Species Status Assessment of Big Red Sage
(*Salvia pentstemonoides* Kunth and Bouché)

U.S. Fish and Wildlife Service

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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 C.

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Summary of Version Updates

Version 1.0: The previous version of the big red sage SSA Report was intended for peer and partner review and will be updated following revisions from that review.

Version 1.1: This version of the big red sage SSA Report incorporated input from peer and partner review.

EXECUTIVE SUMMARY

Big red sage is a perennial herbaceous plant in the Mint Family (Lamiaceae) that occurs along streams and narrow ravines in the Edwards Plateau of central Texas. Its long, crimson flowers with purplish bases adorn 5-foot tall stalks that arise from rosettes of shiny, dark green leaves. Ferdinand Lindheimer collected the first specimens of big red sage on the upper Pedernales River in 1845. In 1848, Kunth and Bouché based their description of a new species, *Salvia pentstemonoides*, on these specimens. Although the species name has frequently been misspelled, botanical authorities have consistently regarded *S. pentstemonoides* as a distinct, valid species.

On June 18, 2007, Forest Guardians (now called Wild Earth Guardians) submitted a petition to list *Salvia pentstemonoides* among 475 taxa under the Endangered Species Act. On December 16, 2009, in response to this petition, we determined that listing as threatened or endangered may be warranted (74 FR 66866). This Species Status Assessment evaluates the species' current and future viability in terms of its population resilience, redundancy, and genetic and ecological representation.

The vegetation of the Edwards Plateau is influenced by very wide annual variation in rainfall and frequent, long droughts. Due to the shallow, rocky soils and steep topography, surface runoff is rapid. Intact woodland and savanna vegetation aids the infiltration of rainwater into the labyrinthine fissures of the karstic limestone substrate. The unsaturated water-conducting strata that are above the water table comprise the vadose zone, and the phreatic zone consists of the saturated strata below the water table; the elevation of the water table varies with the recharge of aquifers through rainfall and the discharge through springs and pumping. Most big red sage plants occur in discrete locations on bluffs, ledges, and slopes along watercourses and ravines where groundwater slowly seeps through limestone fissures to the surface. This may occur where the fissures of limestone strata in the vadose zone are exposed along slopes. The source of seep moisture that sustains some populations may also be from a major aquifer—the Edwards-Trinity or Trinity, at least when aquifer levels are high. Some populations occur where seep moisture may have a combination of vadose and phreatic sources.

Big red sage flowers opportunistically from May through November in response to rainfall and the persistence of soil moisture. The flowers are specifically pollinated by hummingbirds; black-chinned hummingbirds (*Archilochus alexandri*) are the most abundant species throughout the range and flowering period of big red sage. We estimate that hummingbirds foraging along traplines may cross-pollinate individuals of big red sage that are separated by as much as 0.5 to 1.0 km (0.3 to 0.6 mi), and thus are important vectors for the species' gene flow. Nevertheless, the species' fecundity is low, and small, inbred populations produce few viable seeds. Individual plants can live at least 10 years, and the rootstocks may branch to form multiple rosettes that appear to be separate individuals; therefore, the effective population sizes may be less than the numbers of individuals counted in censuses.

The conservation and management of big red sage will benefit from information we do not currently have, including the species' breeding system and reproductive ecology, the longevity of seeds in the soil and the persistence of its soil seed reserve, and the actual forage ranges of traplining black-chinned hummingbirds.

We estimate a minimum viable population (MVP) size of 1,600 mature individuals for big red sage. Due to the decline and extirpation of many of the known populations, we estimate that the species' viability would require 20 or more resilient populations.

Hoban and Garner (2019) compared the population genetics of four wild and three propagated populations. They found that the wild populations preserved more adaptive capability and had lower levels of inbreeding, more unique alleles and genotypes, and greater interpopulation differentiation, compared to propagated plants. Nevertheless, they concluded that the species' overall genetic diversity is critically low. They recommended carefully planned seed collections from wild populations for ex-situ propagation, demographic and genetic augmentation of remaining wild populations, and reintroduction into suitable habitats to augment redundancy.

Big red sage is highly palatable to white-tailed deer (*Odocoileus virginianus*) and introduced ungulates, all of which have very dense populations in the Edwards Plateau. Consequently, big red sage is depleted throughout its range by ongoing severe herbivory by white-tailed deer and introduced ungulates. Urban and residential development has destroyed 15 percent of population sites and currently threatens about 25 percent of the extant populations; losses due to development are expected to continue in proportion to the pace of human population growth. The collection of seeds and whole plants for the commercial horticultural trade has depleted at least one accessible population, and potentially imperils all populations whose geographic locations are publicized. The species is affected throughout its range by hydrological changes that may interrupt the availability and constancy of seep moisture; these include increases in impermeable surfaces and aquifer drawdown through pumping. Furthermore, climate change projections include both an increase in the frequency and severity of drought, which could interrupt the constancy of seep moisture, as well as an increase in the frequency and severity of extreme rainfall and flash floods. Flash floods have severely impacted at least two populations and may have contributed to the extirpation of another population. Finally, the factors that affect populations that have declined far below the estimated MVP level are exacerbated by the demographic and genetic consequences of small population sizes.

Our assessment of the current viability of big red sage is based on the current conditions of its populations, habitats, and geographic distribution. Big red sage has been documented in 18 populations. Four populations are historical records based on herbarium specimens for which the geographic locations are unknown. Of the 14 populations with known locations, five have been completely extirpated, four have both extant and extirpated Source Features (described in Section 2.6), and two have unknown statuses. The total known population has declined from 1,728 to 928 individuals. Only 9 percent of the decline in numbers of individuals is attributed to urban and residential development, although we do not know how many individuals inhabited some populations that were lost to development. Ninety-one percent of the decline occurred in intact habitats and is attributed to ungulate herbivory, flash floods, a landslide, illicit collection, and invasive plant competition; 7 percent of total losses have unknown causes. Seven populations are currently extant, but none had more than 25 percent of the estimated MVP level of 1,600 individuals. In the most recent censuses, the 4 largest populations had 401, 269, 116, and 108 individuals. Five of the 7 extant populations and 88 percent of extant individuals of big red sage occur on privately owned land, one population site is owned by Texas Parks and Wildlife Department, and one is owned by Cibolo Center for Conservation, a non-profit conservation organization.

To assess current and future conditions, we defined high resilience as a population size that would be likely to persist for 100 years; this is the MVP level of 1,600 mature individuals. Moderate resilience, with a threshold of 100 individuals, is a population size that is likely to persist for 10 years and is still able to increase resilience through conservation and management. Low resilience is a population size less than 100 individuals that is not likely to persist 10 years and is unlikely to increase resilience without augmentation as well as conservation and management.

Population resilience also includes the habitat conditions needed to sustain populations. We devised a potential habitat model to evaluate habitat suitability at the seven extant populations of big red sage and one potentially extant population of unknown status. We used the USGS Hydrologic Unit Code (HUC) 10-digit watershed boundaries to delineate four Representation Areas of big red sage, which we named Guadalupe, Cibolo, Frio-Sabinal, and Pedernales. In summary, big red sage has no highly resilient populations, and therefore has low overall resilience. There are only seven known extant populations, and only four are moderately resilient. Three of the four Representation Areas have extant populations. One Representation Area has one extant, moderately resilient population; three populations in another Representation Area have very low resilience; only one Representation Area is moderately resilient; one Representation Area has no extant populations. Therefore, overall redundancy is low. The overall genetic diversity is critically low, so the species has low representation. In synthesis, we conclude that the current viability of big red sage is low.

We assessed the future viability of big red sage during the 2050 to 2074 time frame, which corresponds to the National Climate Change Viewer climatology period we selected for the assessment of threats from climate changes. Two additional sources of changing conditions are human population growth and groundwater depletion. To evaluate these changes, we used the Texas Demographic Center projections that extend to 2060 and the relevant Groundwater Conservation Districts whose projections extend to the 2060 to 2080 time frame. The factors most relevant to the species' future viability include the following threats: herbivory by native and introduced ungulates, land use changes due to human population growth, reduced availability or constancy of seep moisture, collection from the wild and loss of genetic integrity due to propagation for the horticultural trade, climate changes, and the demographic and genetic consequences of small population sizes. Big red sage may also benefit from conservation and private landowner engagement in areas of potential habitat. To project the possible range of future viability, we evaluated each factor under two scenarios, labeled 1 and 2, that represent the range of likely outcomes for big red sage viability, and then assessed how these scenarios will affect each population.

During the 2050 to 2074 assessment period, under Scenario 1, the species would have one moderately resilient population in the Guadalupe Representation Area, one moderately resilient population and two with low resilience in the Cibolo Representation Area, and one population with low resilience in the Frio-Sabinal Representation Area; two additional populations will be extirpated. Under Scenario 2, the Guadalupe and Cibolo Representation Areas will each have one population with low resilience, and three more populations will be extirpated. Hence, both resilience and redundancy will likely decline. Representation is currently low and will also likely decrease during the assessment period. In summary, under both scenarios, the low current viability of big red sage will decline further during the 2050 to 2074 assessment period.

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1. Introduction and Analytical Framework

Big red sage (*Salvia pentstemonoides*) is a perennial herbaceous plant in the Mint Family (Lamiaceae) that occurs along streams and narrow ravines in the Edwards Plateau of central Texas. On July 1, 1975, the Smithsonian Institution recommended it as a candidate for protection as a threatened species under the Endangered Species Act (ESA; 40 FR 27824). On September 30, 1993, we, the U.S. Fish and Wildlife Service (USFWS) placed "*Salvia pentstemonoides*" on the list of Category 2 Candidates for listing under the ESA (see discussion on the species name in Section 2.2; 58 FR 51184). On June 18, 2007, Forest Guardians (now called Wild Earth Guardians) submitted a petition to list *Salvia pentstemonoides* among 475 taxa under the ESA. On December 16, 2009, in response to this petition, we determined that listing as threatened or endangered may be warranted (74 FR 66866).

USFWS uses a Species Status Assessment (SSA) Framework (USFWS 2016; Smith *et al.* 2018) to review the best available scientific information about the life history and ecology of a species, assess its current species viability and trends, and project its future viability under a range of scenarios. The SSA compiles the information and analyses that support many ESA actions, including candidate conservation, listing, recovery planning, Section 7 consultations, permitting, five-year reviews, and reclassification. Nevertheless, the SSA itself does not convey a decision to protect a species under the ESA or not.

USFWS defines species viability as the ability to sustain populations in the wild over time (USFWS 2016, p. 21). The assessment of viability is derived from an analysis of the species' requirements in terms of its resilience, redundancy, and representation.

• Resilience refers to the ability of species and populations to endure random environmental and demographic variations (Shaffer and Stein 2000, pp. 308-310). Resilient populations are better able to recover from losses caused by variations in rainfall or wildfire frequency (environmental stochasticity) and fluctuations in recruitment (demographic stochasticity). The metrics of resilience are the sizes and growth rates of populations (USFWS 2016, p. 21).

• Redundancy refers to the ability of a species to endure catastrophic events (Shaffer and Stein 2000, pp. 308-310). Catastrophic events are rare occurrences, usually of finite duration, that cause severe impacts to one or more populations. Examples include tropical storms, floods, prolonged drought, and unusually intense wildfire. The metrics of redundancy are the number of resilient populations and their geographic distribution and connectivity.

• Representation refers to the ability of a species to adapt to novel changes in its biological and physical environment (USFWS 2016, p. 21). Representation is the genetic and ecological diversity, both within and among populations, necessary to conserve long-term adaptive capability (Shaffer and Stein 2000, pp. 307-308).

2. Species Information

2.1. Species description.

The following species description is adapted from Correll and Johnston (1979, p. 1368), Poole *et al*. (2007, pp. 436–437), and Wester (2007, pp. 45, 72, 85, 89, and 102), as well as our observations.

Big red sage is a herbaceous perennial plant of the Mint Family (Lamiaceae). The plants initially form a basal rosette of smooth, thick, dark green, narrow to oblong-lanceolate, long-petioled leaves with prominent midribs; individual leaves have a total length of up to 13 centimeters (cm; 5.1 inches (in)). The plants remain in a vegetative state as the root systems develop. A series of dried petioles persisting on the short, perennating, rhizome-like lower stem reveals that leaves die back during drought or cold weather and new leaves emerge when moisture and warmth return (see Figure 2.1.b). It is likely that individuals store carbohydrates in the roots. Healthy individuals may flower in response to rainfall, usually between June and October. Individual rootstocks produce one to several four-sided flower stalks, up to 1.5 meters (m) (4.9 feet (ft)) tall, that bear opposite leaves that are gradually shorter and narrower toward the tip of the flower stalk; flower stalks may be simple or have one to several primary branches. Groups of up to five flowers arise from the axils of leaves in short cymes; these are specialized flowering branches in which the terminal flower opens first, followed by the adjacent lower flowers and so on in sequence toward the branch base. The bell-shaped green calyx becomes purplish with age and has a three-lobed upper lip and a 2-lobed lower lip. The deep crimson corolla is up to 4 cm (1.6 in) long, consisting of a narrow tube 15 to 27 millimeters (mm) (0.6 to 1.1 in) long, an upper lip 11 to 16 mm (0.4 to 0.6 in) long, and a three-lobed lower lip 9 to 11 mm (0.35 to 0.43 in) long. Flowers have two stamens, each with a single theca (pollen sac) that is enveloped by the upper corolla lip; stamens have elongated connective arms attached to flexible joints; the connective arms extend into the corolla tube, blocking access to nectaries at the base of the tube (see Section 2.3-Reproduction). The style extends through and is exserted beyond the upper lip, and the stigma is divided into two short lobes. Fertilized flowers produce a cluster of 4 one-seeded nutlets that are enclosed by the maturing calyx.

The distinguishing identification features are summarized in Table 2.1.

Table 2.1. Identification features that distinguish big red sage from other Texas *Salvia* species (Correll and Johnston 1979, pp. 1364, 1365, 1368).

Feature	Description
Lifespan	Perennial
Leaves	Entire or obscurely denticulate, linear to narrowly oblong-elliptic or lanceolate, tapered at base, nearly glabrous; mid-nerve prominent beneath.
Stems	Herbaceous, up to 1.5 m tall.

Flowers	Floral leaves and bracts conspicuous, lanceolate, cuspidate; bracts rarely as long as calyx; calyx lacking conspicuous ring of hair in throat; corolla crimson, about 4 cm long.

In the field, big red sage might be mistaken for other red-flowered *Salvia* species of the Edwards Plateau, such as cedar sage and tropical sage (*S. roemeriana* and *coccinea*, respectively), as well as cardinal flower (*Lobelia cardinalis*) and red-flowered penstemons (Poole *et al.* 2007, p. 437). The other red-flowered Texas salvias are much smaller than big red sage, and are also distinguished by their smaller, rounded or deltoid leaves with bluntly toothed margins. Cardinal flower is found in moist stream-side habitats where one would expect to find big red sage, and its stature and terminal racemes of crimson flowers justify a closer inspection; but the leaves are alternate and coarsely toothed, and the flowers are not two-lipped, as in *Salvia*. The red-flowered penstemons of central Texas have much stouter flowers that are not two-lipped, and they are not restricted to moist habitats.

2.2. Taxonomic classification and phylogenetics.

The German botanist Ferdinand Lindheimer collected the first specimens of big red sage on the upper Pedernales River, in Gillespie County, on October 10, 1845. He sent the specimens to George Engelmann, at Missouri Botanical Garden, who then sent them to Karl Kunth and Carl Bouché, in Germany; Kunth and Bouché (1848) based their description of a new species, *Salvia pentstemonoides*, on these specimens (Ward 2009a, b). The species' name is derived from a vague similarity to *Chelone pentstemon* (Plantaginaceae; Poole *et al.* 2007, p. 436); the currently accepted name for that species is *Penstemon buckleyi* (Tropicos 2021a,b). This genus was spelled both as *Penstemon* and *Pentstemon* until botanists settled on the former variant. This has led to confusion over the correct spelling of the *Salvia* species; it has been spelled *penstemonoides* by some (58 FR 51144; ITIS 2021) and *pentstemonoides* by others (74 FR 66866; Forest Guardians 2007, p. 33; NRCS 2021; Poole *et al.* 2007, p. 436; Tropicos 2021c; University of Texas 2021). The International Code of Botanical Nomenclature (2001, article 11.4) requires conservation of prior published names; therefore, we use *pentstemonoides* throughout this document, even where cited sources used the other synonym. Regardless of the spelling, all these sources regard this taxon as a valid species.

The genus *Salvia* has about 1,000 species distributed across Europe, Asia, Africa, and North, Central, and South America (Walker *et al.* 2004, p. 1115; Wester 2007, p. 1). The genus is distinguished by having only two anterior stamens, due to the abortion of the two posterior stamens, and by significant elongation of the connective tissue between the two thecae of each stamen; nevertheless, a molecular phylogenetic study based on two chloroplast DNA regions revealed that *Salvia* is not monophyletic but consists of two or three lineages that diversified mostly along biogeographical lines (Walker *et al.* 2004, pp. 1115, 1119–1121). This study found that *S. pentstemonoides* is most closely related to *S. texana*, which has an identical rbcL sequence and differs in only one trnL-trnF site; the genetic sequences and calyx and leaf morphology indicate an affinity with section Salviastrum (Walker *et al.* 2004, p. 1122). However, the chromosome count, 2n = 28, links *S. pentstemonoides* with other New World species of section Heterosphace. Section Salviastrum and New World species of section Heterosphace form a weak monophyletic group (Walker *et al.* 2004, pp. 1122–1123).

Walker and Sytsma (2007, (pp. 375–391) investigated *Salvia* staminal evolution through an additional phylogenetic study based on two chloroplast DNA regions and the nuclear rDNA Internal Transcribed Spacer (ITS) region. They identified three *Salvia* clades, among which they described 9 distinct stamen types and concluded that the staminal-lever pollination system evolved independently three times. *S. pentstemonoides* is among 8 New World species within clade I and has stamen type A, in which the two posterior thecae are expressed and not fused (pp. 382, 387). Among 15 species with type A stamens, *S. pentstemonoides* is most closely related to two species of central and west Texas, *S. texana* and *S. whitehousei* (p. 387). The unique stamen-lever pollination systems of *Salvia* are discussed in Section 2.3-Reproduction.

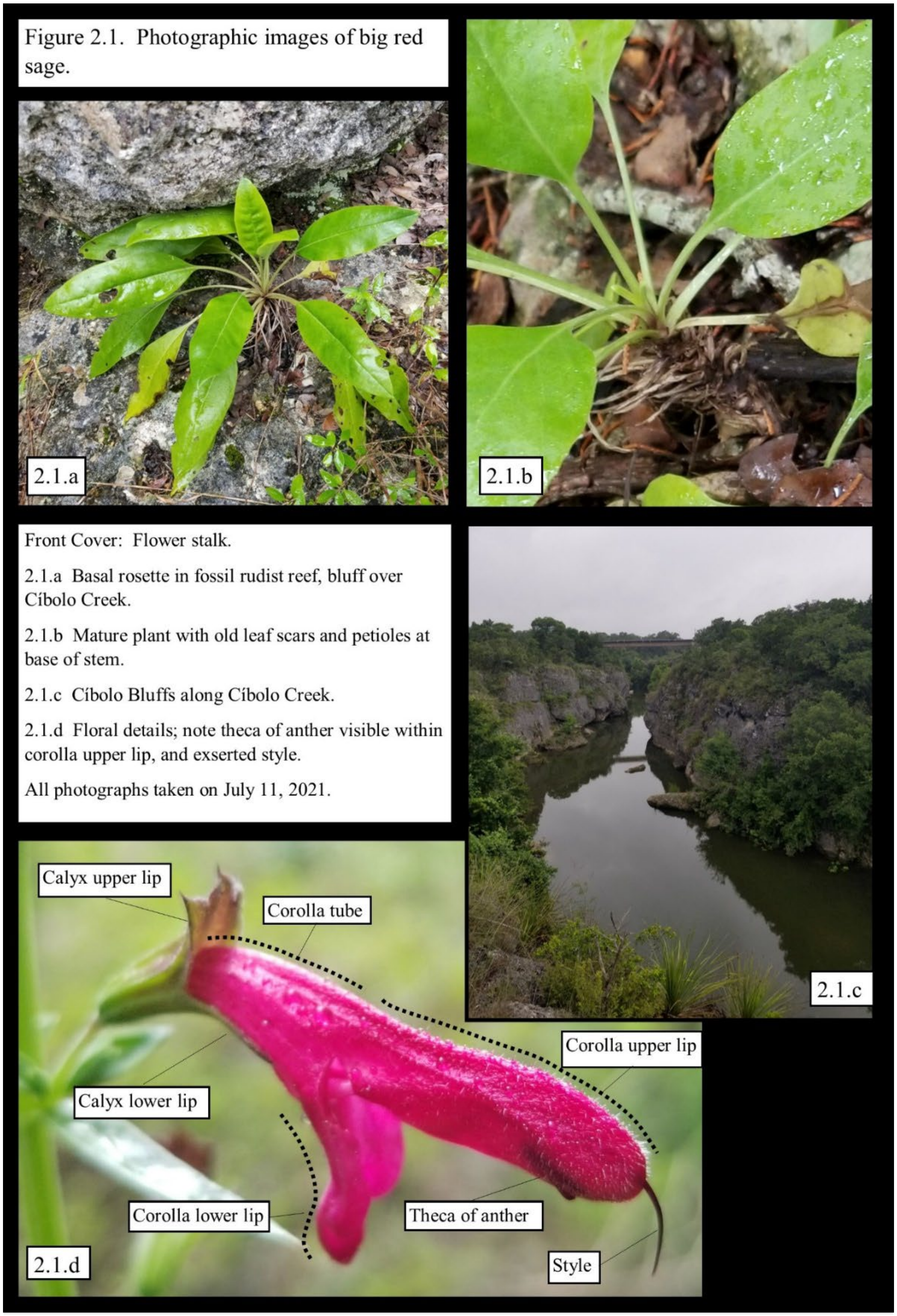


Figure 2.1. Photographic images of big red sage.

2.3. Life history: Phenology, reproduction, demographic trends, life span, and mortality.

Phenology.

Figure 2.2 summarizes observations of big red sage in vegetative and flowering states, obtained from herbarium records and Element Occurrence (EO) and Source Feature (SF) data (Texas Natural Diversity Database (TXNDD) 2021; see Section 2.6-Populations, Source Features, Element Occurrences, and geographic distribution). Flowering has been observed from May through November, with the greatest frequency in July and August. However, this apparent flowering peak is skewed, because botanists conducted surveys more frequently when they expected to find the species in flower; the species was also observed in a vegetative condition most often in July and August. The percent of individuals that were flowering was lower in July (38 percent) than in all other months from May through November (from 50 to 100 percent), although this difference may be due to the intensity of survey efforts at different times of the year. It is likely that the species is able to flower throughout the warm months of the year when prior periods of rainfall have restored seep moisture in occupied habitats. Similarly, the vegetative rosettes may be evident at any time of the year if habitats have available soil moisture. Conversely, during the long spells of hot, dry weather that often occur in this semi-arid region, the rosettes whither and may be undetectable, although the rootstocks may survive in a dormant condition for an unknown length of time.

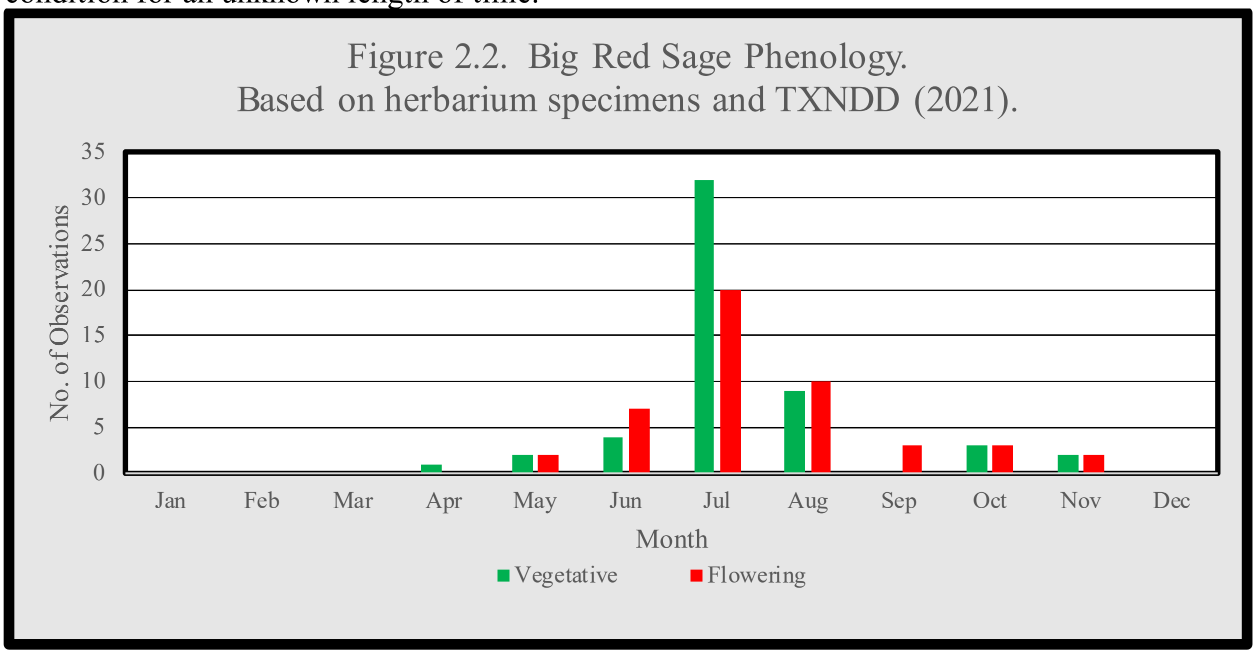


Figure 2.2. Big red sage phenology. Based on herbarium specimens and TXNDD (2021).

Reproduction.

Wester (2007, pp. 1–132) investigated bird pollination (ornithophily) in the genus *Salvia*. Nearly all bird-pollinated *Salvia* species occur in the Americas. Based on direct observations of pollinators of wild or cultivated *Salvia* species, complemented by floral data (Wester 2007, pp. 36, 37, 40), Wester determined that 182 of the 591 New World *Salvia* species in this study (30.8%) were bird-pollinated, including *S. pentstemonoides* (Wester 2007, pp. 40, 72). Bird-pollinated *Salvia* species typically have the following characteristics: 97 percent are perennial herbs, shrubs, or sub-shrubs; floral tubes are long, and floral architecture prevents bees from contacting reproductive structures; the lower corolla lip is reduced or reflexed and flowers lack a stable landing platform for insect pollinators; 49 percent have red corollas, and 33 percent have yellow, orange, pink, purple, or lavender corollas, while only 9 percent have blue corollas; flowers produce abundant nectar with lower concentrations of sugars, and often have a nectar retention structure; and flowers lack scent and nectar guides (Wester 2007, pp. 37–38, 45–46, 48–49). Like many bird-pollinated species, bee-pollinated Salvias often have ventral teeth or barriers at the stamen connectives that block access to nectar, pollen sacs enclosed in the upper corolla lip, and an active lever mechanism that pushes the pollen sacs onto the body of an organism attempting to access nectar. In contrast to bird-pollinated species, the corollas of bee-pollinated *Salvias* are often blue or violet, although some species are pink, purple, or yellowish, and there usually are nectar guides; the flowers support a bee's weight; and nectaries produce small amounts of highly concentrated nectar (Wester 2007, pp. 49, 51).

Birds have potentially much larger forage ranges than bees and are more reliable pollinators than bees because they are less affected by weather and do not collect pollen to feed offspring (Wester 2007, p. 105). Hummingbirds are the most important bird pollinators of *Salvia* species (Wester 2007, p. 36), and the distribution of bird-pollinated *Salvia* species corresponds closely to the distribution of hummingbird species (Wester 2007, p. 57). *Salvia pentstemonoides* is included among *S. fulgens*-type flowers with active stamen lever-movement, a well-functioning joint, pollen sacs hidden within the upper corolla lip, and a blocked floral entrance (Wester 2007, pp. 86, 90). When a bird inserts its bill into a flower with this architecture, it pushes against the posterior connective arms of the stamens that block access to the nectar at the base of the floral tube; this forces the anterior ends and pollen sacs to swing downward from the shrouds of the upper corolla lip, thereby dusting a specific portion of the bird's head or neck with pollen (Wester 2007, p. 78). If the bird subsequently visits several flowers of different species with different sized flowers, the pollen may not contact any part of those flowers but may remain attached to the feathers until the bird visits another flower of the same *Salvia* species, upon which the pollen is precisely delivered to the flower's receptive stigmas. These processes are illustrated in Figure 2.3.

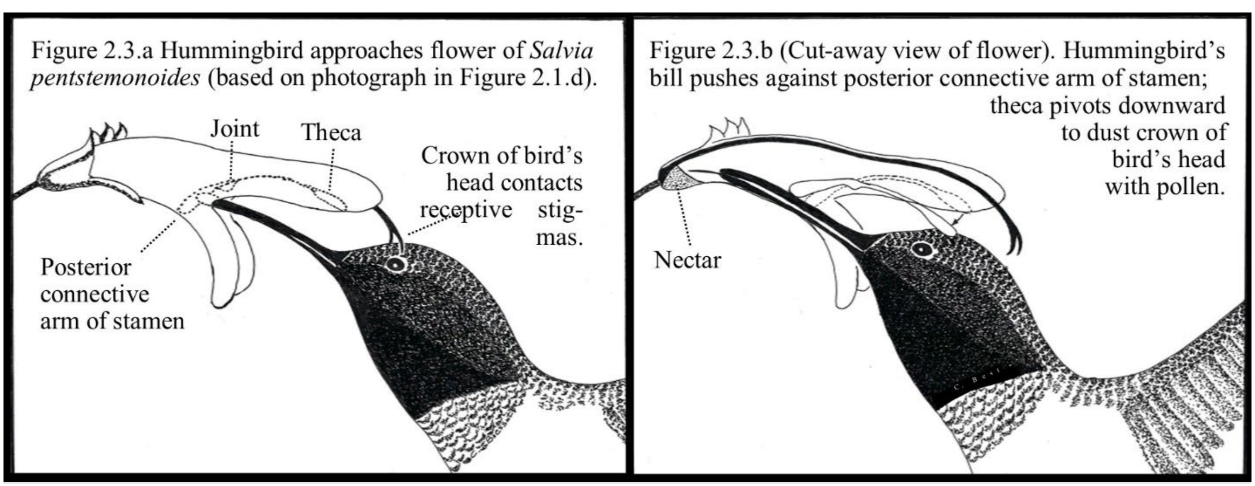


Figure 2.3. Hummingbird pollination of *Salvia pentstemonoides*.

The flowers of big red sage are very attractive to hummingbirds (Lady Bird Johnson Wildflower Center 2014); in February 2022 a webpage of the Lady Bird Johnson Wildflower Center (https://www.wildflower.org/donate) had an extraordinary photograph of a female black-chinned (*Archilochus alexandri*) or ruby-throated hummingbird (*A. colubris*) nectaring at a big red sage flower, its crown copiously smeared with pollen. Based on this information and on the descriptions of bird-pollinated *Salvia* species in Wester (2007, all), we conclude that hummingbirds are effective pollinators of this species.

Hummingbirds forage for nectar by two different strategies. At times they forage within discrete territories they establish and defend around concentrated nectar sources; for example, Avery and van Riper III (1993, all) described territorial foraging by Costa's hummingbirds (*Calypte costae*) around dense patches of flowering wooly bluecurls (*Trichostema lanata*). Alternatively, hummingbirds may also forage in a more dispersed pattern along traplines, in which rewarding nectar sources are visited repeatedly in a predictable sequence (Tello-Ramos *et al.* 2015, p. 812–813); trapline foraging may be invoked by competition from more aggressive hummingbird species or when nectar sources are widely dispersed. Pollinators that forage along traplines enable outcrossing among plants that occur at low densities (Janzen 1971, pp. 203–205). Black-chinned hummingbirds are the most common hummingbirds within the geographic range and flowering season of big red sage (Bird Locations.com 2022) and have been observed hovering in the vicinity of flowering big red sage plants (Cibolo Center for Conservation 2021, p. 4); hence, black-chinned hummingbirds are likely pollinators of big red sage; for this reason, we estimate gene flow for big red sage based on the forage range of black-chinned hummingbirds. However, other hummingbird species may also pollinate big red sage. Arizmendi and Ornelas (1990, p. 177) documented trapline foraging of black-chinned hummingbirds in Jalisco, México. We are unaware of any documentation of the forage ranges of black-chinned hummingbirds. However, Gill (1988, all) reported trapline foraging by male long-tailed hermits (*Phaethornis superciliosus*) in Costa Rica spanning distances greater than 500 m (1,640 ft). We hypothesize that black-chinned hummingbirds foraging up and down canyons of the Edwards Plateau may be vectors of gene flow between groups of big red sage separated by 500 to 1,000 m (1,640 to 3,281 ft). In synthesis, pollination by traplining black-chinned hummingbirds (or other hummingbird species) may allow fertilization, outcrossing, and gene flow among widely dispersed individuals of big red sage; functioning populations may be larger than the small, isolated clusters of individuals that have most often been discovered.

Effective conservation of rare plant species requires knowledge of their breeding systems. Unfortunately, the breeding system of big red sage has not been investigated. Within the genus *Salvia*, breeding systems range from species that are highly self-compatible to highly self-incompatible (Haque and Ghoshal 1981, all; Subaşi and Güvenson 2011; Jorge *et al.* 2015, p. 1490; Esmaeili *et al.* 2020, all). *S. elegans* is an endemic shrubby species of central Mexico that, like *S. pentstemonoides*, also has bilabiate, tubular red flowers that are primarily pollinated by hummingbirds (Lara 2006, all). Rosas-Guerrero *et al.* (2017, all) investigated the reproductive biology of *S. elegans*. They found that the flowers, which usually open for 4 days, exhibit incomplete dichogamy: anthers mature first, and pollen has highest viability on days 2 and 3, while stigmas had the highest receptivity on days 3 and 4 (pp. 4131–4132). Therefore, the partial temporal overlap of male and female fertility allows some self-pollination to occur. Nevertheless, self-pollination is not autogamous in *S. elegans*, but requires the activity of hummingbird pollinators; this may be due to the physical separation of the stigmas and anthers.

Self-pollinated and outcrossed flowers had no significant differences in fruit set, seed number, seed mass, or seed viability; hence, there was no evidence of inbreeding depression (p. 4132). There was also no evidence of pollen limitation in *S. elegans* (p. 4132). Pollen limitation may occur among small plant populations or when there are insufficient pollinators. Both hummingbirds and *S. elegans* were abundant in the habitat studied (p. 4130). In contrast, *S. pentstemonoides* occurs only in small, isolated groups of individuals, and may be affected by both inbreeding depression and pollen limitation. This comparison with *S. elegans* illustrates the need to document the breeding system and reproductive ecology of *S. pentstemonoides*.

Each pollinated flower of big red sage can produce up to four nutlets, each containing a single seed, that are enclosed within the maturing calyx. When fully mature, the seeds simply fall from the calyx or may be dislodged by raindrops. Like many Salvias, the seed coat soon becomes gelatinous when wet; this enables the seeds to adhere to the soil rather than to be washed away. This species has been widely cultivated by wildflower enthusiasts (discussed in Section 4.1) who report that the seeds germinate easily and without special treatments (Lady Bird Johnson Wildflower Center 2014, p. 1).

We have no direct evidence of the level of fecundity but estimate seed production based on the numbers of mature calices evident in photographs of intact herbarium specimens that were collected from wild plants. Fifteen specimens had from 10 to 72 calices and averaged 34.3 per flower stalk. Based on data collected at Cibolo Bluffs (Cibolo Center for Conservation 2021), flowering individuals average 1.36 flowering stalks each. This yields an average of 187 seeds per flowering individual in the wild per season. Due to the combined effects of competition with other plants, lack of water, pathogens, and seed parasites, seeds produced by wild plants typically are not all viable. Even if seed viability rates are high, this amount of annual seed production is low compared to many other herbaceous plants. However, we expect that propagated individuals in gardens that benefit from supplemental watering and reduced competition produce much larger numbers of viable seeds.

The formation of a persistent soil seed reserve is an important plant survival strategy, particularly in climates where environmental parameters, such as rainfall, are highly variable (Venable and Brown 1988, pp. 360, 363; Mašková and Poschlod 2022, p. 2); section 2.4-Climate discusses the wide variation in rainfall throughout the range of big red sage. We have no information on the duration of seed viability for big red sage or the persistence of its soil seed reserve. Seeds of several native *Salvia* species of arid regions in southern California can maintain viability in the soil for many years (Keeley 1986, p. 1; Meyer 2008, p. 1011). Conversely, some desert ecotypes of *S. columbariae* lose viability more rapidly (Capon *et al.* 1978, p. 373). Lovegren (2022) noted that seeds of *S. coccinea* also become gelatinous when wet and speculated that this may retain moisture levels in the seed, thereby enhancing germination; conversely, once seeds have been exposed to moisture, the gelatinous coating may reduce their longevity in storage and in the soil. Hence, big red sage seeds may not persist very long in the moist seeps where it occurs naturally.

In addition to sexual reproduction, big red sage reproduces vegetatively, although to a limited extent, by means of multiple rosettes (ramets) arising from a single rootstock. The underground connections between rosettes may not be evident without disturbing the soil, and it is possible that multiple rosettes that originated from a single individual could develop independent root systems and eventually become separated from each other. Consequently, field censuses may not be able to distinguish which rosettes are genetically distinct individuals (genets), and effective population sizes may actually be smaller than population censuses indicate.

Demographic trends, life span, and mortality.

Most populations of big red sage have not been observed frequently enough to reveal their demographic trends. The three EOs that have been observed most often are EO 5 (Cibolo Bluffs), EO 11 (Lost Maples State Natural Area (SNA)), and EO 14 (Interstate 10 and Frederick Creek). These populations are discussed in greater detail in section 2.6; see also figures 2.6 and 2.7. The population at EO 5 declined 25 percent from 2014 to 2015, possibly due to a large flood, but has been relatively stable since that time. EO 11 declined from 23 individuals in 1988 to 3 individuals in 2019. A major portion of EO 14 declined from 576 individuals in 1992 to 0 by 2012; possible causes include a major flood, competition from invasive plants, ungulate browsing, and illicit collection. In addition, Taylor and O'Kennon (2013, p. 6) found no surviving individuals at 8 of the 13 EOs they visited in 2013. None of the EOs that have been accurately censused have had populations large enough to be considered viable (see Section 3.2); however, see the discussion above on hummingbird pollination in section 2.3-Reproduction.

Big red sage is a perennial species that reaches maturity (from seed germination to development of mature seeds) in as little as 16 months (Prosperie 2022). Although no formal studies have documented the life span of big red sage, Taylor (2021a,b) used photographs of a group of individuals on a limestone bluff at EO 11 to demonstrate that individuals can persist for at least 10 years; these plants were inaccessible to white-tailed deer (*Odocoileus virginianus*) and introduced ungulates (Figure 2.4). Considering that new rosettes often branch from established rootstocks and may outlive the original plant (and others in succession), it is possible that individuals present today may have originated from a seed that germinated many decades ago. Like many perennial plant species, big red sage has an indeterminate life span with no upper limit. Known causes of mortality include herbivory, flooding, and collection from the wild; severe or extended drought is also assumed to cause mortality (see Section 4.1).

Figure 2.4. Big red sage growing from a crevice in a limestone bluff at EO 11 (Taylor 2021b).

2.4. Climate, habitats, and ecology.

Climate.

Hot, dry summers and mild winters characterize the climate across the geographic range of big red sage. The amounts and frequency of rainfall are greatest in May, September, and October. Figure 2.5 shows the 20-year average monthly temperatures and precipitations for the Boerne, Texas weather station (National Centers for Environmental Information 2022). Central Texas also experiences very wide annual fluctuation in rainfall, as indicated in Figure 2.6. For example, in 2008 and 2011, annual precipitation totaled just 375 and 451 mm (14.8 and 17.8 in), respectively. In 2002, 2004, and 2007, precipitation totals were 1,585, 1,537, and 1,477 mm (62.4, 60.5, and 58.1 in), respectively. Extended droughts contrast sharply with brief periods of extreme rainfall (see discussion of EO 5 in section 2.6-Populations). Streamside populations of big red sage are particularly vulnerable to flash floods in the narrow canyons of the Edwards Plateau.

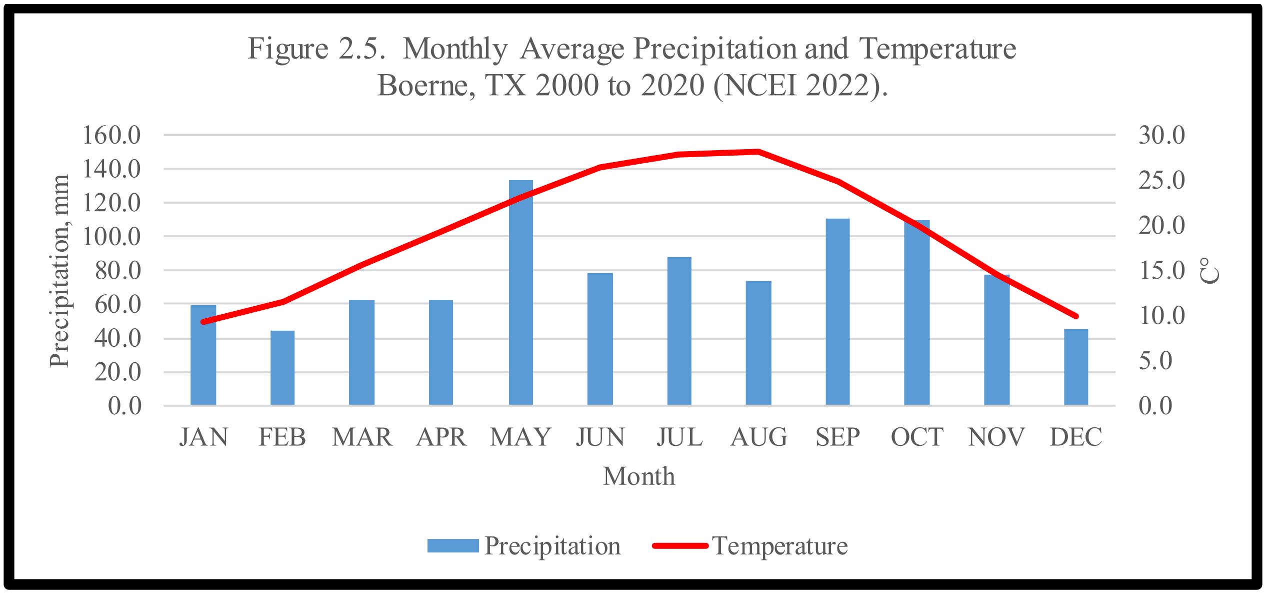


Figure 2.5. Monthly average precipitation and temperature, Boerne, TX 2000 to 2020 (NCEI 2022).

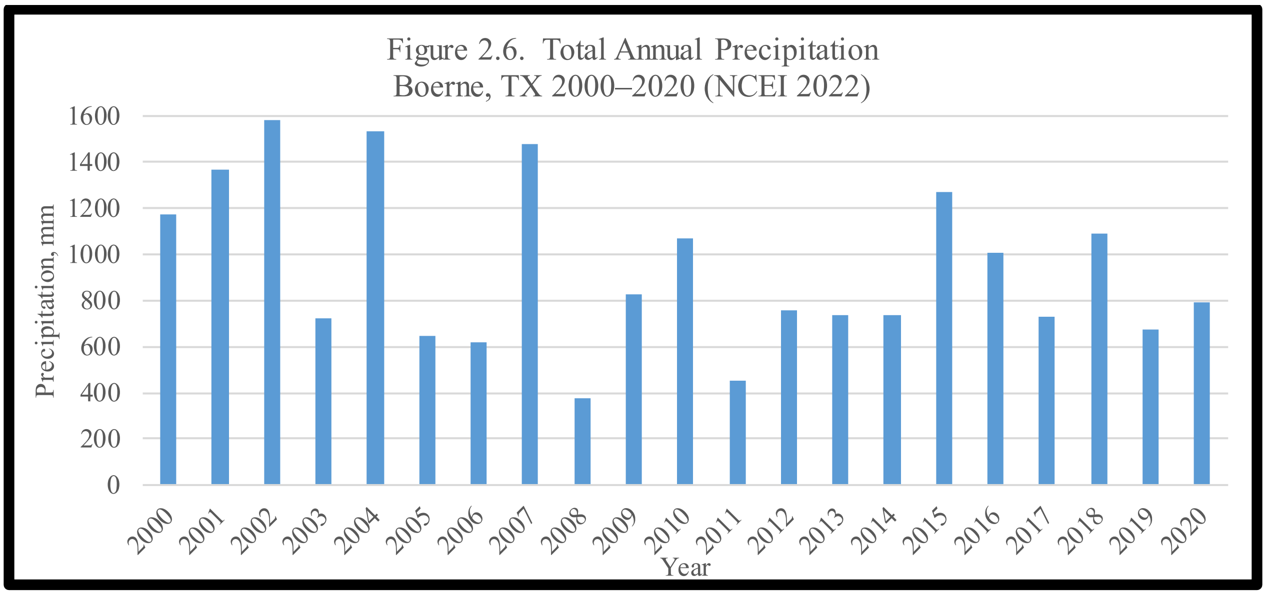


Figure 2.6. Total annual precipitation, Boerne, TX 2000 – 2000 (NCEI 2022).

Habitats and ecology.

Taylor and O'Kennon (2013, pp. 3–5) modeled potential habitats of big red sage based on the habitat parameters of all known EOs (Section 2.5 and Figures 2.9 and 2.10). They determined that populations occur on Cretaceous limestones of the Edwards, Glen Rose, and Devils River formations; within 50 m (164 ft) of watercourses; and where slopes are greater than 25 percent, based on Digital Elevation Models (DEMs) with 10-m (32.8-ft) pixels. Taylor and O'Kennon conducted field surveys of areas identified as high-potential habitats. They found plants on vertical bluffs, ledges, rocky limestone slopes, and terraces and hilltops with little or no slope—

which would appear to contradict the 25 percent slope parameter. However, slope is calculated on DEMs by comparing the elevation of each 100-m^2 area to its neighbors; a small level terrace adjacent to a bluff would become part of a slope. Associated watercourses ranged from rivers to intermittent drainages (first order streams in the Strahler stream order). Most plants were in light to heavy shade, but some plants on north-facing slopes of narrow canyons grew in full sunlight. Taylor and O'Kennon observed populations associated with seep moisture, as others have indicated (Correll and Johnston 1978, p. 1368; Pasztor 2004, p. 1; Poole *et al.* 2007, p. 437); although seep moisture was not evident at other populations, they stated, "it is likely that all sites have some degree of seepage from the limestone substrate" (p. 7).

Table 2.2 combines data (including plant species names) from 7 reports that list the plant species that were found at one or more big red sage habitats. The plants listed in 5 or more reports include spreading least-daisy, Ashe juniper, Texas red oak, Lindheimer's silk-tassel, maidenhair fern, and hairy sycamore-leaf snowbell. Taylor and O'Kennon's list (2013, p. 7) of the five most frequent associated plants also includes big-tooth maple, sotol, wand butterfly-bush, American sycamore, and sycamore-leaf snowbell. Ashe juniper and Texas red oak are very abundant throughout the Edwards Plateau. Conversely, spreading least-daisy and the subspecies of sycamore-leaf snowbell are rare endemics of the Edwards Plateau and are listed on Texas Parks and Wildlife Department's (TPWD) Species of Greatest Conservation Need (TPWD 2020). Maidenhair fern is indicative of seep moisture, and the snowbell, butterfly-bush, silk-tassel, and big-tooth maple occur primarily in canyons. American sycamore is ubiquitous along watercourses in the eastern half of North America. Some of the associated plants, such as Texas kidneywood, blazing star, and sotol, are typically found in open vegetation on limestone outcrops and rocky slopes; their occurrences near big red sage are due to the fine scale of habitat mosaics associated with big red sage.

Wide extremes in rainfall, from torrents to extended droughts, create harsh conditions that restrict plant growth over much of the Edwards Plateau. Due to the shallow, rocky soils and steep topography, surface runoff is rapid, particularly during heavy rainfall. A portion of the rainfall infiltrates into the abundant fissures and cavities of the karstic Edwards and Devils River limestones. Intact native vegetation slows runoff and increases infiltration; conversely, runoff increases and infiltration decreases where there are impervious surfaces, sparsely vegetated soils, and exposed rock. Sporadic rainfall intermittently percolates into the vadose zone through labyrinthine channels in the limestone strata. Where the fractures of limestone strata are exposed along slopes, small amounts of groundwater may seep over long periods of time, rather like a drip irrigation system. This seep moisture may not be visible at the surface, but is available to plant roots that penetrate cracks in the limestone. Some of the groundwater in the vadose zone recharges the Edwards-Trinity (Plateau) and Trinity aquifers and eventually discharges, relatively slowly and steadily, in springs and seeps (if not pumped for human use). Portions of some EOs appear to obtain moisture from a major aquifer. Narrow canyons create shaded, relatively mesic environments, particularly along north-facing slopes. Big red sage is endemic to these riparian ravines etched into the Edwards Plateau, and it persists in specific positions where intermittent seepage occurs. It is possible that this species is a Pleistocene relict that once was more abundant and widespread, and now persists only in protected sites as the climate warmed; alternatively, its geographic range and habitats may always have been as restricted as they are today.

Table 2.2. Plant species associated with big red sage habitats.

Family[1]	Genus[1]	Species[1]	Common Name[2]	SGCN Rank[3]	Citation[4]	Frequency Rank[5]
Acanthaceae	*Ruellia*	*humilis*	Wild petunia		5	
Aceraceae	*Acer*	*grandidentatum*	Big-tooth maple		6, 7	4
Anacardiaceae	*Rhus*	*trilobata*	Aromatic sumac		4, 5	
Anacardiaceae	*Rhus*	*virens*	Evergreen sumac		4, 5	
Anacardiaceae	*Toxicodendron*	*radicans*	Poison ivy		1, 4, 5, 7	19
Apiaceae	*Chaerophyllum*	*tainturieri*	Hairy chervil		4	
Apiaceae	*Torilis*	*arvensis*	Beggar's ticks		4	
Apocynaceae	*Asclepias*	*texana*	Texas milkweed		3, 4, 7	10
Aquifoliaceae	*Ilex*	*decidua*	Possum haw		1, 5	
Aristolochiaceae	*Aristolochia*	*serpentaria*	Virginia snakeroot		5, 7	20
Asparagaceae	*Dasylirion*	*texanum*	Sotol		1, 2, 4, 7	3
Asparagaceae	*Nolina*	*lindheimeriana*	Devil's shoestring		4, 7	15
Asparagaceae	*Nolina*	*texana*	Texas beargrass		2, 5	
Asparagaceae	*Yucca*	*rupicola*	Twist-leaf Yucca		2, 5	
Asparagaceae	*Yucca*	*sp.*	Yucca		4	
Asteraceae	*Ageratina*	*altissima*	White snakeroot		3	
Asteraceae	*Ageratina*	*havanensis*	Shrubby boneset		1, 4, 7	22
Asteraceae	*Ambrosia*	*trifida*	Giant ragweed		5	
Asteraceae	*Brickellia*	*cylindracea*	Bricklebush		2, 3, 4, 5	
Asteraceae	*Chaetopappa*	*bellidifolia*	Dwarf white aster		4	
Asteraceae	*Chaetopappa*	*effusa*	Spreading least-daisy	S3S4/G3 G4	1, 2, 3, 4, 5, 6, 7	21
Asteraceae	*Eupatorium*	*serotinum*	White boneset		6	
Asteraceae	*Helianthus*	*hirsutus*	Rough sunflower		4	
Asteraceae	*Heterotheca*	*stenophylla*	Sticky granite-daisy		5	
Asteraceae	*Liatris*	*punctata*	Blazing star		4	
Asteraceae	*Perityle*	*lindheimeri*	Lindheimer's rockdaisy		4	
Asteraceae	*Prenanthes*	*carrii*	Carr's rattlesnake-root	S2/G2	3, 7	12
Asteraceae	*Silphium*	*radula*	Roughstem rosinweed		4	
Asteraceae	*Silphium*	*sp.*	Rosinweed		7	11
Asteraceae	*Solidago*	*nemoralis*	Gray goldenrod		4	
Asteraceae	*Symphyotrichum*	*drummondii v. texanum*	Drummond's aster		2, 5	
Asteraceae	*Symphyotrichum*	*praealtum*	Tall aster		4	
Asteraceae	*Tetraneuris*	*scaposa*	Slender-stem bitterweed		4	
Asteraceae	*Verbesina*	*virginica*	Frostweed		3, 4, 6, 7	7
Asteraceae	*Vernonia*	*lindheimeri*	Wooly ironweed		4, 6	
Boraginaceae	*Heliotropium*	*tenellum*	White heliotrope		5	
Buddlejaceae	*Buddleja*	*racemosa*	Wand butterflybush		1, 2, 5, 7	1
Campanulaceae	*Triodanis*	*coloradoensis*	Western Venus's looking-glass		1	
Caprifoliaceae	*Lonicera*	*albiflora*	White bush-honeysuckle		1, 2, 4, 5	
Caprifoliaceae	*Sambucus*	*nigra ssp. canadensis*	Elderberry		3	
Commelinaceae	*Tinantia*	*anomala*	False dayflower		4	
Convolvulaceae	*Ipomoea*	*lindheimeri*	Lindheimer morning-glory		1	
Cornaceae	*Cornus*	*drummondii*	Rough-leaf dogwood		4, 5, 6	

Family[1]	Genus[1]	Species[1]	Common Name[2]	SGCN Rank[3]	Citation[4]	Frequency Rank[5]
Cupressaceae	*Juniperus*	*ashei*	Ashe juniper		1, 2, 3, 4, 5, 6	
Cyperaceae	*Eleocharis*	*montevidensis*	Sand spikerush		6	
Cyperaceae	*Fuirena*	*simplex*	Western umbrella-sedge		6	
Cyperaceae	*Rhynchospora*	*nivea*	Showy whitetop		5	
Ebenaceae	*Diospyros*	*texana*	Texas persimmon		2, 5	
Ericaceae	*Arbutus*	*xalapensis*	Texas madrone		3	
Euphorbiaceae	*Acalypha*	*phleoides*	Three-seeded mercury		4, 7	23
Euphorbiaceae	*Croton*	*fruticulosus*	Bush croton		2, 5	
Euphorbiaceae	*Stillingia*	*texana*	Queen's delight		4	
Euphorbiaceae	*Tragia*	*nigricans*	Darkstem noseburn	S3/G3	1, 5, 6	
Fabaceae	*Senegalia*	*roemeriana*	Roemer Acacia		4	
Fabaceae	*Amorpha*	*fruticosa*	False indigo		5	
Fabaceae	*Cercis*	*canadensis v. texensis*	Texas redbud		3, 4	
Fabaceae	*Eysenhardtia*	*texana*	Kidneywood		2, 5	
Fabaceae	*Mimosa*	*borealis*	Pink mimosa		4	
Fabaceae	*Phaseolus*	*texensis*	Boerne bean	S2/G2	3, 4	
Fagaceae	*Quercus*	*fusiformis*	Plateau live oak		1, 2, 4, 5	
Fagaceae	*Quercus*	*buckleyi*	Texas red oak		2, 3, 4, 5, 6	
Fagaceae	*Quercus*	*laceyi*	Lacey oak		3	
Fagaceae	*Quercus*	*sinuata ssp. breviloba*	Scalybark oak		1, 2, 5	
Garryaceae	*Garrya*	*ovata ssp. lindheimeri*	Lindheimer's silktassel		1, 2, 3, 4, 5, 6, 7	9
Hydrangeaceae	*Philadelphus*	*texensis v. ernestii*	Canyon mock-orange	S3/G3T3	1, 2, 5	
Hydrangeaceae	*Philadelphus*	*texensis v. texensis*	Texas mock-orange		6	
Hydrophyllaceae	*Phacelia*	*congesta*	Blue curls		4	
Juglandaceae	*Carya*	*illinoinensis*	Pecan		5	
Juglandaceae	*Juglans*	*major*	Arizona walnut		1	
Juglandaceae	*Juglans*	*microcarpa*	Little walnut		4, 6	
Juncaceae	*Juncus*	*texanus*	Texas rush		6	
Lamiaceae	*Hedeoma*	*acinoides*	Annual pennyroyal		4	
Lamiaceae	*Hedeoma*	*drummondii*	Mock pennyroyal		4	
Lamiaceae	*Salvia*	*coccinea*	Tropical sage		1	
Lamiaceae	*Salvia*	*roemeriana*	Cedar sage		4	
Lamiaceae	*Teucrium*	*canadense*	American germander		4, 6	
Linaceae	*Linum*	*rupestre*	Rock flax		4	
Loasaceae	*Mentzelia*	*oligosperma*	stickleaf		5	
Menispermaceae	*Cocculus*	*carolinus*	Snailseed		4	
Oleaceae	*Forestiera*	*pubescens*	Elbowbush		4, 5	
Oleaceae	*Fraxinus*	*sp.*	Ash		5	
Oleaceae	*Ligustrum*	*lucidum*	Wax-leaf privet		7	14
Orchidaceae	*Epipactis*	*gigantea*	Stream orchid		7	6
Orobanchaceae	*Agalinis*	*edwardsiana*	Plateau Agalinis		6	
Orobanchaceae	*Seymeria*	*texana*	Texas Seymeria	S3/G3	2	
Passifloraceae	*Passiflora*	*affinis*	Bracted passionflower		4, 5	
Passifloraceae	*Passiflora*	*lutea*	Yellow passionflower		1, 5	

Family[1]	Genus[1]	Species[1]	Common Name[2]	SGCN Rank[3]	Citation[4]	Frequency Rank[5]
Plantaginaceae	*Maurandella*	*antirrhiniflora*	Snapdragon vine		1, 5	
Plantaginaceae	*Penstemon*	*triflorus*	Hill Country Penstemon	S3/G3T3	5, 6	
Platanaceae	*Platanus*	*occidentalis*	American sycamore		3, 4, 6, 7	5
Poaceae	*Bromus*	*japonicus*	Japanese Brome		4	
Poaceae	*Chasmanthium*	*latifolium*	Inland sea-oats		4	
Poaceae	*Dichanthelium*	*acuminatum ssp. lindheimeri*	Hairy panicgrass		3	
Poaceae	*Dichanthelium*	*oligosanthes*	Heller's rosettegrass		4	
Poaceae	*Limnodea*	*arkansana*	Ozarkgrass		4	
Poaceae	*Muhlenbergia*	*lindheimeri*	Lindheimer's muhly		4	
Poaceae	*Muhlenbergia*	*reverchonii*	Seep muhly		3	
Poaceae	*Panicum*	*virgatum*	Switchgrass		4	
Poaceae	*Schizachyrium*	*scoparium*	Little bluestem		2, 4	
Poaceae	*Tridens*	*buckleyanus*	Buckley's Tridens	S3S4/G3 G4	6	
Poaceae	*Tripsacum*	*dactyloides*	Eastern gamagrass		4	
Primulaceae	*Samolus*	*ebracteatus*	Limewater brookweed		3, 4	
Primulaceae	*Samolus*	*sp.*	Brookweed		6	
Primulaceae	*Samolus*	*valerandi*	Seaside brookweed		4	
Pteridaceae	*Adiantum*	*capillus-veneris*	Maidenhair fern		2, 3, 4, 5, 6, 7	8
Ranunculaceae	*Anemone*	*edwardsiana*	Two-flower Anemone		2	
Ranunculaceae	*Aquilegia*	*canadensis*	Eastern columbine		1, 6, 7	18
Ranunculaceae	*Clematis*	*pitcheri*	Purple leatherflower		4	
Ranunculaceae	*Clematis*	*texensis*	Scarlet leatherflower		3, 4	
Rhamnaceae	*Ceanothus*	*herbaceus*	Redroot		5, 7	17
Rhamnaceae	*Frangula*	*caroliniana*	Carolina buckthorn		4, 7	13
Rosaceae	*Prunus*	*serotina*	Black cherry		4	
Rosaceae	*Prunus*	*serotina ssp. eximia*	Escarpment black cherry		3, 5	
Rubiaceae	*Cephalanthus*	*occidentalis*	Buttonbush		5	
Rubiaceae	*Stenaria*	*nigricans*	Bluets		5	
Salicaceae	*Salix*	*nigra*	Black willow		6	
Sapindaceae	*Ungnadia*	*speciosa*	Mexican buckeye		1, 4, 5, 7	16
Sapotaceae	*Sideroxylon*	*lanuginosum*	Gum bumelia		5	
Smilacaceae	*Smilax*	*bona-nox*	Greenbriar		4	
Styracaceae	*Styrax*	*platanifolius ssp. platanifolius*	Sycamore-leaf snowbell	S3/G3T3	7	2
Styracaceae	*Styrax*	*platanifolius ssp. stellata*	Hairy sycamore-leaf snowbell	S3/G3T3	1, 2, 5, 6	
Thelypteridaceae	*Thelypteris*	*ovata ssp. lindheimeri*	Lindheimer's marsh fern		3, 6	
Tilaceae	*Tilia*	*americana*	American basswood		5	
Ulmaceae	*Celtis*	*laevigata v. reticulata*	Netleaf hackberry		1, 4, 5	
Ulmaceae	*Ulmus*	*crassifolia*	Cedar elm		1, 2, 4, 5	
Urticaceae	*Parietaria*	*pensylvanica*	Pennsylvania pellitory		4	
Verbenaceae	*Callicarpa*	*americana*	American beautyberry		1	
Vitaceae	*Parthenocissus*	*quinquefolia*	Virginia creeper		2, 3, 4, 5	

Family[1]	Genus[1]	Species[1]	Common Name[2]	SGCN Rank[3]	Citation[4]	Frequency Rank[5]
Vitaceae	*Vitis*	*cinerea v. helleri*	Heller's grape		4	
Vitaceae	*Vitis*	*monticola*	Sweet mountain grape		4	

1. Taxonomic classifications follow Tropicos 2021.
2. Common names as used in Enquist 1987a; Wrede 2005; Shaw 2012; and NRCS 2021.
3. Species of Greatest Conservation Needs as ranked by TPWD (2020), using NatureServe rank calculator.
4. 1 = Carr 2004; 2 = Carr 2018; 3 = Carr 2019a; 4 = Carr 2019b; 5 = Cibolo Center for Conservation 2021; 6 = Poole *et al.* 2007; 7 = Taylor and O'Kennon 2013.
5. Frequencies ranked in Taylor and O'Kennon 2013; 1 = most frequent, 23 = least frequent.

2.5. Estimate of potential habitat.

Taylor and O'Kennon (2013, pp. 3–5) developed a potential habitat model based on proximity to mapped watercourses, limestone substrate, and slope greater than 25 percent (discussed also in section 2.4-Habitats and ecology). They used the ESRI ArcMap 10.2 software to classify areas as optimal, sub-optimal, or unsuitable habitat. Figures 2.9 and 2.10 display the resulting shapefiles of optimal and sub-optimal habitat. Our analyses of this data are summarized in Table 2.3. The average size of both optimal and sub-optimal habitats is small, and only 410 areas of optimal habitat greater than 1 ha (2.471 ac) were identified. Due to the map scale in Figure 2.9 (1:1,000,000) and the small size of the potential habitat polygons, optimal and sub-optimal habitats are combined to increase visibility (indicated as a yellow overlay); nevertheless, many habitat polygons are difficult to see at this scale or are obscured beneath the EO symbols. Figure 2.10 is a larger-scale detail (1:25,000) showing the distribution of both optimal and sub-optimal habitats near EO 11. As described in 2.3-Reproduction, viable populations may consist of numerous small groups of individuals that are close enough for a hummingbird to vector pollen between neighboring groups. Figure 2.10 illustrates how geographic clusters of many small habitat areas may collectively support viable populations.

Table 2.3. Summary of optimal and sub-optimal habitats (Taylor and O'Kennon 2013).

Statistic	Sub-Optimal Habitats		Optimal Habitats	
	Ha	Ac	Ha	Ac
Total Area	40,162	99,241	2,564	6,336
Maximum Area	60	149	5	13
Average Area	0.29	0.73	0.15	0.37
Number of Areas	136,879		17,052	
Number > 1.0 ha	8,337		410	

2.6. Populations, Source Features, Element Occurrences, and geographic distribution.

USFWS assesses a species' viability based on the resilience, redundancy, and representation of its populations (described in Section 1). Simply stated, populations are groups of interbreeding organisms of a particular taxon. Measurements of the size, number, and distribution of populations require their delineations, which are defined by barriers to gene flow between individuals. For terrestrial plants, the barriers to gene flow are distances greater than the ranges of pollination and seed dispersal, as well as reproductive isolation due to differing phenologies, pollinators, or genetic incompatibilities. Thus, a comprehensive understanding of plant populations derives from data on the habitat requirements, phenology, pollination systems, pollinators, the longevity of pollen viability, seed dispersal mechanisms, the persistence of soil seed reserves, breeding systems, and population genetics.

The TPWD Texas Natural Diversity Database (TXNDD) maintains geographic and population data of plant and animal species of conservation concern in Texas. This data is contributed and used by many entities involved in conservation, including TPWD and other state agencies, federal agencies, academic researchers, environmental consultants, non-profit conservation organizations, and private individuals. Data for each species is organized by standard geographical units for populations and habitats called Source Features (SFs) and Element Occurrences (EOs) (NatureServe 2002). Source Features and EOs are geographic locations where a species has been recorded one or more times. They may be displayed as points, lines, or polygons buffered by their estimated geographic precision. One or more SFs that are separated by less than the recommended minimum EO separation distance may be combined into a single EO. When specific data about pollination and seed dispersal ranges are unavailable, the recommended default separation distance between plant EOs is 1 km (0.6 mi) for gaps of unsuitable habitat or unoccupied suitable habitat and 0.5 km (0.3 mi) for gaps of cultural vegetation (i.e., planted by humans; NatureServe 2002, p. 26). The reported populations occur or occurred within, but not necessarily throughout, the buffered EO points, lines, and polygons (see Figure 2.9).

For big red sage and other plant species of conservation concern, we use the EO standard as the unit of analysis for two reasons. First, the use of a single standard benefits coordination among all the partners concerned with the conservation and management of a species. Additionally, the comprehensive understanding of populations described above requires many scientific investigations spanning many years. Furthermore, since about 95% of Texas is privately owned (summitpost.org 2023; Texas A&M University Natural Resources Institute 2023), access to conduct population studies may not be granted. EOs are practical approximations of populations, based on the best available scientific information, that allow us to make timely decisions and conduct conservation actions now. Throughout this document, SF and EO refer specifically to the data compiled by the TXNDD, as shown in Table 2.4 and Figure 2.9; we use the term "population" in the more general sense, including occurrences that have not been documented, as well as discussions about the requirements of populations.

<u>Descriptions of big red sage Element Occurrences.</u>

The following list includes all big red sage EOs provided to us in the most recent update of big red sage in the TXNDD (2021), together with relevant information about these populations we have obtained from additional sources. Table 2.4 summarizes the EO data and TXNDD EO ranks (possible ranks are excellent, good, marginal, poor, extant/present, historical/no field information, destroyed/extirpated, and obscure). Note that, for brevity, we use the EO numbers in the text and maps of this document, while the following list and Table 2.4 also link these with the EO IDs, which are unique identifiers in the TXNDD database. We include in this list the TXNDD EO ranks as well as our assessments of current conditions, which we develop in section 5. We are unable to assess the current conditions of some SFs and EOs due to uncertainty of the geographic locations or lack of access to sites on private properties. When we cannot determine whether previously documented populations are extant or extirpated, they are not included in the assessments of current or future viability and are therefore designated as “non-contributing”.

Element Occurrence 1 (EO ID 3182; Barron Creek). H.B. Parks collected several specimens here from 1938 until 1941; the herbarium specimens say only “Barron Creek, Kendall County”. Although the exact location is not known, the TXNDD (2021, pp. 1–2) indicates this site is at Waring, along the Guadalupe River, in Kendall County. Taylor and O’Kennon (2013, pp. 8) list this EO as “habitat not found.” Consequently, this population’s EO rank is historical. However, there are no watercourses in Kendall County called Barron Creek, but there is a Barons Creek in Gillespie County that flows through Fredericksburg and joins the Pedernales River 10 km (6.2 mi) north of Kendall County. Therefore, it is likely that Parks simply wrote down the wrong county name. We conclude that the location of this EO, near Waring, is incorrect; the actual site of Parks’ collections has not been monitored, and in our assessment this EO is non-contributing.

Element Occurrence 2 (EO ID 7288; north bank of Guadalupe River at Kerrville). A.A. Heller collected several herbarium specimens here in 1894. He indicated that about 50 plants occurred on a moist limestone ledge. There are no subsequent records from this EO, which now lies within the developed areas of Kerrville. Taylor and O’Kennon (2013, pp. 8) list this EO as “habitat not found”, and the EO is ranked historical. In our assessment, we conclude that this EO was extirpated.

Element Occurrence 3 (EO ID 2294; Verde Creek south of Kerrville). In 1946, D.S. Correll collected a specimen here from seepage in a limestone bank above the creek. This Verde Creek flows into the Guadalupe River 21.6 km (13.4 mi) below Kerrville; there is another Verde Creek that is a tributary of Hondo Creek in Medina County. There are no subsequent records from this EO. Taylor and O’Kennon (2013, pp. 8) list this EO as “habitat not found”, and the TXNDD (2021, p. 8) ranks this EO as historical. Nevertheless, areas of extant habitat still occur along Verde Creek south of Kerrville, and since the exact collection site was not specified, we conclude that this EO is non-contributing.

Element Occurrence 4 (EO ID 521; Turtle Creek south of Kerrville). In 1943, V.L. Cory collected specimens of big red sage on Turtle Creek; the specimen labels (TEX22823; GH 1696434) state these were collected 14 miles southwest or west of Kerrville. If Cory measured the distance from Main Street in Kerrville along Highway 16 south to Turtle Creek, and then west along whatever local roads followed Turtle Creek at that time, this location would have been in the upper portions of the creek. O’Kennon collected specimens from a small limestone bluff along lower Turtle Creek in 1991, 1993, and 1994; he estimated this population had 25 to 35 individuals (Taylor and O’Kennon 2013, p. 4). The specimen labels state that the site is 6 miles south of Kerrville, 4.1 miles east of Highway 16. Therefore, the Cory and O’Kennon collection sites must be about 12.5 km (7.8 mi) apart. The Cory and O'Kennon sites are included in EO 4 as SFs 15836 and 28460, respectively, and the EO Rank is extant (TXNDD (2021, p. 9). Taylor and O'Kennon (2013, p. 8) indicate that the habitat was intact at O'Kennon's collection sites, but they did not observe big red sage there. We conclude that this SF is extirpated. We have no reports from the upper Turtle Creek SF since Cory's collections in 1943. Potential habitat models, discussed in Section 5.2, reveal that substantial amounts of good and excellent habitat remain along upper Turtle Creek. Nevertheless, due to the lack of recent surveys from this area, we conclude that the current condition of this SF is non-contributing.

Element Occurrence 5 (EO ID 6141; Cibolo Bluffs). In June 1849, F.J. Lindheimer collected big red sage from at least two locations. The label of one specimen (GH01696431) states, "Fl. dark purple—2-3-5 feet high rocky or gravelly banks of streams—thickets—Cibolo". Although the collection site remains unknown, Cibolo clearly refers to Cibolo Creek and not the community in Guadalupe County, which was not called by this name until the 1870s (Weinert 2021, p. 1). Cibolo Creek was called Arroyo del Cíbolo or Río del Cíbolo (accent on the first syllable) by Spanish settlers in 1721 (Anonymous 2022); the term cíbolo, meaning buffalo, probably originates from an Indigenous language (Forest Service 2022).

In 1916, Ernest J. Palmer collected specimens from "moist rich ledges, Upper Cebelo Creek, near Boerne, Kendall County, Texas". The exact location of the Palmer collection (SF 15830) is unknown. However, on May 10, 2004, Pasztor (2004, all) and Ward (2009, p. 1) discovered a relatively large population along the south side of Cibolo Creek at Cibolo Bluffs. TXNDD (2013, pp. 12–15) has designated two SFs at Cibolo Bluffs (28786 and 31273), and an additional SF (28787) is on adjacent private land; the EO Rank is extant and our assessment of current conditions is also extant. The 10.5-ha (26-ac) Cibolo Bluffs property is now owned by Cibolo Center for Conservation (formerly Cibolo Nature Center), which is organized as a 501(c)(3) non-profit organization called Friends of Cibolo Wilderness. The population of big red sage is scattered along a steep bluff of Cretaceous limestone formed from a fossil reef of rudists and corals (Pasztor 2004, p. 1; Carr 2018, p. 1; see Figure 2.1.c). The exposed fossil reef is riddled with holes, and the sharp-edged, uneven surface of the limestone is difficult for people and ungulates to walk on. The sponge-like nature of this substrate perched above less permeable Glen Rose limestone creates many seepage sites along the bluff. In addition to big red sage, Carr (2019c, all) documented a remarkable diversity of rare and endemic plant species at this site. This may be due to the inability of white-tailed deer and other ungulate browsers to traverse the treacherously jagged surface and steep bluff.

The Cibolo Bluffs population has been monitored annually (Cibolo Center for Conservation 2021; Figure 2.7) since 2008 by volunteers and trustees of a separate 501(c)(3) non-profit organization, Cibolo Preserve, which manages an adjacent property. This is the best-protected population of big red sage, and one of the largest and most stable. Nevertheless, the harmonic means of population sizes has declined from 146 individuals in 2008–2014 to 100 individuals in 2015–2021. Similarly, the harmonic means of total flower stalks has declined from 63 in 2012–2014 to 25 in 2015–2021. We intuitively expect that drought would affect population size and reproductive output, but these measures of population size and health were remarkably resilient to the severe droughts of 2003, 2005, 2006, 2008, and 2011. The population declined abruptly after 2014 but has been relatively stable since then. In May 2015 more than 23 cm (9 in) of rain fell in Boerne in 24 hours (City of Boerne 2021). Considering the proximity of the big red sage plants to the normal water level and the nearly vertical slopes of the canyon, this population must have been inundated during the flood, which likely explains the sudden population decline that year. Cibolo Preserve trustees informed us that in March 2019 a swallet—a sinkhole within the bed of a stream—suddenly opened in Cibolo Creek about 500 m (1,640 ft) upstream from the big red sage population. About 0.3 m^3 (10 ft^3) per second of water plunge into the swallet, leaving the creek bed downstream from the swallet dry except during periods of high flow. Currently, we do not know what effect this change in stream flow will have on the population of big red sage.

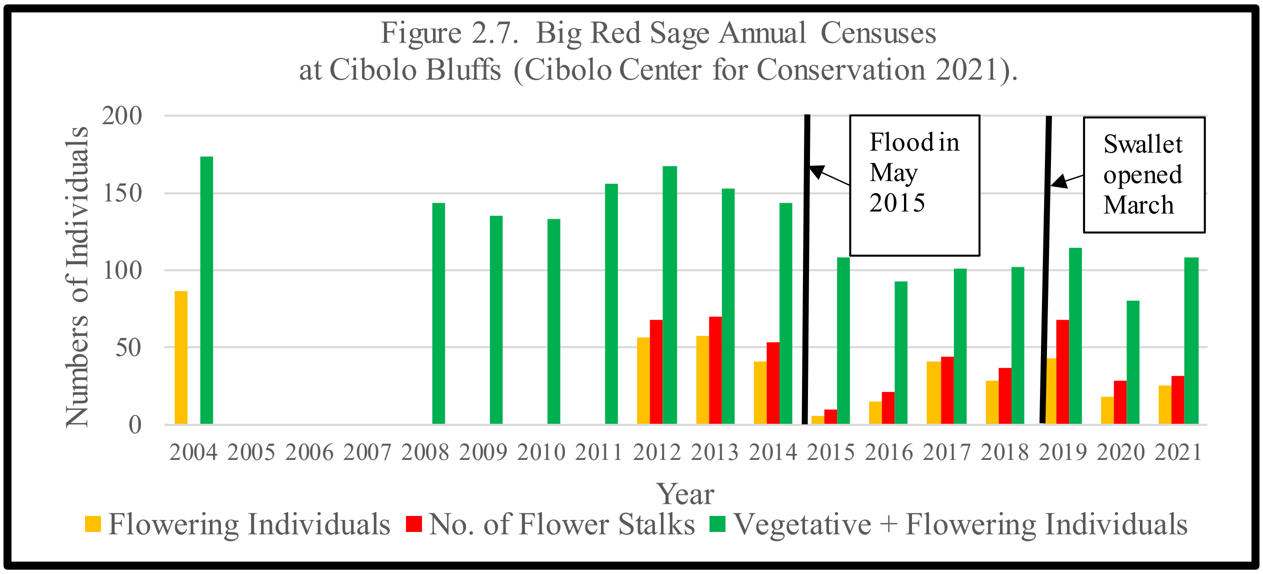


Figure 2.7. Big red sage annual censuses at Cibolo Bluffs (Cibolo Center for Conservation 2021).

Element Occurrence 7 (EO ID 6980; Sutherland Springs). Dr. Edward Palmer (not to be confused with Ernest J. Palmer, mentioned above) collected several specimens of big red sage in August 1879. The labels of these specimens state, "Southerland Springs, Wilson County, Texas; 25 miles southeast of San Antonio..." However, nineteenth-century botanists often labeled plants not with the actual collection sites but with the place of shipment to a herbarium. Sutherland Springs, on the lower Cibolo Creek, is more than 40 km (25 miles) downstream from the typical Edwards Plateau habitats of this species. All confirmed populations of big red sage occur in close association with seepages along karstic limestone bluffs, but these geological features do not occur near Sutherland Springs. Taylor and O'Kennon (2013, p. 6) and Carr (2019c, p. 2) concluded that this specimen must have been collected elsewhere. We concur that the actual collection site is unknown; in our assessment, this EO is non-contributing.

Element Occurrence 8 (EO ID 1579; Frio Water Hole). In 1895, R.J. Hill collected specimens of big red sage at "Frio Water Hole, Edwards County", according to the specimen labels. TXNDD (2021, p. 18) places this EO in Kerr County, along the uppermost tributary arroyos of the East Frio River. There are no records from this site after 1895. Modern topographic maps, such as the U.S. Geological Survey Hillcrest Ranch 7.5-minute quadrangle, do show a "Frio Water Hole" at this uninhabited location, about 33 km (20 miles) north of Leakey. Taylor and O'Kennon (2013, p. 8) were unable to access this location; consequently, TXNDD (2021, p. 18) ranks this EO as historical. However, Frio Water Hole was an inhabited community in Edwards County that had a post office until 1888 (Smyrl 1995); the former town site is in the portion of southeastern Edwards County that became Real County in 1913. Descriptions of Frio Water Hole and the distances from its post office to other post offices indicate that this must have been near what is now called Blue Hole (EO 21), about 12 road miles north of Leakey. We conclude that the R.J. Hill collection site was not in Kerr County, as indicted by the current EO location. Considering the abundance of intact habitat along the upper Frio River, it may indeed be the same site as EO 21 or one of the other deep pools in this stretch of the East Frio River. Consequently, we assess this EO as non-contributing.

Element Occurrence 10 (EO ID 7510; Bear Creek and Pedernales River). Gustav Jermy was a Hungarian geologist and botanist who moved to Texas in the 1870s (Jermy.org 2022). Jermy collected a specimen of big red sage along “Bears Creek”, Gillespie County. Although the specimen label lacks a date, the specimen, number 710, was among more than 5,000 of his specimens purchased by Missouri Botanical Garden in 1897. Hence, the collection would have been made between 1870 and 1897, and given the low number, probably occurred early in that period. TXNDD (2021, p. 21) assigns this collection as SF 15838 of EO 10. Since the exact location is unknown, the EO includes all tributaries of Bear Creek. In 1990, O’Kennon (Taylor and O’Kennon 2013, pp. 4, 6) observed about 5 or 10 big red sage individuals at the confluence of Bear Creek and the Pedernales River (SF 28481); by 2013, the habitat at that site had been modified and the species was no longer evident (Taylor and O’Kennon 2013, p. 8). TXNDD (2013, p. 21) ranks the entire EO as extant. Nevertheless, we conclude that the O’Kennon SF is extirpated. Since 125 years have passed since Jermy’s collection, we assess that SF as non-contributing.

Element Occurrence 11 (EOID 6190; Lost Maples SNA). Enquist observed big red sage at Lost Maples SNA in about 1980, and, in August 1987, he and other botanists returned and documented 12 individuals growing in 3 distinct groups (Enquist 1987b, pp. 4–5). This EO has been monitored in 6 years between 1987 and 2019; its 5 SFs (2831, 4439, 6190, 15387, and 28456) totaled 23 individuals in 1988. By 2013, the population had declined to four individuals in two SFs (Taylor and O’Kennon 2013, p. 8). In 2019, botanists collected samples from this EO for the genetic study reported in Section 2.7 (Hoban and Garner 2019); they found only 3 individuals in 2 SFs (Carr 2019a, pp. 1–3). Although the habitat is intact and the site is protected as a State Natural Area, this population has declined 87 percent over 31 years. Factors that may have contributed to this decline include herbivory by over-abundant white-tailed deer and introduced ungulates, and the demographic and genetic consequences of small population sizes. Since the collection sites have been publicized, it is also possible that illicit collection may also have contributed to this decline. In our assessment, we concur with the TXNDD EO rank of extant.

Element Occurrence 14 (EO ID 76; Frederick Creek at Interstate 10). In July 1984, O’Kennon collected the first specimen (O’Kennon 770) of big red sage from this site, which is beneath the Interstate 10 bridge over Frederick Creek on the southwest side of Boerne. This location is identified as one of two SFs (15826) of EO 14 (TXNDD 2021, p. 31). In about 1986, native plant enthusiasts collected seeds from this population, which were propagated and sold at Madrone Nursery in Hays County (Enquist 1987b, p. 5; Ward 2009b, p. 3). In 1987, Enquist observed at least 250 individuals here in 3 separate groups and collected a herbarium specimen

(TEX23770). Poole (1987) judged that the population of big red sage at this site had about 2,000 individuals that year, of which 90 percent were flowering. Figure 2.8 displays the results of annual censuses of this EO from 1991 through 2013; note that censuses were not reported from 2009 through 2011. In 1991 and 1992 there were 464 and 576 individuals, respectively, of which 105 and 258 individuals flowered. The numbers of flowering and non-flowering individuals have steadily declined since 1993. The last flowering individuals were observed in 2003, and by 2008 only 5 non-flowering individuals remained. In 2012 observers did not find any big red sage plants at the original site. However, in 1990, a herbarium specimen (O'Kennon 8090) was collected from a group of big red sage on adjacent private land; that group numbered about 200 individuals (Taylor and O'Kennon 2013, p. 6; TXNDD 2021, p. 35). This adjacent site is the other SF (28459) of EO 14, and these numbers are also shown in Figure 2.8. In 2013 this adjacent site had a total of 401 individuals, of which 216 were flowering (TXNDD 2021, p. 35). TXNDD ranks this EO as extant. In our assessment, one SF is extirpated, and the other is extant. The decline of the SF 15826 population has been attributed to a major flood that impacted this site in June 1997 (Ward 2009b, p. 4; Ward 2010, p. 2; Taylor and O'Kennon 2013, p. 10) as well as to competition from introduced plants and browsing by white-tailed deer and introduced ungulates (Ward 2010, p. 2). An additional factor is the vulnerability of this easily accessible site to plant collectors. In 1988, the State Department of Highways and Public Transportation placed signs at this site stating, "Non Mowing Area", "Wildflower Research Area", and "Property of State of Texas, Penalty for Private Use." On June 27, 1989, maintenance personnel found the signs pulled out of the ground with cut flowering stems of the big red sage placed on top of them. They observed evidence of digging and cutting of the plants and provided to USFWS photographs of cut stalks of big red sage (Collier 1989, pp. 1–2). Therefore, illicit collection of seeds and whole plants has also impacted this population.

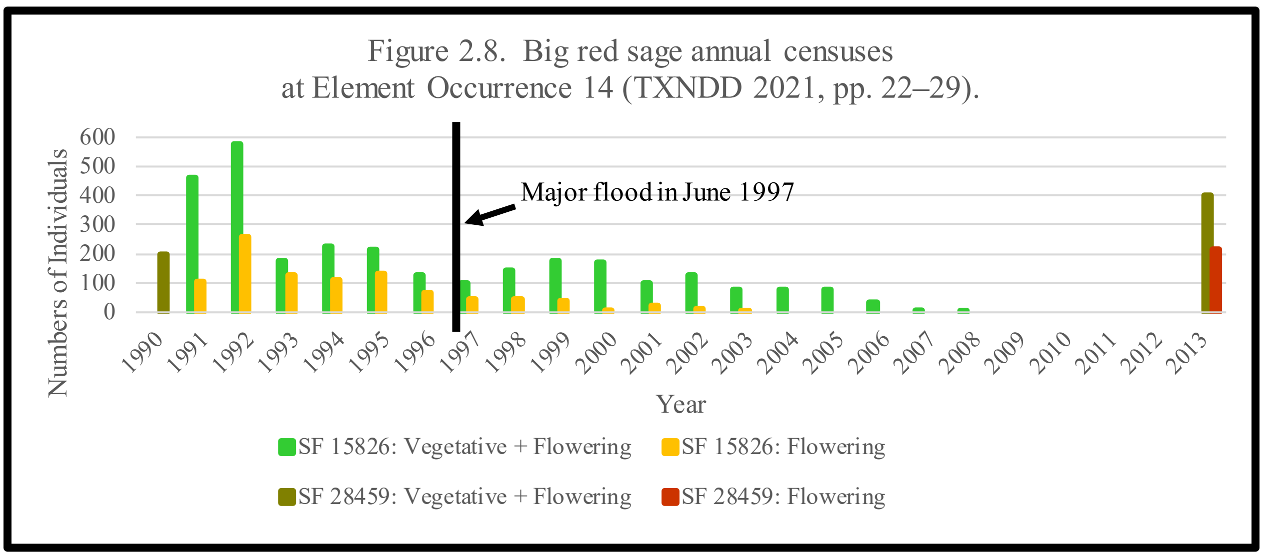


Figure 2.8. Big red sage annual censuses at Element Occurrence 14 (TXNDD 2021, pp. 22–29).

Element Occurrence 15 (EO ID 2092; Big Joshua Creek west of FM 289). In 1988 Enquist observed 20 immature and 5 flowering individuals associated with seep moisture on a steep, north-facing limestone bluff on the south side of Big Joshua Creek (Ward 2009b, p. 3; TXNDD 2021, p. 38). In 1991 and 1996 observers reported three flowering individuals. By 2003, the bluff had collapsed due to apparent natural causes and the population had been buried in the landslide. Taylor and O'Kennon (2013, p. 9) found no individuals here in 2013. Although ranked as extant (TXNDD 2021, p. 36), we conclude that this EO is extirpated.

Element Occurrence 16 (EO ID 3908; Wilson Hollow along the Dry Frio River). In July 1991, Keeney observed two individuals of big red sage in this moist canyon (TXNDD 2021, p. 40). Taylor and O'Kennon (2013, p. 9) contacted landowners but were not granted access to survey this privately owned site. Since the habitat appears to be intact, this EO is ranked extant by TXNDD (2021, p. 39) as well as in our assessment.

Element Occurrence 17 (EO ID 8807; Neal's Lodges). This occurrence was based on a casual observation in 2006 by a leading Texas botanist, but no voucher specimens were collected. Taylor and O'Kennon (2013, pp. 6, 9) visited the exact site but found only a different, red-flowered species, tropical sage (*Salvia coccinea*); they observed that the site did not resemble typical big red sage habitats and concluded that this report may have been a misidentification. Although this EO is ranked extant in the TXNDD, we concur that this unconfirmed report was likely misidentified.

Element Occurrence 19 (EO ID 8999; Comanche Springs). In June 1849 Lindheimer collected a number of duplicates of his collection number 1092 from a location described on his labels as "San Antonio" and "Comanche Spring: New Braunfels, etc." Although there are several "Comanche Springs" in Texas, Ward (2009b, p. 2) concluded that this particular Comanche Spring was near the house of John Meusebach, on the upper Salado Creek, where Lindheimer was a guest at that time. Another German botanist, Ferdinand von Roemer (1849, p. 223), also described this spring on the upper Salado Creek. This site is now within the 11,327 ha (27,990 ac) Camp Bullis, a military training facility of Joint Base San Antonio. Due to development of the spring site, the TXNDD rank is historical. We conclude that this population was extirpated.

Element Occurrence 20 (EO ID 12592; North Fork of the Guadalupe River). In July 1991 O'Kennon observed from 18 to 30 big red sage plants along the North Fork of the Guadalupe River (Taylor and O'Kennon 2013, p. 4). TXNDD (2013, pp. 49–51) now recognizes 5 SFs (28086, 28457, 28458, 31245, and 31246) of this EO over a span of about 1.4 km (0.9 mi) on both sides of the river. Most of these SFs have only been monitored once. The largest numbers were reported at SF 28086 in 2010: 161 individuals, of which 46 were flowering; this SF was described by Ward (2010, pp. 1–2). In 2013, observers recorded 70 individuals, including 21 in flower, at SF 28457; many of these plants were on a ledge about 2.3 m (7.5 ft) above the water level, and were vulnerable to flooding. In 2016, observers recorded 8 individuals at 2 additional locations. In 2019, Carr (2019b) observed 12 individuals on a stream-side ledge on private property along the river and collected leaf samples from 6 rosettes for the genetic study reported in Section 2.7 (Hoban and Garner 2019). We concur with the TXNDD rank of extant.

Element Occurrence 21 (EO ID 12722; Blue Hole, East Frio River). TXNDD (2021, pp. 53–55) recognizes three SFs (28415, 28416, and 37234) of this EO. All are located on private property owned by an NGO that provides free educational retreat facilities to underserved youth and families. This EO was reported by a board member of the NGP foundation in 2015. From that year through 2018, 29 individuals have been observed, but the most seen in any one year was 17; the three SFs have never all been monitored in the same year. As discussed above, R.J. Hill's

1895 specimen is likely to have been collected at or near EO 21. We concur with the TXNDD rank of extant for this EO.

Element Occurrence 22 (EO ID 12746; Pedernales River at Friedrich Rd). O'Kennon observed 20 to 25 big red sage individuals at this location in 1990; by 2013, the habitat at this site had been modified, and the species was not observed (Taylor and O'Kennon 2013, pp. 4, 8). This site may be near the site of Lindheimer's type collection in 1845 (Ward 2009a, p. 2; Ward 2009b, pp. 3–4; Taylor and O'Kennon 2013, pp. 6, 8). Although TXNDD ranks this EO as extant (TXNDD 2021, p. 56), we conclude that it has now been extirpated.

Element Occurrence 23 (EO ID 12747; South Grape Creek east of Luckenbach). O'Kennon observed an undisclosed number of big red sage plants at this location in 1990 and 1991; in 2013, the habitat was still intact, but the species was not observed (Taylor and O'Kennon 2013, pp. 4, 9). TXNDD (2021, p. 58) ranks this EO as extant; nevertheless, we conclude that it has now been extirpated.

Element Occurrence 24 (EO ID 12748; canyon of tributary of Frederick Creek 5 miles west of Boerne). This population on private property was first reported to TPWD in 2007. In 2010, botanists recorded 62 big red sage individuals in two locations, including 11 flowering plants (TXNDD 2021, p 61; SF 28783). Taylor and O'Kennon (2013, p. 6) requested, but did not receive landowner permission to monitor this site; however, they report that Pasztor and Kirby observed 54 individuals near this location in 2010 (2013, p. 9), listed by the TXNDD as a separate SF (28482). We interpret this data to mean that 62 individuals were observed at one SF in 2010 and an additional 54 were observed at another SF in 2013, totaling 116 in this EO. We concur with the TXNDD rank of extant for this EO.

Table 2.4. Element Occurrence records of big red sage (TXNDD 2021).

EO No.	EO ID	Site Name	County	1st Obs	TXNDD Rank[1]	Maximum Population	Maximum Year	Most Recent Population	Most Recent Survey	Source Features
1	3182	Barron Creek	Kendall	1938	H					3182
2	7288	Guadalupe River at Kerrville	Kerr	1894	H	50	1894	50	1894	7288
3	2294	Verde Creek S of Kerrville	Bandera/ Kerr	1946	H					15835
4	521	Turtle Creek S of Kerrville	Kerr	1943	E	30	1994	0	2013	15836, 28460
5	6141	Cibolo Creek near Boerne	Kendall	1916	E	174	2004	170	2013	15830, 28786, 28787, 31273
7	6980	Sutherland Springs	Wilson	1879	H					6980
8	1579	Frio Waterhole	Kerr	1895	H					1579
10	7510	Confluence of Bear Creek and Pedernales River	Gillespie	1889	E	5	1990	0	2013	15838, 28481
11	6190	Can Creek and Hale Hollow at Lost Maples SNA	Bandera/ Real	1987	E	23	1988	4	2013	2831, 4439, 6190, 15837, 28456
14	76	Frederick Creek at IH10	Kendall	1984	E	576	1992	401	2013	15826, 28459
15	2092	Big Joshua Creek	Kendall	1988	E	25	1988	0	2013	2092
16	3908	Wilson Hollow	Real	1991	E	2	1991	2	1991	3908
17	8807	Neal's Lodges, Frio River	Uvalde	2006	E	3	2006	0	2013	12629
19	8999	Comanche Springs on Salado Creek	Bexar	1849	H					15857
20	12592	North Fork Guadalupe River above FM 1340	Kerr	1991	E	161	2010	8	2016	28086, 28457, 28458, 31245, 31246

EO No.	EO ID	Site Name	County	1st Obs	TXNDD Rank[1]	Maximum Population	Maximum Year	Most Recent Population	Most Recent Survey	Source Features
21	12722	Blue Hole	Real	2015	E	17	2017	15	2018	28415, 28416, 37234
22	12746	Pedernales River at Friedrich Rd	Gillespie	1990	E	20	1990	0	2013	28479
23	12747	South Grape Creek east of Luckenbach.	Gillespie	1990	E	2	1991	0	2013	28480
24	12748	Canyon near Frederick Creek	Kendall	2007	E	111	2010	54	2013	28482, 28783

1. Ranks: H = Historical; E = Extant

2.7. Population genetics.

Hoban and Garner (2019, pp. 1–2) investigated genetic variation within and between four wild populations and 3 ex-situ propagated sources of big red sage. Botanists collected DNA samples for this study from 62 individuals at EO 5, EO 11, EO 20, and an undisclosed site in Real County, as well as 109 individuals from two commercial nurseries and the Lady Bird Johnson Wildflower Center. It is likely that at least one propagated source originated from EO 14; unfortunately, the origins of the other propagated sources could not be determined with certainty. After an initial evaluation of about 100 microsatellite DNA markers that had been developed for other *Salvia* species, genotyping was attempted with 26 markers (p. 2). Only a single marker was heterozygous and amplified consistently for *S. pentstemonoides*; however, this marker was present at 2 loci. This data was used to determine the following genetic statistics: The numbers of unique genotypes, which is a measure of genetically unique individuals; the ratio of unique genotypes to total individuals, which is the proportion of a population that is genetically unique; heterozygosity, which ranges from 0 (highly inbred) to 1 (highly outcrossed); and numbers of alleles, which are alternate forms of a gene; the numbers of alleles were also corrected to represent the samples of differing size. Table 2.5 presents these summary statistics.

Table 2.5. Genetic summary statistics for wild and propagated big red sage (reprinted from Hoban and Garner 2019, p. 3).

Statistic	**Wild populations**	**Propagated populations**
Total samples	62	109
Unique genotypes	16	7
Ratio of unique genotypes to total samples	0.258	0.064
Heterozygosity	0.422	0.292
Number of alleles	9	5
Number of alleles corrected for sample size	9	4.91

The lack of allelic diversity in most of the markers tested suggests low genetic diversity at the species level but could be due in part to the development of the markers for other *Salvia* species (p. 3). Among the 3 propagated sources, the ratio of unique genotypes to sample size ranged from 0.074 to 0.167, and the heterozygosity ranged from 0.036 to 0.307. The ratio of unique genotypes to sample size among the 4 wild populations ranged from 0.244 to 0.750, and heterozygosity ranged from 0.205 to 0.496. Collectively, the wild populations had more than twice as many unique alleles despite the much smaller sample sizes. Hence, although the overall genetic diversity is low, the wild populations preserve more adaptive capability and had lower levels of inbreeding than the propagated plants. This is not surprising, because propagated populations typically originate from a small number of source plants, and subsequently, due to small population sizes and selective breeding, they become even less diverse through the loss of rare alleles. Hoban and Garner (pp. 4–6) also calculated fixation index (Fst) statistics, which indicate levels of genetic differentiation between populations; however, the authors state that these results should be interpreted with caution due to the very small number of markers and small sample sizes of 3 of the wild populations. This revealed greater differentiation between the wild populations than between the propagated sources. Wild populations had several genotypes that were not present in the propagated populations. One propagated population had very low genetic diversity; this may explain the very low amount of seed production in several propagated populations, particularly if the species is an obligate outcrosser.

Based on these findings, Hoban and Garner made the following recommendations (pp. 6–7):

- To prevent the likely continued loss of genetic variation from small populations, first improve habitat conditions, then augment the remaining wild populations to substantially more than 500 individuals.

- To reduce the risk of extinction, establish new self-sustaining populations, as has been done successfully with the Tennessee coneflower (*Echinacea tennesseensis*), another species with few populations and low genetic variation.

- Due to the similarity of occupied habitats and historical gene flow between them, outcrossing between populations is unlikely to be harmful; however, conduct outcrossing trials to ensure that these produce viable progeny. Augment gene flow and genetic variation through the introduction of seeds from other compatible populations.

- Monitor wild populations annually to determine population sizes, demographic trends, and rates of natural seed set.

- Search for new populations and genotype additional wild populations.

- Increase the genetic representation of conservation collections in botanical gardens through additional seed collection from wild populations. Seed collection should be done by conservation professionals to prevent harm to wild populations, collect source population data, and maintain high seed viability.

- Develop additional genetic markers specifically for *Salvia pentstemonoides*, or use next-generation sequencing, to improve genotype resolution and to identify additional wild genotypes.

In comparison, Erbano *et al.* (2015) used Inter Simple Sequence Repeat (ISSR) molecular markers to investigate the genetic variability and population structure of *Salvia lachnostachys*, a rare endemic species of Paraná, Brazil that is threatened by over-collection for traditional medicinal uses. They identified 152 polymorphic amplified bands among three populations studied (pp. 7840–7843) and determined that the species has high levels of genetic variability (p. 7844). Most of the genetic variation for this species occurred within populations rather than between them (pp. 7842–7843), which the authors attribute to high rates of gene flow between populations and high levels of outcrossing (pp. 7844–7845). This study suggests that this rare Brazilian *Salvia* has far greater genetic diversity than *S. pentstemonoides*. However, the difference may be due in part to the small sample sizes and the very low number of genetic markers used in the Hoban and Garner study.

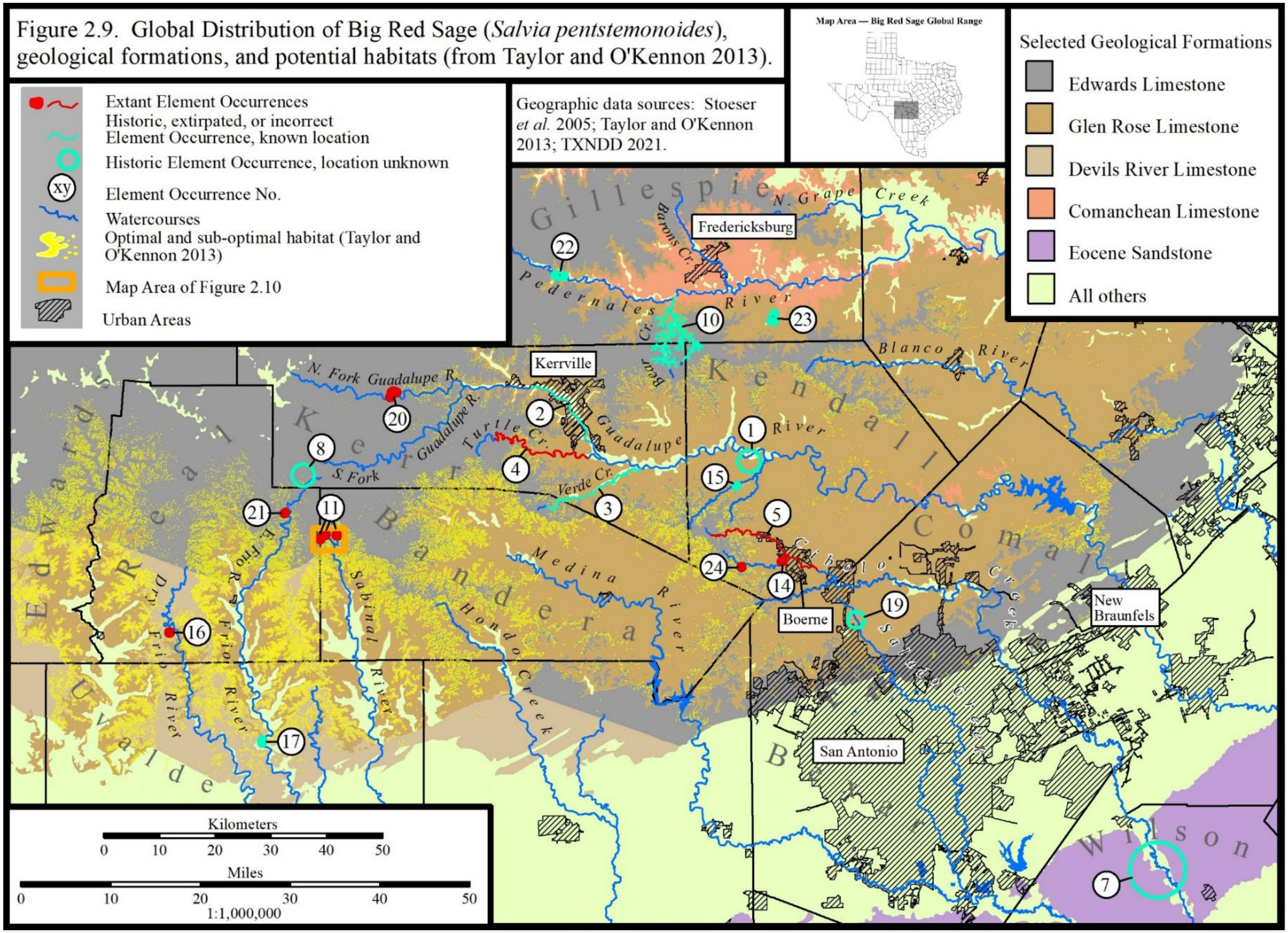


Figure 2.9. Global distribution of big red sage (*Salvia pentstemenoides*), geological formations, and potential habitats (from Taylor and O'Kennon 2013).

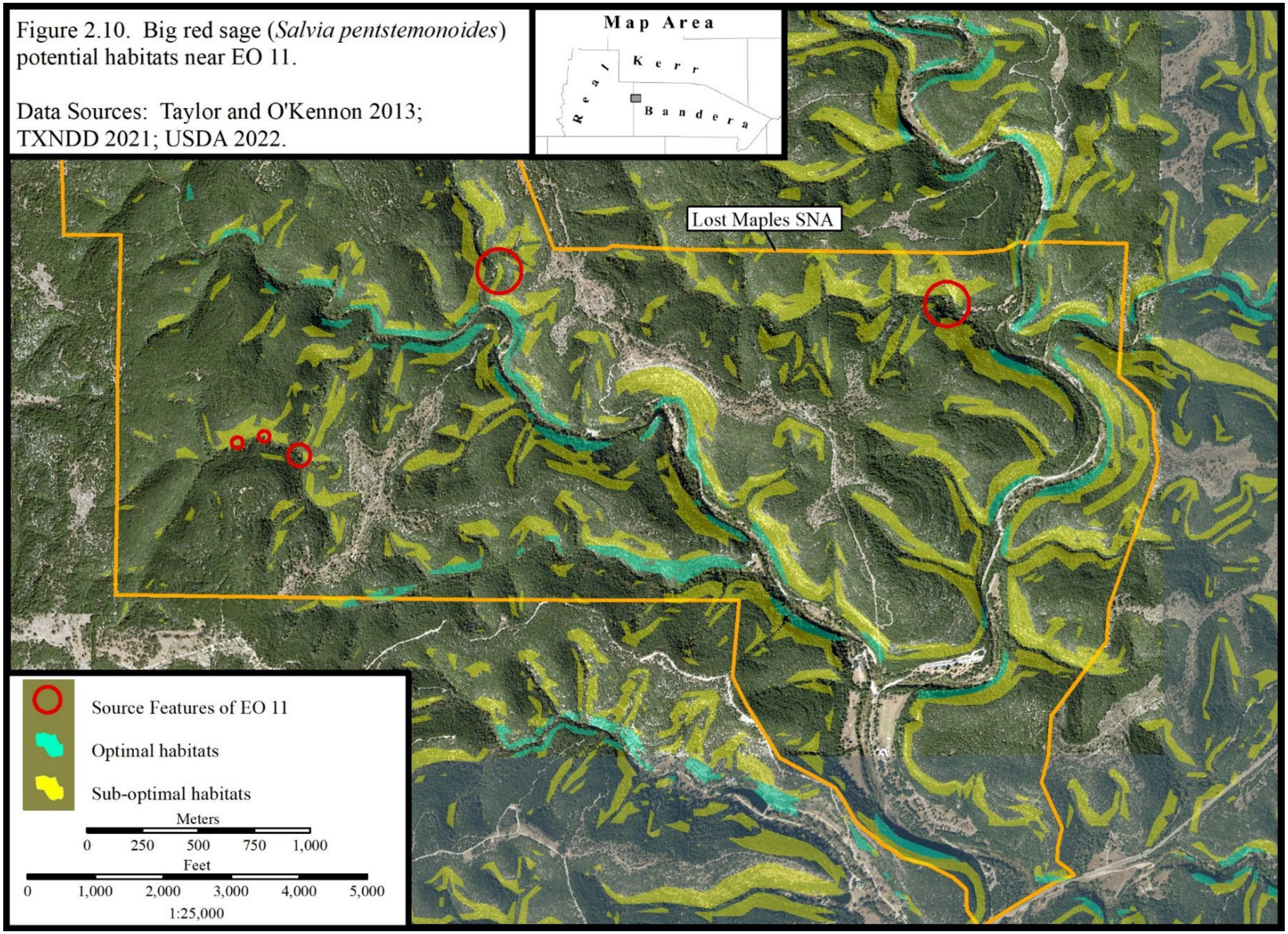


Figure 2.10. Big red sage (*Salvia pentstemenoides*) potential habitats near EO 11.

3. SUMMARY OF INDIVIDUAL, POPULATION, AND SPECIES REQUIREMENTS

This summary is based on the species information cited and described in Section 2.

3.1. Individual requirements.

Habitats: Individuals establish on bluffs, ledges, and slopes along watercourses (including first-order streams) where soil moisture is relatively persistent. Growth and flowering require the maintenance of soil moisture through rainfall and/or seepage through fissures and cavities in the limestone substrate. The persistence of seep moisture in turn requires infiltration into porous rock strata that is aided by large areas of intact native vegetation and where there are relatively few impermeable surfaces.

Reproduction: Flowering occurs opportunistically from May through November in response to rainfall and the presence of soil moisture. Individuals are effectively pollinated by hummingbirds; black-chinned hummingbirds are the most abundant species throughout the range and flowering period of big red sage. It has not been determined whether outcrossing is required for fertilization and seed set. Some propagated populations that have low levels of genetic diversity produce little or no viable seed, which may indicate an outcrossing requirement. Even if capable of self-pollination, outcrossed individuals are less likely to suffer from inbreeding depression.

Persistence: Individuals can live at least 10 years, and they may produce multiple rosettes that sprout from rhizome-like stems. Hence, through vegetative reproduction, a single individual may give rise to many individuals that persist long after the original plant dies. However, as described in Section 4.1, browsing by native white-tailed deer, introduced ungulates, and goats is a significant cause of mortality; most individuals that have persisted occur in niches that are inaccessible to these herbivores.

3.2. Population requirements

Minimum Viable Population (MVP) size. Populations of big red sage must be large enough to have 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. This metric of population resilience is called minimum viable population (MVP). This estimate of population viability is applicable to individual populations, as defined in Section 2.6.

Table 3.1 is an adaptation of a method for estimating plant MVPs published in Pavlik (1996, p. 137). Species with traits that all fall under column A would have MVPs of about 50 individuals. Those with traits that all ascribe to column C would have MVPs around 2,500 individuals. We added an intermediate column (B) to Pavlik's table to account for species with intermediate traits. The bold letters in the table indicate values, if known, for big red sage. The species is perennial and occurs in old-growth (climax successional) vegetation; these two factors require fewer individuals. Individuals may produce a moderate number of rosettes (ramets) that branch off the original root system; we rank this as an intermediate value. The species is herbaceous, has low fecundity (discussed in Section 2.3-Reproduction), individual survivorship is low (discussed in Section 2.3- Demographic trends, life span, and mortality), and environmental variation is high, due to wide variation in annual rainfall (discussed in Section 2.4-Climate). Hence, four factors require more individuals. The breeding system and the longevity of seed viability are unknown, so are not included in the estimate. Therefore, our estimate of MVP is the weighted average of these factors:

$$\frac{(2 \times 50) + (1 \times 1{,}275) + (4 \times 2{,}500)}{7} = 1{,}625 \text{ (or about 1,600 individuals).}$$

Table 3.1. Minimum viable population guidelines applied to big red sage (adapted from Pavlik 1996, p. 137).

Factor	**A. MVP of 50 individuals for species with these traits.**	**B. Intermediate MVP of 1,275 individuals for species with intermediate or unknown traits.**	**C. MVP of 2,500 individuals for species with these traits.**
Longevity	**Perennial**		Annual
Breeding System	Selfing	**Unknown**	Outcrossing
Growth Form	Woody		**Herbaceous**
Fecundity	High		**Low**
Ramet Production	Common	**Moderate**	Rare or None
Survivorship	High		**Low**
Longevity of Seed Viability	Long	**Unknown**	Short
Environmental Variation	Low		**High**
Successional Status	**Climax**		Seral or Ruderal

This estimate of MVP is based only on numbers of mature individuals (those that have flowered at least once or are judged capable of flowering) because juveniles that die before they reproduce do not contribute to the effective population size or future genetic diversity. To accurately assess the maturity of individuals, population censuses should be conducted during the peak of flowering and fruiting (following significant rainfall from April through October).

Resilient populations must also have stable or increasing demographic trends over time. This means that recruitment of new individuals is at least as great as mortality. Viable populations must also have sufficient numbers of individuals that are not too closely related or too widely dispersed for effective pollination, outcrossing, and seed production.

As discussed in Section 2.6, plant populations are delineated by the limits of gene flow through pollination, seed dispersal, or reproductive barriers. The seeds of big red sage have a very limited dispersal range. Hummingbirds are effective pollinators, and black-chinned hummingbirds are the most abundant species during the flowering season of big red sage, so the forage range of black-chinned hummingbirds determines the typical limits of gene flow between individuals. We estimate that this limit may be from 0.5 to 1.0 km (0.3 to 0.6 mi). However, we lack data on the actual forage ranges of black-chinned hummingbirds. When the limits of gene flow are unknown, the TXNDD uses the NatureServe default minimum separation distance of 1.0 km (0.6 mi) to delineate populations (NatureServe 2004). We also adopt his provisional separation distance for big red sage.

Genetic diversity. Small, reproductively isolated populations are susceptible to the loss of genetic diversity, to genetic drift, and to inbreeding (Barrett and Kohn 1991, pp. 3−30).

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 the loss of genetic diversity is likely to be a loss of fitness and lower chance of survival of populations and of the species. Hoban and Garner (2019, pp. 3–4) concluded that big red sage "... is in a poor, and perhaps critical, situation for genetic diversity. Combined with low population sizes, it is possible that current populations could continue to lose genetic diversity and start to suffer inbreeding depression..." However, these conclusions were based on a small number of samples and a single genetic marker at two loci.

Genetic drift is the random change in the frequencies of alleles in a population over time. Genetic drift is caused by 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 most commonly has a negative effect, especially among outcrossing species; this is due to the expression of deleterious recessive alleles that have become homozygous. It is also a cause of the loss of genetic diversity in small populations.

Inbreeding depression is the loss of fitness among progeny arising from sexual reproduction between closely related individuals. The probability of sexual reproduction between closely related individuals increases in small, isolated populations. However, plant species differ greatly in response to inbreeding; currently, we do not know if inbreeding of big red sage leads to inbreeding depression. Nevertheless, Hoban and Garner (2019, p. 4) observed that propagated populations with very low genetic diversity did not produce viable seeds, which may be an indication of inbreeding depression.

3.3. Species requirements

We assessed the requirements of big red sage in terms of its resilience, redundancy, and representation (Shaffer and Stein 2000, pp. 307-310).

Resilience, discussed in Section 3.2, refers to population sizes and demographic trends; larger populations, and populations with positive long-term demographic trends, are more likely to endure than small or declining populations. We provisionally estimate that viable populations have at least 1,600 individuals of reproductive age, as described above.

Redundancy indicates the number of populations and their distribution over the species' range. Species that have more populations distributed over a broader geographic range have a greater chance of surviving catastrophic events. Greater redundancy increases the probability that at least some populations will survive catastrophic events, such as extended drought. There is no established minimum viable number of populations. Our review of approved recovery plans for listed plant species indicates that the criterion of redundancy for endangered plant recovery typically ranges from five to 20 populations. Species that form stable, long-lived populations can be secure with fewer populations, and species with unstable, short-lived populations require greater redundancy. Of the 14 EOs of big red sage that have known locations, nine have declined since they were first observed, 5 of which are completely extirpated; 3 EOs have SFs that are extirpated; the total number of individuals has declined by 46 percent since 1990; and only four EOs had more than 100 individuals when last observed (see Section 5.1). Due to the declines of documented populations, we provisionally estimate that the species' viability requires 20 or more resilient populations. These populations should be distributed over the species' known range.

Representation refers to the breadth of genetic diversity and environmental adaptation necessary to conserve long-term adaptive capability. Viable species typically possess both intra- and inter-population genetic diversity; inter-population differentiation reflects adaptation to a range of ecological factors and increases the likelihood that at least some portion of a species will be able to adapt to changing climates and other future threats. A preliminary investigation of the species' population genetics (Hoban and Garner 2019, discussed in Section 2.7) found low levels of genetic variation at the species and population levels, although the wild populations preserved greater diversity than propagated populations.

4. FACTORS THAT AFFECT THE SURVIVAL OF BIG RED SAGE.

This section describes factors that either positively or negatively affect the continued survival of big red sage.

4.1. Threats.

<u>Herbivory.</u>

Big red sage is palatable to browsing herbivores, such as white-tailed deer, introduced ungulates, and goats (*Capra hircus*). The Edwards Plateau has by far the highest density (individuals per acre) of white-tailed deer in Texas, and the density has increased about 60 percent from 2012 to 2019 (Morrow 2022, p. 7). The range of big red sage occurs in TPWD Deer Management Units 05, 06, 07 South, and 07 North, where the 2018–2019 censuses tallied 94, 77, 175, and 293 deer per 407 ha (1,000 ac), respectively (Morrow 2022, p. 8). TPWD recommends that deer population sizes in the eastern and central Edwards Plateau should not exceed one individual per 4.0 to 6.4 ha (10 to 16 ac); this corresponds to 63 to 100 individuals per 1,000 ac (Armstrong and Young 2000, p. 20). Hence, within large portions of the range of big red sage, the numbers of white-tailed deer are about 3 times greater than the recommended sustainable levels. Throughout this area, distinct “browse lines” (Armstrong and Young 2000, p. 11) provide direct evidence that over-abundant deer have depleted palatable vegetation. Ward (2010, p. 2) believed that native and introduced deer contributed to decline of EO 14. Taylor and O’Kennon (2013, p. 10) state that browsing from unsustainably large populations of deer has eradicated big red sage from all known habitats except areas that are inaccessible to deer, such as bluffs and steep slopes. White-tailed deer herbivory may explain, at least in part, why EO 11 has declined, despite the protection it receives at Lost Maples SNA.

In addition to native white-tailed deer, several species of non-native ungulate game animals have been introduced in the Edwards Plateau to create economic opportunities, through hunting leases, for landowners (Mungall and Sheffield 1994, pp. 188-194). Some introduced ungulates, including aoudads (*Ammotragus lervia*), blackbuck antelope (*Antilope cervicapra*), axis deer (*Axis axis*), and fallow deer (*Dama dama*), have escaped and established large breeding populations in the wild, compounding the browsing pressure from native white-tailed deer. Ranchers also introduced large numbers of goats in Real County (and elsewhere in the Edwards Plateau) beginning in the early 20th century; by 1930 there were 137,000 goats in the county—more than any other county in the U.S. (Minton 2019, p. 3). Since goats are voracious browsers and nimble scalers of rocky slopes, such large numbers of goats likely had a severe impact on populations of big red sage before conservationists began searching for the species. Flores (1985) attributed the decline of big red sage to the 1950s drought and to domesticated herbivores.

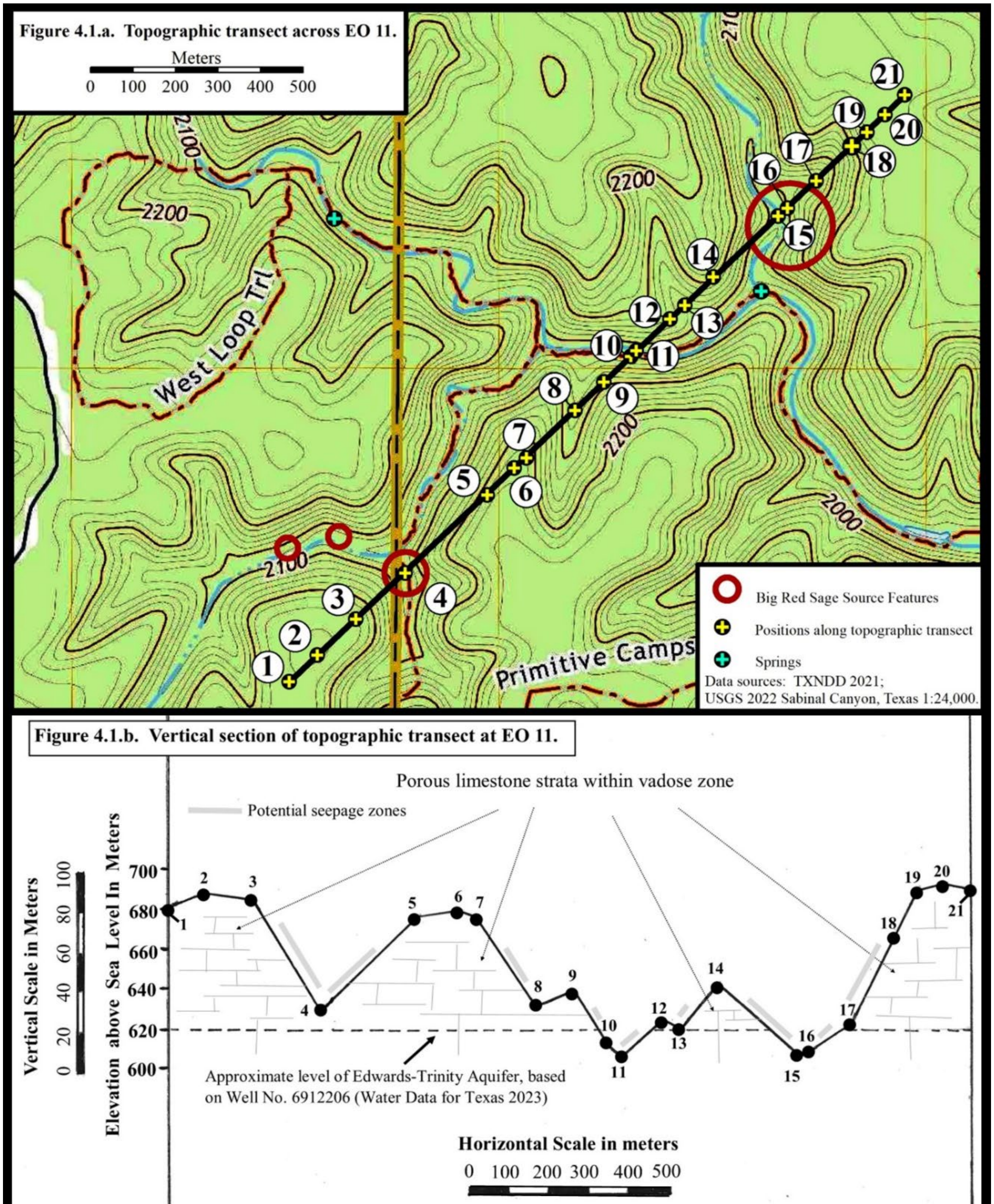
We conclude that herbivory, and thus mortality of individual plants, by native and introduced ungulates has severely affected all populations throughout the species’ range and is a continuing severe threat throughout the range.

Urban and residential development.

Current rates of human population growth are stable or decreasing in Real, Bandera, and Uvalde counties, increasing moderately in Kerr and Gillespie counties, and increasing rapidly in Kendall County (Texas Demographic Center 2022, 2023; see Table 6.2). Therefore, EOs 5, 14, and 24 are currently at the greatest risk to development. Figure 6.1 and the discussion in Section 6.3 document current development impacts to EO 14. Although bluffs and steep slopes are not suitable for most forms of development, many populations occur near watercourses where human activities are concentrated. Houses, roads, bridges, and recreational uses may impact these populations. We conclude that land use changes represent a continuing, potentially severe threat throughout the species' range. Based on the extent of land use changes to known populations, we estimate that this threat currently affects 25 percent of all populations.

Reduced availability and constancy of seep moisture.

Taylor and O'Kennon (2013, pp. 10–11) stated, "It is likely that continued drying of seepage areas may impact *S. pentstemonoides* sites." The groundwater that sustains populations seeps where the fissures between limestone strata within the vadose zone are exposed along slopes. This moisture may also derive from one of the major aquifers, the Edwards-Trinity or Trinity aquifer. To illustrate this, Figure 4.1 shows a transect across the Sabinal Canyon 7.5-minute topographic map (U.S. Geological Survey 2022a) through part of EO 11, where some SFs are above the approximate level of the Edwards-Trinity aquifer while others are below this level. The level indicated (620 m (2,034 ft)) above sea level) is based on the water depth of state groundwater monitoring well no. 6912206, located 5.2 km (3.2 mi) northeast of these SFs, on August 2, 2023 (Water Data for Texas 2023a). The actual upper level of the Edwards-Trinity aquifer at EO 11 may differ and varies over time and distance. Thus, part of EO 11 may be vulnerable to drawdowns of the Edwards-Trinity aquifer while the rest may be sustained only through percolation through the vadose zone. The infiltration of rainwater into the vadose zone may be reduced by changes that occur throughout its recharge zone, such as an increase in the amount of impermeable surfaces or a loss of vegetative cover; this in turn may reduce the availability and constancy of seep moisture to population sites, which is a resource need of big red sage. Changes in the amount and distribution of rainfall (discussed under climate changes, below) may also reduce the availability and constancy of seep moisture. We conclude that the reduced availability and constancy of seep moisture is a potential threat of unknown severity and immediacy throughout the species' range.



The transect across the Sabinal Canyon topographic map (above) passes through or near four Source Features of EO 11. The vertical section (below) plots elevation above sea level of 21 points along the transect; vertical scale is 5X horizontal scale. The approximate level of the Edwards-Trinity aquifer indicated (620 m elevation) is taken from a well that is 5.2 km northeast. The porous Edwards limestone strata above the aquifer level stores infiltrated rainwater in the vadose zone; where exposed along slopes, seepage may occur. Two springs are located at 628 m and 594 m elevation.

Figure 4.1. Topographic transect across EO 11 and vertical section of topographic transect at EO 11.

Collection from wild populations.

Big red sage is an attractive plant that is used in landscapes and pollinator gardens, both within its native range in Texas as well as throughout North America and elsewhere. It has been propagated and sold by several commercial nurseries since 1986 (Enquist 1987, p. 5). Seeds and entire plants have been collected from the wild for landscaping and commercial propagation from at least two EOs (14 and 20) that are accessible to the public (Collier 1989, pp. 1–2; Taylor and O'Kennon 2013, p. 11). EO 14, the source of at least one propagated population (Hoban and Garner 2019, p. 1), was widely known and easily accessible to the public. Over-collection may have contributed to the decline of that population. Other EOs, such as 11 and 21, are vulnerable to collection from the wild; undocumented populations may also have been discovered and depleted by collectors. We conclude that collection from wild populations is a potentially severe, continuing threat to all populations that occur in sites that are known to and accessible by the public.

Loss of genetic integrity due to inappropriate propagation.

Propagation is a useful tool for plant conservation, but there are several potential risks if conducted without regard to the conservation of a species' genetic integrity. First, over-collection of seeds from small wild populations can reduce recruitment of new individuals and contribute to the decline of those populations. In addition, propagated plant populations often arise from a very small number of founders collected from the wild. For example, initial attempts to augment the population size of the endangered Mauna Kea silversword (*Argyroxiphium sandwicense* ssp. *sandwicense*), during the 1970s, used propagules that descended from just two or three founders; this created a genetic bottleneck in the reintroduced population (Friar *et al.* 2000, all).

Propagated populations may lose alleles through genetic drift or through deliberate or inadvertent selection. Genetic drift is the random reduction in frequency of alleles or the complete loss of alleles; it occurs most rapidly when the number of breeding individuals is small. Founder effects can be considered a special case of genetic drift; it occurs when the initial number of individuals that starts a wild or cultivated population is small. A genetic bottleneck is another special case of genetic drift in which a population is small for only a few generations. Random changes in allele frequencies can reduce average fitness even when the gene pool of a population has not lost alleles.

In contrast, selection leads to non-random changes in allele frequencies and non-random losses of alleles. Deliberate selection occurs when seeds are selected from plants with specific desirable traits, such as size, form, or flower color, and are used to propagate subsequent generations. Inadvertent selection occurs as an unintended consequence of propagation. For example, growers typically retain only the individuals that germinate readily and then use those individuals as future seed sources; consequently, propagated populations frequently lose the seed dormancy mechanisms that benefit the survival of wild populations. Each successive propagated generation incrementally changes the frequencies of alleles in the gene pool, including the complete loss of alleles. Ultimately, both deliberate and inadvertent selection lead to plants that are more fit in cultivation but less likely to persist if transplanted back into the wild.

Through propagation, it is possible to create unlimited numbers of individuals that, once released to the wild, may interbreed with and overwhelm the much smaller wild populations with a very narrow sample of the species' original genetic diversity, thus causing the loss of rare wild genotypes. This problem is compounded for obligate outcrossing species if the individuals in a population are so closely related that they cannot fertilize each other. Release of individuals bred in cultivation may also introduce genes that reduce fitness, such as loss of seed dormancy, into the wild population, as discussed above. Finally, horticulturalists and plant collectors may bring big red sage into proximity with other *Salvia* species that are geographically separated in the wild; if these taxa are inter-fertile, this could lead to inter-specific hybridization. An escape of hybridized Salvias into the wild populations could lead to the extinction of the original wild genotype through interbreeding.

We have no evidence that the progeny of propagated individuals of big red sage have colonized wild population sites. Nevertheless, Hoban and Garner (2019, p. 4) confirmed that propagated big red sage populations have very low genetic diversity. We conclude that inappropriate propagation is a potentially severe threat of unknown extent to the genetic integrity of the remaining wild populations and the species.

Flash floods and bank erosion.

Section 2.4-Climate describes the severity of flash flooding in the Edwards Plateau. Flash floods have caused population declines at EOs 5 and 14. Additionally, EO 15 was completely destroyed by a landslide when the bluff above it collapsed; this may have resulted indirectly from flooding along Big Joshua Creek. Flood waters may uproot individual plants or wash away their substrates, or the plants may be buried under silt and debris. Taylor and O'Kennon (2013, p.10) observed that many EOs along watercourses have individuals established below the high-water level that will eventually be wiped out in a flood. We conclude that the direct and indirect effects of flash floods represent a potentially severe threat, throughout the species' range, to the portions of populations that are close to watercourses and below the high-water level of floods.

Impacts from climate change.

The principal conclusions of the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) are listed in the Summary for Policy Makers (SPM; IPCC 2021). Regarding the current state of the climate, the SPM confirmed that:

- It is unequivocal that human influence has warmed the atmosphere, ocean, and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere, and biosphere have occurred (p. 5).

- The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years (p. 9).

- Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes, such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report (p. 10).

The SPM lists projected climate changes by the end of the 21st century, relative to the 1850 to 1900 averages. The projections that are relevant to the status of big red sage include the following:

- Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5° C and 2° C will be exceeded during the 21st century unless deep reductions in CO_2 and other greenhouse gas emissions occur in the coming decades (p. 16).

- Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and the proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover, and permafrost (p. 19).

- With every additional increment of global warming, changes in extremes continue to become larger. For example, every additional 0.5° C of global warming causes clearly discernible increases in the intensity and frequency of hot extremes, including heatwaves (very likely), and heavy precipitation (high confidence), as well as agricultural and ecological droughts in some regions (high confidence). Discernible changes in intensity and frequency of meteorological droughts, with more regions showing increases than decreases, are seen in some regions for every additional 0.5° C of global warming (medium confidence). Increases in the frequency and intensity of hydrological droughts become larger with increasing global warming in some regions (medium confidence). There will be an increasing occurrence of some extreme events unprecedented in the observational record with additional global warming, even at 1.5° C of global warming (p. 19).

- It is very likely that heavy precipitation events will intensify and become more frequent in most regions with additional global warming. At the global scale, extreme daily precipitation events are projected to intensify by about 7 percent for each 1° C of global warming (high confidence). The proportion of intense tropical cyclones (categories 4-5) and peak wind speeds of the most intense tropical cyclones are projected to increase at the global scale with increasing global warming (high confidence) (p. 20).

- Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation, and the severity of wet and dry events (p. 25).

- A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought (high confidence), but the location and frequency of these events depend on projected changes in regional atmospheric circulation, including monsoons and mid-latitude storm tracks. It is very likely that rainfall variability related to the El Niño–Southern Oscillation is projected to be amplified by the second half of the 21st century in the SSP2-4.5, SSP3-7.0 and SSP5-8.5 scenarios (p. 25).

Similarly, the U.S. Global Climate Research Program (USGCRP) Fourth National Climate Assessment (USGCRP 2017) reports that average annual temperatures from 1986 to 2016 have increased in the Southern Great Plains (including the range of big red sage) by 0.42° C (0.76° F), compared to the 1901 to 1960 baseline (USGCRP 2017, Chapter 6, Table 6.1). Average annual temperatures in the Southern Great Plains are projected to increase by 2.65° to 4.69° C (4.78° to 8.44° F), under moderate and high emission scenarios, respectively, by the late 21st century (USGCRP 2017 Chapter 6, Table 6.4). By the end of the 21st century, under the highest emissions scenario, precipitation in the range of big red sage is projected to decrease from 10 to 20 percent during the winter and spring and to increase 10 percent during summer and fall; however, these projected changes are smaller than natural variations (USGCRP 2017 Chapter 7, pp. 15–16 and Figure 7.5). The frequency of heavy precipitation events in the Southern Great Plains has increased from 1901 to 2016 and 1948 to 2016 (USGCRP 2017 Chapter 7 pp. 5–9 and Figures 7.2–7.4) and is projected to continue to increase under both moderate and high emission scenarios (USGCRP 2017 Chapter 7 pp. 18–24 and Figures 7.6–7.8).

The magnitude of projected changes varies widely, depending on which scenario of future greenhouse gas emissions is used. In the Fifth Assessment Report (IPCC 2013), these scenarios were called Representative Concentration Pathways (RCPs). Under the best-case scenario of RCP 2.6, 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 RCP 4.5, RCP 6.0, and RCP 8.5 scenarios, respectively (IPCC 2013, p.22). These scenarios were updated in the Sixth Assessment Report and are called Shared Socio-economic Pathways or SSPs.

To evaluate how the climate of big red sage habitats may change, we used the National Climate Change Viewer (U.S. Geological Survey 2022b) to compare past and projected future climate conditions for the Upper Guadalupe River watershed in Texas; this 8-digit hydrologic unit code (HUC) watershed, in the center of the range of big red sage, occupies parts of Kerr, Kendall, and Comal counties. The baseline for comparison was the observed mean values from 1981 through 2010, and 20 climate models were used to project future conditions for 2050 through 2074. We selected the climate parameters of May precipitation, annual soil storage, and summer evaporative deficit. May is the month of greatest average rainfall in the Edwards Plateau; these pulses of moisture drive the growth and flowering of big red sage. Annual soil storage is the amount of water stored in the soil column during a year (Alder and Hostetler 2021, p. 18). Evaporative deficit is the difference between actual and potential evapotranspiration (Alder and Hostetler 2021, p. 18), which is a better indicator of plant stress than precipitation alone, since it takes temperature into account. We used both the RCP 4.5 and RCP 8.5 scenarios to provide a range of projected values. The results are summarized in Table 4.1 and in Figures 4.2, 4.3, and 4.4. To interpret these results, it is important to consider the means as well as the dispersion of the 20 climate models (Table 4.1); wide dispersion indicates greater uncertainty. The historical baseline May precipitation is 96.66 to 97.92 mm/month (mon) (3.81 to 3.86 in/mon); note that the calculations of historical baselines vary slightly, depending on the RCP scenario used. The means of 20 models indicate May precipitation will increase 2.89 mm/mon (0.11 in/mon) under RCP 4.5 and decrease 5.08 mm/mon (0.20 in/mon) under RCP 8.5, respectively, by 2050–2074. However, the individual models vary widely, and these projected changes are not statistically significant. The historical baseline for annual soil storage is 32.88 and 33.59 mm (1.29 and 1.32 in) under RCPs 4.5 and 8.5, respectively. Soil storage will decrease by 5.03 to 9.42 mm (0.20 to

0.37 in) under RCPs 4.5 and 8.5, respectively; these projected changes are statistically significant. The historical baselines for summer evaporative deficit are 12.53 to 12.73 mm/mon (0.49 to 0.50 in/mon) under RCPs 4.5 and 8.5, respectively. Summer evaporative deficit will increase 13.69 to 21.71 mm/mon (0.54 to 0.85 in/mon) under RCPs 4.5 and 8.5, respectively; these projections are also statistically significant.

Table 4.1. Means and dispersion of projected changes of 20 climate projection models for the Upper Guadalupe River watershed, Texas: 2050 to 2074 compared to 1981 to 2010 (U.S. Geological Survey 2022b).

Climate Parameter	1981–2010 baseline:	RCP	Projected changes 2050–2074, means of 20 models	Ranges of individual models
May Precipitation.	96.66 mm/mon (3.81 in/mon)	4.5	+2.89 mm/mon (+0.11 in/mon)	-42.35 to +56.79 mm/mon (-1.67 to +2.23 in/mon)
	97.92 mm/mon (3.86 in/mon)	8.5	-5.08 mm/mon (-0.20 in/mon)	-35.77 to +27.88 mm/mon (-1.41 to +1.09 in/mon)
Annual Soil Storage.	32.88 mm (1.29 in)	4.5	-5.03 mm* (-0.19 in)*	-17.68 to +10.79 mm (-0.69 to +0.42 in)
	33.59 mm (1.32 in)	8.5	-9.42 mm* (-0.37 in)*	-25.92 to +0.05 mm (-1.02 to +0.002 in)
Summer Evaporative Deficit.	12.53 mm/mon (0.49 in/mon)	4.5	+13.69 mm/mon* (+0.54 in/mon)*	-8.73 to +31.94 mm/mon (-0.34 to 1.26 in/mon)
	12.73 mm/mon (0.50 in/mon)	8.5	+21.71 mm/mon* (+0.85 in/mon)*	-2.41 to +33.29 mm/mon (-0.09 to +1.31 in/mon)

* = Statistical significance.

We do not know how big red sage responded to prior climate changes. For example, it may have occupied a greater proportion of the Edwards Plateau during the Pleistocene, and then during the Holocene (the last 11,700 years) became restricted to relatively cool, shaded canyons as the climate warmed. Alternatively, the species may have migrated into Edwards Plateau from limestone canyons in northern Mexico, or it may always have been restricted to the habitats where it is found today. We do know that the species exists today only where there is seep moisture along the slopes and bluffs of canyons and ravines, so we conclude that it requires relatively persistent soil moisture (discussed in Section 3.1). The projected decrease in soil water storage and increase in summer evaporative deficit by 2050 to 2074 indicate that soil moisture will become more limiting to plant growth. This may restrict big red sage to a smaller amount of suitable habitat. Although climate models do not consistently project how total rainfall may change, the ongoing trend toward greater extremes in rainfall will likely increase with rising temperatures. We expect that mortality will increase and recruitment will decrease during longer, more severe droughts. Furthermore, the increasing frequency and intensity of heavy rainfall events will also exacerbate the threat of flash flooding (discussed above). Therefore, climate changes present several potentially severe threats of low immediacy throughout the species' range.

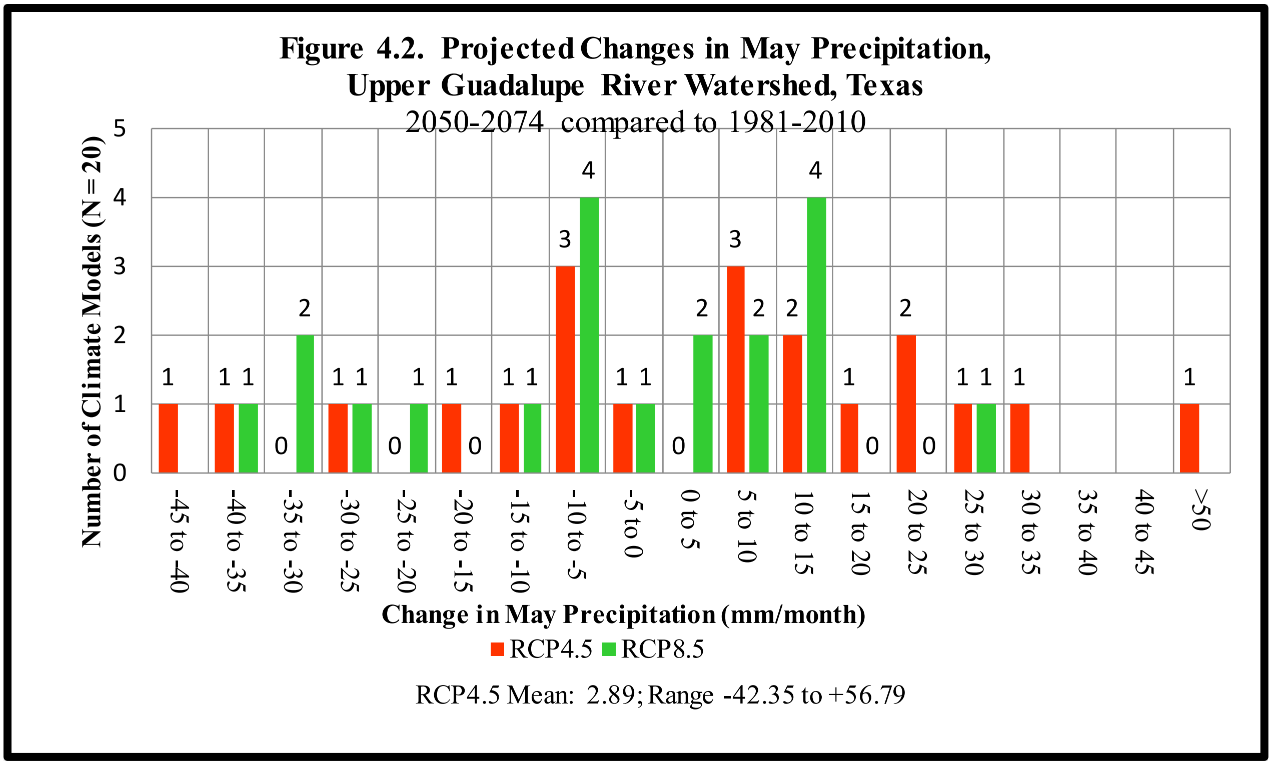


Figure 4.2. Projected changes in May precipitation, Upper Guadalupe River Watershed, Texas.

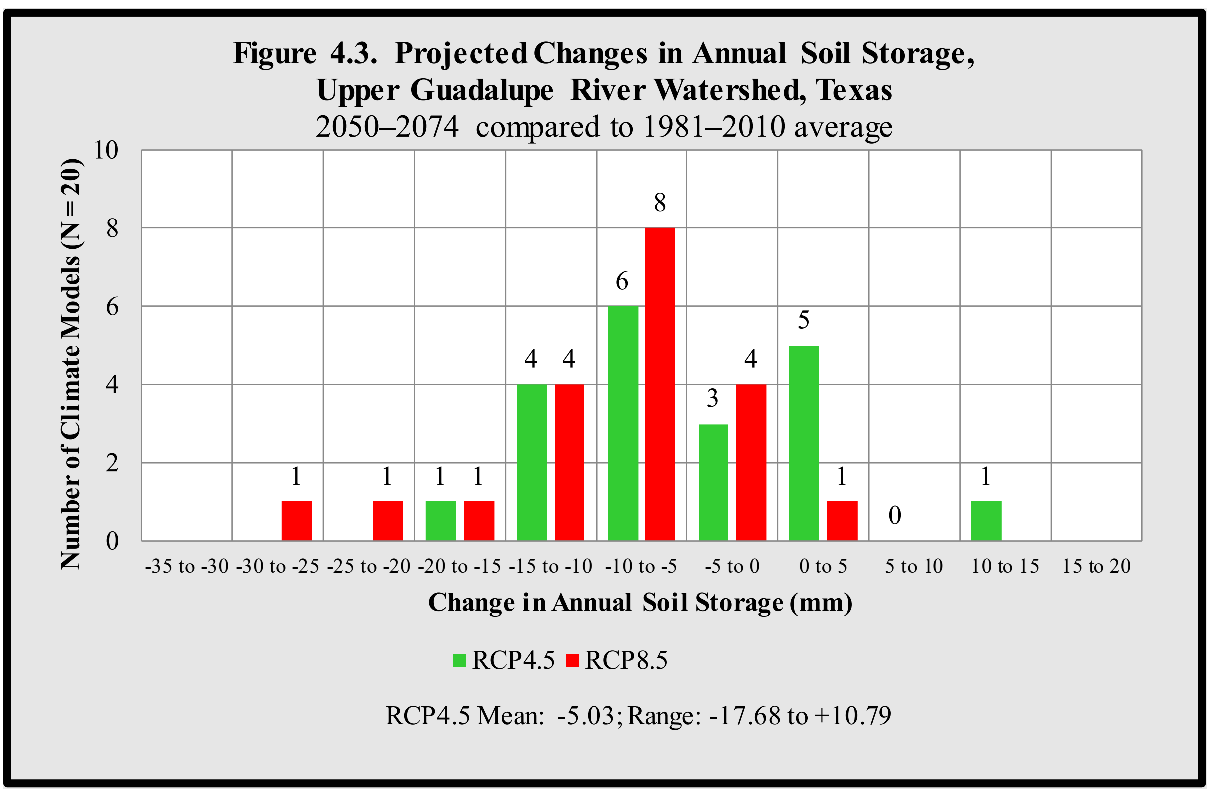


Figure 4.3. Projected changes in annual soil storage, Upper Guadalupe River Watershed, Texas.

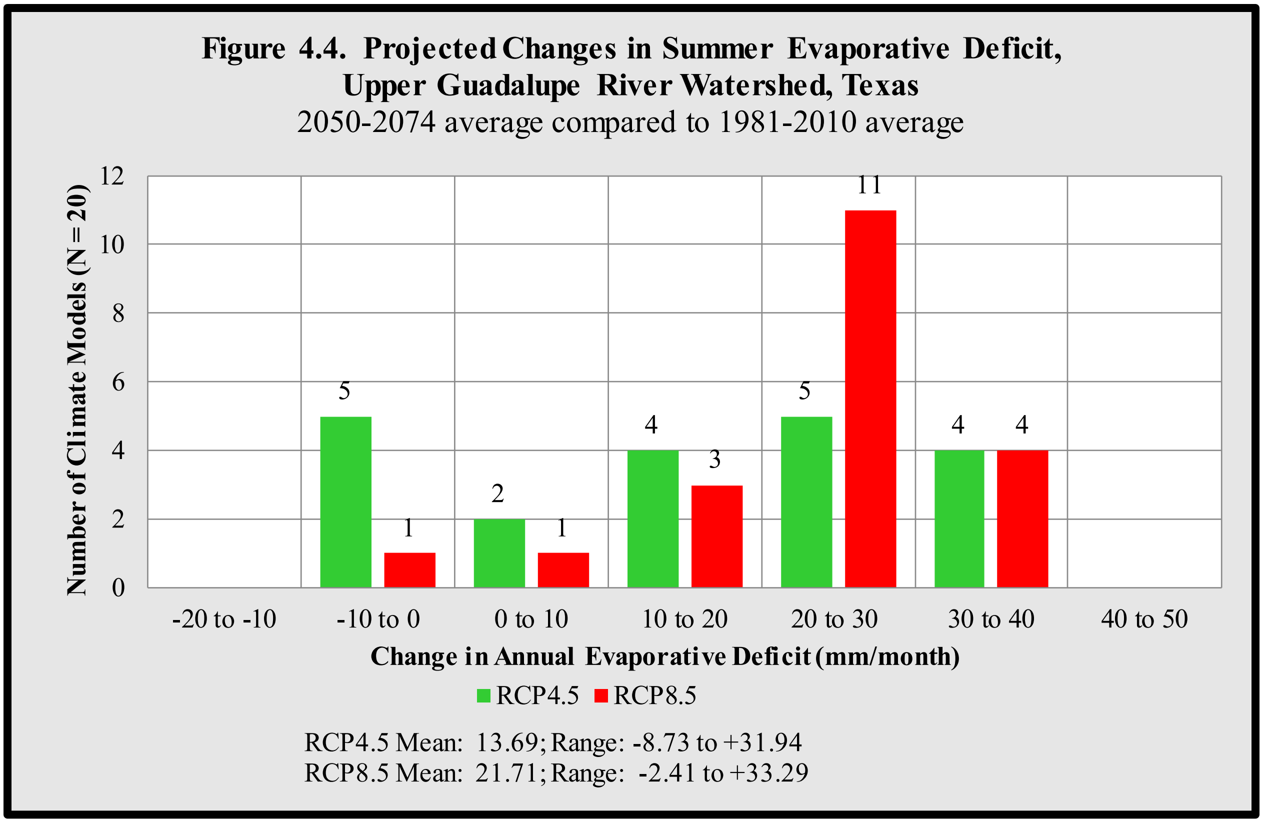


Figure 4.4. Projected changes in summer evaporative deficit, Upper Guadalupe River Watershed, Texas.

4.2. Land ownership.

Five of the 7 extant populations (as defined in Section 5.1) and 88 percent of extant individuals of big red sage occur on privately owned land, one population site is owned by TPWD, and one is owned by a non-profit conservation organization. Private land ownership can benefit conservation efforts, but it can also make accessing lands for conservation more challenging. Texas law strictly protects private lands from trespass. Populations of big red sage on private land may be better protected from illicit collection than populations that are accessible to the public. Conservation-minded landowners take pride in protecting the unique features of their property, including rare plants. The USFWS Partners for Fish and Wildlife Program, TPWD, and non-profit conservation organizations work with private landowners who voluntarily wish to conserve rare plants on their lands. On the other hand, 95 percent of Texas is privately owned, including areas of potential habitat that have not been surveyed for big red sage populations. It is time-consuming to review county cadastral records to find out who owns the thousands of individual properties where the species may be present and to contact the landowners, and many landowners may prefer not to allow access to their lands for rare plant surveys. Successful conservation partnerships with private landowners may not endure when the ownership eventually changes hands.

Table 4.2. Land ownership of extant big red sage Element Occurrences.

EO No.	Most Recent Population Size	Owners
4[a]	0	Large number of private landowners
5	108	Large number of private landowners; extant population owned by an NGO
11	3	TPWD
14	401	TxDOT (extirpated); extant population is private land along public watercourse
16	2	Private land
20	269	Private land along public watercourse
21	29	Private land along public watercourse
24	116	Private land
TOTAL:	928	

a. EO Condition is non-contributing, but intact habitats persist here.

4.3. Conservation.

One of the largest and most stable populations of big red sage occurs at Cibolo Bluffs (EO 5). As discussed in Section 2.6, the Cibolo Bluffs property is owned by Cibolo Center for Conservation and is monitored annually by volunteers of the Cibolo Center for Conservation and trustees of Cibolo Preserve.

The population at EO 11 is protected by TPWD at Lost Maples SNA. As discussed in Section 2.6, despite the protection from development and the ability to manage the habitat, this population has declined from 23 individuals in 1988 to 3 in 2019.

Texas Parks and Wildlife Department has supported two grants that promoted the conservation of big red sage. The 2012 Texas Conservation Action Plan identified a research priority to study the distribution and threats of big red sage. This led to a Wildlife Conservation Grant to update the species' status (Taylor and O'Kennon 2013). The TPWD Conservation License Plate Program supported an investigation of the species' conservation genetics (Hoban and Garner 2019). These projects are discussed in Sections 2.5 and 2.7, respectively.

William Ward, a retired professor of geology, conducted a small reintroduction of big red sage at Cibolo Nature Center (now Cibolo Center for Conservation). The Center provided to us photographs and hand-written notes and data sheets that document this work. Dr. Ward and other volunteers obtained seeds of big red sage from the Lady Bird Johnson Wildflower Center and collected additional seeds from the wild (although the sources are not stated, these may have originated from Cibolo Bluffs).

The seeds were planted in seedling containers on July 22 and October 30, 2004, and within one year the seedlings were well established in 1-gallon plant pots. On October 29, 2005, the volunteers planted 51 seedlings: 45 were protected within a long, narrow wire fence exclosure about 91 by 91 cm (36 by 36 in) tall and wide, and another 6 seedlings were planted outside the exclosure. After 1 month, survival was 100 percent, and the rosette basal diameters averaged 26 cm (10.2 in). Dr. Ward and other volunteers collected data over the next 6 years on survival, flowering, and the incidence of herbivory and flood damage. Our analyses of this data are summarized in Figure 4.5.

The unprotected seedlings were repeatedly browsed by white-tailed deer, produced no flower stalks, and all died within 4.5 years. Within the exclosure, 11 plants were also browsed, perhaps due to the small size of the exclosure, and 12 plants were damaged or destroyed during a flood. Nevertheless, 40 percent of the protected plants were still alive after 6 years. The protected plants had produced at least 332 flower stalks by 2011; based on the estimate described under “Reproduction” in Section 2.3, this represents a potential production of over 45,000 seeds. Individuals produced 6 times as many flower stalks 20 months after transplanting compared to 9 months after transplanting (this corresponds to 3 and 2 years after germination).

The annual number of flower stalks (124) and flower stalks per live individual (4.0) both peaked in May 2008, a year of extremely low rainfall (375 mm; 14.8 in) in Boerne. This pulse of reproduction may have reflected the much higher amount of rainfall in 2007 (1,477 mm; 58.1 in); note that average rainfall in Boerne from 2000 through 2020 was 936 mm (36.8 in). Rainfall was also very low in 2011 (451 mm; 17.8 in); nevertheless, in August of that year, the surviving plants were still able to average 1.8 flower stalks per individual.

These results suggest that big red sage may be relatively resilient to the wide extremes in annual rainfall that characterize the Edwards Plateau. Although the sample size is very small, the annihilation of all unprotected individuals before they could produce a single seed is further evidence that herbivory by over-abundant white-tailed deer is a severe threat to the survival of big red sage. While the protected individuals declined 60 percent over this time frame, they also produced large numbers of seeds. On September 14, 2013, observers noted that many new big red sage individuals were growing near the plot along a creek. In summary, this small pilot reintroduction demonstrates that it is possible to establish new populations that have positive growth rates or to augment existing populations—provided that the sites are protected from white-tailed deer and other ungulates.

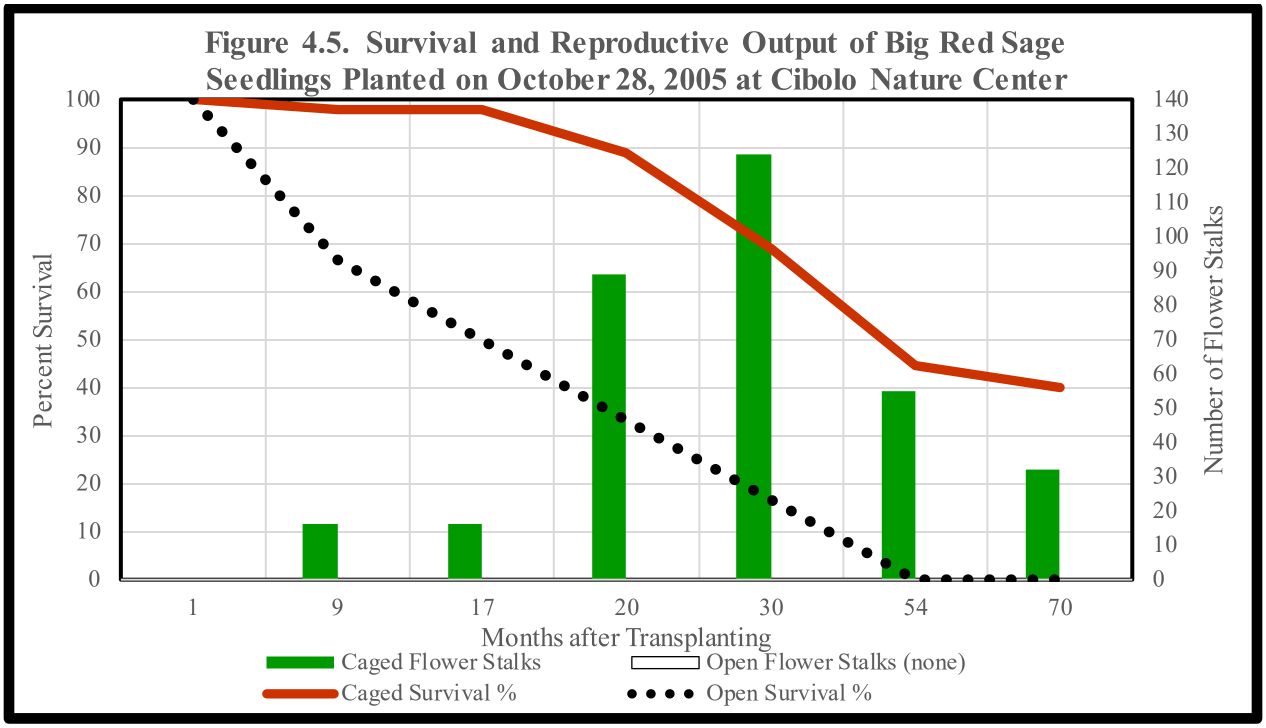


Figure 4.5. Survival and reproductive output of big red sage seedlings planted on October 28, 2005 at Cibolo Nature Center.

Summary of factors affecting the survival of big red sage.

- Herbivory by white-tailed deer, introduced ungulates, and goats is a current and continuing threat of high severity throughout the species' range.
- Land use changes (including urban and residential development) are current and continuing, potentially severe threats that have affected about 25 percent of the species' populations.
- Reduced availability or constancy of seep moisture is a potential threat of unknown severity and immediacy throughout the species' range.
- Collection from wild populations is a current and continuing, potentially severe threat to all populations.
- Loss of genetic integrity due to inappropriate propagation is a current and continuing threat of unknown severity throughout the species' range.
- Flash floods and bank erosion are intermittent, potentially severe threats to the portions of populations that are close to watercourses.
- Impacts from climate change, specifically the increased incidence and severity of prolonged droughts and heavy rainfall, are likely to negatively affect all populations by the 2050 to 2074 time frame.
- The prevalence of private land ownership presents both opportunities for conservation as well as challenges for most of the species' populations.
- The species benefits from conservation, management, and protection at Cibolo Bluffs. Despite protection from development at Lost Maples SNA, EO 11 has declined nearly to the point of extirpation. Two research grants from TPWD have increased knowledge of the species' range, current status, and conservation genetics. One small pilot reintroduction

project generated useful information about survival, growth rates, reproductive output, and the effect of browsing, and demonstrated that reintroduction can be successful if sites are protected from browsing animals.

Table 4.3. Summary of threats to big red sage.

Threats	Immediacy	Severity	Extent
Herbivory by white-tailed deer, introduced ungulates, and goats	Current, continuing	High severity	Throughout the range
Land use changes	Current, continuing	Potentially severe	Has affected about 25% of populations
Reduced availability or constancy of seep moisture	Unknown	Unknown	Throughout the range
Collection from wild populations	Current, continuing	Potentially severe	Throughout the range
Inappropriate propagation	Current, continuing	Potentially severe	Unknown; publicly accessible populations are more vulnerable
Flash floods and bank erosion	Intermittent	Potentially severe	Portions of all populations close to watercourses
Impacts from climate change	Low immediacy	Potentially severe	Throughout the range

5. Current Conditions and Viability of Big Red Sage.

Assessments of a species' current viability are based on the current conditions of its populations, habitats, and geographic distribution (see Smith *et al.* 2018, p 306).

5.1. Current conditions of populations.

Table 5.2 lists the statuses, sizes, and trends of the documented populations of big red sage. As used here, population status refers to whether a population is extant, extirpated, or non-contributing. In summary:

- Big red sage has been documented at 35 SFs grouped into 18 EOs. Individual EOs may have multiple SFs that may each have different statuses.

- One EO (17) was based on an anecdotal report, without herbarium voucher, that later was determined to have been misidentified. Therefore, we do not include EO 17 among the 18 confirmed EOS or in further analyses.

- The statuses of 7 SFs at 7 EOs are non-contributing, as described in Section 2.6. All SFs of 4 EOs (1, 3, 7, and 8) are non-contributing. EOs 4 and 10 have both non-contributing and extirpated SFs. EO 5 has both non-contributing and extant SFs.

- Eleven SFs at 9 EOs are extirpated. This includes 5 SFs at 3 EOs (4, 11, and 23) where habitats are intact, but no individuals were observed during the most recent surveys and are therefore assumed to be extirpated. All SFs of 5 EOs (2, 15, 19, 22, and 23) are completely extirpated, and 2 EOs (11 and 14) have both extant and extirpated SFs.

- Seventeen SFs at 7 EOs (5, 11, 14, 16, 20, 21, and 24) are extant.

- Source Feature 15836 in EO 4 represents herbarium specimens collected in 1943 in the upper portion of Turtle Creek. We are not aware of subsequent surveys in this area. However, recent aerial photographs of upper Turtle Creek reveal large amounts of contiguous potential habitat and relatively little development; we conclude that extant populations may persist in this area and have therefore included EO 4 in the habitat condition analyses.

- The largest numbers of big red sage individuals recorded in censuses of 27 SFs at 13 EOs total 1,728. The most recent censuses recorded at these 27 SFs total 928 individuals. Hence, the known populations have declined by 800 individuals (46 percent).

- Development of population sites destroyed at least 75 individuals (9 percent of the total population decline). However, some populations were never censused prior to development, so development losses may be higher. Populations in intact habitats have declined by 725 individuals. This includes the loss of 91 individuals to natural causes—floods and a landslide (11 percent of total population decline). A combination of flooding, illicit collection, invasive plant competition, and ungulate herbivory contributed to a loss of 576 individuals (72 percent of total population decline). The loss of 58 individuals in intact habitats cannot be attributed to known causes (7 percent of total population decline).

- During the most recent censuses, none of the EOs had more than 25 percent of the estimated MVP level of 1,600 individuals. The EOs with the 4 largest populations were EO 14 (401 individuals), EO 20 (269 individuals), EO 24 (116 individuals), and EO 5 (108 individuals).

- Quantitative annual censuses have only been conducted at EOs 5 and 14 (discussed in Sections 2.3 and 2.5).

For subsequent analyses, we ranked population sizes in five conditions: Highly resilient (1,600 or more individuals), moderately resilient (100 to 1,600 individuals), low resilience (1 to 99 individuals), non-contributing, and extirpated. The highly resilient condition of 1,600 individuals is based on the estimated MVP level required for long-term survival (at least 100 years; see Section 3.2). The threshold of 100 individuals for the moderately resilient population condition is derived from the recommendation of Albrecht and Maschinski (2012, pp. 182–186, 296) that founder population sizes for plant reintroductions should be greater than 50 individuals, and that this minimum level should be increased for herbaceous perennial plants (such as big red sage). We interpret this recommendation to mean 100 or more individuals for herbaceous perennials; Monks *et al.* (2012, p. 201) indicate that this number should increase to 200 or more for obligate outcrossing species. We provisionally adopt these levels as metrics for a mid-term survival objective.

Based on the observed lifespan of at least 10 years (Taylor 2021a, b), we adopt 10 years as the time frame for mid-term survival because it is long enough for both recruitment and mortality to occur and for demographic trends to emerge. Populations that are moderately resilient have moderate demographic and genetic resources. Populations with low resilience are unlikely to have sufficient demographic and genetic resources to be able to increase resilience without augmentation of numbers and genetic diversity, in addition to conservation and management. The non-contributing condition applies to populations that were reliably recorded in the past, but where there have been no recent visits, or the exact geographic location is unknown. Extirpation is likely when habitats are destroyed or significantly altered. Censuses that detect no live plants in intact habitats may have overlooked live, dormant plants, and populations may also recover from the soil seed reserve. To confirm extirpation, it may be necessary to conduct multiple censuses in consecutive years that detect no live plants.

No EOs are currently ranked highly resilient. Most EOs have not been monitored frequently enough to determine demographic trends.

Table 5.1. Summary of population resilience ranks.

Population Resilience Rank	Criteria	Projected Population Viability
High	≥ 1,600 mature individuals	≥ 90% probability of persisting 100 years
Moderate	≥ 100 mature individuals	Likely to persist 10 years; able to become highly resilient through conservation and management

Low	< 100 mature individuals	Likely to become extirpated within 10 years; unlikely to improved resilience without genetic and demographic augmentation
Non-Contributing	No recent visits to site or location unknown	May or may not persist
Extirpated	No individuals observed after multiple consecutive censuses	No live plants remain, and soil seed reserve is completely depleted

Table 5.2. Current population conditions of big red sage Element Occurrences and Source Features (Taylor and O'Kennon 2013; Carr 2019a; Carr 2019b; Cibolo Center for Conservation 2021; TXNDD 2021).

EO No.	SF	Current Population Condition	Maximum Year	Maximum Observation	Recent Observation	Recent Population Size	Change	Cause of decline	Losses from Development	Losses in Extant Habitat
1	3182	Non-contributing	1941	Unknown	1941	Unknown	NA	NA	NA	NA
2	7288	Extirpated	1894	50	2013	0	-50	Develop-ment	50	
3	15835	Non-contributing	1946	Unknown	1946	Unknown	NA	NA	NA	NA
4	15836	Non-contributing	1943	Unknown	1943	Unknown	NA	NA	NA	NA
4	28460	Extirpated	1991	25	2013	0	-25	Unknown	NA	25
5	15830	Non-contributing	1916	Unknown	1916	Unknown	NA	NA	NA	NA
5	28786, 28787, 31273	Extant	2004	174	2021	108	-66	Flood	NA	66
7	6980	Non-contributing	1879	Unknown	1879	Unknown				
8	1579	Non-contributing	1895	Unknown	1895	Unknown	NA	NA	NA	NA
10	15838	Non-contributing	1897	Unknown	1897	Unknown	NA	NA	NA	NA
10	28481	Extirpated	1990	5	2013	0	-5	Habitat change	5	NA
11	2831	Extirpated	1988	19	2013	0	-19	Unknown	NA	19
11	4439	Extirpated	1988	2	2019	0	-2	Unknown	NA	2
11	6190	Extant	2013	3	2019	2	-1	Unknown		1
11	15837	Extirpated	2006	10	2019	0	-10	Unknown	NA	10
11	28456	Extant	2013	1	2019	1		NA	NA	NA

EO No.	SF	Current Population Condition	Maximum Year	Maximum Observation	Recent Observation	Recent Population Size	Change	Cause of decline	Losses from Development	Losses in Extant Habitat
14	15826	Extirpated	1992	576	2013	0	-576	Flood/ Collection/ Herbivory/ Invasive Plants	NA	576
14	28459	Extant	2013	401	2013	401		NA	NA	
15	2092	Extirpated	1988	25	2013	0	-25	Landslide	NA	25
16	3908	Extant	1991	2	1991	2		NA	NA	NA
17	12629	Misidentified	2006	0	2013	0			NA	NA
19	15857	Extirpated	1849	Unknown	1849	Unknown		Develop-ment	Unknown	NA
20	28086	Extant	2010	161	2010	161		NA	NA	NA
20	28457	Extant	2013	70	2013	70		NA	NA	NA
20	28458	Extant	1991	18	1991	18	NA	NA	NA	NA
20	31245	Extant	2016	7	2016	7	NA	NA	NA	NA
20	31246	Extant	2016	1	2016	1	NA	NA	NA	NA
20	Unknown	Extant	2019	12	2019	12	NA	NA	NA	NA
21	28415	Extant	2018	15	2018	15	NA	NA	NA	NA
21	28416	Extant	2015	3	2015	3	NA	NA	NA	NA
21	37234	Extant	2017	11	2017	11	NA	NA	NA	NA
22	28479	Extirpated	1990	20	2013	0	-20	Habitat change	20	NA
23	28480	Extirpated	1991	1	2013	0	-1	Unknown		1
24	28482	Extant	2013	54	2013	54	NA	NA	NA	NA
24	28783	Extant	2010	62	2010	62	NA	NA	NA	NA
		Totals:		1728		928	-800		75	725

5.2. Current conditions of habitats at Extant EOs.

The Taylor and O'Kennon (2013) potential habitat model (described in Section 2.4) is useful for range-wide habitat modeling; unfortunately, it does not have sufficient precision for larger-scale modeling of habitats at the individual EO level (for example, note the misalignment of documented populations with high potential habitat in Figure 2.10). We devised a potential habitat model in ArcMap to evaluate habitat suitability at extant EOs of big red sage. We included EO 4 because habitats appear largely intact in the upper portion of Turtle Creek; this area has not been surveyed since 1943, so populations may persist there.

The methods and data sources used for the potential habitat model are described in detail in Appendix A. Briefly, the model intersects three digital geographic data layers—vegetation type, degree of slope, and proximity to watercourses—that influence the distribution of big red sage habitats. The model assigns higher ranks to polygons that have broadleaf forest, greater degree of slope, and are closer to watercourses. The resulting maps in Figures 5.1 through 5.8 classify habitat potentials as low, good, and excellent.

Big red sage habitats occur in narrow bands along watercourses, including first-order streams (according to Strahler stream order). The extant EOs range from 10 to 200 m in width or diameter. Since surrounding areas have a relatively large influence on habitats within these narrow EO boundaries, we evaluated habitats within the EOs as well as a 50-m wide buffer around each EO.

The evaluation of current habitat conditions at extant EOs includes the amount and percent of good and excellent habitat, the presence of gaps between areas of good or excellent habitat, the proximity of urban and residential development, and the abundance of forested ravines and tributaries that connect to the EOs. As discussed in Section 2.3, larger gaps may discourage trapline foraging of black-chinned hummingbirds—a known pollinator of big red sage—and consequently would reduce outcrossing and gene flow between separate groups of big red sage individuals; this in turn would increase population fragmentation and inbreeding.

Although we have no data on black-chinned hummingbird forage ranges, in Section 3.2 we estimated they may forage up to 0.5 to 1.0 km (0.3 to 0.6 mi); hence, populations separated by more than 500 m may be reproductively isolated. Habitat gaps less than 50 m (164 ft) wide would be easily traversed by hummingbirds, and therefore probably do not prevent cross-pollination. We tentatively estimate that habitat gaps begin to interfere with big red sage pollination somewhere between 50 and 500 m. Intensively developed urban and residential areas, where native vegetation has been cleared and replaced by introduced plants, buildings, and pavement, and where drainage and topography have been altered, are also formidable barriers to big red sage colonization and gene flow.

In contrast, forested ravines and tributaries increase and extend potential habitats beyond the surveyed limits of EOs; undiscovered populations along tributaries, if present, would enhance the viability of the known population within the EO boundary. These tributaries may also serve as hummingbird trapline routes and therefore as conduits for gene flow between watersheds (see Figure 5.10).

Element Occurrence 4 habitat conditions (Figure 5.1.a). EO 4 is a 60-m (197-ft) wide corridor along fourth- and fifth-order sections of Turtle Creek in Kerr County, beginning 3.2 km (2.0 mi) above its confluence with the Guadalupe River and extending 29.5 km (18.3 mi) upstream (Figure 5.1.a). Due to its length and dissimilar habitat conditions in different sections, we evaluated separately the upper, middle, and lower Turtle Creek sections of EO 4.

Upper Turtle Creek (Figure 5.1.b). The upper Turtle Creek section of EO 4 is 13.7 km (8.5 mi) long. Over 38 percent of this section (83.5 ha (206 ac)) has good or excellent potential habitat for big red sage. Nearly 20 ha (49 ac) of excellent habitat occurs where steep bluffs line the creek, providing relatively cool, shaded habitats and protection from herbivory. This section has only four habitat gaps greater than 50 m (164 ft) wide, the longest of which is 133 m (436 ft). The surrounding landscape is mostly naturally vegetated rangeland, forest, and woodland, with some improved pasture along the lower 3.5 km (2.2 mi) of this section. A row of recreational homes spans 1.1 km (0.7 mi) of streamside, but since the opposite side is a steep, forested bluff with excellent habitat, this residential area is not a habitat barrier. At least 14 forested tributary ravines in upper Turtle Creek increase the available habitat and potential for gene flow between groups of plants. We plotted a route that V.L. Cory may have taken in 1943, starting at the courthouse in Kerrville, following SH 16 and then the Upper Turtle Creek Road (which is now FM 1273). We indicate in Figures 5.1.a and 5.1.b two possible locations that are the reported distance Cory traveled from Kerrville; both are in areas of excellent potential habitat. We also indicate a broader range that reflects the uncertainty over the route Cory traveled. In summary, upper Turtle Creek has abundant potential habitat, few if any significant habitat gaps, and abundant tributary habitats, and therefore has a high habitat condition.

Middle Turtle Creek (Figure 5.1.c.). The middle Turtle Creek section of EO 4 is 8.2 km (5.1 mi) long. Twenty percent (26.5 ha (65.5 ac)) is good or excellent potential habitat. This section has 10 habitat gaps of 50 m or larger; the largest is 338 m (1,109 ft). This section has only 3 forested tributary ravines. The surrounding landscape is about 60 percent improved pasture and cropland and 40 percent naturally vegetated rangeland, forest, and woodland. There are no urban or residential areas along this section. In summary, the habitat conditions of middle Turtle creek include relatively little potential habitat, numerous habitat gaps, and few tributary habitats; therefore, this section has a low habitat condition.

Lower Turtle Creek (Figure 5.1.d.). The lower Turtle Creek section of EO 4 is 7.8 km (4.8 mi) long. Good or excellent potential habitat totals 28.1 ha (69.4 ac), comprising 21.9 percent of the evaluated area. This section has 9 habitat gaps greater than 50 m, the largest of which is 210 m (689 ft) wide. This section has no forested tributary ravines. About 82 percent of the surrounding landscape is pasture or cropland, 14 percent is naturally vegetated rangeland, woodland, or forest, and 3 percent is residential. O’Kennon collected big red sage from a low streamside bluff in this section in 1991–1994, but by 2013 the species was no longer present (Taylor and O’Kennon 2013, pp. 4, 6). Due to relatively little potential habitat, numerous gaps, and no tributary habitats, lower Turtle Creek has a low habitat condition.

Figure 5.1.a. EO 4 - Entire.

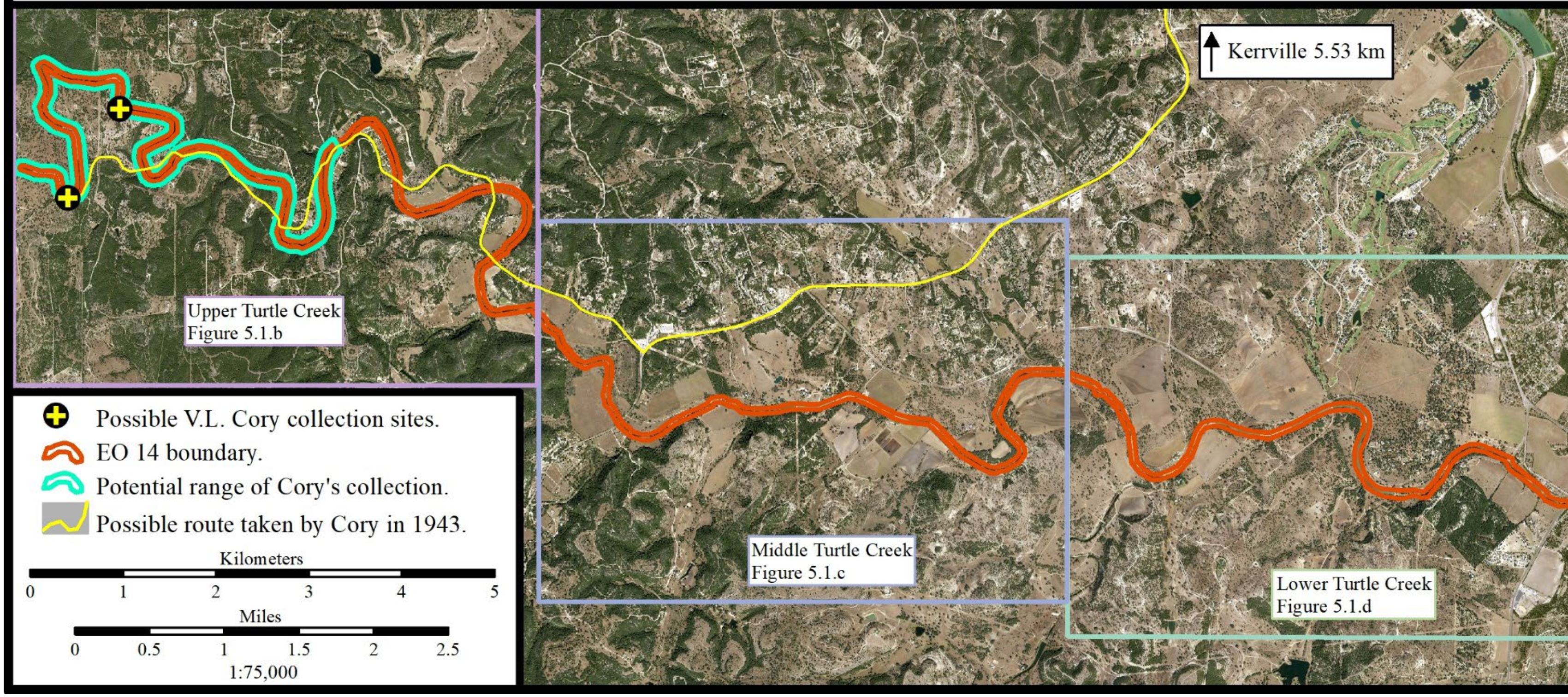
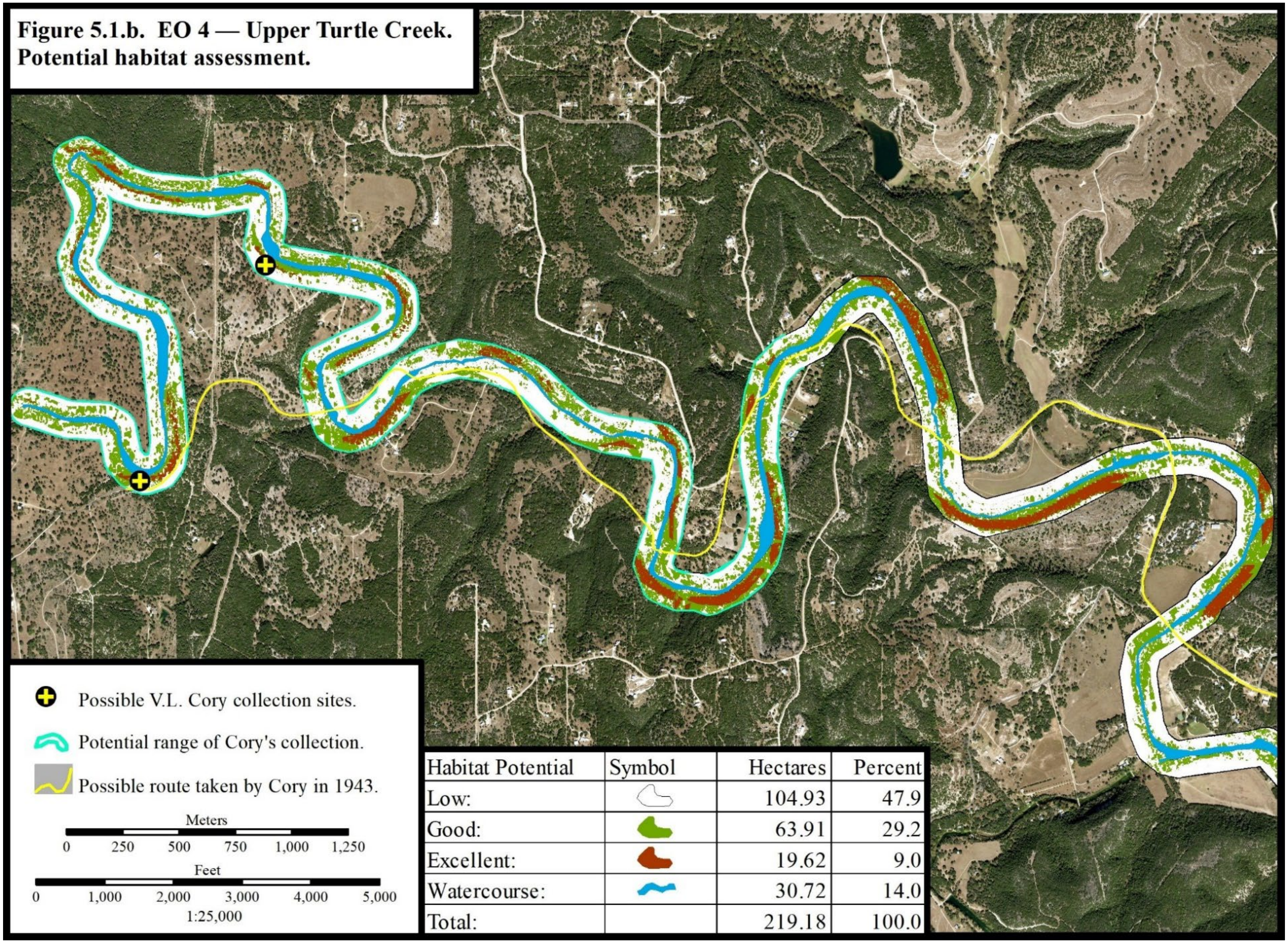
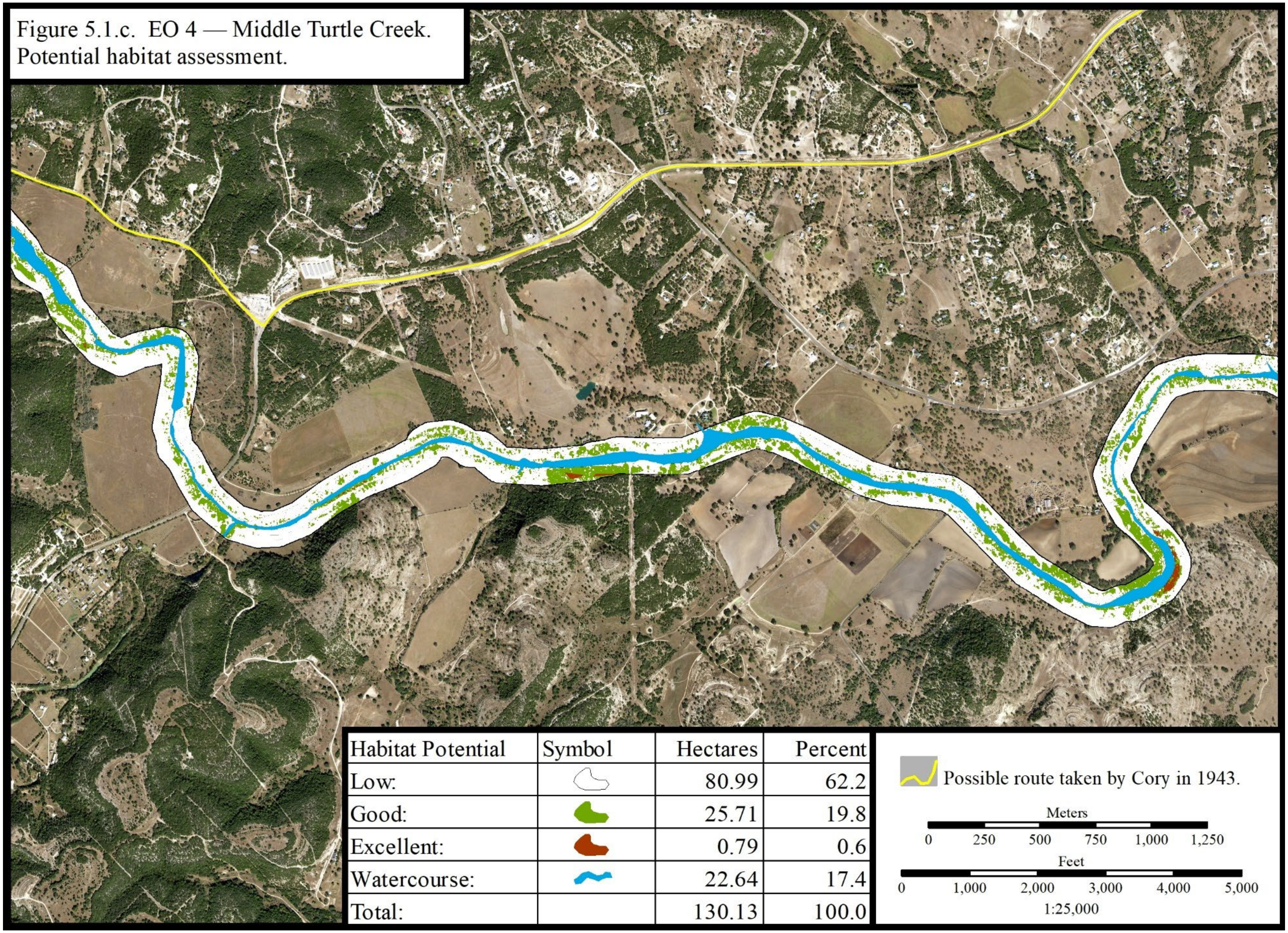


Figure 5.1.b. EO 4 — Upper Turtle Creek. Potential habitat assessment.

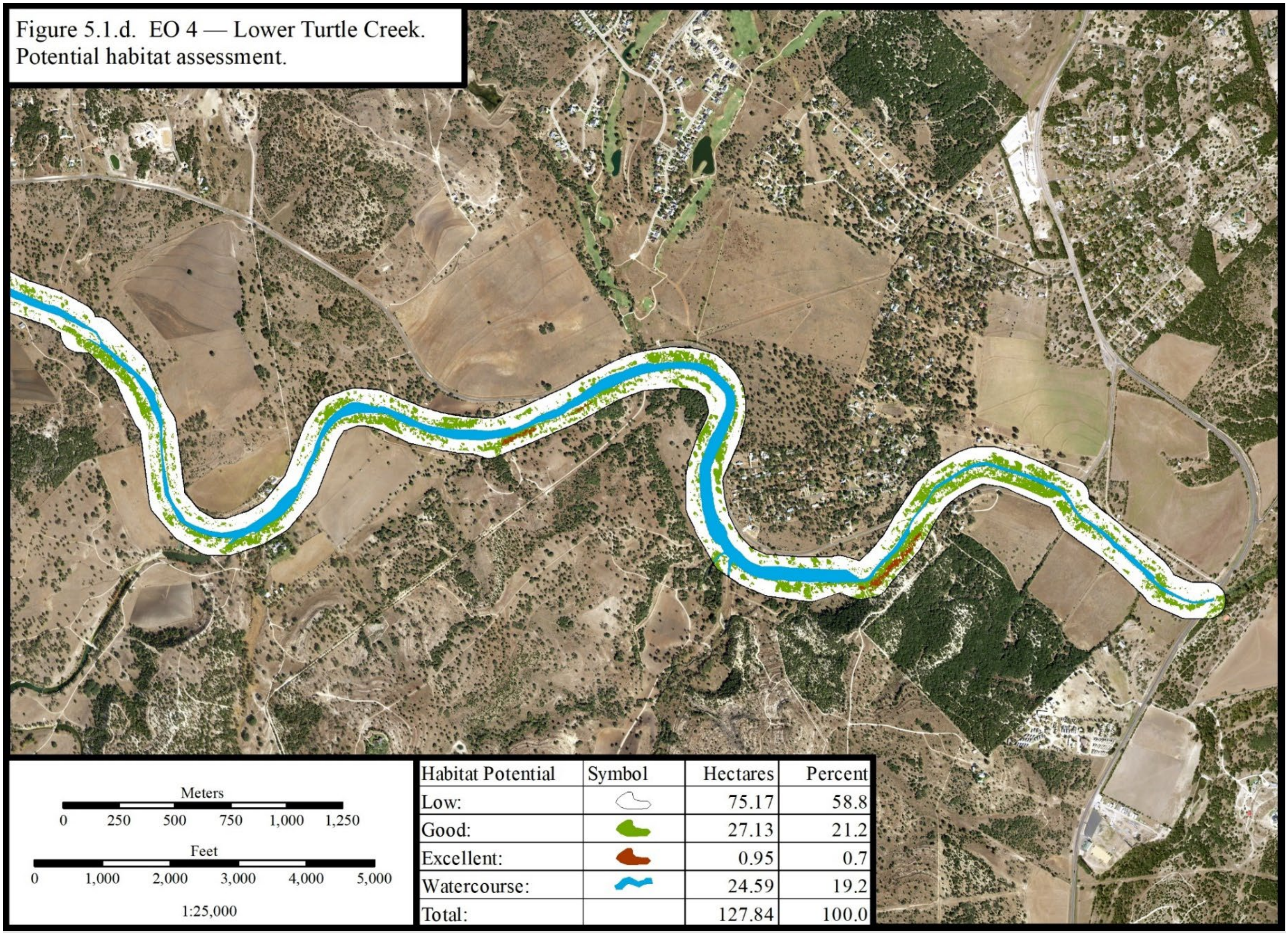


Habitat Potential	Symbol	Hectares	Percent
Low:		104.93	47.9
Good:		63.91	29.2
Excellent:		19.62	9.0
Watercourse:		30.72	14.0
Total:		219.18	100.0

Figure 5.1.c. EO 4 — Middle Turtle Creek. Potential habitat assessment.



Habitat Potential	Symbol	Hectares	Percent
Low:		80.99	62.2
Good:		25.71	19.8
Excellent:		0.79	0.6
Watercourse:		22.64	17.4
Total:		130.13	100.0



Habitat Potential	Symbol	Hectares	Percent
Low:		75.17	58.8
Good:		27.13	21.2
Excellent:		0.95	0.7
Watercourse:		24.59	19.2
Total:		127.84	100.0

Figure 5.1a–d. Potential habitat of: a) EO 4 – entire; b) Upper Turtle Creek; c) Middle Turtle Creek; and d) Lower Turtle Creek.

Element Occurrence 5 habitat conditions (Figure 5.2.a). EO 5 is a 10-m (33-ft) wide corridor along third-, fourth-, and fifth-order sections of Cibolo Creek in Kendall County, beginning 7.2 km (4.5 mi) below its confluence with Frederick Creek and extending 29.3 km (18.2 mi) upstream (Figure 5.2.a). Due to its length and dissimilar habitat conditions in different sections, we evaluated separately the upstream, midstream, and downstream Cibolo Creek sections of EO 5 (note that Cibolo Creek continues below EO 5 for about 223 km (139 mi) to its confluence with the San Antonio River).

Upstream Cibolo Creek (Figure 5.2.b). The upstream Cibolo Creek section of EO 5 is 10.3 km (6.4 mi) long. Sixty-six percent (62.7 ha (155.0 ac)) is good or excellent potential habitat with 12.8 ha (31.5 ac) of excellent potential habitat. This section has only 2 habitat gaps of 50 m or larger; the largest is 107 m (351.0 ft). This section has 12 forested tributary ravines. The surrounding landscape is about 61 percent naturally vegetated rangeland, forest, and woodland and 39 percent improved pasture. There are no urban or residential areas along this section. In summary, the upstream Cibolo Creek section has abundant potential habitat, no significant habitat gaps, and abundant tributary habitats, and therefore has high habitat condition.

Midstream Cibolo Creek (Figure 5.2.c). The midstream Cibolo Creek section of EO 5 is 10.3 km (6.4 mi) long. This section has 44.22 ha (109.3 ac) of good potential habitat and 0.6 ha (1.4 ac) of excellent habitat; 39.8 percent of this section is good or excellent potential habitat. There are 4 habitat gaps over 50 m, including a gap of 2.4 km where the EO crosses Boerne Lake. This section has no forested tributary ravines. The surrounding landscape is about 9 percent naturally vegetated rangeland, woodland, and forest, 54 percent improved pasture and cropland, 15 percent open water, and 23 percent is urban or residential. In synthesis, although good potential habitat is relatively abundant within the EO and buffer, the large gaps from the reservoir and urban areas and the lack of adjoining tributary habitats may deter hummingbird-mediated gene flow between the upstream and downstream habitats. However, this could be mitigated through a focused big red sage conservation effort in and near the City of Boerne. This section of EO 5 has a moderate habitat condition.

Downstream Cibolo Creek (Figure 5.2.d). The downstream Cibolo Creek section of EO 5 is 8.7 km (5.4 mi) long. Good and excellent potential habitat total 42.9 ha (106.0 ac) and 0.4 ha (1.1 ac), respectively, comprising 45 percent of this EO and buffer. There are 4 habitat gaps of 50 m or larger within the EO and buffer, the largest of which is 141 m (463 ft) wide. Nevertheless, urban and residential development within the City of Boerne occupy 3.6 km (2.2 mi) along both sides of this section of Cibolo Creek; the influence of these adjacent developed areas may interfere with habitat connectivity. This section has one important tributary, Frederick Creek; an extant population of big red sage, EO 14, is located just 1.5 km (0.9 mi) above its confluence with Cibolo Creek. Lower Frederick Creek and the confluence with Cibolo Creek are also within the urban area of the City of Boerne. About 42 percent of the surrounding landscape in this downstream EO 5 section is urban and residential. Below the City of Boerne, 11 percent of this section's landscape is improved pasture and cropland, and 48 percent is naturally vegetated forest, woodland, and grassland. Much of this stretch of naturally vegetated land is owned or managed by Cibolo Center for Conservation and Cibolo Preserve (described in Section 2.6). In summary, due to the protection of an extant habitat, the downstream Cibolo Creek section of EO 5 has a high habitat condition.

Figure 5.2.a. EO 5 — Entire.

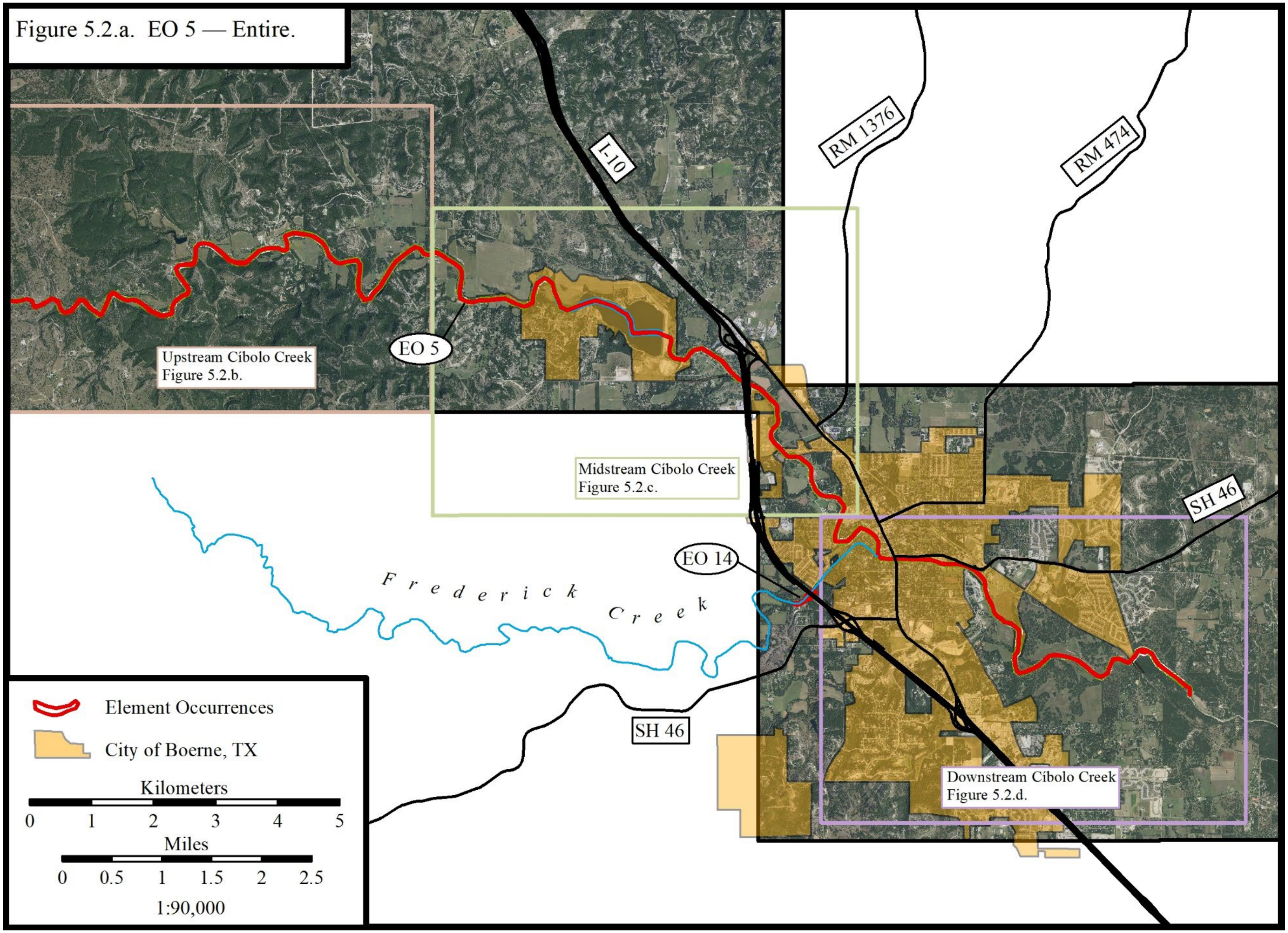
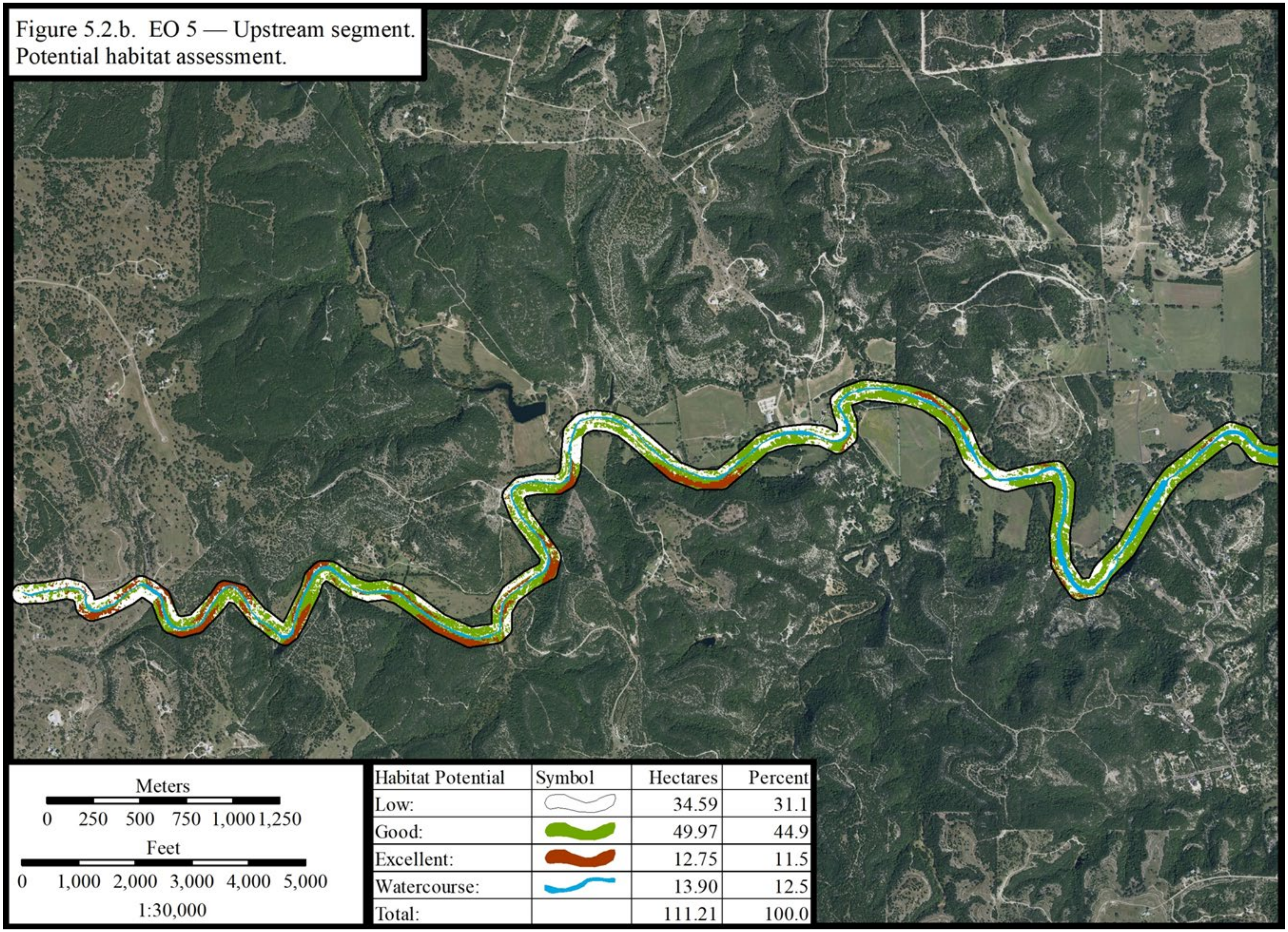
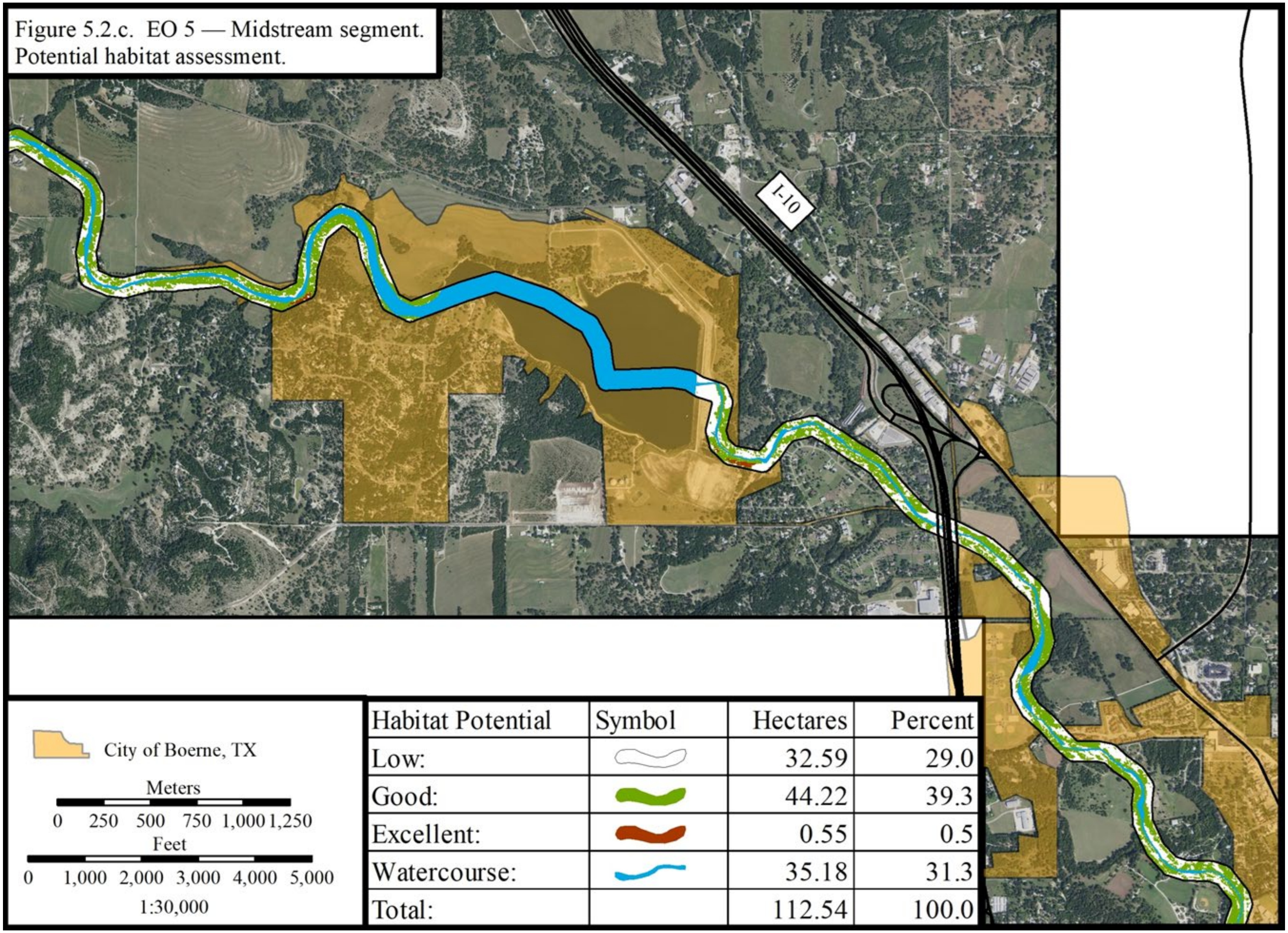


Figure 5.2.b. EO 5 — Upstream segment. Potential habitat assessment.

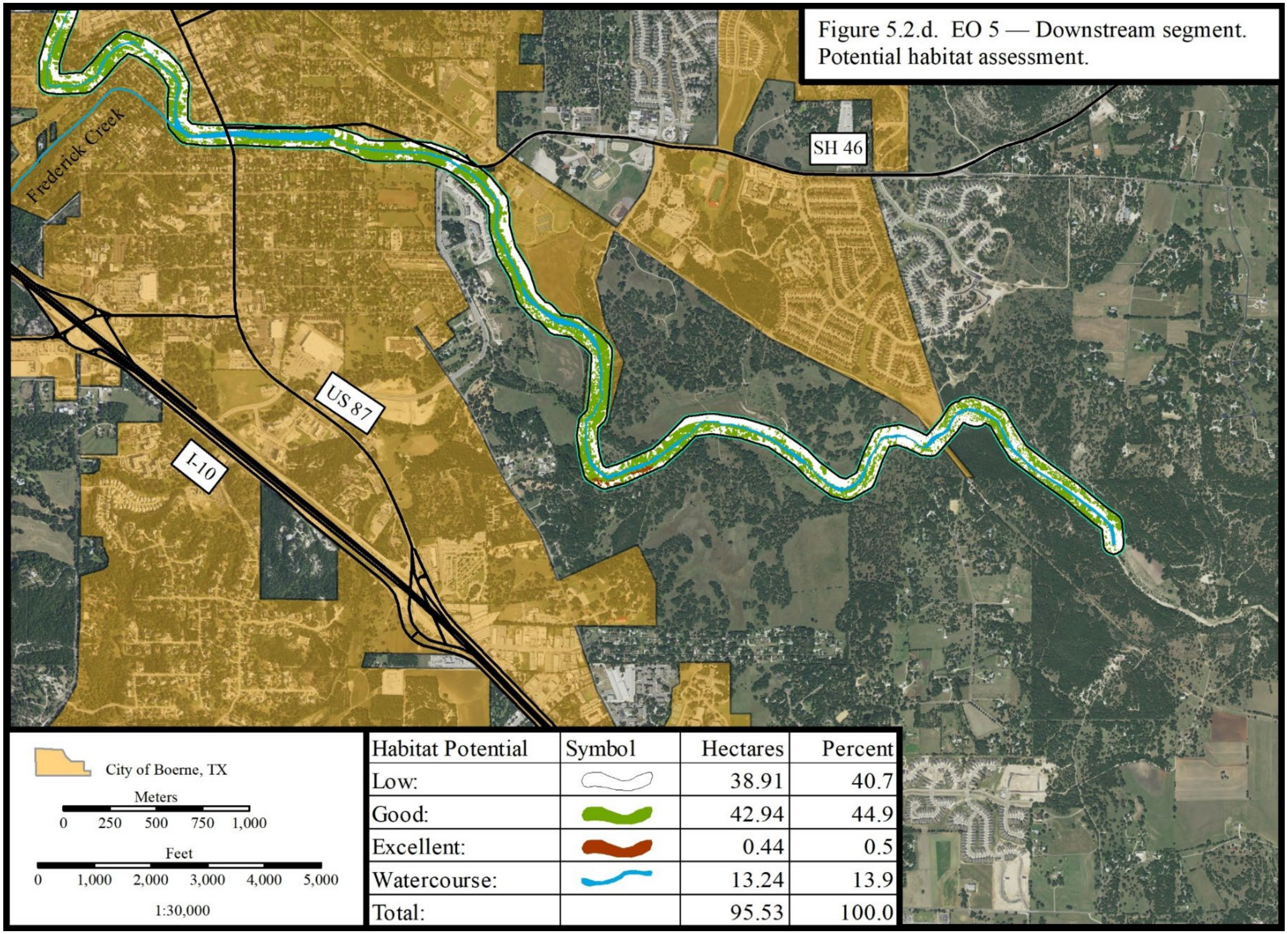


Habitat Potential	Symbol	Hectares	Percent
Low:		34.59	31.1
Good:		49.97	44.9
Excellent:		12.75	11.5
Watercourse:		13.90	12.5
Total:		111.21	100.0

Figure 5.2.c. EO 5 — Midstream segment.
Potential habitat assessment.



Habitat Potential	Symbol	Hectares	Percent
Low:		32.59	29.0
Good:		44.22	39.3
Excellent:		0.55	0.5
Watercourse:		35.18	31.3
Total:		112.54	100.0



Habitat Potential	Symbol	Hectares	Percent
Low:		38.91	40.7
Good:		42.94	44.9
Excellent:		0.44	0.5
Watercourse:		13.24	13.9
Total:		95.53	100.0

Figure 5.2a–d. Potential habitat assessment of a)EO 5 – entire; b)EO 5 – upstream segment; c)EO 5 – Midstream segment; and d)EO 5 – Downstream segment.

Element Occurrence 11 habitat conditions (Figure 5.3). EO 11 consists of five circular areas that are located along first- and second-order tributaries of the Sabinal River in Bandera and Real counties. The areas are 50, 100, or 200 m (164, 328, or 656 ft) in diameter. The EO and buffers include 8.6 ha (21.2 ac) of good potential habitat and 6.0 ha (14.8 ac) of excellent potential habitat; 71 percent of the area is good or excellent potential habitat. There are no habitat gaps, and the EO areas are interconnected through 12 forested ravines. The entire surrounding landscape is naturally vegetated and is protected within Lost Maples SNA. Enquist re-discovered big red sage here in 1980 (discussed in Section 2.6). Although the very small population here has declined and may already be extirpated, the EO has a high habitat condition. The proximity of EOs 11, 16, and 24 to first-order streams demonstrates that undiscovered populations may yet persist in upper canyons of the Edwards Plateau where they may be protected from deer and from plant thieves by steep slopes and inaccessible terrain.

Element Occurrence 14 habitat conditions (Figure 5.4; see also Figure 6.1). EO 14 is a 20- to 85-m (66- to 279-ft) wide corridor along a fourth-order section of Frederick Creek in Kendall County, beginning 1.5 km (0.9 mi) above its confluence with Cibolo Creek and extending 481 m (1,578 ft) upstream (Figure 5.4). Good or excellent potential habitat makes up 23 percent of this EO and buffer, totaling 1.62 ha (4.0 ac). There are no significant habitat gaps (the apparent gaps in the habitat model are due to the concrete lanes of the Interstate 10 bridge, but the habitat is below the bridge). The surrounding landscape is about 26 percent improved pasture, 41 percent naturally vegetated rangeland and woodland, and 33 percent urban and residential. The original SF (15826) has been known since 1984 and is the source of many of the propagated populations. This population formerly thrived in the artificial shade of the Interstate 10 bridge over Frederick Creek. As described in Section 2.6, this SF gradually declined and was extirpated by 2009, but an additional SF (28459) on adjacent private land had 401 individuals in 2013. Another extant EO (24) occurs further up the Frederick Creek watershed, and several north-facing bluffs between EOs 24 and 14 along Frederick Creek have excellent potential habitats. In summary, due to the habitat barriers isolating EO 14 from downstream habitats and proximity to the Interstate highway, EO 14 has a moderate habitat condition—but the potential could improve if habitat connectivity with neighboring populations can be restored.

Element Occurrence 16 habitat conditions (Figure 5.5). EO 16 is a circular area located along a first-order tributary of the Dry Frio River in Real County. The EO is 200 m (656 ft) in diameter. The EO and buffer have 3.7 ha (9.1 ac) of good or excellent habitat (52 percent of the total). The entire surrounding landscape is naturally vegetated and there are 5 forested tributary ravines adjacent to this EO. This privately owned site has only been observed once, in 1991, and only two individuals were recorded. We do not know whether those plants were part of a larger viable population scattered through the ravines, or if any individuals remain. Aside from this uncertainty, EO 16 and the surrounding area has abundant good and excellent potential habitat and a high habitat condition.

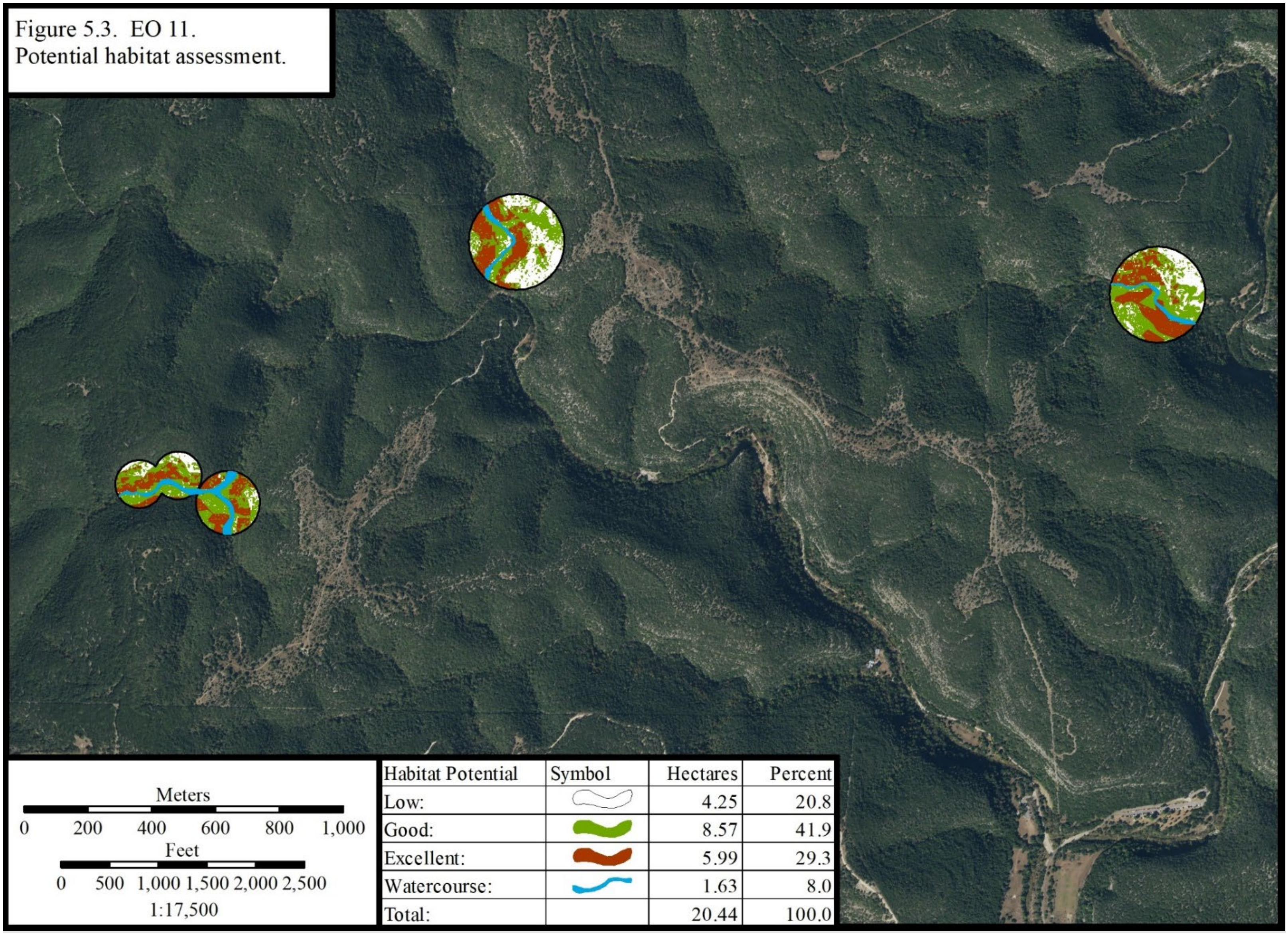


Figure 5.3. EO 11 potential habitat assessment.

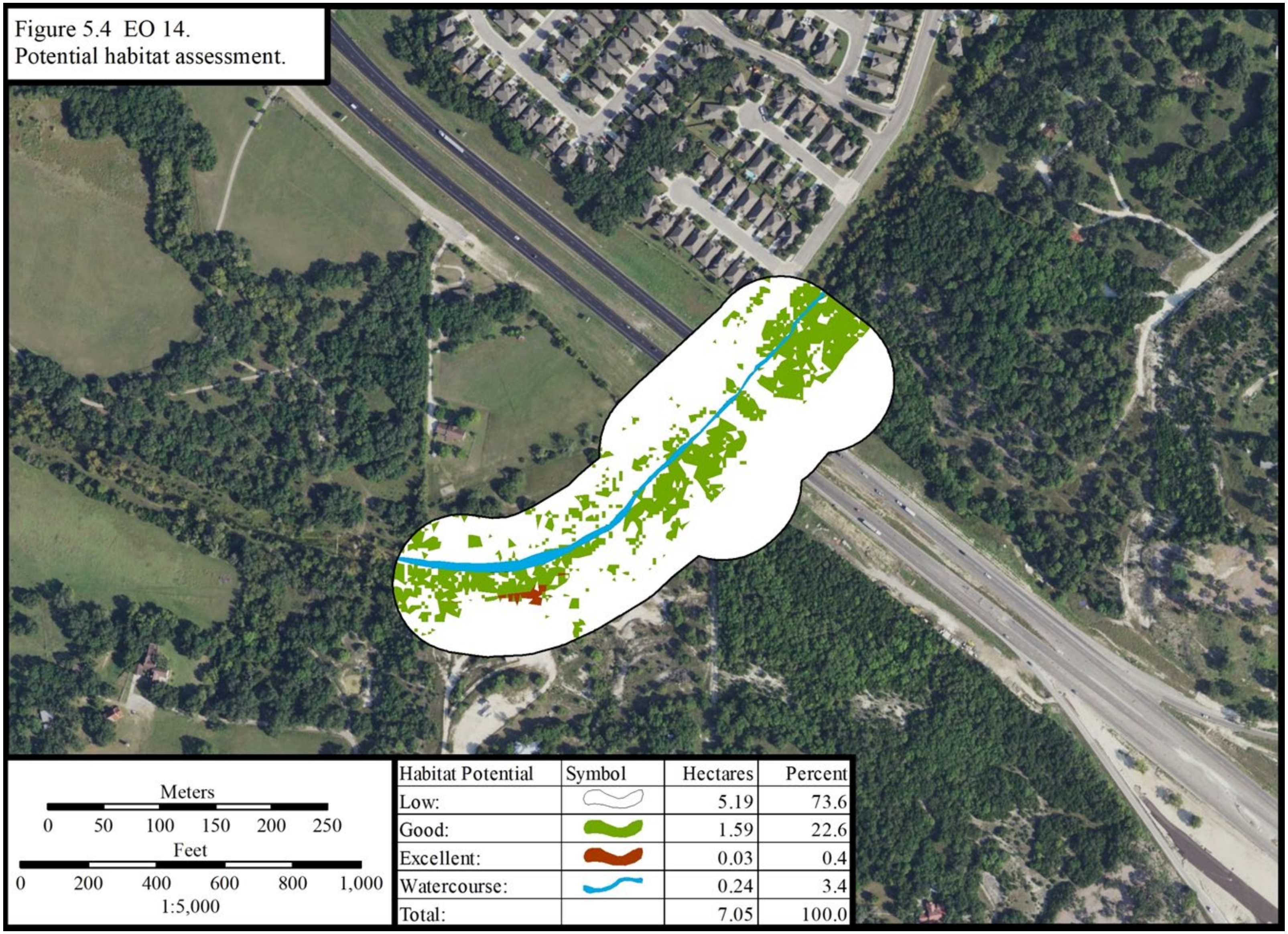


Figure 5.4. EO 14 potential habitat assessment.

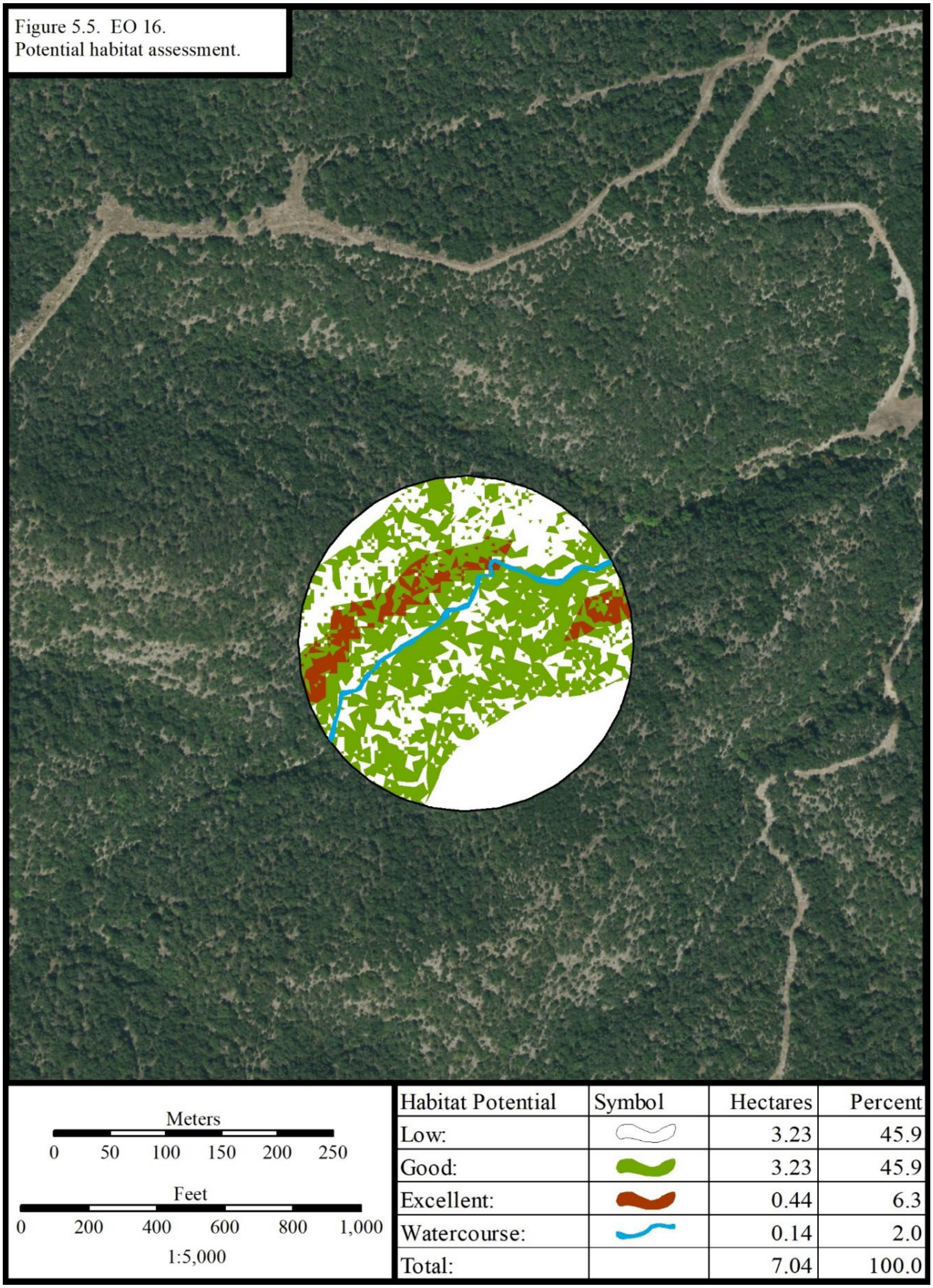


Figure 5.5. EO 16 potential habitat assessment.

Element Occurrence 20 habitat conditions (Figure 5.6). The 5 SFs of EO 20 are corridors along the North Fork of the Guadalupe River, a 6th-order stream, in Kerr County. The SFs are grouped into two 10-m (33-ft) wide strips along the river, widening to a 50-m (164-ft) diameter circle at the southwest end, totaling 1,369 m (4,491 ft) in length. The EO and buffer include 5.7 ha of good or excellent potential habitat (32 percent of the total area). The surrounding landscape is about 64 percent naturally vegetated rangeland, forest, and woodland, and 36 percent improved pasture and mowed lawn. A single forested ravine connects to the northeast side of this EO. However, abundant potential habitats exist both up- and downstream along the North Fork of the Guadalupe and several tributaries. In summary, the habitat conditions of EO 20 confer a high habitat condition.

Element Occurrence 21 habitat conditions (Figure 5.7). EO 21 has three circular SFs, 50 m (164 ft) in diameter, located along a 210-m (689-ft) span of a steep, east- and southeast-facing bluff of a fifth-order stream, the East Frio River, in Real County. The EO and buffer have 2.27 ha (5.6 ac) of good or excellent habitat (56 percent of the total area). The surrounding landscape is evenly divided between naturally vegetated river bluffs on one side of the East Frio River and the buildings and lawns of a recreational camp on the other side. Although there are no tributary ravines that connect directly to this small EO, the canyon of the East Frio River has abundant potential habitat and numerous tributary canyons that are potential habitat corridors to adjacent watersheds. Figure 5.9 shows two possible routes that trap-lining hummingbirds could take between the East Frio and Sabinal watersheds. We hypothesize that groups of big red sage scattered along these routes would enable hummingbird-mediated gene flow between EO 11 and EO 21. In summary, EO 21 has a high habitat condition.

Element Occurrence 24 habitat conditions (Figure 5.8). The two SFs of EO 24 are circular areas 50 m (164 ft) in diameter and 62 m (203 ft) apart along a first-order tributary of Frederick Creek in Kendall County. Good and excellent potential habitat total 2.0 ha (5.0 ac), 77 percent of the total area. All of the surrounding landscape is naturally vegetated forest, woodland, and rangeland. This small EO lies within a forested canyon about 1.5 km (0.9 mi) long that has twelve branches, expanding the range of its potential habitat. Due to the limited area, this EO has a moderate habitat condition. Although the valley of the upper 10 km (6.2 mi) of Frederick Creek has been developed for improved pastures, a golf course, residences, and reservoirs, there are at least 20 tributary canyons of upper Frederick Creek with habitats similar to EO 24.

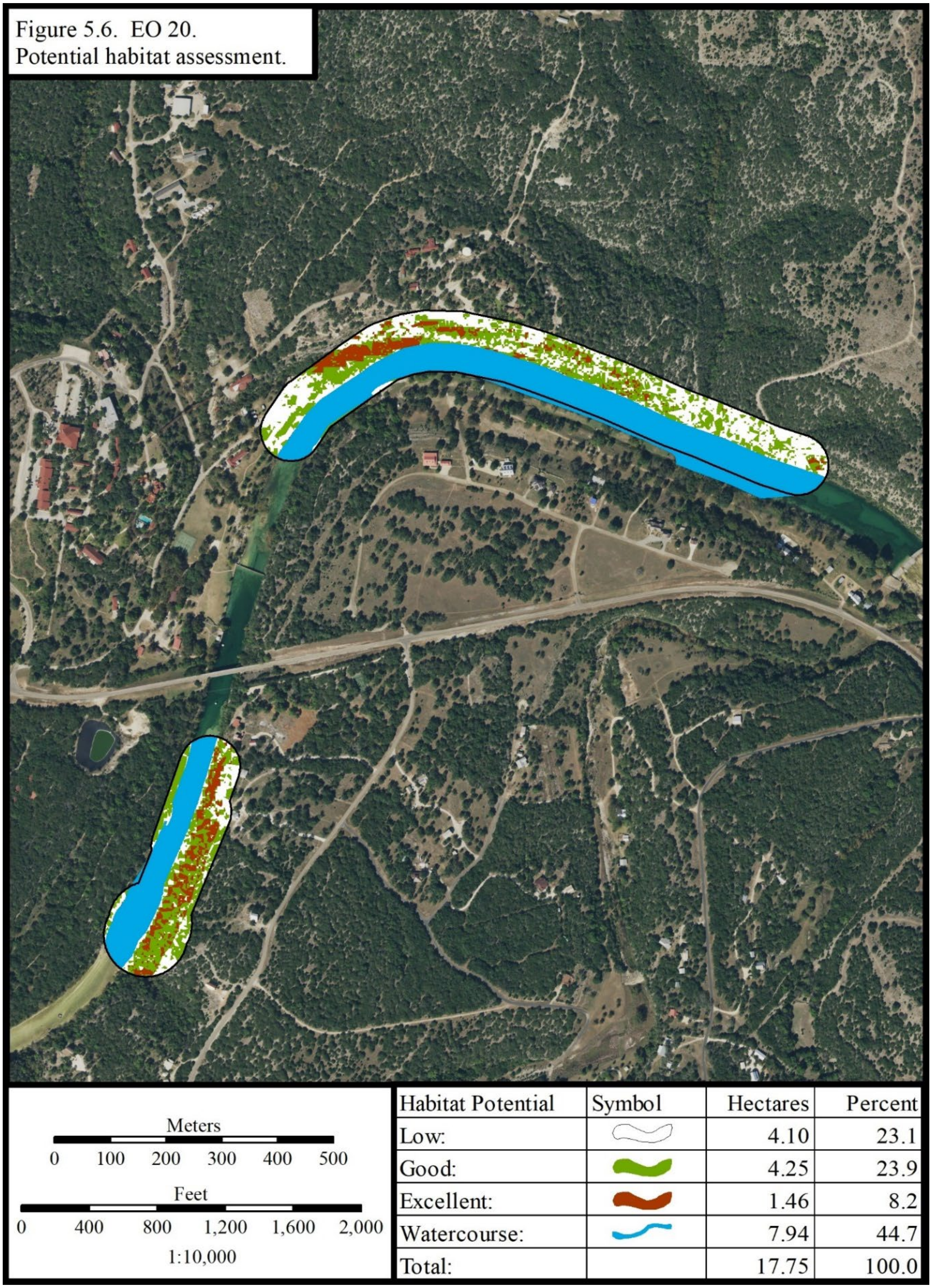
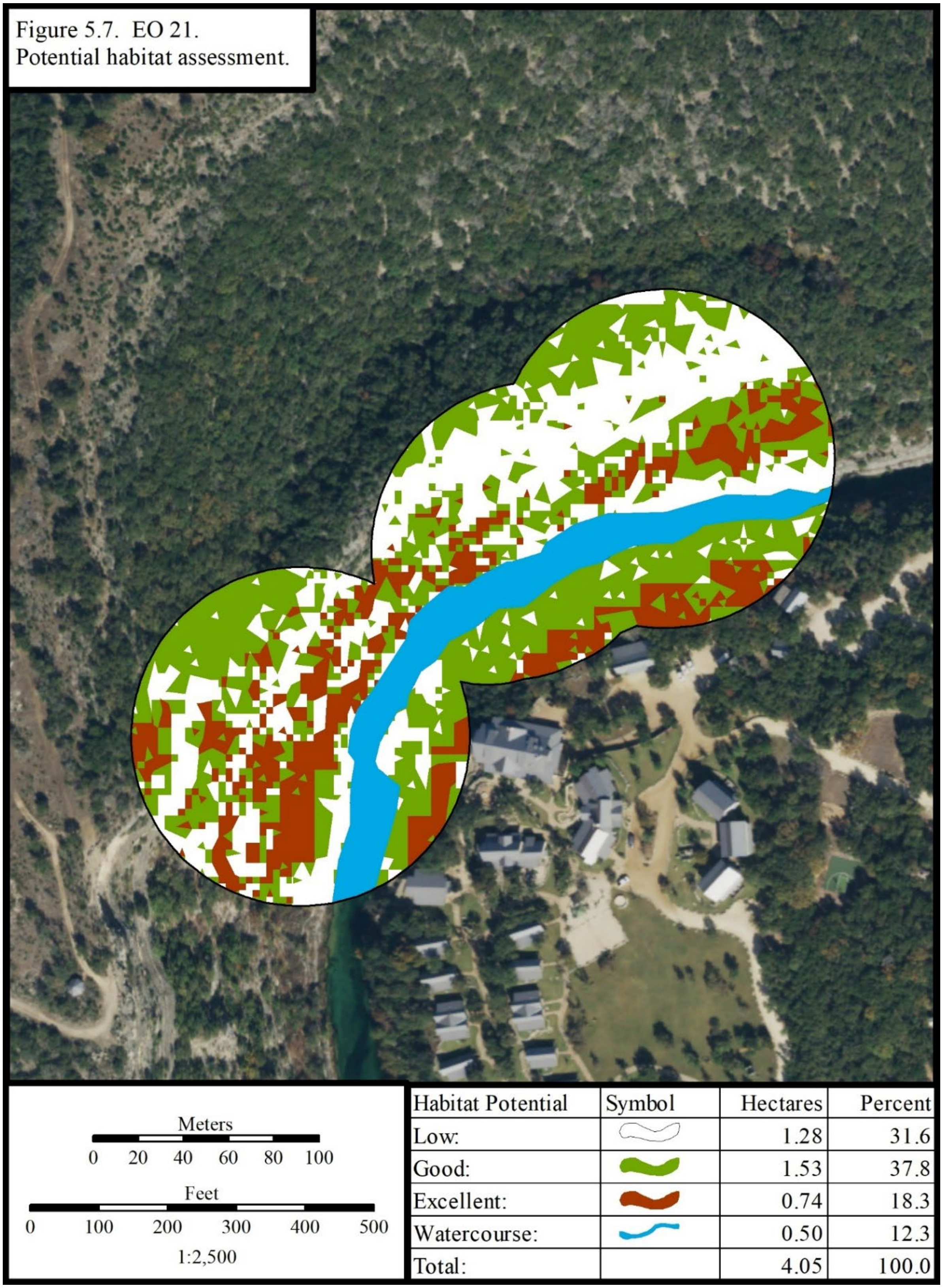


Figure 5.6. EO 20 potential habitat assessment.



Habitat Potential	Symbol	Hectares	Percent
Low:		1.28	31.6
Good:		1.53	37.8
Excellent:		0.74	18.3
Watercourse:		0.50	12.3
Total:		4.05	100.0

Figure 5.7. EO 21 potential habitat assessment.

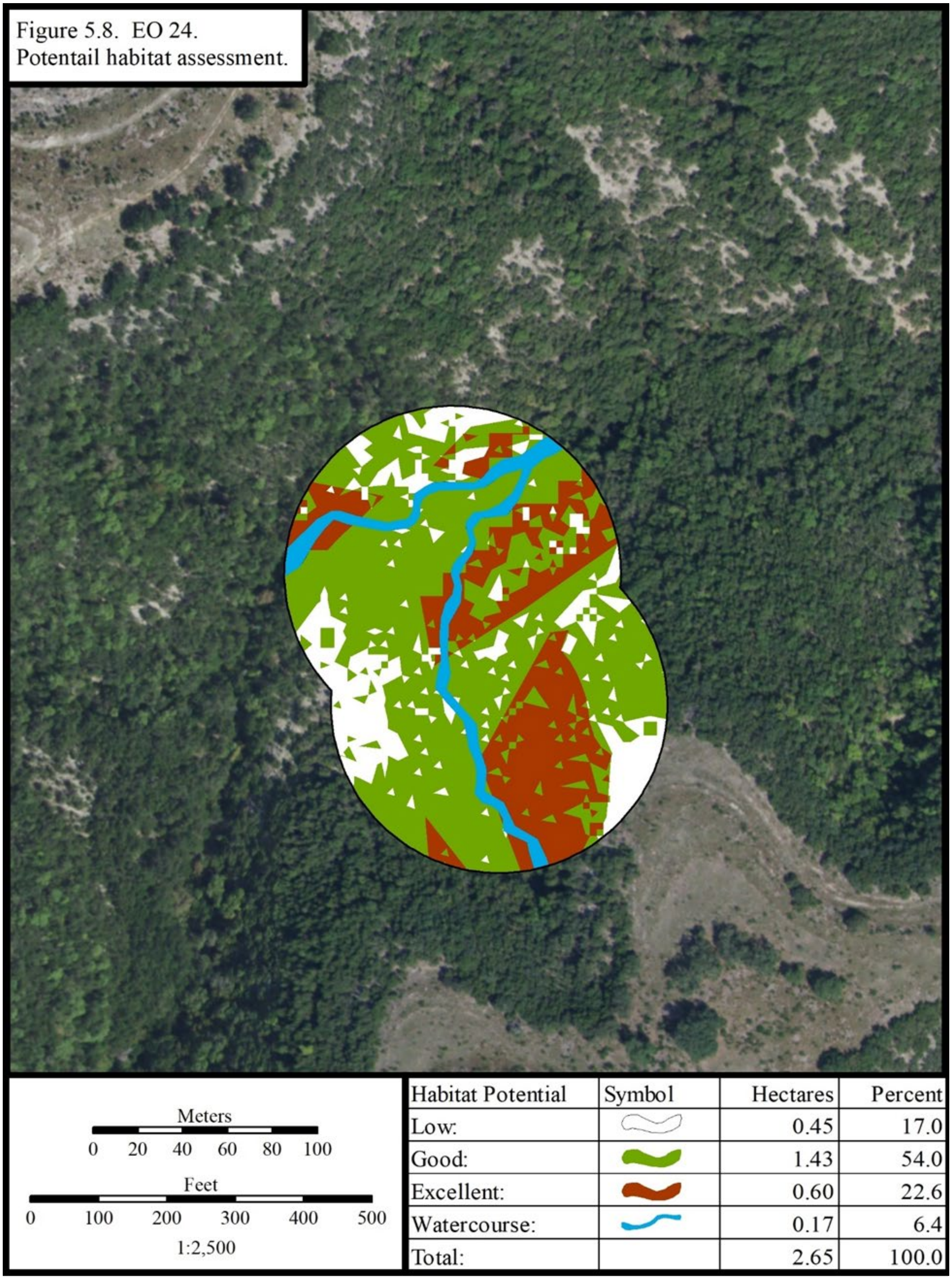


Figure 5.8. EO 24 potential habitat assessment.

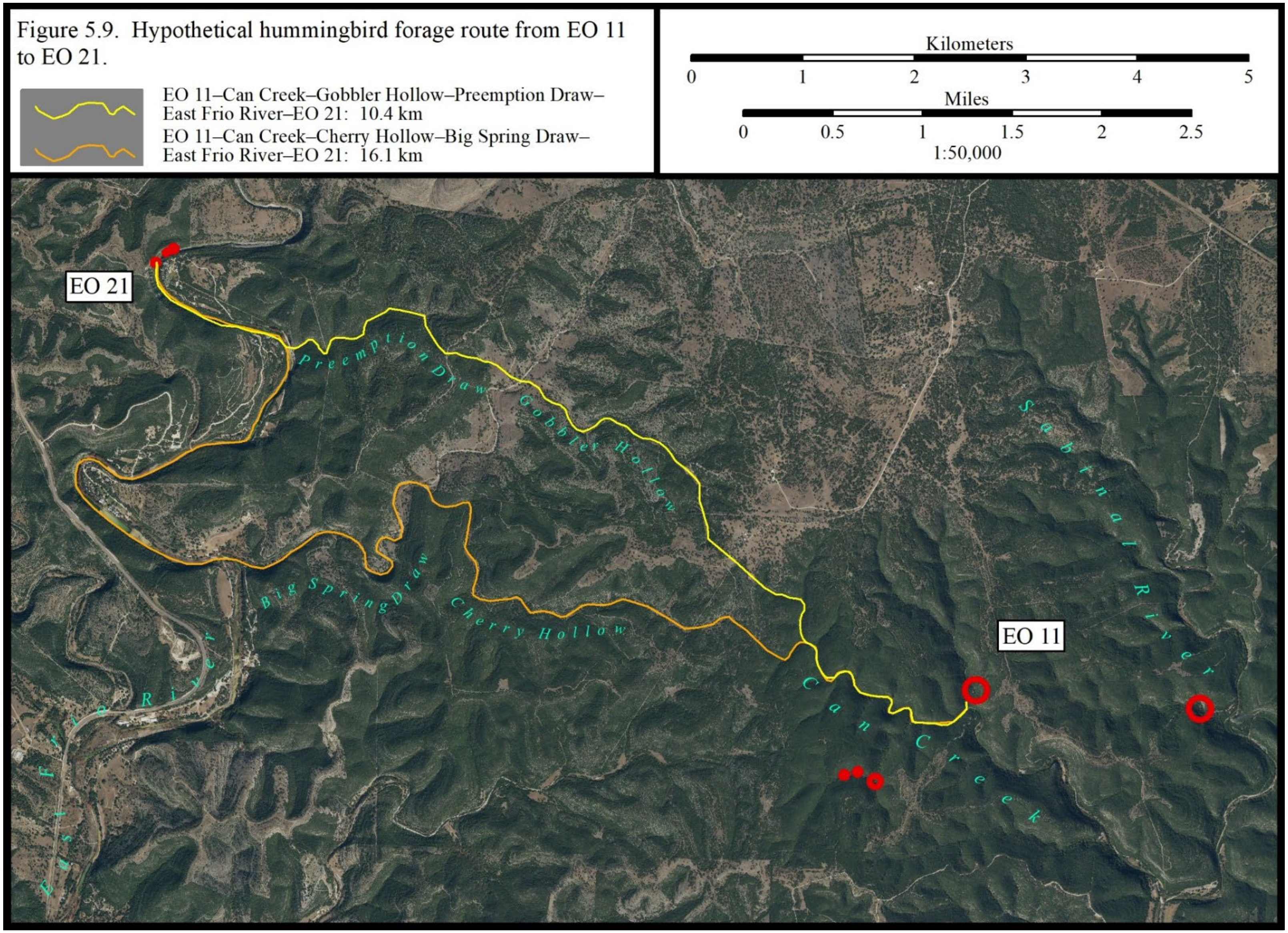


Figure 5.9. Hypothetical hummingbird forage route from EO 11 to EO 21.

5.3. Representation Areas and Redundancy of big red sage.

Representation Areas are sectors of a species' geographic range where distinct reservoirs of its overall genetic and ecological diversity occur. Big red sage habitats occur along streams and the species' seed and pollen dispersal occurs primarily along stream corridors. Consequently, we expect that the individuals within a watershed are more closely related to each other than to those present in other watersheds. Therefore, we used the USGS Hydrologic Unit Code (HUC) 10 watershed boundaries (U.S. Geological Survey 2023) to delineate Representation Areas where extant populations of big red sage occur (Table 5.3), named for the principal watercourses in each area: Guadalupe, Cibolo, and Frio-Sabinal.

Redundancy, expressed as the number of resilient populations and their geographic distribution and connectivity, applies to the species as a whole, as well as to each of its Representation Areas. Big red sage is currently represented by 7 extant populations distributed within 3 Representation Areas (Table 5.4; Figure 5.10). Four extant EOs of big red sage are moderately resilient, although they are all far below the estimated MVP level of 1,600 individuals. Three extant EOs have low resilience. The Cibolo Representation Area has three moderately resilient EOs and is therefore moderately redundant. The Guadalupe Representation Area has a single moderately resilient EO and therefore has low redundancy. However, since the area of EO 4 along upper Turtle Creek has not been surveyed since 1943, it is possible that this population may be extant; in this case, it would contribute to the redundancy of the Guadalupe Representation Area. The Frio-Sabinal Representation Area has three EOs, all with low resilience, and therefore has low redundancy.

We also recognize a fourth Representation Area, Pedernales, where there are 3 extirpated EOs, because undiscovered extant populations may persist there. In addition, as discussed in Section 2.6, the correct location of EO 1 is likely to be on Barons Creek within this fourth Representation Area; consequently, its condition is non-contributing rather than extirpated. Table 5.3 lists the Representation Areas and their component HUC-10 watersheds. We did not designate a Representation Area for EO 19, in the Headwaters of Salado Creek, because the site and most of that watershed is within developed areas of Camp Bullis and the City of San Antonio.

Table 5.3. Representation Areas of big red sage.

Representation Area Name	Watershed Names (10-Digit Hydrologic Unit Codes)
Guadalupe	Headwaters Guadalupe River (1210020101), Turtle Creek-Guadalupe River (1210020102), and Block Creek-Guadalupe River (1210020103)
Cibolo	Headwaters Cibolo Creek (1210030401)
Frio-Sabinal	Headwaters Frio River (1211010602), Dry Frio River (1211010603), West Frio River (1211010601), Upper Sabinal River (1211010606)
Pedernales	Headwaters Pedernales River (1209020601), North Grape Creek-Pedernales River (1209020602)

5.4. Current species viability of big red sage.

Table 5.4 summarizes the population and habitat conditions from the previous sections and ranks the overall resilience for EOs within each Representation Area. Population resilience requires a viable population size as well as the habitat conditions needed to sustain it; a large population in a deteriorated habitat will likely decline, and therefore has low resilience. We ranked the overall resilience of each EO as the lesser of the population condition and habitat condition. The map in Figure 5.10 displays the EO conditions and the geographic extent of the Representation Areas.

The four largest EOs, when most recently censused, had from 108 to 401 individuals, far below the estimated MVP of 1,600. Considering that populations of big red sage occur in narrow bands associated with seep moisture in discrete locations along streams, most habitats are not large enough to support viable populations in any one place. Formerly, viable populations likely consisted of many small clusters of individuals scattered along riparian corridors stretching up to the highest canyons of first-order tributaries; hummingbirds would have preserved gene flow and the genetic integrity of these dispersed populations through occasional incidents of longer-distance pollination. The species' distribution may have become more restricted during Holocene warming. Since the beginning of European settlement, populations have become increasingly fragmented, due to the browsing of goats, over-abundant white-tailed deer, and introduced ungulates, to urban and residential development, and to over-collection of seeds and entire plants for the horticultural trade. What remains is a very small number of isolated fragments of former populations, none of which have viable population sizes.

Only three EOs have been censused multiple times. Element Occurrence 5 suffered a catastrophic loss from a severe flood but subsequently stabilized at a lower population size. EO 14 appears to have followed a similar pattern: a portion of the population was lost, due in part to flooding, while a surviving portion remained unscathed by the raging torrent. Other factors, including illicit collection, also contributed to that decline. If these marginally resilient populations do not recover from losses—which they have not, so far—it is likely that they will periodically decline to lower levels after each drought or flood, descending each time ever closer to extirpation. Element Occurrence 11 declined from 23 to 3 individuals between 1988 and 2019. The fate of EO 11 may be emblematic of other small populations; despite legal protection and high potential habitats, the population sizes may be too low to endure random variations in weather, herbivory, or other factors.

The species' total known populations have declined by 46 percent since 1988. Thirty-one percent of known SFs and 28 percent of known EOs have been completely extirpated. All known EOs in the Pedernales Representation Area are extirpated. The Guadalupe Representation Area has only one remaining EO, which is moderately resilient. The Frio-Sabinal Representation Area has three EOs, all of which have low resilience. The Cibolo Representation Area has three moderately resilient EOs that are currently isolated, or nearly isolated, from each other by urban, residential, and recreational development.

In synthesis, there are only seven known extant populations, only four are moderately resilient, and none are highly resilient. Therefore, the species has low overall resilience (Table 5.4). Redundancy is low because three of the four Representation Areas have extant populations, but one Representation Area has only one extant population, and all populations in another

Representation Area have very low resilience; only one Representation Area is moderately resilient and redundant. Furthermore, Hoban and Garner (2019) found that the overall genetic diversity is low. Therefore, the species has low representation. Based on these factors, we conclude that the current viability of big red sage is low.

Table 5.4. Summary of Representation Areas, population and habitat conditions, and overall resilience of the extant EOs of big red sage.

Representation Area	Element Occurrence	Population Condition	Habitat Condition	Overall EO Resilience
Guadalupe or Pedernales	1	Non-Contributing	Not Determined	Non-Contributing
Guadalupe	2	Extirpated	Developed	Extirpated
Guadalupe	3	Non-Contributing	Not Determined	Non-Contributing
Guadalupe	4-Upper Turtle Creek	Non-Contributing	High	Non-Contributing
Guadalupe	4-Middle Turtle Creek	Non-Contributing	Low	Non-Contributing
Guadalupe	4-Lower Turtle Creek	Extirpated	Low	Extirpated
Guadalupe	15	Extirpated	Not Determined	Extirpated
Guadalupe	20	Moderate	High	Moderate
Unknown	7	Non-Contributing	Unknown	Non-Contributing
Cibolo	5-Upstream Cibolo Creek	Non-Contributing	High	Non-Contributing
Cibolo	5-Midstream Cibolo Creek	Non-Contributing	Moderate	Non-Contributing
Cibolo	5-Downstream Cibolo Creek	Moderate	High	Moderate
Cibolo	14	Moderate	Moderate	Moderate
Cibolo	24	Moderate	Moderate	Moderate
Frio-Sabinal	8	Non-Contributing	High	Non-Contributing

Representation Area	Element Occurrence	Population Condition	Habitat Condition	Overall EO Resilience
Frio-Sabinal	11	Low	High	Low
Frio-Sabinal	16	Low	High	Low
Frio-Sabinal	21	Low	High	Low
Pedernales	10	Extirpated/Non-Contributing	Not Determined	Extirpated/Non-Contributing
Pedernales	22	Extirpated	Not Determined	Extirpated
Pedernales	23	Extirpated	Not Determined	Extirpated
Headwaters Salado Creek	19	Extirpated	Developed	Extirpated

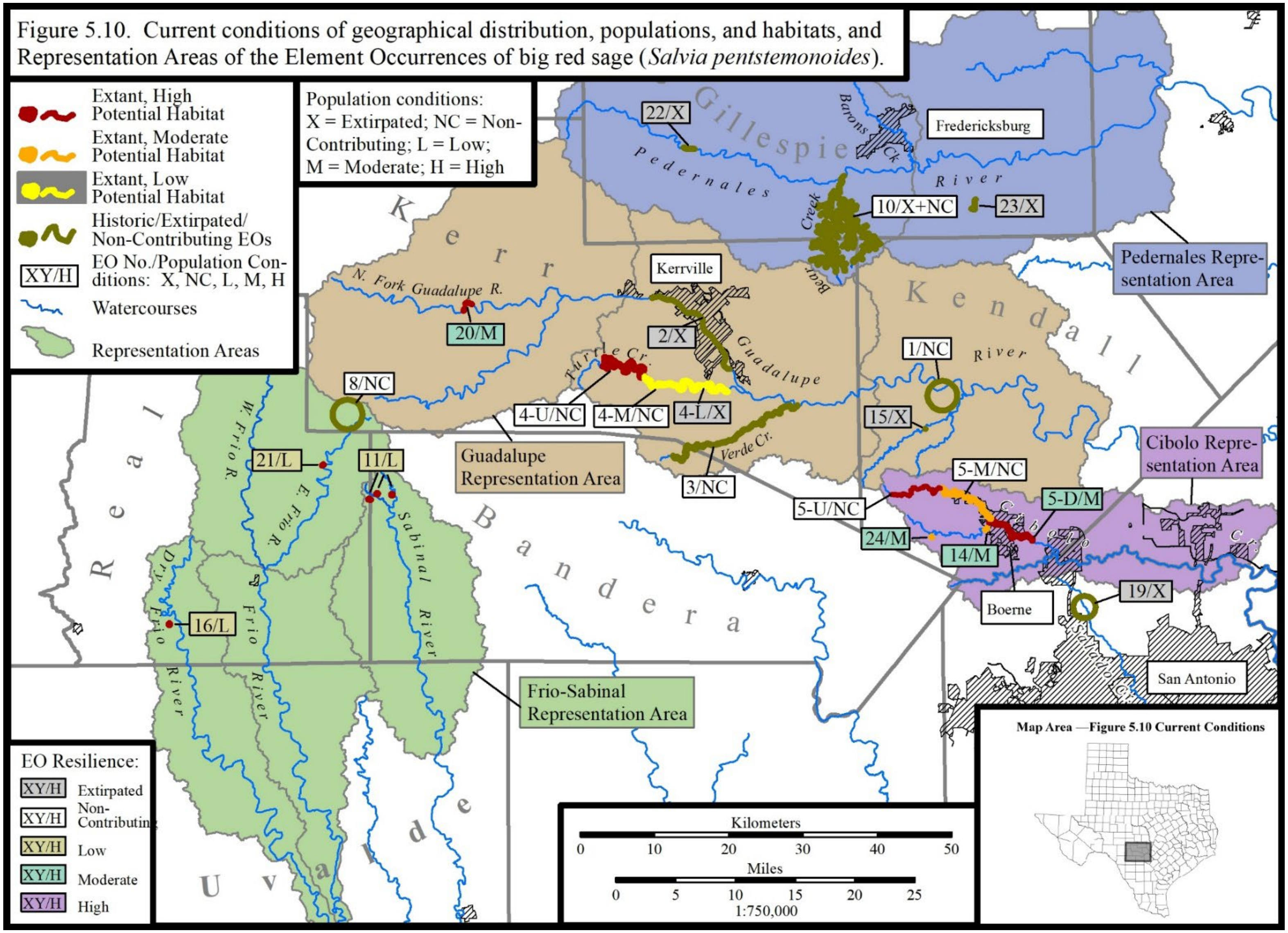


Figure 5.10. Current conditions of geographical distribution, populations, and habitats, and Representation Areas of the Element Occurrences of big red sage (*Salvia pentstemenoides*).

6. Projections of the Future Viability of Big Red Sage.

The future viability of big red sage—its ability to sustain populations in the wild over time—will be influenced by the development of threats and conservation efforts and their interacting effects on the species' resilience, redundancy, and representation. We project how these factors may affect the species' viability during the 2050 to 2074 time frame, which corresponds to the National Climate Change Viewer climatology period we selected for the assessment of threats from climate changes (Section 4.1). Additionally, to assess the threats associated with human population growth (below), we used the Texas Demographic Center (TDC) projections that extend to 2060. Similarly, the projections of the relevant Groundwater Conservation Districts extend to the 2060 to 2080 time frame. We did not consider an earlier time frame because, prior to the 2050 to 2074 period, climate changes, population growth, and aquifer drawdown may not have progressed to the point that their effects on big red sage are detectable. Neither did we consider later time frames because the precision of climate, demographic, and groundwater projections, and our ability to ascertain their effects on the species' viability, diminishes the further into the future they extend.

In Section 4 we described the factors that affect the species' survival. The factors most relevant to the species' future viability include the following threats: herbivory by native and introduced ungulates, land use changes due to human population growth, reduced availability and constancy of seep moisture, collection from the wild and loss of genetic integrity due to propagation for the horticultural trade, impacts from climate changes, and the demographic and genetic consequences of small population sizes. Big red sage may also benefit from conservation and private landowner engagement in areas of potential habitat.

To project the possible range of future viability, we evaluated each factor under two scenarios, Scenario 1 and Scenario 2, that represent the range of plausible outcomes for big red sage viability. The scenarios for each factor should not be interpreted as mutually exclusive. For example, by 2050, due to discoveries of new resilient populations, the number and geographic distribution of populations may be closer to Scenario 1, while Scenario 2 might best describe the effects of climate changes and habitat loss from urban development (or vice-versa).

6.1. Scenarios 1 and 2 for threats and their effects on the resilience, redundancy, and representation of big red sage.

<u>Resilience.</u>

Browsing by white-tailed deer and introduced ungulates.

The severity of this threat is proportional to browse pressure and herd density. At lower deer densities, deer eat some of the flower stalks before seeds mature; severity increases during dry years when browse is scarce. At higher deer densities, deer kill entire plants through repeated browsing of the foliage. Hence, populations decline through reduced recruitment and increased mortality. A continuation of current practices of deer and ungulate herd management, which have led to severe deer overpopulation, defines Scenario 2. Under Scenario 1, deer and ungulate herd management do not exceed the habitat's carrying capacity. Browsing currently affects many if not all populations of big red sage; hence, its effect on the species' viability is more immediate than other factors that have a cumulative or gradual effect. However, it is possible that deer and introduced ungulates may have already extirpated all the accessible populations of big red sage, leaving only the plants that cling to crevices in steep bluffs or cluster in the protection of fossil rudist reefs. In this case, the effects of browsing are not cumulative, but would prevent population growth.

Reduced availability and constancy of seep moisture.

In Section 4, we describe how populations of big red sage are likely sustained by seep moisture that may depend on groundwater percolating through porous limestone strata in the vadose zone as well as the Edwards-Trinity or Trinity aquifers, illustrated in Figure 4.2. Reductions in the amount or the constancy of seep moisture will shorten the growing season of big red sage and contribute to increased mortality and reduced recruitment, and therefore a loss of resilience. The principal factors that could lead to interruptions in the constancy of seep moisture are reduced infiltration into the porous strata of the vadose zone, changes in the amount and distribution of rainfall, and aquifer drawdowns from pumping. We evaluate reduced infiltraton into vadose zones as a component of urban and residential development, and rainfall changes as a component of climate change. Here we evaluate aquifer depletion due to pumping.

Section 36.002 of the Texas Water Code affirms the Rule of Capture, which establishes that groundwater is real property belonging to the owner of the land surface above it. Landowners have the right to drill and produce groundwater, but do not have the right to a specific amount of groundwater and are subject to limitations and prohibitions of well spacing, groundwater production, and tract sizes established by Groundwater Conservation Districts (GCD)s. Since 1951, 98 GCDs have been established in Texas to regulate the spacing of water wells, the production from water wells, or both. In 1957, the Texas Legislature created the Texas Water Development Board (TWDB) to provide leadership, information, education, and support for planning, financial assistance, and outreach for the conservation and responsible development of water for Texas (Texas Water Development Board 2016, p. 1). In 1995, and through subsequent amendments, the Texas Legislature authorized TWDB to designate Groundwater Management Areas (GMAs) to manage all major and minor aquifers in the state. In 1997, the 75th Texas Legislature enacted Senate Bill 1, authorizing TWDB to designate 16 water planning regions (South Central Texas Regional Water Planning Group 2015, p. ES−1). Note that the boundaries of the 16 designated GMAs do not align with the 16 water planning regions or the 98 GCDs.

Groundwater conservation districts are responsible for developing Desired Future Conditions (DFCs) that balance the highest practicable amount of groundwater production with the long-term conservation and protection of groundwater resources. The 2010 (or earlier) aquifer levels establish the baselines for measuring changes, and the future time frames range from 2060 to 2080. TWDB hydrologists then estimate the average amount of groundwater that may be produced annually, known as Modeled Available Groundwater, that will achieve the DFC. GCDs base their regulation of well spacing and production on Modeled Available Groundwater so that the long-term DFC goal will be attained.

In Section 5.3 we identified four Representation Areas where extant EOs and potential habitats occur. Table 6.1 lists the GMAs, GCDs, major aquifers, and DFCs that apply to the EOs of big red sage within these Representation Areas (Texas Water Development Board 2023). The DFCs of four GCDs that regulate these aquifers call for little or no reduction in aquifer levels over the next four to six decades. Scenario 1 for big red sage viability is the achievement of these DFCs. However, two GCDs have established DFCs allowing for 30 feet of drawdown in the Trinity aquifer in Kendall and Kerr counties through 2060. This amount of drawdown is based on a projected increase in pumping from the Trinity aquifer in GMA 9 from about 74.0 million cubic meters per year (m^3/y) (60,000 acre-feet per year (ac-ft/y)) in 2008 to 123.3 million m^3/y (100,000 ac-ft/y) in 2060 (Hutchison 2010, p.5). The rate of pumping from the Trinity aquifer in 2008 has lowered the aquifer by about 12.2 m (40 ft) and has reduced spring and base flows from 243.0 million to 202.3 million m^3/y (197,000 to 164,000 ac-ft/y), compared to no pumping (Hutchison 2010, pp. 8–9). Increasing pumping to 113.5 million m^3/y (92,000 ac-ft/year) is projected to decrease the aquifer level by an additional 8.8 m (29 ft) and to decrease spring and base flows to 185.0 million m^3/y (150,000 ac-ft/y) by 2060 (Hutchison 2010, pp. 8–9). In other words, by 2008, pumping had reduced spring and base flows by 17 percent, compared to flow rates without pumping. If pumping is increased by 50 percent, by 2060 spring and base flows will decrease by an additional 7 percent to 76 percent of the flow rate without pumping. This amount of aquifer drawdown and reduction in spring and base flows, or the failure to achieve the DFCs in other GCDs, constitutes Scenario 2 for big red sage viability.

Table 6.1. Groundwater Management Areas, Groundwater Conservation Districts, major aquifers, and Desired Future Conditions (Texas Water Development Board 2023) applicable to the Element Occurrences of big red sage.

GMA	GCD	Major Aquifer	Desired Future Condition	Element Occurrences
7	Real-Edwards C and R District	Edwards-Trinity	Total net drawdown not to exceed 4 feet in 2070 compared to 2010 aquifer levels	16, 21
7	Hill Country UWCD	Trinity	Total net drawdown not to exceed 5 feet in 2070 compared to 2010 aquifer levels	10, 22, 23
9	Bandera County River Authority & Groundwater District	Edwards-Trinity	No average water level decline in 2080 compared to 1997 water levels	11
9	Cow Creek GCD	Trinity	Increase in average drawdown of approximately 30 feet through 2060	5, 14, 24
9	Headwaters GCD	Edwards-Trinity	No significant pumping	4, 20
9	Headwaters GCD	Trinity	Increase in average drawdown of approximately 30 feet through 2060	4

Collection from wild populations.

The digging of entire plants from wild populations directly reduces population resilience; the loss of a single individual from a small population incrementally depletes the population's genetic variation and increases the risk of its extirpation. Overcollection of seeds may not cause mortality of any individuals, but still reduces resilience by decreasing recruitment. Furthermore, seed collection for landscaping and the horticultural trade is not mitigated by any conservation benefit to populations or the species.

Conversely, carefully limited seed collection for seed banking and ex-situ conservation may be an important tool for the species' conservation. This implies adherence to Center for Plant Conservation (CPC) seed collection guidelines and coordination among conservation partners to prevent over-collection from the same sites and individuals. Section 7 includes CPC seed collection guidelines for ex-situ conservation that are applicable to big red sage. In summary, collection of whole wild plants and uncontrolled seed collection from wild populations represent Scenario 2. Element Occurrence 14, and perhaps other populations, declined at least in part due to collection after the locations were publicized. Therefore, the publication of precise geographic locations of existing or newly discovered populations increases the likelihood of Scenario 2. Scenario 1 has no collection of wild plants but may include controlled seed collection strictly for the purposes of seed banking and ex-situ conservation efforts.

Demographic consequences of small population sizes.

Section 3.2 describes the rationale for estimating an MVP of 1,600 mature individuals, which we adopt as Scenario 1. As described in Section 5.1, Scenario 2 is a population size less than 100.

Impacts from climate change.

In Section 4 we discuss the specific threats of climate changes to big red sage. In summary, in both RCP 4.5 and RCP 8.5, the means of 20 climate models do not project significant changes in May rainfall within the Guadalupe River watershed. However, in both RCP 4.5 and 8.5, the models do project with statistical significance that soil water storage will decrease, and evaporative deficit will increase; these changes are due mainly to increasing temperatures. Additional projections applicable to the southern Great Plains include greater annual variation in rainfall, an increased frequency and severity of drought, and an increased incidence of heavy rainfall and flash flooding. These climate changes potentially affect resilience, redundancy, and representation and are discussed in all three sections. Scenarios 1 and 2 involve both the intensity of climate changes (RCP 4.5 versus RCP 8.5) as well as the response of big red sage to these changes. However, the severity of the RCP 8.5 climate changes would likely outweigh the species' ability to respond and would invoke Scenario 2. The less severe RCP 4.5 climate changes may result in Scenario 1 or Scenario 2, depending on other factors.

Longer, more severe droughts that disrupt the constancy of seep moisture that sustains populations of big red sage will likely cause higher mortality and lower recruitment. Flash floods have destroyed portions of two EOs and may have contributed to the extirpation of another EO. Both factors are likely to reduce population resilience. In Scenario 2, population declines would be cumulative and would not recover during years of greater or more consistent rainfall. In Scenario 1, population losses due to droughts and floods would recover during years of more consistent rainfall; in other words, population sizes would become more variable between high and low years, but average population sizes would not trend downward. Nevertheless, even under Scenario 1, small populations may be completely extirpated during drought years. Both Scenario 1 and Scenario 2 are plausible; the ability of established plants to endure drought years as dormant rootstocks and the longevity of dormant seeds in the soil will determine which scenario prevails. Currently we cannot answer these questions; however, the resistance of EO 5 to drought (see Figures 2.6 and 2.7) is encouraging.

<u>Redundancy.</u>

Urban and residential development.

It is likely that human population growth will stimulate increased urban and residential development, which in turn may destroy big red sage habitats and populations, increase fragmentation of populations, and disrupt its pollination corridors and gene flow; increases in the amount of impermeable surfaces may also reduce the infiltration of rainwater into porous strata of the vadose zone that sustain populations through seepage. We base our projections for the resulting loss of the species' redundancy on projections of human population growth for Texas counties for the 2020-to-2060 time frame (TDC 2022). The TDC projections use two growth models that are based on assumptions about the rates of immigration into and away from Texas. The 1.0 migration scenario assumes migration will continue at 100 percent of the 2010-2020 migration rate and the 0.5 migration scenario assumes migration will continue at 50 percent of this rate. The 1.0 migration scenario is recommended for near-term planning and the 0.5 migration scenario is recommended for longer-term planning (TDC 2023). We use the 1.0 migration projections to represent Scenario 2 for big red sage viability, due to faster rates of human population growth in most of the range of big red sage, and the 0.5 migration projections to represent Scenario 1.

Tables 6.2 and 6.3 present these projections of human population growth in the Representation Areas and counties occupied by big red sage. In both scenarios, human populations grow in the Guadalupe, Cibolo, and Pedernales Representation Areas but decline in the Frio-Sabinal Representation Area.

Table 6.2 Projected human population growth based on the 1.0 migration scenario (Texas Demographic Center 2023).

Representation Area	County	2020	2060	Change	Percent Change
Frio-Sabinal	Real	2,758	1,187	-1,571	43.0
Frio-Sabinal	Bandera	20,851	22,586	1,735	108.3
Frio-Sabinal	Uvalde	24,564	16,822	-7,742	68.5
Frio-Sabinal	Total	48,173	40,595	-7,578	84.3
Guadalupe	Kerr	52,598	63,589	10,991	120.9
Guadalupe	Kendall	44,279	111,448	67,169	251.7
Guadalupe	Total	96,877	175,037	78,160	180.7
Cibolo	Kendall	44,279	111,448	67,169	251.7
Cibolo	Comal	161,501	584,380	422,879	361.8
Cibolo	Total	205,780	695,828	490,048	338.1
Pedernales	Gillespie	26,725	33,419	6,694	125.0
Pedernales	Total	26,725	33,419	6,694	125.0

Table 6.3. Projected human population growth based on the 0.5 migration scenario (Texas Demographic Center 2023).

Representation Area	County	2020	2060	Change	Percent Change
Frio-Sabinal	Real	2,758	1,544	-1,214	56.0
Frio-Sabinal	Bandera	20,851	21,702	851	104.1
Frio-Sabinal	Uvalde	24,564	22,142	-2,422	90.1
Frio-Sabinal	Total	48,173	45,388	-2,785	94.2
Guadalupe	Kerr	52,598	54,123	1,525	102.9
Guadalupe	Kendall	44,279	65,422	21,143	147.7
Guadalupe	Total	96,877	119,545	22,668	123.4
Cibolo	Kendall	44,279	65,422	21,143	147.7
Cibolo	Comal	161,501	290,856	129,355	180.1

Representation Area	County	2020	2060	Change	Percent Change
Cibolo	Total	205,780	356,278	150,498	173.1
Pedernales	Gillespie	26,725	27,931	1,206	104.5
Pedernales	Total	26,725	27,931	1,206	104.5

Climate changes.

The effects of climate changes on the species' redundancy, as with its resilience, are influenced by the ability of individual plants to endure in a dormant state and by the longevity of viable seeds in the soil. The difference between Scenarios 1 and 2 is the potential of populations to recover during years of consistent rainfall. Nevertheless, even under Scenario 1, smaller populations that decline during drought years to the point of extirpation cannot subsequently recover. Therefore, climate changes are likely to decrease the redundancy of big red sage under both scenarios.

<u>Representation.</u>

Genetic consequences of small population sizes.

Hoban and Garner (2019, pp. 3–4) determined that the current level of genetic diversity of extant populations of big red sage is poor and perhaps critically low. This conclusion and its continuation into the future represents Scenario 2. Scenario 1 is invoked if reserves of genetic diversity remaining on private lands are discovered and conserved, inter-population gene flow is restored, and population sizes are augmented, as recommended by Hoban and Garner (2019, pp. 6–7), through facilitated propagation and reintroduction.

Loss of genetic integrity due to inappropriate propagation.

As described in Section 4, indiscriminate propagation of a rare plant species without regard to its population genetic structure can lead to a loss of the genetic integrity of its wild populations. Currently, we have no evidence that this has taken place, but any instance of propagated individuals escaping into wild populations would constitute Scenario 2. Scenario 1 is defined by the development of protocols for the management of the genetic integrity of propagated big red sage and the adoption of these protocols by conservation organizations, horticulturalists, and plant collectors who want to grow this species.

Climate Changes.

Under the climate change scenarios discussed under resilience and redundancy, population sizes become more variable during years of consistent rainfall versus extended drought. However, even under Scenario 1, wider variations in population size are likely to lead to the loss of rare alleles, particularly in smaller populations, and would therefore reduce the species' overall genetic variation—its representation. Hoban and Garner (2019, pp. 3–4) determined that genetic variation within populations is already at a critically low level. Under Scenario 2, the species' genetic variation would continue to decline and would contribute to the increased likelihood of extinction. Under Scenario 1, the population bottlenecks caused by climate-induced variation in population sizes would purge deleterious alleles, and the surviving population would have a higher level of fitness, particularly with regard to the species' ability to persist during years of extended drought.

6.2. Conservation efforts.

Scenario 1 consists of conservation efforts that effectively mitigate threats. For example, the immediate and continuing threat of browsing from over-abundant white-tailed deer and introduced ungulates may be reduced through improved herd management. Although it may not be feasible to fence entire big red sage habitats, deer fencing may be used to protect core population areas. Protection of riparian corridors from urban and residential development would preserve wildlife corridors for hummingbird foraging (and would also provide outdoor recreational areas and reduce economic losses from flash floods and erosion). The development and promotion of seed collection and propagation protocols will reduce the threat of the loss of genetic integrity from this threat. Small populations that are on the verge of extirpation may be rescued through ex-situ propagation for seed increase and population augmentation. Gene flow between extant wild populations may be enhanced through the protection and restoration of pollinator habitat corridors that include hummingbird forage plants. Scenario 2 is a failure to implement conservation that reduces threats to big red sage.

Private landowners own 75 percent of the land where extant EOs occur and where 93 percent of extant individuals of big red sage occur (Table 4.2). Furthermore, nearly all potential habitats of big red sage that have not been surveyed occur on private lands. Private landowners who have unoccupied potential habitats may be willing to restore the species on their lands to enhance connectivity with neighboring populations. Private landowners who do not have populations or potential habitats of big red sage on their properties can still benefit the species by conserving and restoring pollinator corridors that promote gene flow among populations. Therefore, active engagement with private landowners is an essential element of the species' conservation.

Scenario 1 is exemplified by conservation efforts that benefit the species in coordination with private landowners who choose to become involved in the species' conservation, or who allow access to survey their properties for undiscovered populations and to monitor, conserve, and manage extant populations. Under Scenario 2, little or no conservation is accomplished on private land that benefits big red sage populations, habitats, or pollinators.

Table 6.4. Plausible range of conditions for each threat under Scenarios 1 and 2.

Factor	**Scenario 1**	**Scenario 2**
Browsing by white-tailed deer and introduced ungulates	Herd management does not exceed carrying capacity	Overpopulation of deer and ungulates

Depletion of aquifers	Achievement of Desired Future Conditions (DFCs) and minimal drawdown of Trinity and Edwards-Trinity aquifers	Failure to achieve DFCs and aquifer drawdown that results in a reduction in spring and base flows
Collection from wild populations	No plant collection, but may include seed collection for conservation efforts	Collection of whole plants and uncontrolled seed collection
Demographic consequences of small population sizes	Populations reach MVP level of 1,600 mature individuals	Populations fall below 100 individuals
Impacts from climate change	RCP 4.5: Populations may decline due to droughts and floods but recover during years of consistent rainfall	RCP 4.5: Populations decline cumulatively during droughts or floods and do not subsequently recover RCP 8.5: Population declines are very likely
Urban and residential development	0.5 migration scenario: assumes migration will continue at 50 percent of the 2010-2020 migration rate	1.0 migration scenario: assumes migration will continue at 100 percent of the 2010-2020 migration rate
Genetic consequences of small population sizes	Undiscovered reserves of genetic diversity remain and are conserved; gene flow within and among populations is restored	Genetic diversity within and among populations remains extremely low and continues to decline
Inappropriate propagation	Development and adoption of protocols for the management of the genetic integrity of propagated big red sage	Absence of propagation protocols leads to individuals escaping into wild populations

6.3. Synthesis: Projections of the future conditions of big red sage by Representation Area and EO.

Within each Representation Area we list its EOs, describe the factors that affect them, evaluate the future conditions of the EOs, and provide a summary assessment for the Representation Area. Tables D.1 through D.7 in Appendix D summarize the factors and scenarios for each EO. The table cells indicate what effect each factor and scenario would have on the species' conditions (improving, stable, or decreasing). Table 6.5 lists the projected future resilience of each EO under scenarios 1 and 2. Table 6.6 summarizes these results by Representation Area.

<u>Guadalupe Representation Area</u>

Element Occurrence 20 is the only known extant population in the Guadalupe Representation Area. It is the second largest population, with 269 individuals in the most recent censuses, and its current resilience is moderate. Table D.1 summarizes projections of its future viability under Scenarios 1 and 2. Element Occurrence 20 depends at least in part on the Edwards-Trinity aquifer in the Headwaters GCD, where the DFC is “no significant pumping”; percolation through porous limestone in the vadose zone may also contribute to this EO. Therefore, under Scenario 1, EO 20 has relatively low vulnerability to aquifer pumping. The EO has five SFs distributed on private property along the banks and bluffs of the North Fork of the Guadalupe River in a popular area for outdoor recreation. Consequently, at least portions of this population are vulnerable to flash floods and collection of wild seeds and plants. The relatively large population size, compared to most other EOs, confers a greater probability of enduring and recovering from flash flooding and variations in rainfall; nevertheless, the population size is far below the estimated MVP of 1,600. If Scenario 1 prevails for all factors, EO 20 is likely to remain moderately viable into the 2050 to 2074 time frame. Conversely, if Scenario 2 prevails for all factors, the population is very likely to become extirpated. Some individual factors in Scenario 2, such as severe deer browsing or severe droughts, could outweigh all others and cause extirpation. Scenario 1 for conservation and landowner engagement would greatly enhance the condition of this population.

We also evaluated the future viability of EO 4 (Table D.2). Although the most recently observed population was extirpated by 2013, the Cory collection from 1943 has never been revisited, and the exact location is unknown. We do not know if a population persists at the Cory collection site or other potential habitats nearby. We do know that habitat conditions along upper Turtle Creek remain high. The 2060 projections of human population growth in Kerr County range from a factor of 1.03 to 1.21 in Scenario 1 and Scenario 2, respectively. Most of this growth would likely occur closer to Kerrville and along Interstate Highway 10. The middle and lower sections of Turtle Creek, where relatively little potential habitat remains, would therefore be more vulnerable to development, but upper Turtle Creek is less likely to experience significant development during the assessment period due to its more remote location. Upper Turtle Creek is within the Edwards-Trinity aquifer and is less vulnerable to aquifer drawdown from pumping. Middle and lower Turtle Creek are within the Trinity aquifer, where Headwaters GCD has established a DFC allowing for 9.1 m (30 ft) of drawdown by 2060. Private land ownership limits access to much of upper Turtle Creek, which may have protected populations from over-collection. For all of these reasons, it is reasonable to conclude that one or more populations may persist along upper Turtle Creek and its narrow tributary canyons. Landowner engagement is the salient factor needed to discover and conserve any remaining populations along upper Turtle Creek; nevertheless, publication of any extant populations in this area should be avoided to prevent depletion from collection.

Guadalupe Representation Area Summary: Big red sage currently has one known, moderately resilient population with very low genetic diversity in the Guadalupe Representation Area. Future viability ranges from likely to persist through the 2050 to 2074 assessment period if Scenario 1 prevails in the conservation and landowner outreach factors, to unlikely to persist if Scenario 2 prevails.

<u>Cibolo Representation Area</u>

Element Occurrence 5 is a moderately resilient population with low genetic diversity on a site owned and managed by an NGO conservation organization. Table D.3 summarizes projections of its future viability under Scenarios 1 and 2. The population is monitored annually and has varied from 80 to 115 individuals from 2015 through 2021 (Figure 2.7); although the population trend is relatively stable, it is far below the estimated MVP of 1,600 individuals, and it is dangerously close to a population size that could be completely extirpated during severe or extended drought. The site is naturally protected from ungulate herbivory by the steep slope and sharp-edged rocks.

The projected human population growth by 2060 in Kendall County ranges from a factor of 1.5 to 2.5 under Scenario 1 and Scenario 2, respectively; this very rapid development is mainly expansion of the San Antonio urban perimeter along Interstate Highway 10 and growth of the city of Boerne as a San Antonio exurb. While the EO 5 site itself is protected from development, the rapid development of surrounding areas is likely to increase impermeable surfaces and reduce infiltration into porous strata of the vadose zone. EO 5 is within the Trinity aquifer area, where the Cow Creek GCD has established a DFC allowing for 9.1 m (30 ft) of drawdown by 2060. We evaluated whether this future drawdown could reduce seep moisture at EO 5. State monitoring well 6811817 is 0.43 km (0.27 mi) south of EO 5 (Water Data for Texas 2023b). During this well's period of record (February 2022 through August 2023), the level of the Trinity aquifer in this well was 351 to 355 m (1,153 to 1,166 ft) above sea level (Water Data for Texas 2023b), far below the elevation at EO 5 of 403 to 408 m (1,323 to 1,340 ft) above sea level. Therefore, we conclude that further drawdown of the Trinity aquifer will have relatively little effect on seep moisture at EO 5. On the other hand, rapid development is likely to reduce infiltration into vadose strata, and therefore the viability of EO 5 may decline due to interrupted constancy of seep moisture. The NGO landowner is dedicated to the conservation of the species on the property and will likely be an important promoter of its conservation in the community and beyond. The future viability of EO 5 is likely to be moderate, mainly due to the habitat protection and landowner engagement; nevertheless, conservation efforts, such as augmentation of population size and genetic diversity, may be necessary to maintain moderate conditions through 2050 to 2074.

Element Occurrence 14 (Table D.4) is adjacent to and beneath Interstate Highway 10 at the edge of the City of Boerne. The genetic diversity of this population has not been investigated. The accessible portion was completely extirpated between 1992 and 2009 due to deer herbivory, a flash flood, collection from the wild, and perhaps other factors. The adjacent SF on private land is the largest remaining population, with 401 individuals in 2013. Private land ownership may confer some protection from collection, and the relatively large population size, although far below the estimated MVP level, increases the likelihood of recovery following a decline due to severe drought, flood, or other factors. The site is near EO 5 and is also located within the Trinity aquifer area. State monitoring well 6811417 is 1.63 km (1.01 mi) north of EO 14 (Water Data for Texas 2023c). During the period of record (December 2006 through August 2023), the water level of the Trinity aquifer in this well has ranged from 342 to 364 m (1,123 to 1,195 ft) above sea level, while EO 14 is located from 433 to 435 m (1,420 to 1,427 ft) above sea level. Again, the upper level of the Trinity aquifer has remained below the surface level of EO 14 and could not have been a source of its seep moisture; further drawdown may have little effect. Conversely, increased development by 2050 to 2074 may reduce infiltration into the porous strata of the vadose zones that supply water to this EO. Finally, after we completed our assessment of habitat conditions (Figure 5.4), aerial photography from July 2023 reveals that part of this EO was recently bulldozed for construction of a new bridge and access road (Figure 6.1). Due to the vulnerability to herbivory, accessibility to plant collectors, the likely reduction of infiltration into the vadose strata, and the proximity and intensity of urban development, the future viability of EO 14 is likely to be low. Scenario 1 for conservation and landowner engagement would enhance the future condition of this population.

Element Occurrence 24 (Table D.5), which had 116 individuals in 2010 to 2013, is in an upper canyon of a first-order tributary of upper Frederick Creek. The genetic diversity of this population has not been investigated. This EO is within the Trinity aquifer area. The population ranges from about 527 to 555 m (1728 to 1820 ft) above sea level. The aquifer level in the nearest state monitoring well (no. 6810616), which is 7.0 km (4.4 mi) northeast, has ranged from 319 to 364 m (1,045 to 1,193 ft) above sea level during the period of record (June 2009 through August 2023; Water Data for Texas 2023d). Hence, EO 24 is not vulnerable to future drawdown of the Trinity aquifer. Nevertheless, the vadose strata s it depends on would have recharge areas limited to the upper portions of nearby hills. If the vegetative cover of those recharge areas is replaced with impermeable surfaces, the recharge of the vadose strata would diminish and the constancy of water to this population would be interrupted.

Like most other populations, this EO is likely to be vulnerable to ungulate browsing and may not persist without deer herd management or deer exclusion fencing. The population size barely reaches the threshold for moderate resilience; hence, the increasing frequency and severity of drought projected during the assessment time frame could reduce this population to the point of inevitable extirpation. However, if pollination corridors connect EO 24 to other populations along Frederick Creek, they may be sufficiently close to function as a single larger population that is somewhat less vulnerable to demographic and genetic consequences of small population sizes. Based on vulnerability to herbivory, reduced infiltration into vadose strata, and small population sizes, the likely condition of this population into the 2050 to 2074 assessment period is low, but under Scenario 1 for conservation and landowner engagement future viability would likely be moderate.

Cibolo Representation Area Viability Summary: Currently, the Cibolo Representation Area has three moderately resilient EOs and has the highest overall resilience. The genetic diversity of populations that have been sampled is very low, and two of the three are affected by severe deer herbivory. By 2060 the human population of this Representation Area will increase by a factor of 1.7 to 3.4 under the 0.5 and 1.0 migration scenarios, respectively. The projected 9.1-m (30-ft) drawdown of the Trinity aquifer by 2060 is not likely to affect any of these EOs because the aquifer level has been far below their elevations since at least 2006. Therefore, the seepage at these EOs must be supplied by porous strata of the vadose zones, and the recharge of these vadose strata may be reduced by the increasing amount of impermeable surfaces that will likely result from the projected growth of the human population. Development may also destroy habitats directly; EO 14 was partially destroyed by a construction project during the course of our assessment. Consequently, urban and residential development may severely reduce the best remaining reserve of the species' resilience, and its future viability would decline. Nevertheless, development does not inevitably destroy habitats. Development projects can be designed to enhance groundwater infiltration and reduce runoff. Effective conservation planning and public outreach could preserve the habitats and populations of big red sage and its habitat connectivity in an increasingly developed landscape. In summary, the future condition in the Cibolo Representation Area through the 2050 to 2074 assessment period is likely to decline to a single moderately viable EO. However, under Scenario 1 in the conservation and landowner outreach factor, it may be possible to conserve the viability of the other two EOs.

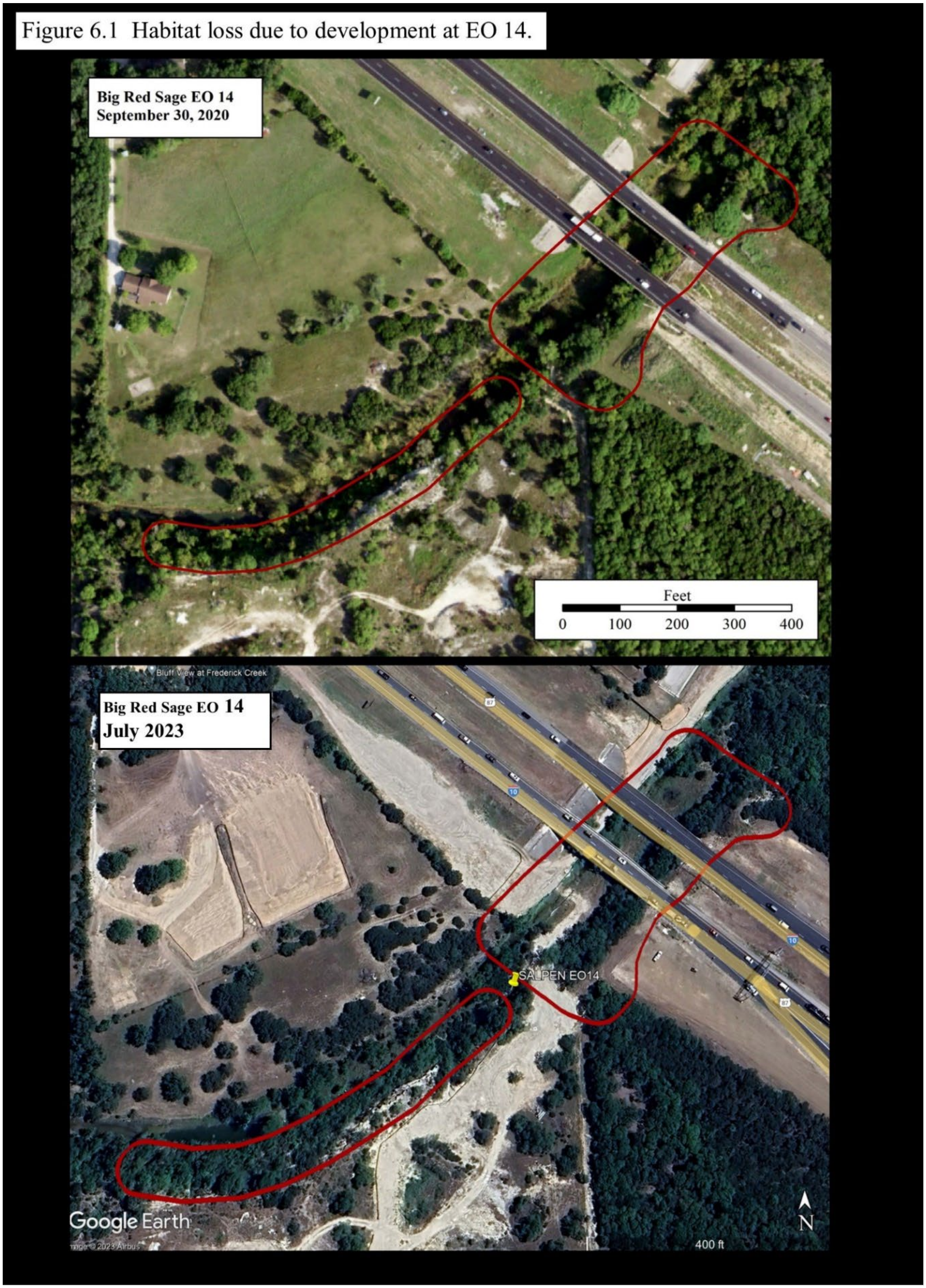


Figure 6.1. Habitat loss due to development at EO 14.

Frio-Sabinal Representation Area

Element Occurrence 11 and EO 16 have similar characteristics and are evaluated together (Table D.6). Only three individuals remained at EO 11 when genetic samples were collected in 2019; they revealed a low level of genetic diversity. Only two individuals were observed at EO 16 in 1991, although this report may not have been a complete census; the population has not been surveyed since then. EO 11 is in a protected, but publicly accessible State Natural Area, and EO 16 is privately owned. Severe herbivory by white-tailed deer and introduced ungulates may have contributed to the decline of EO 11; herbivory is also likely to affect EO 16. Illicit collection may have affected EO 11, due to its accessibility; due to inaccessibility, it is unlikely that EO 16 has been plundered by collectors.

These sites are both within the Edwards-Trinity aquifer area. EO 11 is in the Bandera County River Authority and Groundwater District, where the DFC is "no average water level decline in 2080 compared to 1997 water levels". The relationship of EO 11 to aquifer levels is described in Section 4.1 and Figure 4.1. EO 16 is in the Real-Edwards Conservation and Reclamation District, which has established a DFC of "total net drawdown not to exceed 4 feet in 2070 compared to 2010 aquifer levels". EO 16 is about 588 m (1,930 ft) above sea level. There are no state monitoring wells in the Edwards-Trinity aquifer that are close enough to provide meaningful data on the aquifer at EO 16. However, due to their higher topographic positions, seep moisture at both EO 11 and 16 are likely to be supplied at least in part by porous strata of the vadose zones. Hence, these EOs would not be vulnerable to aquifer drawdown under Scenario 1.

The human population in this Representation Area is projected to decline during the assessment period, so habitat loss and reduced infiltration into vadose strata are not likely to reduce the viability of big red sage populations. Even under Scenario 1 for climate changes, both populations were very close to extirpation when last observed and were very likely to become extirpated during even minor population declines. Due to demographic and genetic factors, the recovery of such small populations is extremely unlikely unless undiscovered groups of individuals exist nearby. Therefore, the future condition is likely to be extirpated. However, if some remnant of these populations is extant, under Scenario 1 of the conservation and landowner engagement factor, it may be possible to conserve these populations.

Element Occurrence 21 (Table D.7) is a very small population on a site owned and managed by an NGO as an educational retreat center. The genetic diversity of this population is likely to be very low. The remaining plants are clustered on seep ledges of a steep limestone bluff overlooking the East Frio River and are unlikely to be browsed by deer or introduced ungulates. The nearest state aquifer monitoring well (no. 6912206) is 9.9 km (6.1 mi) east of EO 21 (Water Data for Texas 2023a). The upper level of the Edwards-Trinity aquifer in this well during the period of record (August 2018 through August 2023) has varied from 620 to 622 m (2,033 to 2,040 ft) above sea level. The elevation at EO 21 is 600 to 606 m (1,967 to 1,987 ft) above sea level. Although the distance from this EO to the monitoring well is large, and aquifer levels vary over distance, it is possible that the seep moisture at this EO may derive, at least in part, from the Edwards-Trinity aquifer. The Real-Edwards Conservation and Reclamation District has established a DFC allowing up to 4 feet of drawdown during our assessment period, which is our Scenario 1. If the DFC is achieved, this may have little effect on seepage at EO 21. Seepage at

EO 21 probably also derives from porous vadose strata that could be depleted if there is an increase in impermeable surfaces in the recharge area. The human population in Real County is projected to decline during the assessment period to 56 percent or 43 percent of the 2020 level, under Scenario 1 and Scenario 2, respectively. Therefore, development of recharge areas of the vadose strata is unlikely. Due to the very small population size, EO 21 is at high risk to decline to the point of extirpation during periods of extended, severe drought, and this risk will increase by 2050 to 2074. Consequently, the future condition of EO 21 is low. Nevertheless, conditions would improve under Scenario 1 for conservation and landowner engagement. Furthermore, if undiscovered groups of big red sage plants exist nearby, the actual population size would be larger and have higher viability.

Frio-Sabinal Representation Area summary: The Representation Area has only three EOs with very low resilience; the known populations were small to begin with and have not been monitored recently or have declined nearly to extirpation. Deer and introduced ungulate herbivory may have affected two of the EOs, while the third is less vulnerable to herbivory due to the steep slope. All three EOs are in the Edwards-Trinity aquifer area where the DFCs call for little or no drawdown during the assessment period. Porous vadose strata likely supply part of the seep moisture at all sites. Although the human population of Bandera County will increase slightly under both migration scenarios, it is projected to decline substantially in Real and Uvalde counties under both migration scenarios (Tables 6.2 and 6.3; Texas Demographic Center 2023). Consequently, it is unlikely that large increases in impermeable surfaces will disrupt infiltration into vadose strata. In summary, based on the best available information, the Frio-Sabinal Representation Area has very low future viability; one EO may persist with low viability, and two EOs will likely be extirpated. Nevertheless, the Frio-Sabinal Representation Area has a large amount of potential habitat on private land that has never been surveyed. It is possible that undiscovered, resilient populations persist there; thus, it may be an important, relatively secure reserve of the species' overall resilience. Scenario 1 for conservation and landowner engagement may help to discover and conserve any remaining populations and improve the species' future condition in this Representation Area.

Pedernales Representation Area

The Pedernales Representation Area has no known extant populations of big red sage. Element Occurrences 10, 22, and 23 had small populations in the early 1990s that were extirpated by 2013. EO 10 also includes a historical collection somewhere on Bear Creek that has an unknown status. The topography in the Pedernales Representation Area is more level than the other three Representation Areas, and a larger portion of the landscape is used for improved pasture or cropland. In other parts of its range, big red sage often occurs on towering bluffs and in narrow canyons. In contrast, the documented populations of big red sage in the Pedernales area occurred on low bluffs, banks, and ledges along streams where the plants thrived just beyond the reach of ravenous ungulate herbivores. This type of habitat is still abundant along the Pedernales River and its tributaries, including North Grape Creek, South Grape Creek, Rocky Creek, Barons Creek, Meusebach Creek, Live Oak Creek, Bear Creek, Left Bear Creek, Wolf Creek, White Oak Creek, Klein Branch, and Nott Branch.

We are not aware of any surveys for big red sage along any of these streams other than the few reported in Taylor and O'Kennon (2013). Therefore, it is possible that extant populations persist in this Representation Area. Most of the Pedernales River and its tributaries flow through areas of the Trinity aquifer. The Hill Country Underground Water Conservation District has established a DFC for the Trinity aquifer of a "total net drawdown not to exceed 5 feet in 2070 compared to 2010 aquifer levels". If this DFC is achieved, this relatively minor amount of aquifer drawdown is not likely to significantly affect extant populations—if any remain; this comprises our Scenario 1. The human population of Gillespie County will grow by a factor of 1.05 or 1.25 in Scenario 1 and Scenario 2, respectively; whether this will affect extant populations depends on where development occurs in relation to population sites. In summary, based on the best available information, big red sage has been eradicated from the Pedernales Representation Area and therefore it also has no future viability. We are not able to assess the future viability of undocumented populations. Nevertheless, extant populations may remain. As with other Representation Areas, under Scenario 1 of the conservation and landowner engagement factor, it may be possible that currently unknown, extant populations will be discovered and conserved, and would thereby improve the species' future viability in this Representation Area.

6.4. Summary of the future conditions of big red sage.

In Section 5.1 we defined high resilience as a population size that would be likely to persist for 100 years. Moderate resilience is a population size that is likely to persist for 10 years and is still able to increase resilience through conservation and management. Low resilience is a population that is not likely to persist 10 years and is unlikely to increase resilience without augmentation as well as conservation and management. Big red sage currently has four populations that are moderately resilient and three that have low resilience, and current viability is low. Under Scenario 1, during the 2050 to 2074 assessment period the species would have one moderately resilient population in the Guadalupe Representation Area, one moderately resilient population and two with low resilience in the Cibolo Representation Area, and one population with low resilience in the Frio-Sabinal Representation Area; two additional populations will be extirpated (Figure 6.2). Under Scenario 2, three additional populations will be extirpated, and only two populations with low resilience will remain (Figure 6.3). Hence, both resilience and redundancy will likely decline under both scenarios. Representation is currently low and will also likely decrease during the assessment period. In summary, the low viability of big red sage will decline further during the 2050 to 2074 assessment period.

Table 6.5. Future conditions of big red sage Element Occurrences under Scenarios 1 and 2.

Representation Area	Element Occurrence	Scenario 1 Future EO Condition	Scenario 2 Future EO Condition
Guadalupe or Pedernales	1	Non-Contributing	Non-Contributing
Guadalupe	2	Extirpated	Extirpated
Guadalupe	3	Non-Contributing	Non-Contributing
Guadalupe	4-Upper Turtle Creek	Non-Contributing	Non-Contributing
Guadalupe	4-Middle Turtle Creek	Non-Contributing	Non-Contributing

Representation Area	Element Occurrence	Scenario 1 Future EO Condition	Scenario 2 Future EO Condition
Guadalupe	4-Lower Turtle Creek	Extirpated	Extirpated
Guadalupe	15	Extirpated	Extirpated
Guadalupe	20	Moderate	Low
Unknown	7	Non-Contributing	Non-Contributing
Cibolo	5-Upstream Cibolo Creek	Non-Contributing	Non-Contributing
Cibolo	5-Midstream Cibolo Creek	Non-Contributing	Non-Contributing
Cibolo	5-Downstream Cibolo Creek	Moderate	Low
Cibolo	14	Low	Extirpated
Cibolo	24	Low	Extirpated
Frio-Sabinal	8	Non-Contributing	Non-Contributing
Frio-Sabinal	11	Extirpated	Extirpated
Frio-Sabinal	16	Extirpated	Extirpated
Frio-Sabinal	21	Low	Extirpated
Pedernales	10	Extirpated/Non-Contributing	Extirpated/Non-Contributing
Pedernales	22	Extirpated	Extirpated
Pedernales	23	Extirpated	Extirpated
Headwaters Salado Creek	19	Extirpated	Extirpated

Table 6.6. Numbers and future conditions of big red sage EOs under scenarios 1 and 2 in each representation area.

	Scenario 1					Scenario 2				
Representation Area	**High**	**Mod**	**Low**	**Ext**	**Overall Condition**	**High**	**Mod**	**Low**	**Ext**	**Overall Condition**
Guadalupe	0	1	0	3	Low	0	0	1	3	Low
Cibolo	0	1	2	0	Low	0	0	1	2	Low
Frio-Sabinal	0	0	1	2	Low	0	0	0	3	Extirpated
Pedernales	0	0	0	3	Extirpated	0	0	0	3	Extirpated
Totals	0	2	3	8	Low	0	0	2	11	Low

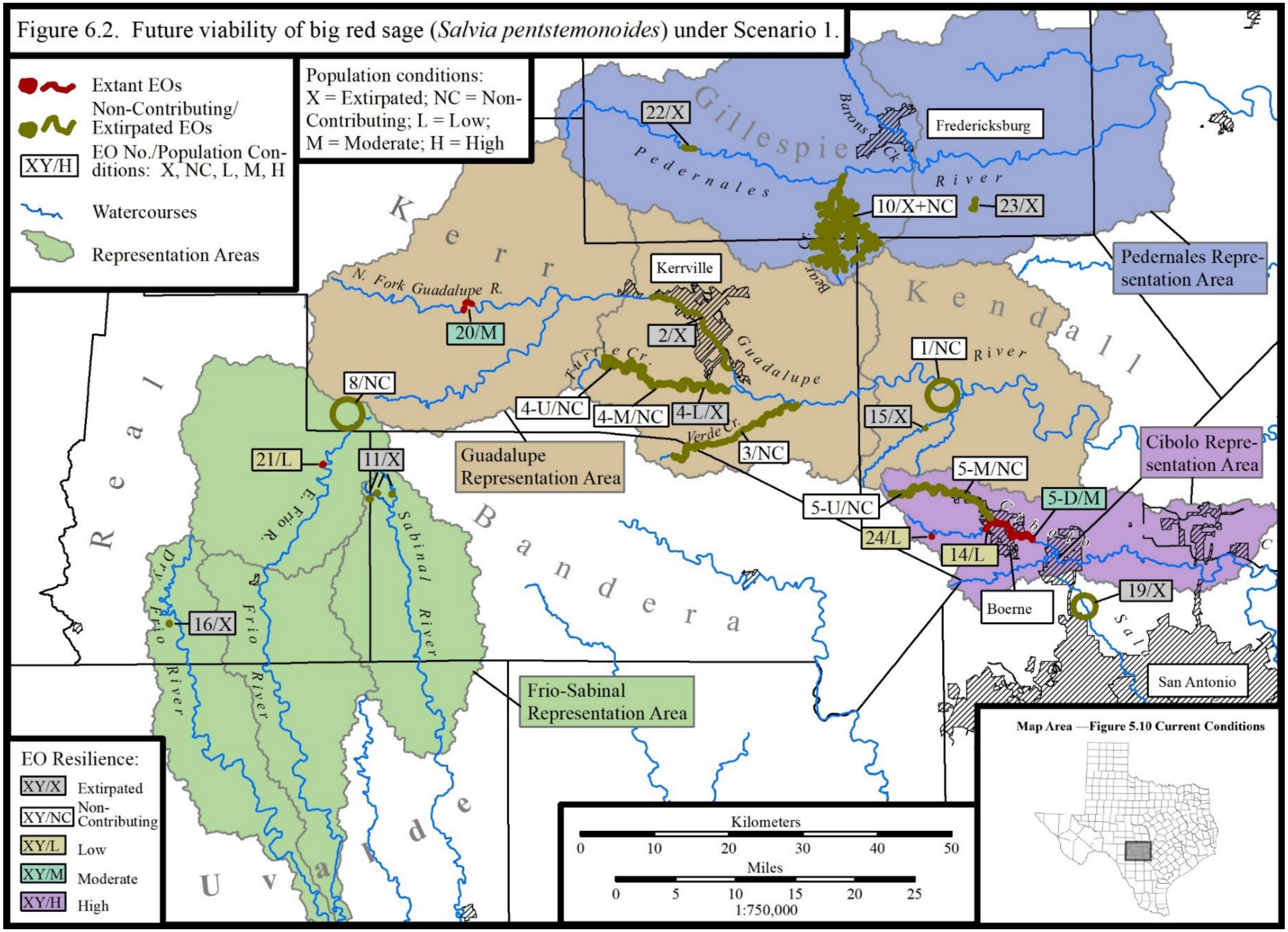


Figure 6.2. Future viability of big red sage (*Salvia pentstemonoides*) under Scenario 1.

Figure 6.2. Future viability of big red sage (*Salvia pentstemenoides*) under Scenario 1.

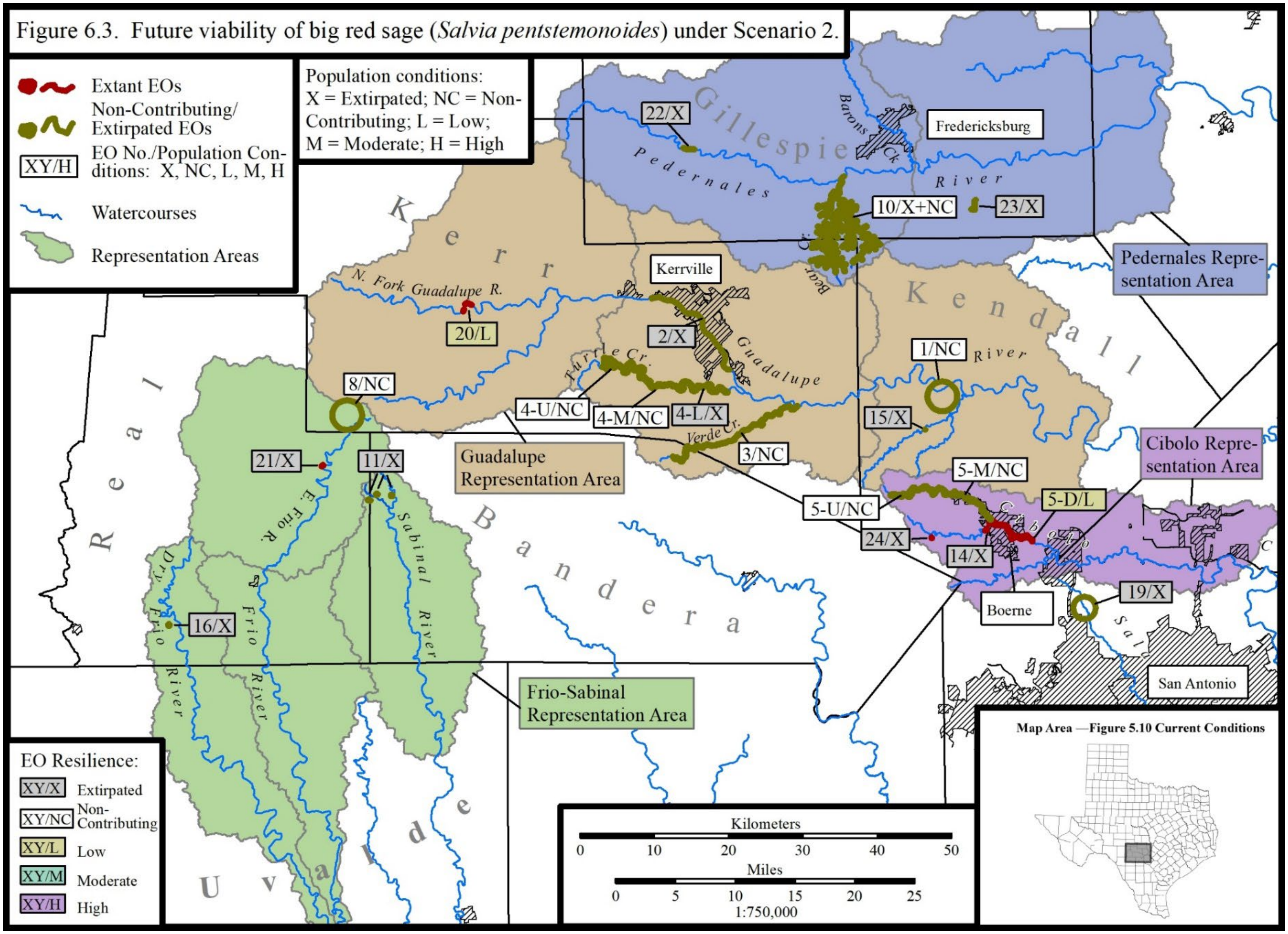


Figure 6.3. Future viability of big red sage (*Salvia pentstemenoides*) under Scenario 2.

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9. Additional Information

9.1. Photograph and drawing credits.

Cover: Chris Best, USFWS.
Figures 2.1.a.–2.1.e: Chris Best, USFWS
Figure 2.3: Chris Best, USFWS
Figure 2.4: Donna Taylor, Cibolo Preserve.

9.2. List of aerial images used in figures.

File Name	Accessed:	Figures
Google Earth. Image Date July 9, 2023.	August 11,2023	6.1
naip20-nc-cir-60cm_2998101_20201002.jp2	January 24, 2023	5.2a-d
naip20-nc-cir-60cm_2998102_20201002.jp2	January 24, 2023	5.2a-d
naip20-nc-cir-60cm_2998103_20201002.jp2	January 24, 2023	5.2a-d, 5.8
naip20-nc-cir-60cm_2998104_20201002.jp2	January 24, 2023	5.2a-d
naip20-nc-cir-60cm_2998113_20200930.jp2	January 24, 2023	5.2a-d, 5.4, 6.1
naip20-nc-cir-60cm_2998114_20200930.jp2	January 24, 2023	5.2a-d
naip20-nc-cir-60cm_2999062_20201030.jp2	January 17, 2023	5.1a-d
naip20-nc-cir-60cm_2999071_20201030.jp2	January 13, 2023	5.1a-d
naip20-nc-cir-60cm_2999072_20201030.jp2	January 13, 2023	5.1a-d
naip20-nc-cir-60cm_2999081_20201002.jp2	January 13, 2023	5.1a-d
naip20-nc-cir-60cm_2999112_20201115.jp2	February 14, 2023	5.7, 5.9
naip20-nc-cir-60cm_2999121_20201030.jp2	January 25, 2023	2.9, 5.3, 5.9
naip20-nc-cir-60cm_2999122_20201030.jp2	December 12, 2022	2.9
naip20-nc-cir-60cm_2999123_20201030.jp2	December 12, 2022	2.9
naip20-nc-cir-60cm_2999124_20201030.jp2	December 12, 2022	2.9
naip20-nc-cir-60cm_2999174_20201010.jp2	February 9, 2023	5.5
naip20-nc-cir-60cm_3099611_20201030.jp2	February 13, 2023	5.6
naip20-nc-cir-60cm_3099613_20201030.jp2	February 13, 2023	5.6

9.3. Scientific units.

Scientific Terms	Symbols	Scientific Terms	Symbols
Acre	ac	Inches	in
Celsius degrees	C°	Kilometers	km
Centimeter	cm	Meters	m
Fahrenheit degrees	F°	Mile	mi
Feet	ft	Millimeter	mm
Hectare	ha	Month	mon

9.4. Acronyms used.

CPC	Center for Plant Conservation	NRCS	Natural Resource Conservation Service
DEM	Digital Elevation Model	RCP	Representative Concentration Pathways
DFC	Desired Future Conditions	ROW	Right of Way
DNA	Deoxyribonucleic acid	SGCN	Species of Greatest Conservation Need
EO	Element Occurrence	SNA	State Natural Area
ESA	Endangered Species Act	SPM	Summary for Policy Makers
FR	Federal Register	SSA	Species Status Assessment
GCD	Groundwater Conservation District	SSP	Shared Socio-economic Pathway
GMA	Groundwater Management Areas	TDC	Texas Demographic Center
HUC	Hydrologic Unit Code	TPWD	Texas Parks and Wildlife Department
IPCC	Intergovernmental Panel on Climate Change	TWDB	Texas Water Development Board
ITIS	Integrated Taxonomic Information System	TxDOT	Texas Department of Transportation
ITS	Internal Transcribed Spacer	TXNDD	Texas Natural Diversity Database
MVP	Minimum Viable Population	USFWS	U.S. Fish and Wildlife Service
NCDC	National Climate Data Center	USGCRP	U.S. Global Climate Research Program.
NGO	Non-Governmental Organization	USGS	U.S. Geological Survey

APPENDIX A. METHODS USED TO CREATE A POTENTIAL HABITAT MODEL FOR BIG RED SAGE.

To evaluate the suitability and quantity of habitats at the extant Element Occurrences (EOs) of big red sage, we constructed a potential habitat model in ArcMap that intersects digital data layers of three geographic features—vegetation type, degree of slope, and proximity to watercourses—that influence the distribution of big red sage habitats. The extant EOs range from 10 to 200 m in width or diameter. Since surrounding areas have a relatively large influence on habitats within these narrow EO boundaries, we evaluated habitats within the EOs as well as a 50-m wide buffer around each EO. Therefore, the habitat analyses were performed in areas that ranged from 110 to 300 m in width or diameter.

Vegetation classification.

We used supervised classifications of Digital Ortho Quarter-Quad (DOQQ) aerial images to create vegetation cover maps of each EO and buffer zone. We used the Texas NAIP Imagery 2020 images available from the Texas Natural Resource Information Service (TNRIS 2023a), listed in the Species Status Assessment (USFWS 2023) Section 9. When more than one DOQQ was needed to cover an entire EO, we first created image mosaics. We set the display properties to show color-infrared versions of the images, which enhanced the distinctions between vegetation types.

In the infra-red images, six cover types are easily distinguishable. Broadleaf forest has a bright, deep red to yellowish-red signature and, due to the greater height of the trees, more evident shadows. Clear patterns of broadleaf forest dominate along watercourses and within narrow ravines, particularly on north-facing slopes. Woodlands and shrublands of Ashe juniper are distinguished by a uniform, dull reddish-brown signature with smaller shadows. Juniper woodland/shrubland dominates exposed slopes and arid uplands. Grass and forb vegetation can be bright to dull grayish- to brownish-pink, depending on moisture levels, and without evident shadows. Grass/forb vegetation appears uniform in the case of improved pasture, while native grassland is variegated. Exposed rock and unpaved roads appear white to light gray. Paved roads, parking lots, and some building roofs appear dark gray to bluish gray. Water appears dark blue, where it is deep and cool, to turquoise, pale blueish-green, and yellowish-green where it is shallow.

We used the Image Classification tool to run interactive supervised classifications of the infrared images. Within each image mosaic, we identified 15 or more training sites within each of the six cover types. We selected training sites that clearly fit into one of the classes, used small polygons, and distributed the training sites across the geographic range of the image mosaics. We then used the Raster to Polygon tool to convert the classified raster images into polygon shapefiles. To assess the accuracy of the classifications, we created 100 random points within the EO boundaries and compared the classifications at each point with our assessment of the cover type at the same points in the unclassified images; Table A.1 shows the results. However, we did not ground-truth the classification, as this would have greatly exceeded the scope of this exercise. Figure A.1 provides an example of the supervised classification in the vicinity of EO 24.

Appendix A: Potential Habitat Model

Table A.0.1. Habitat classifications of extant big red sage EOs and accuracy assessment.

EO No.	Shrub	Forest	Grass/Forb	Bare	Water	Pavement	Totals	Accuracy
4	16.1	35.3	37.9	1.9	7.2	1.6	100.0	94
5	4.2	53.8	28.0	2.4	9.8	1.8	100.0	92
11	29.5	67.5	1.9	1.0	0.1	0.0	100.0	97
14	15.5	33.4	41.3	2.7	0.7	6.3	100.0	88
16	36.1	61.0	3.0	0.0	0.0	0.0	100.0	95
20	24.9	22.8	12.9	2.3	37.0	0.4	100.0	94
21	25.9	42.9	21.5	0.5	9.2	0.5	100.0	95
24	20.6	75.3	4.1	0.0	0.0	0.0	100.0	97

Slope classification.

We used Digital Elevation Models (DEMs) from the National Elevation Dataset 2010, available from TNRIS (2023b), and the Spatial Analyst Slope and Reclassify tools, to classify raster images into 10-degree slope intervals (0 to 9.99°, 10 to 19.99°, etc.). We then used the Raster to Polygon tool to convert the classified raster images into polygon shapefiles. Although the pixel size of the DEMs (10 m) is much larger than the pixels in the DOQQ images (60 cm), the DEM data set, DOQQ images, and Global Position System (GPS) data from populations all aligned geographically. Table A.2 shows the range of slopes found within the boundaries of each extant EO. All extant EOs have areas of nearly level ground (0° to 10° slopes) and all have slopes of at least 30° to 40°, with some ranging up to 60° to 70°.

Table A.0.2. Range of slopes, in 10-degree intervals, of extant big red sage EOs.

	Degrees of Slope						
EO	0-10	10-20	20-30	30-40	40-50	50-60	60-70
4	x	x	x	x	x	x	
5	x	x	x	x	x	x	x
11	x	x	x	x	x	x	
14	x	x	x	x			

16	x	x	x	x			
20	x	x	x	x	x	x	x
21	x	x	x	x	x	x	x
24	x	x	x	x			

Distance from watercourses.

Using the DEMs described above, we used the Spatial Analyst/Hydrology/Stream Order and associated tools and procedures to map stream flow direction, accumulation, and Strahler Stream Order. This revealed that the extant EOs of big red sage occur in proximity to streams of the 1st through 6th order. However, these procedures created linear stream features that frequently veered tens of meters away, and as much as 300 m away, from the stream courses that could be observed in the DOQQ images. Hence, the stream lines created by the Hydrology tools were not useful for habitat modelling at the required scales. Other linear stream shapefiles aligned better with the aerial images, but as linear features they did not reflect the varying width of stream channels; landowners in the Edwards Plateau frequently construct low-water dams across intermittent streams to create pools. To measure the distances more accurately from watercourse edges, we digitized polygon features of all streams within the buffered EO boundaries; where obscured by overhanging tree canopies, we connected the nearest observable stream edges with straight lines. The stream polygons extend from high bank to high bank, as defined by an observed change from vegetated surfaces to water or to the gravel, bare rock, or bare silt of intermittent stream channels.

We estimated the distances from big red sage plants to watercourses by measuring from the boundaries of each EO to the edges of the nearest watercourse polygons. Texas Natural Diversity Database (TXNDD) establishes EO boundaries based on their understanding of a species' distribution at a population site buffered by the estimated precision of the location report. Hence, low-precision reports have wider buffers. Consequently, our estimates of the distances to watercourses could represent the actual distances from big red sage plants, but may also be overestimated due to low-precision location data. Although this is the best currently available data, this component of the species' distribution model can be improved by using more precise geographic coordinates of plant locations using differentially corrected GPS. Table A.3 lists the ranges of maximum distances to watercourses at each EO, and Table A.4 shows the frequency distribution of the maximum distances.

Table A.0.3. Maximum distances of big red sage EOs from watercourse edges (m).

EO	Stream Order	Range of maximum distances (m) from edge of watercourse	Maximum
4	4	32 – 53	53
4	5	39 – 62	62
5	3	7 – 35	35

5	4	13 – 35	35
5	5	0 – 30	30
11	1	41	41
11	2	49 – 102	102
14	4	0 – 63	63
16	1	125	125
20	6	9 – 28	28
21	5	25 – 47	47
24	1	21 – 38	38

Table A.0.4. Frequency distribution of maximum distances from watercourse edges (m).

Average:	54.9
Standard Deviation:	28.8
Least:	28.0
Greatest:	125.0
Percent less than 50:	58.3
Percent greater than 50 and less than 100	25.0
Percent greater than 100 and less than 150	16.7
Percent greater than 150 and less than 200	0.0

Potential habitat model.

Examination of known species locations overlaid on the vegetation classification layer revealed that extant populations are most often found in areas classified as broadleaf forest, to which we assigned a factor of 2. Some populations also included areas classified as juniper woodland or a broadleaf-juniper mosaic, to which we assigned a factor of 1. We assigned factors of 0 to areas of grass and forbs, water, bare rock, and pavement. Although known locations of big red sage can occur on level ground, most occur on slopes, and steep slopes provide greater protection from ungulate browsers as well as shade. We assigned factors of 1, 1.5, 2, and 3 to areas with slopes of 0 to 9.99°, 10° to 19.99°, 20° to 29.99°, and 30° or greater, respectively. To give greater weight to areas closer to watercourses, we assigned factors of 4, 3, 2, 1, and 0 to areas that are 0 to 50 m, 50 to 100 m, 100 to 150 m, 150 to 200 m, and greater than 200 m from watercourses, respectively. Table A.5 lists the factors assigned to each classification.

We constructed the potential habitat model through the intersection of the vegetation classification, degree of slope, and distance to watercourse shapefiles in ArcMap.

In the resulting intersected shapefile, we added a new field to the Attribute Table that represents the potential habitat model. We used the Calculate Field function to multiply all three factors in the potential habitat field for each resulting polygon. This product of factors is one of 14 discrete values for the intersected polygons: 0, 1, 1.5, 2, 3, 4, 4.5, 6, 8, 9, 12, 16, 18, and 24. We examined known locations of big red sage overlaid on the potential habitat model shapefile and determined empirically that extant populations occurred where polygons had combined of 8 or higher, and excellent habitats ranked 16 through 24. Polygons ranked below 8 had low potential to support big red sage. Figure A.2 demonstrates the intersections of layers along a small portion of the upper Turtle Creek at EO4.

Table A.0.5. Factors assigned to vegetation, slope, and distance to watercourse polygon classifications.

Vegetation Cover		Slope (Degrees)		Distance to Watercourse (m)	
Class	Factor	Class	Factor	Class	Factor
Water	0	0 to 10	1	200 or greater	0
Pavement	0	10 to 20	1.5	150 to 200	1
Rock	0	20 to 30	2	100 to 150	2
Grass/Forb	0	30 or greater	3	50 to 100	3
Juniper	1			0 to 50	4
Broadleaf Tree	2				

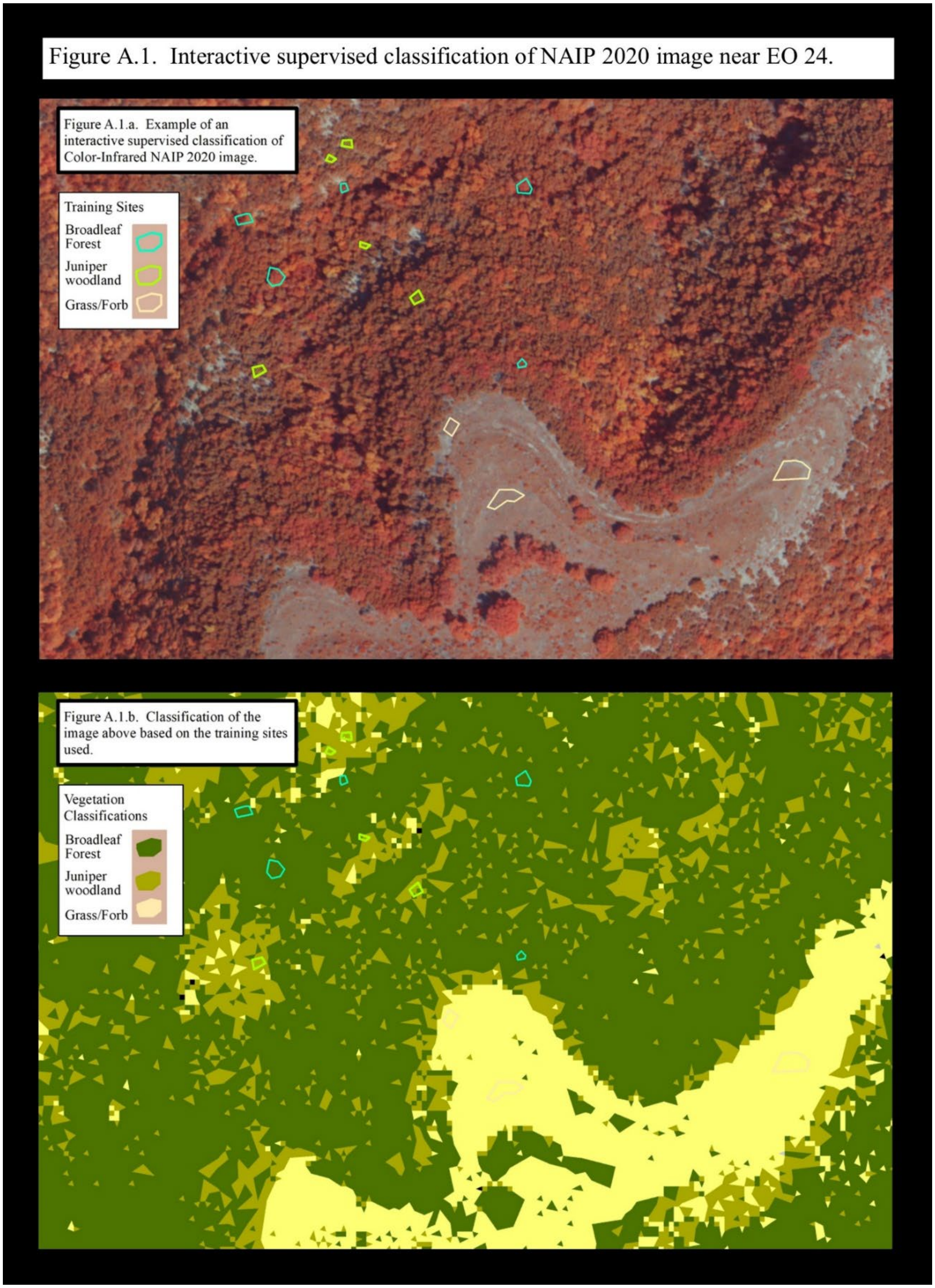

Figure A.0.1. Interactive supervised classification of NAIP 2020 near EO 24.

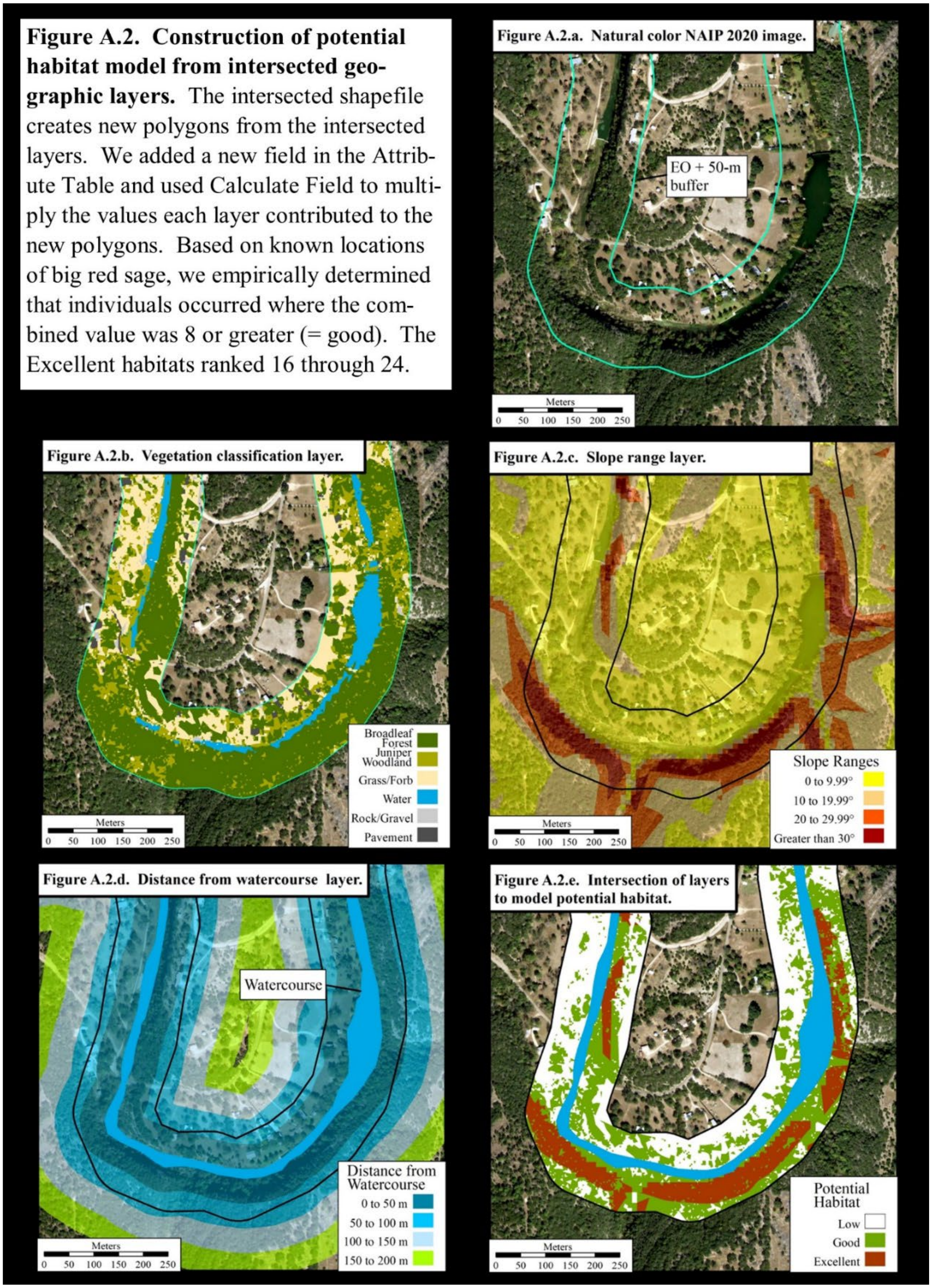

Figure A.2. Construction of potential habitat model from intersected geographic layers.

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Texas Natural Resource Information Service 2023a. National Elevation Dataset 2010. ned13-10m_2998.img, ned13-10m_2099.img, ned13-10m_3098.img, ned13-10m_3099.img. https://data.tnris.org/collection/?c=49c7fa9b-ab48-4c17-8f19-27253f7cfd08. Accessed March 2, 2023.

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APPENDIX B. LIST OF BIG RED SAGE HERBARIUM SPECIMENS.

Table B.0.1. Big red sage (*Salvia pentstemonoides*) herbarium specimens.

Collector Surname	Collector Name	Location	Location Number[a]	County	Mon	Year	Herbarium	Specimen No.	Herbarium barcode
Lindheimer	Ferdinand J.	Upper Pedernales River	1	Gillespie	Oct	1845	MO	673 (460)	MO-847078 (Type)
Lindheimer	Ferdinand J.	Upper Pedernales River	1	Unk	Oct	1845	NY	460	348
Lindheimer	Ferdinand J.	Unk	n/a	Unk	Unk	1848	GH	673	01696436
Wright		Unk	n/a	Unk	Unk	1848	GH	s.n.	01696439
Lindheimer	Ferdinand J.	Cibolo	2	Unk	Jun	1849	GH	66	01696431
Lindheimer	Ferdinand J.	Comanche Spring, New Braunfels, etc.	3	Unk	Jun	1849	GH	1092	01696433
Lindheimer	Ferdinand J.	San Antonio; Comanche Spring; New Braunfels etc.	3	Bexar	Jun	1849	MO	1092(66)	MO-847074, MO-847075, MO-847076
Lindheimer	Ferdinand J.	Comanche Spring, New Braunfels, etc.	3	Bexar	Jun	1849	LL, TEX	1092(254)	TEX00022825
Lindheimer	Ferdinand J.	Comanche Spring, New Braunfels, etc.	3	Comal	Jun	1849	NY	1092	38179
Lindheimer	Ferdinand J.	San Antonio, Comanche Spring, New Braunfels, etc.	3	Bexar	Jun	1849	US	1092	02799985
Lindheimer	Ferdinand J.	San Antonio	3	Bexar	Jun	1849	NMC	1092	23256
Lindheimer	Ferdinand J.	Comanche Spring, New Braunfels, etc.	3	Comal	Jun	1849	RENO	1092	55912
Lindheimer	Ferdinand J.	Unk	n/a	Unk	Unk	1849	NY	s.n.	38178
Unk		Unk	n/a	Unk	Unk	1849	GH	s.n.	01696437
Unk		Unk	n/a	Unk	Unk	1849	NY	s.n.	38180
Unk		Unk	n/a	Unk	Unk	1853	GH	s.n.	01696438
Palmer	Edward	Sutherland Springs	4	Wilson	Aug	1879	GH	1077	01696435
Palmer	Edward	Sutherland Springs	4	Wilson	Aug	1879	NY	1077	38177
Jermy	Gustav	Bears Creek	5	Gillespie	Unk	1889	MO	710	MO-847071
Heller	A. Arthur	About Kerrville	6	Kerr	Jun	1894	MO	1894	MO-847077

Appendix B: Herbarium Specimens

Collector Surname	Collector Name	Location	Location Number[a]	County	Mon	Year	Herbarium	Specimen No.	Herbarium barcode
Heller	A. Arthur	About Kerrville	6	Kerr	Jun	1894	NY	s.n.	38176
Heller	A. Arthur	About Kerrville	6	Kerr	Jun	1894	US	1894	02799984
Heller	A. Arthur	About Kerrville	6	Kerr	Jun	1894	US	1894	02799987
Heller	A. Arthur	About Kerrville	6	Kerr	Jul	1894	GH	s.n.	01696430
Hill	R.J.	Frio Water Hole	7	Edwards	Jun	1895	US	48	02799982
Hill	R.J.	Frio Water Hole	7	Edwards	Jun	1895	US	52	02799983
Nichols	J.M.	Kerrville	8	Kerr	Nov	1895	ASU	882	ASU0111465
Palmer	Ernest J.	Upper Cibolo Creek near Boerne	9	Kendall	Sep	1916	MO	10865	MO-847072
Palmer	Ernest J.	Upper Cibolo Creek near Boerne	9	Kendall	Sep	1916	US	10865	02799986
Parks	H.B.	Barron Creek	10	Kendall	Sep	1938	BRIT	14620[b]	BRIT09720
Parks	H.B.	Barron Creek	10	Kendall	Sep	1940	MO	3194	MO-847073
Parks	H.B.	Barron Creek	10	Kendall	Aug	1941	MO	2631	MO-847070
Cory	V.L.	Turtle Creek, 14 mi. SW of Kerrville	11	Kerr	Aug	1943	GH	43030	01696434
Cory	V.L.	Turtle Creek, 14 mi W of Kerrville	11	Kerr	Aug	1943	LL, TEX	43029 (254)	TEX00022823
Correll	Donovan S.	Verde Creek	12	Bandera, Kerr	June	1946	BRIT	12805[c]	
O'Kennon	Bob	Frederick Creek and I-10 Bridge	13	Kendall	Jul	1984	BRIT	770[d]	
Enquist	Marshall	Lost Maples SNA	14	Bandera	Aug	1987	LL, TEX	s.n.	TEX00022824
Enquist	Marshall	Creek near Boerne	13	Kendall	Oct	1987	LL, TEX	s.n.	TEX00023770
O'Kennon	Bob	Frederick Creek and I-10 Bridge	13	Kendall	Sep	1990	BRIT	8090[d]	
O'Kennon	Bob	Frederick Creek and I-10 Bridge	13	Kendall	Jul	1991	BRIT	9203[d]	
O'Kennon	Bob	Turtle Creek, 6 mi S of Kerrville	11	Kerr	Aug	1991	BRIT	9725[d]	

Appendix B: Herbarium Specimens

Collector Surname	Collector Name	Location	Location Number[a]	County	Mon	Year	Herbarium	Specimen No.	Herbarium barcode
O'Kennon	Bob	Turtle Creek, 6 mi S of Kerrville	11	Kerr	June	1993	BRIT	11668[d]	
O'Kennon	Bob	Turtle Creek, 6 mi S of Kerrville	11	Kerr	June	1994	BRIT	12338[d]	999999
Miller	Ann	San Antonio Botanical Garden, cultivated	n/a	Bexar	June	2000	LL, TEX	s.n.	TEX00375896
Taylor, O'Kennon, and Barieau		Frederick Creek and I-10 Bridge	13	Kendall	June	2013	BRIT	2256[e]	

a. To clarify which specimens were collected from the same locations, this column numbers the collection locations in the chronological order that they were first collected. For example, V.L. Cory first collected the species southwest of Kerrvile on Turtle Creek in 1943. O’Kennon collected it from or near this location in 1991, 1993, and 1994.
b. TXNDD 2021, p. 2.
c. TXNDD 2021, p. 6.
d. Taylor and O’Kennon 2013, p. 4.
e. TXNDD 2021, p. 31.

APPENDIX C. GLOSSARY OF SCIENTIFIC AND TECHNICAL TERMS.

Term	Definition
Allele	Alternate forms of a gene.
Anther	The pollen-bearing part of the stamen. (Correll and Johnston 1979).
Aquifer	Underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or silt) from which groundwater can be extracted using a water well (Wikipedia 2017).
Augmentation	Introduction of additional individuals or propagules to an existing population.
Autogamy	In plants, self-pollination within the same flower; see geitonogamy.
Axil	Upper angle formed by a leaf or branch with the stem (Correll and Johnston 1979).
Bract	A reduced leaf subtending a flower, usually associated with an inflorescence (Correll and Johnston 1979, p. 1747).
Breeding System	The ability of a plant species to reproduce via outcrossing, self-fertilization, apomixis, or a combination (Wikipedia 2015).
Browsing	Herbivory of the leaves and stems of woody plants (as opposed to grazing).
Calyx	The external whorl of a flower (Correll and Johnston 1979, p. 1747); the sepals, collectively.
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 2013).
Connective	Portion of a filament connecting the two cells of an anther (Correll and Johnston 1979).
Corolla	The inner perianth of a flower (Correll and Johnston 1979, p. 1749); the petals, collectively.
Cretaceous	Geologic period and system from 145 ± 4 to 66 million years (Ma) ago (Wikipedia 2016).
Cuspid	Tipped with a short, rigid point (Correll and Johnston 1979, p. 1749).
Cyme	A determinate flower cluster in which the first flower is terminal on the main axis, the next flower(s) terminal on axes arising from the axils of bracts subtending the first flower, and so on; often flat-topped or convex (Correll and Johnston 1979, p. 1749).
Demography	Scientific study of populations.
Denticulate	Slightly and finely toothed margin (Correll and Johnston 1979, p. 1750).
Dichogamy	In plants, the maturation of anthers and stigmas at different times; this reduces the incidence of self-pollination.
Digital Elevation Model	Digital model or 3D representation of a terrain's surface — commonly for a planet (including Earth), moon, or asteroid — created from terrain elevation data (Wikipedia 2015).

Appendix C: Glossary

DNA	Deoxyribonucleic acid; the primary type of molecular genetic information storage in Eukaryotes.
Effective population size	The size of an idealized population in which individuals contribute equally to the gamete pool and have the same variation in allele frequencies and levels of inbreeding as the observed population (Barrett and Kohn 1991).
Element Occurrence	An area of land and/or water in which a species or natural community is, or was, present (NatureServe 2002).
Endemic	An organism restricted to a specific habitat or geographic range.
Evaporative deficit	The difference between actual and potential evapotranspiration (USGS 2014, p. 11).
Evapotranspiration	The combined loss of water vapor from an ecosystem by evaporation and transpiration from plants.
Ex-situ	Off site (as opposed to *in situ*). Usually a controlled environment, such as a botanical garden, arboretum, or laboratory.
Fixation index	"…a measure of population differentiation due to genetic structure. It is frequently estimated from genetic polymorphism data, such as single-nucleotide polymorphisms (SNP) or microsatellites." Wikipedia 2020.
Forb	A broad-leafed herbaceous plant.
Geitonogamy	In plants, self-pollination between anthers and pistils of different flowers on the same individual.
Gene	A specific region of a chromosome that controls a single heritable trait.
Gene flow	The transfer of alleles or genes from one population to another (Wikipedia 2013).
Genetic bottleneck	An event that greatly restricts an organism's genetic diversity.
Genetic drift	Random changes in allele frequencies as well as complete loss of alleles from the gene pool of a population.
Genotype	The genetic composition of a cell, organism, or individual (Wikipedia 2012).
Glabrous	Lacking surface ornamentation, such as trichomes; glabrate = nearly glabrous (Correll and Johnston 1979).
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.
Habitat	Ecological or environmental area that is inhabited by a particular species of animal, plant or other type of organism (Wikipedia 2013).
Herbaceous	Plant tissues, such as leaves and stems, that are not lignified and typically last for a single season or year; as opposed to woody plants and tissues.
Herbarium	A repository for long-term storage and study of preserved plant specimens.
Heterozygous	A diploid (or polyploid) organism possessing two (or more) alleles at a specific gene locus on homologous chromosomes.
Historical population	A previously documented population that has been extirpated or can no longer be found.

Appendix C: Glossary

Holocene	Geological epoch which began approximately 12,000 years ago (Wikipedia 2013).
Homologous chromosomes	Chromosome pairs originating from an organism's male and female parents that have the same genes at the same loci.
Homozygous	A diploid (or polyploid) organism possessing the same allele at a specific gene locus on homologous chromosomes.
Hydrologic Unit Codes	The numerical identifier of a specific hydrologic unit consisting of a 2-digit sequence for each specific level within the delineation hierarchy (NRCS 2006, p. 18).
Improved pasture	Livestock grazing lands in which most native plants have been replaced with a small number of preferred forage species.
Inbreeding	Sexual reproduction between closely related individuals.
Inbreeding depression	The reduction of fitness caused by mating between relatives (Edmands 2007, p. 464).
Indeterminate growth	Growth that is not terminated once a genetically pre-determined structure has completely formed (Wikipedia 2023).
Inflorescence	A plant structure bearing two or more flowers.
Internal Transcribed Spacer (ITS)	Spacer DNA (non-coding DNA) situated between the small-subunit ribosomal RNA (rRNA) and large-subunit rRNA genes (Wikipedia 2015).
Invasive	Species that is non-native (or alien) to the ecosystem under consideration and whose introduction causes or is likely to cause economic or environmental harm or harm to human health (Clinton 1999; 64 FR:6183-6186, February 3, 1999).
Karst	A topography formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum (Wikipedia 2017).
Lanceolate	Lance-shaped; much longer than broad, tapering from below the middle to the apex and (more abruptly) to the base (Correll and Johnston 1979, 1755).
Limestone	A carbonate sedimentary rock composed mainly of the minerals calcite and aragonite, which are different crystal forms of calcium carbonate ($CaCO_3$) (Wikipedia 2019).
Locus	The specific position of a gene on a chromosome.
Mesic	Habitat or ecological region with intermediate moisture availability (between wet and xeric).
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 2012).
Minimum viable population	The fewest individuals required for a specified probability of survival over a specified period of time (Pavlik 1996; Mace and Lande 1991); see Population Viability Analysis.
Monophyly	A group of organisms that consists of all the descendants of a single common ancestor.
Nectary	An organ that secretes nectar (Correll and Johnston 1979, p. 1756).

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Nucleus	A membrane-bound organelle in Eukaryotic organisms that contains the chromosomes.
Nutlet	"Diminutive of nut; applied to any small and dry nutlike fruit or seed. Thicker-walled than an achene." (Correll and Johnston 1979, p. 1757).
Outcross	In plants, sexual fertilization involving the union of gametes from different individuals.
Perched aquifer	A water-storing geological stratum in a higher topographic position than a main aquifer due to their separation by an impermeable layer (an aquiclude or aquitard).
Perennial	A plant that lives for more than one full year.
Petiole	A leaf stalk (Correl and Johnston 1979, p. 1758).
Phenology	Seasonal pattern of plant growth, development, and reproduction.
Phreatic zone	The saturated soil and rock strata that are below the water table.
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 2013).
Pistil	The ovule-bearing portion of a flower, consisting of stigma and ovary, usually with a style between (Correll and Johnston 1979, p. 1758).
Pleistocene	Geological epoch beginning about 2,588,000 years ago and ending about 11,700 years ago (Wikipedia 2013).
Pollen Limitation	Reduced reproductive output of a plant due either to insufficient pollen sources or a lack of pollinators.
Population	Collection of inter-breeding organisms of a particular species (Wikipedia 2013).
Ramet	An individual, genetically identical plant reproduced as a clone of the parent plant.
Rangeland	Land on which the potential natural vegetation is predominantly grasses, grasslike plants, forbs, or shrubs suitable for grazing or browsing (NRCS 2008, p. 212).
Raster	In computer graphics...a dot matrix data structure representing a generally rectangular grid of pixels, or points of color, viewable via a monitor, paper, or other display medium (Wikipedia 2015).
rDNA	Ribosomal DNA. rDNA sequences may be used to reveal phylogenetic relationships.
Recessive allele	An allele whose expression is masked or dominated by a homologous allele of a diploid or polyploid organism.
Recruitment	Addition of new individuals to a population.
Redundancy	The number of populations or sites necessary to endure catastrophic losses (Shaffer and Stein 2000, pp. 308-310).
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).

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Rhizome	Horizontal stems that grow under the surface of the ground.
Rosette	A radially symmetrical whorl of leaves formed at the base of a plant stem, usually during a vegetative (non-reproductive) growth phase.
Rudist	Extinct, box-, tube- or ring-shaped marine heterodont bivalves, order Hippuritida, that were major reef-building organisms during the Cretaceous (Wikipedia 2023).
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.
Shapefile	A digital geospatial vector data storage format developed by Esri. (Wikipedia 2015).
Soil seed reserve	Dormant and non-dormant seeds present in the soil that are able to germinate.
Source Feature	"Points, lines, or polygons where a species has been observed one or more times, together with the data recorded for each observation" (NatureServe 2019)
Species	One of the basic units of taxonomic identity (Wikipedia 2013). Multiple species definitions exist, including the biological, phylogenetic, evolutionary, etc. The biological definition ("... groups of actually or potentially interbreeding natural populations, which are reproductively isolated from other such groups" (Mayr 1942)) is adopted in the ESA but does not apply well to all organisms.
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).
Stamen	Male reproductive structure of the flower, consisting of a filament and anther: the androecium (Anderson 2001).
Stigma	The receptive part of the pistil on which the pollen germinates. (Correll and Johnston 1979).
Stochastic	Random.
Strahler stream order	First-order streams are the outermost tributaries of a stream. Two streams of the same order join to form a stream of the next highest order (two first-order streams form a second-order stream). Two streams of different order merge and continue with the order of the higher of the two (a second- and third-order stream merge and continue as a third-order stream) (Wikipedia 2023).
Style	A narrowed, often elongate portion of a pistil between the stigma and ovary (Correll and Johnston 1979).

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Succession	Ecological succession is the change in composition and structure of an ecological community over time.
Survey	In the context of this plan, surveying is the search for new individuals or populations of a species or new habitat occurrences (as distinguished from monitoring).
Swallet	A sinkhole within the bed of a stream.
Taxon	(Plural, taxa). A natural group of organisms at any rank in the taxonomic hierarchy (Anderson 2001).
Taxonomy	Scientific classification of living organisms.
Theca	An anther; the pollen bearing part of the stamen (Correll and Johnston 1979, pp. 1746, 1763).
Trapline foraging	Foraging by repeatedly visiting rewarding locations in a predictable sequence (Tello-Ramos et al. 2015, p. 812), as opposed to remaining at a single large food source until it is depleted.
Vadose zone	The unsaturated water-conducting soil and rock strata that are above the water table.
Watershed	A physiographic area bound by a drainage divide and within which precipitation drains to a point of interest (NRCS 1999-Present).
Woodland	Vegetation type with discontinuous tree cover.

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APPENDIX D. FUTURE EO CONDITIONS.

Table D.0.1. EO 20 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Moderate	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing if protected from deer.	Declining or extirpated.
Aquifer depletion	Stable; DFC projects no significant pumping from Edwards-Trinity aquifer.	Declining or extirpated due to drawdown of aquifer.
Collection from the wild	Stable or increasing if used to augment population size.	Declining or extirpated.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Both severity and frequency of drought and flash flooding	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Stable.	Declining or extirpated.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to deer protection, population augmentation, restored gene flow, and genetic augmentation.	Declining.
Landowner engagement	Improving, due to access for monitoring and management.	Declining.
Future Condition Assessment	Moderate population condition through 2050–2074 is likely under Scenario 1. Under Scenario 2 a low condition or extirpation is very likely.	

Table D.0.2. EO 4 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Unknown; one or more populations may be extant	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing.	Declining or extirpated.

Aquifer depletion	Stable. Upper Turtle Creek is in the Edwards-Trinity aquifer; vadose strata may contribute.	Stable or declining, depending on the proportion of seepage from the Trinity aquifer.
Collection from the wild	Stable, if unknown to collectors.	Declining or extirpated, if known to collectors.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Severity and frequency of drought	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Unknown.	Unknown.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Deer herd management, restored gene flow, and genetic augmentation may benefit unknown populations.	Declining or extirpated.
Landowner engagement	Access for surveys could lead to rediscovery of Cory population.	Unknown.
Future Condition Assessment	Current condition unknown and future condition undetermined. Landowner engagement is the most important factor to discover and conserve any extant populations.	

Table D.0.3. EO 5 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Moderate	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing; deer cannot access population.	Stable or declining; introduced ungulates, such as goats, access and browse site.
Aquifer depletion	Stable or declining; DFC would result in additional 7 % reduction in spring and base flows.	Declining or extirpated, due to development of vadose strata recharge areas.
Collection from the wild	Stable or increasing if used to augment population size.	Declining or extirpated.

Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Both severity and frequency of drought and flash flooding	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Stable.	Declining or extirpated.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to population augmentation, restored gene flow, and genetic augmentation.	Declining.
Landowner engagement	Stable; landowner monitors and manages site.	Declining.
Future Condition Assessment.	Future condition is moderate. Vulnerable to reduced seepage due to increased development of vadose strata recharge areas. Scenario 1 conservation efforts, such as augmentation of population size and genetic diversity, may be necessary for the condition of this EO through 2050—2074.	

Table D.0.4. EO 14 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Moderate	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing.	Declining or extirpated.
Aquifer depletion	Stable or declining; DFC would result in additional 7 % reduction in spring and base flows.	Declining or extirpated, due to development of vadose strata recharge areas.
Collection from the wild	Stable or increasing if used to augment population size.	Declining or extirpated.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Both severity and frequency of drought and flash flooding	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Stable.	Declining or extirpated.

Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to deer protection, population augmentation, restored gene flow, and genetic augmentation.	Declining.
Landowner engagement	Improving, due to access for monitoring and management.	Declining.
Future Condition	Future condition is low. Vulnerable to ungulate herbivory, collection, reduced seepage due to increased development of vadose strata recharge areas, and adjacent urban development. Scenario 1 conservation efforts, such as augmentation of population size and genetic diversity, may enhance the condition of this EO through 2050—2074.	

Table D.0.5. EO 24 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Moderate	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing.	Declining or extirpated.
Aquifer depletion	Stable; seepage likely depends on vadose strata.	Declining; development of vadose strata recharge areas would reduce seep moisture.
Collection from the wild	Stable or increasing if used to augment population size.	Declining or extirpated.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Severity and frequency of drought	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Stable.	Declining or extirpated.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to deer protection, population augmentation, restored	Declining.

	gene flow, and genetic augmentation.	
Landowner engagement	Improving, due to access for monitoring and management.	Declining.
Future Condition	Future condition is likely to be low. Vulnerable to ungulate herbivory, depletion of vadose strata if recharge areas are converted to impermeable surfaces, and small population sizes. Scenario 1 in conservation and landowner engagement enhance population condition during the 2050–2074 assessment period, so moderate condition is possible.	

Table D.0.6. EO 11 and EO 16 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Low	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing.	Extirpated.
Aquifer depletion	Stable. No significant drawdown of Edwards-Trinity aquifer; seepage from vadose strata is not likely to be developed.	Declining. Drawdown of Edwards-Trinity aquifer affects site; vadose strata recharge area is converted to impermeable surfaces.
Collection from the wild	Stable or increasing if used to augment population size.	Extirpated.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Severity and frequency of drought	Population sizes more variable but recover during years of higher rainfall.	Extirpated.
Demographic effects of small populations	Stable.	Extirpated.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to deer protection, population augmentation, restored gene flow, and genetic augmentation.	Extirpated.
Landowner engagement	Improving, due to access for monitoring and management.	Extirpated.
Future Condition Assessment	Nearly extirpated when last monitored; future condition is likely to be extirpated. If either population is extant, its future	

	condition may be enhanced under Scenario 1 for conservation and landowner engagement.

Table D.7. EO 21 future conditions under Scenarios 1 and 2.

Factor	Resilience	
Current condition	Low	
Scenario	Scenario 1	Scenario 2
Herbivory	Stable or increasing; plants are on steep bluff not accessible to deer.	Declining; deer or introduced ungulates browse plants on bluff.
Aquifer depletion	Stable. No significant drawdown of Edwards-Trinity aquifer; seepage from vadose strata is not likely to be developed.	Declining. Drawdown of Edwards-Trinity aquifer affects site; vadose strata recharge area is converted to impermeable surfaces.
Collection from the wild	Stable or increasing if used to augment population size.	Declining or extirpated.
Loss of genetic integrity due to propagation	Stable or increasing if used to augment gene flow.	Declining due to genetic swamping, hybridization, etc.
Climate changes: Severity and frequency of drought	Population sizes more variable but recover during years of higher rainfall.	Declining or extirpated.
Demographic effects of small populations	Stable.	Declining or extirpated.
Genetic effects of small populations	Stable or improving through restored gene flow, genetic augmentation, etc.	Declining due to loss of diversity, genetic bottleneck, genetic drift, and inbreeding.
Conservation	Improving, due to deer protection, population augmentation, restored gene flow and genetic augmentation.	Declining or extirpated.
Landowner engagement	Improving, due to access for monitoring and management.	Declining or extirpated.
Future Condition	Future condition is low. Future condition may be enhanced under Scenario 1 for conservation and landowner engagement, particularly if additional populations are discovered nearby.	