SPECIES STATUS ASSESSMENT REPORT FOR TOBUSCH FISHHOOK CACTUS (*SCLEROCACTUS BREVIHAMATUS* SSP. *TOBUSCHII* (W.T. MARSHALL) N.P. TAYLOR)

February, 2017
Southwest Region
U.S. Fish and Wildlife Service
Albuquerque, NM

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Suggested citation:

U.S. Fish and Wildlife Service. 2017. Species status assessment of Tobusch Fishhook Cactus (*Sclerocactus brevihamatus ssp. tobuschii* (W.T. Marshall) N.P. Taylor). U.S. Fish and Wildlife Service Southwest Region, Albuquerque, New Mexico. 65 pp. + 2 appendices.

EXECUTIVE SUMMARY

Tobusch fishhook cactus is a small cactus, with curved "fishhook" spines, that is endemic to the Edwards Plateau of Texas. It was federally listed as endangered on November 7, 1979 (44 FR 64736) as *Ancistrocactus tobuschii*. At that time, fewer than 200 individuals had been documented from 4 sites. Tobusch fishhook cactus is now confirmed in 8 central Texas counties: Bandera, Edwards, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde. In recent years, over 4,000 individuals have been documented in surveys and monitoring plots.

Recent phylogenetic evidence supports classifying Tobusch fishhook cactus as *Sclerocactus brevihamatus* ssp. *tobuschii*. It is distinguished morphologically from its closest relative, *S. brevihamatus* ssp. *brevihamatus*, on the basis of yellow versus pink- or brown-tinged flowers, fewer radial spines, and fewer ribs. Additionally, subspecies *tobuschii* is endemic to limestone outcrops of the Edwards Plateau, while subspecies *brevihamatus* occurs in alluvial soils in the Tamaulipan Shrublands and Chihuahuan Desert. A recent investigation found genetic divergence between the two subspecies, although they may interact genetically in a narrow area where their ranges overlap.

Tobusch fishhook cactus grows slowly, reaching a reproductive size of about 2 centimeters (0.8 inches) in diameter after 9 years. It flowers between late January and mid-March, and its major pollinators are honey bees and halictid bees. The breeding system is primarily out-crossing, but the species is capable of self-fertilization. Reproductive individuals produce an average of 112 seeds per year. Ants may be seed predators, dispersers, or both. Mammals or birds may also accomplish longer-distance seed dispersal. We have little evidence of a persistent soil seed bank.

The riparian habitats described in the original status report are atypical. The great majority of documented populations occur in upland sites dominated by Ashe juniper-live oak woodlands and savannas on outcrops of early Cretaceous limestone. Soils are classified in the Tarrant, Ector, Eckrant, and similar series. Within a matrix of woodland and savanna, the species occurs in discontinuous patches of very shallow, gravelly soils where bare limestone rock and rock fragments comprise a large proportion of the surface cover. Associated vegetation includes small bunch grasses and forbs. The species' distribution within habitat patches is clumped and tends to be further from woody plant cover. The presence of spikemosses (*Selaginella* spp.), and perhaps other cryptogams, may be useful indicators of fine-scale habitat suitability. Wildfire (including prescribed burning) causes negligible damage to Tobusch fishhook cactus populations. The species probably does not require fire for germination, establishment, or reproduction, but periodic burning may be necessary to prevent the encroachment of woody plants into its habitats.

In 2016, the Texas Native Diversity Database listed 97 Element Occurrences of Tobusch fishhook cactus, totaling 3,336 individuals (TXNDD 2016). Texas Parks and Wildlife Department botanists monitored 118 permanent plots at 12 protected natural areas from 1991 through 2013. Annual mortality in plots was often greater than 20 percent, and consistently exceeded recruitment. In particular, infestations by insect larvae caused catastrophic population declines. However, mortality and recruitment determinations are confounded by the great difficulty in detecting live plants in the field. Despite the decline of many individual colonies,

the total known population sizes have steadily increased, due to the discovery of previously undetected individuals and colonies.

Factors that may negatively affect the continued survival of Tobusch fishhook cactus include changes in the wildfire cycle and juniper encroachment, parasite infestation, illicit collection, and the demographic and genetic consequences of small population sizes. Land subdivision may have both beneficial and detrimental effects. Well-managed livestock grazing is probably compatible with the subspecies' conservation. Projected climate changes may have beneficial and detrimental effects, and we do not know what the net effect will be. The high proportion of privately-owned land within the subspecies' range creates additional challenges to its conservation.

Demographic population viability analyses of monitoring plot data predicted stable or increasing trends for 2 or 3 populations, moderate declines for 2 populations, and large to precipitous declines in 5 populations over the next 50 years. When expected climate changes were included in the analyses, 4 populations responded negatively to climate changes and 6 populations responded positively (compared to PVA without climate changes).

Support for the recovery of Tobusch fishhook cactus has come from a variety of sources. Conservation measures from 9 formal consultations under section 7 of the Endangered Species Act (ESA) supported scientific investigations, the salvage of individuals that would have been destroyed by development, and a contribution of over $158,000 to the Tobusch Fishhook Cactus Conservation Fund. The Lady Bird Johnson Wildflower Center manages the Fund through a Memorandum of Agreement with USFWS. The Fund supported 3 projects that contributed significantly to our knowledge of the ecology, conservation genetics, and population viability analyses of Tobusch fishhook cactus. Five grants under section 6 of the ESA have supported scientific investigations and extensive inventory and monitoring of the subspecies on State Highway ROWs, State Parks, Wildlife Management Areas, and State Natural Areas. Four graduate-level investigations focused on Tobusch fishhook cactus, leading to 3 Master's Theses and a Doctoral Dissertation, and provided information that is essential to the subspecies' conservation and recovery.

Recent surveys conducted for development projects found 660 new individuals representing many new Element Occurrences. Based on data accumulated from 25 quantitative surveys, we estimate that the global population size for Tobusch fishhook cactus is about 473,000 individuals distributed over an area of more than 2 million hectares (5 million acres). Thus, it is likely that Tobusch fishhook cactus has multiple, resilient populations. Genetic data from wild populations indicates that the subspecies currently possesses sufficient genetic diversity to conserve long-term adaptive capability. However, habitat fragmentation and disruption of gene flow among populations may have occurred too recently to be detected through genetic analyses. Considering the naturally low densities of Tobusch fishhook cactus populations, gene flow among them may be easily disrupted. Therefore, maintaining the continuity of potential habitats throughout the subspecies' range should have a high conservation priority. We also recommend that viability monitoring should be continued long enough to determine population dynamics and demographic trends at the metapopulation and subspecies levels.

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I. Introduction.

Tobusch fishhook cactus (*Sclerocactus brevihamatus ssp. tobuschii*) is a small cactus, with curved "fishhook" spines, that is endemic to the Edwards Plateau of Texas. It was federally listed as endangered on November 7, 1979 (44 FR 64736) as *Ancistrocactus tobuschii*. At that time, fewer than 200 individuals had been documented from 4 sites. Tobusch fishhook cactus is now confirmed in 8 central Texas counties: Bandera, Edwards, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde. In recent years, over 4,000 individuals have been documented in surveys and monitoring plots.

This Species Status Assessment (SSA) is a comprehensive status review of Tobusch fishhook cactus to inform a decision about the species' status under the Endangered Species Act (ESA) and to guide future conservation efforts. This SSA will also provide the background information to guide future actions and documents, which may include additional listing rules, revised recovery plans, 5-year reviews, and section 7 consultations. We will update this SSA as new information becomes available.

The SSA framework (Figure 1; USFWS 2015, entire) summarizes the information assembled and reviewed by the Service, incorporating the best available scientific and commercial data, to conduct an in-depth review of a species' biology and threats, evaluate its biological status, and assess its resources and conditions needed to maintain long-term viability. For the purpose of this assessment, we define the viability of Tobusch fishhook cactus as its ability to sustain populations in the wild beyond the end of a specified time period. Using the SSA framework, we consider what the species needs to maintain viability through an assessment of its **resilience**, **redundancy**, and **representation**.

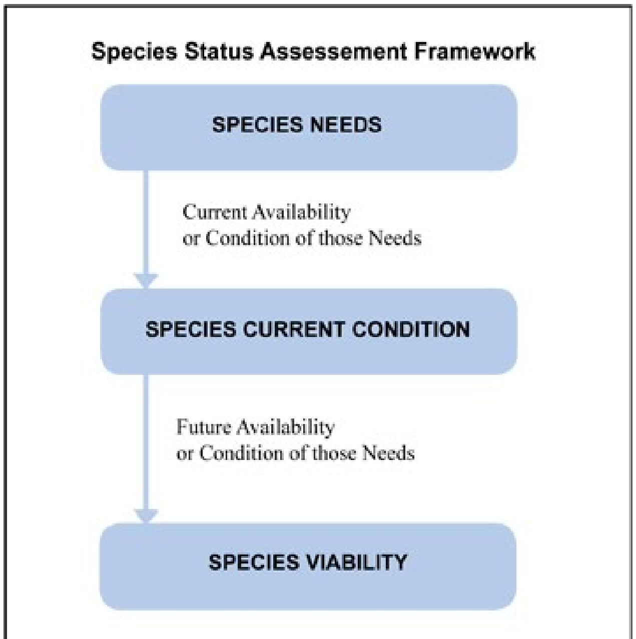


Figure 1. Species Status Assessment Framework.

• **Resilience** refers to the population size necessary to endure stochastic environmental variation (Shaffer and Stein 2000, pp. 308-310). Resilient populations are better able to recover from losses caused by random variation, such as fluctuations in recruitment (demographic stochasticity), variations in rainfall (environmental stochasticity), or changes in the frequency of wildfires.

• **Redundancy** refers to the number and geographic distribution of populations or sites necessary to endure catastrophic events (Shaffer and Stein 2000, pp. 308-310). As defined here, catastrophic events are rare occurrences, usually of finite duration, that cause severe impacts to one or more populations. Examples of catastrophic events include tropical storms, floods, prolonged drought, and unusually intense wildfire. Measured by the number of populations, their resiliency, and their distribution (and connectivity), redundancy gauges the probability that the species has a sufficient margin of safety to withstand or recover from catastrophic events.

• **Representation** refers to the genetic diversity, both within and among populations, necessary to conserve long-term adaptive capability (Shaffer and Stein 2000, pp. 307-308). Representation can be measured by the breadth of genetic or environmental diversity within and among populations and gauges the probability that a species is able to adapt to environmental changes (natural or human caused) and to colonize new sites.

In summary, this SSA is a scientific review of the available information related to the biology and conservation of Tobusch fishhook cactus. It does not provide or pre-determine the Service's decision that Tobusch fishhook cactus does, or does not, warrant protection under the Act. The Service will make that decision after reviewing this document, along with the supporting analyses, other relevant scientific information, and all applicable laws, regulations, and policies, and the results of the decision will be announced in the *Federal Register*.

Throughout this document, the first uses of scientific and technical terms are underscored with dashed lines; these terms are defined in the glossary in Appendix 1. Appendix 2 describes our methods to model habitats and estimate the global population size, based on quantitative data from 25 surveys.

II. Species Information.

II.1. Description (adapted from Poole et al. 2007, pp. 442-443).

Tobusch fishhook cactus, as the name implies, is a cactus armed with fishhook-shaped spines. The hemispheric or short-columnar stems of mature plants are 3 to 10 centimeters (cm) (1.2 to 3.9 inches (in)) tall and 1 to 10 cm (0.4 to 3.9 in) in diameter; however, although the largest recorded individuals are as much as 10 cm (3.9 in) in diameter, few wild plants are greater than 5 cm (2.0 in) in diameter (Poole and Janssen 2002, p. 7). The stems are supported on short, conical taproots from which emerge numerous fibrous roots that typically grow horizontally along the surfaces and fissures of rock strata. The stems bear tubercles (podaria) up to 12 millimeters (mm) (0.5 in) long that have a groove (sulca) along their upper surfaces. The tubercles are arranged in 5 to 8 ribs (Marshall 1952, p. 79), or from 8 to 12 ribs (Poole et al. 2007, p.442). However, we note that the tubercles within each rib are nearly distinct from each other; the ribs, which may spiral, are difficult to discern, especially in smaller individuals, and the tubercles appear to alternate. Spines arise from areoles at the apex of each tubercle. The spines are of two types: Radial spines are fine, straight, from 1 to 2 cm (0.4 to 0.8 in) long, spreading at right angles to the tubercle from the edges of the areoles. From 3 to 5 thicker, flattened central spines, 2 to 4 cm (0.8 to 1.6 in) in length, arise from nearer the center of the areoles and project more or less outward from the stem; one of the central spines is abruptly recurved, and may reach 180° of curvature in older individuals. Spines are yellowish at first, and may have reddish tips, turning gray with age. Flowers emerge from the bases of young tubercles near the stem apex, and have numerous yellow tepals. Fruits are spineless, elongate, from 2.5 to 3 cm (1 to 1.2 in) long, turning reddish-green and usually splitting open along 1 or more lines when mature (Emmett 1995, p. 97).

Table 1. The diagnostic morphological characters that distinguish the subspecies of *Sclerocactus brevihamatus* (adapted from Poole et al. 2007, p. 442; Porter and Prince 2011, p. 42-45).

	Subspecies		
Character	*brevihamatus*	*tobuschii*	*pallida*
Inner tepal color	Dusky-rose, yellowish-pink, olivaceous, brown, pinkish-brown	Bright yellow, pale yellow, or greenish yellow	White to cream
Number of radial spines	12 to 22	7 to 9 (occasionally up to 12)	7 to 10
Ribs	8 to 13, distinct	5 to 12, indistinct	8 to 13
Diameter of central hooked spine	0.8 to 1.5 mm (0.03 to 0.06 in)		0.3 to 0.6 (0.01 to 0.02 in) (occasionally to 0.8) mm (0.03 in)

The primary distinguishing feature is the yellow or greenish yellow tepals in ssp. *tobuschii*, versus tepals variously tinged with brown, pink, rose, or olive in ssp. *brevihamatus*. However, we note that the outer tepals of ssp. *tobuschii* are often tinged pink or pinkish-brown, and the diagnostic yellow color applies only to the inner tepals. This distinction between the color of inner and outer tepals (perianth segments) was indicated in the species description (Marshall 1952, p. 80) but is omitted elsewhere, which may lead to confusion or misidentification.

II.2 Taxonomy and phylogenetics.

In 1951, Herman Tobusch collected the first specimens of the cactus that now bears his name, on the G. W. Henri Ranch, east of Vanderpool in Bandera County, Texas. W. T. Marshall described a new species, *Mammillaria tobuschii*, based on additional specimens from this population (Marshall 1952). A number of synonyms have subsequently been applied to this taxon, including *Ancistrocactus tobuschii* (W.T. Marshall) W.T. Marshall ex Backeb., *Echinocactus tobuschii* (W.T. Marshall) Weniger, *Ferocactus tobuschii* (W.T. Marshall) N.P. Taylor, *Pediocactus brevihamatus* (Engelmann) Halda ssp. *tobuschii* (W.T. Marshall) Halda, *Ancistrocactus scheeri* Britton & Rose ssp. *tobuschii* (W.T. Marshall) Doweld, and *Sclerocactus brevihamatus* (Engelmann) D.R. Hunt ssp. *tobuschii* (W. T. Marshall) N. P. Taylor.

The published systematic treatments of the Cactaceae (Cactus Family) fail to reach consensus for several reasons. Many species are rare or endemic, seldom observed or collected for scientific study, and not well known. The diagnostic morphological characters, such as flower color, often do not preserve well in herbarium specimens. Additionally, the Cactaceae is one of the most popular families among plant collectors and hobbyists. Cactus enthusiasts have published many species descriptions and taxonomic treatments, not all of which conform to currently accepted phylogenetic classification (Porter and Prince 2011, p. 10). Finally, the steady accumulation of phylogenetic analyses based on DNA sequences has led to continual revisions as new data emerges. The following sources provide a brief review of the recent classifications pertaining to the taxon *tobuschii*.

The Flora of North America recognizes both *Ancistrocactus* (K. Schumann) Britton & Rose (Zimmerman and Parfitt 2003a, pp. 209-211) and *Sclerocactus* Britton & Rose (Heil and Porter 2004, pp. 197-207) as valid genera, and places the species *brevihamatus* in the former genus. Regarding the relationship between *Ancistrocactus* and *Sclerocactus*, Heil and Porter (p. 197) state:

> "There has been considerable controversy concerning generic circumscription of *Sclerocactus*. Some treatments include *Ancistrocactus*, *Echinomastus*, *Glandulicactus*, and *Sclerocactus* as a single genus; whereas others exclude those groups, in addition to *Toumeya*, from *Sclerocactus*. Molecular phylogenetic studies of chloroplast DNA sequences (J. M. Porter et al. 2000; R. Nyffeler 2002) support a close relationship among *Ancistrocactus*, *Echinomastus*, *Toumeya*, and *Sclerocactus*; only *Toumeya* is included with *Sclerocactus* here.…*Ancistrocactus* is sister to *Echinomastus* and *Sclerocactus*, providing merit to a broader circumscription of *Sclerocactus*. *Glandulicactus* and *Pediocactus* are only distantly related to this group, bolstering their exclusion from *Sclerocactus*."

With regard to the taxon *tobuschii*, Zimmerman and Parfitt (2003b, p. 210) state:

> "*Ancistrocactus tobuschii* pertains to the north-easternmost populations, from typical *A. brevihamatus* by yellow flowers, rarely with a hint of pink (pinkish, greenish, or brownish in *A. brevihamatus*), smaller stems and fruits, and thinner, more delicate and yellow spines. All of those characteristics, sometimes considered diagnostic for *A. tobuschii*, are unsatisfactory. The oldest plants of *A. tobuschii* are especially similar to *A. brevihamatus*, but *A. tobuschii* occupies marginal habitat and seldom survives long. Varietal status may be warranted for this and at least two other eco-geographical races within the species."

The statements above regarding the habitat and lifespan of *A. tobuschii* may have been based on Weniger (1979, pp. 3-7) or USFWS (1987, pp. 4-5), but contradict more recent descriptions from field studies that were published prior to the Flora of North America treatment, including Emmett (1995, pp. 34-35, 168-169), Lockwood (1995, p. 428), Sutton (1997, pp. 42-43), Sutton et al. (1997, pp. 442-444), and Poole and Janssen (2002, pp. 1-2, 6-7). Subsequent publications, discussed in Section II.6., confirm that plants conforming to the description of the taxon *tobuschii* occur in a distinct habitat from *brevihamatus* plants and are able to live for decades.

Powell et al. (2008, pp. 240-241) stated, "At present it is not clear whether *A. tobuschii* and *A. brevihamatus* should be regarded as distinct species, two intergrading varieties, or merely integrating flower-color morphs of the same taxon."

Tropicos (2016a-f) appears to list the following taxa as accepted names for each other, without indicating any preference: *Ancistrocactus brevihamatus* (Engelm.) Britton & Rose (2016a), *Ancistrocactus tobuschii* (W.T. Marshall) W.T. Marshall ex Backeb. (2016b), *Sclerocactus brevihamatus* subsp. *brevihamatus* (2016c), *Sclerocactus brevihamatus* subsp. *tobuschii* (W.T. Marshall) N.P. Taylor (2016d), *Ancistrocactus scheeri* (Salm-Dyck) Britton & Rose (2016e), and *Sclerocactus scheeri* (Salm-Dyck) N.P. Taylor (2016f).

The Center for Plant Conservation (2016) and Desert Botanical Garden (2009) continue to recognize the name used by USFWS when the species was listed (*Ancistrocactus tobuschii*).

Tobusch fishhook cactus (a.k.a. shorthorn fishhook cactus) is recognized by the Integrated Taxonomic Information Service (ITIS 2009), NatureServe Explorer (2009), and International Plant Names Index (IPNI 2008) as *Sclerocactus brevihamatus* ssp. *tobuschii* (W.T. Marsh.) N.P. Taylor. This nomenclature was also accepted by the United States Department of Agriculture (USDA) PLANTS database as recently as 2014, although this source has currently reverted to the older name, *Ancistrocactus tobuschii* (W.T. Marshall) W.T. Marshall ex Backeb. (USDA NRCS 2014, 2016).

Rare Plants of Texas (Poole et. al. 2007, pp. 442-443) recognize the taxon as *Sclerocactus brevihamatus* (Engelm.) D.R. Hunt ssp. *tobuschii* (W.T. Marshall) N.P. Taylor. An excerpt of their description includes these diagnostic features: stems 3 – 15 cm tall by 1 – 15 cm wide; tubercles 5 – 12 mm long, shallowly grooved on the upper surface, roughly aligned into 8 – 12 ribs; radial spines 7-9 (-12); central spines 3 – 5, upper 2 forming an erect "V", lower central spine hooked; flowers bright yellow, sometimes pale or greenish; fruit elongate egg-shaped, green, pinkish at maturity; seeds dark brown to black, shiny. Regarding similar species, they state (p.442):

> "*Sclerocactus brevihamatus* subsp. *brevihamatus*, which occurs on the southern and western border of the range of *S. brevihamatus* subsp. *tobuschii*, looks almost identical. *Sclerocactus brevihamatus* subsp. *brevihamatus* has more radial spines (12-22), is larger and more cylindrical, and the flowers are dusky rose to yellowish-pink or olivaceous…Also, *S. brevihamatus* subsp. *brevihamatus* is found within South Texas brushland communities, such as cenizo shrubland…"

Porter and Prince (2011, pp. 6-35) reviewed the historic taxonomic treatments among the related genera of *Ancistrocactus*, *Coloradoa*, *Echinomastus*, *Ferocactus*, *Glandulicactus*, *Neolloydia*, *Pediocactus*, *Sclerocactus*, and *Toumeya*. They developed a phylogeny based on DNA sequences (pp. 36-100) and identified a monophyletic clade that includes *Ancistrocactus*, *Echinomastus*, and *Toumeya*, but not *Glandulicactus*, within *Sclerocactus* (pp. 18-19). The genetic evidence indicated that *Ancistrocactus* is also a monophyletic clade, identified as a subgenus within *Sclerocactus*, which includes the 3 subspecies of *Sclerocactus brevihamatus* and *Sclerocactus scheeri* (pp. 40-47). This treatment recognized 24 species, 8 subspecies, 2 subgenera, and 3 sections of *Sclerocactus*. We concur with Porter and Prince's taxonomic treatment of this challenging group of the cactus family because it is demonstrably based on scientific evidence and represents the best currently available information. These authors do support recognition of *S. brevihamatus* ssp. *tobuschii* largely on the basis of Jackie Poole's field experience with the taxon, and because there was (in 2011) a lack of genetic evidence to the contrary (p. 33).

Rayamajhi's Master's Thesis (2015) is an investigation of the genetic relationship of 10 populations of *Sclerocactus brevihamatus*. Based on morphological features, 8 populations were determined to be subspecies *tobuschii*, 1 population (a conservation area managed by The Nature Conservancy) was subspecies *brevihamatus*, and 1 population (Devils River State Natural Area (SNA)) was primarily *tobuschii* but also had some *brevihamatus* individuals (Sharma 2015, p.1). Rayamajhi isolated DNA from spine tissue of 225 individuals from the 9 *tobuschii* populations and 30 individuals from the *brevihamatus* population (pp. 44, 50). He identified 48 potential nuclear microsatellite (simple sequence repeat) loci, of which 7 loci were suitable for analysis of genetic diversity (pp. 24-37). The *tobuschii* populations had a total of 61 alleles at the 7 loci, ranging from 4 to 10 alleles per locus (p.50). The *brevihamatus* population had 42 alleles, ranging from 2 to 16 per locus (p. 51). The average pairwise Wright's genetic distance (F_{ST}) among the 9 *tobuschii* populations was 0.059 (ranging from 0.02 to 0.1), and the average pairwise Nei's genetic distance (G_{ST}) was 0.043 (ranging from 0.01 to 0.09). These results indicate that there was relatively little genetic differentiation among these 9 populations (pp. 53, 54, 65, 66, 79, 80). The average pairwise F_{ST} and G_{ST} values between 8 *tobuschii* populations (not including Devils River SNA) and the *brevihamatus* population were 0.139 and 0.124, respectively, indicating that these populations have diverged (pp. 79, 80, 98). The pairwise F_{ST} and G_{ST} values between Devils River SNA and the *brevihamatus* population were 0.03 and 0.02, respectively (pp. 79, 80), revealing very little genetic divergence between these populations; this is not surprising, considering that these sites in the lower Devils River area are only 5.6 mi (9 km) apart. The genetic similarity between these adjacent populations may be due to a mixed population, or to hybridization between the two subspecies (pp. 67-68; Sharma 2015, p. 1). Bayesian Cluster analysis, principal coordinate analysis, and majority rule consensus all indicated that the *brevihamatus* population and *tobuschii* populations are genetically different, lending support to their recognition as separate subspecies (pp. 67, 98).

Sharma (2015, p. 1), Rayamajhi's graduate advisor, cautions that this study included only 30 individuals from a single population of the putative subspecies *brevihamatus*. This is, however, the only genetic comparison to date of populations that are morphologically identified as subspecies *brevihamatus* and *tobuschii*, and constitutes the best currently available information. Based on the morphological, phylogenetic, and ecological data (discussed in II.6.), we conclude that Tobusch fishhook cactus is a valid, distinct subspecies, *tobuschii*, of *Sclerocactus brevihamatus*. Some populations along the southern and western edge of the range of ssp. *tobuschii*, in Kinney and Val Verde counties, are in close proximity to the range and habitat type of ssp. *brevihamatus*. Both subspecies are present, and may interact genetically, at some sites along this taxonomic and ecological boundary.

II.3. Conservation genetics.

Rayamajhi (2015, discussed above) also investigated genetic data relevant to species conservation. He determined that the mean expected heterozygosity (H_e) for 9 populations of ssp. *tobuschii* was 0.59, and mean observed heterozygosity (H_o) was 0.37 (p. 57). Through comparison to columnar cactus species that are endemic or have limited geographic distribution, Rayamajhi concluded that H_e was moderately high and H_o was moderate (pp. 58-61). The moderate H_o may be attributed to small population sizes and elevated levels of inbreeding within populations (p. 57). By comparison, H_e and H_o for *Sclerocactus glaucus*, a federally listed threatened species from Colorado, were 0.66 and 0.47, respectively, while for *Sclerocactus parviflorus*, a relatively widespread species, H_e and H_o were 0.62 and 0.39 (Schwabe et al. 2015, p.449). The mean inbreeding coefficient ($F_{IS)}$ was 0.38 (range of 0.15 to 0.63) for ssp. *tobuschii* and 0.47 for ssp. *brevihamatus* (pp. 63-64). For comparison, the average F_{IS} for *S. glaucus* and *S. parviflorus* was 0.28 and 0.37 (Schwabe et al. 2015, p. 449). Three populations of ssp. *tobuschii* and the single ssp. *brevihamatus* population were at relatively higher risk of inbreeding effects and may have suffered recent genetic bottlenecks through population declines (P. 97). The higher level of inbreeding in these populations may be due to small, isolated populations, mating of close relatives within populations, the limited range of seed dispersal, and the limited range and foraging behavior of a primary pollinator (see II.4), halictid bees (p. 64). However, the relatively low levels of genetic differentiation among populations of ssp. *tobuschii* (low pairwise F_{ST} and G_{ST} levels, discussed in II.2), as well as isolation by distance analysis, indicates substantial gene flow among populations, suggesting that the documented populations of ssp. *tobuschii* may interact with additional (undocumented) populations (at least in the recent past) (p. 67).

In summary, there were relatively few genetic differences between the 9 Tobusch fishhook cactus populations in Rayamajhi's study, regardless of the distance between populations. This evidence supports a hypothesis that gene flow has occurred throughout the subspecies' range, at least until recently; however, recently isolated populations may not yet show genetic differentiation, in part because individuals can live and contribute to the local gene pool at least for several decades. While most populations had an apparently healthy degree of out-crossing, 3 populations showed higher levels of inbreeding, the likely consequence of small population size and isolation. The relative lack of genetic differentiation by distance also has implications for the species' management. For example, it indicates that the use of seeds or salvaged plants from one site to replant at another appropriate site within the species' range would incur a lower risk of outbreeding depression.

II.4. Life history: Growth, phenology, reproduction, and mortality.

Lockwood (1995, pp. 428-430) described the life history of a Tobusch fishhook cactus population discovered in February 1992 at Kickapoo Caverns State Park (SP) in Kinney and Edwards counties. He collected nine insect species visiting the flowers, and noted that the bee *Dialictus cumulus* and the common honey bee (*Apis mellifera*) were the probable pollinators. He also observed other halictid bees, including *Dialictus pruinosiformis*, *Lasioglossum morrilli*, *Osmia subfaciata*, and *Agapostemon* sp. The only other native plant flowering concurrently with Tobusch fishhook cactus at the site, in late January to early February, was ten-petal anemone (*Anemone heterophylla*). A native shrub, agarita (*Berberis trifoliata*), blooms in mid-February. Although many native bee species are not yet active this early in the year, there were also few competing sources of pollen and nectar.

Raymond Emmett investigated the growth, reproduction, seed ecology, and mortality of Tobusch fishhook cactus for his doctoral dissertation (Emmett 1995). From 1991 to 1994, he collected field data from three populations at Walter Buck Wildlife Management Area (WMA) (Kinney Co.), Devil's Sinkhole SNA (Edwards Co.), and Kickapoo Caverns SP. He summarized the phenology and reproduction (p. 4): The species flowers once per year, from early February to mid-March. Up to eight or more yellow to yellow-green flowers per plant arise from the axils of previous-year tubercles. The flowers remain open for up to one week, or until they are pollinated. The green to greenish-pink fruits ripen in mid-May and split open when dry. Each fruit produces from 20 to 40 papillate seeds that are 1.5 mm long by 1 to 1.5 mm wide. The only known means of reproduction is through sexually-produced seeds.

Poole and Janssen (2002, p. 8) observed that Tobusch fishhook cactus populations flower for 2 to 3 weeks per year; flowering season begins as early as late January in the southern portion of the species' range, and lasts as late as mid-March in the northern part of the range. Plants become reproductive when they are at least 2 cm in diameter (also reported in Emmett 1995, p. 161), and bear an average of 2 to 3 flowers per plant (p. 1).

In controlled pollination experiments (Emmett 1995, p. 70), flowers cross-pollinated by hand had 98 percent fruit set, averaging 38.9 seeds per flower, while flowers self-pollinated by hand had only 5 percent fruit set and 1.1 seeds per flower. The experimentally cross-pollinated seeds had a germinability of 22.7 percent versus only 6.3 percent for self-pollinated seeds. We deduce from this data that cross-pollinated flowers produce nearly 127 times as many progeny as self-pollinated flowers, and conclude that Tobusch fishhook cactus is almost completely self-incompatible. In comparison, 67.4 percent of naturally-pollinated flowers set fruit, averaging 16.0 seeds per flower; seed germinability of naturally-pollinated fruits was 24.5%. The lower fruit set and seed production of naturally-pollinated versus experimentally cross-pollinated flowers may indicate that insufficient pollinator populations limited reproduction (p. 85).

Emmett (1995, pp. 77-81) found no significant difference in the effectiveness of pollen collected from neighboring plants and pollen from distant colonies with respect to fruit set, seed set, and seed germination rate, and both pollen sources were comparable to uncontrolled natural pollination. He observed that several species of halictid bees were the most common floral visitors, and European honey bees (*Apis mellifera*) were rare. At Devil's Sinkhole SNA, *Lasioglossum* (*Dialictus*) *morrilli* was the most commonly observed floral visitor (pp. 74-75). Noting that bee pollinators typically visit flowers within a small area before moving to more distant areas, he concluded that "…the general degree of interrelatedness of plants within each colony is not that great; the self-incompatibility system is functioning adequately to reduce the level of inbreeding; there is sufficient genetic diversity within the colonies and/or that *A. tobuschii* at this site are not especially prone to the potentially negative effects of inbreeding." (p. 87).

Reemts and Becraft (2013) investigated pollination of Tobusch fishhook cactus at The Nature Conservancy's Love Creek Preserve, in Bandera Co. Flowering began on February 14, and pollinator observations were made from February 27 until March 14 (p. 3). The observed flower visitors (pp. 6-7) included two species of halictid bees, *Lasioglossum semicaeruleum* and *Agapostemon texanus* (green sweat bee), and two species of bees in the family Apidae, *Anthophora californica* and honey bees. Other possible pollinators included sulphur and hairstreak butterflies and tumbling flower beetles. *Osmia lignaria* (orchard mason bee) was present, but not observed on Tobusch fishhook cactus. In controlled pollination with cages, 43 percent of flowers were not visited within 60 minutes, but uncaged flowers were usually visited within 15 minutes, suggesting that the cages may have disrupted early-morning floral visitation patterns (p. 11).

Langley's Master's Thesis (2015) is an additional investigation of the pollination ecology of Tobusch fishhook cactus, conducted near Junction in Kimble Co. and at Kerr WMA in Kerr Co. She determined that the flowers are protandrous; anthers dehisce before buds open, and stigmas are receptive 1 to 2 days after flowers open (p.17). Most pollen was removed by honey bees on the first day that flowers opened. Using 4 different methods, Langley determined that the flowers do not produce nectar, but she detected a glucose-rich fluid exuding from extra-floral nectaries in the tubercle tips that may serve to attract ants (pp. 19-20, 31). Time-lapsed photography of floral visits recorded 376 observations of honey bees, 328 visits by halictid bees, and 214 by ants (pp. 21-23). Honey bees spent an average of 30.7 seconds (s) in flowers, selected young versus mature flowers, and made the most frequent visits early in the season. Halictid bees spent an average of 2.1 minutes (m) in flowers, selected mature versus young flowers, and were most abundant by mid-March. However, halictid bees contact the stigma only 15 percent of the time, and thus may be less effective pollinators than honey bees (pp. 29-30). Controlled pollination experiments showed that out-crossed and open-pollinated flowers had a statistically similar rate of fruit set (44 percent and 30 percent, respectively), but self-pollinated flowers had a significantly lower rate (3 percent) than out-crossed and open-pollinated flowers (pp. 24-27). There was no observed difference in pollen tube growth between out-crossed and self-pollinated stigmas, nor was there a significant difference in seed viability between out-crossed, open-pollinated, and self-pollinated flowers. Langley concluded that Tobusch fishhook cactus is primarily self-incompatible (p. 28).

Emmett (1995) determined that average Tobusch fishhook cactus plants of reproductive size produced an average of 112 seeds per plant per year (p. 108). He observed that a species of ant, *Forelius foetidus* (Dolichoderinae), quickly removed up to 85 percent of seeds from split fruits, and carried the seeds, fruit pulp, and funiculi to their mounds (p. 112-114). However, Emmett did not determine the fate of the seeds taken to ant mounds (p. 124). Gravity and rainwater dispersed the remaining seeds, and most of the Tobusch fishhook cactus progeny he observed were in the immediate vicinity of mature, reproductive plants. Although he did not directly observe mammals or birds consuming the fruits, indirect evidence (damaged fruits) led him to estimate that about 5 percent of the annual fruit production is consumed by mammal or bird species and may provide occasional longer distance seed dispersal (pp. 115-116, 126).

The fate of Tobusch fishhook cactus seeds collected by ants merits further investigation. González-Espinosa and Quintana-Ascencio (1986, pp. 276-277) observed that harvester ants (*Pogonomyrmex barbatus*) in central Mexico collected and carried into their nests up to 400 seeds of *Opuntia robusta* and *O. streptacantha* per day. The ants removed the seed funiculus (or adhering pulp) without killing the embryos and ejected most of the seeds into the surrounding gravel disks. More than 80 percent of dyed seeds offered to the ants were ejected into gravel mounds within 24 hours. These ants rarely foraged more than 10 to 12 (meters) m from their nests.

Emmett (1995) reported seed germination in the laboratory ranging from 1 percent to 67 percent; almost all seed germination occurred within 7 to 10 days (pp. 116-117). By placing seeds in protective exclosures in-situ at Walter Buck WMA and Devil's Sinkhole SNA, he found an average of 20 percent (ranging from 7 to 27 percent) germinated within 1 year; 62 percent and 89 percent (respectively) of the in-situ germination occurred between February and May (pp. 118-120). He also attempted to quantify the soil seed bank (pp. 120-122) by extracting soil cores that measured 20 mm in diameter by 40 mm in depth. The sampling was done in late March and April, prior to dispersal of the current year's seeds. After initial sampling strategies detected no seeds, he employed a biased sampling of soil adjacent to reproductive plants. He recovered small numbers of germinable seeds from two sites, and concluded that moderate quantities of viable seeds were present in the soil seed bank and may allow for recovery of populations and genetic diversity following catastrophic losses (pp. 129-30).

Emmett (1995, pp. 151-152) found that stem diameter growth of Tobusch fishhook cactus plants ranged from one to several mm/year, but decreased during some years. The stems of many cactus species swell and shrink, depending on the amount of water they store. Based on observed growth rates, he estimated that Tobusch fishhook cactus plants take at least 9 years to reach reproductive size and 25 years to reach a diameter of 30 mm; the largest plants he observed, measuring 40 mm to 60 mm in diameter, could be over 50 years old (pp. 168-169).

Poole and Janssen (2002, p. 7) stated that Tobusch fishhook cactus normally grows slowly, but can increase one centimeter (cm) in diameter in years of higher rainfall, which may be due to water stored in the stem. Individuals begin reproducing when the stem diameter reaches 2 cm, and can live 10 years or more (p. 7). The largest individuals they observed were 10 cm in diameter, but most populations have few individuals greater than 5 cm, and most individuals measure from 1 to 5 cm (p. 7).

Reemts (2014) reported that 1,103 Tobusch fishhook cactus plants at Love Creek Preserve, in Bandera County, had an average diameter of 1.7 cm, and increased in diameter 16 percent during a 6 month period of observation; the corresponding average diameters and growth at a ranch in Real County were 1.5 cm and 22 percent (p.7). To compare to growth rates reported elsewhere, we interpret these figures to mean that average incremental growth in diameter was 2.7 mm and 3.3 mm at these sites. The average diameters of flowering Tobusch fishhook cactus plants at the Bandera and Real county sites was 2.5 cm and 2.1 cm, respectively, and flowering individuals were significantly larger than non-flowering individuals (p. 8). The largest of 1,270 individuals at the Bandera and Real county sites had diameters of 4.8 cm and 4.0 cm, respectively (p.7), and some individuals had as many as 14 flowers and 12 fruit (p. 8). The rates of flowering (fl) and fruiting (fr) were 0.20 (fl) and 0.11 (fr), and 0.22 (fl) and 0.08 (fr), at the Bandera and Real county sites, respectively (p.8); thus, the rate of fruit set at these sites was 0.58 and 0.36 (p.8).

The annual mortality rate during Emmett's study at Walter Buck WMA and Devil's Sinkhole SNA exceeded 20 percent, and three-year mortality was 55 percent and 69 percent, respectively; annual mortality was 9 percent at Kickapoo Caverns SP (Emmett 1995, pp. 155-161). The majority of attributable mortality was due to infestation by larvae of two Coleopteran cactus parasites, *Moneilema armata* LeConte (Cerambycidae) and an undescribed species of *Gerstaeckeria* (Curculionidae); these parasites always killed the host. The latter species accounted for 85 percent of the mortality caused by insect larvae. Mammal herbivory accounted for a relatively minor amount of mortality. Emmett observed that Tobusch fishhook cactus plants browsed by mammals often sprout new stems.

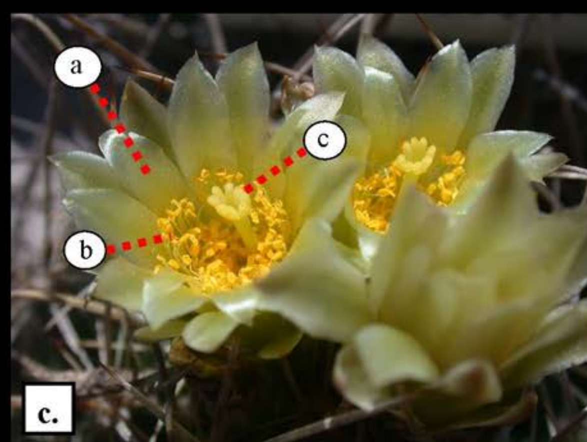
Other investigators have also reported high mortality rates in populations of Tobusch fishhook cactus; however, see the discussion in Section II.7.3 regarding detection probability for this species. Lockwood (1995, p. 429) determined annual mortality rates of 15 percent and 8 percent at Kickapoo Caverns SP between 1992 and 1994. Reemts (2014, p. 8) reported an apparent mortality (observed dead plus missing individuals) over 6 months was 24 percent and 29 percent at sites in Bandera and Real county sites, respectively. In particular, infestations of the Tobusch fishhook cactus weevil were the primary cause of mortality at the Devil's Sinkhole population, which declined from 1,100 individuals in 1994 to only 24 in 1999 (Poole and Janssen 2002, p. 9). Zimmerman (pers. comm. 1992, quoted in Emmett 1995, p. 37) believed that low population densities are less prone to weevil predation, and are therefore more secure.

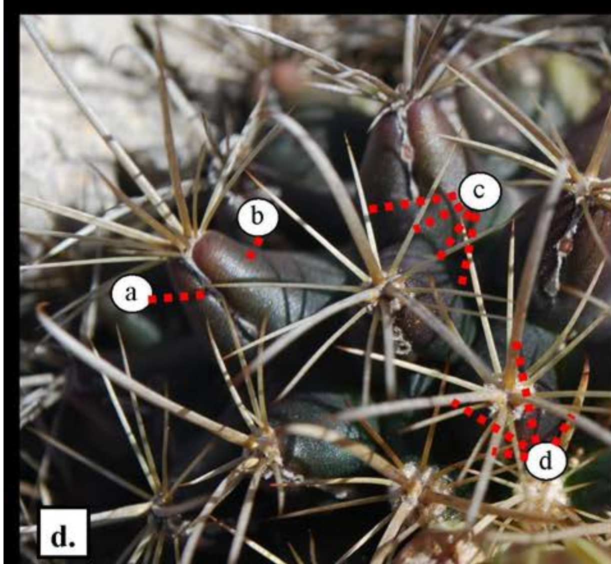
The Tobusch fishhook cactus weevil, as it is now called, was investigated by William Calvert (Calvert 2003; Poole and Birnbaum 2003). This species of *Gerstaeckeria* accounted for 44.8 percent of mortality in 256 unhealthy Tobusch fishhook cactus that were collected from the field and studied in terrariums (p. 5). *Gerstaeckeria* larvae overwinter inside the cactus stems, emerge from the end of April until mid-July, then mate and oviposit after emergence (p. 7). Other causes of mortality included a rot of undetermined origin (34.7 percent) and larvae of a cerambycid beetle, *Moneilema crassum* (7.5 percent). The life history of *Moneilema* is similar to the Tobusch fishhook cactus weevil, except the pupae emerge from April to May (pp. 7-8). During the wet spring of 2001, *Copestylum* fly larvae may have contributed to15 percent of mortality. All *Gerstaeckeria* species are cactus parasites whose larvae feed and pupate inside cactus stems. Adults are primarily nocturnal and are flightless, due to fused elytra (p. 9). Charles O'Brien, a specialist in this genus, determined that the species parasitizing Tobusch fishhook cactus was previously unknown to science (p. 1). Calvert found other *Gerstaeckeria* spp. in other cactus species at Tobusch population sites (*Opuntia* sp. and *Coryphantha sulcata*) that did not feed on Tobusch fishhook cactus (pp. 5-10). The Tobusch weevil may be highly specific to Tobusch fishhook cactus, but this has not been confirmed (p. 10).

Summary of the characteristics of Tobusch fishhook cactus life history:

- Growth rates are very slow, averaging from 1 to several mm per year. Plants become reproductive when they attain an average of at least 2 cm in diameter; this takes an estimate of 9 years.
- Flowering occurs between late January and mid-March, depending on locality, and lasts a few weeks in each population. Honey bees and halictid bees are effective pollinators, although the latter group may be more active later in the flowering season.
- The breeding system is primarily out-crossing, but the species is capable of self-fertilization.
- Fruits ripen around mid-May. Ants remove a large proportion of seeds, pulp, and funiculi, but whether the ants consume the seeds, or effectively disperse them, is not known. Mammals or birds also consume fruits and may account for longer-distance seed dispersal.
- A single study found moderate numbers of viable seeds in the soil near live plants; this study may be misinterpreted as confirmation that the species does not maintain an effective soil seed bank. Considering the difficulty of quantifying soil seed banks, and the very limited scope of this study, we conclude only that we lack the evidence of a persistent seed bank.
- Annual mortality rates are often greater than 20 percent, and in many cases appear to exceed recruitment rates. In particular, infestations by the larvae of an undescribed species of weevil and of a species of cerambycid beetle can cause catastrophic population declines. Nevertheless, the presence of some larger specimens indicates that the potential lifespan is decades long. Additionally, determinations of mortality and recruitment are confounded by the great difficulty in detecting live plants in the field (discussed in Section II.7.3).

Figure 2 Photographic images.





a. *Sclerocactus brevihamatus* ssp. *tobuschii*. Note inner tepals yellow; fewer, finer radial spines; ribs indistinct.

b. *Sclerocactus brevihamatus* ssp. *brevihamatus*. Note pinkish-brown tinge on all tepals; more, heavier radial spines; distinct ribs.

c. Detail of ssp. *tobuschii* flowers. a = inner tepal; b = stamen; c = stigma.

d. Detail of ssp. *tobuschii* morphology. a = sulca; b = tubercle; c = radial spines; d = central spines.

II.5. Habitats and Ecology.

The recovery plan (USFWS 1987, p. 5) stated, "The cacti occur in gravelly soils along rivers and plants are periodically disturbed by flooding. Severe floods will destroy plants but some disturbance appears to benefit the species because non-flooded areas become very grassy which tends to crowd out the cacti." Although these observations accurately describe the type locality, Poole and Janssen (2002, p. 2) noted:

> "When the original status report for Tobusch fishhook cactus (*Ancistrocactus tobuschii*) was written, the species was thought to occur primarily on gravel bars or limestone ledges along floodplains or stream terraces in two counties on the Edwards Plateau of central Texas (Weniger 1979). Thus, it was subject to threat from the inevitable flooding that shapes the Edwards Plateau. In fact, it was such a flood in August 1978 that destroyed two of the four known populations of Tobusch fishhook cactus, and led to the listing (USFWS 1979)…However by the early 1990s many new locations had been discovered, and the species was known from eight counties. Most sites were no longer in the floodplain, but found from lower slopes to ridge tops…"

Emmett (1995, p. 13-14) listed live oak (*Quercus fusiformis* Small), Ashe juniper (*Juniperus ashei* Buchh.), Texas persimmon (*Diospyros texana* Scheele), elbowbush (*Forestiera pubescens* Nutt), and agarito (*Mahonia trifoliolata* Moric. Fedde) as the dominant plant species of Tobusch fishhook cactus sites at Walter Buck WMA, Devil's Sinkhole SNA, and Kickapoo Caverns SP. Mexican piñón (*Pinus remota* (Little) D.K. Bailey & Hawksw.) was also present at Devil's Sinkhole and Kickapoo Caverns, but not Walter Buck. Although this list includes the most evident species in the general area of populations, these are not the species closely associated with Tobusch fishhook cactus within microsites.

Lockwood (1995, p. 428) described the habitat of a Tobusch fishhook population at Kickapoo Caverns SP. This population occupied an area of 0.65 hectares (ha) (1.6 acres (ac)) on a south-facing slope, from 579 – 586 m elevation. Tobusch fishhook cactus plants occurred in shallow, gravelly soils among blocks of exposed Cretaceous limestone. Associated species included Peruvian spike-moss (*Selaginella peruviana*), scattered paper-shell pinyon (*Pinus remota*) and sandpaper oak (*Quercus pungens*), button cactus (*Epithelantha micromeris*), scarlet hedgehog cactus (*Echinocereus coccineus*), pitaya (*E. enneacanthus*), and pricklypear (*Opuntia* spp).

Sutton et al. (1997, pp. 441-445) investigated the fine-scale plant associations of the Tobusch fishhook cactus population at Walter Buck WMA. These authors (p. 443) note that previous descriptions of Tobusch fishhook cactus vegetation associations focused on the landscape-scale tree species that occurred in the area. Due to this cactus's small size, the vegetation and physical structure of its immediate vicinity may be more important. They visually estimated the percent cover of 41 plant species and other surface features found in 291 square, 1.0 m^2 plots centered on individual Tobusch fishhook cactus plants. The median number of associated species per plot was 5 (range of 1 to 12), and the composite vegetative cover was 33 percent; most quadrats ranged between 10 percent and 39 percent plant cover. Table 5 lists the composite percent cover and percent frequency of seven cover classes within the plots. The authors conclude (pp. 442-

443) that Tobusch fishhook cactus was most closely associated with coarse rock fragments and limestone bedrock.

Our interpretation of the cover data at this site is that, within 71 cm of Tobusch fishhook cactus plants, solid and fragmented rock comprise about twice as much cover as all classes of vegetation combined.

Table 2. Cover classes in 1.0 m^2 plots centered on Tobusch fishhook cactus plants at Walter Buck WMA (adapted from Sutton et al. 1997, p. 443).

Cover Class	**Composite % Cover**	**% Frequency**
Coarse rock fragments	44	93
Grasses	26	n/r
Bedrock	19	69
Bare ground	4	13
Forbs	3	n/r
Pteridophytes	2	20
Woody and succulent plants	2	n/r

n/r = not reported.

Poole and Janssen (2002, p. 6) provide this physical description of typical Tobusch fishhook cactus habitats:

> "Edaphically the habitat consists of discontinuous patches of very shallow, moderately alkaline, rocky loams or clays (primarily of the Tarrant, Ector, or Eckrant series) over massive, fractured limestone bedrock (usually the Edwards formation or an equivalent formation). Typically the sites are on level to slightly sloping hills or ridge tops of no particular aspect. Occasionally plants will be found on steeper slopes, but on level to gently sloping microsites. The sites are open, in full sunlight, with a thin herbaceous cover of grasses and other herbaceous species, but within a matrix of woodland or savanna. This surrounding community is primarily the live oak–juniper woodland community, although pinyon pine–oak is found in the western part of range, and the species is occasionally found in little bluestem grasslands or ceniza shrublands. The plants regularly grow in a thin layer of soil, gravel, rock crack, or spikemoss…associated species vary across the range…"

Emmett (1995, p. 42) noted that a wildfire at Devil's Sinkhole SNA in April 1988 burned the entire area where the largest known population of Tobusch fishhook cactus, with over 400 individuals within an area of 2000 m^2, was later discovered. The larger cacti he observed in his study probably were present prior to and survived this fire. This revelation led him to observe (p.43), "If occasional disturbance is indeed required by *A. tobuschii* to maintain and/or allow the establishment of populations, human-caused suppression of natural disturbance factors such as fires and floods may be limiting the amount of suitable habitat available for *A. tobuschii* colonization and persistence."

Sutton's Master's Thesis (1997) compared the initial effects of livestock grazing, prescribed burning, Ashe juniper removal, and combinations of these treatments on stem diameter, flower and fruit production, and mortality of Tobusch fishhook cactus at Walter Buck WMA. The author concluded that the mortality rates for grazing (18.1 percent), combined juniper removal and grazing (37 percent), and combined juniper removal, grazing, and prescribed burning (22.2 percent) were significantly higher than mortality rates in the control (6.7 percent) (p. 21, 29-33). No significant differences were evident between the control and burning, juniper removal, burning combined with juniper removal, and burning combined with grazing. However, due to small sample sizes (USFWS 2010, pp. 29-30), it is difficult to draw inferences from the results or to attribute the higher mortality directly to grazing.

Tobusch fishhook cactus plants were discovered after prescribed burns were conducted at Lost Maples SNA and Kerr WMA. Poole and Birnbaum (2003, p. 12) observed, "The fire appeared to have little, if any, permanent effect on the plants. Even when all the spines and tubercles are burned off, and the epidermis turns white, red, or purple, the cactus somehow manages to produce new epidermis and eventually tubercles and spines. At Lost Maples only one plant died directly from the fire." However, they noted that the lack of baseline data make it impossible to determine if other Tobusch fishhook cactus plants were burned up. Fire during late bud formation, flowering, or fruiting would damage reproductive structures and diminish that year's seed production.

Thinning of junipers and prescribed burning are common land management practices in the Edwards Plateau, and may benefit Tobusch fishhook cactus by reducing the encroachment of woody plants. However, cut junipers are often left in large piles that smother vegetation beneath them. When burned, large piles of cut juniper are hot enough to sterilize the soil, which can then remain bare for years. Alternative procedures, such as letting individual cut junipers fall in place, and chipping of cut junipers, should be compatible with management of Tobusch fishhook cactus habitat.

Reemts (2014) investigated the effects of shading by woody shrubs on Tobusch fishhook cactus at Love Creek Preserve and at a private ranch in Real County, where she found 1,103 and 167 individuals, respectively (p. 7). Spatial analyses (pp. 9-10) showed that the Tobusch plants were strongly clustered, and were further from woody plants than expected if randomly distributed, at Love Creek and marginally further from woody plants at the Real County site. Regression analyses based on cover were less conclusive, but this may be due to determining cover with a densiometer positioned 1 m above ground; due to the small stature of this cactus, determining cover with light meters placed on the ground may better detect the actual amount of shading that the plants experience (p. 15).

The presence of spikemoss (*Selaginella*) in the immediate vicinity of Tobusch fishhook cactus plants has been reported by Poole (1989, p. 1), Lockwood (1995, p. 428), Emmett (1995, p. 106), Sutton (1997, p. 43), Sutton et al. (1997, pp. 442, 444), and Poole et al. (2003, p. 3); Emmett also mentions the presence of *Nostoc* (a blue-green algae), moss, and lichen (p. 106). In addition to spikemoss, the 5-year status review (USFWS 2010, p. 17) noted that abundant blue-green algae (Cyanobacteria), mosses, and lichens grow in the immediate vicinity of Tobusch fishhook cactus at some sites, and are evident in many photographs of the species taken by species experts. The presence of these cryptogams within an otherwise arid environment indicates microsites where soil moisture persists somewhat longer. Examples include places where soil moisture, trapped along the upper surfaces or channeled through cracks of limestone strata, seeps to the soil surface, and shallow, concave surfaces of exposed limestone strata where moisture, organic debris, and soil accumulate. We speculate that the species escapes competition from larger bunch grasses, forbs, and woody plants by occupying areas of very shallow, gravelly soil overlying impermeable slabs of rock, and within such sites, flourishes where moisture persists. Additionally, the cryptogams could benefit the species by providing structure that seeds adhere to and by stabilizing the soil surface. The presence of nitrogen-fixing blue-green algae could also contribute higher nitrogen levels through their decomposition.

Summary of the characteristics of Tobusch fishhook cactus habitats and ecology:

- The riparian habitats described in the original status report (Weninger 1979) are atypical. However, the microsite features of those riparian sites, such as shallow soils overlying limestone outcrops, may have been overlooked (see Appendix B, Section 2.1 and Table B4).
- The great majority of documented populations occur in upland sites dominated by Ashe juniper-live oak woodlands and savannas on the Edwards Plateau. Soils are classified in the Tarrant, Ector, and Eckrant series (and other similar types, described in Section II.6).
- Within a matrix of woodland and savanna, the species occurs in discontinuous patches of very shallow, gravelly soils where bare rock and rock fragments comprise a large proportion of the surface cover.
- Associated vegetation (within 1 m of Tobusch fishhook cactus plants) includes small bunch grasses and forbs. The species' distribution within occupied microsites is clumped and tends to be further from woody plant cover. We propose that cryptogam presence may be a useful indicator of microsite habitat suitability, at least in some sites.
- Wildfire (including prescribed burning) causes negligible damage to Tobusch fishhook cactus populations (although plants would be killed if cut junipers are placed in close proximity and then burned). However, burning during late winter or early spring, which is not the natural fire season, could damage reproductive structures and diminish that year's seed production. The species probably does not require fire for germination, establishment, or reproduction, but periodic burning may be necessary to prevent the encroachment of woody plants into its habitats.

Table 3 lists the composite cover and frequency of all associated plant species detected in plots (Sutton et al. 1997), together with associated plant species reported by Lockwood (1995), Emmett (1995b), and the recovery plan (USFWS 1987).

Table 3. Plants associated with Tobusch fishhook cactus.

		Sutton et al. 1997		Lockwood 1995	Emmett 1995b	Recovery Plan
Genus	**Species[1]**	**% Cover**	**% Freq.**	**Present**	**Present**	**Present**
I. Grasses and sedges						
Aristida	*spp.*	2	44			
Bothriochloa	*laguroides ssp. torreyana*	<1	<25			
Bouteloua	*curtipendula*	6	50			X
Bouteloua	*hirsuta*	4	38			
Bouteloua	*rigidiseta*	<1	<25			
Bouteloua	*trifida*	2	32			
Dichanthelium	*pedicellatum*					X
Digitaria	*cognata*	1	22			
Elymus	*canadensis*					X
Eragrostis	*intermedia*	<1	<25			
Erioneuron	*pilosum*	<1	<25			
Hilaria	*belangeri*	4	27			
Muhlenbergia	*reverchonii*	<1	<25			
Nassella	*leucotricha*	<1	<25			
Panicum	*hallii*	3	46			
Rhynchospora	*nivea*					X
Schizachyrium	*scoparium*	<1	<25			
Sporobolus	*compositus*	<1	<25			
Tridens	*muticus*	<1	<25			
Tripsacum	*dactyloides*					X
II. Forbs						
Acalypha	*phleoides*	<1	13			X
Anemone	*berlandieri*			X		
Aphanostephus	*ramosissimus*	<1	7			
Asclepias	*viridis*					X
Boerhavia	*linearifolia*	<1	<1			
Calylophus	*berlandieri*					X
Centaurium	*calycosum*					X
Chaetopappa	*bellidifolia*					X
Chaetopappa	*effusa*					X
Chamaesyce	*angusta*					X
Chamaesyce	*serpens*	<1	12			
Chasmanthium	*latifolium*					X
Chrysactinia	*mexicana*					X
Croton	*monanthogynus*	<1	2			
Desmanthus	*velutinus*					X
Dryopteris	*filix-mas*					X
Euphorbia	*cyathophora*					X
Euphorbia	*marginata*					X
Evax	*verna*	<1	3			
Fallugia	*paradoxa*					X

		Sutton et al. 1997		Lockwood 1995	Emmett 1995b	Recovery Plan
Gaillardia	*pulchella*					X
Gaillardia	*suavis*					X
Galphimia	*angustifolia*	<1	1			X
Giliastrum	*incisum*					X
Giliastrum	*rigidulum*					X
Glandularia	*bipinnatifida*	<1	3			
Hedeoma	*drummondii*					X
Lespedeza	*texana*					X
Liatris	*punctata v. mucronata*					X
Lithospermum	*inicisum*					X
Matelea	*edwardsensis*					X
Melampodium	*leucanthum*					X
Mentzelia	*oligosperma*					X
Nolina	*lindheimeriana*					X
Oxalis	*drummondii*	<1	1			
Paronychia	*jamesii*					X
Phyllanthus	*polygonoides*	<1	14			X
Plantago	*helleri*					X
Polanisia	*dodecandra*					X
Polygala	*lindheimeri v. parvifolia*					X
Portulaca	*pilosa*	<1	5			
Salvia	*farinacea*					X
Salvia	*roemeriana*					X
Scutellaria	*wrightii*					X
Selaginella	*peruviana*	2	20	X		
Sida	*abutifolia*	<1	27			
Stillingia	*texana*					X
Tetraneuris	*scaposa*					X
Teucrium	*canadense*					X
Thelesperma	*curvicarpum*					X
Thymophylla	*pentachaeta*	<1	3			
Tragia	*nigricans*					X
Tragia	*spp.*	<1	39			
Unidentified forbs		<1	24			
Verbena	*canescens*	<1	25			
Verbesina	*microptera*					X
Vernonia	*lindheimeri*					X
Wedelia	*acapulcensis v. hispida*					X
Yucca	*rupicola*	<1	1			X
III. Cacti						
Coryphantha	*sulcata*				X	X
Cylindropuntia	*leptocaulis*				X	
Echinocactus	*texensis*				X	
Echinocereus	*coccineus*			X	X	

		Sutton et al. 1997		**Lockwood 1995**	**Emmett 1995b**	**Recovery Plan**
Echinocereus	*enneacanthus*			X	X	
Echinocereus	*reichenbachii ssp. reichenbachii*				X	
Echinocereus	*spp.*	<1	<1			
Epithelantha	*micromeris*			X	X	X
Mammillaria	*heyderi*	<1	<1		X	
Opuntia	*engelmannii v. lindheimeri*				X	
Opuntia	*phaeacantha*				X	
Opuntia	*spp.*	<1	18	X		
Sclerocactus	*brevihamatus ssp. tobuschii*[2]	<1	2			
IV. Trees, shrubs and vines						
Acacia	*spp.*	<1	1			
Baccharis	*texana*					X
Brickellia	*dentata*					X
Cephalanthus	*occidentalis*					X
Diospyros	*texana*				X	X
Eysenhardtia	*texana*					X
Forestiera	*pubescens*				X	
Forestiera	*reticulata*					X
Fraxinus	*albicans*					X
Garrya	*ovata ssp. lindheimeri*					X
Juglans	*microcarpa*					X
Juniperus	*ashei*	<1	7		X	X
Mahonia	*trifoliolata*			X	X	X
Pinus	*remota*			X	X	
Platanus	*occidentalis*					X
Quercus	*buckleyi*					X
Quercus	*fusiformis*	<1	2		X	X
Quercus	*laceyi*					X
Quercus	*pungens*			X		
Rhus	*aromatica*					X
Rhus	*virens*	<1	<1			X
Smilax	*bona-nox*					X
Sophora	*secundiflora*					X
Toxicodendron	*radicans*					X
Ungnadia	*speciosa*					X

1. For consistency, this table employs the taxonomic nomenclature of USDA-NRCS 2016, http://www.plants.usda.gov, accessed: November 29, 2016.
2. This exception to USDA-NRCS 2016 is discussed in Section II.2.

Figure 3. Habitat and ecology.

a. Live Tobusch fishhook cactus retracting into soil; Love Creek Preserve, Bandera Co.

b. These two Tobusch fishhook cacti were not observed during previous 9 years of intensive surveys; estimated age is 40 and 60 years; private property, Bandera Co.

c. Habitat at Kickapoo Caverns State Park, Kinney Co. Several plants are within shallow depression indicated.

d. Habitat at Love Creek Preserve.

e. Flowering Tobusch fishhook cactus hidden among rocks.

f. Seedling stage Tobusch fishhook cacti (about 1 to 3 years old). Note lichens and dried blue-green algae in substrate.

II.6. Geographic range and distribution.

Tobusch fishhook cactus has been documented in eight Texas counties (Bandera, Edwards, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde). For some purposes, the species' range has been represented by the political boundaries of these counties, totaling 3,142,400 ha (7,764,870 ac). However, county boundaries do not accurately represent the natural features that influence a species' range and distribution. Therefore, we have attempted to refine and quantify the distribution of potential habitats based on the soils of documented Tobusch fishhook cactus populations (Table 4), using digitized soil maps available from NRCS (2007). Since some of the occupied soils can be found far beyond the species' credible range, we further limited the range to the watersheds of the species' documented populations (Table 5), using digitized maps of 10-digit hydrologic units, available from USDA-NRCS (1999-Present). Appendix B includes a detailed description of the methods used to create this potential habitat model.

The resulting potential habitat model (Figure 4) extends into 6 adjacent counties (Crockett, Gillespie, Kendall, Menard, Sutton, and a miniscule area of Mason county). This does not mean that populations of Tobusch fishhook cactus have been confirmed in those counties, but it does indicate that potential habitat may exist there. Considering that about 95 percent of Texas is privately owned, and that rare plant surveys have been conducted on a very small proportion of private land, it is plausible that additional populations of Tobusch fishhook cactus may occur where potential habitats extend into these adjacent counties.

The potential habitat model we present here totals 2,043,972 ha (5,050,655 ac) in the 14 counties mentioned above. This is 35 percent less area than the range based on the boundaries of the 8 occupied counties. However, only a small proportion of the area indicated by this model would be suitable habitat for Tobusch fishhook cactus. The actual suitable habitats are the microsites described in section II.5: Discontinuous patches of very shallow, gravelly soils where bare rock and rock fragments comprise a large proportion of the surface cover. The approximate size range of these microsites is 0.05 to 5 ha (0.12 to 12 ac). These small, irregular microsites are unevenly distributed throughout the areas of selected soils and watersheds indicated as potential habitat. This simple habitat model could be enhanced by identifying additional geographic features that are either positively or negatively correlated with Tobusch fishhook cactus populations. Areas with a high proportion of exposed limestone would be positively correlated, while areas with a high proportion of woody plant overstory would be negatively correlated.

Even if the suitable habitat can be precisely identified and mapped, we often observe that rare plants, including Tobusch fishhook cactus, are present on only a small fraction of the suitable habitat (Emmett 1995, p.14). This may be explained in part by incomplete knowledge of a species' habitat requirements. However, another explanation is that plant populations migrate through suitable habitats over the course of many lifespans. For example, established Tobusch fishhook colonies may die out from parasitism by insect larvae or excessive shading from encroaching junipers. Concurrently, new colonies may establish where birds or ants have carried seeds beyond the range of the flightless *Gerstaeckeria* weevils, or where wildfire has cleared woody plants to make habitats more suitable. If the cactus eventually occupies all available habitats, the parasite population would also increase exponentially throughout the entire metapopulation. Thus, the patchy distribution of small populations in a small fraction of available habitat may be more stable and more likely to persist. Although speculative, this example illustrates why, even though Tobusch fishhook cactus occupies only a small amount of suitable habitat at any given time, it would require large, contiguous areas of suitable habitat for long-term persistence (see Section III.2, Distribution of suitable habitat patches).

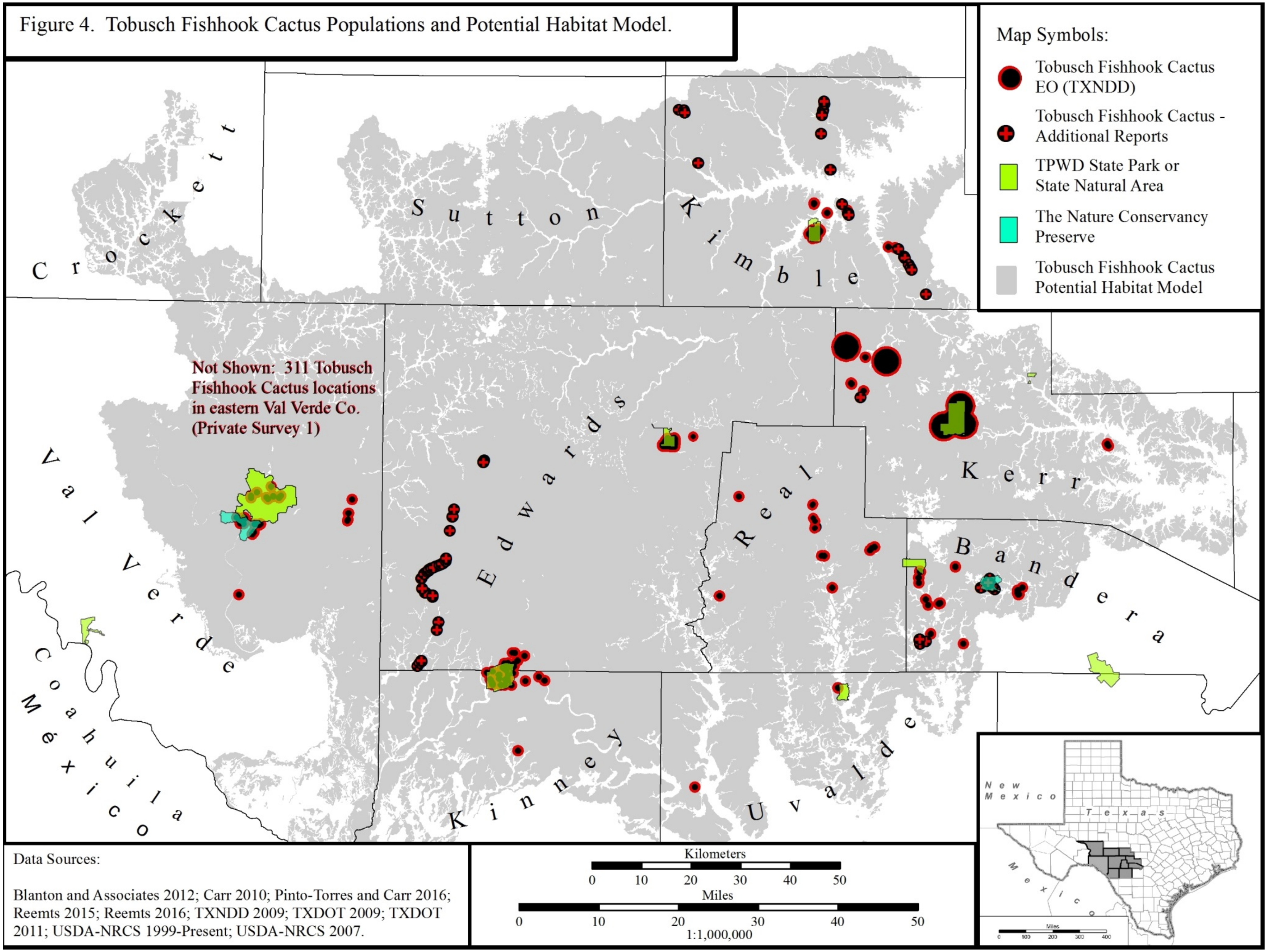
Table 4. Soil Map Units of documented Tobusch fishhook cactus populations (USDA-NRCS 2007; see Appendix B).

Anhalt Clay	Oakalla Silty Clay
Dev and Dev-Riverwash Complex	Olmos soils
Dina-Eckrant Complex	Olmos Very Gravelly Loam
Divot Clay Soils	Oplia-Rock Outcrop Complex
Eckrant-Comfort Association	Orif-Boerne Association
Eckrant-Rock Outcrop Complex	Pratley Clay
Ector Soils and Rock Outcrop	Real-Oplin Complex
Kavett-Tarrant Stony-Clay Complex	Spires-Tarpley Association
Kerrville Association	Tarrant Soils
Krum Silty Clay	Tarrant-Doss Association
Leakey Silty Clay Loam	Tarrant-Eckrant Association
Mailtrail Very Gravelly Clay Loam	Tarrant-Rock Outcrop Association
Mailtrail-Mereta Complex	Tarrant-Valera Complex
Nuvalde Silty Clay	

Table 5. Watersheds (10-digit hydrologic units) of documented Tobusch fishhook populations (USDA-NRCS 1999-Present).

Hydrologic Unit Code	Hydrologic Unit Name	Hydrologic Unit Code	Hydrologic Unit Name
120902,203	Middle North Llano River	1211010604	Headwaters Frio River
1209020402	Johnson Fork	1211010607	Upper Sabinal River
1209020402	Lower South Llano River	1304030111	Dry Devils River - Devils River
1209020403	Big Saline Creek - Llano River	1304030203	Deaton Draw - Devils River
1210020103	Turtle Creek - Guadalupe River	1304030203	Dolan Creek - Devils River
1210030202	North Prong Medina River	1304030203	Lower Dry Devils River
1211010103	East Prong Nueces River	1304030204	Devils River - Amistad Reservoir
1211010104	Headwaters Nueces River	1304030304	Buffalo Draw
1211010202	Headwaters West Nueces River	1304030304	Red Bluff Creek
1211010203	Upper West Nueces River	1308000103	West Fork Sycamore Creek - Sycamore Creek
1211010204	Middle West Nueces River	1308000105	Pinto Creek
1211010301	Montell Creek - Nueces River	1308000105	Sacatosa Creek - Sycamore Creek
1211010602	West Frio River		

Figure 4. Tobusch Fishhook Cactus Populations and Potential Habitat Model.



Data Sources:

Blanton and Associates 2012; Carr 2010; Pinto-Torres and Carr 2016; Reemts 2015; Reemts 2016; TXNDD 2009; TXDOT 2009; TXDOT 2011; USDA-NRCS 1999-Present; USDA-NRCS 2007.

II.7. Populations and demographic trends.

II.7.1. Populations, sites, colonies, and element occurrences. A population of an organism is a group of individuals within a geographic area that are capable of interbreeding or interacting. Although the term is conceptually simple, it may be difficult to determine the extent of a population of rare or cryptic species, and this is certainly the case for Tobusch fishhook cactus. Thorough surveys on public lands, such as state parks and highway rights-of-way, have detected groups of individuals, but since the vast majority of the surrounding private lands have not been surveyed, we do not know if these are small, isolated populations, or parts of larger interacting populations or metapopulations. For convenience, we often informally use the terms “site”, referring to a place where the species was found, and “colony”, referring to a cluster of individuals, when we do not know the extent of the local population.

TPWD manages the State’s Natural Diversity Database (TXNDD), which compiles data on tracked plant and animal species that are submitted by Federal, State, academic, non-governmental organizations (NGOs), private researchers, and consultants. The TXNDD currently tracks 440 rare, threatened, and endangered plant species in Texas. The geographic, population, and other relevant data for each species are tracked as Element Occurrences. “An Element Occurrence (EO) is an area of land and/or water in which a species or natural community is, or was, present,” (NatureServe 2002, p. 10). The EOs may consist of one or many “sites” or “colonies” as reported by surveyors. In the geographic information system (GIS) component of the TXNDD, EOs are displayed as points and polygons buffered by their estimated geographic precision. For this reason, historic reports that do not contain precise geographic coordinates are shown as relatively large polygons, while more recent survey data collected with geographic positioning system (GPS) instruments are represented by smaller polygons. Therefore, it must be understood that the tracked species occur within, but not necessarily throughout, the polygons displayed in the GIS. The TXNDD is an essential tool for the long-term conservation and management of species at risk. The USFWS makes frequent use of the TXNDD in listing actions, for planning and tracking recovery of listed species, for section 7 consultations, and for Habitat Conservation Plans.

II.7.2. Documented populations. When Tobusch fishhook cactus was federally-listed as endangered, in 1979, less than 200 individuals had been found in Bandera and Kerr Counties, Texas (44 FR 61736). The Recovery Plan (USFWS 1987, pp. 4-5) states that the original populations in Bandera and Kerr Counties had been extirpated by a flood, but new populations had been found since 1985 in Real, Kimble, and Uvalde Counties. Data provided by the TXNDD (2016, pp. 1-202) indicates that 3,336 individuals have been documented in 97 EOs in eight counties of the Edwards Plateau (Bandera, Edwards, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde).

Poole and Janssen (2002, pp. 4-6) visited 80 of 102 EOs mapped in the TXNDD (note that the number of EOs changes as new populations are discovered, while others may be combined or determined to be invalid). They were not able to visit 22 reported sites due to access problems. They also continued and expanded the annual monitoring, begun by Emmett (1995, p. 141) in 1991, of all populations within State Parks, State Natural Areas, and Wildlife Management Areas (reported in greater detail in Poole and Birnbaum 2003; discussed in II.7.4). They found no

Tobusch fishhook cactus at 14 sites, although the habitat was still intact. The species had been misidentified at five sites. They were not able to find one site due to vague location data. They combined 21 previously-reported sites into five EOs, following the EO guidance from NatureServe (2002, pp. 23-29). Of 56 properties surveyed, 19 were publicly owned, including highway ROWs, State Parks, State Natural Areas, and Wildlife Management Areas, and 37 were privately owned; 29 properties had 1 or more EO. They verified about 2000 individual Tobusch fishhook cactus in August 1999 in 53 populations, including 1,363 individuals in 10 long-term monitoring plots. Twenty populations had 10 or fewer individuals, and 20 others had from 20 to 100 individuals. Four populations had more than 100 individuals, and the largest had more than 500.

Figure 4 shows our current understanding of the range of documented Tobusch fishhook cactus populations. In addition to the EOs tracked in the TXNDD, following publication of the 5-year review (USFWS 2010), we received several new reports from surveys conducted over wide portions of the species' range that have increased our knowledge of its distribution and abundance. These additional sources are discussed in Section II.7.5 and in Appendix B.

II.7.3. The detection problem.

Longer-term monitoring of Tobusch fishhook cactus populations has consistently revealed that individual surveys usually do not detect all of the live, mature individuals of reproductive size (> 2 cm in diameter) in populations. Poole and Janssen (2002, p. 5) wrote:

> "Confounding the situation was the discovery of new, previously unseen plants in the plots. These were usually not seedlings, but plants of some size, often reproductive. Tobusch fishhook cactus seedlings are extremely small (0.3 mm or less) and almost impossible to detect. Thus it was difficult to determine the annual recruitment to the plots. Also plants sometimes disappeared, only to reappear during the next monitoring session."

Carr (2010) described an intensive survey for Tobusch fishhook cactus of the Love Creek Preserve, in Bandera County. The survey team found 810 individuals. Reemts (2014, pp. 14-15) surveyed 9 plots at this site from 7 to 9 times over a 6-month period, where 1,103 individuals were detected. Regarding the difficulty of detection, she observed:

> "During dry periods, the cacti appear to shrink back into the soil, pulling their spines together. On several occasions, cacti that we had previously noted as dead or possibly dead were found with bright green flesh visible again. ... Cacti sometimes recovered from herbivory by re-sprouting from surviving areoles... Some cacti were covered in soil and gravel by ants; these cacti did not always survive the burial... Inexperienced volunteers likely missed many small cacti. However, even experienced staff continued to find new cacti at the final visit in September. These newly discovered cacti were not necessarily new seedlings, since more than half were over 1 cm in diameter."

Based on these repeated surveys, Reemts (2014, p. 8) calculated that the probability of detecting a previously undetected Tobusch fishhook cactus in a single survey ranged from 15 to 89 percent; individuals that were fruiting or flowering had the highest detection rate (82 percent). The overall detection rate was about 50 percent (p. 1).

We have also found large, reproductive individuals that had previously remained undetected in sites that had been intensively surveyed for up to 9 years (Figure 3.b). The clumped spines of living cacti that have retracted into the soil surface are almost indistinguishable from the involute or curled leaves of locally abundant native grasses, such as red grama (*Bouteloua trifida*), Hall's Panicum (*Panicum hallii*), slim tridens (*Tridens muticus*), and threeawns (*Aristida* sp.) (Figure 3.a). This difficulty in detecting the number of living individuals at any one time introduces a great deal of statistical "noise" and uncertainty in calculations of demographic trends and population viability analyses.

However, we speculate that the ability to endure drought by retracting into the soil in a desiccated, dormant state may also allow some portion of a population to avoid outbreaks of weevil parasitism.

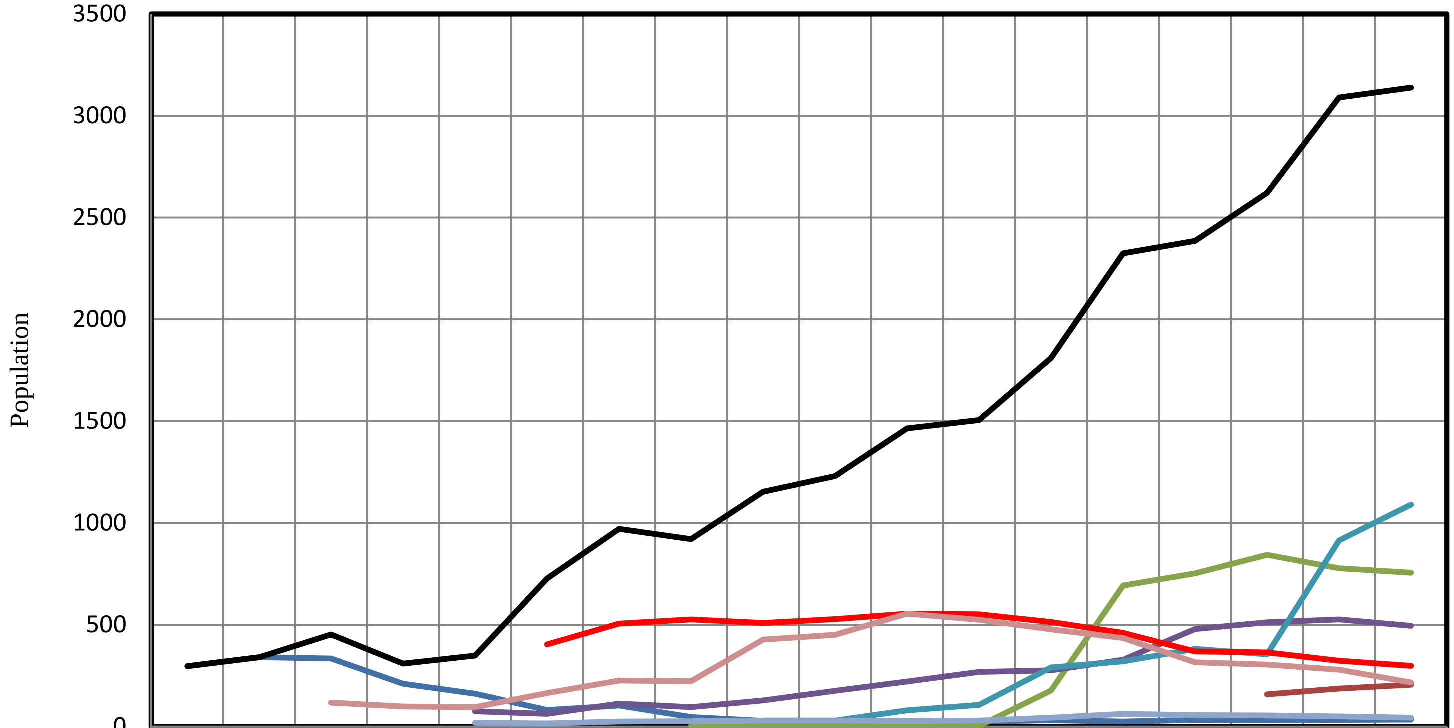
II.7.4. Demographic trends.

Poole and Birnbaum (2003) reported the results of continued monitoring of 118 permanent plots at 12 protected sites, as well as a study of the Tobusch cactus weevil (*Gerstaeckeria* sp. nov.) (Calvert 2003). These are circular plots of varying size, with radii of up to 100 m, that were established where colonies of Tobusch fishhook cactus were discovered. By May 2003, 91 plots still had live plants. The authors stated, "Although the total number of live plants from all sites found at the end of the 2003 monitoring season (1,936) appears to be almost double that of the 1998 season (1,108), much of this increase is due to the finding of new, previously overlooked plants and populations rather than true recruitment." Within previously monitored plots, annual mortality consistently outweighed recruitment. Combined recruitment ranged from 1.6 percent in 1998 to 10.3 percent in 2003, and was not correlated to population size or number of reproductive individuals. Unknown causes and *Gerstaeckeria* weevils accounted for 64 percent and 20 percent of mortality, respectively, from 1998 – 2003.

Significantly, new populations were discovered at Kerr WMA in 2001 and 2003, where previously-monitored plots had nearly been extirpated by weevils (Poole and Birnbaum 2003, p. 7). Although populations with fewer than 10 individuals have a low probability of surviving, a small population at the Vireo Territory at Kickapoo Caverns SP expanded phenomenally, suggesting that "even sites where all plants have died should be checked occasionally," (pp. 12-13). The authors ask (p.13), "If populations die off in an area, how do they become established at other sites and how often?" They conclude that (p. 13), "At present the overall picture may appear stable, but mortality is high and not all sites are stable or increasing. It is too early to determine where the trends for the species as a whole are heading."

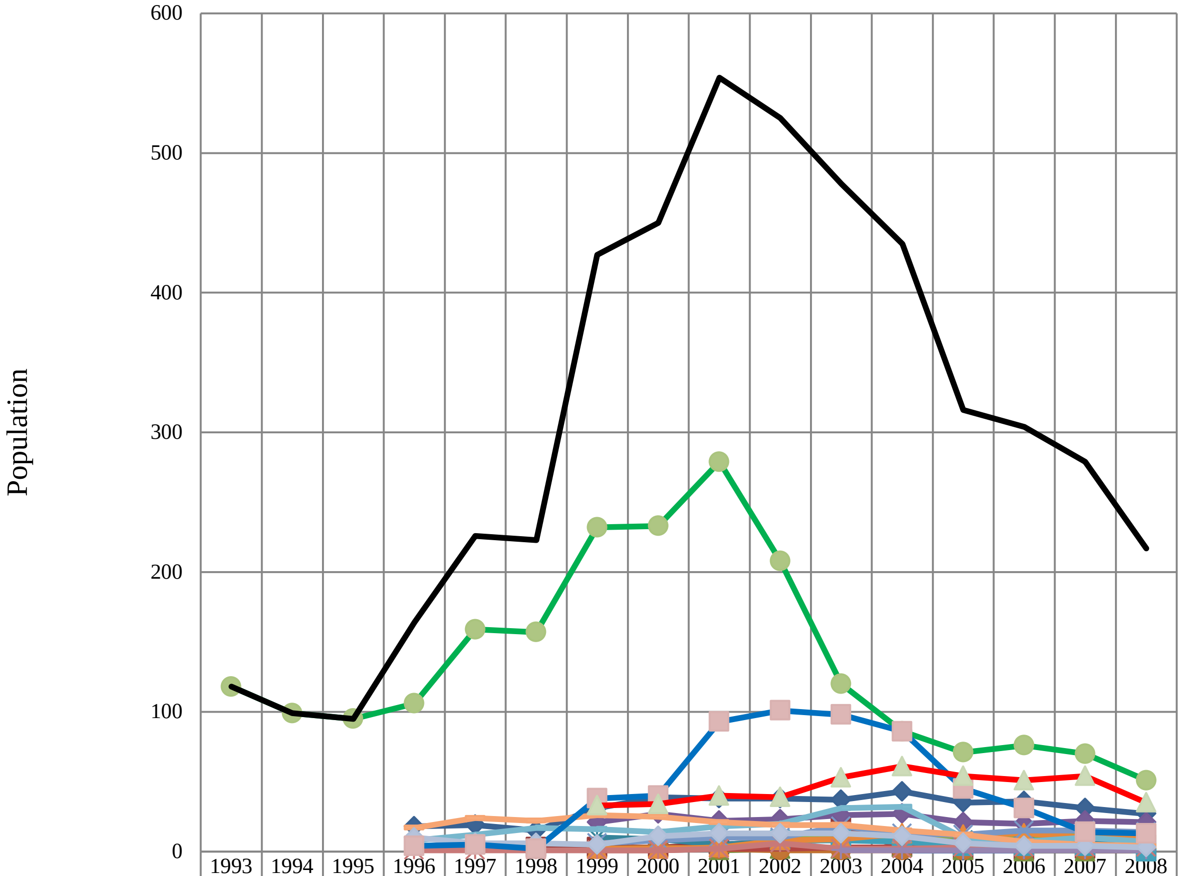
Poole (2009) generously provided to USFWS a series of spreadsheets that display the data from the monitoring plots begun by Emmett (1995a, 1995b), Poole and Janssen (2002), and Poole and Birnbaum (2003). Since 1991, these researchers have mapped and tagged thousands of individual Tobusch fishhook cactus in the field and recorded their growth, reproduction, and mortality. This data set provides valuable information on the demographics and population dynamics of the species. Our preliminary analysis of this data indicates that in 2008, a total of 3,139 individuals were recorded in 119 plots (stakes) at 28 sites in 8 monitored areas. The data are summarized in Figures 5-6. Figure 5 graphically illustrates the steady increase in the total numbers of individuals detected (black line) while the number of individuals at specific sites tends to fluctuate over time. Figure 6 summarizes the data from one managed area, Kickapoo Caverns SP, where 28 monitoring plots are distributed among 21 sites. The total population at Kickapoo reached a low of 95 individuals in 1995, then steadily increased to 554 in 2001, and subsequently declined to 217 by 2008. The demographic pattern emerging from this data suggests an asymmetric oscillation, where colonies and populations establish and increase gradually, then rapidly decline from weevil infestations to a point too low to sustain the parasites. Although natural, these oscillations tend to obscure long-term population trends.

Figure 5. TPWD Annual Surveys of Tobusch Fishhook Cactus Sites



	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Devil's Sinkhole	297	341	334	210	161	81	103	47	28	15	26	24	31	25	32	31	32	34
Buck																158	187	205
Garner SP								2	2	3	2	2	177	693	753	843	778	755
Junction					75	63	112	96	128	176	221	268	276	328	479	512	526	495
Kerr WMA									29	29	79	107	291	320	381	355	914	1090
Lost Maples						403	506	526	509	528	554	551	514	460	369	364	323	299
Pole Hollow					18	16	24	26	30	30	28	29	44	63	56	54	50	44
Kickapoo SP			118	99	95	164	226	223	427	450	554	525	478	435	316	304	279	217
TOTALS:	297	341	452	309	349	727	971	920	1153	1231	1464	1506	1811	2324	2386	2621	3089	3139

Figure 6. Population Fluctuation at Kickapoo Sites



	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
Butterfly				18	19	15	31	39	38	38	37	43	35	36	31	27
Dan's Site						3	3	3	5	7	18	3	1	1	2	2
Deep Well									1	2	2	3	1	0	0	0
Goose Chase												5	5	7	8	4
JD-1							10	9	5	7	9	10	8	9	8	9
JD-3							2	3	2	1	1	1	1	1	1	0
JD-4												1	0	1	1	1
Kelly B Mem							1	1	2	2	3	3	3	6	4	3
Kickapoo										13	10	12	11	11	12	10
Linda's Site							21	27	22	23	26	27	21	20	22	21
Mark2										8	8	7	4	4	4	0
NE Corner							2	2	3	8	9	13	12	13	10	9
N Gate							6	8	10	10	18	13	12	15	15	14
Quailtran				1	1	1	1	1	2	6	2	2	3	3	3	3
Ray's Site	118	99	95	106	159	157	232	233	279	208	120	86	71	76	70	51
Sardine											1	1	1	1	1	1
Shag Carpet				8	12	17	16	14	18	20	31	32	10	7	10	7
Stu Cave				17	24	22	26	25	21	19	19	15	12	7	5	4
Tank Hill				10	6	6	5	11	13	13	13	11	6	4	4	3
Vireo Trail				4	5	2	38	40	93	101	98	86	45	31	14	13
Wait Gate							33	34	40	39	53	61	54	51	54	35
TOTAL:	118	99	95	164	226	223	427	450	554	525	478	435	316	304	279	217

II.7.5. Minimum viable population and population viability analysis.

Minimum viable population (MVP) refers to the smallest population size that has a high probability of surviving a prescribed period of time. For example, Mace and Lande (1991, p. 151) propose that species or populations be classified as vulnerable when the probability of persisting 100 years is less than 90 percent. Determinations of MVP usually take into account the effective population size, rather than total number of individuals; 10 genetically identical individuals (for example, clones) would have an effective population size of 1. The recovery plan (USFWS 1987, p. 14) established a recovery criterion of 4 protected populations with at least 3,000 individuals, but did not show how this level was determined. However, we now understand that insect parasites are able to devastate large, dense populations. We conclude that few large populations are much more vulnerable than many small populations, and that this recovery criterion should be amended. Poole and Birnbaum (2003, p. 1), using the surrogate species method of Pavlik (1996, pp. 136-137), estimated a MVP for Tobusch fishhook cactus of 1,200 individuals.

A related term is quasi-extinction threshold, which is a population size below which extinction is very likely due to genetic or demographic risk.

Population Viability Analysis (PVA) addresses the survival probability of specific populations. Using the monitoring plot data described above, Zaya et al. (2014) conducted PVAs based on population counts (pp. 15-27) as well as on demographic field data (pp. 29-42) for Tobusch fishhook cactus, and compared the results of both methods. These authors caution that count-based PVA requires assumptions that are difficult to meet with this data set, and is more suited as a comparative tool rather than to calculate an absolute extinction risk (p. 26-27). This analysis found that the Kickapoo Caverns and Los Rincones Preserve populations had the highest risk of extinction, and Devil's Sinkhole had a moderate risk of extinction. The extinction risk was intermediate for the Lost Maples population, and Pole Hollow and Junction were the most stable. The analyses of demographic data used Integral Projection Models. The authors state (p. 29), "The ability of such models to incorporate abiotic conditions that change over time make them especially useful for predicting population trends in an environment affected by climate change. The additional information included in PVA that incorporate full demographic data make them more reliable than analyses based solely on counts of individuals..." These population models predicted (pp. 35-37) the most optimistic outcomes for the Kerr WMA and Los Rincones Preserve, and predicted that Pole Hollow would decline or remain stable, depending on interpretation. The models predicted moderate declines for the Garner SP and Lost Maples populations, while the Kickapoo Caverns population would decrease by a median of 35.8% after 10 years and 88.2% after 50 years. The likelihood that the populations at Devils River SNA, Devil's Sinkhole SNA, Junction, and Frank's Place would decrease below 10 percent of the 2013 levels is greater than 80 percent. Small to medium-sized reproductive individuals (20 to 30 mm diameter) had the greatest influence over population trajectories.

However, the demographic population models predicted significantly different trajectories at all populations, and at 10- and 50-year intervals, when expected climate change parameters (gradual warming and drying) are included (Zaya et al. 2014, pp. 37-38). Interestingly, the trends were mixed, with the populations at Kerr WMA, Frank's Place, Garner SP, and Devils River SNA responding negatively to climate changes, while the other 6 populations responded positively. The negative response would be due in most cases to lower survival and fecundity, while a positive response would be due to increased individual growth rates.

II.7.6. Preliminary estimate of the global population of Tobusch fishhook cactus.

We describe in Appendix B the methods we used to estimate the extent and distribution of Tobusch fishhook cactus potential habitats and the average population density. The estimate of population density is based on data from the long-term monitoring plots from 2003 to 2009, described in 11.7.4, at 10 protected sites, as well as data from 15 surveys conducted since 2009 in association with development projects; we used the most recent available data on population sizes. These 25 surveys are reasonably well distributed across the species' known range (see Figure 4). We estimated the global population size (the total of all populations, known and unknown) by extrapolating the average density per unit area to the total area of the species' potential habitats. Tables 6 and 7 summarize the results. The estimated population size is not a precise determination, but is the best estimate we are currently able to make with available quantitative data.

Table 6. Summary of Tobusch fishhook cactus surveys (conducted from 2003 to 2015).

Survey Type	No. of Surveys	Area Surveyed Ha	Area Surveyed Ac	No. of Tobusch Fishhook Cactus	Tobusch Density / Ha	Tobusch Density / Ac
Protected Natural Areas	10	18,458.9	45,611.9	3,904	0.21	0.09
Highway ROWs	12	133.4	329.6	150	1.12	0.46
Linear Surveys	2	749.7	1,852.6	424	0.57	0.23
Powerline	1	128.1	316.4	86	0.67	0.27
Totals:	25	19,470.0	48,110.5	4,564	0.23	0.09

Table 7. Estimation of the global population (see Section II.6 and Appendix B).

Estimate of Total Tobusch Fishhook Cactus Habitat (ha):	2,043,972
Average Density of Tobusch Fishhook Cactus per Ha:	0.231
Extrapolated Total Population Estimate:	473,015

Summary and synthesis of populations and demographic trends.

- The TXNDD (2016) lists 97 EOs, totaling 3,336 individuals in 8 counties of the Edwards Plateau of Texas.
- From 2009 to 2016 we received additional sources of population data, primarily from surveys conducted for development projects.
- A total of 118 permanent plots at 12 protected natural areas have been monitored from 1991 through 2013. Plot data reveals that mortality is often very high, and consistently exceeds recruitment; however, the known population sizes have steadily increased, due to the discovery of previously undetected individuals and colonies.
- The probability of detecting live Tobusch fishhook cactus individuals during a single survey is highly variable; Reemts (2014) calculated an overall detection rate of 50 percent. The inability to detect all living members of a population confounds determinations of population size and demographic trends.
- Demographic population viability analyses of monitored populations, using integral projection models, predicted stable or increasing trends for 2 or 3 populations, moderate declines for 2 populations, and large to precipitous declines in 5 populations over the next 50 years. When expected climate changes were included in the analyses, 4 populations responded negatively to climate changes and 6 populations responded positively (compared to PVA without climate changes). We estimate that the global population size for Tobusch fishhook cactus is about 473,000 individuals distributed over an area of over 2 million ha (5 million ac).

Intuitively, it appears difficult to reconcile the persistence or resurgence of populations where nearly a quarter-century of monitoring plot data consistently shows that mortality exceeds recruitment. This may be explained, at least in part, by the detection problem: not all plants that appear dead or missing are truly dead, and recruitment may be occurring undetected. Additionally, we suspect that the appearance of consistent decline may be an artifact of the establishment of static plots on top of colonies that existed at the beginning of the study (as opposed to plots established according to an unbiased sample design). Over the years, new plots have been established upon discovery of new colonies, but these are not considered true recruitment, and each colony is a separate demographic study. Sooner or later, all or most colonies die out, and the prognosis for the species is inevitably gloomy. This method would not detect the demographic trends of a geographically dynamic population consisting of many individual colonies asynchronously establishing, growing, and dying out in scattered habitat patches distributed over a larger landscape.

III. Summary of Individual, Population, and Species Requirements.

III.1. Requirements of Individuals.

Habitats.

Tobusch fishhook cactus is endemic to the Edwards Plateau of Central Texas. Most documented populations occur in upland sites dominated by live oak- Ashe juniper or pinyon pine-oak woodlands and savannas on Edwards formation limestone, although the subspecies has occasionally been found along watercourses. In either case, plant distribution is not random, but is restricted to discontinuous microsites where limestone strata are exposed or very near the surface and there is little or no woody plant cover. Soils, of the Tarrant, Ector, Eckrant, or similar series, are moderately alkaline, rocky or gravelly, and very thinly overlie limestone strata. Occupied sites may occur from the lower slopes to crests of hills, but slopes within microsites are moderate. The species' distribution within occupied microsites is clumped and tends to be further from woody plant cover. Associated vegetation (within 1 m of Tobusch fishhook cactus plants) is sparse, and includes small bunch grasses and forbs. The presence of cryptogams may be a useful indicator of microsite habitat suitability, such as seep moisture, at least in some sites. Wildfire (including prescribed burning) causes negligible damage to Tobusch fishhook cactus individuals, but could interfere with reproduction if conducted in late winter or early spring (although plants would be killed if cut junipers are placed in close proximity and then burned). The species probably does not require fire for germination, establishment, or reproduction, but periodic burning may be necessary to prevent the encroachment of woody plants into its habitats.

Suitable habitats for Tobusch fishhook cactus, meaning the microsites described above, occupy a small fraction of the potential habitats that are widely distributed over about 2 million hectares (5 million acres) of the Edwards Plateau. The traditional land use in this area, livestock ranching, appears to have little impact on these habitats, and may be compatible with habitat conservation if prescribed burning or juniper control are practiced. The ongoing shift toward subdivision of large ranches and recreational land uses may have both beneficial and detrimental effects on Tobusch fishhook habitat conservation, and the net effect of this shift is currently unknown.

Reproduction.

Tobusch fishhook cactus plants begin reproducing when they have grown to a diameter of about 2 cm (occasionally less); this is estimated to require 9 years of growth in the wild. Flowering occurs between late January and mid-March, depending on locality, and lasts a few weeks in each population. Honey bees and halictid bees are effective pollinators, although the latter group may be more active later in the flowering season. The breeding system is primarily by out-crossing, although self-fertilization occurs rarely. Fruits ripen around mid-May. Ants remove a large proportion of seeds, pulp, and funiculi, but whether the ants consume the seeds, or effectively disperse them, is not known. Mammals or birds also consume fruits and may accomplish longer-distance seed dispersal. Moderate numbers of viable seeds have been found in the soil near live plants, but the extent and longevity of soil seed banks is unknown.

The slow growth rate, long time required to reach reproductive maturity, and high mortality rate (discussed below) are factors that limit reproduction of Tobusch fishhook cactus. Although capable of self-fertilization to a limited degree, most reproduction is through out-crossing. Out-crossing requires genetically diverse cactus populations within the foraging range of pollinators, and is less likely to occur in small, isolated populations. Emmett (1995, p. 85) observed that insufficient pollinator populations may limit successful fertilization in some Tobusch fishhook cactus populations; hence, native pollinator conservation is essential for successful reproduction of this species. Healthy pollinator populations, in turn, require intact, diverse, native plant communities. Halictid bees, the apparent natural pollinators of Tobusch fishhook cactus, are relatively small bees, so we expect their foraging ranges to be fairly limited (Greenleaf et al. 2007). Therefore, the health and diversity of native vegetation within the vicinity of cactus populations may be particularly important for successful cactus reproduction; for these purposes we suggest that a range of 50 to 500 m is of greatest importance. Healthy pollinator populations also require the least possible exposure to agricultural pesticides within their foraging ranges.

<u>Lifespan and mortality rates.</u>

The lifespan of Tobusch fishhook cactus is potentially decades long. Poole and Janssen (2002, p. 7) observed individuals that had lived for more than 10 years. Based on observed growth rates, individuals become reproductive at about 9 years of age, and large individuals may be at least 50 years old. However, annual mortality rates of established individuals are often greater than 20 percent. Assuming an average annual mortality of 20 percent, only 13 percent of individuals would live long enough to reproduce once.

The demographic population viability analyses of Zaya et al. (2014, p. 37) indicate that the number of reproductive individuals of about 20 to 30 mm in diameter have the greatest influence over population trajectories. This suggests a population management objective of maximizing the number of individuals that survive at least 9 to 14 years.

III.2. Requirements of Populations.

<u>Stable or increasing demographic trends</u>.

Population persistence depends on stable or increasing demographic trends: Recruitment of new individuals must equal or exceed mortality. Recruitment requires successful reproduction (described above). However, data from permanent plots at protected natural areas has consistently shown that mortality exceeds recruitment, and the colonies within some monitored plots have died out (Poole and Birnbaum 2003, p. 10). Emmett (1995, pp.155-161) reported that 85 percent of attributable mortality is due to infestation by insect larvae, among which, an undescribed species of *Gerstaeckeria* is a principal contributor.

Nevertheless, even where individual plot colonies have died out, total populations at many protected natural areas have been stable or increasing, due to discoveries of new individuals and groups of individuals. This apparent anomaly may be due, at least in part, to the great difficulty in detecting live plants in the field (discussed in Section II.7.4), which confounds determinations of mortality and recruitment. Additionally, much depends on how populations are delimited. If populations are considered to include multiple colonies (e.g., as metapopulations), then the metapopulation demographics are often stable or increasing, even though individual colonies periodically decline. In this case, metapopulation persistence would require recruitment of new colonies, and/or reestablishment at sites of former colonies that previously collapsed. Although this hypothesis has not been tested, these phenomena have been observed at and in the vicinity of the permanent plots (Poole and Janssen, 2002, pp. 5-6; Poole and Birnbaum 2003, pp. 5-8).

The population dynamics of Tobusch fishhook cactus are greatly influenced by the periodic infestations of the larvae of the *Gerstaeckeria* weevil and one or more species of cactus longhorn beetles (*Moneilema* spp.), and perhaps other invertebrates (see Section II.4). Calvert (2003, pp. 5-12) determined mortality rates of 44.8 percent and 7.5 percent due to these parasite species, respectively; the undescribed *Gerstaeckeria* species fed only on Tobusch fishhook cactus, and other *Gerstaeckeria* species were found on other cactus species near Tobusch sites, but did not feed on Tobusch fishhook cactus. Assuming these are not newly-introduced species, Tobusch fishhook cactus has been co-evolving with them and is able to persist. The adults of both parasites are flightless, so their dispersal to new colonies and populations must be very limited. We assume that when colonies of the cactus hosts die off, the parasites also die off, rendering those patches of suitable habitat available for cactus re-colonization. We hypothesize that the determination of demographic trends is more realistically based on metapopulations at a landscape geographical scale, rather than individual colonies. Within such landscapes, at any given time only a small fraction of the suitable habitats (microsites) support living colonies, and the distances between colonies is a protection against parasite infestations.

Genetic diversity.

The degree of genetic diversity within Tobusch fishhook cactus populations is important for several reasons. First, diversity within and among populations should confer populations, and the subspecies, greater resistance to pathogens and parasites, and greater adaptability to environmental stochasticity (random variations, such as annual rainfall and temperature patterns) and climate changes. Second, low genetic diversity within interbreeding populations leads to a higher incidence of inbreeding, and potentially to inbreeding depression. Finally, the breeding system of Tobusch fishhook cactus is primarily out-crossing. Emmett (1995, pp. 77-81, 87) reported evidence that small colonies possessed sufficient genetic diversity for effective fertilization. Nevertheless, Rayamajhi (2015, pp. 63-64) found relatively high inbreeding coefficients in 3 of 8 populations, which he attributed to mating of close relatives within small, isolated populations.

Distribution of suitable habitat patches.

The distance between colonies has two opposing effects on their persistence. Greater distance reduces susceptibility to parasite infestation (discussed above), but also reduces the amount of gene flow, by means of pollinators vectoring pollen, or through seed dispersal, between colonies. Thus, the persistence of entire populations would require fairly large landscapes where discontinuous suitable habitats (microsites) are distributed and populated at a density just low enough to hold the parasites at bay, but just high enough for halictid bees and other pollinators and seed dispersers to vector genes between them.

Fire.

Fire, whether natural or prescribed, appears to have little effect on individual Tobusch fishhook cactus plants, but could interfere with reproduction if conducted in late winter or early spring. This is because the plants occur where vegetation is very sparse, and the plants protrude very little above the ground and are protected by surrounding rocks from the heat of vegetation burning nearby; even when burned, Tobusch fishhook cactus often recover. On the other hand, periodic fire is likely to be necessary for population persistence to reduce juniper encroachment into suitable habitats. Furthermore, the diverse shrub and forb vegetation that sustains healthy pollinator pollinations is maintained by periodic wildfire; without fire, dense juniper groves frequently displace these shrubs and forbs. Hence, if the native plant diversity of entire landscapes surrounding Tobusch fishhook cactus populations succumbs to juniper encroachment, pollinator populations will likely decline, and reproduction of Tobusch fishhook cactus and gene flow between its colonies may be reduced.

Minimum viable population size and population viability analysis.

Pavlik's guidelines (1996, pp. 136-137) use a surrogate species approach to estimate MVP. Poole and Birnbaum (2003, p. 1) employed this method to estimate a MVP for Tobusch fishhook cactus of 1,200 individuals. We concur and suggest that if this (or some other) level is used as a benchmark for recovery criteria, it should apply to metapopulations rather than individual colonies.

The demographic PVA of Zaya et al. (2014, pp. 29-42), assuming the current climate conditions remain stable, predicted stable or increasing trends for 2 or 3 populations, moderate declines for 2 populations, and large to precipitous declines in 5 populations over the next 50 years. When expected climate changes were included in the analyses, 4 populations responded negatively to climate changes and 6 populations responded positively (compared to PVA without climate changes). These models project population sizes at 10- and 50-year spans, but the authors expressed greater confidence in accuracy of the 10-year projections. They state (p. 40), "We do not emphasize the absolute values of the population sizes projected with climate change because the underlying models rely on extrapolations of temperature that deviate largely from anything ever observed. While we do not know the degree to which Tobusch fishhook cactus vital rates will be affected, we have more confidence in the direction of effect."

III.3. Species Requirements.

The viability of a species can be assessed in terms of its resilience, redundancy, and representation (Shaffer and Stein 2000, pp. 307-310). Resilience refers to population sizes; larger populations are more likely to endure than small ones. Redundant populations increase the species' chances of surviving catastrophic events. Representation refers to the breadth of genetic diversity necessary to conserve long-term adaptive capability. With regard to resilience, we estimate, provisionally, that viable metapopulations must have 1,200 individuals. The best available information does not indicate what the minimum viable degree of representation and redundancy should be; it is reasonable to conclude that more is better. Rayamajhi (2015, p. 67) found little genetic differentiation among 9 populations of ssp. *tobuschii*, suggesting that the subspecies does not have multiple areas of genetic representation.

IV. Factors Affecting the Survival of Tobusch Fishhook Cactus: Threats, Vulnerabilities, and Conservation Challenges.

The following list describes factors that affect, either positively or negatively, the continued survival of Tobusch fishhook cactus.

<u>Land Use Changes</u>.

Relatively little urban and industrial development is occurring within the semi-arid, sparsely populated eight-county known range of Tobusch fishhook cactus. However, a significant ongoing trend throughout the species' range is the subdivision of large ranches into many small "ranchettes," leading to a proliferation of roads, fences, power lines, and residential development, all of which contribute incrementally to habitat loss and fragmentation.

Land subdivision also engenders changes in land use and management which may be both beneficial and detrimental to Tobusch fishhook cactus. For example, the predominant, historic land use throughout the Edwards Plateau has been grazing of livestock, including goats, cattle, sheep, and horses. In many cases, poor rangeland management during the last century has caused the depletion of herbaceous vegetation, cessation of the natural wildfire cycle, proliferation of dense juniper stands, soil erosion, and reduced infiltration and storage of rainwater in the soil profile; all of these changes are likely to have harmed Tobusch fishhook cactus populations. The change to a primarily recreational land use often entails continued grazing, in order to obtain agricultural tax exemptions, but at a sustainable stocking density (landowners may subsequently convert an agricultural exemption to a wildlife exemption). Currently, both large and small landowners are more aware of and concerned with conservation issues than during the last century.

Prescribed burning may be one of the most important vegetation management tools for sustaining Tobusch fishhook cactus populations; the proliferation of residential development within the species' habitat makes this tool more challenging for natural resource managers to use.

The subdivision of privately-owned land and associated threats are likely to continue.

<u>Changes in vegetation and wildfire frequency.</u>

Bray (1904, pp. 14–15, 23–24) documented the rapid transition of grasslands to woodlands in the Edwards Plateau occurring more than a century ago; he attributed this change to over-grazing, the depletion of grasses, and the cessation of wildfires. Fonteyn et al. (1988, p. 79) state that savannas covered portions of the pre-settlement Edwards Plateau, and since 1850 were transformed to shrubland or woodland "primarily by suppression of recurring natural and anthropogenic fires and the introduction of livestock." They list the fire-sensitive Ashe Juniper as the most successful of many woody plants that have invaded grasslands. Reemts (2014 p. 1) lists the encroachment of woody plants into the rocky, open habitat as one of several habitat-related threats to Tobusch fishhook cactus. However, the historic extent of grasslands in the Edwards Plateau is an area of active scientific debate. It is likely that woodlands were most abundant on slopes in the Balcones Escarpment (which includes the southern and eastern portion of the Tobusch fishhook cactus range) and that grasslands were more abundant on flatter, deeper soils in the western Edwards Plateau (Diamond et al. 1995, pp. 191-193; Diamond and True 2008, pp. 53-54; Murray et al. 2013, pp. 298, 302).

Livestock grazing.

The recovery plan stated "*Ancistrocactus tobuschii* plants have been observed that were either uprooted or had apical meristem injuries from livestock trampling." Nevertheless, livestock trampling and herbivory have not subsequently been identified as significant causes of mortality or damage to Tobusch fishhook cactus plants. The recurved spines and small size probably discourage herbivory of Tobusch fishhook cactus plants. Livestock are not attracted to the sparsely vegetated outcrops where Tobusch fishhook cactus plants typically occur, and the plants are protected to some degree by surrounding rocks. While livestock trampling probably occurs in grazed habitats, particular where animals are concentrated, we have no evidence that it represents a significant threat to the species. A number of healthy Tobusch fishhook cactus populations occur on well-managed rangeland. We conclude that livestock grazing, especially where juniper thinning and prescribed burning are used to manage rangeland, is generally compatible with conservation of this cactus.

Illicit collection.

Many rare cactus populations have been depleted by overzealous collectors. The recovery plan lists collection by unscrupulous cactus and succulent fanciers as a threat to the species. Westlund (1991, pp. 2, 35, 39) found six specimens of Tobusch fishhook cactus, grown legally from seed, for sale in commercial nurseries. Poole and Janssen (2002, p.9) noted that one population of Tobusch fishhook cactus was heavily depleted by collection, but concluded that "collection is not currently perceived to be a grave threat." Although illicit collection has not significantly impacted the species, the wild populations openly accessed by the public remain vulnerable. The potential threat of illicit collection might be diminished if seeds and plants of legally-propagated Tobusch fishhook cactus are easier and less expensive to obtain than wild-dug specimens.

Parasites.

The Tobusch fishhook cactus weevil (*Gerstaeckeria sp. nov*.) and cactus longhorn beetle (*Moneilema spp*.) parasitize and kill Tobusch fishhook cactus plants and have contributed significantly to drastic declines in many of the known populations (Calvert 2003, all).

Considering that the weevil (*Gerstaeckeria sp. nov*.) is a new species, and that it may be an obligate parasite of Tobusch fishhook cactus (Calvert 2003, p. 12), the weevil itself may be no less endangered than its host.

Periodic outbreaks of insect parasitism appear to be an unavoidable natural cycle. For this reason, the recovery criterion of 3,000 individuals per population may be unattainable or unsustainable, as such large cactus populations would eventually host very large parasite populations, leading to their collapse. The most appropriate conservation strategy may be to protect larger numbers of small, widely-spaced populations, rather than fewer large populations that are more vulnerable to parasites; however, we do not currently know what the optimal parameters of size and spacing should be.

Other herbivory.

Poole and Birnbaum (2003, pp. 11-12) report that jackrabbits browse the cactus, but in most sites cause less than 2 percent mortality. If the root systems are not too badly damaged, they may regenerate one or more new stems. Feral hogs have uprooted plants in many sites (also observed by Reemts (2015, p. 1)). An unidentified ant species has also caused 1 percent mortality at some sites by creating mounds on top of the stems.

Federally-listed plants occurring on private lands have limited protection under the ESA, unless also protected by State laws; the State of Texas also provides very little protection to listed plant species on private lands. Approximately 95 percent of Texas land area is privately-owned. It is reasonable to assume that the vast majority of existing Tobusch fishhook cactus habitat, including sites that have not been documented, occurs on private land. Therefore, most of the species' populations and habitats are not subject to Federal or State protection unless there is a Federal nexus, such as provisions of the Clean Water Act or a federally-funded project.

The ESA does provide some protection for listed plants on land under Federal jurisdiction. However, Tobusch fishhook cactus populations have not been documented on Federal land.

International trade of Tobusch fishhook cactus (as *Sclerocactus brevihamatus* ssp. *tobuschii*) is regulated under CITES Appendix I (Convention on International Trade in Endangered Species of Wild Fauna and Flora 2009).

Demographic consequences of small population size and density.

Poole and Birnbaum (2003, p. 1) estimated an MVP of 1,200 individuals (Section II.7.5). Small populations are less able to recover from losses caused by random environmental changes (Shaffer and Stein 2000, pp. 308-310), such as fluctuations in recruitment (demographic stochasticity), variations in rainfall (environmental stochasticity), or changes in the frequency of wildfires. Tobusch fishhook cactus has a predominantly out-crossing breeding system. The probability of successful fertilization between unrelated individuals is reduced in small, isolated populations. The remaining plants would produce fewer viable seeds, further reducing population recruitment and engendering a downward spiral toward extirpation. The demographic consequences of small population size are compounded by genetic consequences (discussed below), since reduced out-crossing corresponds to increased inbreeding. In addition to population size, it is likely that population density also influences population viability; density must be high enough for gene flow within metapopulations, but low enough to minimize parasite infestations.

Genetic consequences of small population sizes (Barrett and Kohn 1991, pp. 3-30).

Small, reproductively isolated populations are susceptible to the loss of genetic diversity, to genetic drift, and to inbreeding. The loss of genetic diversity may reduce the ability of a species or population to resist pathogens and parasites, to adapt to changing environmental conditions, or to colonize new habitats. Conversely, populations that pass through a "genetic bottleneck" may subsequently benefit through the elimination of harmful alleles. Nevertheless, the net result of loss of the genetic diversity is likely to be a loss of fitness and lower chance of survival of populations and of the subspecies.

Genetic drift is a change in the frequencies of alleles in a population over time. Genetic drift can arise from random differences in founder populations and the random loss of rare alleles in small isolated populations. Genetic drift may have a neutral effect on fitness, but is also a cause of the loss of genetic diversity in small populations. Genetic drift may also result in the adaptation of an isolated population to the climates and soils of specific sites, leading to the development of distinct ecotypes and to speciation. For example, the genetic divergence of *Sclerocactus brevihamatus* subspecies *brevihamatus* and *tobuschii* (Section II.2; Rayamajhi 2015, pp. 67, 98) may have resulted when populations of the species *brevihamatus* migrated into separate geographic regions, and once separated, each population adapted to different soils, climate, and pollinator species.

Inbreeding depression is the loss of fitness among offspring of closely related individuals. While most animal species are susceptible to inbreeding depression, plant species vary greatly in response to inbreeding. Rayamajhi (2015, pp. 63-64) found relatively high inbreeding coefficients in 3 of 8 populations, which he attributed to mating of close relatives within small, isolated populations. Nevertheless, we do not know to what extent inbreeding has reduced fitness of these populations.

Private land ownership.

A large portion of the known individuals and populations of Tobusch fishhook cactus occurs on privately owned land. This does not constitute a threat to the subspecies, and in fact many landowners have demonstrated interest and enthusiasm for its conservation. However, private ownership makes conservation more challenging for several reasons. Access to populations and habitats is subject to the interests of hundreds of individual landowners. Consequently, our knowledge of the subspecies' actual status is far from complete. Establishing and maintaining cooperative relationships with large numbers of private landowners is time-consuming, and these important relationships may lapse when personnel of conservation organizations retire or pursue other career choices. The ownership of private lands changes hands over time, and future owners may choose not to continue conservation efforts that were supported by previous owners. Hence, it is difficult to assure permanent conservation on private lands. These challenges underscore the importance of effective landowner outreach in the conservation of Tobusch fishhook cactus.

Climate change.

The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2013, p. 23) projects the following changes by the end of the 21st century, relative to the 1986 to 2005 averages: It is virtually certain that most land areas will experience warmer and/or fewer cold days and nights; it is virtually certain that most land areas will experience warmer and/or more frequent hot days and nights; it is very likely that the frequency and/or duration of warm spells and heat waves will increase in most land areas; it is very likely that the frequency, intensity, and/or amount of heavy precipitation will increase in mid-latitude land masses; it is likely that the intensity and/or duration of droughts will increase on a regional to global scale. The magnitude of projected changes varies widely, depending on which scenario of future greenhouse gas emissions is used. These scenarios are called Representative Concentration Pathways (RCPs). Under the best-case scenario of RCP2.6, the combined emissions of carbon dioxide, methane, and nitrous oxide, expressed as the carbon dioxide equivalent, will stabilize at 475 parts per million (ppm) by the year 2100. This figure rises to 630, 800, and 1,313 ppm under the RCP4.5, RCP6.0, and RCP8.5 scenarios, respectively (IPCC 2013, p.22).

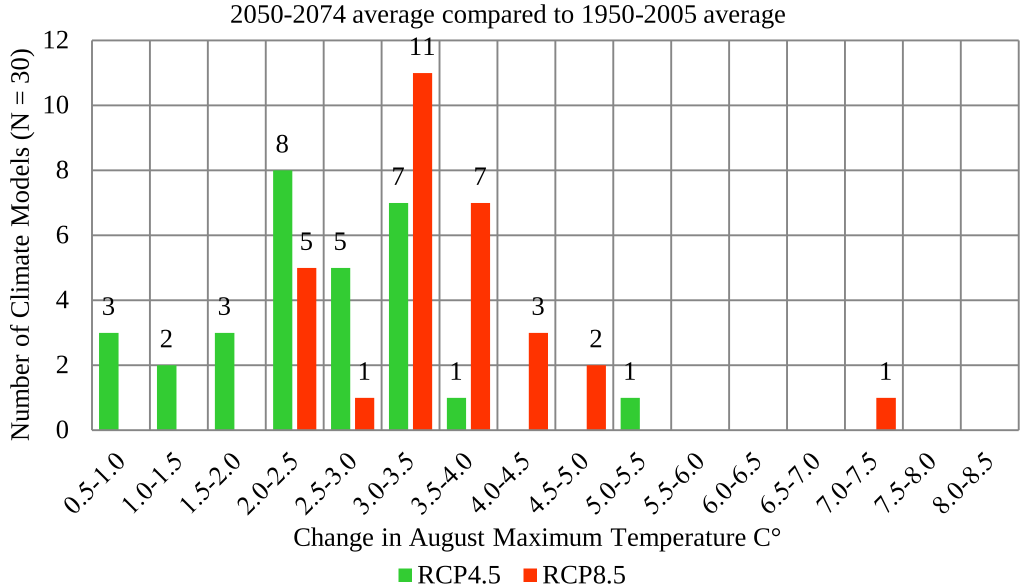
To evaluate how the climate of Tobusch fishhook cactus habitats may change, we used the National Climate Change Viewer (U.S. Geological Survey 2015) to compare past and projected future climate conditions for Edwards County, Texas. The baseline for comparison was the observed mean values from 1950 through 2005, and 30 climate models were used to project future conditions for 2050 through 2074. We selected the climate parameters of August maximum temperature, January minimum temperature, annual mean precipitation, and annual mean evaporative deficit, and used both the RCP4.5 and RCP8.5 scenarios to provide a range of projected values. The results are summarized in Table 8 and in Figures 7, 8, 9, and 10. To interpret these results, it is important to consider the means as well as the dispersion of the 30 climate models (Table 8). The historic baseline average annual precipitation is 1.6 mm/day, or 584 mm/year (23.0 in/year). Although the model mean projects no change in rainfall, these models do not simulate well the projected patterns of regional precipitation (IPCC 2013, p. 11); hence, the projection of “no change” reflects a lack of precision, rather than a determination that there will be no change in precipitation. On the other hand, the models do project a greater increase in evaporative deficit due to increasing temperatures. Evaporative deficit, defined as the difference between actual and potential evapotranspiration (U.S. Geological Survey 2014, p. 11), may be a better indicator of plant stress than precipitation alone, since it takes temperature into account. The baseline evaporative deficit for Edwards County is 36.7 mm/month (17.3 in/year). Hence, these models project that plant growth and survival in Edwards County will become more moisture-limited, although the degree of change depends on the RCP model. Under the RCP8.5 scenario, the projected changes in temperatures and evaporative deficit are greater, as one would expect. Interestingly, the projected change in annual precipitation differs little from the RCP4.5 scenario.

Table 8. Means and dispersion of 30 climate models for Edwards County Climate Projections: 2050 to 2074 compared to 1950 to 2005 (U.S. Geological Survey 2015).

Climate Parameter	RCP	Mean of 30 models	Range of individual models
August maximum temperature	4.5	2.4° C (4.3° F)	0.6° to 3.6° C (1.1° to 6.5° F)
	8.5	3.5° C (6.3° F)	2.1° to 7.1° C (3.8° to 12.8° F)

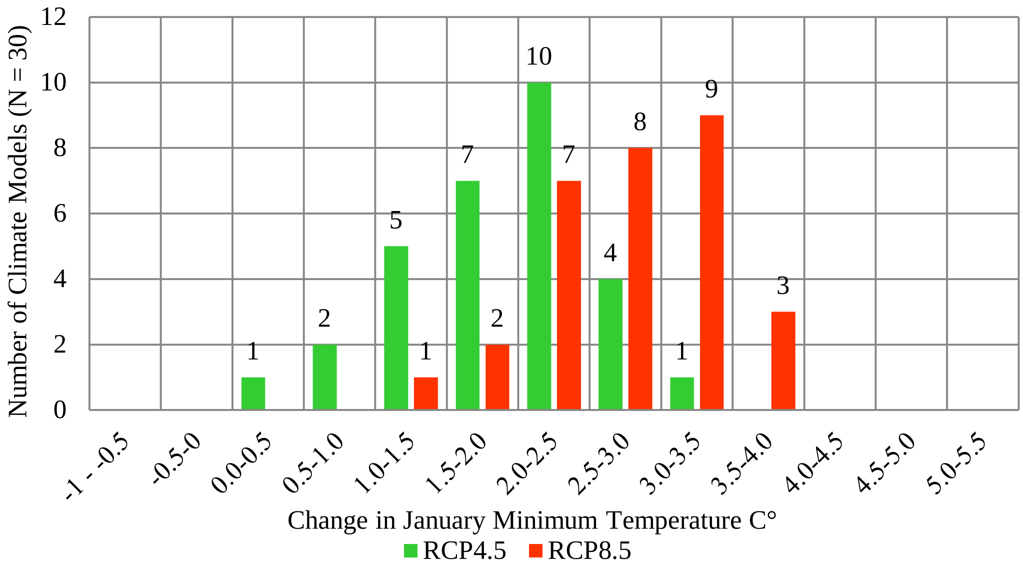
January minimum temperature	4.5	1.8° C (3.2° F)	0.3° to 3.4° C (0.5° to 6.1° F)
	8.5	2.7° C (4.9° F)	1.3° to 3.9° C (2.3° to 7.0° F)
Average annual precipitation	4.5	0.0 mm/day (0.0 in/day)	-0.4 to 0.3 mm/day (-5.75 to 4.31 in/year)
	8.5	-0.1 mm/day (-0.004 in/day)	-0.4 to 0.4 mm/day (-5.75 to 5.75 in/year)
Evaporative Deficit	4.5	13.7 mm/mo (0.54 in/mo)	-2.6 to 28.6 mm/mo (-0.1 to 1.1 in/mo)
	8.5	21.4 mm/mo (0.84 in/mo)	6.8 to 39.0 mm/mo (-0.27 to 1.54 in/mo)

Figure 7. Projected Changes in August Maximum Temperature (C°), Edwards Co., TX
2050-2074 average compared to 1950-2005 average



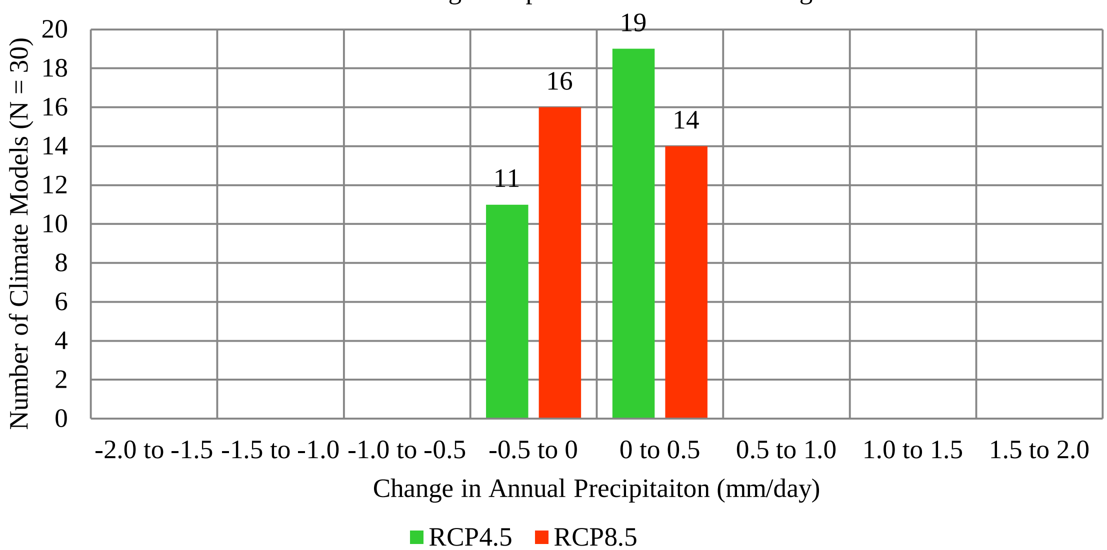
RCP4.5 Mean: 2.4°; Range 0.6° - 3.6°

Figure 8. Projected Changes in January Minimum Temperature (C°), Edwards County, TX
2050-2074 average compared to 1950-2005 average



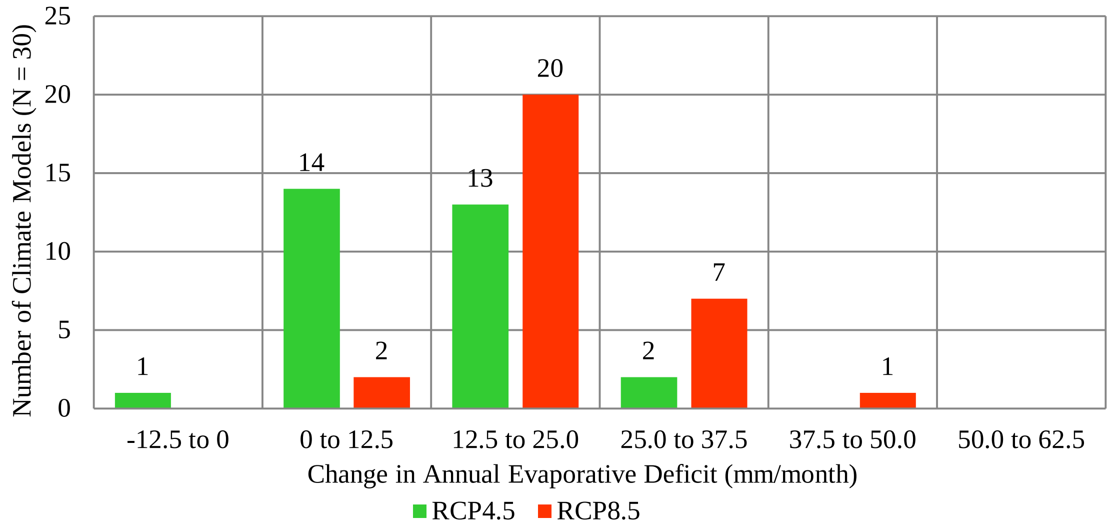
RCP4.5 Mean: 1.8°; Range: 0.3° - 3.4°

Figure 9. Projected Changes in Annual Precipitation (mm/day), Edwards County, TX
2050-2074 average compared to 1950-2005 average



RCP4.5 Mean: 0.0 mm/day; Range: -0.4 - +0.3 mm/day

Figure 10. Projected Changes in Annual Evaporative Deficit (mm/month), Edwards County, TX
2050-2074 average compared to 1950-2005 average



RCP4.5 Mean: 13.7 mm/month; Range: -2.6 - 28.6 mm/month

Nevertheless, we do not know how Tobusch fishhook cactus responded to prior climate changes, nor can we determine how these projected climate changes, forecast by the range of models and emissions scenarios, will affect the synecology of Tobusch fishhook cactus and its habitat. Warmer winters could extend the growing season and improve reproduction and survival of Tobusch fishhook cactus, but might also increase survival of parasite larvae. Heavier, less frequent rainfall could reduce establishment of Tobusch fishhook cactus seedlings, but perhaps less so than the bunch grasses that it competes with. Zaya et al. (2014, pp. 37-38) projected that expected climate changes will be detrimental to 4 populations and beneficial to 6 others. Thus, although it is likely that the projected climate changes will affect the survival of Tobusch fishhook cactus in infinitely complex ways, we do not currently know what the net result of beneficial and detrimental effects will be.

Summary of factors affecting the survival of Tobusch fishhook cactus.

- Tobusch fishhook cactus faces potential threats, as well as potential benefits, from land use changes.
- Well-managed livestock grazing, especially where juniper thinning and prescribed burning (subject to the limitations described above) are used to manage rangeland, appears to be compatible with the subspecies’ management.
- Encroachment from juniper trees reduces habitat suitability, and may be a consequence of reduced fire frequency.
- The rooting of feral hogs has damaged some populations.
- Illicit collection has been documented at least once.

- Many populations are small and isolated, and potentially suffer from demographic and genetic effects.
- Naturally occurring parasites appear to be drivers of population dynamics, and may interact with population density.
- The high proportion of private land ownership within the subspecies' range creates conservation challenges; however, many landowners enthusiastically support the subspecies' conservation.
- Climate changes are likely to affect Tobusch fishhook cactus, but we do not yet know what the net effect of those changes will be.

V. Conservation Efforts.

Section 7 Consultations.

The 5-year status review (USFWS 2010, pp. 6-10) describes 6 formal consultations under section 7 of the ESA that have led to actions that address one or more objectives listed in the recovery plan. These actions were described variously as "conservation measures," "conservation recommendations," or "proposed minimizations to offset impacts to listed species" in USFWS biological opinions.

Three formal section 7 consultations completed since 2010 have involved Tobusch fishhook cactus, including construction of a power line (21450-2011-F-0211) and two separate pipeline ROWs (02ETAU00-2012-F-0149 and 02ETAU00-2013-F-0275). Surveys encountered about 460 Tobusch fishhook cactus plants within the construction footprints of these projects; since the plants were on privately-owned lands, they were not subject to incidental take permits. Conservation measures provided for the removal of individuals that would otherwise have been destroyed. These plants were provided to the Lady Bird Johnson Wildflower Center, along with funding to support their use in future reintroduction projects and scientific research to support the subspecies' conservation. Additionally, the geographic data on Tobusch fishhook cactus locations from these projects has contributed significantly to our understanding of the distribution and abundance of the subspecies (Section II.7.6 and Appendix 2).

Tobusch Fishhook Cactus Conservation Fund

In 2000, USFWS and the National Fish and Wildlife Foundation (NFWF) signed a letter of agreement establishing a Tobusch Fishhook Cactus Conservation Fund (Fund), to be administered by NFWF, to receive and distribute appropriately funds raised to benefit the species' conservation, such as the compensation funds generated through section 7 consultation described above (USFWS and NFWF 2000). In 2005, the Tobusch Fishhook Cactus Conservation Fund was transferred to Lady Bird Johnson Wildflower Center (LBJWC) through a Memorandum of Agreement (MOA; USFWS and LBJWC 2005). The Fund was continued through a second MOA (USFWS and Lady Bird Johnson Wildflower Center 2012) and was subsequently awarded to three projects through its Endangered Species Conservation Grants program (listed in Table 9) (Lady Bird Johnson Wildflower Center 2014). All three projects were completed successfully and generated detailed technical reports (cited below) that have contributed significantly to the information compiled in this SSA.

Table 9. Lady Bird Johnson Wildflower Center conservation grants for Tobusch fishhook cactus (Lady Bird Johnson Wildflower Center 2014).

Organization	Principal Investigator	Subject	Report Citation
The Nature Conservancy	Charlotte Reemts	Effects of shading by woody shrubs on Tobusch fishhook cactus.	Reemts 2014
Texas Tech University	Dr. Jyotsna Sharma	Conservation genetics of Tobusch fishhook cactus.	Rayamajhi 2015
University of Illinois	Dr. Brenda Molano-Flores	Climate change vulnerability index and population viability analyses for Tobusch fishhook cactus.	Zaya 2014

Section 6-Funded Grants.

"The Cooperative Endangered Species Conservation Fund (section 6 of the ESA) provides grants to States and territories to participate in a wide array of voluntary conservation projects for candidate, proposed, and listed species. The program provides funding to States and territories for species and habitat conservation actions on non-Federal lands" (USFWS 2009). The USFWS has awarded five section 6 grants in Texas that support Tobusch fishhook cactus conservation. These projects are briefly summarized in Table 10; the results of these projects are discussed in further detail in the 5-year review (USFWS 2010, pp.14-24).

Table 10. Section 6 Grants Involving Tobusch fishhook cactus.

Job no./ Grant no.	Year completed	Principal investigator and literature citation.	Project title
Job no. 10	1991	J.M. Poole (Westlund 1991).	Cactus trade and collection impact monitoring.
Project no. 30, grants E-1-3 through E-1-7	1995	Raymond Emmett (Emmett 1995).	A study of the reproductive biology of the Tobusch fishhook cactus (*Ancistrocactus tobuschii*).
Project 35, Grant E-1-6	1997	J.M. Poole and G. Janssen (Poole and Janssen 1997).	Managing and monitoring rare and endangered plants on highway right-of-ways in Texas.
Project WER22(67), Grant E-1-11	2002	J.M. Poole and G. Janssen (Poole and Janssen 2002).	Status update of Tobusch fishhook cactus (*Ancistrocactus tobuschii*).
Project WER56	2003	J.M. Poole, S.J. Birnbaum and W. Calvert (Poole and Birnbaum 2003, Calvert 2003).	Annual monitoring of Tobusch fishhook cactus (*Ancistrocactus tobuschii*) to address the requirement of possible delisting and an assessment of the threat of *Gerstaeckeria* sp.

Additionally, section 6 grant no. E-1 (Project WER71) contributed to the creation of Rare Plants of Texas (Poole et al. 2007), an invaluable compilation of data on 232 rare, threatened, and endangered plants of Texas, including Tobusch fishhook cactus.

Summary of accomplishments toward meeting the recovery criteria.

- Tobusch fishhook cactus has been documented at 105 EOs, including12 protected sites. Botanists from TPWD monitored the Tobusch fishhook cactus populations of eight of these sites annually. In 2008, these monitored populations ranged from 34 to 1,090 Tobusch fishhook cactus plants, and their total was 3,139 plants. Since 2009, 9 surveys related to highway, power line, and pipeline developments detected 660 additional plants. The plants tended to be irregularly clustered along these long, narrow surveys, and probably represent many new EOs.
- Nine formal section 7 consultations have involved Tobusch fishhook cactus. Three consultations led to scientific investigations of the impacts of management practices on Tobusch fishhook cactus populations, and long-term monitoring of these populations at Walter Buck and Kerr WMAs. Three consultations led to the salvage of about 460 Tobusch fishhook cacti that would have been destroyed by development projects. These plants were donated with funding to Lady Bird Johnson Wildflower Center, and are being used for reintroduction and scientific research.
- The Tobusch Fishhook Cactus Conservation Fund supported 3 projects that contributed significantly to our knowledge of the ecology, conservation genetics, and population viability analyses of Tobusch fishhook cactus.
- Five section 6 grants have supported scientific investigations and extensive inventory and monitoring of Tobusch fishhook cactus on State Highway ROWs, State Parks, Wildlife Management Areas, and State Natural Areas.
- Four graduate-level investigations have focused on Tobusch fishhook cactus and have provided information that is essential to its conservation and recovery – and to this Species Status Assessment. These projects supported 3 completed master's theses (Sutton 1997, Langley 2015, and Rayamajhi 2015) and one doctoral dissertation (Emmett 1995).
- Additional surveys and geographic data provided through section 7 consultations and other sources have allowed us to conduct a preliminary estimate of the global population and distribution of potential habitat.

VI. Current Status.

Tobusch fishhook cactus has been documented at 105 EOs in eight counties of the Edwards Plateau. This includes 12 protected sites where monitored populations range from 34 to 1,090 individuals, and total 3,139 individuals. Recent surveys found 660 new Tobusch fishhook cactus that probably represent many new EOs.

Data collected at permanent monitoring plots from 1991 through 2013 reveal that many individual colonies of Tobusch fishhook cactus have declined and some have died out completely. At the same time, total populations in monitored sites (consisting of multiple colonies; metapopulations) have remained steady or have increased, due to the discovery of new colonies or re-colonization of formerly depleted colonies. A principle cause of colony decline is parasitism by the larvae of flightless insects, including an undescribed species of *Gerstaeckeria* (a cactus weevil) and one or more species of *Moneilema* (cactus longhorn beetles). We believe that Tobusch fishhook cactus co-evolved with these organisms, and that they are important drivers of its population dynamics. Large, dense populations become susceptible to larval parasitism and decline until parasite populations cannot be sustained. Metapopulations, consisting of multiple, widely-dispersed colonies, appear to be stable; however, we do not know what the long-term demographic trends are at the metapopulation or subspecies level.

We developed a potential habitat model based on the soils and watersheds of documented populations. This model predicts that over 2 million ha (5 million ac) of potential habitats occur in the 8 counties of the currently-known range, as well as in some adjacent counties (mainly Crockett and Sutton counties); nevertheless, we have no records of Tobusch fishhook cactus occurring in any of these adjacent counties, nor have any surveys been conducted there, to our knowledge. Within these areas of potential habitat, only a small fraction of the total area contains suitable habitat, consisting of discontinuous, open areas on or near exposed limestone strata. Based on 25 surveys distributed throughout the subspecies range, we estimate that the global population is about 480,000 individuals.

VII. Assessment of Current and Future Viability.

VII.1. Current Viability.

Resilience and Redundancy.

Resilience refers to the population size necessary to endure stochastic environmental variation (Shaffer and Stein 2000, pp. 308-310). Redundancy refers to the number and geographic distribution of populations or sites necessary to endure catastrophic events (Shaffer and Stein 2000, pp. 308-310). The recovery plan (USFWS 1987, p. 14) established a recovery criterion of 4 protected populations with at least 3,000 individuals, but did not show how this level was determined. However, we now understand that insect parasites are able to devastate large, dense populations. We conclude that few large populations are much more vulnerable than many small populations, and that this recovery criterion should be amended. Poole and Birnbaum (2003, p. 1), using the surrogate species method of Pavlik (1996, pp. 136-137), estimated a MVP for Tobusch fishhook cactus of 1,200 individuals (Section II.7.5). Since few individual colonies reach this size, and since large colonies are more vulnerable to insect parasites, we recommend that the MVP of 1,200 individuals be applied to metapopulations that consist of multiple colonies distributed at a landscape scale.

The resilience of Tobusch fishhook cactus derives not merely from the size of metapopulations, but also their density. Colonies that are too small or too isolated may incur loss of genetic diversity and inbreeding; Rayamajhi (2015, pp. 63-64) found relatively high inbreeding coefficients in 3 of 8 populations, which he attributed to mating of close relatives within small, isolated populations. Conversely, vulnerability to insect parasitism increases when metapopulations become too dense, or when colonies become too large. Therefore, we believe that there must be some optimal range of metapopulation density and colony size, although we do not currently know what those optima are. These concepts of metapopulation size and density depend on how metapopulation boundaries are delimited. The EO concept is a good starting point, but may have to be revised for Tobusch fishhook cactus considering its specific population dynamics.

The determination of Tobusch fishhook cactus viability is more challenging, since few surveys have been conducted on the roughly 95 percent of the potential habitat that is privately owned. Furthermore, since the populations are small and widely distributed, there is a low probability of detecting populations on any fixed area, such as a state park. It is likely that metapopulations are distributed over areas that are larger than individual parks and natural areas. We can speculate that the population densities found on the small number of areas that have been quantitatively surveyed are representative of the entire global distribution of this subspecies. Since 2009, several new quantitative surveys were conducted for highway, pipeline, and power line developments. These surveys provided data from transects that cross the subspecies' range and provide more evidence for its range of densities. Based on all available evidence, we provisionally estimate that the global population size is about 480,000 individuals (Appendix 2). Regardless of how this number is divided into metapopulations, we believe that it is likely that Tobusch fishhook cactus has multiple, resilient populations.

Representation.

Representation refers to the genetic diversity, both within and among populations, necessary to conserve long-term adaptive capability (Shaffer and Stein 2000, pp. 307-308). Rayamajhi (2015, (pp. 53, 54, 65, 66, 79, 80) found relatively low levels of genetic differentiation among 9 populations of Tobusch fishhook cactus (low pairwise F_{ST} and G_{ST} levels, discussed in II.2), regardless of the distance between populations. He found evidence of substantial gene flow among populations, suggesting that the documented populations may interact with additional (undocumented) populations (at least in the recent past) (p. 67). However, recently isolated populations may not yet show genetic differentiation, in part because individuals can live and contribute to the local gene pool at least for several decades. Most of the populations studied had healthy levels of outbreeding, but 3 populations were at relatively higher risk of inbreeding effects and may have suffered recent genetic bottlenecks through population declines (P. 97).

Based on controlled pollination experiments, Emmett (1995) found effective fertilization (fruit set, seed production, and seed viability) within isolated colonies in his study area (p. 87). This affirms empirically that at least some isolated colonies still possess a sufficient level of genetic diversity.

The low level of genetic differentiation among populations is not unusual for endemic taxa, and may also indicate a fairly recent divergence of subspecies *tobuschii* from subspecies *brevihamatus*. There is evidence of gene flow throughout the subspecies' range and possible interaction of the monitored populations with undocumented populations on surrounding private lands. Genetic differentiation within most, but not all populations, is sufficiently high for effective fertilization and out-crossing.

We conclude that Tobusch fishhook cactus currently possesses sufficient genetic diversity to conserve long-term adaptive capability. However, habitat fragmentation and disruption of gene flow among populations may have occurred too recently to be detected through genetic analyses. Considering the naturally low densities of Tobusch fishhook cactus populations, gene flow among them may be easily disrupted. Therefore, maintaining the continuity of potential habitats throughout the subspecies range should have a high conservation priority. We recommend that viability monitoring should be continued long enough to determine population dynamics and demographic trends at the metapopulation and subspecies levels.

Table 11. Summary of requirements, factors affecting survival, and current conditions of Tobusch fishhook cactus individuals and populations, and the species' viability (representation, redundancy, and resilience).

INDIVIDUALS	METAPOPULATIONS	SPECIES
I. Requirements of Tobusch fishhook cactus.		
• Suitable Habitats: Microsites of sparse vegetation over/near exposed limestone. • Reproduction: Sexual maturity at 9 years; fertilization requires genetic diversity within pollinator forage range. • Breeding system: Primarily out-crossing. • Pollinators: Honey bees and halictid bees; requires diverse native vegetation within forage range and low exposure to pesticides. • Seed ecology: Ants may be seed-predators or seed-dispersers (or both). • Lifespan: Potentially at least 50 years.	• Resiliency: Estimated MVP of 1,200. • Stable or increasing demographic trends. • Sufficient genetic diversity to impart adaptive capability, low inbreeding, and sexual out-crossing. • Fire Cycle: Reduce juniper encroachment. • Distribution: Optimal population density is high enough to allow gene flow, but low enough to limit parasite infestation.	• Redundancy: Greater redundancy confers higher probability of enduring catastrophic events. • Representation: Greater genetic diversity confers more adaptive capability.

II. Factors affecting the survival of Tobusch fishhook cactus.		
• Insect parasites kill individual plants. • Illicit collectors remove individuals from the gene pool. • Feral hogs damage and destroy individuals. • Livestock trampling may damage or kill individuals.	• Small population size increases risks of loss from stochastic events and from reduced genetic fitness. • Reduced fire frequency may increase encroachment and competition from juniper trees. • Livestock grazing may be compatible with Tobusch fishhook cactus habitat management, through appropriate vegetation management. • Subdivision of land may have benefits and detriments; net effect is unknown.	• High proportion of private land ownership through subspecies' range creates conservation challenges. • Climate changes are likely to affect Tobusch fishhook cactus, but net effect is unknown. Demographic PVA predicted some populations improve, while others decline, under projected climate changes.

III. Current Conditions of Tobusch fishhook cactus.		
• Individuals have high mortality rate. • Flightless insect parasites are a major cause of mortality.	• TXNDD lists 105 EOs in 8 counties. • Monitored plots in 12 protected natural areas had 3,139 individuals. • Linear surveys across potential habitats found 660 new individuals representing numerous new EOs. • Many colonies have declining populations, although metapopulations appear to be stable or increasing.	• We estimate the total potential habitat is over 2 million ha (5 million ac). • We estimate the total global population is about 480,000 individuals. • Tobusch fishhook cactus is likely to have multiple resilient metapopulations. • Sampled populations show little genetic divergence among populations. • Most, but not all, populations have sufficient genetic diversity for fertilization and out-crossing.

VII.2. Future Viability.

We project what the viability of Tobusch fishhook cactus could be, between 2050 and 2074, under three scenarios. The "better than expected" scenario represents improvements over current conditions. The "moderate" scenario represents the most likely conditions if current trends continue. The "worse than expected" scenario represents deteriorating conditions. We describe, below, the relevant characteristics of these scenarios, and subsequently, their effects on populations. Table 12 summarizes our projections of the future species viability of Tobusch fishhook cactus under each of these scenarios.

Better than Expected Scenario.

a. Conservation support: Government agencies, non-profit conservation organizations, academic institutions, and private landowners collaborate and contribute sufficient human and financial resources to conserve Tobusch fishhook cactus and its habitats. Private landowners are aware of the species and enthusiastically support its conservation. Development projects are evaluated and modified, if necessary, to avoid detriment to Tobusch fishhook cactus and its habitats.

b. Surveys: Qualified botanists obtain access to survey a large number of the highest-potential habitats throughout the species range. Both the presence and absence of Tobusch fishhook cactus populations in these habitats contributes to improved understanding of the species' ecology, management, abundance, and true geographical range.

c. Geographic range: Extant Tobusch fishhook cactus populations are documented throughout its range of potential habitats.

d. Habitat management: Extant populations are managed appropriately. This may include prescribed burning, juniper thinning, and other practices to maintain a high diversity of native plants and healthy pollinator populations.

e. Population management: Extant colonies and metapopulations of Tobusch fishhook cactus are monitored periodically to track demographic trends. Observed threats, such as juniper encroachment or feral hogs, are prevented before populations are significantly impacted. Small, declining populations are recovered through facilitated augmentation of numbers and genetic diversity or other effective practices.

f. Climate changes: The effects of climate changes on Tobusch fishhook cactus habitats are relatively moderate, and are well-tolerated by the species.

Moderate Scenario.

a. Conservation support: Government agencies, non-profit conservation organizations, academic institutions, and private landowners collaborate and contribute some human and financial resources for conservation of Tobusch fishhook cactus and its habitats. Public outreach has increased awareness of the species among private landowners and has generated increasing support for its conservation. Development projects are evaluated and modified, if necessary, to minimize or mitigate impacts to Tobusch fishhook cactus and its habitats.

b. Surveys: Qualified botanists obtain access to survey a representative sample of the highest-potential habitats. Both the presence and absence of Tobusch fishhook cactus populations in these habitats contributes improved understanding of the species' ecology, management, and true geographical range.

c. Geographic range: New extant Tobusch fishhook cactus populations are documented within the range of potential habitats.

d. Habitat management: At least some extant populations are managed appropriately. This may include prescribed burning, juniper thinning, and other practices to maintain a high diversity of native plants and healthy pollinator populations.

e. Population management: At least some extant populations of Tobusch fishhook cactus are monitored periodically to track demographic trends. Observed threats, such as juniper encroachment or feral hogs, are prevented before populations are significantly impacted. Small, declining populations are monitored to see if they recover spontaneously.

f. Climate changes: Climate changes have significant impacts on Tobusch fishhook cactus habitats, but with appropriate management the species' overall status remains stable.

<u>Worse than Expected Scenario</u>.

a. Conservation support: Government agencies, non-profit conservation organizations, academic institutions, and private landowners fail to collaborate or contribute sufficient human and financial resources to conserve extant Tobusch fishhook cactus populations and high-potential habitats. Landowners remain largely unaware of the species and are unsupportive of its conservation. Development projects significantly impact Tobusch fishhook cactus and its habitats.

b. Surveys: Qualified botanists are unable to access representative samples of the highest-potential habitats. Nothing new is learned about the species' ecology, management, and true geographical range.

c. Geographic range: No new extant Tobusch fishhook cactus populations are documented, or if additional populations are found, they cannot be protected or conserved.

d. Habitat management: Known extant populations are not managed appropriately.

e. Population management: Known extant populations of Tobusch fishhook cactus are not monitored periodically.

f. Climate changes: Climate changes have severe impacts on Tobusch fishhook cactus habitats and the species' overall status declines.

Table 12. Future species viability under a range of scenarios.

Viability Elements	Scenarios		
	Better than Expected	Moderate	Worse than Expected
Population Resilience	Many public and private landowners are active participants in long-term protection, monitoring, and management. Numerous metapopulations meet or exceed MVP of 1,200 individuals and show stable or positive demographic trends.	Most public and some private landowners allow protection, monitoring, and management of populations on their lands. Appropriate management, augmentation, and reintroduction (as appropriate) are sufficient for positive demographic trends toward MVP levels.	Public and private landowners are unable or unwilling to protect other extant populations.
Species Representation	Genetic diversity within metapopulations remains sufficiently high for out-crossing to occur. Gene flow occurs regularly between colonies and metapopulations. Samples are collected from all populations for seed banking, augmentation and reintroduction, genetic analyses, or other conservation purposes as necessary.	Genetic diversity within metapopulations remains sufficiently high for out-crossing to occur. Gene flow occurs regularly between colonies and metapopulations.	Portions of the subspecies' global population are destroyed, and overall genetic variation and gene flow decline.
Species Redundancy	The number of known, protected, managed, and resilient populations is sufficient to ensure long-term survival.	Surveys are conducted on a portion of the highest-priority potential habitats, lead to improved understanding of habitats and geographic range, and allow an estimate of the number of known and unknown extant populations. At least some populations are protected, well-managed, and resilient.	The known, extant populations are declining, or cannot be protected and managed.
Overall Viability	Excellent.	Moderate; Species survives but requires continued conservation, management, and protection.	Declining toward extinction.

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IX. Additional Information.

IX.1. Photograph credits.

Cover:	Chris Best, USFWS.
Figure 2.a:	Chris Best, USFWS.
Figure 2.b:	Jackie Poole, Texas Parks and Wildlife Department.
Figure 2.c:	Chris Best, USFWS.
Figure 2.d:	Chris Best, USFWS.
Figure 3.a:	Charlotte Reemts, The Nature Conservancy.
Figure 3.b:	Chris Best, USFWS.
Figure 3.c:	Chris Best, USFWS.
Figure 3.d:	Charlotte Reemts, The Nature Conservancy.
Figure 3.e:	Chris Best, USFWS.
Figure 3.f:	Chris Best, USFWS.

XI.2 Scientific Units.

ac	Acre	km	kilometer
cm	Centimeter	m	meter
ha	Hectare	mi	mile
in.	inch	mm	millimeter

IX.3. Acronyms Used.

CITES	Convention on International Trade in Endangered Species of Wild Flora and Fauna
CPC	Center for Plant Conservation
DBG	Desert Botanical Garden
EO	Element Occurrence
ESA	Endangered Species Act
FR	Federal Register
GIS	Geographic Information System
GPS	Global Positioning System
IPCC	Intergovernmental Panel on Climate Change
IT IS	Integrated Taxonomic Information Service
LBJWC	Lady Bird Johnson Wildflower Center
MOA	Memorandum of Agreement
MVP	Minimum Viable Population
NFWF	National Fish and Wildlife Foundation
NGO	Non-Governmental Organization
NRCS	Natural Resources Conservation Service
PVA	Population Viability Analysis
RCP	Representative Concentration Pathways
ROW	Rights of Way
SNA	State Natural Area
SP	State Park
SSA	Species Status Assessment
TPWD	Texas Parks and Wildlife Department
TXDOT	Texas Department of Transportation
TXNDD	Texas Natural Diversity Database
USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
WMA	Wildlife Management Area

Appendix A - Glossary of Scientific and Technical Terms

Appendix A. Glossary of Scientific and Technical Terms.

Term	Definition
Alkaline (Soil)	Soil having a basic (pH > 7) soil solution due to a high content of alkaline minerals, such as calcium carbonate.
Anther	The pollen-bearing part of the stamen. (Correll and Johnston 1979).
Areole	Specialized axillary bud or short shoot in cactus species; the spine cushion, producing leaves, spines, and flowers (Anderson 2001)
Bayesian Cluster Analysis	Statistical method for classifying items into groups using Bayesian algorithms (Wikipedia 2016).
Breeding System	The ability of a plant species to reproduce via outcrossing, self-fertilization, apomixis, or a combination (Wikipedia 2016).
Bunch-grass	Grass that reproduces vegetatively through the proliferation of tillers from basal bud primordia.
Central spines	One of the innermost spines of an areole (Anderson 2001).
Chihuahuan Desert	Arid region between the Sierra Madre Oriental and Sierra Madre Occidental of northern Mexico, extending into southwest Texas and southern New Mexico of the U.S.
Chloroplast	A double-membrane organelle found in higher plants in which photosynthesis takes place.
Clade	The scientific classification of living and fossil organisms to describe a monophyletic group, defined as a group consisting of a single common ancestor and all its descendants (Wikipedia 2016).
Conservation Measures	Actions to benefit or promote the recovery of listed species that are included by the Federal agency as an integral part of the proposed action. These actions will be taken by the Federal agency or applicant, and serve to minimize or compensate for, project effects on the species under review. These may include actions taken prior to the initiation of consultation, or actions which the Federal agency or applicant have committed to complete in a biological assessment or similar document (USFWS and NMFS 1998, p. xii).
Cretaceous	Geologic period and system from 145 ± 4 to 66 million years (Ma) ago (Wikipedia 2016).
Cryptogam	Collective term for primitive plants that reproduce by spores rather than seeds.
Demography	Scientific study of populations.
Densiometer	Optical device used to estimate the density of canopy cover above a fixed point.
DNA Sequence	The sequence of nucleotide bases in a DNA molecule (or portion of a molecule); see gene sequence.
Ecotype	A genotype that is specifically adapted to a particular ecological area.

Appendix A - Glossary of Scientific and Technical Terms

Term	Definition
Edaphic	Adjective referring to soil.
Element Occurrence	An area of land and/or water in which a species or natural community is, or was, present (NatureServe 2002).
Elytron	Modified, hardened forewings of certain insect orders, notably beetles (Coleoptera) and true bugs (Hemiptera); plural elytra (Wikipedia 2016).
Endangered	"…any species which is in danger of extinction throughout all or a significant portion of its range other than a species of the Class Insecta determined by the Secretary to constitute a pest whose protection under the provisions of this Act would present an overwhelming and overriding risk to man." U.S. Congress 1988.
Endemic	An organism restricted to a specific habitat or geographic range.
Evaporative deficit	The difference between actual and potential evapotranspiration (USGS 2014, p. 11).
Extra-floral nectary	Specialized nectar-producing gland located outside the flower (Anderson 2001).
Fibrous root	One of many multiply-divided roots of roughly equal size and dominance.
Forb	A broad-leafed herbaceous plant.
Genetic bottleneck	An event which greatly restricts an organism's genetic diversity.
Genetic drift	A change in allele frequencies within a population over time.
Germinability	Germination capacity. The percent of seeds that are able to germinate; distinguished from germination rate.
Germination rate	Germination of seeds tracked over a course of time (usually percent by day).
GIS	Geographic Information System; computer software used to store, analyze, and create maps using geographic data.
GPS, d-GPS	Global Positioning System; electronic system for calculating geographic position using satellite data. D-GPS is differentially-corrected GPS, which uses a reference position of known geographic location to increase accuracy.
Greenhouse gas	Gases such as carbon dioxide, water vapor, and methane that contribute to the atmosphere's thermal insulation through absorption of light in the infra-red spectrum.
Habitat Conservation Plan	Under section 10(a)(2)(A) of the Act, a planning document that is a mandatory component of an incidental take permit application, also known as a Conservation Plan (USFWS and NMFS 1998, p. xiv).
Halictid	A cosmopolitan family of the order Hymenoptera consisting of small (> 4 mm) to midsize (> 8 mm) bees which are usually dark-colored and often metallic in appearance; commonly referred to as sweat bees (Wikipedia 2016).

Appendix A - Glossary of Scientific and Technical Terms

Term	Definition
Heterozygous	A diploid (or polyploid) organism possessing two (or more) alleles at a specific gene locus on homologous chromosomes.
Inbreeding	Sexual reproduction between closely-related individuals.
Inbreeding coefficient	Coefficient to measure the degree of inbreeding in individuals (Wright 1922).
Inbreeding depression	The reduction of fitness caused by mating between relatives (Edmands 2007, p. 464).
Loam	Soil containing moderate amounts of sand, silt, and clay.
Majority rule phylogenetic trees	Phylogenetic trees composed of all those subsets that appear in a majority of a collection of trees (Felsenstein 1985, p. 786).
Metapopulation	A group of spatially separated populations of the same species that interact at some level (Wikipedia 2016).
Micro-habitat	Very specific or fine-scale portion of a habitat that is occupied by a species.
Microsatellite DNA	Repeating sequences of 2 to 6 base pairs in DNA that may be used as genetic markers in kinship and population studies (Wikipedia 2016).
Microsite	Micro-habitat.
Monophyly	A group of organisms which consists of all the descendants of a single common ancestor.
Nei's genetic distance	Mathematical procedure to measure the genetic divergence between species or populations developed by Masatoshi Nei (Nei 1972).
Nuclear DNA	DNA contained within the nucleus of a Eukaryotic organism.
Outbreeding depression	The reduction in reproductive fitness in the first or later generations following attempted crossing of populations (Frankham et al. 2011, p. 466).
Outcross	In plants, sexual fertilization involving the union of gametes from different individuals.
Papillate	Possessing a minute nipple-shaped projection (Correll and Johnston 1979).
Perianth	The floral envelopes collectively; usually used when calyx and corolla are not clearly differentiated. (Correll and Johnston 1979).
Phenology	Seasonal pattern of plant growth, development and reproduction.
Phylogeny	The study of evolutionary relatedness among various groups of organisms (e.g., species, populations), which is discovered through molecular sequencing data and morphological data matrices (Wikipedia 2016).
Podarium	Outgrowth of the stem surface (Anderson 2001).
Population	Collection of inter-breeding organisms of a particular species (Wikipedia 2016).

Appendix A - Glossary of Scientific and Technical Terms

Term	Definition
Population dynamics	Changes in the size and age composition of populations over time, and the biological and environmental processes influencing those changes (Farlex, Inc. 2011).
Population Viability Analysis	Statistical models used to predict the probability of extinction of a population after a specified period of time.
Principle Coordinate Analysis	Classical multidimensional scaling. Mathematical procedure used to visualize the level of similarity in pairs of terms in a data matrix (Wikipedia 2016).
Protandrous	Flower type in which anthers mature before pistils (Correll and Johnston 1979).
Quasi-extinction	Population size below which extinction is very likely due to genetic or demographic risk.
Radial spines	One of the outermost spines of an areole, often radiating or appressed (Anderson 2001).
Recruitment	Addition of new individuals to a population.
Recurved	Bent backwards; curved downward or backwards (Correll and Johnston 1979, p. 1700).
Redundancy	The number of populations or sites necessary to endure catastrophic losses (Shaffer and Stein 2000, pp. 308-310).
Reintroduction	Restoration of populations of a species where it is currently absent but within its former range and habitat.
Representation	The genetic diversity necessary to conserve long-term adaptive capability (Shaffer and Stein 2000, pp. 307-308).
Resilience	The size of populations necessary to endure random environmental variation (Shaffer and Stein 2000, pp. 308-310).
Savanna	Mosaic of trees or shrubs and grassland; between 40% and 10% cover by trees and shrubs (NatureServe 2010).
Section 6	Cooperative Endangered Species Conservation Fund (Section 6 of the ESA). (USFWS 2009)
Section 7	The section of the Endangered Species Act of 1973, as amended, outlining procedures for interagency cooperation to conserve Federally listed species and designated critical habitats (USFWS and NMFS 1998, p. xviii).
Self-fertilization	Sexual reproduction involving the union of gametes from a single individual.
Self-incompatible	Incapable of self-fertilization.
Self-pollination	Fertilization of a flower with pollen from the same individual.
Simple sequence repeat	Microsatellite DNA.

Appendix A - Glossary of Scientific and Technical Terms

Term	Definition
Soil seed bank	Dormant and non-dormant seeds present in the soil that are able to germinate.
Speciation	The evolutionary process by which new biological species arise (Wikipedia 2016).
Species viability	A species' ability to sustain populations in the wild beyond the end of a specified time period, assessed in terms of its resilience, redundancy, and representation (USFWS 2015).
Stigma	The receptive part of the pistil on which the pollen germinates. (Correll and Johnston 1979).
Stochastic	Random.
Subspecies	A taxonomic group that is a division of a species; usually arises as a consequence of geographical isolation within a species (Biology-online.org 2011).
Sulca	A furrow or groove (Correll and Johnston 1979).
Synecology	Ecology of groups of coexisting organisms.
Systematics	The study of the diversification of life on the planet Earth, both past and present, and the relationships among living things through time, visualized as evolutionary trees (Wikipedia 2016).
Tamaulipan shrubland	The semi-arid, subtropical ecological region of northeast Mexico and south Texas characterized by shrub vegetation.
Taproot	Predominantly long or thick central root; may function to access deep soil moisture, storage of water and carbohydrates, or both.
Taxon	(Plural, taxa). A natural group of organisms at any rank in the taxonomic hierarchy (Anderson 2001).
Taxonomy	Scientific classification of living organisms.
Tepal	Sterile leaflike structure of the flower when the perianth parts are not differentiated into sepals and petals (Anderson 2001).
Threatened	"…any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." United States Congress 1988.
Tubercle	A conical or cylindrical outgrowth or protuberance from a cactus stem, usually bearing all or part of the areole; podarium (Anderson 2001).
Vegetative cover	The proportion of an area that is intercepted vertically by tissues of a specified taxon or type of plants; total cover may exceed 1 due to multiple layers.
Woodland	Vegetation type with discontinuous tree cover.
Wright's genetic differentiation	Mathematical procedure for determining the genetic differentiation of populations advanced by Sewall Wright (Wright 1943).

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Appendix B. Estimates of potential habitat and global population size for Tobusch fishhook cactus.

1. Introduction.

To assess the current viability and viability trends of Tobusch fishhook cactus, we need to know the geographic extent and range of its potential habitats, the proportion of these habitats that are occupied, and the size, distribution, and demographic trends of its populations. These are challenging objectives, due to the difficulty in detecting this diminutive, cryptic cactus in its habitat, and to the high proportion of private land ownership and restricted access throughout its range. When listed as endangered in 1979 (44 FR 64736), no more than 200 individuals had been found in four sites. Since then, Tobusch fishhook cactus has been documented in more than 100 Element Occurrences (EOs), and quantitative population data has been collected from at least 119 permanent plots at 12 sites (including 10 protected natural areas). Quantitative surveys have also been conducted where development projects have invoked section 7 consultation with USFWS. Collectively, these quantitative surveys from many areas of known size allow us to estimate both the range and extent of potential habitats as well as the total population size.

2. Estimate of the range and extent of potential habitats of Tobusch fishhook cactus.

2.1. Determination of occupied soils.

USFWS and others have, until now, represented the geographic distribution of Tobusch fishhook cactus as the boundaries of the 8 counties where this cactus has been documented: Bandera, Edwards, Kerr, Kimble, Kinney, Real, Uvalde, and Val Verde. However, species distribution is more realistically represented using geographic data – if it exists – of the natural features that the species requires. Although a very small proportion of Tobusch fishhook cactus individuals have reported from atypical habitats, the vast majority of individuals occur where limestone strata occur at or very near the surface of the soil. These "microsites" have thin, gravelly soil that supports only sparse herbaceous vegetation and little or no woody plant cover, and typically range in size from 0.05 to 5 ha (0.12 to 12 ac). Currently, geographic data is not available that specifically identifies these limestone microsites. However, the Natural Resources Conservation Service (NRCS) Soil Survey Geographic Database (SSURGO) provides digital maps of the soils where these outcrops frequently occur (USDA NRCS 2007).

We have received geographic coordinates for 511 Tobusch fishhook cactus sites from the following sources (summarized in section 3.1):

- 91 Element Occurrence Representations (EORs) provided by the Texas Natural Diversity Database (TXNDD) (TXNDD 2016). Most of the EORs have buffers of up to about 100 m (328 ft) and 7 had buffers of 2 km (1.2 mi), and therefore often occurred in more than one soil map unit.
- Global position system (GPS) data of 20 occupied sites detected in surveys conducted by Texas Department of Transportation (TxDOT) on 12 segments of existing highway rights-of-way that may be impacted by planned highway improvement projects (TxDOT 2009; TxDOT 2011; Pinto-Torres and Carr 2016).

- GPS data of 377 occupied sites detected in two privately-funded surveys, conducted by SWCA Environmental Consultants in 2012 and 2013, associated with development projects. One survey in eastern Val Verde County was 60.1 m (200 ft) wide and 79.6 km (49.5 mi) long; the total area including additional workspaces was 485.5 ha (1,199.7 ac). The developer voluntarily provided Tobusch fishhook cactus location data to USFWS, but requested that the locations not be published due to concerns from private landowners. An unrelated survey in Edwards and Kinney counties was 22.86 m (75 ft) wide and about 130.1 km (76.1 mi) long, and totaled about 297.4 ha (734.9 ac). These long, narrow surveys, similar to transects, spanned large portions of the species' global range, sampling areas irrespective of ownership or land use; thus, they may better represent habitat conditions throughout the range, compared to state parks, state natural areas, and state wildlife management areas, where we expect habitat management to be optimal for Tobusch fishhook cactus and other species of concern.
- GPS data of 19 occupied sites detected in a series of 195 surveys conducted by the Lower Colorado River Authority (LCRA) prior to construction of a new 140-mile long high-tension power line from Schleicher County to Kendall County (Blanton and Associates 2012). Each survey consisted of a 45.72-m (150-ft) radius circle in the potential impact areas of planned tower construction sites. Like the privately-funded surveys mentioned above, land ownership of the survey sites was predominantly private.
- GPS data of 5 occupied sites at The Nature Conservancy's Love Creek Preserve in Bandera County (these are also included in the TXNDD data) (Reemts 2016).
- GPS data of 4 occupied sites in Bandera County where a landowner voluntarily participates in the USFWS Partners for Fish and Wildlife program to conserve Tobusch fishhook cactus (USFWS and McAllen 2016).

As used here, "sites" are geographic locations that may include a single individual, a colony, or an entire population (see the discussion in the SSA, Section II.7.1). Although some location data, such as historic records, lacks geographic precision, we based the soil analysis on the 511 sites described above that had precisions ranging from a few meters to about 100 meters (7 sites had buffers of 2 km (1.2 mi), but fell within a small number of soil map units). We used the ArcGIS 10.3.1 geographic information system software to determine which soil map units these sites occupied. Sites that spanned boundaries between soil map units were divided evenly between the units; for example, a site overlapping three map units would be counted as 0.33 occupied soils in each map unit. Some map units include complexes or associations of two major soils, in which case both soils were counted as one occupied soil; for this reason, the total number of occupied soils (866) exceeds the total number of sites. Since the SSURGO uses different map symbols and classification criteria in different counties for the same or similar soils, this analysis was based on the major soils listed in the soil map unit descriptions. The results are summarized in Tables B.1, B.2, and B.3, and Figure B.1.

Appendix B – Estimates of Potential Habitat and Global Population Size

Table B1. Occupied Soils of Tobusch fishhook cactus sites.

County	Numbers of Occupied Soils by Data Source						Map Unit Symbol	Description	Major Soils in Map Unit	
	Private Survey 1	Private Survey 2	TXNDD	TxDOT	LCRA	USFWS PFW			A	B
Bandera			0.25				AN	Anhalt Clay 0-2% slopes	Anhalt	
Bandera			0			2	BKX	Kerrville Association, undulating	Kerrville	
Bandera			0.25				FR	Oakalla silty clay, occasionally flooded	Oakalla	
Bandera			1				KM	Krum silty clay, 1-3% slopes	Krum	
Bandera			0.5				ND	Nuvalde silty clay, 0-1% slopes	Nuvalde	
Bandera			4.5				OKX	Orif-Boerne Association, frequently flooded	Orif	Boerne
Bandera			1			2	TDX	Tarrant-Doss Association, undulating	Tarrant	Doss
Bandera			2.75				TRX	Tarrant-Rock Outcrop Association, undulating	Tarrant	Rock
Bandera			0.75				TSX	Tarrant-Rock Outcrop Association, steep	Tarrant	Rock
Edwards		78.5	5	1			EcF	Eckrant-Rock Outcrop Complex, 1-20% slopes	Eckrant	Rock
Edwards			0.5				EcG	Eckrant-Rock Outcrop Complex, 20-60% slopes	Eckrant	Rock
Edwards		20.5	0				ErF	Ector-Rock Outcrop Complex, 1-20% slopes	Ector	Rock
Edwards		5.5	6				ErG	Ector-Rock Outcrop Complex, 20-60% slopes	Ector	Rock
Edwards		24.5	5				MaD	Mailtrail Very Gravelly Clay Loam, 1-8% slopes	Mailtrail	
Edwards			0.5				OrG	Oplin-Rock Outcrop Complex, 20-60% slopes	Oplin	Rock
Edwards		4	0				TvB	Tarrant-Valera Complex, 0-3% slopes	Tarrant	Valera
Kerr			2				ECC	Eckrant-Comfort Association, gently undulating	Eckrant	Comfort
Kerr			1				ERG	Eckrant-Rock Outcrop Association, steep	Eckrant	Rock
Kerr			1				STC	Spires-Tarpley Association, gently undulating	Spires	Tarpley
Kerr			6	1			TTC	Tarrant-Eckrant Association, gently undulating	Tarrant	Eckrant
Kimble			7	11	19		TaC	Tarrant Soils, undulating	Tarrant	
Kimble			5				TrG	Tarrant-Rock Outcrop Complex, steep	Tarrant	Rock
Kinney			1				Ec	Ector Soils, 1-2% slopes	Ector	
Kinney			0.5				Fr	Divot (Frio) Clay Soils, occasionally flooded	Divot (Frio)	

County	Numbers of Occupied Soils by Data Source						Map Unit Symbol	Description	Major Soils in Map Unit	
	Private Survey 1	Private Survey 2	TXNDD	TxDOT	LCRA	USFWS PFW			A	B
Kinney			0.5				Kc	Kavett-Tarrant Stony-Clay Complex, 8-20% slopes	Kavett	Tarrant
Kinney			2.5				Kh	Olmos soils, 0-2% slopes	Olmos	
Kinney			8				Lr	Rock Outcrop-Ector, 20-70% slopes	Rock	Ector
Kinney			2.5				Tr	Tarrant-Rock Outcrop Complex, 8-20%	Tarrant	Rock
Real			1.33				DeB	Dev-Riverwash Complex, 0-3% slopes, frequently flooded	Dev	Riverwash
Real			0	1			DnD	Dina-Eckrant Complex, 1-8% slopes	Dina	Eckrant
Real			1.5	3			EcF	Eckrant-Rock Outcrop Complex, 1-20% slopes	Eckrant	Rock
Real			2.5	1			EcG	Eckrant-Rock Outcrop Complex, 20-60% slopes	Eckrant	Rock
Real			0	2			LkB	Leakey Silty Clay Loam, 1-3% slopes	Leakey	
Real			1.33				MmC	Mailtrail-Mereta Complex, 0-5% slopes	Mailtrail	Mereta
Real			0.33				RaF	Real-Oplin Complex, 1-20% slopes	Real	Oplin
Uvalde			0.5				ERE	Ector Soils and Rock Outcrop, hilly	Ector	Rock
Uvalde			0.5				LS	Rock Outcrop-Ector, steep	Rock	Ector
Uvalde			1				PrB	Pratley Clay, 0-3% slopes	Pratley	
Val Verde	9.5		0				DE	Dev soils, frequently flooded	Dev	
Val Verde	98		5.5				ERF	Ector-Rock Outcrop Association, hilly	Ector	Rock
Val Verde	71		7.5				ERG	Ector-Rock Outcrop Association, very steep	Ector	Rock
Val Verde	2		4				OmD	Olmos Very Gravelly Loam, 1-8% slope	Olmos	
Val Verde	0.5		0				Rv	Riverwash and Dev Soils, frequently flooded	Riverwash	Dev
Val Verde	63		0				TAD	Tarrant Association, undulating	Tarrant	
Totals:	244	133	91	20	19	4				

Figure B1. Occupied Soils of Tobusch Fishhook Cactus Sites.

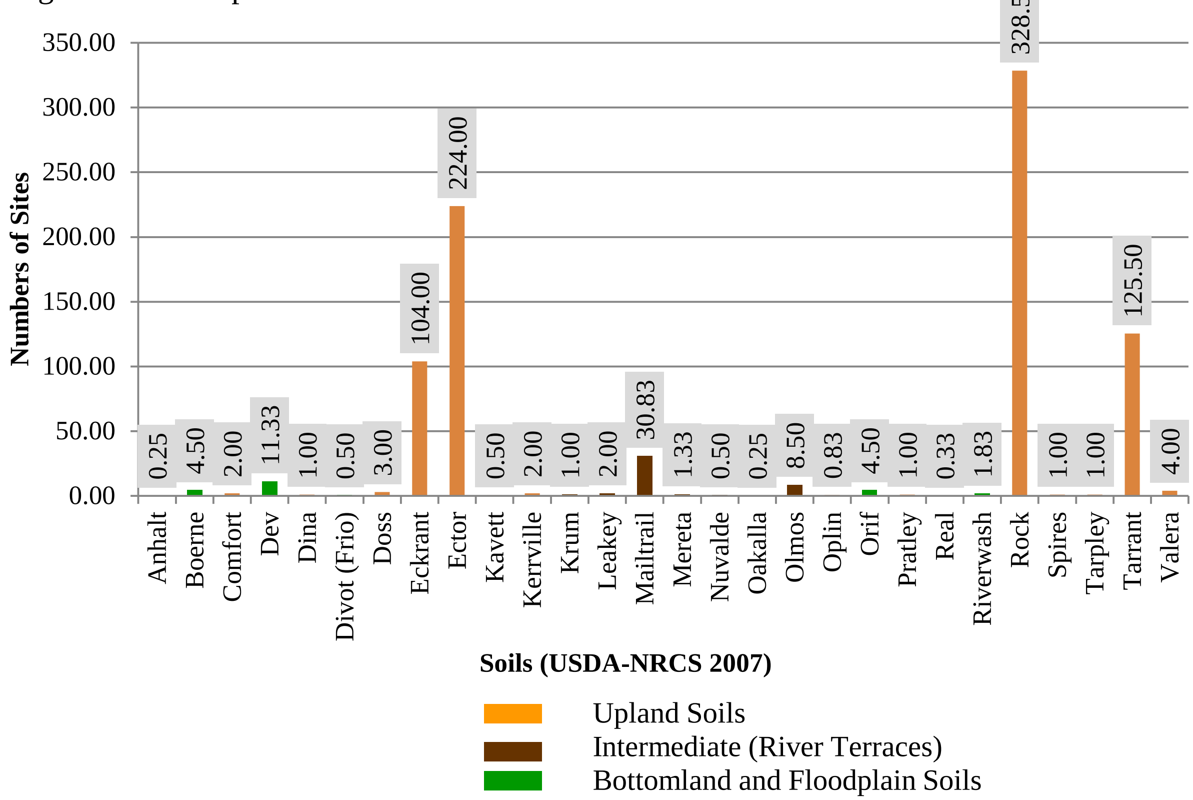


Table B.2. Summary of occupied soils of Tobusch fishhook cactus.

Soil Topography	Number of Occurrences	Percent of Occurrences
Uplands	798.9	92
Intermediate (terraces and upper valleys)	44.2	5
Bottomlands and floodplains	22.9	3
Total:	866	100

Table B.3. Most frequently occupied soils of Tobusch fishhook cactus (n = 866).

Soil	Number	Percent
Rock	328.5	37.9
Ector	224.0	25.8
Tarrant	125.5	14.5
Eckrant	104	12.0
Total:	782	90.2

Descriptions of soils listed in Table B.3 (adapted from USDA Natural Resources Conservation Service and Texas AgriLife Research 2000).

Ector: (p. 127). Very shallow and shallow, well-drained, convex, low hills, ridges, summits, shoulders, and slopes. Elevations range from 488 to 838 m (1,600 to 2,750 ft). Slopes range from 1 to 40 percent. Parent material is loamy residuum weathered from limestone. Taxonomic class is loamy-skeletal, carbonatic, thermic Lithic Calciustolls. Typical profile: Surface layer 0 to 8 inches deep, moderately alkaline, dark grayish brown, very cobbly clay loam; subsoil is 8 to 15 inches deep, moderately fractured limestone; underlying material is 15 to 60 inches deep, indurated, coarsely fractured limestone bedrock. Depth to limestone bedrock ranges from 6 to 20 inches. Limestone fragments range from 35 to 80 percent.

Eckrant Series: (pp. 125-126). Very shallow and shallow, well drained, convex ridges, shoulders, and slopes. Elevations range from 305 to 732 m (1000 to 2,400 ft). Slopes range from 0 to 60 percent. Parent material is residuum weathered from limestone. Taxonomic class is clayey-skeletal, smectitic, thermic Lithic Haplustolls. Typical soil profile: Organic layer 0 to 2 inches deep, composed of decomposing juniper and mountain laurel leaves. Surface layer 2 to 11 inches deep, neutral to moderately alkaline, very dark gray, very cobbly silty clay. Underlying material 11 to 80 inches deep, light brownish gray indurated limestone bedrock. Depth of solum to limestone ranges from 4 to 20 inches. Coarse limestone fragments comprise 35 to 80 percent by volume.

Tarrant Series (pp. 153-154): Very shallow and shallow, well-drained undulating plains. Parent material is residuum weathered from limestone. Elevations range from 305 to 732 m (1,000 to 2,400 ft). Slopes range from 0 to 5 percent. Taxonomic class is clayey-skeletal, smectitic, thermic Lithic Calciustolls. Typical profile: Surface layer is 0 to 7 inches deep, moderately alkaline, very dark grayish brown, 45 percent limestone fragments; subsoil is 7 to 15 inches deep, brown, moderately alkaline, 55 percent limestone fragments; underlying material is 15 to 80 inches deep, indurated limestone bedrock; depth of solum to bedrock ranges from 6 to 20 inches, and contains 35 to 85 percent coarse limestone fragments.

Rock: Early Cretaceous limestone and dolostone strata, primarily of the Edwards, Glen Rose, Devils River, and Salmon Peak formations (U.S. Geological Survey 2007).

Discussion. In addition to the relatively large geographic buffers of the EO representations, specific soils rarely have sharply defined boundaries, but most often merge or intergrade with neighboring soils; hence, the geographic delimitations of soil map units are approximate. Furthermore, soil map units may include two or more major soils that are mapped together. These factors introduce uncertainty regarding the actual soils occupied by Tobusch fishhook cactus populations. Fortunately, the large number of reported sites helps distinguish this species' actual soil affinities from the "noise" created by the lack of geographic precision. The 511 sites occur in 866 mapped soil units comprising 28 different soils. However, 92 percent of occurrences intercepted upland soils, and another 5 percent are intermediate in topographic position. The four most frequent soils, bare rock, Ector, Tarrant, and Eckrant, occur at more than 90 percent of reported sites. These data confirm that Tobusch fishhook cactus is predominantly an upland species of Ector, Tarrant, Eckrant, and similar soils, and is closely associated with rock outcrops. Furthermore, it is likely that the relatively few sites reported from bottomlands and intermediate topographic positions actually occur in or near small outcrops of limestone strata included in these map units. This hypothesis is supported by the site descriptions of EOs in the TXNDD; of 26 EOs that we identified in bottomland or intermediate soils, 19 contain site descriptions, and all but one clearly describes an association with limestone bedrock or other limestone features (TXNDD 2016; see Table B.4.).

Table B.4. Site descriptions of Element Occurrences reported from bottomland and intermediate (terrace) soils (TXNDD 2016).

EO	Map Units	Site Description
2	OKX	Rocky limestone floodplain; live-oak-juniper woodland; with *Juniperus ashei*, *Quercus fusiformis*, *Platanus occidentalis*, *Schizachyrium scoparium*, *Yucca rupicola*, *Baccharis* spp.
13	De	First terrace north of river; limestone rockland; live oak-juniper woodland; with *Juniperus ashei*, *Quercus fusiformis*, *Berberis trifoliolata*, *Schizachyrium scoparium*.
14	OKX	Rocky limestone floodplain; live oak-juniper woodland; with *Juniperus ashei*, *Yucca rupicola*, *Opuntia lindheimeri*, *Quercus fusiformis*, *Bouteloua* sp., *Carex planostachys*
17	OKX	Coarse limestone alluvial stream terrace between perennial river and live oak-juniper woodland, being invaded my mid-grasses; associates include *Bouteloua trifida*, *Quercus fusiformis*, *Aristida* sp., *Schizachyrium scoparium*, *Diospyros texana*, *Nostoc* sp., *Stipa leucotricha*, *Bothriochloa ischaemum*, *Salvia farinacea*, *Juniperus ashei*, *Chaetopappa* sp., *Phyllanthus polygonoides*, *Berberis trifoliolata*, *Verbena neomexicana*, *Senna lindheimeri*, *Cenchrus incertus*, *Lygodesma texana*, *Tragia* sp., and *Oxalis dillenii*.
19	OmD	(No description)
22	ND, OKX	Limestone gravel floodplain; open with scattered vegetation; sycamore-little walnut woodland; associated species include *Platanus occidentalis*, *Juglans microcarpa*, *Juniperus ashei*, *Thelesperma* sp., *Indigofera suffruticosa*, *Evolvulus sericeus*, *Opuntia lindheimeri*, *Hedeoma drummondii*, *Parthenium hysterophorus*, *Eragrostis* sp., *Verbena bipinnatifida*, *Phyllanthus polygonoides*, *Brickellia* sp., *Thamnosma texana*, *Aristida* sp., *Aphanostephus* sp.
27	MaD	Live oak motte on small hilltop amidst lower slopes; thin, rocky, clayey limestone-derived soils.
41	MaD	Live oak-juniper woodland; south-facing, lower slope (ca. 10 degrees); limestone bedrock covered by gravel and rock platelets with patches of spikemoss and very shallow dark brown clayey soils.
47	MaD	Pine-oak-juniper woodland, almost level, thin clay soil over limestone gravel and bedrock; with *Juniperus ashei*, *Pinus remota*, *Quercus fusiformis*, *Opuntia lindheimeri*, *Karwinskia humboldtiana*, *Berberis trifoliolata*, *Condalia spathulata*, *Diospyros texana*, *Sophora secundiflora*.
48	MaD	(No description)

51	OmD	Slopes of 0 to 10 degrees; gravelly clay soil with stones and cobbles covering 50% of surface; cenizo-guajillo shrubland with Selaginella openings; see site F in report in GMF.
57	OmD	Selaginella-covered limestone bedrock with shallow clay soil pockets; shrubland.
69	OKX	Very rocky (limestone) floodplain with thin clay soils; grassland with clumped scattered shrubs (Plateau live oak-midgrass series); with *Quercus fusiformis*, *Juniperus ashei*, *Schizachyrium scoparium*, *Berberis trifoliolata*, *Aristida* sp., *Mimosa biuncifera*, *Yucca rupicola*, *Bothriochloa barbinodis*, *Sophora secundiflora*, *Diospyros texana*.
71	Km	Juniper-invaded Texas oak woodland; thin brown soil over gravelly limestone on gentle (5 degree) northeast facing slope in openings with full or partial sun with *Juniperus ashei*, *Quercus buckleyi*, *Sophora secundiflora*, *Carex planostachya*, *Schizachyrium scoparium*, *Erioneuron pilosum*, crustose lichens, and moss.
74	Fr	Upland site is a grassland dominated by *Muhlenbergia dubia*; east-facing, gently sloping (0-5 degrees), gravelly limestone rockland ridgetop; with *Muhlenbergia dubia*, *Aristida* sp., *Erioneuron pilosum*, *Carex planostachys*, *Diospyros texana*, *Lesquerella* sp., *Anemone heterophylla*, *Sophora secundiflora*, *Chaetopappa* sp., *Coryphantha similis*, *Echinocereus reichenbachii*, *Cooperia drummondii*, *Evax* sp., *Astragalus nuttallianus*, *Opuntia lindheimeri*, *Juniperus ashei*, *Plantago rhodosperma*, *Nostoc* sp., *Berberis trifoliolata*, *Pinaropappus roseus*, *Scutellaria drummondii*; floodplain site is a semi-natural transition between an old field and the wooded creek bank, gravelly limestone terrace with thin clay soils, with *Bothriochloa ischaemum* var. *songarica*, *Quercus fusiformis*, *Berberis trifoliolata*, *Carex planostachys*, *Lithospermum incisum*, *Nothoscordum bivalve*, and *Scutellaria drummondii*.
77	MmC	Limestone outcrop in mowed grass of highway right-of-way.
82	Kh	Live oak-juniper woodland; level floodplain terrace.
83	Fr	(No description)
84	Kh	(No description)
85	Kh	Opening within live oak-juniper woodland; gentle (5 degrees), east-facing, lower slope; gravelly, thin, clayey soils over limestone bedrock; lots of exposed bedrock; with *Selaginella wrightii*, *Aristida purpurea*, *Berberis trifoliolata*, *Condalia spathulata*, *Karwinskia humboldtiana*, *Juniperus ashei*, *Quercus fusiformis*, *Pinus remota*.
89	MaD	Live oak-juniper woodland with rocky, grassy openings; level floodplain terrace with shallow, gravelly, clayey soils over limestone bedrock; with *Quercus fusiformis*, *Juniperus ashei*, *Berberis trifoliolata*, *Diospyros texana*, *Karwinskia humboldtiana*.
90	MaD	Rocky and grassy openings within live oak-juniper woodland; level, floodplain terrace; shallow, rocky, clayey soils over limestone bedrock; with *Quercus fusiformis*, *Juniperus ashei*, *Selaginella wrightii*, *Bothriochloa barbinodis*, *Aristida purpurea*, *Erioneuron pilosum*, *Berberis trifoliolata*, *Opuntia lindheimeri*, *Diospyros texana*, *Karwinskia humboldtiana*.

91	MaD	Live oak-juniper woodland; gentle (5 degree), east-facing lower slope; exposed limestone bedrock with spikemoss, gravel, and thin clayey soil; with *Selaginella wrightii*, *Juniperus ashei*, *Quercus fusiformis*, *Diospyros texana*, *Berberis trioliolata*, *Aristida purpurea*, *Erioneuron pilosum*, *Karwinskia humboldtiana*.
93	MaD	(No description)
108	DeB, MmC	(No description)
113	OmD	(No description)

2.2. Development of Tobusch fishhook cactus potential habitat model from soil and watershed data.

Tobusch fishhook cactus has now been documented in hundreds of sites spanning its known range. Nevertheless, these surveys were limited to public lands, such as state parks and highway rights-of-way, and sites of development projects where surveys were conducted in conjunction with section 7 consultation with USFWS. Within the species' range, there are large gaps where no surveys have been conducted. We assume that a named soil that has documented populations in one county may also support populations in other counties. Figure B.2 shows the geographic extent of all upland soils that have at least one documented population of Tobusch fishhook cactus.

The named soils that support Tobusch fishhook cactus extend well beyond the counties where the species is currently known, but we do not know how far the range actually extends. We assume that natural geographic features more accurately reflect the species' range than county limits. Birds or small mammals are the probable longer-distance dispersers of Tobusch fishhook cactus seeds (Emmett 1995, p. pp. 115-116, 126), and honeybees and halictid bees are primary pollinators (Lockwood 1995, pp. 428-430; Emmett 1995, pp. 74-75; Reemts and Becraft 2013, pp. 6-7; Langley 2015, pp. 21-23, 29-30). We hypothesize that the forage ranges and habitats of birds, small mammals, and bees, and therefore seed dispersal and gene flow of Tobusch fishhook cactus, are probably more frequent within watersheds than between watersheds. For these reasons, we have chosen occupied watersheds as a first approximation of the range extent of Tobusch fishhook cactus; if at least one population is documented in a watershed, we assume that the species may occur in suitable soils throughout that watershed. We identified 22 10-digit hydrologic units (USDA-NRCS 1999-Present) where populations have been documented (Table B5). For a description of hydrologic unit delineation and use, see https://www.nrcs.usda.gov/wps/portal/nrcs/main/national/water/watersheds/dataset/.

We have also provisionally included 4 hydrologic units that are between two or more occupied watersheds, where Tobusch fishhook cactus has yet to be documented, but is likely to be present (Table B6). Figure B3 shows these occupied and probable watersheds.

Table B5. Watersheds (hydrologic units) where Tobusch fishhook cactus populations have been documented (Hydrologic Units delineated in USDA-NRCS 1999-Present).

County	Population / Area	HU10 Name	HU10DS	HU12 Name	HU12DS
Bandera	TXNDD EOs	North Prong Medina River	1210030202	Headwaters North Prong Medina River	121003020102
Bandera	TXNDD EOs	Upper Sabinal River	1211010607	Evans Creek - Mill Creek	121101060603
Bandera	TXNDD EOs	Upper Sabinal River	1211010607	Brushy Creek - Sabinal River	121101060603
Bandera	TXNDD EOs	Upper Sabinal River	1211010607	Long Hollow - Sabinal River	121101060605
Bandera	Washington Springs	Upper Sabinal River	1211010607	West Sabinal River	121101060605
Bandera	Washington Springs	Upper Sabinal River	1211010607	Long Hollow - Sabinal River	121101060605
Bandera	TXNDD EOs	Upper Sabinal River	1211010607	Little Creek - Sabinal River	121101060606
Edwards	Private Survey 2	Headwaters West Nueces River	1211010202	Geronimo Creek - West Nueces River	121101020104
Edwards	Private Survey 2	Headwaters West Nueces River	1211010202	Little Hackberry Draw - West Nueces River	121101020105
Edwards	Private Survey 2	Headwaters West Nueces River	1211010202	5-Mile Draw - West Nueces River	121101020203
Edwards	Private Survey 2	Lower Dry Devils River	1304030203	Upper Mail Trail Creek	130403030402
Edwards	Private Survey 2	Buffalo Draw	1304030304	Wittenburg Draw	130403030204
Edwards	Private Survey 2	Red Bluff Creek	1304030304	Riggs Draw - Red Bluff Creek	130403030302
Edwards	Private Survey 2	West Fork Sycamore Creek - Sycamore Creek	1308000103	Sycamore Creek	130800010203
Kerr	LCRA CREZ Survey	Johnson Fork	1209020402	Headwaters Johnson Fork	120902040102
Kerr	TXNDD EOs	Johnson Fork	1209020402	Headwaters Johnson Fork	120902040102
Kerr	TXNDD EOs	Turtle Creek - Guadalupe River	1210020103	Quinlan Creek - Guadalupe River	121001010103

County	Population / Area	HU10 Name	HU10DS	HU12 Name	HU12DS
Kerr	TXNDD EOs	Turtle Creek - Guadalupe River	1210020103	Goat Creek - Guadalupe River	121002010203
Kimble	LCRA CREZ Survey	Middle North Llano River	1209020203	Lower West Copperas Creek	120902020206
Kimble	LCRA CREZ Survey	Middle North Llano River	1209020203	East Copperas Creek - Copperas Creek	120902020207
Kimble	LCRA CREZ Survey	Lower South Llano River	1209020402	Cedar Creek	120902030405
Kimble	LCRA CREZ Survey	Johnson Fork	1209020402	Lower Mudge Draw	120902040107
Kimble	LCRA CREZ Survey	Johnson Fork	1209020402	Joy Creek - Johnson Fork	120902040108
Kimble	LCRA CREZ Survey	Johnson Fork	1209020402	Sycamore Creek - Johnson Fork	120902040201
Kimble	TXNDD EOs	Johnson Fork	1209020402	Sycamore Creek - Johnson Fork	120902040201
Kimble	TXNDD EOs	Lower South Llano River	1209020402	Joy Creek - South Llano River	120902040201
Kimble	LCRA CREZ Survey	Big Saline Creek - Llano River	1209020403	The Bogs - Llano River	120902040203
Kimble	TxDOT ROWs	Big Saline Creek - Llano River	1209020403	Gentry Creek	120902040203
Kimble	TxDOT ROWs	Big Saline Creek - Llano River	1209020403	The Bogs - Llano River	120902040203
Kimble	TXNDD EOs	Big Saline Creek - Llano River	1209020403	The Bogs - Llano River	120902040203
Kinney	TXNDD EOs	East Prong Nueces River	1211010103	Upper Hackberry Creek	121101010102
Kinney	TxDOT ROWs	East Prong Nueces River	1211010103	Lower Hackberry Creek	121101010301
Kinney	TXNDD EOs	Middle West Nueces River	1211010204	Griffin Creek - West Nueces River	121101020305
Kinney	TXNDD EOs	Upper West Nueces River	1211010203	Cherry Creek - West Nueces River	121101020304

County	Population / Area	HU10 Name	HU10DS	HU12 Name	HU12DS
Kinney	Private Survey 2	West Fork Sycamore Creek - Sycamore Creek	1308000103	Headwaters Sycamore Creek	130800010202
Kinney	TXNDD EOs	Sacatosa Creek - Sycamore Creek	1308000105	Upper East Fork Sycamore Creek	130800010304
Kinney	TXNDD EOs	Pinto Creek	1308000105	Headwaters Pinto Creek	130800010402
Real	TXNDD EOs	East Prong Nueces River	1211010103	Lower East Prong Nueces River	121101010301
Real	TXNDD EOs	Headwaters Nueces River	1211010104	Dry Creel - Nueces River	121101010305
Real	TxDOT ROWs	West Frio River	1211010602	Short Prong West Frio River	121101060103
Real	TxDOT ROWs	West Frio River	1211010602	Middle West Frio River	121101060105
Real	TXNDD EOs	West Frio River	1211010602	Middle West Frio River	121101060105
Real	TXNDD EOs	West Frio River	1211010602	Upper East Frio River	121101060107
Real	TXNDD EOs	West Frio River	1211010602	Lower West Frio River	121101060201
Real	TXNDD EOs	West Frio River	1211010602	Lower East Frio River	121101060201
Uvalde	TXNDD EOs	Montell Creek - Nueces River	1211010301	French Creek - Nueces River	121101010406
Uvalde	TXNDD EOs	Headwaters Frio River	1211010604	Cherry Creek - Frio River	121101060204
Val Verde	Private Survey 1	Dry Devils River - Devils River	1304030111	Lower Buckley Draw	130403010809
Val Verde	Private Survey 1	Dolan Creek - Devils River	1304030203	Fawcett Ranch - Middle Dolan Creek	130403020203
Val Verde	Private Survey 1	Dolan Creek - Devils River	1304030203	Upper Dolan Creek	130403020204
Val Verde	Private Survey 1	Deaton Draw - Devils River	1304030203	Blue Springs - Devils River	130403020301
Val Verde	Private Survey 1	Dolan Creek - Devils River	1304030203	Lower Dolan Creek	130403020301
Val Verde	Private Survey 1	Lower Dry Devils River	1304030203	Cedar Draw - Dry Devils River	130403020302

County	Population / Area	HU10 Name	HU10DS	HU12 Name	HU12DS
Val Verde	TXNDD EOs	Lower Dry Devils River	1304030203	Vinegarone Draw - Dry Devils River	130403030404
Val Verde	Private Survey 1	Lower Dry Devils River	1304030203	Open Hollow - Dry Devils River	130403030405
Val Verde	TXNDD EOs	Devils River - Amistad Reservoir	1304030204	Indian Creek - Devils River	130403020302
Val Verde	TXNDD EOs	Devils River - Amistad Reservoir	1304030204	Dark Canyon - Devils River	130403020304
Val Verde	Private Survey 1	Devils River - Amistad Reservoir	1304030204	Big Satan Creek - Amistad Reservoir	130403020401
Val Verde	TXNDD EOs	Lower Dry Devils River	1304030203	Cedar Draw - Dry Devils River	130403020302
Val Verde	Private Survey 1	Red Bluff Creek	1304030304	Miers Draw - Red Bluff Creek	130403030304
Val Verde	TXNDD EOs	Red Bluff Creek	1304030304	Miers Draw - Red Bluff Creek	130403030304
Val Verde	Private Survey 1	Red Bluff Creek	1304030304	Carruthers Draw	130403030305
Val Verde	Private Survey 1	Red Bluff Creek	1304030304	Glenn Spring - Red Bluff Creek	130403030405
Val Verde	Private Survey 1	West Fork Sycamore Creek - Sycamore Creek	1308000103	Lower West Fork Sycamore Creek	130800010206

Table B6. Watersheds (hydrologic units) where Tobusch fishhook cactus populations have not been documented, but are likely to occur. (Hydrologic units delineated in USDA-NRCS 1999-Present).

Counties	HU10 Name	HU10DS
Edwards, Real, Kerr, Kimble	Paint Creek	1209020304
Edwards, Sutton, Kimble	Upper South Llano River	1209020302
Sutton	Upper North Llano River	1209020202
Sutton, Edwards	Halbert Draw – Dry Devils River	1304030107

Finally, in ArcGIS 10.3.2, we used the Intersect tool to create new shapefiles consisting of areas that had occupied soils that occur within occupied (and likely occupied) 10-digit hydrologic units (Figure B4). In addition to the 8 counties where populations have been identified, this model predicts that potential habitat could extend into 6 adjacent counties (Crockett, Gillespie, Kendall, Menard, Sutton, and a miniscule area of Mason county). This predicted range extension adds 272,785 ha (674,051 ac) of potential habitat, comprising 13 percent of the total estimated habitat.

The largest amounts of predicted habitat extension are in Sutton and Crockett counties (Table B7). However, we emphasize that no Tobusch fishhook cactus populations have yet been found in these additional counties.

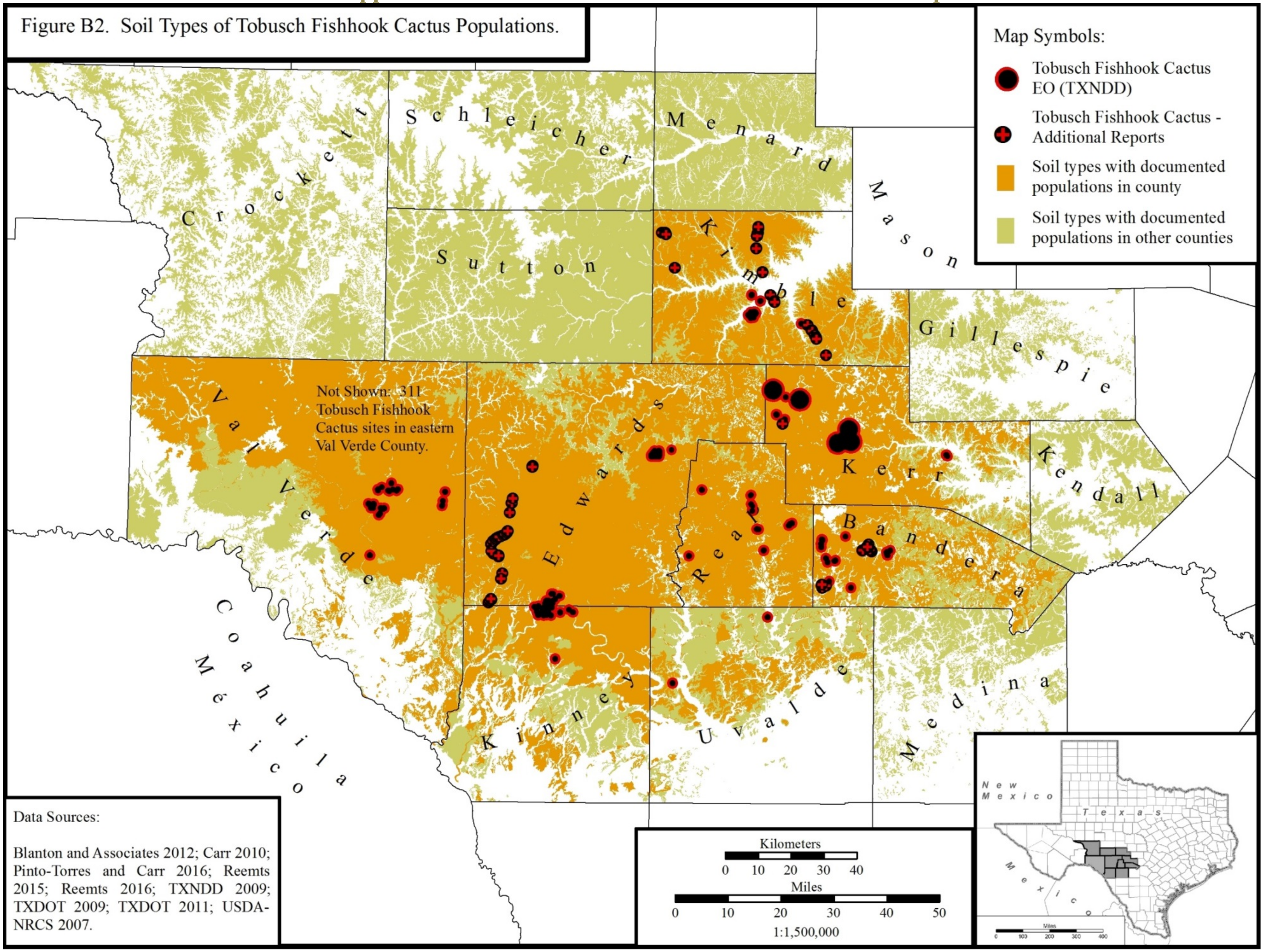
Table B7. Estimated Tobusch fishhook cactus potential habitat.

County	Range	Hectares	Acres	Percent of Total
Bandera	Known	73,504.4	181,629.4	3.6
Edwards	Known	520,615.8	1,286,441.6	25.5
Kerr	Known	208,726.1	515,762.2	10.2
Kimble	Known	206,122.3	509,328.2	10.1
Kinney	Known	149,157.4	368,567.9	7.3
Real	Known	169,257.6	418,235.5	8.3
Uvalde	Known	107,121.4	264,697.0	5.2
Val Verde	Known	336,679.7	831,935.5	16.5
Sub-Total	Known	1,771,184.7	4,376,597.4	86.7
Crockett	Predicted	54,505.5	134,683.1	2.7
Gillespie	Predicted	5,634.7	13,923.3	0.3
Kendall	Predicted	2,478.2	6,123.6	0.1
Mason	Predicted	1.7	4.2	0.0
Medina	Predicted	0.0	0.0	0.0
Menard	Predicted	10,076.5	24,899.0	0.5
Schleicher	Predicted	0.0	0.0	0.0
Sutton	Predicted	200,088.2	494,417.9	9.8
Sub-Total	Predicted	272,784.8	674,051.2	13.3
TOTAL*		2,043,972	5,050,655	100.0

* The totals are slightly greater than column sums due to rounding of digits.

Discussion: Habitat modelling for Tobusch fishhook cactus would be more precise if it could be based directly on the amount of exposed limestone outcrop, rather than the soil map units where these outcrops occur. This could be accomplished through electronic classification of digitized aerial images, provided that the resolution is fine enough to detect the small size of habitat microsites (0.05 ha (0.12 ac) or less). Spatial analysis based on the amount of exposed limestone could help identify areas with higher concentrations of potential habitat, and would provide an important tool for prioritizing conservation areas. More sophisticated habitat modelling could also be accomplished with additional data collected directly from occupied sites, such as the actual local soil, vegetative cover, slope, elevation, or other features. Nevertheless, the habitat modelling we present here is based on the best currently available data, and is an improvement over range estimates based solely on occupied counties.

Figure B2. Soil Types of Tobusch Fishhook Cactus Populations.



Data Sources:

Blanton and Associates 2012; Carr 2010; Pinto-Torres and Carr 2016; Reemts 2015; Reemts 2016; TXNDD 2009; TXDOT 2009; TXDOT 2011; USDA-NRCS 2007.

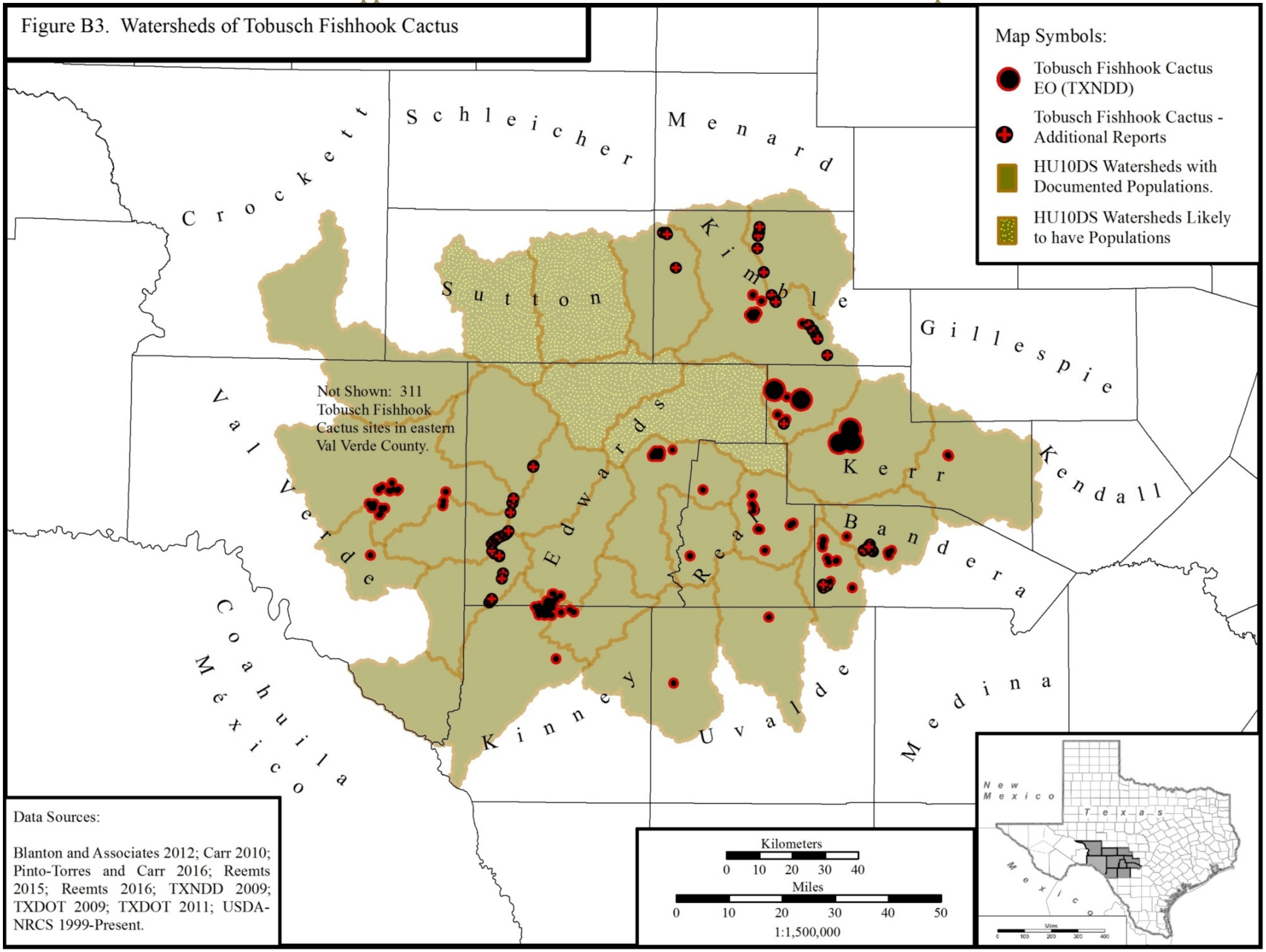
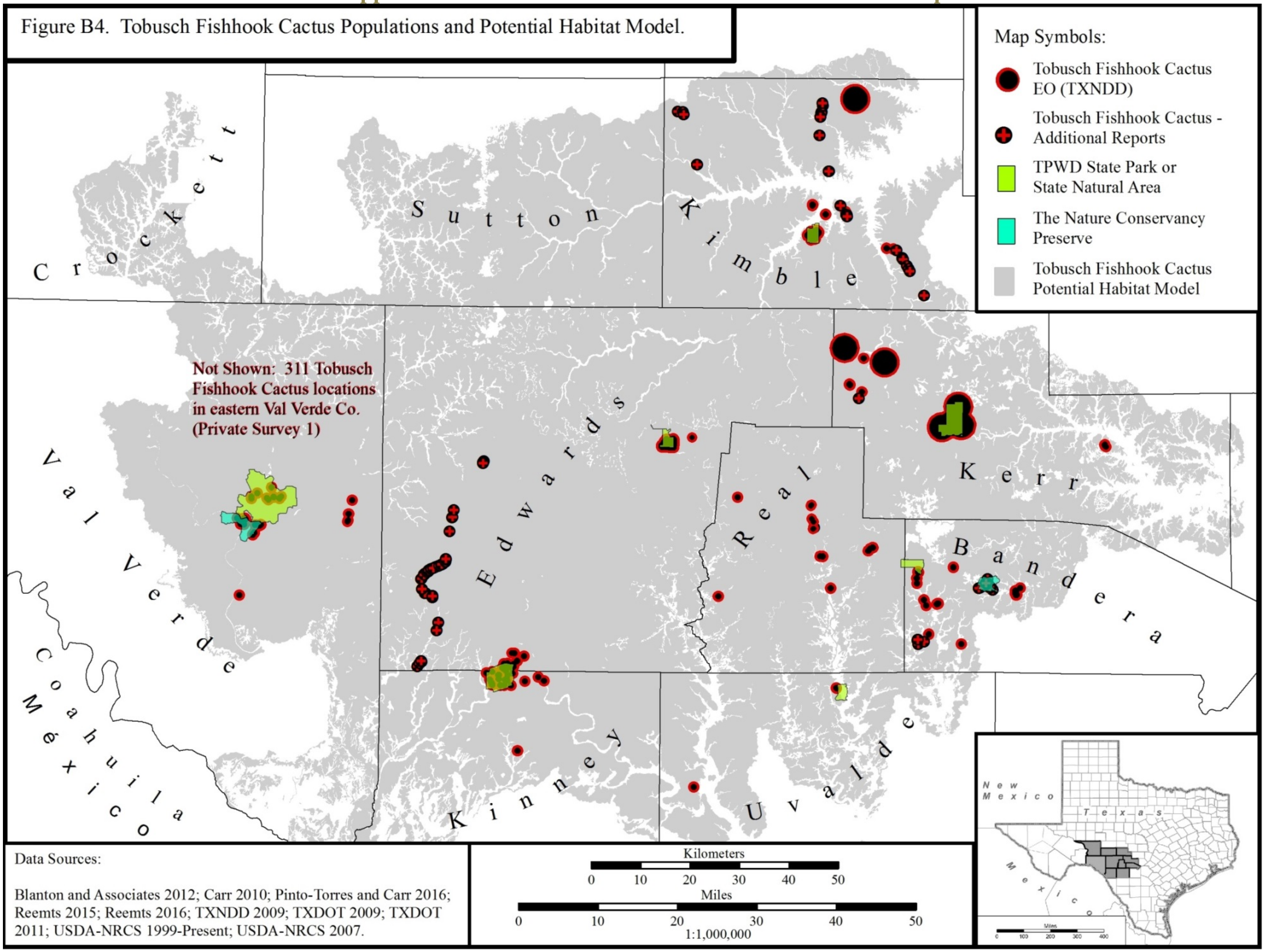


Figure B3. Watersheds of Tobusch Fishhook Cactus
Map Symbols:
Tobusch Fishhook Cactus EO (TXNDD)
Tobusch Fishhook Cactus - Additional Reports
HU10DS Watersheds with Documented Populations.
HU10DS Watersheds Likely to have Populations
Crockett
Schleicher
Menard
Sutton
Kimble
Gillespie
Val Verde
Edwards
Kerr
Kendall
Real
Bandera
Kinney
Uvalde
Medina
Coahuila México
Not Shown: 311 Tobusch Fishhook Cactus sites in eastern Val Verde County.
Data Sources:
Blanton and Associates 2012; Carr 2010; Pinto-Torres and Carr 2016; Reemts 2015; Reemts 2016; TXNDD 2009; TXDOT 2009; TXDOT 2011; USDA-NRCS 1999-Present.
Kilometers
0 10 20 30 40
Miles
0 10 20 30 40 50
1:1,500,000
New Mexico
Texas
Mexico

Figure B4. Tobusch Fishhook Cactus Populations and Potential Habitat Model.



3. Estimate of the global population size of Tobusch fishhook cactus.

3.1. Quantitative surveys for Tobusch fishhook cactus.

We received the following quantitative surveys for Tobusch fishhook cactus from the sources indicated. We describe below how we determined the population densities from each survey; in order to extrapolate these population densities to the entire potential habitat model, it is necessary to determine the amount of potential habitat covered by each survey. Except as indicated (the LCRA survey in section 3.1.3), we did this by intercepting shapefiles of each survey area with the potential habitat shapefile described in section 2.2.

3.1.1. Tobusch fishhook cactus surveys along Texas Department of Transportation highway rights-of-way.

TxDOT provided the surveys used here, which included geographic data of the ROW segments surveyed and the locations and numbers of Tobusch fishhook cactus detected. These surveys attempted to detect all individuals within the surveyed areas. We calculated the lengths of potential habitat intercepted by the surveyed segments using the Intercept tool in ArcGIS 10.3.1. We estimated the net widths of each survey segment, based on the average of 5 or more measurements of the apparent right-of-way widths observed in 1-m resolution digital ortho quarter-quad (DOQQ) aerial photographs. The habitat area surveyed is the product of habitat length intercepted multiplied by net survey width.

Table B8. Tobusch fishhook cactus surveys along Texas Department of Transportation highway rights-of-way (TxDOT 2009; TxDOT 2011; Pinto-Torres and Carr 2016).

Survey Segment	Survey Length (m)	Surveyed Habitat Length (m)	Net Survey Width (m)	Habitat Area Surveyed (ha)	Number Detected	Number per Hectare
US83_S1	12,421	12,259	24.1	29.54	1	0.03
RM336_S1	630	631	21.3	1.35	14	10.40
RM336_S2	569	569	21.3	1.21	0	0.00
RM336_S3	380	380	21.3	0.81	0	0.00
RM336_S4	1,332	1,332	21.3	2.84	10	3.52
RM336_S5	2,147	2,147	21.3	4.58	65	14.19
RM336_S6	1,994	1,995	21.3	4.26	0	0.00
RM337_S1	10,322	10,322	23.2	24.00	0	0.00
RM337_S2	6,021	3,963	22.7	9.00	0	0.00
RM335_S1	710	633	21.6	1.36	0	0.00
RM335_S2	5,717	5,625	21.6	12.13	37	3.05
US83_S2	23,132	19,434	21.8	42.30	23	0.54
TOTALS	65,375	59,290		133.37	150	1.12

3.1.2. Privately-funded surveys of Tobusch fishhook cactus associated with development projects.

SWCA Environmental Consultants provided geographic data of the sites surveyed and locations and numbers of Tobusch fishhook cactus detected in these private surveys. These surveys attempted to detect all individuals within the surveyed areas. We calculated the amount of potential habitat area intercepted by the surveys using the Intercept tool in ArcGIS 10.3.1. Note that all Tobusch fishhook cactus detected were removed from project sites prior to construction and were donated to Lady Bird Johnson Wildflower Center for use in scientific studies and reintroduction into appropriate habitats.

Table B9. Privately-funded surveys of Tobusch fishhook cactus associated with development projects (SWCA Environmental Consultants 2012, 2013, 2016).

Survey	Survey Length (km)	Surveyed Habitat Length (km)	Survey Width (m)	Habitat Area Surveyed (ha)	Number Detected	Number per Hectare
Private Survey 1	79.6	±78.1	60.1	469.70	311	0.66
Private Survey 2	130.1	104.07	22.86	237.91	113	0.47
TOTALS:				707.61	424	0.60

3.1.3. Tobusch fishhook cactus surveys of tower construction sites for an LCRA electric power transmission line.

LCRA provided the survey, conducted by Blanton and Associates, and geographic data of the locations and numbers of Tobusch fishhook cactus detected. These surveys attempted to detect all individuals within the surveyed areas. However, we did not receive geographic data of the tower sites locations. Hence, we were not able to determine the amount of habitat intercepted by the surveys. However, the surveyors visually inspected the 490 tower sites and determined that 208 had potential habitat; due to access restrictions, they were only able to survey 195 sites. For the purpose of estimating population density and size, we assume that all 195 survey sites consisted of potential habitat.

Table B10. Tobusch fishhook cactus surveys of tower construction sites for an LCRA electric power transmission line (Blanton and Associates 2012)

Survey	Survey Radius (m)	No. Surveys	Habitat Area Surveyed (ha)	Number Detected	Number per Hectare
LCRA	45.72	195	128.06	86	0.67

3.1.4. Tobusch fishhook cactus surveys of protected natural areas.

The numbers of Tobusch fishhook cactus summarized here were detected in long-term monitoring plots (Poole and Birnbaum 2003; Poole 2009) and ongoing research at Love Creek Preserve (Reemts 2014, 2016). The site areas are the total property sizes of each protected natural area, and the habitat area surveyed is the amount of potential habitat within each property. However, since the numbers of Tobusch fishhook cactus reported here are from fixed plots, and are not exhaustive surveys of the entire properties, the actual population sizes and densities may be larger.

Table B11. Tobusch fishhook cactus surveys of protected natural areas (Poole and Birnbaum 2003; Poole 2009; Reemts 2015, 2016).

Site Name	Survey Year	Site Area (ha)	Habitat Area Surveyed (ha)	Number Detected	Number per Hectare
Coto los Rincones (TLC)[1]	2003	55.04	52.18	84	1.61
Devils River SNA (TPWD)	2003	8,032.90	8,020.80	17	0.00
Devil's Sinkhole SNA (TPWD)	2008	754.00	754.10	34	0.05
Dolan Falls Preserve (TNC)	1992	2,005.60	1,962.60	100	0.05
Garner SP (TPWD)	2008	612.20	163.10	755	4.63
Kerr WMA (TPWD)	2008	2,613.10	2,393.70	1,090	0.46
Kickapoo Caverns SP (TPWD)	2008	2,577.30	2,460.10	217	0.09
Lost Maples SP (TPWD)	2008	879.40	879.40	299	0.34
Love Creek Preserve (TNC)	2015	1,011.95	962.70	1035	1.08
Walter Buck WMA (TPWD)	2008	872.30	810.20	205	0.25
Totals:		19,413.79	18,458.88	3,836	0.21

1. Habitat area estimated as average percent habitat/site area of the other 9 areas.

3.2. Summary of quantitative surveys of Tobusch fishhook cactus and extrapolated total population size.

Table B12 totals the amount of habitat area surveyed and number of Tobusch fishhook cactus detected in all 25 surveys described in section 3.1. The estimated total population is calculated as the total estimated potential habitat multiplied by the average population density.

Table B12. Summary of quantitative surveys of Tobusch fishhook cactus and extrapolated total population size.

Number of Surveys	Habitat Area Surveyed (ha)	Number Detected	Number per Hectare
25	19,428	4,496	0.231
Estimate of Total Tobusch Fishhook Cactus Habitat (ha):			2,043,972
Extrapolated Total Population Estimate:			473,015

Discussion.

This estimate of the total population size of Tobusch fishhook cactus is a simple extrapolation of the average population density within surveys of potential habitat to the total amount of potential habitat. The extremely uneven distribution of this cactus complicates estimates of the true population size. Population density ranged from 0.21 per ha (0.08 per ac) at protected natural areas to 1.12 per ha (0.45 per ac) along highway rights-of-way. However, the reported numbers of Tobusch fishhook cactus at protected natural areas are from fixed monitoring plots and may not represent the total populations on those properties. Since 95 percent of the surveyed habitat area was within protected natural areas, the low population density found there has a very large influence on the average of all areas surveyed, 0.231 per ha (0.093 per ac). If equal weight is given to all surveys, regardless of survey size, the average density would be 0.651 per ha (0.263 per ac), and the estimated total population would be 1,330,265.

The accuracy of this estimate may be influenced by potential sources of bias, since population surveys were not randomly distributed, but were conducted where public and private conservation land exists and along proposed routes of development projects. Highway rights-of-way are usually cleared of woody vegetation, and state parks may have greater cover of woody plants than private ranch land, both of which would skew the results. The amount of land occupied by buildings, parking lots, roads, etc. increases with the pace of development and land subdivision and decreases the amount of potential habitat.

Therefore, this estimated total population size of 473,015 should be considered provisional and, due to potential sample biases, may overestimate the actual population size.

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Appendix B. Analyses of