HABITAT AVAILABILITY ASSESSMENT FOR THE GULF COAST KANGAROO RAT (*DIPODOMYS COMPACTUS)* IN SOUTH-CENTRAL TEXAS

by

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DEDICATION

I would like to dedicate this thesis to women in science, past and present. An enormous thank you to the women who came before me and struggled to make this possible. Specifically, I am grateful for my grandmother Reba Earle Felts (née Smith), a science educator and a fellow Texas State University alumni. She inspired me to be curious about the natural world, and she encouraged me to pursue higher education and follow my passion for learning. Thank you.

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ABSTRACT

As the human population increases worldwide, urbanization, habitat destruction, and habitat modification also increase. Recently the urbanization rate in Central Texas has become one of the highest in the nation. The consequential loss of natural habitat could jeopardize native wildlife species that are already somewhat limited in their distribution. Based on specialized life-history traits that limit large-scale mobility, kangaroo rats (*Dipodomys spp*.) have been found to be especially sensitive to urbanization-induced habitat modification and fragmentation. *Dipodomys compactus* is one of five kangaroo rat species found in Texas; this species has narrow, specific habitat requirements. Using a geographic information system (GIS)-based habitat suitability model, I determined that due to isolation among suitable habitat patches, actual *D. compactus* range in south-central Texas is highly fragmented, and the particular population in south-central Texas may be more isolated than currently thought. The assessment strategy of GIS habitat mapping can be broadly applied to other vulnerable species with similarly narrow habitat parameters to predict current and future management requirements

I. INTRODUCTION

Kangaroo rats (*Dipodomys*) are granivorous, burrowing rodents adapted to a narrow range of arid to semi-arid conditions; they are nocturnal and active year-round (Nowak 1999). There are 20 species of kangaroo rat in North America, yet only two species, *D. merriami* and *D. ordii*, are widely distributed throughout western North America. Many species in this genus are endemic to the United States or have restricted ranges (typically defined as area < 50,000 km^2), and thus can be regarded as geographically-limited arid habitat specialists. At a smaller scale, specific soil properties can also limit the distribution of many kangaroo rat species; soil that is too dense or too shallow cannot be used for burrowing. Further, some thick exotic grasses can degrade suitable habitat so that it is unfit for kangaroo rats (USFWS 2011; Eldridge and Whitford 2014). Most kangaroo rats require open habitat (little or minimal woody canopy cover) and sandy soil. Unfortunately, this habitat type is also attractive for agricultural and urban development (Williams et al. 1993). As an example, *D. ingens* historically had a range of 7,558 km^2. in southern and central California, but by 1987 due to the conversion of lands to agriculture, *D. ingens* only occupied 1.5% of this habitat (Williams et al. 1993). Another geographically-restricted species, *D. stephensi*, in southern California also experienced significant amounts of habitat loss; by 1984 its range was only 40% of its original extent due to the conversion of land to agriculture and urbanization (Price and Endo 1989).

Kangaroo rats are ecologically significant to the maintenance and functioning of both grassland and rangeland ecosystems. Members of the genus *Dipodomys* have been identified as keystone species, ecosystem engineers, and indicators of rangeland health; these small rodents often have a disproportionate impact on an ecosystem relative to their abundance and biomass in grassland, rangeland, and desert habitats (Brown and Heske 1990; Guo 1996; Kerley et al. 1997; Krogh et al. 2002; Brock and Kelt 2004; Kerley and Whitford 2009). Specifically, the soil disturbances created by seed-caching and burrow formation have positive cascading effects such as increased plant diversity, increased primary productivity, and maintaining plant heterogeneity (Whitford and Kay 1999; Prugh and Brashares 2012). Kangaroo rat burrows also create critical microhabitat for invertebrates, contributing to the ecosystem through bottom-up control by increasing the abundance of prey items for birds and other mammals (Prugh and Brashares 2012). Additionally, kangaroo rats are an important prey base for a variety of nocturnal predators including, coyotes, foxes, snakes, and owls; this predation risk further reduces their dispersal capacity and range (Brown et al. 1988; Longland and Price 1991).

Most kangaroo rats have a relatively small reproductive potential compared to other rodents; only one to three young are born per breeding cycle (Eisenberg and Isaac 1963). Furthermore, reproduction can decrease based on environmental conditions such as precipitation, or food availability (Eisenberg and Isaac 1963; Price and Endo 1989). Natal dispersion of juveniles can occur from two months to one year after birth, depending on a variety of socio-ecological conditions affecting the juveniles (Jones 1986; Edelman 2011; Edelman 2014). Dispersal for kangaroo rats on average is constrained, Zeng and Brown (1987) found that in the one month between captures, the majority of *D. merriami* juvenile individuals dispersed less than 30 m. *Dipodomys merriami* annual composite home range is approximately 0.49 ha or 0.65 ha, based on circular and principal components methods respectively (Garrison and Best 1990). Moreover, the majority of *D. merriami* individuals move and forage within a circular area ≤ 0.22 ha

(Garner 1970). In addition, kangaroo rats use a bipedal form of locomotion, limiting their ability to traverse easily (during foraging or juvenile dispersal) through dense ground-level vegetation or rocky environments. Based on these specialized life-history traits that limit large-scale mobility, kangaroo rats are likely to be especially sensitive to habitat modification and fragmentation.

Five kangaroo rat species are found in Texas: *D. compactus*, *D. elator*, *D. merriami*, *D. ordii*, and *D. spectabilis*. Although members of the *Dipodomys* genus are all relatively similar ecologically, *D. compactus* has more precise habitat requirements compared to some other Texas *Dipodomys*, specifically *D. ordii* or *D. merriami*. It is similar in size to *D. ordii*, but unlike *D. ordii*, *D. compactus* occupies areas of soft sandy soil, and low, sparse vegetation exclusively (Baumgardner and Schmidly 1985; Oakley 2012). At one time, *D. ordii* and *D. compactus* were regarded as the same biological species but are currently recognized as separate species (Schmidly and Hendricks 1976; Baumgardner and Schmidly 1981). *Dipodomys compactus* occurs from the sand dune habitat of the barrier islands of coastal Texas inward to the region of South Texas known as the sand sheet. Their range also extends northward to south-central Texas where the species occupies a geological formation called the Carrizo Sand Strip. The Carrizo Sand Strip overlays part of the Carrizo-Wilcox aquifer as sandy soil outcroppings extending from southwestern Texas northeastward into Arkansas and Louisiana (McBryde 1933; Ryder 1996) (Figure 1). A population of *D. compactus* has been documented within sandy outcroppings south of Seguin, Texas (Oakley 2012; Phillips 2012). This population and others nearby in south-central Texas may be geographically isolated from larger and more extensive populations further south in Texas although this possibility has not been directly examined.

Conservation of *D. compactus* is currently of greatest concern at the southern end of South Padre Island at which current and future development threaten species habitat availability (TPWD 2011). Likewise, *D. compactus* conservation may also be of great concern on the northern edge of the geographic range, at which the Carrizo Sand Strip populations might be genetically isolated from the southern Texas and barrier island populations. Urban development in this area of the species' range (e.g., Bexar County) is at an all-time high (United States Census Bureau 2014). The human population in Bexar County increased > 10% from 2010 to 2015, and its largest city, San Antonio, is the seventh largest city in the United States and continuing to expand southward into probable kangaroo rat habitat. Habitat destruction in North Texas and Oklahoma has led to the extirpation of the Texas kangaroo rat (*D. elator*) from its historic range in Oklahoma and parts of Texas. It is now found only in a small part of North Texas (Linzey et al. 2008). Current land use changes may be creating similar conditions of impending range contraction for *D. compactus*. Texas Parks and Wildlife Department currently classifies *D. compactus* state abundance ranking as "vulnerable" due to habitat loss within its coastal range (TPWD 2011).

The threat of habitat loss is not unique to kangaroo rats. Permanent habitat alteration or destruction via urbanization and agriculture endangers more species and reduces species diversity more than any other human activity (Czech et al. 2000; McKinney 2006), even more than current climate change (Maxwell et al. 2016). Habitat loss has been one of the major threats to kangaroo rat populations in the United States.

Rapid and widespread agricultural clearing and urbanization in California from the 1850s to the 1970s led to a substantial reduction in endemic kangaroo rat populations (Williams and Germano 1992). From 1985 to 1988, four kangaroo rat species and subspecies (*Dipodomys ingens*, *Dipodomys nitratoides nitratoides*, *Dipodomys nitratoides exilis*, *Dipodomys stephensi*) endemic to California were listed as federally endangered (USFWS 2014). Through population reduction and habitat loss, kangaroo rats in California may have been more affected by urbanization and fragmentation than any other vertebrate group (Goldingay et al. 1997). Based on the effects of habitat modification on California kangaroo rats and the current rate of agricultural clearing and rapid urbanization in Texas, it is clear that detailed monitoring of habitat requirements and distribution is paramount to prevent endangerment of kangaroo rat species in Texas, particularly *D. elator* and *D. compactus*.

In Texas, high levels of habitat loss, modification, and fragmentation have had large-scale damaging effects on numerous native species (Conner and Rudolph 1991; Lindsay et al. 2008). Human-induced habitat fragmentation can often reduce large areas of contiguous useable natural habitat into fragments that are increasingly smaller and more isolated from each other (Fahrig and Merriam 1985). Although these small fragments, or habitat patches, remain intact, their isolation precludes habitat continuity thereby decreasing the ability for animals to disperse among habitat patches and maintain viable populations within a landscape or greater region. Habitat fragmentation often occurs within regions where a large percentage of land is privately owned.

Because land ownership often involves use of the land for monetary profit, agricultural clearing and urbanization change parcels of land and fragment contiguous habitat. As of 2013, approximately 44.6% of United States land surface had been modified to arable lands, permanent crops, or permanent pasture (The World Bank 2013). In Texas, over 94% of the land is privately owned (Wilkins et al. 2000); this land can be altered to various degrees from a natural condition depending on the preferences and desires of the landowner. Furthermore, as of 2000, 80% of Texas' farms and ranches were less than 205 hectares, and many Texas ranches continue to be sub-divided into increasingly smaller parcels and sold to developers to account for the reduction in agriculture land value (Wilkins et al. 2000). Formerly large expansive tracts of rangeland (also serving as kangaroo rat habitat) may be reduced in the process of subdivision. Land use and urban extent in Texas have changed substantially over the last 35 years and have continued to change rapidly. Approximately 1.7 million hectares of working land, including privately owned farms, ranches, and forests, have been converted to suburban or urban development since 1982 (Texas A&M Institute of Renewable Natural Resources 2014).

In addition to habitat loss, this level of urbanization creates a particular challenge for assessing kangaroo rat populations in Texas because the majority of their range is on numerous private land parcels. Roadside surveys may be the most effective method for assessing population status and species distribution within regions where the vast majority of land is private property and thus difficult to access. Using road-side surveys, I was able to find burrow sites efficiently, estimate the extent of occurrence of *D. compactus*, and evaluate landscape scale habitat associations of the species without the labor and time commitment of gaining private land access.

Detailed information on within-range distribution of a species or extent of occurrence can be very valuable. Population viability is often analyzed and assessed using estimated range and distribution; for example, the International Union for Conservation of Nature (IUCN) uses a species' extent of occurrence, or range, as one of the main criteria for determining conservation status. However, actual distribution is often more fragmented than geographical ranges represent. This can lead to an overestimate of a species' distribution (Rondinini et al. 2011). An overestimate of distribution or range might result in an underestimate of the species' conservation and management needs (Jetz et al. 2008). Moreover, species that are geographically limited and ecological specialists are more likely to have range overestimated (Jetz et al. 2008). Species with low reproductive potential, and high ecological specialization are especially susceptible to habitat fragmentation, i.e. poor habitat connectivity (Spinozzi et al. 2012). Connectivity of suitable habitat is essential for persistence of kangaroo rats (Price and Endo 1989; Cosentino et al. 2014). Although IUCN (Linzey and Hammerson 2008) lists the extent of occurrence (geographic range area) of *D. compactus* as much greater than 20,000 km^2, the actual area occupied by populations (i.e., extent of occurrence) may be far less. I hypothesize that due to fragmentation, and thus isolation among suitable habitat patches, the range of *D. compactus* (as indicated by habitat availability) is substantially less than range-map depictions, particularly in the highly fragmented region of south-central Texas.

My study also demonstrates the use of GIS (Geographical Information System) in conservation assessment. Geographical Information System has become an important tool in modern ecology and conservation. Geographical Information System data have been used to examine current land-use and management efficacy such as landscape-level habitat associations (Norris et al. 2002; Feichtinger and Veech 2013), corridor suitability (Walker and Craighead 1997), and prediction of future management needs (Visconti et al. 2011). Previous GIS-based habitat models have correctly predicted, with accuracy > 70%, mammal distribution and range over large geographic areas (Lauver et al. 2002; Rondinini et al. 2011). However, these models may be inaccurate at smaller regional and landscape scales in predicting the extent of occurrence (Brambilla et al. 2009), depending on body size, home range size, and habitat specificity of the focal species. The predictive power of the models can be increased when local habitat associations are also assessed (Loyn et al. 2001; Gibson et al. 2004). Habitat models based on species-specific habitat requirements are an invaluable resource in accurately evaluating the quantity, and quality, of areas potentially usable by the target species. Furthermore, this type of predictive conservation can aid in the development of a comprehensive species risk assessment. In this study, my main objective was to create a GIS-based habitat model (map) for *D. compactus* in the highly fragmented northern edge of its geographic range. The model was based on the specific habitat parameters of *D. compactus* (obtained from previous studies) that were verified by a ground-based survey of kangaroo rat burrows and "camera-trapping" to provide definitive photo documentation. As such, my study examined *D. compactus* distribution and habitat associations on a fine-scale (30 × 30 m pixel resolution of GIS data) and broad spatial extent as represented by a multi-county region in south-central Texas.

The greater impetus behind this research was to understand the coupling of limited habitat availability, species-specific and narrow habitat parameters, and substantial habitat loss to assess the current population status and conservation needs of the species. Another goal of this study was to provide information useful in assessing the geographic distribution of suitable habitat and identifying areas that might be most appropriate to protect and manage for *D. compactus*.

II. METHODS

Study Areas

The study area was a seven-county region in south-central Texas consisting of Atascosa, Bexar, Frio, Gonzales, Guadalupe, Medina, and Wilson counties. Parts of this area are within the Carrizo Sand Strip and thus contain sandy soil that could be potential habitat for *D. compactus* (Figure 1, Oakley 2012; Phillips 2012). Within these counties, the most common land uses are farming cropland, cattle grazing, or ranching of exotic ungulate species. There are also large urban areas, scattered towns and smaller cities, rural-residential housing developments, and large privately-owned ranches. The natural grassland-oak savanna (i.e., rangelands) in this region has high overall levels of habitat modification.

Development of habitat map

Suitable *D. compactus* habitat was defined based on previous studies of habitat associations indicating that the species is restricted to areas with deep sandy soils and minimal woody canopy cover (Baumgardner and Schmidly 1985; Oakley 2012; Phillips 2012). I used ArcMap 10.2.2 (ESRI 2013) to generate a habitat map comprised of two spatial variables: percent woody canopy cover (resolution 30 m) and soil type (resolution 10 m). All GIS data files described below were projected to coordinate system NAD 1983 Universal Transverse Mercator Zone 14N. I obtained woody canopy cover data from the 2011 National Land Cover Database (NLCD). As downloaded, woody canopy layer pixels were classified between 1–100% in 1% increments. The woody canopy cover raster layer was obtained from National Land Cover Database (Jin et al. 2013) and clipped to the extent of the seven counties of interest. I obtained soil data from the Natural Resources Conservation Service (NRCS) Web Soil Survey (Soil Survey Staff 2014). I manually searched the county-specific custom soil reports for soil type descriptions representing deep sandy soil and compiled a list (Table 1, Table 2). I defined deep sandy soil as soils described by the Web Soil Survey as “fine sand” or “loamy fine sand” occurring to a depth approximately $\geq$ 73 cm. Climate is not significantly variable within the study area; thus, no climate variables were used.

For the habitat map, I defined suitable habitat *a priori* as the overlap of 0–25% woody canopy cover with fine sandy or loamy fine sandy soils $\geq$ 73 cm in depth (as described in published county soil descriptions, see below). I defined areas with suitable soil and woody canopy cover in this manner; $\leq$ 10% woody canopy cover were “high suitability”, 11–25% woody canopy cover were “intermediate suitability”, 26–50% woody canopy cover were “low suitability”, > 50% woody canopy cover were “lowest suitability”, and areas without suitable soil were defined as “uninhabitable” (Figure 2). From these data, a potential habitat map covering the seven counties was created, indicating the availability and distribution of suitable habitat regardless of specific categorization (Figure 2). The suitable habitat distribution map was a combination of high and intermediate-suitability areas (Figure 3). This suitable habitat distribution map was developed in part as a guide for roadside burrow surveying (see next section). I used the suitable habitat distribution map to visualize all the publically-accessible roads within the requisite habitat area and thus to target all potential survey areas within the seven-county habitat distribution.

Roadside surveying for kangaroo rat burrows

To generate random roadside points for burrow surveying (see next paragraph), I obtained statewide publicly-accessible road data (GIS shape files) from Texas Department of Transportation (Texas Department of Transportation 2014). I also obtained census block data (in GIS format) for the state of Texas from the United States Census Bureau (2010) to guarantee that generated survey points were in publicly accessible, non-urban areas, with low population density (less than 250 people per square mile). I chose areas with low population density in order to reduce the number of sites located in areas too urban to survey. The “random” points were established (placed on the map) in ArcGIS by first clipping roads and population data to the extent of the seven-county study area, then areas of high population density (greater than 250 people per square mile) were eliminated using the “select” tool. Interstate highways were also removed from the roads layer using select. The roads layer without interstate highways was further clipped to include only areas of low population density. Finally, I used the “dissolve” tool to convert the selected roads into a single polyline on which to generate random points.

I conducted roadside surveys for *D. compactus* burrows at the random points generated using ArcGIS. Some of the points were within the defined (presumably suitable) habitat while others were not. Points within and outside of suitable habitat were surveyed given that one of my goals was to verify further the habitat associations previously reported. As such, it was important to collect data on the absence of kangaroo rats in areas thought not to be suitable habitat as well as presence/absence data at points within suitable habitat. Part of the overall project also included the task of finding new populations of the species and delineating its range boundaries within the multi-county region. Therefore, I also surveyed at points intentionally located within suitable habitat and systematically placed throughout the area so as to leave no sizeable areas of suitable habitat unsearched.

At each of the survey points, two surveyors walked through the grassy vegetation along the road shoulder and visually scanned (within a width of 5 – 7 m) for burrows 50 m in front of and behind the vehicle for a total transect length of 100 m on each side of the road (Figure 4). Burrows of kangaroo rats are visually distinct in that the opening is about the size of a baseball and usually not obscured by vegetation (Figure 5a, b). Typically, there were also short, clear runways extending about 20 – 30 cm out from a burrow opening and loose sand around the opening. I took two photographs of the transect on each side of the road, a total of four photographs for each transect. I later examined the photographs to derive general qualitative measures of habitat (e.g., short versus tall grass) on the transect and immediate vicinity (Figure 4). These photos were not intended to provide analytical data, but rather ancillary information that could be useful in explaining the absence of kangaroo rats at points within suitable habitat (e.g., locations with deep loose sand and minimal woody canopy cover but tall, thick grass). To ensure a sufficient sample size for accomplishing the described study objectives, I conducted surveys until > 20 presence points (transects having kangaroo rat burrows) were documented. Including commuting time, I spent over 210 hours completing these road-based surveys which occurred between 9 October 2014 and 4 December 2015. On nearly all occasions, searching for burrows (walking the transects at a point) involved two people and required a minimum of 10 – 12 minutes. Altogether the burrow surveying amounted to over 100 person-hours of search effort for 289 points (see Results).

Camera Surveying

The roadside surveys provided only indirect evidence of species presence (in the form of active burrows). Therefore, after the road surveys were completed, I used motion-activated cameras (Bushnell Natureview Cam HD Max Trail 8 Megapixel Camera) to confirm species presence. To conduct camera surveys, presence transects (those with burrows found on first survey), were resurveyed to relocate burrows. Two or more surveyors walked along the road shoulder and visually scanned (within a width of 5–7 m) for burrows 50 m in front of and behind the vehicle for a total transect length of 100 m on each side of the road. Once active burrows were located, one camera was placed less than 1 m from the burrow entrance. On each camera, I used an F460 mm lens and covered one section of the LED flash with electrical tape to optimize close-up resolution and prevent over-exposure. I scattered a handful of bird seed in front of the camera to facilitate a kangaroo rat moving into the field of view. At each presence point, I deployed cameras until photo evidence of kangaroo rats was obtained or, up to a maximum of 6 nights. Camera surveying occurred between 19 February 2016 and 19 May 2016.

After camera surveys were completed, a few of the points initially classified as presence were removed from that category because either no burrows were found during the re-survey or a species other than *D. compactus* was photographed. In addition, there were a few points at which I found burrows during the initial survey; but when resurveyed the burrows were concluded to be those of another rodent species, based on their size and configuration. Both types of points were removed from further mapping and statistical analysis because presence/absence for *D. compactus* could not be unequivocally confirmed. Some of the randomly generated points were located in rural neighborhoods and near to houses; these could not be surveyed on foot but were surveyed from within the vehicle using binoculars and the naked eye. These points are treated as a separate category representing absence of *D. compactus* due to the close proximity of human habitation and disruptive activities. Also, there were a few points where I relocated obvious kangaroo rat burrows, but the game cameras only captured photos of mesocarnivores such as raccoons (*Procyon lotor*), or gray foxes (*Urocyon cinereoargenteus*) that likely prevented kangaroo rats from entering the field of view. These latter points were retained as presence points. I used presence, absence, and urban-absence points for mapping, but I only used presence and absence points for statistical analyses of habitat associations.

Habitat associations

I used ArcGIS to create 200 m and 400 m circular buffers around each absence and presence point overlain on the GIS layers of soil types and woody canopy cover. I chose 200 m and 400 m based on the average body size and dispersal capacity of kangaroo rats. Specifically, a 200 m circular buffer would contain the entire average home range for *D. merriami* (Garner 1970; Garrison and Best 1990). As is typical in studies using GIS data to examine wildlife-habitat relationships, I chose to analyze two buffer distances so that I could examine whether a scaling effect exists for the habitat associations. Given the relatively sedentary behavior and small home range size of most kangaroo rats, I expected habitat associations to be strongest at the 200 m scale.

To prevent buffer overlap and to ensure statistical independence, I used the “point analysis” tool to determine which pairs of points were within a 400-m or 200-m radius of each other and removed one survey point of the pair randomly. Only a few points had to be removed; one presence point and five absence points from the 400 m analysis and four absent points from the 200 m analysis. Within each circular buffer, I calculated the soil type percent composition and average percent woody canopy cover. Additionally, to visualize the encroachment of established urban areas on suitable habitat availability I obtained an urban areas layer from the Texas General Land Office (Texas General Land Office 2014).

The woody canopy cover layer was clipped to the extent of the buffers, and then I used the “zonal statistics as a table” tool to produce a summary of average percent woody canopy cover for each of the survey points. I then used the “intersect” tool to reduce the soil layer to the extent of each of the buffers. I used the “intersect” tool on the soil layers instead of the “clip” tool because it reduces the extent of the layer while still maintaining each survey point’s unique ID. After each intersection, I used the “summary statistics” tool to summarize the area of each of the soil types by Map Unit Symbol (MUSYM) within each unique survey point buffer. I then calculated the percent composition and standard deviation of the soil types within each survey point buffer. Organization of woody canopy cover results and production of dot plots were completed in Rstudio Version 0.99.482 (R Core Team 2015) using the ggplot2 package (Wickham 2009).

Assessment of geographic isolation

To assess possible isolation between the northern edge (i.e., Carrizo Sand Strip) and southern populations (sand sheet and barrier islands), I examined whether suitable habitat might have historically existed to “connect” the northern edge populations to the southern populations. Specifically, such a long-term (geological) connection could exist if suitable soils occur in the intervening area between the northern and southern populations. Therefore, I obtained spatial soil data for eight counties between south Texas, where this species is known to be relatively common, and my study area. These counties were Bee, DeWitt, Goliad, Karnes, La Salle, Lavaca, Live Oak, and McMullen. Each county had ≥ 50 county-specific soil codes and descriptions. As before, I searched through the descriptions to identify the soil types consisting of deep fine sand. I then used ArcGIS to create a map showing the areas of suitable soil, without regard for woody canopy cover.

III. RESULTS

Quantifying potential habitat and patch-specific population sizes

In the seven-county study area, only 19 soil types met the criteria for deep sandy soil (Table 1). The distribution of deep sandy soil and < 25% woody canopy cover was very concentrated within two of the seven counties and fragmented throughout the seven-county region (Figure 3). As expected, suitable habitat or potential extent of occurrence for *D. compactus* does not fully cover the depicted IUCN range map (Figure 6). There were approximately 1,317 km^2 of suitable habitat available for *D. compactus* in the combined seven counties (Figure 3). Therefore, in the seven-county region, only 6.8% of the total land area is suitable for kangaroo rats. The habitat was not evenly distributed, the majority was located in Atascosa County and Wilson County, in the northwestern portion of both counties. The largest continuous habitat patch was 133 km^2 and found in Wilson County; the smallest patches were 900 m^2 (the size of a single pixel in the map), and the average habitat patch area was 0.79 km^2. Most of the habitat patches were small and total suitable habitat area was highly fragmented; there were 1,661 habitat patches in the seven-county study area and 91% of these were less than 1 km^2. *D. compactus* populations in south-central Texas have an average density of 7 individuals/0.01 km^2 (Phillips 2012). Based on average population density, 47% of the total predicted habitat patches could support at least 100 individuals ($\geq$ 0.14 km^2), but only 14% of patches could support at least 500 individuals ($\geq$ 0.71 km^2) (Figure 7).

Roadside surveys

Including urban-absence points, I surveyed a total of 289 roadside points in the seven-county study area. After resurveying each of the 41 survey points at which kangaroo rats were initially found, I relocated *D. compactus* burrows and placed game cameras at 19 survey points. From these 19 survey points, 17 survey points were confirmed with photos of *D. compactus* and two were retained as presence without confirmed photos due to mesocarnivore interference (Figure 8). Four resurveyed points were reclassified as absence, and 18 were classified as either no burrows at the time of resurvey or burrows present but not *D. compactus*; these 22 points were not included in analyses.

Of the 19 survey points with kangaroo rats present, 18 (95%) were within suitable habitat. Of the 212 survey points absent of kangaroo rat burrows, 100 (47%) were located outside of suitable habitat. Yates' chi-square test applied to 2 x 2 contingency table revealed that presence points were significantly more likely to be in suitable habitat and significantly less likely to be in unsuitable habitat ($\chi^2 = 12.68$, df = 1, n = 231, p = 0.0002; Table 3). Observed frequencies of absence points did not differ from expected frequencies indicating that *D. compactus* absence was not closely tied to habitat suitability prediction (Table 3).

Although suitable habitat was predicted to exist in Gonzales County, I did not find kangaroo rat burrows at any of the 20 survey points in this eastern-most county (Figure 9). The single survey point with kangaroo rats present in unsuitable habitat was located in Wilson County on Alum loamy fine sand. This soil type was not included in the suitable habitat model because it did not meet the 73-cm depth requirement. According to the map, this survey point was approximately 2 km from the nearest patch of suitable habitat. The majority of survey points with kangaroo rat burrows present were located on large contiguous tracts of suitable habitat with two or more suitable habitat patches nearby (Figure 9). Further, many of the largest contiguous habitat patches were located near the largest urban area within the study area, San Antonio.

Habitat associations

After excluding six overlapping points, 18 presence points and 207 absence points were analyzed at 200 m. There were 17 soil types within 200 m of the 18 presence points (Table 4), 11 of these represented deep sand types as used in the habitat mapping model. There were 141 soil types within 200 m of the 207 absence points. After excluding four overlapping points, 19 presence points and 208 absence points were analyzed at 400 m. There were 28 soil types within 400 m of the 19 presence points, 10 of which were types used in the model. There were 174 soil types within 400 m of the 208 absence points. Thus, absence points tended to be surrounded by a much greater diversity of soil types at both the 200 and 400 m spatial extents.

Average overall woody canopy cover within the 200-m buffers of the absence points was 13.45% (*SD* = 11.62%) and 13.00% (*SD* = 13.62%) for the presence points. Within the 400 m buffers, average overall woody canopy cover for the absence points was 14.88% (*SD* = 16.30%). For the presence points, average woody canopy cover was 15.65% (*SD* = 11.72%). Mean woody canopy cover did not differ between the presence and absence points at either 200 m or 400 m (Figure 10).

Geographic isolation

In the eight counties between the study area and the south Texas populations of *D. compactus*, only eight soil types met the criteria for deep sandy soil (Table 2). The availability of suitable habitat (i.e. deep sandy soil and < 25% woody canopy cover) was very sparse (Figure 11). There was a total of only 135 km^2 of suitable habitat in the eight counties. The largest continuous habitat patch was 6.4 km^2 and found in McMullen County; the average habitat patch area was 0.16 km^2. The habitat availability was mostly low in these counties; there were 825 habitat patches in the eight-county area, and 63% of the habitat patches were less than 0.1 km^2.

IV. DISCUSSION

The distribution of *D. compactus* was found to be restricted in the seven-county study area. Specifically, the actual distribution of available habitat and species presence were significantly less than indicated by the IUCN range map. I confirmed at a regional scale that the habitat associations of *D. compactus* are useful predictors of their occurrence, but not all the predicted available habitat is occupied. *D. compactus* was significantly more likely to be found in the ArcGIS predicted suitable habitat than in the unsuitable habitat; species presence was observed in predicted habitat 95% of the time and species absence was observed outside of the habitat 47% of the time. Kangaroo rat burrows were primarily associated with areas of deep sandy soil and low woody canopy cover. These findings are consistent with previous studies of the habitat associations of *D. compactus* (Baumgardner and Schmidly 1985; Oakley 2012; Phillips 2012). However, although only five presence points had woody canopy cover greater than 25% (at 200 and 400 m), mean woody canopy cover between presence and absence points was not significantly different. This similarity was likely due to study design. I designed the roadside surveys to target suitable habitat to ensure adequate sample size for presence points. Thus the vast majority of survey points were conducted within suitable habitat, that is, areas with woody canopy cover less than 25%. Survey results also exhibit a boundary of absence points around the outside perimeter of the majority of presence points suggesting that the extent of *D. compactus* occurrence in Central Texas is much narrower than indicated by a range map. However, there were also large portions of predicted habitat in which no burrows were found. Suitable habitat areas without burrows indicate that large areas of habitat could be recolonized if appropriate land management practices are implemented.

One of the strengths of this study was the on-the-ground verification of the predicted habitat map. The roadside surveys were exhaustive in the area searched; I drove slowly searching all public roads within predicted suitable habitat throughout the region. Thus, it is unlikely any populations (i.e. areas of extensive burrows) went unnoticed.

Using GIS analysis, I was successful in visualizing, quantifying, and evaluating differences in habitat suitability based on soil characteristics and woody canopy cover density. *D. compactus* is highly adapted to specific edaphic and vegetation conditions; therefore, adequate habitat availability is paramount to the continued survival of the species. My results showed that there are approximately 1,317 km^2 of suitable habitat in the seven-county study region, 6.75% of the total land area in the region, but this habitat is far from contiguous. Due to this fragmentation, fewer than half of the potential habitat patches could support a minimum viable population size of at least 100 individuals, given reported densities of 7 individuals per hectare (Phillips 2012). Although adequate, suitable habitat is available at present, rural residential housing development has, and likely will, continue to fragment large contiguous tracts of habitat required by *D. compactus*. Many of the largest contiguous habitat patches are likely shrinking due to the expansion southward of fast-growing San Antonio and nearby suburbs. *D. compactus* is a highly specialized species with limited long-range mobility, and thus may be heavily affected by urbanization. Reduction in available habitat, the extent of occurrence, and overall geographic range can have a massive impact on a population's resiliency as geographic range has been found to be the most influential ecological predictor of species extinction risk (Davidson et al. 2009).

An unexpected result from this study was the apparent lack of available habitat in the eight counties separating populations in my study area (Carrizo Sand Strip in south-central Texas) and populations of *D. compactus* along the coast and in the sand sheet of south Texas. This lack of available habitat may mean that the Carrizo Sands populations are relatively isolated from the majority of the species overall population. The Carrizo Sands population(s) may represent a peripheral isolate that is somewhat unique genetically although this has not been studied. Additionally, the separation and fragmentation among habitat patches in south-central Texas and between the south Texas portion of the range and that in the Carrizo Sand Strip may force *D. compactus* into a precarious metapopulation structure in which there is very little gene flow. Although the Carrizo Sand Strip extends west and then curves southward forming a potential conduit to south Texas populations (Figure 1), much of this area is occupied by *D. ordii* a species that may be competitively superior to *D. compactus* (Baumgardner and Schmidly 1981).

It is important to know if *D. compactus* exists as one or more metapopulations. The concept of metapopulation dynamics has gained much popularity for use in single species ecology since first introduced by Levins (1969) and further developed by Hanski (1991, 1998). A metapopulation is a population of subpopulations; these subpopulations are spatially disconnected in distinct patches of suitable habitat within a patch network (Levins 1969; Hanski 1998). These habitat patches have some degree of individual movement among them, however, if one or more subpopulations becomes completely isolated due to stochastic events or patch deterioration, the patch subpopulation has a much greater chance of extinction (Hanski 1985). The extinction risk is greatest if the patches are smaller and farther apart, and particularly high as the isolation of smaller patches increases (Drechsler et al. 2003).

At the landscape scale, most wildlife habitats, especially that of an ecological specialist, are heterogeneous, and thus, naturally somewhat patchy. Human-induced habitat degradation, such as urbanization, can reduce habitat patch size and quality so much so that the local subpopulation cannot persist; further, if the density of habitat patches becomes too small the entire metapopulation can crash (Hanski 1985). Landscape-scale habitat fragmentation can create small, isolated subpopulations, and without access to other subpopulations in the patch network, this isolation can quickly lead to local extinctions and possibly the crash of the entire metapopulation (Fahrig and Merriam 1985; Wilcove et al. 1986). The expansion of San Antonio coupled with the apparent lack of habitat between the northern range and the southern Texas and barrier island populations may prevent the northern populations from receiving reinforcing individuals from source populations further south. Thus, the northern population of *D. compactus* may begin to experience local extinctions. Further fragmentation via human modification of the landscape could directly prevent dispersal from large patches to smaller ones, in turn, this could exacerbate the rate of extinction of local populations.

This analysis is the first of its kind for this distinctive species; landscape-scale habitat availability and spatial configuration have not previously been examined anywhere within the range of *D. compactus*. My results imply that conservation efforts should be focused on cooperation between landowners to reduce isolation among suitable habitat patches, thereby encouraging dispersal of kangaroo rats and reducing further habitat loss. The extinction risk is lowest if the patches are larger and have higher connectivity (i.e. dispersal) among them, and as smaller patches gain connectivity, extinction risk drops greatly and the population as a whole gains resilience to stochastic events (Drechsler et al. 2003). Additionally, virtually all *D. compactus* in south-central Texas are on private property, this conservation effort will not only require cooperation among private landowners, but will also require successful partnerships among private landowners and non-governmental conservation organizations, state agencies, and federal agencies.

Endangered kangaroo rat species in both Oklahoma and California are now absent from their historic range due to urbanization and agricultural clearing similar to present day Texas. For example, the Texas kangaroo rat (*Dipodomys elator*), now extirpated from Oklahoma, has narrow habitat requirements and is currently listed by the Texas Parks and Wildlife Department as "threatened" (TPWD 2011). Comparably, *D. stephensi* in California became endangered after suffering catastrophic levels of habitat loss and fragmentation due to the westward urban expansion and agricultural irrigation of Riverside County, California, and has not recovered since becoming listed as federally endangered in 1988 (Price and Endo 1989; Kelt et al. 2005). *D. stephensi* populations have not yet made a strong recovery because regional urban and agricultural development has not been curtailed. In addition, the majority of areas currently occupied by Stephens' kangaroo rat are susceptible to habitat degradation and habitat loss due to non-native grass and shrub encroachment (USFWS 2010a). Habitat specialist, *D. ingens*, has likewise made no significant recovery since it was listed as federally endangered in 1987 after a range contraction of 98.5% (Williams et al. 1993). Moreover, *D. ingens* has had extreme population fluctuations of six- to ten-fold since 1979 (USFWS 2010b); this could have severe consequences for genetic diversity within the population. Furthermore, as desert-adapted animals, kangaroo rats may lose even more habitat as climate change alters regional arid landscapes (Brown et al. 1997). In the future, protection of local kangaroo rat habitat in numerous areas, especially the contiguous areas near San Antonio may be necessary. Accordingly, due to potential spatial isolation, the Central Texas *D. compactus* population requires further assessment of its current conservation status. Future *Dipodomys spp.* work in Texas may need to incorporate community education and outreach to private landowners to improve the habitat in between suitable patches to encourage dispersal and reduce isolation.

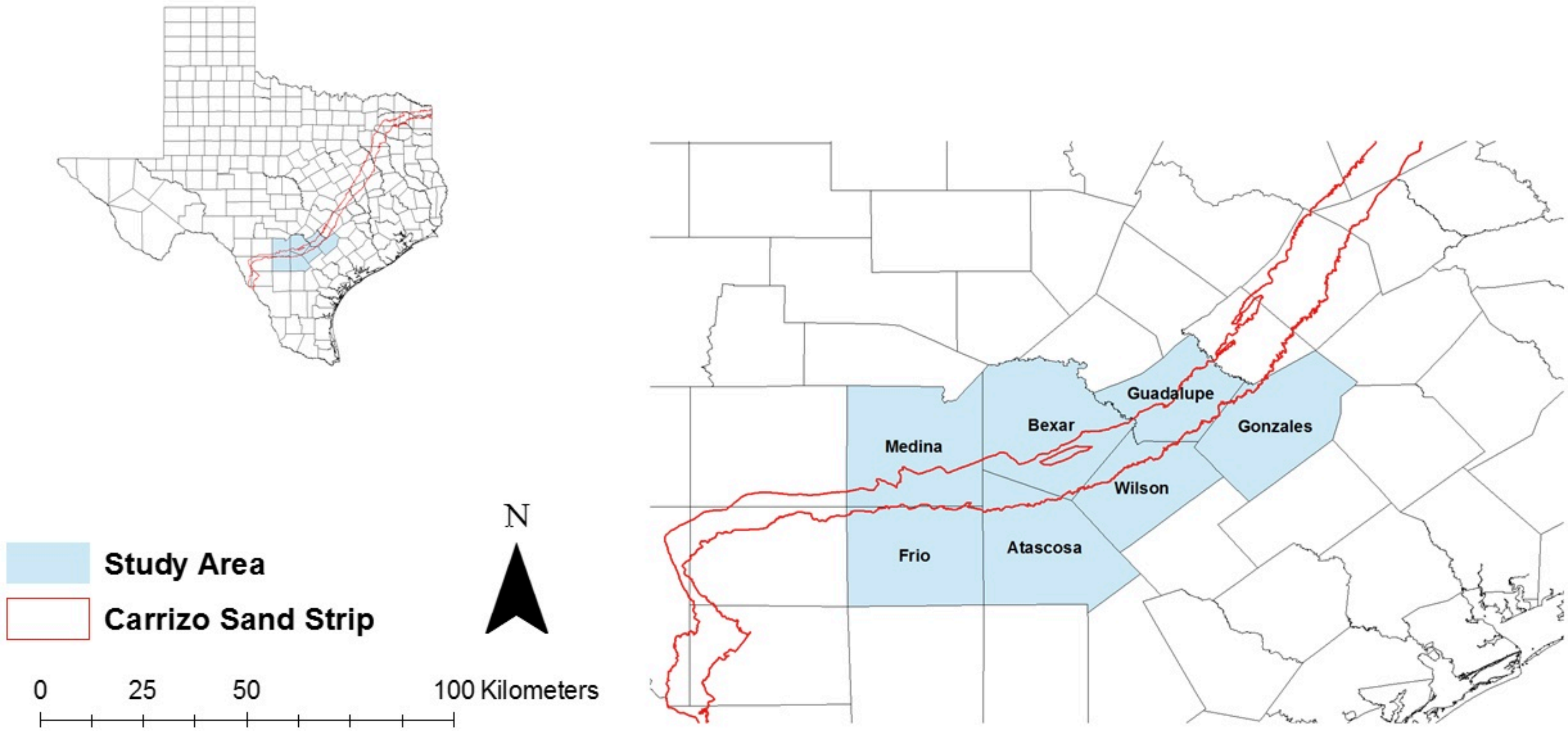

Figure 1. Location of the seven-county study region relative to the Carrizo sand strip.

Table 1. Soil types representing deep sandy soil in the seven county study area (Atascosa, Bexar, Frio, Gonzales, Guadalupe, Medina, and Wilson).

County	Soil Name	Soil Code	Typical Profile
Atascosa	Aluf-Hitilo association, gently undulating	1	Aluf: H1 - 0 to 117 cm: fine sand; H2 - 117 to 203 cm: fine sand. Hitilo: H1 - 0 to 117 cm: sand; H2 - 117 to 137 cm: sandy clay loam; H3 - 137 to 157 cm: sandy clay; H4 - 157 to 203 cm: fine sandy loam
Atascosa	Nusil loamy fine sand, 0 to 3 percent slopes	29	H1 - 0 to 20 cm: loamy fine sand; H2 - 20 to 76 cm: loamy fine sand; H3 - 76 to 102 cm: sandy clay loam; H4 - 102 to 178 cm: sandy clay loam; H5 - 178 to 203 cm: sandy clay loam.
Atascosa	Poth loamy fine sand, 0 to 3 percent slopes	37	H1 - 0 to 76 cm: loamy fine sand; H2 - 76 to 140 cm: sandy clay; H3 - 140 to 173 cm: sandy clay loam.
Atascosa	Nusil-Rhymes association, 0 to 5 percent slopes	76	Nusil: A - 0 to 51 cm: fine sand; E - 51 to 76 cm: fine sand; Bt - 76 to 152 cm: sandy clay loam; BC - 152 to 203 cm: sandy clay loam. Rhymes fine sand: A - 0 to 18 cm: fine sand; E - 18 to 127 cm: fine sand; Bt - 127 to 203 cm: sandy clay loam.
Bexar	Aluf Sand, 0 to 5 percent slopes	EuC	H1 - 0 to 107 cm: fine sand; H2 - 107 to 203 cm: fine sand.
Frio	Comitas loamy fine sand, 0 to 3 percent slopes	CoB	A - 0 to 79 cm: loamy fine sand; Bt - 79 to 150 cm: fine sandy loam; Btk - 150 to 203 cm: fine sandy loam.
Frio	Poth loamy fine sand, 0 to 3 percent slops	PoB	H1 - 0 to 76 cm: loamy fine sand; H2 - 76 to 147 cm: clay; H3 - 147 to 163 cm: sandy clay loam.
Gonzales	Alum loamy fine sand, 0 to 3 percent slopes	AmB	H1 - 0 to 76 cm: loamy fine sand; H2 - 76 to 147 cm: clay; H3 - 147 to 163 cm: sandy clay loam.
Gonzales	Arenosa fine sand, 1 to 5 percent slopes	ApC	A - 0 to 13 cm: fine sand; C1 - 13 to 109 cm: fine sand; C2 - 109 to 203 cm: fine sand.
Gonzales	Nusil loamy fine sand, 0 to 5 percent slopes	NuC	H1 - 0 to 61 cm: fine sand; H2 - 61 to 89 cm: loamy fine sand; H3 - 89 to 124 cm: sandy clay loam; H4 - 124 to 145 cm: sandy clay loam; H5 - 145 to 203 cm: sandy clay loam.
Gonzales	Padina loamy fine sand, 0 to 5 percent slopes	PaC	H1 - 0 to 38 cm: loamy fine sand; H2 - 38 to 125 cm: loamy fine sand; H3 - 125 to 203 cm: sandy clay loam.
Gonzales	Silstid loamy fine sand, 1 to 5 percent slopes	SsC	H1 - 0 to 66 cm: loamy fine sand; H2 - 66 to 76 cm: loamy fine sand; H3 - 76 to 137 cm: sandy clay loam; H4 - 137 to 203 cm: sandy clay loam.
Gonzales	Tremona loamy fine sand, 1 to 5 percent slopes	TtC	H1 - 0 to 76 cm: loamy fine sand; H2 - 76 to 160 cm: sandy clay; H3 - 160 to 203 cm: sandy clay loam.
Guadalupe	Arenosa fine sand, 1 to 8 percent slopes	ArD	H1 - 0 to 13 cm: fine sand; H2 - 13 to 245 cm: fine sand.

Guadalupe	Patilo and Arenosa soils, 1 to 8 percent slopes	PaD	Patilo: H1 - 0 to 20 cm: fine sand; H2 - 20 to 132 cm: fine sand; H3 - 132 to 213 cm: sandy clay loam. Arenosa: H1 - 0 to 13 cm: fine sand; H2 - 13 to 244 cm: fine sand.
Medina	Nusil soils, 0 to 5 percent slopes	NuC	H1 - 0 to 36 cm: fine sand; H2 - 36 to 89 cm: fine sand; H3 - 89 to 107 cm: sandy clay loam; H4 - 107 to 135 cm: sandy clay loam; H5 - 135 to 239 cm: sandy clay loam
Medina	Hitilo-Aluf association, gently undulating	PEC	Hitilo: H1 - 0 to 48 cm: fine sand; H2 - 48 to 56 cm: sandy clay loam; H3 - 56 to 72 cm: sandy clay loam; H4 - 72 to 203 cm: sandy clay loam. Aluf: H1 - 0 to 142 cm: fine sand H2 - 142 to 252 cm: fine sand.
Wilson	Aluf and Hitilo soils, undulating	EPB	Aluf: H1 - 0 to 46 cm: fine sand; H2 - 46 to 99 cm: fine sand, sandy clay loam. Hitilo: H1 - 0 to 137 cm: fine sand; H2 - 137 to 178 cm: sandy clay loam; H3 - 178 to 203 cm: sandy clay loam.
Wilson	Poth loamy fine sand, 0 to 3 percent slopes	PtB	H1 - 0 to 76 cm: loamy fine sand; H2 - 76 to 112 cm: sandy clay; H3 - 112 to 188 cm: sandy clay loam.

Table 2. Soil types representing deep sandy soil in the eight counties (Bee, De Witt, Goliad, Karnes, La Salle, Lavaca, Live Oak, and McMullen) between the seven county study area (Atascosa, Bexar, Frio, Gonzales, Guadalupe, Medina, and Wilson) in Central Texas and coastal counties (Aransas, Calhoun, Jackson, Nueces, Refugio, San Patricio, and Victoria)

County	Soil Name	Soil Code	Typical Profile
Bee	Nusil-Rhymes association, 0 to 5 percent slopes	28	Nusil: A - 0 to 51 cm: fine sand; E - 51 to 76 cm; fine sand; Bt - 76 to 152 cm: sandy clay loam; BC - 152 to 203 cm: sandy clay loam. Rhymes: A - 0 to 18 cm: fine sand E - 18 to 127 cm: fine sand; Bt - 127 to 203 cm: sandy clay loam.
DeWitt	Catilla fine sand, 0 to 5 percent slopes	CaC	H1 - 0 to 25 cm: fine sand; H2 - 25 to 117 cm: fine sand; H3 - 117 to 191 cm: sandy clay loam
DeWitt	Nusil-Rhymes association, 0 to 5 percent slopes	NsC	Nusil: A - 0 to 51 cm: fine sand; E - 51 to 76 cm; fine sand; Bt - 76 to 152 cm: sandy clay loam; BC - 152 to 203 cm: sandy clay loam. Rhymes: A - 0 to 18 cm: fine sand E - 18 to 127 cm: fine sand; Bt - 127 to 203 cm: sandy clay loam.
Karnes	Nusil fine sand, 1 to 5 percent slopes	NuC	H1 - 0 to 25 cm cm: fine sand; H2 - 25 to 91 cm: fine sand; H3 - 91 to 112 cm: sandy clay loam; H4 - 112 to 183 cm: sandy clay loam; H5 - 183 to 203 cm: sandy clay loam.
Lavaca	CtC—Catilla loamy sand, 1 to 5 percent slopes	CtC	H1 - 0 to 25 cm: loamy sand; H2 - 25 to 125 cm: loamy fine sand; H3 - 125 to 203 cm: sandy clay loam.
Lavaca	Dutek loamy fine sand, 1 to 5 percent slopes	DuC	A - 0 to 18 cm: loamy fine sand; E - 18 to 74 cm: loamy fine sand; Bt1 - 74 to 137 cm: sandy clay loam; BCt - 137 to 203 cm: fine sandy loam.
Liveoak	Nusil fine sand, 1 to 5 percent slopes	NuC	H1 - 0 to 74 cm: fine sand; H2 - 74 to 94 cm: fine sand; H3 - 94 to 137 cm: sandy clay loam; H4 - 137 to 178 cm: sandy clay loam; H5 - 178 to 203 cm: sandy clay loam
McMullen	Nusil-Rhymes association, 0 to 5 percent slopes	RNB	Nusil: A - 0 to 51 cm: fine sand; E - 51 to 76 cm; fine sand; Bt - 76 to 152 cm: sandy clay loam; BC - 152 to 203 cm: sandy clay loam. Rhymes: A - 0 to 18 cm: fine sand E - 18 to 127 cm: fine sand; Bt - 127 to 203 cm: sandy clay loam.

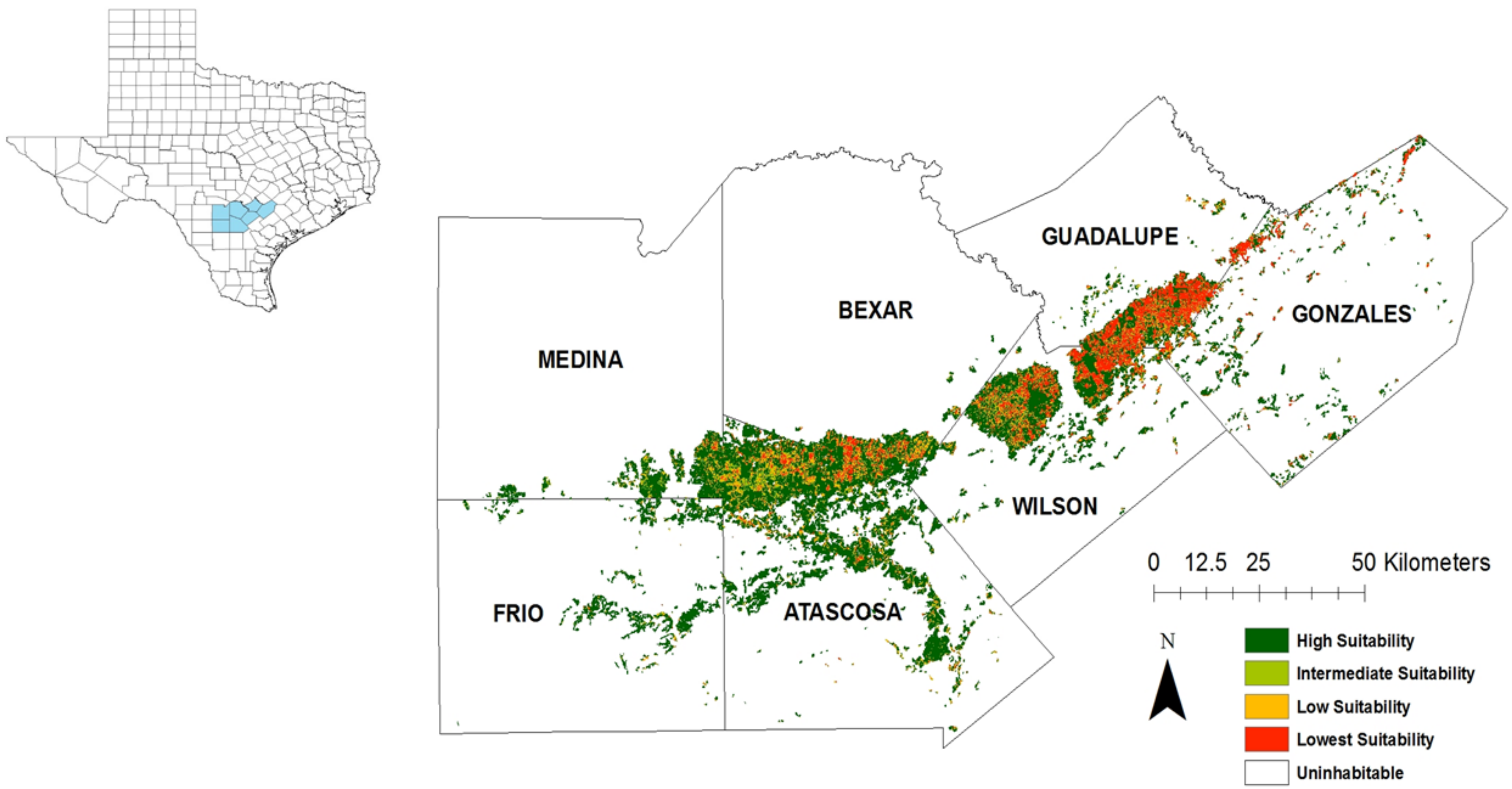

Figure 2. Distribution of *Dipodomys compactus* potential habitat in the seven-county study area. Map indicates habitat suitability as based on deep sandy soils and a range of woody canopy cover values. Areas with suitable soil and woody canopy cover ≤ 10% were defined as "high suitability", areas with suitable soil and woody canopy cover 11–25% were defined as "intermediate suitability", areas with suitable soil and woody canopy cover 26–50% were defined as "low suitability", areas with suitable soil and woody canopy cover > 50% were defined as "lowest suitability", and areas without suitable soil were defined as "uninhabitable".

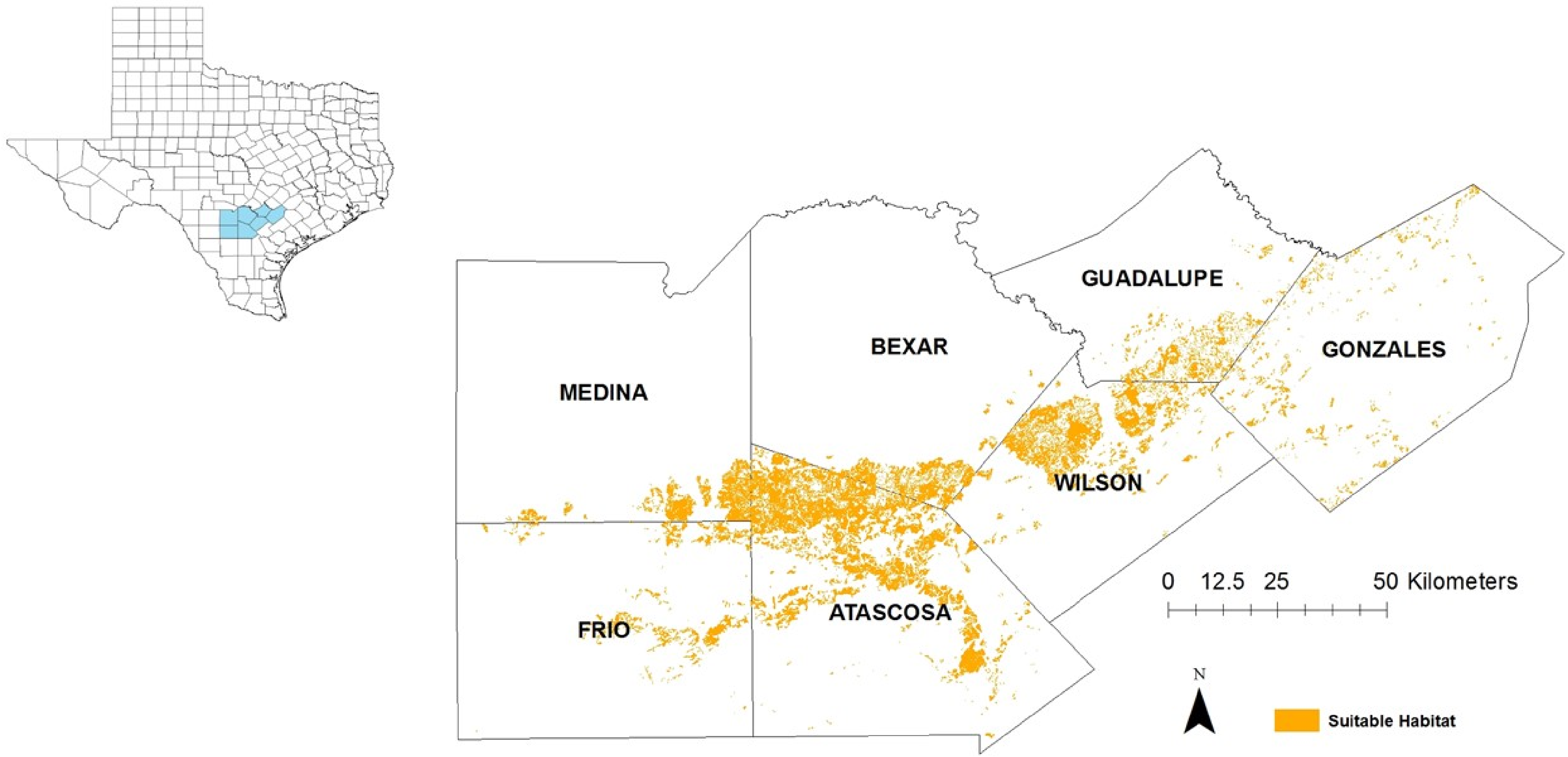

Figure 3. Distribution of *Dipodomys compactus* suitable habitat (i.e. combination of high and intermediate-suitability habitat) in the seven-county study area.

Figure 4. An example of one of the four photos taken at each burrow survey 100-meter transect. These photos were later interpreted to derive general qualitative measures of habitat.

Figure 5a. Distinct burrow opening of *Dipodomys compactus*.


Figure 5b. Distinct burrow opening of *Dipodomys compactus*.

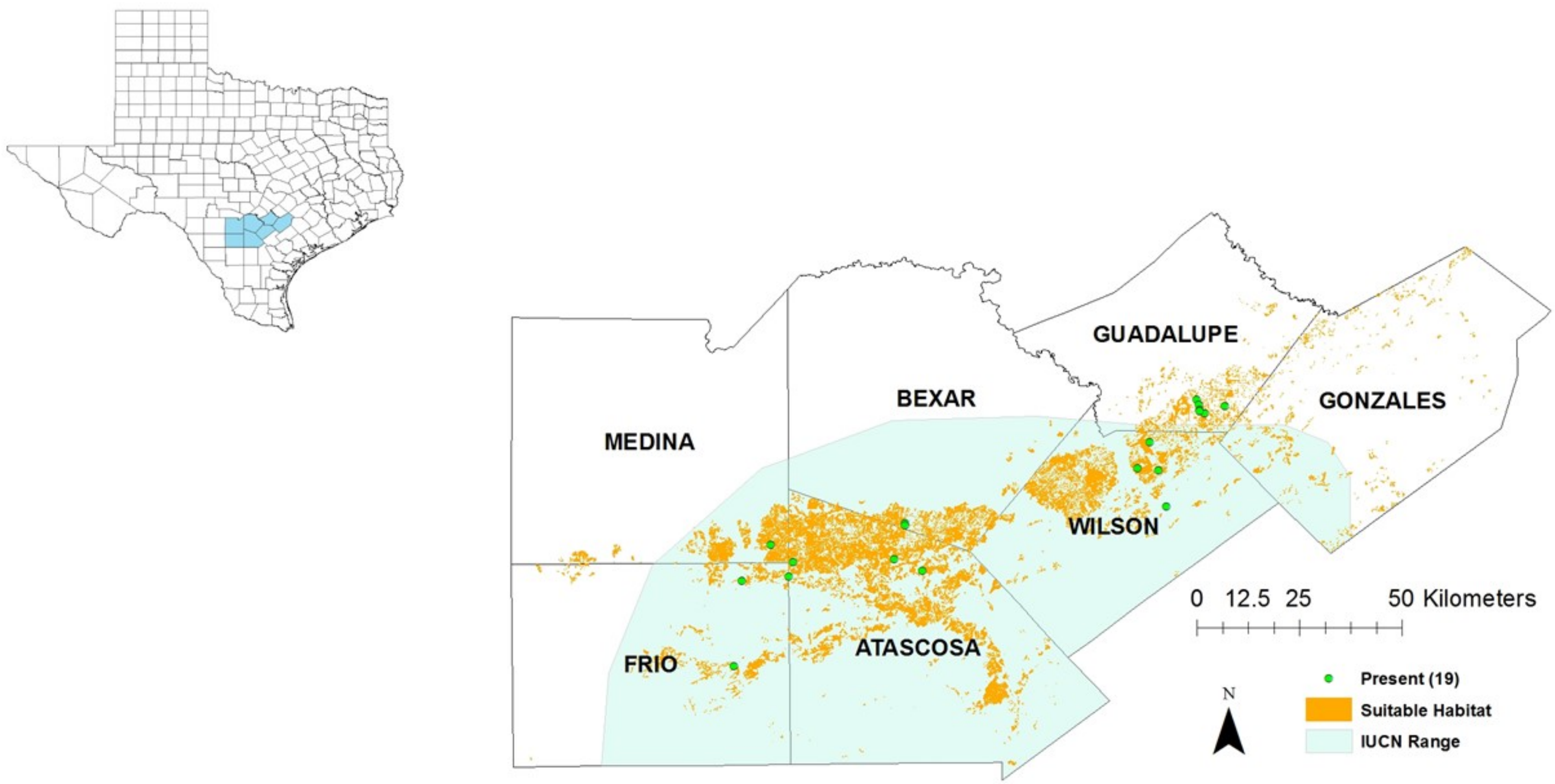

Figure 6. Points at which *Dipodomys compactus* presence was photo confirmed, the distribution of suitable habitat in the seven-county study areas, and the IUCN range of *D. compactus* for the seven-county study area.

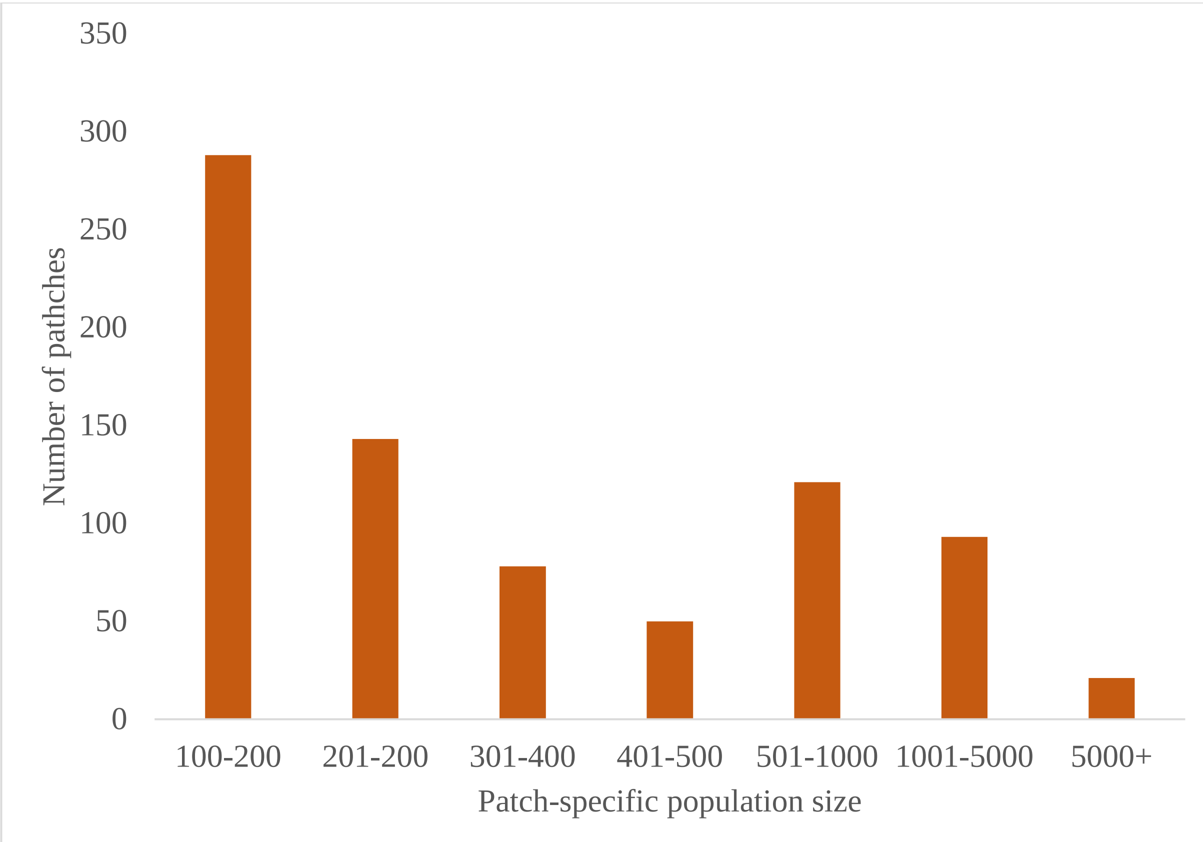

Figure 7. The statistical distribution of patch-specific population size (n = 794).

Figure 8. Mesocarnivore interference prevented *Dipodomys compactus* observation at these two point locations.

Table 3. Observed and expected values for kangaroo rat absence and presence points with regard to suitable habitat (n = 231), expected values are shown parenthetically. Expected values were calculated as the product of the following: total number of cases in the respective row divided by the total sample size, the total number of cases in the respective column divided by the total sample size, and the total sample size.

	Within suitable habitat	Outside suitable habitat	Proportion of total
Presence	18 (11)	1 (8)	0.082
Absence	112 (119)	100 (93)	0.918
Proportion of total	0.563	0.437	

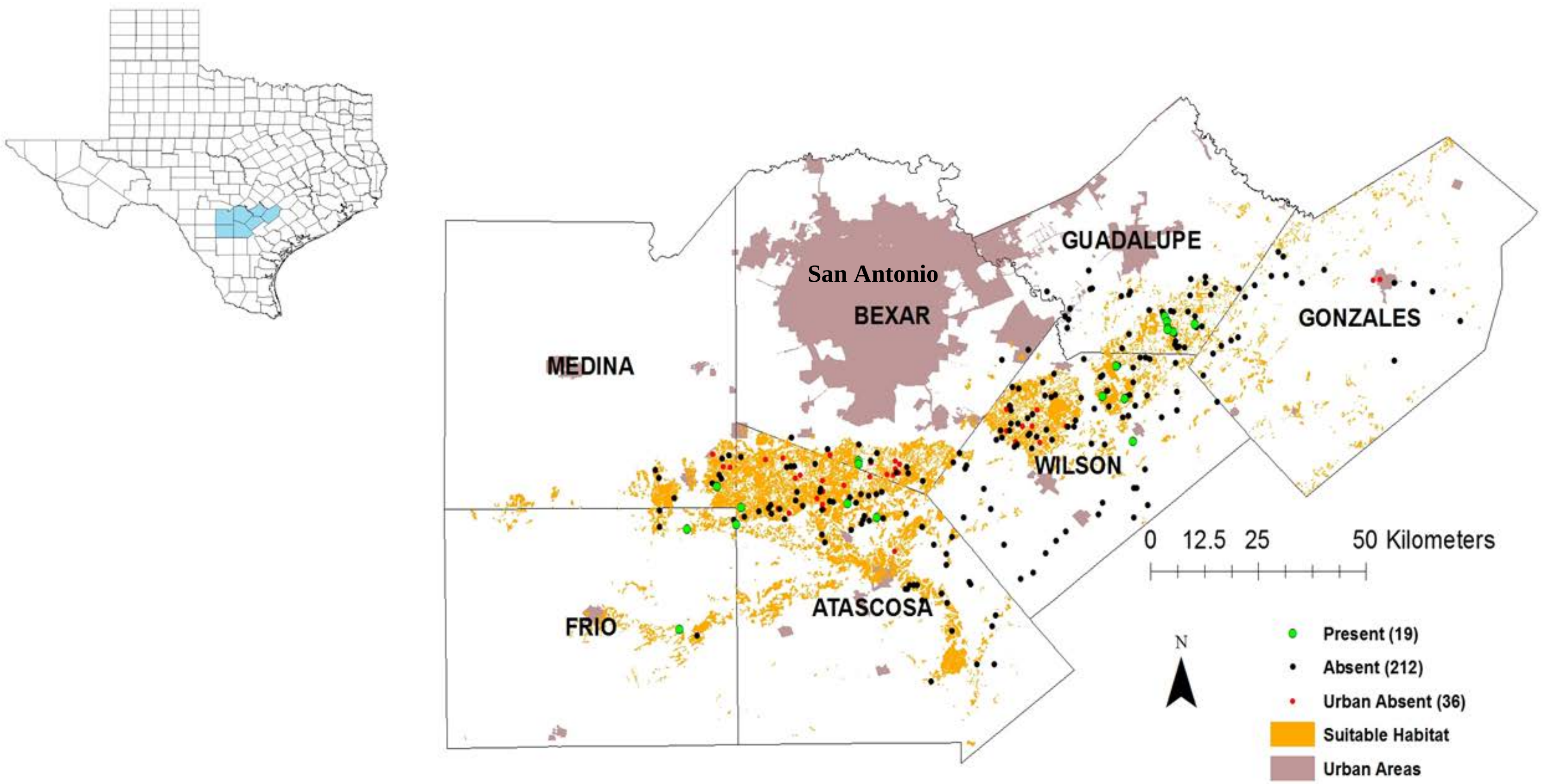

Figure 9. Points at which *Dipodomys compactus* presence was photo confirmed (19 green points), points at which no kangaroo presence was observed (212 black points), points at which urbanization was too intense to survey (36 red points), the distribution of suitable habitat in the seven-county study area, and urban areas in the seven-county study area; specifically, the city of San Antonio in Bexar County.

Table 4. Web Soil Survey soil types present within a 200-m radius of the 19 photo confirmed presence points.

County	Soil Type	Top layer of typical profile
Atascosa	Aluf-Hitilo association, gently undulating	Aluf: H1 - 0 to 117 cm: fine sand; Hitilo: H1 - 0 to 117 cm: sand
Atascosa	Miguel fine sandy loam, 1 to 3 percent slopes	H1 - 0 to 23 cm: fine sandy loam
Atascosa	Poth loamy fine sand, 0 to 3 percent slopes	H1 - 0 to 76 cm: loamy fine sand
Atascosa	Nusil-Rhymes association, 0 to 5 percent slopes	Nusil: A - 0 to 51 cm: fine sand; Rhymes: A - 0 to 18 cm: fine sand.
Atascosa	Sinton soils, frequently flooded	H1 - 0 to 112 cm: clay loam
Atascosa	Wilco loamy fine sand, 0 to 3 percent slopes	H1 - 0 to 41 cm: loamy fine sand
Bexar	Aluf Sand, 0 to 5 percent slopes	H1 - 0 to 107 cm: fine sand
Frio	Comitas loamy fine sand, 0 to 3 percent slopes	A - 0 to 79 cm: loamy fine sand
Frio	Poth loamy fine sand, 0 to 3 percent slops	H1 - 0 to 76 cm: loamy fine sand
Frio	Wilco loamy fine sand, 0 to 3 percent slopes	H1 - 0 to 41 cm: loamy fine sand
Guadalupe	Arenosa fine sand, 1 to 8 percent slopes	H1 - 0 to 13 cm: fine sand
Guadalupe	Patilo and Arenose soils, 1 to 8 percent slopes	H1 - 0 to 20 cm: fine sand
Medina	Nusil soils, 0 to 5 percent slopes	H1 - 0 to 36 cm: fine sand
Medina	Hitilo-Aluf association, gently undulating	Hitilo: H1 - 0 to 48 cm: fine sand; Aluf: H1 - 0 to 142 cm: fine sand
Wilson	Aluf and Hitilo soils, undulating	H1 - 0 to 46 cm: fine sand; Hitilo: H1 - 0 to 137 cm: fine sand
Wilson	Alum loamy fine sand, 1 to 3 percent slopes	H1 - 0 to 71 cm: loamy fine sand
Wilson	Alum loamy fine sand, 3 to 5 percent slopes	H1 - 0 to 71 cm: loamy fine sand

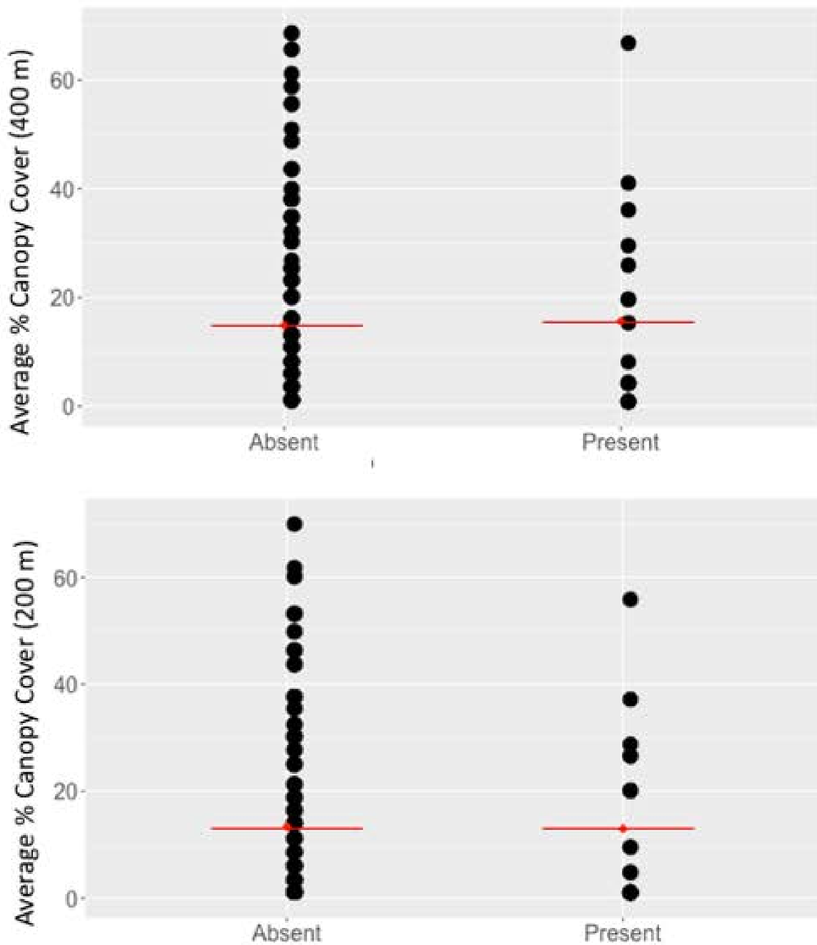

Figure 10. Dot plot of the average woody canopy cover (%) within a 200-meter buffer and 400-meter buffer at 19 (400 m) or 18 (200 m) presence points and 208 (400 m) or 207 (200 m) absence points. The mean is indicated by a red diamond and red line.

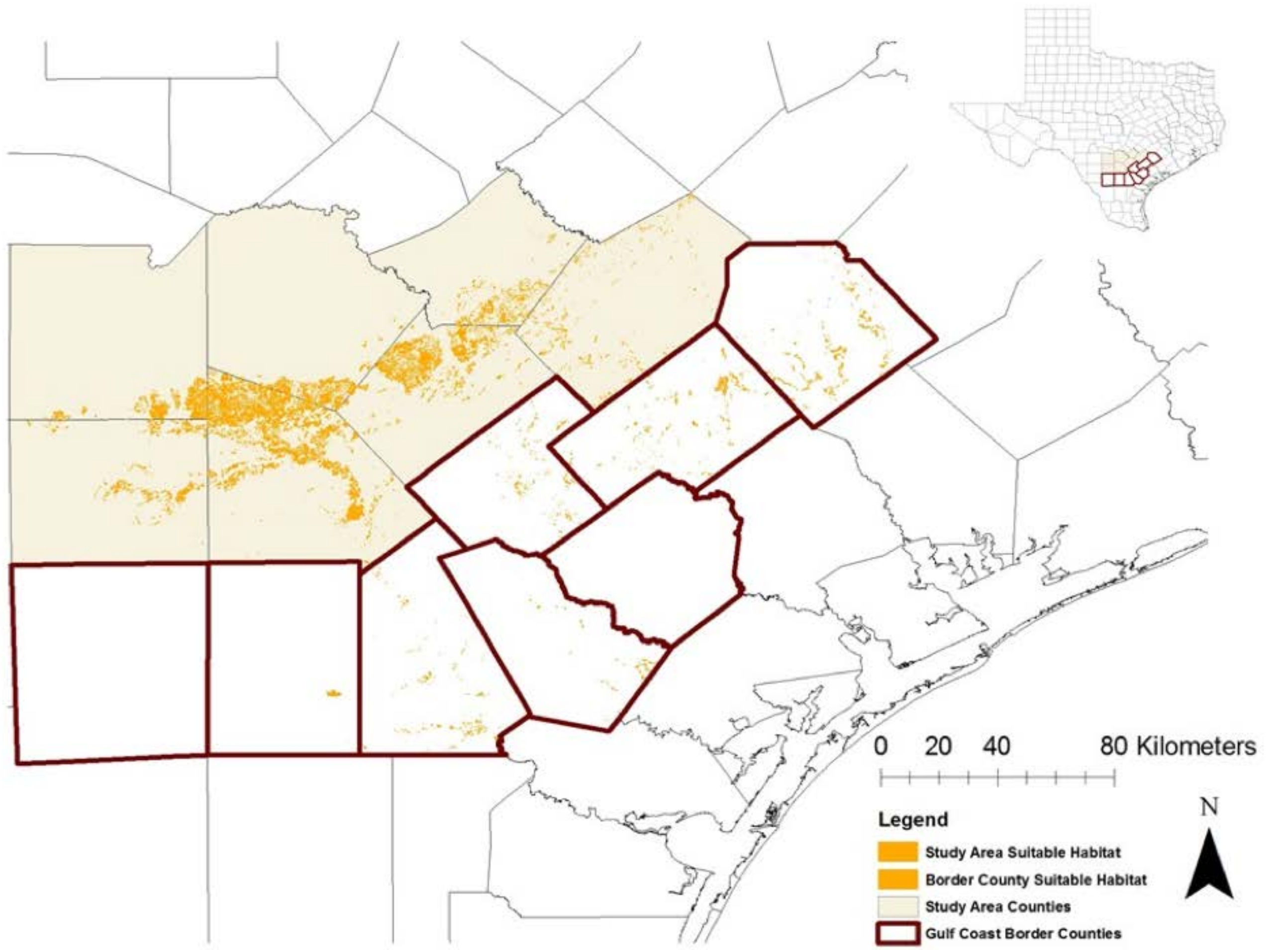

Figure 11. Distribution of *Dipodomys compactus* suitable habitat in the seven-county study area and the eight counties between the northern and southern populations.

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