, which contains the most DSL habitat overall, exhibits the greatest similarity in delineation of habitat between the two maps followed by southern Andrews County. Alternatively, delineation of habitat for the suitability model for western Andrews, Ector, Ward, and Crane Counties resulted in an increase in habitat extent relative to the delineation for the TCP Permit Area/Likelihood of Occurrence Map. This increase in extent for the habitat suitability map reflects our use of soil type and parent material data from the Soil Survey Geographic Database (SSURGO 2.2, http://soils.usda.gov/survey/ geography/ssurgo/) and surface geology from Geologic Atlas of Texas (GAT) to delineate habitat as opposed to delineation by subject matter expert.

Most of the habitat extending beyond the boundaries of the TCP Permit Area/Likelihood of Occurrence Map is predicted to be habitat with very low suitability (red) (Figs. 6.3 and 6.4; Table 6.5). Two exceptions to this pattern are located in western Andrews County and northern Crane County, where habitats extending beyond the boundaries of the TCP Permit Area/Likelihood of Occurrence Map are predicted to exhibit very high suitability (dark green). In western Andrews County, this very high suitability prediction is most likely caused by localized over-representation of sand in the imagery classification and remote sensing steps of our analysis. The result is an over-representation of suitable habitat (dark or light green) in that area. In northern Crane County, this very high suitability prediction is most likely caused by localized over-representation of Shinnery Oak in the imagery classification and remote sensing steps of our analysis, and the result is again an over-representation of suitable habitat (dark or light green) in that area. Ground truthing in these two areas could help to determine the accuracy of these unexpected high suitability habitat predictions that fell outside the TCP Permit Area/Likelihood of Occurrence Map.

Table 6.5. Area of each category (acres) for the TCP Permit Area/Likelihood of Occurrence Map and the DSL Habitat Suitability map.

Category	Likelihood of Occurrence	Proportion	Habitat Suitability	Proportion
Very High	64,293	0.33	79,548	0.17
High	31,876	0.16	42,858	0.09
Low	32,572	0.16	56,775	0.12
Very Low	68,865	0.35	279,921	0.61
Total	197,606	1.00	459,102	1.00

Table 6.6. Number of DSL detections across each habitat suitability category.

	Very Low	Low	High	Very High	Total
Detected	6	9	13	72	100
Not Detected	49	14	7	5	75
Total	55	23	20	77	175

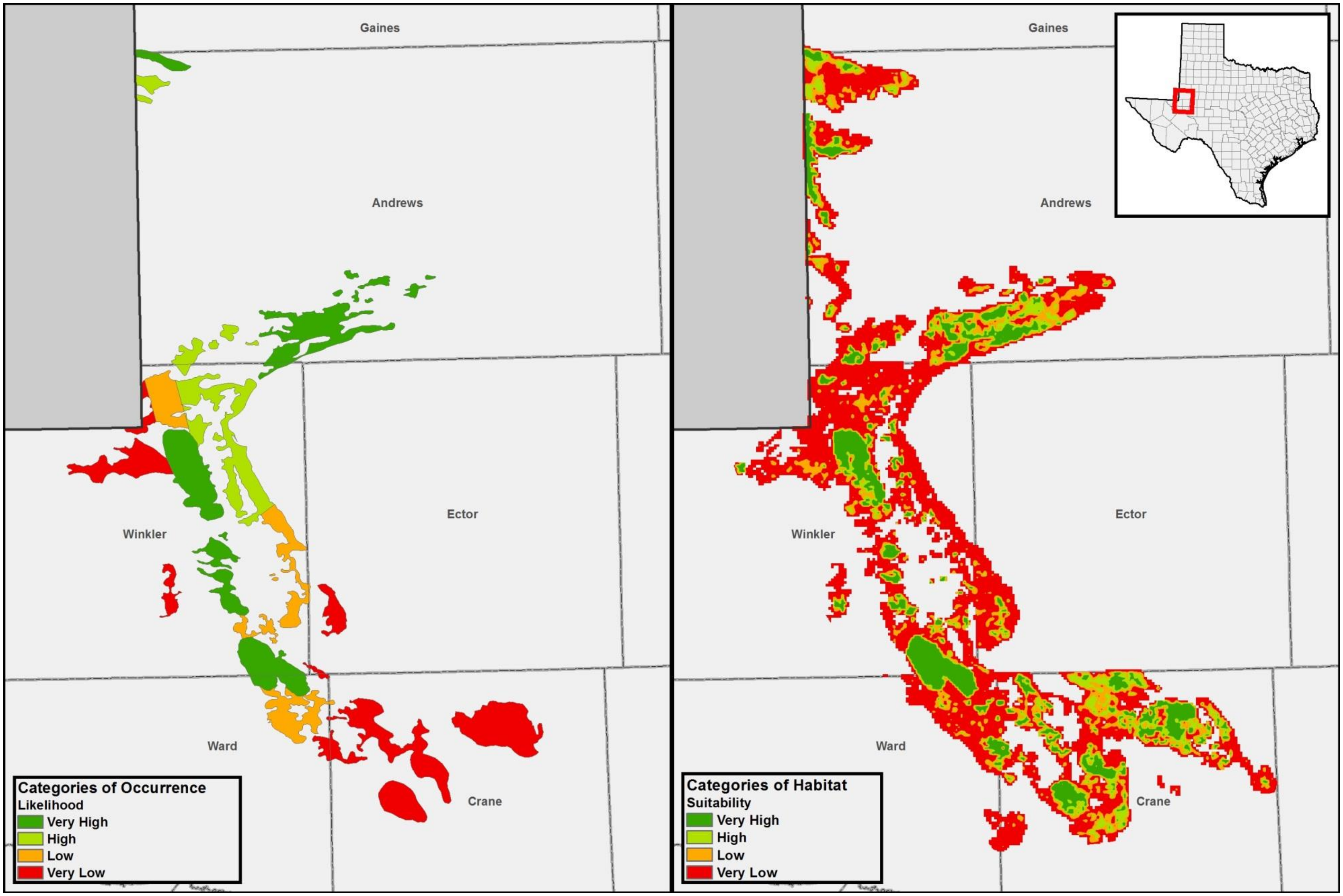


Figure 6.2. TCP Permit Area/Likelihood of Occurrence Map (left) and the DSL Habitat Suitability Map (right; projected in smoothed format).

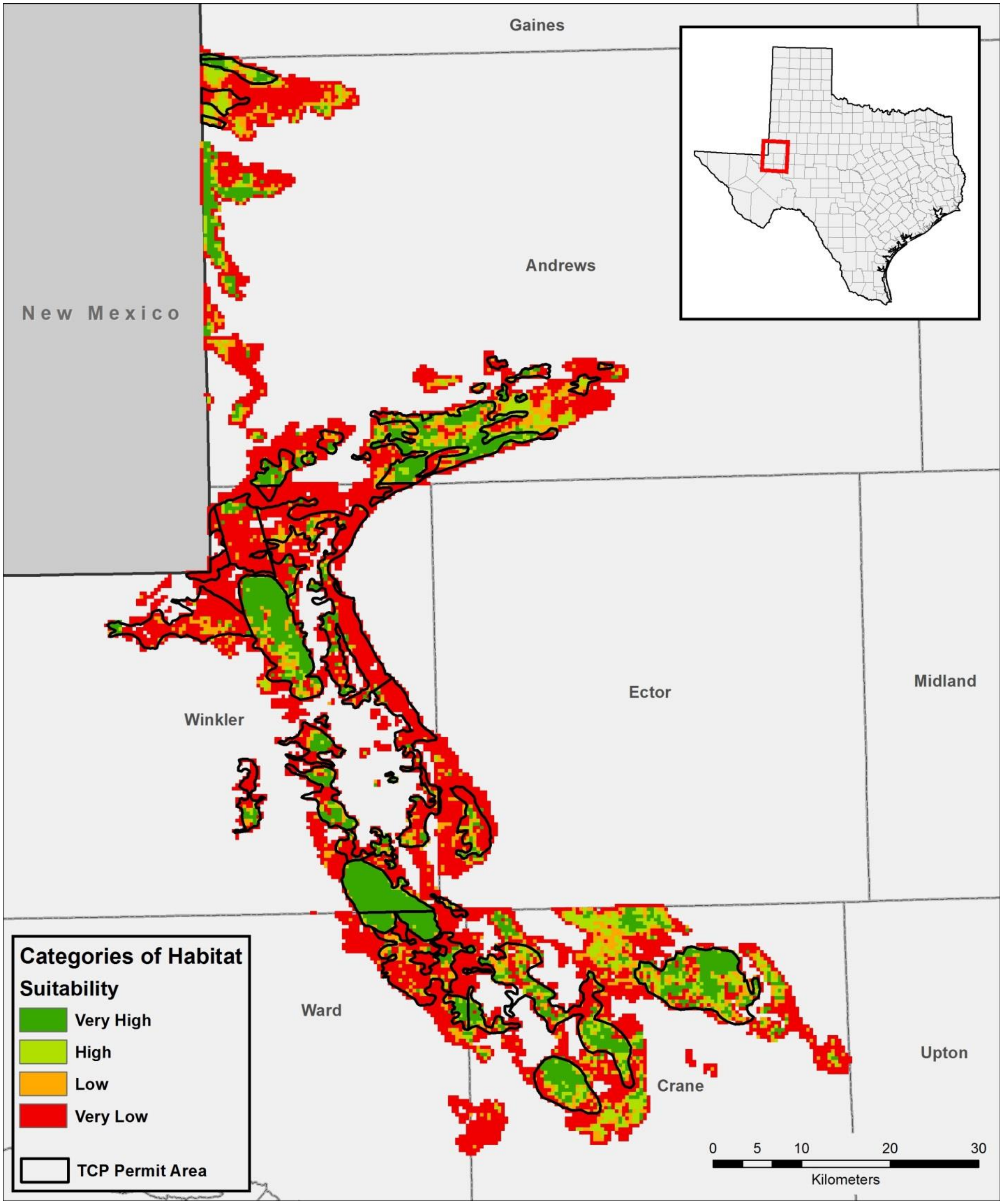


Figure 6.3. Habitat Suitability Map (projected in grid cell format) overlaid on top of the habitat delineation identifying the TCP Permit Area.

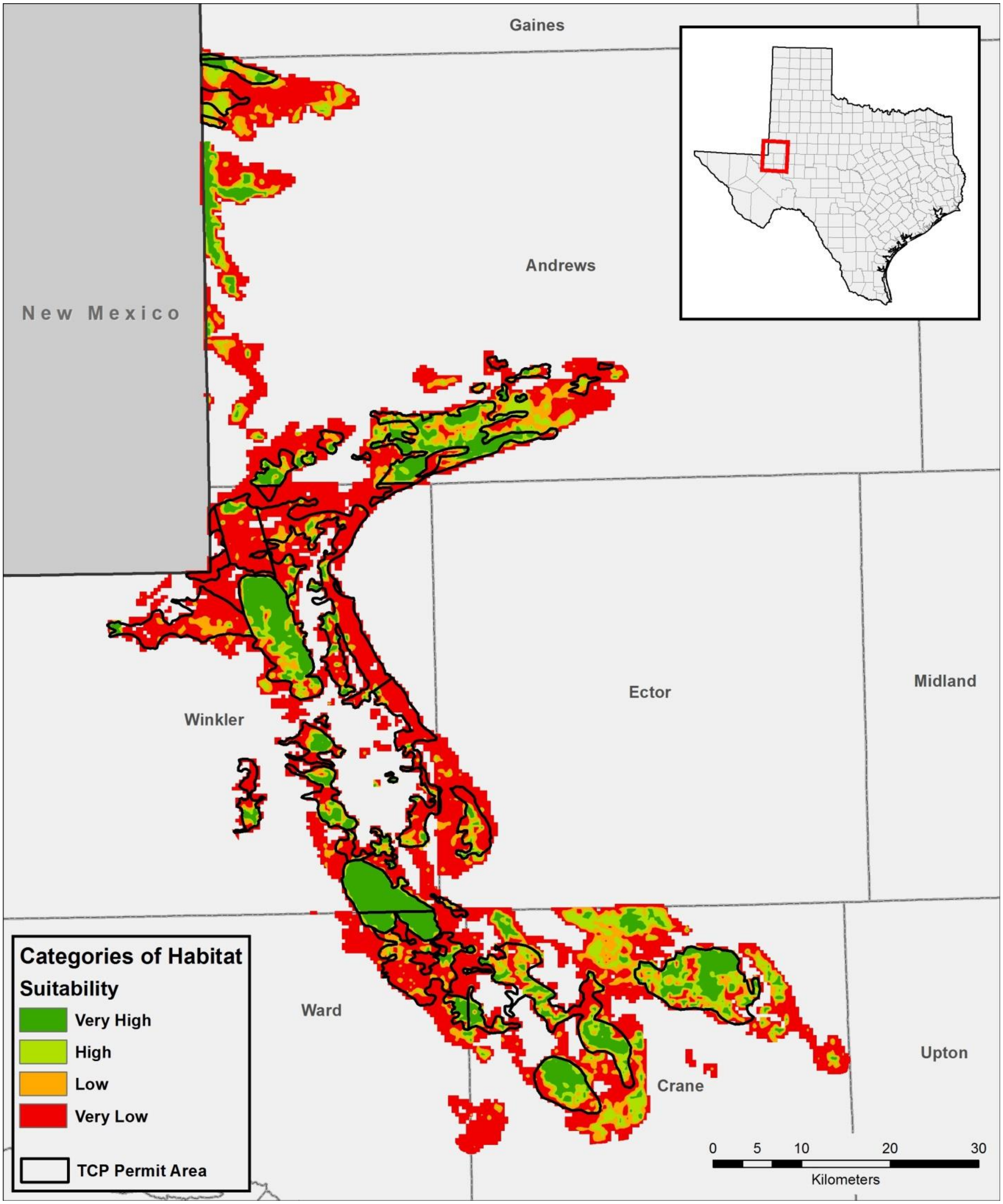


Figure 6.4. Habitat Suitability Map (projected in smoothed format) overlaid on top of the habitat delineation identifying the TCP Permit Area.

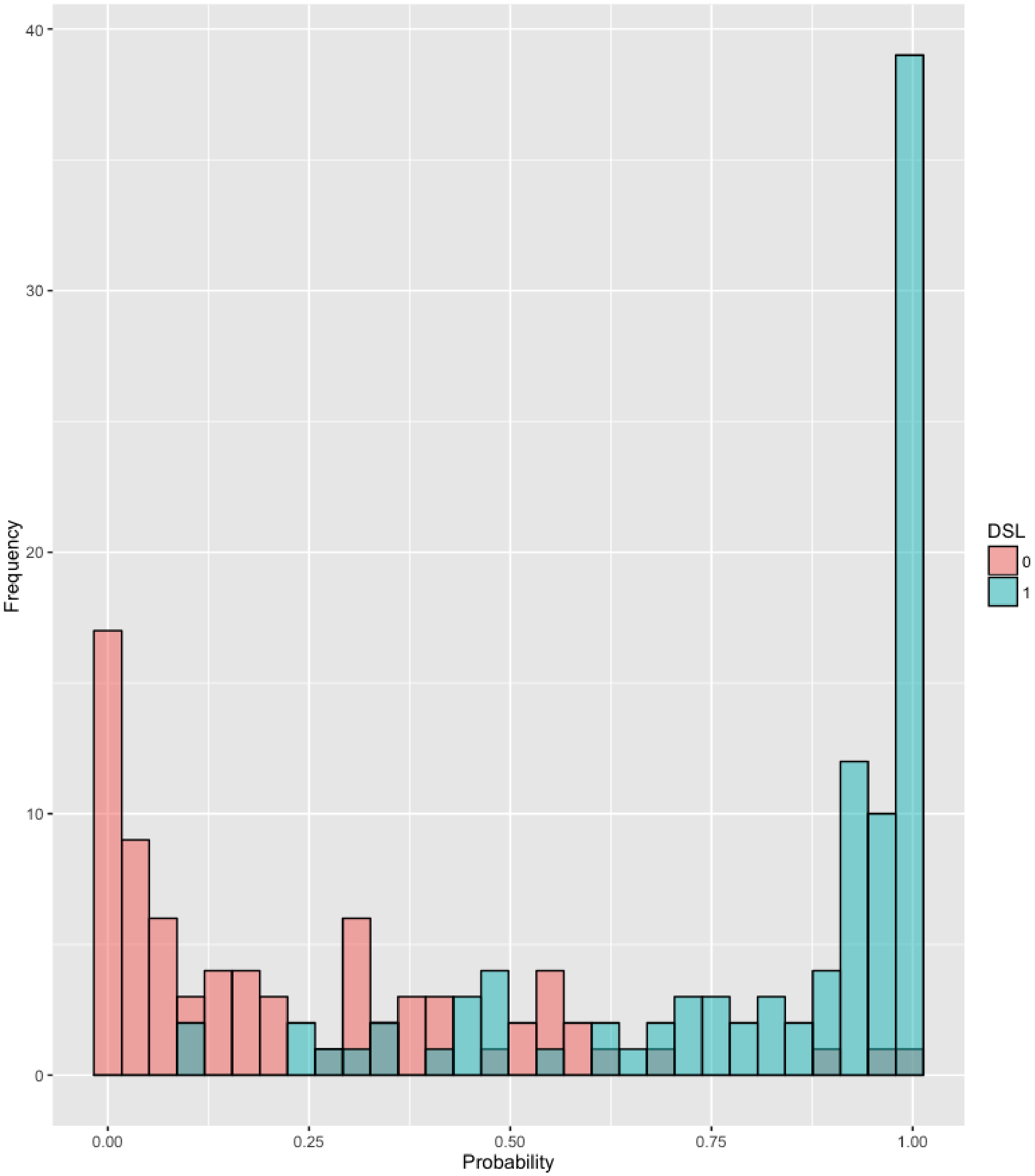


Figure 6.5. Histogram showing the presence ("1") and absence ("0") of the DSL by habitat suitability (probability of occurrence; very high 1.00-0.75, high 0.74-0.50, low 0.49-0.25, and very low 0.24-0.00) for all 2011-2015 surveyed locations in Texas.

6.4 Conclusions

Is the DSL Habitat Suitability Map at least as accurate as the current TCP Permit Area/Likelihood of Occurrence Map?

No, not range-wide in Texas. The current TCP Permit Area/Likelihood of Occurrence Map is less precise, but more accurate in predicting occupancy of the DSL than the DSL Habitat Suitability Map (Fig. 6.2). As such, the current TCP Permit Area/Likelihood of Occurrence Map is conservative in its preservation of DSL habitat at landscape scales. Under the Habitat Suitability Map, 15% of DSL detections (n = 15) occur in sites predicted to have low and very low habitat suitability (orange and red; Table 6.6, Fig. 6.5), whereas zero DSL detections occur in sites with low and very low likelihood of occurrence (CHAPTER 5). This indicates that increasing precision in habitat suitability came at a cost of model accuracy in certain regions within the DSL distribution in Texas. This trade-off between increased precision and accuracy in the habitat suitability map is partially explained by localized limitations in available imagery causing over and under-representation of habitat features during imagery classification and remote sensing steps of our analysis. It is possible that this trade-off between increased precision and accuracy can be mitigated with additional custom imagery at specific locations.

Despite its administrative limitations, the DSL Habitat Suitability Map can help identify areas where habitat conservation should be a priority and guide current and future research related to conservation and management objectives under the TCP, especially in habitats with very high suitability (dark green). A major conclusion of the research presented in this report is that roads fragment DSL habitat and subdivide populations by restricting individual movements. Road removal could possibly facilitate individual movements and restore population connectivity ensuring DSL persistence. By overlaying roads on top of the Habitat Suitability Map, we can identify priority areas for road removal in southern Andrews and central Crane Counties, which contain the most habitat exhibiting very high suitability under the greatest threat from roads (Fig. 6.6). This fine scale information was not available before, especially for Crane County.

This approach has already been used to identify sites for research related to conservation and management objectives under the TCP in Crane County. Specifically, we are researching 1) the effects of road and well pad reclamation on DSL habitat suitability, and 2) the feasibility of re-establishing populations of the DSL in unoccupied but otherwise suitable habitats using translocation (Appendix A).

<u>Recommendation</u>: The observed accuracy of the current TCP Permit Area/Likelihood of Occurrence Map over the last four years of surveys indicates that it is more effective at preserving DSL habitat at landscape scales than the Habitat Suitability Map. No updates to the TCP Permit Area/Likelihood of Occurrence Map are needed at this time.

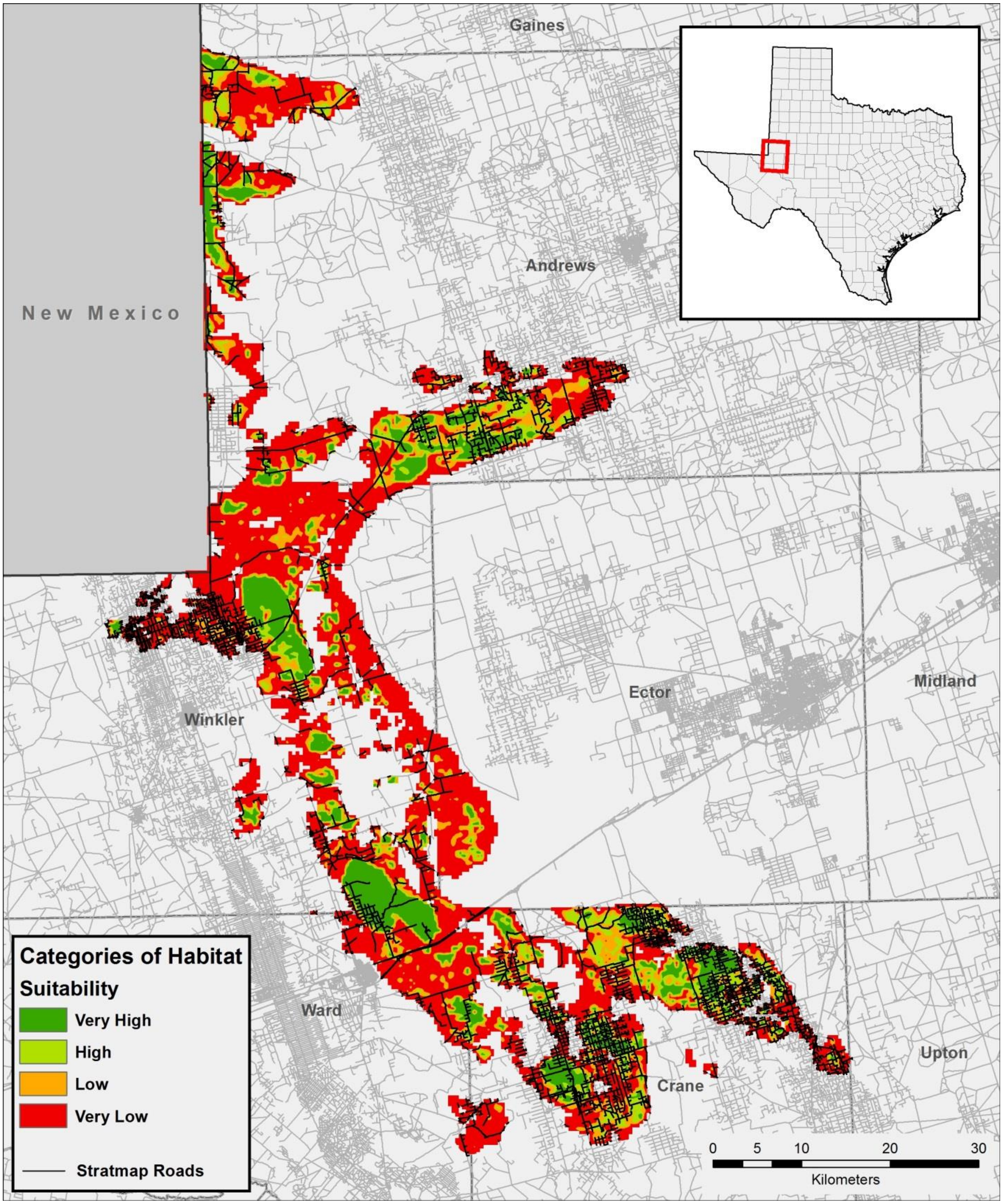


Figure 6.6. Habitat Suitability Map (projected in smoothed format) with major roads overlaid on top. Southern Andrews and Crane Counties contain the most habitat exhibiting very high suitability with the greatest density of roads.

APPENDIX A – FUTURE RESEARCH ON THE DUNES SAGEBRUSH LIZARD IN TEXAS

A.1 Background

The overarching goal for conservation of the Dunes Sagebrush Lizard (DSL; *Sceloporus arenicolus*) is to sustain a broad pattern of habitat occupancy throughout the range of the species. There are numerous areas with highly suitable, but unoccupied habitat for the DSL. Based on the movement, demographic, and road avoidance research described here (CHAPTERS 2-4), we know that re-establishment of the DSL in these areas with highly suitable habitat can only happen in the near term with assisted colonization via translocations. Additionally, based on distribution surveys and the model of habitat suitability (CHAPTERS 5-6), we know there are numerous unoccupied habitats that have been fragmented by roads and well pads and encroached by mesquite. Restoration of these habitats followed by successful establishment of DSL via translocations will sustain a broad pattern of habitat occupancy throughout the species' range and ensure the conservation of this species into the future.

To accomplish this conservation goal, we developed the following 3 research projects:

- Translocation of the DSL to Unoccupied Habitat in Texas
- Effects of Road and Well Pad Reclamation on DSL Habitat Suitability
- Effects of Mesquite on DSL Habitat Suitability and Occupancy

These projects will also support continued annual survey and monitoring efforts to evaluate the status and trends of DSL occupancy and occurrence across different quality habitats through time. Power analyses of our current distribution survey data (CHAPTER 5) indicate that an additional year of surveys (2016) could almost double our power or ability to detect differences in occupancy across most modeled habitat suitability classes (CHAPTERS 6). Results from these continued surveys and the ensuing occupancy analysis will help determine if conservation actions are meeting, exceeding, or falling short of expected conservation benefits.

A.2 Translocation of the DSL to Unoccupied Habitat in Texas

A.2.1 *Research Approach*

The DSL was known to occur at localities in Crane County, TX and elsewhere in the species' range, but have not been detected at those sites in several decades. A number of these sites represent opportunities for re-establishing populations. In April 2016, we began a research project designed to translocate the DSL from relatively large populations to unoccupied sites where the species was historically known to occur and where habitat conditions are highly suitable (CHAPTER 6). We will use a soft-release strategy in a series of nearby enclosures in the translocation area. Soft-release involves keeping translocated individuals in temporary enclosures during an acclimation period. After the acclimation period, the enclosures are opened and individuals can disperse throughout the larger area of habitat. The soft-release strategy with enclosures is a proven technique that allows translocated individuals to become accustomed to new surroundings and each other and to encounter refugia in their new habitat.

Translocation success will be monitored and evaluated over 4 years of trapping, including year 1, the translocation year. In the year following translocation (year 2), trapping will confirm the survival of founding individuals and quantify the number of hatchlings they produced. Trapping in subsequent years (3-4) will confirm the survival and reproduction of those hatchlings, and provide data used to determine the population growth rate. Long-term population viability will be estimated at the end of the four-year study.

A.2.2 *Conservation Implications*

The results from this research will help determine the feasibility of re-establishing populations of the DSL in unoccupied but otherwise suitable habitats. Information gathered from this translocation study will help create a standardized protocol for all future translocations in both restored habitats and unoccupied suitable habitats.

A.3 Effects of Road and Well Pad Reclamation on DSL Habitat Suitability

A.3.1 *Research Approach*

Research consistently points to the quality and connectivity of large contiguous areas of suitable habitat as the main factor affecting DSL persistence. Habitat fragmentation and degradation from roads and well pads have been identified as a threat to suitable habitats and DSL populations range-wide. Restoration of these degraded habitats, and the future translocation of DSL populations to them, will help maintain a broad pattern of occupancy throughout the species' range.

To accomplish this goal, several sites within highly suitable, but unoccupied DSL habitat were identified for road and well pad reclamation. In 2015-16, the caliche layer at each of these reclamation sites was removed leaving the underlying sand exposed. We will use before-after and control-treatment comparisons of physical habitat features (e.g., sand grain composition, soil compaction) known to be important for DSL persistence to characterize changes in habitat suitability at these sites over time following the road and well pad reclamation. Analysis of these data will allow us to determine if reclaimed sites have the characteristics of sand, topography, and vegetative cover that are known to predict the occurrence of DSL. We anticipate three years of habitat surveys post-treatment.

A.3.2 *Conservation Implications*

The results from this research will help create a standardized protocol for future road and well pad reclamation in highly suitable habitats. Restored sites in unoccupied but highly suitable habitat will be considered acceptable for potential translocations.

A.4 Effects of Mesquite on DSL Habitat Suitability and Occupancy

A.4.1 *Research Approach*

In the TCP (section 8.6.2), mesquite and invasive species removal are listed as conservation measures that Participants may undertake to enhance the survival of the DSL and conserve DSL habitat. Removing mesquite may indirectly benefit DSL by curbing continued mesquite invasions and improving rangelands regionally. Indeed, the presence of mesquite in DSL habitat was associated with the absence of DSL in our habitat suitability analyses (CHAPTER 6). That said, a direct effect of brush management on DSL populations has not been observed. Current and future research is designed to better understand the relationship between mesquite, habitat degradation, habitat restoration, and DSL population dynamics.

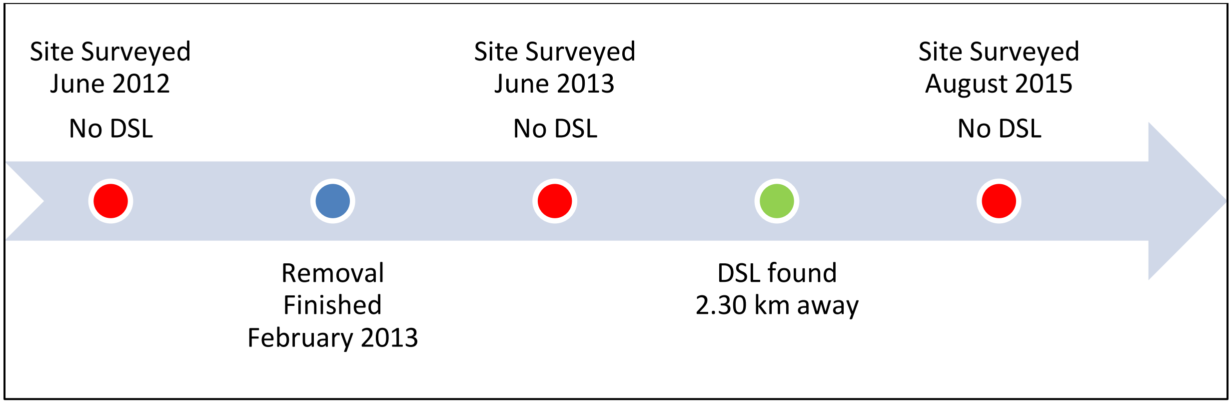
In the last 3 years (2013-15), four mesquite removal experiments were initiated to study the effectiveness of this conservation practice for restoring degraded DSL habitats and populations. Removal techniques have been successful at eliminating nearly all mesquite without major habitat disturbances; however, habitat surveys before and after mesquite removal indicate that it is uncertain if habitat for the DSL will become suitable at these sites (Fig. A.1). Additionally, lizard surveys before and after mesquite removal indicate that DSL populations did not, and presently do not, occupy these sites, although occupied suitable habitats exist nearby.

Figure A.1. Four mesquite control projects have been initiated to date. Below we present the project timelines for each. Different colored circles in the timeline represent the following events:

🔴 Negative DSL survey
🟢 Positive DSL survey
🔵 Mitigation action

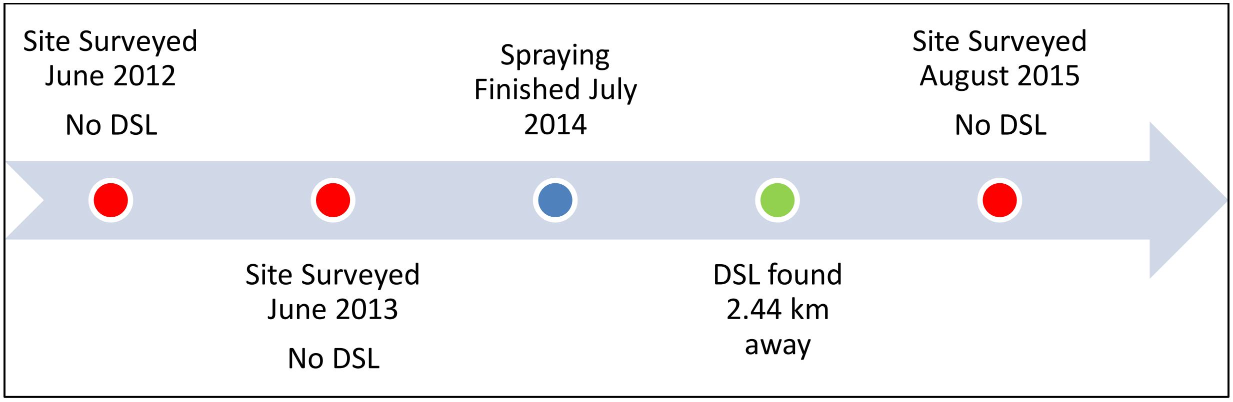
<u>Project 001</u> – Mechanical mesquite removal

<u>Timeline</u>



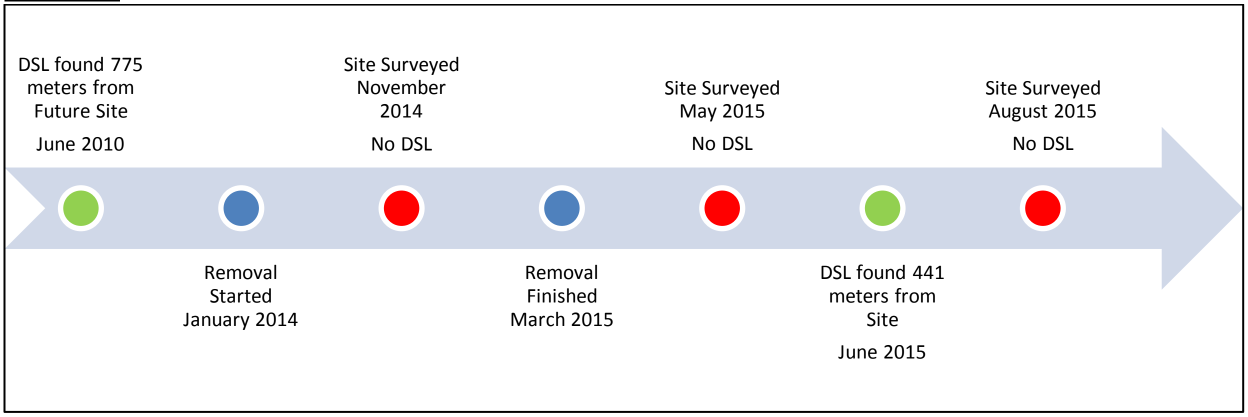
Project 003 – Mesquite spray treatment

Timeline



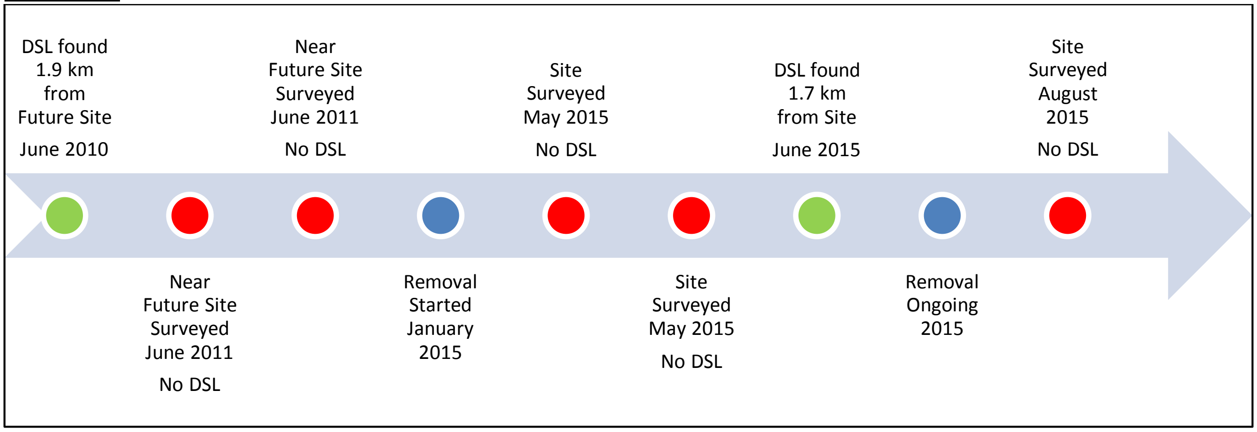
Project 004 – Mechanical mesquite removal

Timeline



Project 005 – Mechanical mesquite removal

Timeline



If suitable habitat were to regenerate at these sites, natural colonization by DSL populations would occur slowly. We propose to continue tracking changes in habitat suitability at these sites and to monitor their potential for DSL colonization.

Given the expected slow rate of change at these sites, we propose additional research designed to characterize changes in habitat suitability and DSL occupancy based on historical patterns of mesquite encroachment. We will use a chronosequence methodology to investigate the effect of mesquite on DSL habitat suitability and occupancy. A chronosequence is a sample of locations in DSL habitat that have been invaded by mesquite at different points in time. Some sites will have recent encroachment, and other sites will be decades old. Each site represents a different "stage" (e.g., early, late) in the encroachment process. Data on habitat and landscape condition across these sites will help document long-term changes in how habitat suitability for DSL changes as it is invaded by mesquite. The advantage of chronosequence methodology is results can be obtained in several years versus several decades.

In this current study, preliminary analyses indicate that historical mesquite encroachment into DSL habitats can be observed using Change Detection Analyses (CDA). These analyses will identify sites within DSL habitat that are in different "stages" of mesquite encroachment. By measuring physical habitat features known to be important for DSL persistence across encroachment sites at different stages, we can characterize the mechanism and estimate the speed with which mesquite degrades suitable habitats and disrupts DSL population dynamics.

Changes in habitat suitability and DSL occupancy across the four mesquite removal sites will be monitored and evaluated over 4 years using standardized habitat suitability and lizard surveys. Changes in habitat suitability and DSL occupancy across the chronosequence of mesquite encroachment sites will also be quantified over 4 years using the same habitat and lizard survey methods. Baseline rates of mesquite encroachment into DSL habitats and natural rates of DSL habitat movement, creation and stabilization will be quantified. Comparisons of these rates, changes in the pattern and configuration of dunes, and other physical habitat features (e.g., sand grain composition, soil compaction) across the chronosequence mesquite sites and mesquite removal sites will help characterize effects of mesquite on DSL habitat suitability and occupancy.

A.4.2 *Conservation Implications*

In the Texas Conservation Plan (TCP), mesquite removal has the largest recovery value, but the conservation value of this practice for enhancing DSL populations is uncertain. The results from this research will determine the efficacy of mesquite removal practices for DSL conservation and help evaluate their current recovery value. Additionally, information gathered from this study will help identify future mesquite removal sites and provide a standardized protocol for identifying restored suitable habitats that are acceptable for translocations.

APPENDIX B – LITERATURE CITED

Abell, A.J. 1997. Estimating paternity with spatial behaviour and DNA fingerprinting in the striped plateau lizard, *Sceloporus virgatus* (Phrynosomatidae). Behavioral Ecology and Sociobiology 41: 217-226.

Abell, A.J. 1999. Male-female spacing patterns in the lizard, *Sceloporus virgatus*. Amphibia-Reptilia 20: 185-194.

Al-Ahmadi, F.S. and A.S. Hames. 2008. Comparison of four classification methods to extract land use and land cover from raw satellite images for some remote arid areas, Kingdom of Saudi Arabia. JKAU; Earth Sciences 20: 167-191. Available online at http://www.kau.edu.sa/Files/320/Researches/51473_21608.pdf

Andrews, K.M., J.W. Gibbons, D.M. Jochimsen, and J. Mitchell. 2008. Ecological effects of roads on amphibians and reptiles: a literature review. Herpetological Conservation 3:121-143.

Axtell, R.W. 1988. Interpretive Atlas of Texas Lizards – *Sceloporus graciosus arenicolus*. Privately printed. No. 5:1-4.

Beyer, H.L. 2004. Hawth's Analysis Tools for ArcGIS. Available online at http://www.spatialecology.com/htools.

Brehme, C.S., J.A. Tracey, L.R. McClenaghan, and R. Fisher. 2013. Permeability of roads to movement of scrubland lizards and small mammals. Conservation Biology 27: 710-720.

Burnham, K.P. and D.R. Anderson. 1998. Model selection and inference: a practical information-theoretic approach. Springer-Verlag: New York. 353 pp.

Burt, W.H. 1943. Territoriality and home range concepts as applied to mammals. Journal of Mammalogy 24: 346-352.

Chan L.M., J.W. Archie, A.D. Yoder, and L.A. Fitzgerald. 2013. Review of the systematic status of *Sceloporus arenicolus* (Degenhardt and Jones 1972) with an estimate of divergence time. Zootaxa 3664: 312-320.

Chan, L.M., L.A. Fitzgerald, and K.R. Zamudio. 2007. Characterization of microsatellite markers for the endemic sand dune lizard, *Sceloporus arenicolus*. Molecular Ecology Notes 7: 337-339.

Chan, L.M., L.A. Fitzgerald, and K.R. Zamudio. 2009. The scale of genetic differentiation in the dunes sagebrush lizard (*Sceloporus arenicolus*), an endemic habitat specialist. Conservation Genetics 10: 131-142.

Clark, B.K., B.S. Clark, L.A. Johnson, and M.T. Haynie. 2001. Influence of roads on movements of small mammals. The Southwestern Naturalist 46: 338-344.

Collins, J. 1991. Viewpoint: a new taxonomic arrangement for some North American amphibians and reptiles. Herpetological Review 22: 42-43.

Crooks, J.A. and M.E. Soulé. 1999. Lag times in population explosions of invasive species: causes and implications. In: O.T. Sandlund, P.J. Schei, and Å. Viken, (Eds), Invasive species and biodiversity management. Kluwer Academic Publishers, Dordrecht, Netherlands. pp 103-125.

Degenhardt, W.G. and K.L. Jones. 1972. A new sagebrush lizard, *Sceloporus graciosus*, from New Mexico and Texas. Herpetologica 28: 212-217.

Degenhardt, W.G., C.W. Painter, and A.H. Price. 1996. Amphibians and reptiles of New Mexico. Albuquerque: University of New Mexico Press. 434 pp.

Delgado, J.D., N.L. Arroyo, J.R. Arévalo, and J. Fernández-Palacios. 2007. Edge effects of roads on temperature, light, canopy cover, and canopy height in laurel and pine forests (Tenerife, Canary Islands). Landscape and Urban Planning 81: 328-340.

Devictor, V., R. Julliard, and R. Jiguet. 2008. Distribution of specialist and generalist species among spatial gradients of habitat disturbance and fragmentation. Oikos 117:507-514.

Driscoll, D.A., S.C. Banks, P.S. Barton, D.B. Lindenmayer, and A.L. Smith. 2013. Conceptual domain of the matrix in fragmented landscapes. Trends in Ecology & Evolution 28: 605-613.

Du Preez, C. 2015. A new arc-chord ratio (ACR) rugosity index for quantifying three-dimensional landscape structural complexity. Landscape Ecology 30: 181-192. DOI : 10.1007/s10980-014-0118-8.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. Annual Review of Ecology, Evolution, and Systematics 34: 487-515.

Fahrig, L., J.H. Pedlar, S.E. Pope, P.D. Taylor, and J.F. Wegner. 1995. Effect of road traffic on amphibian density. Biological Conservation 74: 177-182.

Fahrig, L. and T. Rytwinski. 2009. Effects of roads on animal abundance: an empirical review and synthesis. Ecology and Society 14: 21.

Ferner, J.W. 1974. Home-range size and overlap in *Sceloporus undulatus erythrocheilus* (Reptilia: Iguanidae). Copeia 1974: 332-337.

Fitzgerald, L.A., T. Allen, L.M. Chan, J. Chopp, J.R. Dixon, G. Ferguson, A. Gluesenkamp, T.J. Hibbitts, D. Hill, M.T. Hill, R. Howard, D.J. Leavitt, D.B. Miles, C.W. Painter, E. Pifer, W.A. Ryberg, M. Sears, and H.L. Snell. 2012. The Research Program on *Sceloporus arenicolus*: integration of findings, gaps in knowledge, and priorities for conservation-oriented research. Final Report to Center of Excellence for Hazardous Materials Management (CEHMM), Carlsbad, NM. 20 pp.

Fitzgerald, L.A. and C.W. Painter. 2009. Dunes sagebrush lizard (*Sceloporus arenicolus*). In: L.L.C. Jones and R.E. Lovich, (Eds.), Lizards of the American Southwest: a photographic field guide. Rio Nuevo Publishers, Tucson, Arizona. pp 198-201.

Fitzgerald, L.A., C.W. Painter, T.J. Hibbitts, W.A. Ryberg, and N.L. Smolensky. 2011. The range and distribution of *Sceloporus arenicolus* in Texas: results of surveys conducted 8-15 June 2011. Submitted to Institute of Renewable Natural Resources, Texas A&M University. 38 pp.

Fitzgerald, L.A., C.W. Painter, D.A. Sias, and H.L. Snell. 1997. The range, distribution and habitat of *Sceloporus arenicolus* in New Mexico. Final report to New Mexico Department of Game and Fish, Santa Fe. 30 pp + appendices.

Fitzgerald, L.A., M.W. Sears, and C.W. Painter. 2005. Interdune dispersal of sand dune lizards (*Sceloporus arenicolus*) in the Mescalero Sands Ecosystem. Final Report to New Mexico Department of Game and Fish, Santa Fe. 13 pp.

Forman, R.T. and L.E. Alexander. 1998. Roads and their major ecological effects. Annual Review of Ecology and Systematics 29: 207-231.

Forman, R.T.T. 2000. Estimate of the area affected ecologically by the road system in the United States. Conservation Biology 14: 31-35.

Forman, R.T.T., D. Sperling, J.A. Bissonette, A.P. Clevenger, C.D. Cutshall, V.H. Dale, L. Fahrig, R. France, C.R. Goldman, K. Heanue, J.A. Jones, F.J. Swanson, T. Turrentine, T.C. Winter. 2003. Road ecology: science and solutions. Island Press, Washington. 481 pp.

Futuyma, D.J. and G. Moreno. 1988. The evolution of ecological specialization. Annual Review of Ecology, Evolution, and Systematics 19: 207-233.

Gardner, T.A., J. Barlow, and C.A. Peres. 2007. Paradox, presumption and pitfalls in conservation biology: the importance of habitat change for amphibians and reptiles. Biological Conservation 138: 166-179.

Gerlach, G. and K. Musolf. 2000. Fragmentation of landscape as a cause for genetic subdivision in bank voles. Conservation Biology 14: 1066-1074.

Gibbs, J.P. and W.G. Shriver. 2002. Estimating the effects of road mortality on turtle populations. Conservation Biology 16: 1647-1652.

Gibbons, W., D.E. Scott, T.J. Ryan, K.A. Buhlmann, T.D. Tuberville, B.S. Metts, J.L. Greene, T. Mills, Y. Leiden, S. Poppy, and C.T. Winne. 2000. The global decline of reptiles, déjá vu amphibians. BioScience 50: 653-666.

Gilbert-Norton, L., R. Wilson, J.R. Stevens, and K.H. Beard. 2010. A Meta-Analytic Review of Corridor Effectiveness. Conservation Biology 24:660-668.

Haenel, G.J., L.C. Smith, and H.B. John-Alder. 2003. Home-range analysis in *Sceloporus undulatus* (eastern fence lizard). I. spacing patterns and the context of territorial behavior. Copeia 2003: 99-112.

Hanski, I. 1999. Metapopulation ecology. Oxford University Press, Oxford. 313 pp.

Hathcock, C.D. and M.T. Hill. 2012. Loggerhead shrike predation on dunes sagebrush lizards in southeastern New Mexico. Final Report submitted to Center of Excellence for Hazardous Materials Management, Carlsbad, NM. 33 pp.

Hels, T. and E. Buchwald. 2001. The effect of road kills on amphibian populations. Biological Conservation 99: 331-340.

Hews, D.K. 1993. Food resources affect female distribution and male mating opportunities in the iguanian lizard *Uta palmeri*. Animal Behaviour 46: 279-291.

Hibbitts, T.J., C.W. Painter, and A.T. Holycross. 2009. Ecology of a population of the narrow headed garter snake (*Thamnophis rufipunctatus*) in New Mexico: catastrophic decline of a river specialist. The Southwestern Naturalist 54: 461-467.

Hibbitts, T.J., W.A. Ryberg, C.S. Adams, A.M. Fields, D. Lay, and M.E. Young. 2013. Microhabitat selection by a habitat specialist and a generalist in both fragmented and unfragmented landscapes. Herpetological Conservation and Biology 8: 104-113.

Hill, M.T. and L.A. Fitzgerald. 2007. Radiotelemetry and population monitoring of sand dune lizards (*Sceloporus arenicolus*) during the nesting season. Final report submitted to Share with Wildlife Program, New Mexico Department of Game and Fish, Santa Fe. 31 pp.

Hulme, P.E. 2009. Trade, transport and trouble: managing invasive species pathways in an era of globalization. Journal of Applied Ecology 46: 10-18.

Jaeger, J.A., G.J. Bowman, J. Brennan, L. Fahrig, D. Bert, J. Bouchard, N. Charbonneau, K. Frank, B. Gruber, and K. Tluk von Toschanowitz. 2005. Predicting when animal populations are at risk from roads: an interactive model of road avoidance behavior. Ecological Modeling 185:329–348.

Laurencio, L.R. and L.A. Fitzgerald. 2010. Atlas of distribution and habitat of the dunes sagebrush lizard (*Sceloporus arenicolus*) in New Mexico. Texas Cooperative Wildlife Collection, Department of Wildlife and Fisheries Sciences, Texas A&M University, College Station, TX 77843-2258. ISBN# 978-0-615-40937-5.

Laurencio, L., D. Laurencio, and L.A. Fitzgerald. 2007. Geographic distribution and habitat suitability of the sand dune lizard (*Sceloporus arenicolus*) in Texas. Final report submitted to Texas Parks and Wildlife Department, Lubbock. 16 pp + appendix.

Leavitt, D.J. 2012. Ecological consequences of landscape fragmentation on the lizard community in the Mescalero-Monahans Shinnery sands. PhD dissertation. Texas A&M University, College Station, TX. 130 pp.

Leavitt, D.J. and L.A. Fitzgerald. 2013. Disassembly of a dune-dwelling lizard community due to landscape fragmentation. Ecosphere 4: 97. DOI: http://dx.doi.org/10.1890/ES13-00032.1

Lebreton, J.-D., K.P. Burnham, J. Clobert, and D.R. Anderson. 1992. Modeling survival and testing biological hypotheses using marked animals: a unified approach with case studies. Ecological Monographs 62: 67-118.

Lesbarrères, D. and L. Fahrig. 2012. Measures to reduce population fragmentation by roads: what has worked and how do we know? Trends in Ecology & Evolution 27:374-380.

Machenberg, M.D. 1984. Geology of Monahans Sandhills State Park, Texas. University of Texas Bureau of Economic Geology Guidebook 21. 39 pp.

Manteuffel, V.M. and M. Eiblmaier. 2008. The influence of competitor density on space use in juvenile striped plateau lizards (*Sceloporus virgatus*). Acta Oecologia 33: 365-371.

McGarigal, K. and S.A. Cushman. 2002. Comparative evaluation of experimental approaches to the study of habitat fragmentation effects. Ecological Applications 12: 335-345.

McGregor, R. 2004. The effect of roads on small mammal move-ment. M.Sc. thesis, Department of Biology at Carleton University, Ottawa, Ontario, 40 pp.

Merriam, G., M. Kozakiewicz, E. Tsuchiya, and K. Hawley. 1989. Barriers as boundaries for metapopulations and demes of *Peromyscus leucopus* in farm landscapes. Landscape Ecology 2: 227–235.

Noss, R.F., H.B. Quigle, M.G. Hornocker, T. Merrill, P.C. Paquet. 1996. Conservation biology and carnivore conservation in the Rocky Mountains. Conservation Biology 10: 949-963.

Ortega, Y.K. and D.E. Capen. 1999. Effects of forest roads on habitat quality for ovenbirds in a forested landscape. The Auk 116: 937-946.

Painter, C.W., L.A. Fitzgerald, D.A. Sias, L. Pierce, and H.L. Snell. 1999. Management plan for *Sceloporus arenicolus* in New Mexico. Management Plan for New Mexico Department of Game and Fish, Bureau of Land Management, US Fish and Wildlife Service. 45 pp + 9 appendices.

Perry, G. and T. Garland Jr. 2002. Lizard home ranges revisited: effects of sex, body size, diet, habitat, and phylogeny. Ecology 83: 1870-1885.

Peterson, M.N., R.R. Lopez, N.J. Silvy, C.B. Owen, P.A. Frank, and A.W. Braden. 2003. Evaluation of deer-exclusion grates in urban areas. Wildlife Society Bulletin 31: 1198-1204.

Pradel, R. 1996. Utilization of capture-mark-recapture for the study of recruitment and population growth rate. Biometrics 52: 703-709.

Reijnen, R. and R. Foppen. 1994. The effects of car traffic on breeding bird populations in woodland. I. evidence of reduced habitat quality for willow warblers (*Phylloscopus trochilus*) breeding close to a highway. Journal of Applied Ecology 31: 85-94.

Reijnen, R., R. Foppen, C. Ter Braak, and J. Thissen. 1995. The effects of car traffic on breeding bird populations in woodland. III. Reduction of density in relation to the proximity of main roads. J. Appl. Ecol. 32: 187–202.

Reijnen, R., R. Foppen, and H. Meeuwsen. 1996. The effects of traffic on the density of breeding birds in dutch agricultural grasslands. Biological Conservation 75: 255–260.

Reijnen, R., R. Foppen, and G. Veenbaas. 1997. Disturbance by traffic of breeding birds: evaluation of the effect and considerations in planning and managing road corridors. Biodiversity Conservation 6: 567–581.

Rose, B. 1982. Lizard home ranges: methodology and functions. Journal of Herpetology 16: 253-269.

Ruby, D.E. and A.E. Dunham. 1987. Variation in home range size along an elevational gradient in the iguanid lizard *Sceloporus merriami*. Oecologia 71: 473-480.

Ryberg, W.A. and L.A. Fitzgerald. 2015. Sand grain size composition influences subsurface oxygen diffusion and distribution of an endemic, psammophilic lizard. Journal of Zoology 295: 116-121.

Ryberg, W.A., M.T. Hill, D. Lay, and L.A. Fitzgerald. 2012. Observations on the reproductive and nesting ecology of the dunes sagebrush lizard (*Sceloporus arenicolus*). Western North American Naturalist 72: 582-585.

Ryberg, W.A., M.T. Hill, C.W. Painter, and L.A. Fitzgerald. 2013. Landscape pattern determines neighborhood size and structure within a lizard population. PLoS ONE 8(2): e56856. DOI:10.1371/journal.pone.0056856.

Ryberg, W.A., M.T. Hill, C.W. Painter, and L.A. Fitzgerald. 2015. Linking irreplaceable landforms in a self-organizing landscape to sensitivity of population vital rates for an ecological specialist. Conservation Biology 29: 888-898.

Rytwinski, T. and L. Fahrig. 2012. Do species life history traits explain population responses to roads? A meta-analysis. Biological Conservation 147: 87-98.

Sabo, J.L. 2003. Hot rocks or no hot rocks: overnight retreat availability and selection by a diurnal lizard. Ecophysiology 136: 329-335.

Sappington, J.M., K.M. Longshore, and D.B. Thomson. 2007. Quantifiying landscape ruggedness for animal habitat analysis: a case study using bighorn sheep in the Mojave Desert. Journal of Wildlife Management 71: 1419-1426.

Saunders, D.A., R.J. Hobbs, and C.R. Margules. 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5: 18-32.

Schoener, T.W. 1981. An empirically based estimate of home range. Theoretical Population Biology 20: 281-325.

Seaman, D.E., J.J. Millspaugh, B.J. Kernohan, G.C. Brundige, K.J. Raedeke, and R.A. Gitzen. 1999. Effects of sample size on kernel home range estimates. Journal of Wildlife Management 63: 739-747.

Shine, R. 2003. Effects of pregnancy on locomotor performance: an experimental study on lizards. Behavioural Ecology 136: 450-456.

Sias, D.S. and H.L. Snell. 1998. The dunes sagebrush lizard *Sceloporus arenicolus* and oil and gas development in southeastern New Mexico. Final report of field studies 1995-1997. Final report to New Mexico Department of Game and Fish. Contract #80-516.6-01. 27 pp.

Smith, D.C. 1985. Home range and territory in the striped plateau lizard (*Sceloporus virgatus*). Animal Behaviour 33: 417-427.

Smolensky, N.L. and L.A. Fitzgerald. 2010. Distance sampling underestimates population densities of dune-dwelling lizards. Journal of Herpetology 44: 372-381.

Smolensky, N.L. and L.A. Fitzgerald. 2011. Population variation in dune-dwelling lizards in response to patch size, patch quality, and oil and gas development. The Southwestern Naturalist 56: 325-324.

Swihart, R.K. and N.A. Slade. 1984. Road crossing in *Sigmodon hispidus* and *Microtus ochrogaster*. Journal of Mammalogy 65: 357-360.

Swihart, R.K. and N.A. Slade. 1985. Testing for independence of observations in animal movements. Ecology 66: 1176-1184.

Taylor, P.D., L. Fahrig, K. Henein, and G. Merriam. 1993. Connectivity is a vital element of landscape structure. Oikos 68: 571-573.

Texas Comptroller of Public Accounts. 2012. Texas conservation plan for the dunes sagebrush lizard (*Sceloporus arenicolus*). Austin.

Turchin, P. 1998. Quantitative analysis of movement: measuring and modeling population redistribution in animals and plants. Sinauer Associates, Inc., Sunderland, Maryland. 396 pp.

United States Fish and Wildlife Service. 2010. Endangered and threatened wildlife and plants; endangered status for dunes sagebrush lizard. Department of the Interior, Washington, DC. Fededral Register, 75, 77801-77817.

United States Fish and Wildlife Service. 2012. Endangered and threatened wildlife and plants; withdrawal of proposed rule to list Dunes Sagebrush Lizard. Department of the Interior, Washington, DC. Fededral Register, 77, 36872-36899.

van der Ree, R., E. van der Grift, C. Mata, and F. Suarez. 2007. Overcoming the barrier effect of roads—how effective are mitigation strategies? An international review of the use and effectiveness of underpasses and overpasses designed to increase the permeability of roads for wildlife. Pages 423–431 in C. L. Irwin, D. Nelson, and K. P. McDermott, editors. Proceedings of the 2007 International Conference on Ecology and Transportation. Center for Transportation and Environment, North Carolina State University, Raleigh, North Carolina, USA.

van der Ree, R., D.J. Smith, and C. Grilo. 2015. Handbook of road ecology. John Wiley & Sons, West Sussex, UK. 522 pp. DOI: 10.1002/9781118568170

Walkup, D.K., D.J. Leavitt, and L.A. Fitzgerald. In review. Effects of habitat fragmentation on population structure of dune-dwelling lizards. Biodiversity and Conservation.

Walkup, D.K., D.J. Leavitt, W.A. Ryberg, and L.A. Fitzgerald. 2014. Results from 2009-2013: effects of landscape fragmentation on the Mescalero dune landscape and populations of the dunes sagebrush lizard, *Sceloporus arenicolus*. Final Report submitted to the Bureau of Land Management, Carlsbad, NM. 36 pp.

Wiens, J.J., C.A. Kuczynski, S. Arif, and T.W. Reeder. 2010. Phylogenetic relationships of phrynosomatic lizards based on nuclear and mitochondrial data, and a revised phylogeny for *Sceloporus*. Molecular Phylogenetics and Evolution 54: 150-161.

Wiens, J.J. and T.W. Reeder. 1997. Phylogeny of the spiny lizards (*Sceloporus*) based on molecular and morphological evidence. Herpetological Monographs 11:1-101.

White, G.C. and K.P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46: Supplement, 120-138.

White, G.C. and R.A. Garrott. 1990. Analysis of wildlife radio-tracking data. Academic Press Inc., San Diego, California. 383 pp.

Whitfield, S.M., K.E. Bell, T. Philippi, M. Sasa, F. Bolaños, G. Chaves, J.M. Savage, and M.A. Donnelly. 2007. Amphibian and reptile declines over 35 years at La Selva, Costa Rica. Proceedings of the National Academy of Sciences 104: 8352-8356.

Whiting, M.J. 1999. When to be neighbourly: differential agonistic responses in the lizard *Platysaurus broadleyi*. Behavioural Ecology and Sociobiology 46:210-214.

Woltz, H.W., J.P. Gibbs, and P.K. Ducey. 2008. Road crossing structures for amphibians and reptiles: informing design through behavioral analysis. Biological Conservation 141: 2745-2750.

Worton, B.J. 1987. A review of models of home range for animal movement. Ecological Modelling 38: 277-298.

Wright, D.J., M. Pendleton, J. Boulware, S. Walbridge, B. Gerlt, D. Eslinger, D. Sampson, and E. Huntley. 2012. ArcGIS Benthic Terrain Modeler (BTM), v. 3.0, Environmental Systems Research Institute, NOAA Coastal Services Center, Massachusetts Office of Coastal Zone Management. Available online at http://esriurl.com/5754.