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A REPORT ON FOUR RARE PLANT SPECIES OF BIG BEND NATIONAL PARK, TEXAS

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A REPORT ON FOUR RARE PLANT SPECIES OF

BIG BEND NATIONAL PARK, TEXAS

by

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REPORT

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“When we try to pick out anything by itself, we find it hitched to
everything else in the Universe.” – John Muir

“The sign of intelligence is that you are constantly wondering. Idiots are always dead sure about every damn thing they are doing in their life.” – Sadhguru

“We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it
with love and respect.” – Aldo Leopold

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Abstract

A REPORT ON FOUR RARE PLANT SPECIES OF

BIG BEND NATIONAL PARK, TEXAS

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The University of Texas at Austin, 2017

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Big Bend National Park in Texas serves as a refuge for many rare plant species, many of which can be found nowhere else in the United States. This study is a summary and synthesis of the available research that has been done on four rare plants in Big Bend National Park: *Coryphantha ramillosa* subspecies *ramillosa* (bunched cory cactus), *Echinocereus chisoensis* var. *chisoensis* (Chisos Mountain hedgehog cactus), *Echinomastus mariposensis* (Lloyd's mariposa cactus), and *Festuca ligulata* (Guadalupe fescue). The objectives of this study were (1) to review and synthesize all existing published and unpublished studies of these species, with a focus on known threats, conservation priorities, and research needs, (2) to create a GIS database of available public and private data relevant to these species, and (3) using this database, to conduct a preliminary analysis identify the primary habitat characteristics of each of these species at both local and landscape scales. At the landscape scale, geological substrate, elevation, and topographic position characterized species' habitats. At a local scale, slope and sometimes soil unit determined species presence. Further research is needed on each species. Each of these species faces multiple threats, and collaborations between government agencies, private

conservation organizations, private landowners, and researchers may be essential to the recovery of these species.

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GEE = Geefour silty clay (3-20% slopes); GEF = Geefour silty clay (10-45% slopes); NNB = Ninepoint clay loam; RIA = Riverwash and Pantera soils; SKE = Solis-Rock outcrop complex; VCA = Vincente, Lomapelona, and Castolon soils)

Figure 7. Results of analyses of *Echinomastus mariposensis* presence-absence data. (A) Points found at lower elevations were more likely to have an ECMA plant present ($p < 0.0001$); (B) Points on less steep slopes were more likely to have ECMA present ($p < 0.0001$). Each point represents one plant location or one pseudo-absence in the data set.

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Figure 9. *Echinomastus mariposensis*: results for geology, soil unit, and soil type. A, C, E: composition of the site and of points with ECMA present. Left bar: site (both presence and pseudo-absence points); right bar: only points with ECMA present. B, D, F: results of analyses of *Echinomastus mariposensis* presence-absence data. Bars represent the predicted probability of a point in each category having an ECMA plant. (BIE = Bissett-Rock outcrop complex; BLD = Blackgap-Rock outcrop complex (1-16% slopes); BLE = Blackgap-Rock outcrop complex (10-30% slopes); GEF = Geefour silty clay (10-45%

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Introduction

Preserving biodiversity in general, and rare species in particular, is an important goal in conservation. As we enter the Anthropocene, the planet is experiencing a crisis of mass extinction, with unprecedented losses of species both locally and globally. As botanists and ecologists, our role includes acquiring information to aid conservation and land management. Understanding habitat and ecological requirements of threatened species, and the threats they face, is a critical component of preserving rare species.

Rare species may have a small geographical range, high habitat specificity, one or only a few populations, small population sizes, or a combination of these (Rabinowitz 1981, Fiedler and Jain 1992). For some species, these characteristics are unrelated to human activities; however, for many species they are in part or entirely the result of human activities, such as habitat destruction and poaching (including illegal collecting of plants). Rarity regardless of cause is often used as a factor to determine where conservation efforts should go (Flather *et al*. 1998), as rare species are more likely to go extinct than common ones (Lawton 1994). A significant number of cacti species are rare, as are some grasses (Hernández *et al.* 2010).

The Endangered Species Act of 1973 (ESA) was enacted to protect and recover rare species in the United States (USFWS 1973). Each species listed under the ESA is classified as either Endangered (at risk of extinction throughout all or part of its range) or Threatened (likely to become Endangered in the near future) (USFWS 1973). The ESA also authorizes declarations of Critical Habitat for a listed species. In general, rare species need a network of protected areas to persist (Prendergast *et al*. 1993). To do that, we need to know what areas to protect, and therefore what the habitat requirements of each rare species are.

This study examines the habitat requirements of four target plant species that occur in Big Bend National Park (Big Bend NP), Texas, and are listed as Endangered or Threatened under the ESA: *Coryphantha ramillosa* subspecies (subsp.) *ramillosa* (CORA), *Echinocereus chisoensis* variety (var.) *chisoensis* (ECCH), *Echinomastus mariposensis* (ECMA), and *Festuca ligulata* (FELI). We also summarize the threats facing each species. The first three of these species are cacti. All three of these species of cacti have been poached for the illegal horticulture trade. It is believed that they are stilled being poached, even on federally protected lands (Sirotnak pers. comm.).

The components of this study are (1) a review and synthesis of published and unpublished studies of these species, including threats, conservation priorities, gaps in our knowledge, and research needs, (2) construction of a GIS (geographic information systems) database of available public and private data relevant to these species, and (3) a preliminary analysis of these data to identify the primary habitat characteristics of these species in Big Bend NP. This study has been designed to provide the groundwork for future studies of these species, with the ultimate aim of improving conservation efforts. Potential future applications include the discovery of new plant populations, the restoration and preservation of suitable habitat, the establishment of reintroduced populations, and improved protection and management of all populations and their habitat.

Methods

Study region

Big Bend National Park is in the southeastern corner of Brewster County, Texas, which is part of the Trans-Pecos region of Texas (Map 1). This region is part of the Chihuahuan Desert, which includes most of West Texas and southern New Mexico in the US and the states of Chihuahua and Coahuila (with extensions into Durango, Zacatecas, San Luis Potosí, and Nuevo León) in México (Shreve 1942, Hernández *et al*. 2010). The park borders the Rio Grande (called the Río Bravo in Mexico), which is also the Texas-Mexico border. The park serves as the northernmost range for many Mexican species, including *Ursus americanus* (the Mexican black bear), *Aphelocoma wollweberi* (the Mexican jay), and *Leptonycteris nivalis* (the Mexican long-nosed bat) (Louie 1996). The Chisos Mountains, which are contained entirely within the park, provide habitat for North American high-elevation species such as *Populus tremuloides* (quaking aspen) and *Pseudotsuga menziesii* (Douglas fir) (Von Loh and Cogan 2011).

Precipitation and temperature vary considerably across Big Bend NP. Lower elevations are generally very arid (~25.5 centimeters [~10 inches] of rain per year at 500 meters), whereas higher elevations in the Chisos Mountains get considerably more rainfall (up to 53 cm [~21 inches] of rain per year). Temperatures along the Rio Grande can be more than 38˚C (100˚F), but only reach 30˚C (~85˚F) in the Chisos Mountains (Turner *et al*. 2011). The dry season is usually from November to April, with the driest month being March; the wet season is usually from May through October, with the wettest month being July (PRISM Climate Group 2016).

Big Bend NP is also home to many endemic plants and animals. This large (324,320 ha; 801,163 ac) National Park contains a variety of habitat types, including desert scrublands, desert grasslands, high-elevation woodlands, and riparian areas (Louie 1996; Saghatelyan 2009). High levels of plant diversity in Big Bend NP are largely due to variation in elevation, from ~500 meters (1,800 feet) near the Rio Grande to 2,385 meters (7,824 feet) on Emory Peak, and to the complex variety of geological substrates (Alex 2014). Bedrock in the eastern portion of the Park is mostly limestone, while elsewhere in the Park volcanic rock formations are common (Maxwell 1968, Evans 1998). At lower elevations, plants characteristic of true desert are found, such as *Larrea tridentata* (creosote). At higher elevations, desert genera such as *Agave* spp. grow intermingled with pines, oaks, and other species of more mesic habitats (Roemer *et al*. 2007). Because Big Bend NP and the surrounding area possess unique combinations of soil, geology, precipitation, and vegetation types, many rare species are found only in this region.

Target species

All four target species of this study are rare plants that are federally listed under the Endangered Species Act of 1973 (USFWS 1973), either as Threatened (three cacti species) or Endangered (a grass species). The three cacti (Cactaceae) species are *Coryphantha ramillosa* subsp. *ramillosa* (CORA), *Echinocereus chisoensis* var. *chisoensis* (ECCH), and *Echinomastus mariposensis* (ECMA). The grass (Poaceae) species is *Festuca ligulata* (FELI) (Table 1). All four are endemic to the Chihuahuan Desert and have extant populations in Big Bend NP (Map 2). (ECMA has an additional population outside of the Park on its western side.) All four have been studied and/or monitored by public and private entities in recent decades (Sirotnak pers. Comm.).

Each of these four species occurs in a single semi-contiguous area in Big Bend NP; if there are other areas in the Park in which one of these species occurs, they are not known to me. In this report, each of these areas is called a site: one site per species. Some previous authors (e.g., USFWS 1993) have identified multiple "populations" within the ECCH site. However, the ECCH site is a single elongated area (~ 20 kilometers along its longest dimension) without any significant divisions. Therefore, I analyzed the data as if the ECCH site represents a single population. The ECMA site is also somewhat elongated. FELI and CORA each occur in much more compact areas.

Literature review

This literature review is based on scientific papers, agency documents, selected semi-popular publications, published and unpublished research reports, and herbarium records. For the four target species, I tried to be as comprehensive as possible. I also included some documents that provided information about Big Bend NP, the Endangered Species Act of 1973, West Texas geology, and so on. However, this review does not include newspapers or popular magazines, and does not summarize every policy decision or federal notice pertaining to these species. Webpages, unless they were an electronic version of an otherwise acceptable document, were also not included.

Google Scholar, JSTOR, and Web of Science were searched for documents about the four target species, using key words such as the current and previous scientific and common names of each species. The websites of governmental agencies and non-governmental organizations were also searched, including those of the U.S. Fish and Wildlife Service (USFWS), the U.S. National Park Service (NPS), the U.S. Department of Agriculture (USDA), the U.S. Geological Survey (USGS), the International Union for Conservation of Nature (IUCN), and The Nature Conservancy (TNC). Relevant unpublished documents were provided by Chris Best (USFWS, Austin, Texas) and Joe Sirotnak (Bureau of Land Management, Boise, Idaho).

Books and recovery plans were obtained from the University of Texas Libraries and the Lady Bird Johnson Wildflower Center. Online herbarium records from the University of Texas and Harvard University were examined. A total of 114 sources were consulted. Not all of these sources are cited within this report, as some provided only redundant material.

A great deal of information about these species and their habitat was obtained first-hand from individuals who have been working with these species for decades. These individuals included Dr. Joe Sirotnak, the Big Bend NP botanist for 17 years, Dr. Jackie Poole, a former Texas Parks and Wildlife (TPWD) botanist who conducted many field surveys and monitored these species in the field, Dr. Martin Terry, professor and cactus expert at Sul Ross State University, who taught me to identify these species in the field, Chris Best, a USFWS botanist, and Marie Landis, GIS specialist at Big Bend NP. Information provided by each of these individuals was vital to this project, and is included in the literature review and elsewhere in this report.

Field surveys

Some data for this report were collected by myself and others in Big Bend NP and the surrounding region. I visited Big Bend NP in mid-August 2016 and mid-March 2017 to collect data and to familiarize myself with the landscape, habitats, and morphological characteristics of these species. The August 2016 trip included Dr. Norma Fowler (my graduate advisor), Dr. Terry, Dr. Sirotnak, and three of Dr. Fowler's other graduate students. We visited three sites, one each for three of the four species (CORA, ECCH, and FELI). Some field data (i.e., GPS [global positioning system] coordinates, photographs) were collected. ECMA sites could not be reached due to rain and washed-out roads. CORA and FELI were flowering at that time.

I made a second trip in March 2017, when ECCH and ECMA were flowering. For each of the four species, a single site was visited. Ten individual plants were examined at the CORA, ECCH, and ECMA sites and five at the FELI site. Field data collected included GPS coordinates, number of fruits and flowers per plant, height and width, elevation, photos and videos of plants and surrounding area, notes on associated plant species, and general notes on the morphology, vigor, and visible damage of plants of the target species.

GIS database construction

Plant locations and other spatial data were obtained from Big Bend NP GIS records, including my own field data. Many different individuals had collected these data (species-specific information in later section). Publicly available spatially-referenced environmental data were obtained from USGS (Digital Elevation Model [DEM], which was used to calculate elevation, slope, and aspect; also geological maps), Texas Natural Resources Information System (TNRIS; land cover, percent canopy cover), and the PRISM (Parameter-elevation Regressions on Independent Slopes Model) Climate Database (climate variables). Soil data came from USDA National Resources Conservation Service (NRCS) Web Soil Survey. Maps from federal reports and recovery plans provided additional data on the locations of historical populations.

All spatial data were imported into ESRI ArcMap (10.1.3; Environmental Systems Research Institute, Redlands, CA, USA) and were projected into the same geographic coordinate system (GCS North American Datum [NAD] 1983). Data were organized in the database based on the source they were acquired from. Digital elevation model (DEM) raster images were used to calculate elevation, slope, and aspect via tools in the Spatial Analyst Toolbox. To extract spatial data for each of the plant locations (point data), the GPS coordinates of these points were combined with the environmental datasets (*Toolbox* > *Data Management* > *Spatial Analyst* > *Spatial join* [raster layer] or > *Extract values to points* [polygon layer]). Summary data (average elevation, average maximum temperature, etc.) were calculated to provide habitat information at the landscape scale.

Presence-Absence

To provide habitat information at a local scale, environmental data at the plant scale were analyzed. A better understanding of plant distributions in relation to environmental variables is obtained if environmental data are available from points where the species does not occur (absences), as well as from where it does occur (presences). True absences were only available for ECCH, but to remain consistent across species this absence data was not used. Instead, pseudo-absence data were created in ArcGIS. A 50-m and a 500-m radius buffer were placed around each individual plant in the database (*Toolbox* > *Spatial Analyst* > *Buffer analysis tool*), and then the 50-m buffer was erased from the 500-m buffer (i.e., creating a "doughnut" around each plant), to provide up to 50-m uncertainty in the exact location of each point.

Randomly generated points located throughout the 50-m "doughnut" buffers were the pseudo-absence points (*Toolbox* > *Spatial Analyst* > *Random points*) (Map 3). By design, there were roughly the same number of presence and absence points. Balancing the design increased statistical power. This was done for each species separately, so each pseudo-absence of a given species was within 500 meters of a known presence of the same species. The number of pseudo-absences per species differed depending on the number of known individual locations (presences) at each site (number of pseudo-absences: CORA = 500, ECCH = 1000, ECMA = 1000, FELI = 250). The locations of these pseudo-absences (henceforth simply *absences*) were added to the ArcGIS database. Presence and absence data were exported from ArcGIS to Microsoft Excel (*Toolbox* > *Data Management* > *Table to excel*) and were then consolidated and organized in SAS (Statistical Analysis System) (SAS 9.4, SAS Institute Inc., Cary, NC, USA).

Statistical analysis

Logistic regressions, a type of generalized linear model, were used to analyze the presence-absence data. The response variable y was the presence of a plant ($y = 1$) or the absence of a plant ($y = 0$) at each point. A binomial distribution with a logit link function was assumed. The SAS GLIMMIX (generalized linear mixed models) procedure was used for each analysis. Each predictor variable was analyzed separately, for each species separately. The statistical models for continuous predictor variables took the general form:

$$\text{logit}\,[P(y = 1)_i] = \beta_{\text{intercept}} + \beta_{\text{slope}} * x_i\,,$$

where i indicates the i^{th} point, $P(y = 1)_i$ is the estimated probability of the species being present at point i, x_i is the value of an environmental variable at point i, and $\beta_{\text{intercept}}$ and β_{slope} are fitted values estimated by the GLIMMIX procedure. The statistical models for categorical predictor variables took the general form:

$$\text{logit}\,[P(y = 1)_{ij}] = \beta_{\text{category}\,i}\,,$$

where i indicates the i^{th} category, j indicates the j^{th} point, $P(y = 1)_{ij}$ is the estimated probability of the species being present at point ij, and $\beta_{\text{category}\,i}$ is the fitted value for the i^{th} category estimated by the GLIMMIX procedure. The logit function is

$$\text{logit}\,(p) = \log_e \frac{p}{(1-p)}\,,$$

so, the estimated value of P(y=1) is

$$\hat{p} = \frac{e^{predicted\ logit\ of\ p}}{1+e^{predicted\ logit\ of\ p}}\ .$$

Eight predictor variables were analyzed: elevation (ELEV_M), slope (SLOPE_DEG), aspect (ASPECT_NAME), woodland landcover (LC_WDLD), percent canopy cover (CAN_%), geology (ROCKTYPE1), soil unit (MUSYM), and soil type (S_ORD) (Table 2). Elevation and slope were continuous variables, and the rest were categorical. Elevation data ranged from ~500 meters to >2100 meters, and slope from 0˚ to ~60˚. The statistical analysis of categorical predictor variables compared the categories of that predictor variable with respect to the estimated probability that the species would be present at a point in that category. Aspect was treated as eight equally-spaced categories based on a degree value given by the DEM analysis (i.e., N = all aspects between 0º and 22.5º, NE = all aspects between 22.6º and 45º, and so on). There were 20 categories of landcover, and four categories of canopy cover: 0-15%, 16-30%, 31-45%, and 46-60% cover. Geology and soil type were usually very general (e.g., limestone, Entisols), but soil unit provided very specific information on the soil complex the plants were on (i.e., Mariscal Rock Outcrop, Boquillas Formation). Results were exported from SAS and plotted using SigmaPlot (Systat Software, San Jose, CA, USA). I also attempted to analyze maximum temperature (ºC), minimum temperature (ºC), and average precipitation (centimeters), but available information on these variables was of too coarse a scale to be useful.

Coryphantha ramillosa subsp. *ramillosa*

Literature review

Coryphantha ramillosa subsp. *ramillosa* (synonyms shown in Table 1) (Cactaceae), is referred to here as CORA (it is CORA7 in USDA PLANTS Database; USDA NRCS 2016). Federal protection was catalyzed by overharvesting for personal collections in the late 1970's (Louie 1996). It is believed that poaching continues today in small numbers (Sirotnak pers. comm. 2016). Although it is still considered a rare species, it is believed to be more common than previously thought (TPWD 2002). It was first listed as a Threatened species under the Endangered Species Act on November 6th, 1979 (USFWS 1979) and was listed as Threatened by the state of Texas on April 29th, 1983 (Poole and Riskind 1987; TPWD 2002**).** It is currently listed as Threatened with no proposals to list it as Endangered.

CORA's historical range included Brewster and Terrell Counties in West Texas and states of Chihuahua and Coahuila in Northern Mexico (Weniger 1984; Heil *et al*. 1985). It has been found between Sanderson Canyon, Texas, and Mariscal Canyon, Texas (Anderson 2001), and has a single known population in Big Bend NP (Map 4). It is also present in the Black Gap Wildlife Management Area, but the officials there are not currently managing it or surveying it, and had no available data for us to consider (Sirotnak pers. comm.). This species is also present on nearby private land, which is mostly used for cattle ranching, and where it therefore has little legal protection (USFWS 1989a).

Most sources agree that CORA lives on calcareous slopes of limestone ledges and canyons in the Chihuahuan Desert, not far from the Rio Grande (Loflin and Loflin 2009; Poole *et al*. 2007; Powell 1988; Weniger 1979). It has been reported to grow on Santa Elena and Buda limestones and in crevices of the Boquillas Formation. Across its range, it is known to be found between 400-1100 meters in elevation (Heil *et al*. 1985). It usually grows on top of hills, ridges, or plateaus (Weniger 1979), and may grow near semi-succulents, shrubs, and other cacti, but more often grows alone (i.e., without a nurse plant) (Heil and Brack 1988). CORA is found not far from the Rio Grande and riparian ecosystems; however, it is not found along the river except in narrow canyons (USFWS 1989a). It is commonly considered to be associated with *Agave lechuguilla* (lechuguilla), *Larrea tridentata* (creosote), *Opuntia* species, and *Fouquieria splendens* (ocotillo) (Heil *et al*. 1985; Loflin and Loflin 2009) (Table 3).

CORA has distinct fuchsia to bright-pink flowers that bloom from July through September (Heil *et al*. 1985), but may bloom as early as April if there is sufficient rainfall (Weniger 1984). The plant itself is globose and approximately the size of a tennis ball (~7.5-18 cm in diameter). Each cluster of spines has a long central spine with a dark black, grey, or brown tip approximately 17-38 cm long (Benson 1982). It was assigned to subspecies *ramillosa* when a yellow-flowered subspecies, *Coryphantha ramillosa* subsp. *santarosa*, was discovered in Mexico in 2000 (Dicht and Lüthy 2003). In the field, it can be confused with its cousin, *Coryphantha macromeris* (nipple-beehive cactus). Although the two species are superficially similar, *C. macromeris* is distinguishable because it normally grows in flat, multi-branched mats, whereas CORA is solitary (Powell *et al*. 2008; Terry 2016). (See Bowers *et al*. (2009), Poole *et al*. (2007) and Loflin and Loflin (2009) for further field identification information)**.**

The 1989 U.S. Fish and Wildlife Service Recovery Plan for *C. ramillosa* (before it was subspecies *ramillosa*) called for the protection of at least three populations of CORA distributed across the geographic range of the species (USFWS 1989a). To achieve this range, it suggested that one of these populations should be in Big Bend NP (presumably the single known population), one on private land in southwestern Terrell or northwestern Brewster County, and one in Mexico. Each of the three populations should initially have at least 500 individuals, with space to sustain 10,000 plants (USFWS 1989a). The Plan also recommended action to ensure that the three populations would be protected and managed appropriately. Currently, population sizes outside Big Bend NP are unknown (Sirotnak pers. comm.). Collaborative efforts have been attempted between U.S. and Mexican researchers. However, many sites are difficult to access due to illegal activity in areas where CORA may be located (Sirotnak pers. comm.).

Field observations

Before our survey, the CORA population in Big Bend NP was last surveyed in 2004 and had 256 individuals at that time. These data were collected by scientists at Big Bend NP with help from the Student Conservation Association (SCA) (Sirotnak pers. comm.). Two additional visits were made during the trips described above. In August 2016, no quantitative data were collected; only photographs and site descriptions were recorded. In March 2017, ten individuals not included in the 2004 survey (based on GPS coordinates) were located in the site of the one known population. This site was located on the southeastern side of the park not far from Rooney's Place and Rio Grande Village, at ~590 m above sea level. The site has limestone hills (Photo 1) interspersed with lower, alluvium-filled areas (Photo 2). Some rose quartz rock was found in limestone gravel. *L. tridentata* (creosote) and *Opuntia* species were common on the site, as was *F. splendens* (ocotillo) (Table 3). The invasive *Cenchrus ciliaris* (buffelgrass) was observed in small quantities near this CORA site (Photo 3).

All ten plants were found growing on top of limestone hills (Photo 4), approximately 15 m above the flatter areas below. Most individuals were growing on 30˚-45˚ slopes between slabs of flakey limestone rock (Photo 5). No plants were found growing between the hills on alluvial gravel. In August 2016 was very wet and CORA appeared to be fully hydrated. CORA was blooming at that time (Photo 6). and a few flowers had set fruit. Most individuals only had one flower, but one individual had two flowers. March 2017 was very dry and most CORA individuals appeared desiccated (Photo 7); seven of the ten plants were scored as dry or very dry. Three CORA skeletons were found. The plants were found at an average elevation of 590.5 meters. The average diameter of these CORA plants was 6.51 cm. Plants showed no visible physical damage. CORA was not blooming in March 2017, so no fruits and flowers were recorded (Table 6). The ten CORA plants were each growing separately from other CORA plants, except for one pair. On average, they were separated from plants of other species by approximately 0.5 meters.

Results

The average elevation for all CORA individuals was 595.32 meters, with an average slope of 7.67º. On average, this area receives 25.4 cm of rain per year (~10 inches). The average maximum temperature is 30.56˚C (~87˚F) and the average minimum temperature is 12.22˚C (~54˚F) (Table 4). The limestone bedrock at the site is the Late Cretaceous Boquillas Formation, which contains alternating layers of limestone and shale (Table 5). Of the eight predictor variables analyzed, seven significantly predicted presence and absence of CORA: slope, aspect, landcover, % canopy cover, geology, soil unit, and soil type (Table 7).

Elevation was the only variable that did not significantly predict the presence of CORA ($p = 0.672$) at a local (individual plant) scale (Fig. 1A). CORA was more likely to be found on steeper slopes, up to 50° (Fig. 1B). CORA was found on slopes of all aspects (Fig. 2A), but there was a higher probability of finding CORA on southeastern or southern slopes than on slopes of other aspects (Fig. 2B). CORA was most frequently found on barren land (BARN) (Fig. 2C), and was more likely to be found there than on scrubland (SCRB) (Fig. 2D). It was never found where there was no landcover. Since there is very little canopy cover near the CORA field site, it is not surprising that it was most frequently found with 0-15% canopy cover (Fig. 2E). CORA was also present under 16-30% canopy cover, and if a point had that cover, there was ~50% chance of finding CORA (Fig. 2F).

The most common geological substrate for CORA was limestone (Fig. 3A), even though ~20% of the area was alluvium. CORA was less likely to be found on alluvium than it was on limestone (Fig. 3B). The probability of finding CORA was highest on Blackgap-Rock outcrop complex soils (BLG), which are Lithic Ustic Haplocalcids (BLG) and on Mariscal-Rock outcrop complex soils (MDE), which are Lithic Ustic Torriorthents (Fig. 3D). The most common soil unit for both the entire site and CORA plants was MDE (Fig. 3C). Therefore, Entisols were the most common soil type for the entire site and for CORA occurrences (Fig. 3E, F).

Echinocereus chisoensis* var. *chisoensis

Literature review

Echinocereus chisoensis var. *chisoensis* (synonyms shown in Table 1) (Cactaceae), is referred to here as ECCH (it is ECCH2 in USDA PLANTS Database; USDA NRCS 2016). Federal protection was catalyzed by overharvesting for commercial and private collectors in the 1970s and 80's (Louie 1996; USFWS 1993). Although the current level of poaching is not known (Sirotnak pers. comm.), illegal collecting remains a concern and a present and future threat. ECCH may have experienced a loss in the number of populations throughout its range, as well as reductions in the number of individuals per population (USFWS 1993). Populations are believed to have once existed in grasslands that were overgrazed in the first half of the 1900s, which led to soil erosion and woody plant encroachment (USFWS 1982a). Suitable habitat may exist in Northern Mexico, but ECCH has not been found there (Heil and Anderson 1982a; USFWS 1988; USFWS 1993). The low viability of the existing population (i.e., low recruitment of new plants) and low regeneration rates (i.e., slow formation of new populations) are also threatening survival (USFWS 1993). Additionally, because the Big Bend NP ECCH site is close to Route 180, a main road in the park, development, maintenance, and recreational activities could now be a threat to it.

ECCH was first federally listed as Threatened under the Endangered Species Act on September 30th, 1988 (USFWS 1988). No critical habitat was set aside for ECCH at that time. It was listed as Threatened in the state of Texas on December 30th, 1988 (Poole *et al*. 2007, TPWD 2002). It is currently listed as Threatened with no proposals to list it as Endangered. The only known ECCH site occurs within Big Bend NP (Map 5) (Sirotnak pers. comm.). ECCH grows on bajadas and other alluvial deposits (USFWS 1982b), below the Sierra del Carmen and the Chisos

Mountains, between 600 and 800 meters in elevation (Norland 1987, USFWS 1988; USFWS 1993; Poole *et al*. 2007; Loflin and Loflin 2009). Sites typically have desert pavement (Louie 1996; Sirotnak pers. comm.). ECCH is not found close to drainages, but sites may receive significant water in the rainy season from surface water flow (Sirotnak pers. comm.). They may grow near semi-succulents, shrubs, and other cacti (Evans 1986). ECCH is the only one of the four target species that is found under putative nurse plants, which are usually *L. tridentata* (creosote), *Cylindropuntia schottii* (dog cholla), *Vachellia constricta* (whitethorn acacia), or *Agave lechuguilla* (lechuguilla) (Heil and Anderson 1982b; Amos and Vassiliou 2001) (Table 9). They are often found in the centers of large mats of this vegetation, making them difficult to locate (Sirotnak pers. comm.).

ECCH plants have large, bright-pink to light-magenta flowers with dark-red centers and fine, bristle-like spines on the floral tube. Plants bloom between mid-March and mid-April (Poole *et al*. 2007), but some sources say they can bloom as late as June (Alex and Norland 1987; USFWS 1993). ECCH plants are mostly easily located when in bloom (Sirotnak pers. comm.). ECCH is a relatively large cactus, normally multi-stemmed and ribbed, with wooly white areoles. Its stems are dark green and up to 30 cm (1 foot) tall. Two varieties exist: var. *chisoensis* and var. *fobeanus* (N.P. Taylor); the latter is endemic to Coahuila, Mexico (Powell and Weedin 2004). ECCH may be easily confused with *Echinocereus dasyacanthus* (the Texas rainbow cactus) or *Echinocereus viridiflorus* (the small-flowered hedgehog cactus) (Alex and Norland 1987). However, when flowering, it is easy to distinguish between these species and ECCH, since both *E. dasyacanthus* and *E. viridiflorus* have yellow flowers. Good field identification guides for EECH are Bowers *et al*. (2009), Poole *et al*. (2007) and Loflin and Loflin (2009).

The 1993 U.S. Fish and Wildlife Service Recovery Plan for *E. chisoensis* called for the establishment of additional populations, in addition to protecting existing populations. The criterion for delisting was at least 50 populations of ECCH, each with at least 100 reproductive individuals. These populations were to be demographically stable over a 10-year monitoring period (USFWS 1993). However, no significant steps towards this goal have been taken. Poaching is a continuing threat, and invasive species, especially *Cenchrus ciliaris* (buffelgrass), and climate change are new threats. Not only does *C. ciliaris* threaten to outcompete ECCH and their nurse plants, it may increase the likelihood of wildfire (McDonald and McPherson 2011).

Field observations

The ECCH population in Big Bend NP was last surveyed in 2010; 1490 individual plants were found. These data were collected by scientists at Big Bend NP with help from the SCA (Sirotnak pers. comm.). I made visits to a portion of the Big Bend NP site. In August 2016, no quantitative data was collected. During our March 2017 trip, ten individuals were found at the site on the eastern side of the park along Route 180, between Panther Junction and the Rio Grande Village. Using GPS data, it was determined that these individuals were not recorded during the previous survey. *F. splendens* (ocotillo), *L. tridentata* (creosote), and *A. lechuguilla* (lechuguilla), among other species, were common in the area (Table 3) (Photo 8). Unfortunately, the invasive *C. ciliaris* (buffelgrass) was also observed in moderate quantities near this site (Photo 9).

The ten plants we found were growing on desert pavement with igneous rock fragments. Although most of the site was flat, it had gullies (dry drainages) between the flat areas. All ten EECH plants were growing on completely flat surfaces. ECCH was relatively easy to identify, and the only similar looking species in the area was *Echinocereus dasyacanthus* (rainbow cactus). We observed that *L. tridentata* (creosote) and *Opuntia* species were apparently serving as nurse plants (Photo 10). A few large individuals did not have nurse plants. Almost all of the ECCH plants were surrounded by *C. schottii* (dog cholla) (Photo 11).

In August 2016, dark green, healthy looking plants were fully hydrated (Photo 12). Only a few dead individuals were observed. In March 2017, six dead plants were found in the area, and three individuals were damaged. Rabbits or mice likely damaged the plants and drought may have caused the death of others. Of the living specimens, most appeared to be healthy (7 of 10) (Photo 13). The plants were found at an average elevation of 622.34 meters. Average plant height was 15.55 cm. In March 2017, ECCH was blooming (Photo 14). All ten individuals examined either had flowers or had flowering buds, with an average of 8 flowers per plant. The large magenta flowers were not fully open for most plants. No mature fruits were observed (Table 8).

Results

The average elevation for all ECCH individuals was 648.57 meters (~2128 feet), with an average slope of 1.66º. On average, this area receives 26.64 cm of rain per year (~10.5 inches). The average maximum temperature is 30.16˚C (~86˚F), and the average minimum temperature is 12.28˚C (~54˚F) (Table 4). Bedrock is the Aguja Formation, a late Cretaceous sandstone interbedded with clay (Table 5).

Of the eight predictor variables analyzed, six significantly predicted the presence of ECCH at a local (individual plant) scale. These were slope, aspect, % canopy cover, geology, soil unit, and soil type (Table 9). Elevation and landcover did not significantly predict the presence of ECCH (p = 0.0959 and p = 0.9994, respectively) (Fig. 4A, 5D). There was no variation in landcover category in the data: all points were in scrubland (SCRB). The greater the slope, the less likely ECCH was to be present (Fig. 4B). In general, ECCH was present on slopes of all aspects (Figs. 5A and 5B). ECCH was more likely to be present if a point had 0-15% canopy cover than 15-30% cover (Fig. 5F). Canopy cover, in this instance, refers to tall woodland cover, and does not imply that there was 0-15% cover by nurse plants.

Points on alluvial fans and clay were slightly more likely to have ECCH than points on gravel (Figs. 6A and 6B). The probability of finding ECCH was highest on Corazones soil (COC), an Ustic Haplocalcid, and Chillon soil (CNB), an Ustic Haplocambid (Fig. 6D and 6E). Both are gravelly loams. The most common unit for both the entire site and ECCH was COC (Fig. 6C). Therefore, Aridisols were the most common soil type for the entire site and for ECCH occurrences (Fig. 6E, F).

Echinomastus mariposensis

Literature review

Echinomastus mariposensis (synonyms shown in Table 1) (Cactaceae), is referred to here as ECMA (it is ECMA2 in USDA PLANTS Database; USDA NRCS 2016). Federal protection was prompted by overharvesting for commercial and private collectors in the 1970s and 1980's (Weniger 1970; USFWS 1989b; Louie 1996). It is believed that poaching continues today in small numbers, but since the Big Bend NP ECMA site is hard to reach, very little poaching has occurred at that site (Sirotnak pers. comm.). ECMA was severely affected by quicksilver mining that occurred in its range in the early 20th century (USFWS 1989b). Oil and gas drilling north of Big Bend NP poses a threat to populations in northern Brewster County (Louie 1996). Other threats include being grazed and trampled by livestock and habitat disturbance by off-road vehicles (USFWS 1979; USFWS 1986).

ECMA was first federally listed as Threatened under the Endangered Species Act on November 6th, 1979 **(**USFWS 1979). No critical habitat was set aside for ECMA at that time. It was listed as Threatened in the state of Texas on April 29th, 1983 (Poole *et al.* 2007, TPWD 2002). It is currently listed as Threatened with no proposals to list it as Endangered. ECMA was listed under the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) in 1983, and therefore must not be imported or exported without permits. It is also protected under the Lacey Act (1981), which prevents ECMA from being sold and transported between states (USFWS 1989b). This may have helped deter unwanted foreign and domestic trading of the species, but further investigation into current poaching and selling of ECMA is needed to determine the impacts of these laws.

ECMA's known range extends from Presidio and Brewster Counties, Texas, to Coahuila, Mexico. Sites in Texas are on the eastern side of Big Bend NP at the foothills of the Sierra del Carmen Mountains, the Terlingua-Lajitas area between Big Bend NP and Big Bend Ranch State Park on land owned by the Lajitas Foundation, and a private ranch north of Black Gap WMA (Anderson and Schmalzel 1997; McKinney 1998). In Coahuila State, Mexico, the species has been found as far south as Cuatro Cienegas Basin and as far east as Cima de la Muralla (375 km southeast of Big Bend NP) (Anderson and Schmalzel 1997). Currently, the only population that is being managed is within Big Bend NP (Map 6).

ECMA grow on lower mesas, ridges, and foothills in dry, gravelly limestone soils in the Chihuahuan Desert (Glass and Foster 1975; USFWS 1989b; NPS 2004; Poole *et al*. 2007; Loflin and Loflin 2009). The range of this species is larger than the range of the other three target species (USFWS 1989b). The Big Bend NP ECMA site is in desert scrubland in the foothills of the Sierra del Carmen Mountains, between 750 and 1,000 meters in elevation (USFWS 1986). The land is gently sloped and is extremely arid. The habitat is very open, except for a few shrubs, cacti, and semi-succulent species (Anderson and Schmalzel 1997). Plants normally occur in full sun, and so do not have nurse plants (Heil *et al*. 1985). Commonly associated species include *Larrea tridentata* (creosote), *Cylindropuntia schottii* (dog cholla), *Agave lechuguilla* (lechuguilla), *Fouquieria splendens* (ocotillo), and *Euphorbia antisyphilitica* (candelilla) (USFWS 1989b) (Table 3).

ECMA is a relatively small cactus, approximately the size of a golf ball. It is ovoid-cylindroid, approximately 10 cm tall (~4 inches) and 4-6 cm in diameter (1.6-2.4 inches). It is covered in overlapping white spines that conceal its blue-green stem (Heil *et al*. 1985). ECMA is an early blooming species in Big Bend NP; it blooms from late February through March (Poole *et al*. 2007). It has small, white, yellow, or light-pink flowers with yellow centers that are ~3 cm (1.2 in) in diameter (USFWS 1986). Flowers open during the warmest part of the day (mid-afternoon) (USFWS 1989b). It may be easily confused with *Mammillaria herrerae* (the golf ball cactus) (USFWS 1979). It can be distinguished from *M. herrerae* because ECMA does not grow in large mats of multiple cacti as *M. herrerae* does, and ECMA is often isolated from other individuals of the same species (Weniger 1984). Good field identification guides are Bowers *et al*. (2009), Poole *et al*. (2007), and Loflin and Loflin (2009)**.**

The 1989 U.S. Fish and Wildlife Service Recovery Plan for *Neolloydia* (now *Echinomastus*) *mariposensis* called for the protection of at least three new populations of ECMA distributed across the geographic range of the species. One site should be established on private land in northeastern Brewster County, TX, the second should be in Big Bend NP, and the third should be in Mexico. Each of these populations should have at least 1,000 individuals, with enough habitat to increase in size. To delist the species, a total of 20,000 individuals must exist in total (USFWS 1989b). However, no new populations have been established.

Field observations

The ECMA site in Big Bend NP was last surveyed in 2005, when 1,084 individual plants were found. These data were collected by scientists at Big Bend NP with help from the SCA (Sirotnak pers. comm.). I made one visit to a portion of the Big Bend NP site. In August 2016, the site could not be accessed and no quantitative data was collected. During the March 2017 trip, ten individuals were found at the site on the eastern side of the park along Old Ore Road between Ernst Tinaja in the south and Dagger Flat Road in the north. Using GPS data, it was determined that these individuals were not recorded during the previous survey. The site itself is in a remote part of the park, roughly an hour away from Route 180. The site has flakey limestone ledges and small hills (~860 meters tall) at the base of the Sierra del Carmen Mountains (Photo 15). Plants common on the site were *Leucophyllum candidum* (Big Bend silverleaf), *L. tridentata* (creosote), *Dasylirion leiophyllum* (green sotol), *Jatropha dioica* (leatherstem), and *Euphorbia antisyphilitica* (candelilla) (Table 3).

Most of the ten ECMA plants were found on flat surfaces on the tops of small hills or ledges (Photo 16). A few individuals were found on limestone slopes of ~30˚ slope above towards dry drainages. Many of the plants were smaller than a golf ball (~2 cm in diameter) (Photo 17). Similar species in the area were *Coryphantha echinus* (sea urchin cactus) and *Epithelantha bokei* (pingpong ball cactus).

Since we were unable to access the site in August 2016, we cannot compare the site between seasons. The conditions in March 2017 were very dry, but the ECMA plants looked healthy (8 of 10) and no dead individuals were found. No visible damage was seen on the observed plants. The plants were found at an average elevation of 784.37 meters. Average plant diameter was 4.86 cm. In March 2017, ECMA was blooming (Photo 18). Four of the ten plants were flowering, with an average of 1.25 flowers per plant (Photo 19). Many small flies and beetles were in or around the light-yellow flowers. There were 28 fruits among all ten plants, with an average of four fruits per plant (Table 10) (Photo 20).

Results

The average elevation for all ECMA individuals in the database was 863.73 meters (~2,835 feet), with an average slope of 5.56º. On average, this site receives 30.02 cm of rain per year (~12 inches). The average maximum temperature is 28.32˚C (~83˚F), and the average minimum temperature is 11.82˚C (~53˚F) (Table 4). Bedrock is the Boquillas Formation, a late Cretaceous limestone. The soil is part of the Mariscal-rock outcrop complex (MDE) (Table 5).

Of the eight predictor variables analyzed at a local (individual plant) scale, seven significantly predicted the presence of ECCH. These were elevation, slope, aspect, % canopy cover, geology, soil unit, and soil type. Only landcover did not significantly predict the presence of ECMA (p = 0.9766) (Table 11). Elevation was found to significantly predict ECMA presence at a local (individual plant) scale: it was more likely to be present if a point was at a lower elevation (Fig. 7A). The greater the slope, the less likely ECMA was to be present (Fig. 7B). In general, ECMA was found on slopes of all aspects (Fig. 8A), but had a slightly higher probability of being present at points on east- or southeast-facing slopes (Figs. 8B). There was no variation in landcover category in the data: almost all presences all absence points were in scrubland (SCRB) (Fig. 8C, 8D). ECMA was more likely to be present if a point had 0-15% canopy cover (Fig. 8F).

Points on shale limestone were more likely to have ECMA than were points on gravel (Figs. 9A and 9B). The probability of finding ECMA was highest on Mariscal-Rock outcrop complex, 5-30% slopes (MDE), and Geefour silty clay, 10-45% slopes (GEF) (Fig. 9C, 9D). Both are Lithic Ustic Torriorthents. Entisol soils were the most common soil type for the entire site and for ECMA occurrences (Fig. 9E, 9F).

Festuca ligulata

Literature review

Festuca ligulata (synonyms shown in Table 1) (Poaceae), is referred to here as FELI (it is also FELI in USDA PLANTS Database; USDA NRCS 2016). FELI is a perennial bunchgrass. It is naturally scarce and has small population sizes, which may limit its genetic diversity (USFWS 2014). It is believed to be a relic of the last ice age, when the climate was cooler (Siber 2017). As temperatures increased, FELI may have died in warmer areas, leaving remnant populations in the mountains (Sirotnak pers. comm.). FELI's historical range includes Brewster and Culberson counties in West Texas and Coahuila State in northern Mexico (Swallen 1932; USFWS 2014). It was first discovered in the Guadalupe Mountains of Texas in 1931 by Moore and Steyermark and was found in the Chisos Mountains by C.H. Mueller the same year (Louie 1996). Swallen described the species a year later (Swallen 1932).

Between 1980 and 1996, FELI was listed as a candidate species (Proposed Endangered) under the ESA at various priority/category levels (USFWS 2016a). It was recently listed as Endangered and critical habitat was designated (USFWS 2017). A total of 7,815 acres (3,163 hectares) in the Chisos Mountains in Big Bend has been designated as critical habitat, although its current range in the Park is less than 12 acres (USFWS 2016a) (Map 7).

As of December 2014, only two extant populations were known (USFWS 2014). It is in Boot Canyon in the Chisos Mountains of Big Bend NP. Six small census plots of FELI were established by Jackie Poole in 1993, and have been monitored annually since then (Louie 1996; Sirotnak pers. comm.; Poole 2017). In September 2013, it was estimated that there were fewer than 200 individuals in this population (USFWS 2014). Historically, there was also a population in McKittrick Canyon in Guadalupe Mountains (NP), Texas. Although extensive searches have been conducted, this population has not been re-located since 1952. It is assumed to be extirpated (USFWS 2014), and the species is considered to no longer exist in that park (NPS 2012). The Guadalupe Mountains NP site is assumed to be unable to support FELI due to the abundance of invasive grasses. This area was not listed as critical habitat for this reason (USFWS 2016a). No known populations exist on private land in the U.S. (USFWS 2014).

The other known location of FELI is in the privately-owned Area de Protección de Flora y Fauna in Madera del Carmen in northern Coahuila, Mexico. Botanists confirmed one population of FELI in this park in 2009, but could not find FELI at the original site, named Sierra El Jardin, where it had been first discovered in 1973 (USFWS 2014). Two other known populations in Mexico (Sierra de la Madera in central Coahuila and Fraile in southern Coahuila) have not been monitored since 1977 and 1941, respectively (Poole 1989). It is believed that these populations are extirpated (USFWS 2016a). Northern Mexico does possess a large amount of potential habitat for FELI. Due to security issues in this area, it has never been extensively surveyed. However, there are few Mexican collaborators who are actively monitoring these species at APFF (Sirotnak pers. comm.).

All historic and extant populations of FELI have been found above 1,800 meters (5,905 feet) in elevation (NPS 2004; USFWS 2016a). We do not know the actual elevation tolerance of this species (USFWS 2016a). The known populations occur on the gentle slopes of canyons, ravines, and north-facing slopes in the mountains, not on mountain tops (USFWS 2016b). FELI grows in mesic soils on rocky talus slopes (Swallen 1932; Poole 1989; USFWS 2016a). The geology is complex, but is mostly volcanic rock; soils are gravelly and sandy loams (Poole 1989). FELI grows where conditions are relatively cool and moist, in the understory of pine-oak-juniper woodlands (NPS 2004). It may grow near plants such as *Agave americana* (agave), but more often grows alone. Poole (1989) stated that it evidently needs canopy cover to survive, but also gaps in the canopy for light to come through. Rainfall is important for the survival and reproduction of FELI, as flowering is positively correlated with rainfall (USFWS2016a).

FELI may be easy overlooked in the field. There are a few other grass species that resemble it, such as *Festuca thurberi* (Thurber's fescue). However, it can be distinguished from similar grasses by its long ligule, which is ~3-3.5 mm long (~0.12-0.14 inches) (Swallen 1932). FELI flowers between late August and September (Poole 1989; Louie 1996). The blades are 6-20 cm long (~2.4-7.9 inches), and the inflorescence can be 45-65 cm long (~17-25 inches) (Poole *et al*. 2007). It is believed that *Odocoileus virginianus carminis* (Carmen white-tailed deer), the most common ungulate in the Chisos, serves as the seed disperser of FELI (USFWS 2015). Commonly associated species are listed in Table 3.

FELI is believed to be adapted to low-intensity fires (Sirotnak pers. comm.). Aggressive fire suppression in the area has led to decades' worth of understory fuel build-up, which has left the Big Bend NP site at risk of wildfire. It is unknown what effects such a wildfire would have on the FELI population. FELI's reproduction and survival rates are highly correlated with rainfall amount and duration (USFWS 2016a), and any changes in rainfall patterns could affect the Big Bend NP FELI population. The hot, dry period between October 2010 and November 2011 was quite damaging for the FELI population in Big Bend NP (USFWS 2014).

Another threat to FELI is trampling by horses and hikers, as most known specimens are very close to the Pinnacles, Boot Canyon, and Colima Trails. Other threats are possible changes in livestock grazing in Mexico, soil erosion, invasive species, fungal infection of seeds, and perhaps limited genetic diversity due to its small, isolated populations (USFWS 2010). Since FELI pollen is wind dispersed, individuals are liking to be pollinated by individuals close in proximity, and therefore most likely closely related. It is likely that they are highly inbred, which may affect their overall fitness (Sirotnak pers. comm.).

Field observations

The FELI population in Big Bend NP was last surveyed in the summer of 2017. However, the data included in this study used census data from 2016. 104 individuals were found (Sirotnak pers. comm.). These data were collected by scientists from Big Bend NP, TPWD, and the USFWS Austin office. I made visits to the Big Bend NP site. In August 2016, no quantitative data was collected. In March 2017, five individuals were found in Boot Canyon. Using GPS data, it was determined that these individuals were not recorded during the previous surveys. I observed that the ground was covered in a thick layer of litter, mostly oak leaves and juniper needles (Photo 21). The associated canopy species were primarily *Quercus grisea* (grey oak), *Pinus cembroides* (Mexican pinyon), and *Juniperus flaccida* (Mexican pinyon) (Table 3). The understory included rhyolite boulders, agave (*Agave americana*), dead tree limbs, and other grasses.

In August 2016, this area was the wettest it had been in almost 17 years (Photo 22) with nearly 5.2 centimeters (2.06 inches) of rainfall falling during our trip (PRISM 2016; Sirotnak pers. comm.), and nearby streams and waterfalls that are normally dry were running strongly. It was also extremely cold, with a high of only 20˚C (68˚F). Plants were very green and easily identified by their inflorescences (Photo 23, 24). March 2017, on the other hand, was extremely hot and dry, with a high of 32˚C (89˚F) and no precipitation (PRISM 2016), and Boot Canyon and Boot Spring were devoid of water. Since FELI is only easily identifiable if there are reproductive inflorescences, it was very difficult to identify in spring 2017. The only other distinguishable feature is its long ligule, which was used to identify the species in March. After many unsuccessful attempts at identifying the species, and finding many similar looking grasses, FELI was located on the talus slopes of Boot Canyon.

Most of the five FELI plants were found on 20-45˚ slope on the slopes of the canyon (Photo 25). A few individuals were found on flat surfaces near the trail (Photo 26). FELI had long, slender blades, approximately 2 mm thick, which folded longitudinally. The ligule was thin, white, papery, and ~6 mm long (Photo 27). Most individuals were ~60% green and ~40% dead material (3 of 5 were rated as healthy), and some plants had red tissue around the blade tips. They grew as single plants ~5 cm in diameter. The plants were found at an average elevation of 2,094.98 meters. Average plant height was 33.33 cm. In August 2016, FELI had inflorescences, which were ~0.75 m tall. No inflorescences or seeds were observed in March 2017. No visible damage was observed on the plants themselves, and no dead individuals were found (Table 12).

Results

The average elevation for all FELI individuals was 2,113.11 meters (~6,930 feet), with an average slope of 12.06º. On average, this area receives 55.75 cm of rain per year (~22 inches). The average maximum temperature is 18.54˚C (~65˚F) and the average minimum temperature is 7.19˚C (~45˚F) (Table 4).

At a local (individual plant) scale, only five of the eight predictor variables could be analyzed. Geology, soil unit, and soil type did not vary among points. Of the five predictor variables that were analyzed, four significantly predicted the presence of FELI: elevation, slope, aspect, and % canopy cover. Landcover was the only analyzed variable that did not predict the presence of FELI (p = 0.9749) (Table 13). FELI was significantly more likely to be present at points at lower elevations (Fig. 10A). FELI was significantly more likely to be present on less steep slopes (Fig. 10B). FELI was only found on eastern or northeastern slopes (Fig. 11B). This is because the only landcover it was found in was evergreen forest (EGFO) (Fig. 11C). FELI was more likely to be present if a point had 16-30% canopy cover, although it was also found under both 31-45% and 46-60% canopy cover (Fig. 11F).

The entire site, including absence points, was on Pine Canyon Rhyolite, which contains lava, volcanic breccia (agglomerate), and vitrophyre. It is part of the South Rim Formation, formed in the Early Oligocene. The soil unit was Puerta-Madrone-Lazarus complex, 20 to 45 percent slopes (PUF), an Alfic Lithic Argiustoll. They are clayey-skeletal, mesic, and smectitic soils that are well-drained with very high runoff (Table 5).

Discussion

In this study, we gathered relevant biological and ecological information on four rare species of plants, with the primary goal of informing future research and management decisions. The values of environmental variables (average and range for quantitative variables; also the identity of the soil, bedrock, etc.) where plants are found helped define the habitat of each species at a landscape scale (Tables 4 and 5). For example, FELI is known only from high, cool elevations in the Chisos Mountains, while the three cacti species are known only from lowland desert sites. At this scale, co-occurring plants did not define species habitat. For example, *Agave lechuguilla* (lechuguilla), *Cylindropuntia schottii* (dog cholla), *Larrea tridentata* (creosote), and *Fouquieria splendens* (ocotillo) were common in most lowland desert sites in Big Bend NP. Similarly, *Pinus cembroides* (Mexican pinyon), *Pseudotsuga menziesii* (Douglas fir), and *Quercus gravesii* (Chisos red oak) were common in the Chisos Mountains, not just in the FELI site.

At a local scale, environmental variable values were used to predict the presence of a given species from points where plants have been found and buffers around them where no plants have been found. Each species had different statistically significant environmental variables. Slope, aspect, % canopy cover, geology, soil unit, and soil type were significant predictors for one or more species. Elevation and landcover were mostly non-significant, probably because each site had little variation in either.

CORA, and perhaps ECMA, are geological specialists on Boquillas limestone. CORA was found on steeper than average slopes for its site, while the other species were found at points that were on average less steep than average for their sites. ECCH, in particular, grew in very flat areas. Aspect appeared most important for FELI, but this may be an artefact of the location of its single population. Alone among these species, only ECCH had apparent nurse plants, or at least was usually found in the midst of other plants, especially *Cylindropuntia schottii* (dog cholla).

Because GIS data from electronic data-bases provided the values of the environmental variables, the statistical analyses were limited in their ability to detect the effects of these variables at the scale of individual plants. For example, analyzing the slope and aspect of CORA cannot tell us the slope angle and orientation experienced by the individual plant. The analysis assigned it the slope of the raster cell calculated from the digital elevation model (DEM), not, for example, the slope of a particular limestone crevice in the rock on top of the hill. It may be that collecting environmental data for each plant individually will be necessary to identify all the factors that define suitable habitat for a species.

Threats

Many threats continue to confront the four target species. A threat that all three cactus species are still facing is poaching, that is, illegal collection, generally by digging up plants (Sirotnak pers. comm.). The illegal cactus trade is still in full force, and affects 47% of all rare cacti globally (Goettsch *et al*. 2015). Enforcement against poachers is difficult, due to the vastness of the Big Bend and Chihuahuan Desert region. Documenting signs of poaching during regularly monitored intervals can help provide more accurate estimates of the frequency and severity of poaching. Cooperation with U.S. Border Patrol Agents, TPWD Game Wardens, NPS Park Rangers, and state and local police is essential. They may need better training on how to identify and recognize these species in the field. New methods and approaches to reduce poaching may be needed. Developing a better understanding of the illegal trade in these species may be useful in this context, perhaps through social media.

Additionally, CORA is currently at risk from the potential border wall construction along the U.S.-Mexico border wall. Some sections of the wall have already been constructed along the U.S.-Mexico border, and there are currently proposals to begin construction along many segments of the Texas border. Even if construction of the wall bypasses Big Bend NP itself, swaths of potential habitat outside the Park along the Rio Grande may be degraded or destroyed due to construction. The increased number of roads built in the area will also threaten habitat for ECCH and ECMA further away from the Rio Grande.

Woody plant encroachment is a possible threat to ECMA. Historical records show that ECMA once grew in more open sites (Anderson and Schmalzel 1997), but today many woody plants, such as *Larrea tridentata* (creosote) and *Salvia dorrii* (desert sage), are growing near ECMA. Future management practices should be address these issues. Another issue facing these species is invasive species. *Marrubium vulgare* (horehound) and *Bothriochloa ischaemum* (King Ranch bluestem) threaten to outcompete and overcrowd FELI. *Cenchrus ciliare* (buffelgrass) found near CORA and ECCH may eventually out-compete the cacti or their nurse plants.

Cenchrus ciliaris is also known to greatly increase the likelihood of fire in desert ecosystems (Brooks *et al*. 2004). Cacti, unlike grasses, are not well-adapted to fire (McDonald and McPherson 2011). Increases in temperatures, and changes in the amount and variability of precipitation, are predicted for West Texas and Chihuahuan Desert (Clark *et al*. 2009). Climate change will most likely create hotter, drier conditions which may increase the frequency and intensity of wildfires. Higher fuel loads created by invasive grasses may increase fire intensity. There may be deleterious effects of wildfire on FELI in the future (USFWS 2016a). Episodic ground fires (roughly every 50 years) were once common in the pinyon-oak-juniper woodlands of Boot Canyon (Moir 1982). To the best of our knowledge, the last known fire in Boot Canyon was 1944 (Moir 1982) and prescribed fire is not currently being used in this area. There is no information available on the effects of fire, intense or otherwise, on this species. The NPS should considered prescribed burns as a management strategy for this area, perhaps using low-intensity fires until the impacts of fire on this species are clearer (USFWS 2016a). Mechanical fuel load reduction might be necessary before the first prescribed fire to reduce fire intensity.

Finally, as mentioned above, climate change may pose the largest threat of all. In general, rare species are more susceptible to the effects of climate change than are species with healthy, stable populations (Thomas *et al*. 2004). Currently, it is unclear how climate change will affect these species. High-altitude species such as FELI are believed to be at disproportional risk for habitat loss (Dirnbock *et al*. 2010) because upslope migration may be limited by available area. FELI is the only species with designated critical habitat – 7,815 acres (3,163 ha) (USFWS 2017). As the climate changes, this large area of protected land may allow further migration upward (USFWS 2016a).

Monitoring and surveying

Monitoring, an essential step in the recovery of these species, has rarely happened for these species in the past decade. All three cacti species have not been monitored in over seven years, and it is unclear whether the initial individuals examined were ever visited again. In preparation for listing FELI, it has been recently monitored more often. In general, Threatened and Endangered species should be monitored frequently, and preferably at least once a year. Regular monitoring of these species is essential to understand the population dynamics of these species.

We also need to conduct periodic surveys of known or potential habitat, and continue surveying extirpated population sites, such as the FELI site in the Davis Mountains. Surveying these places may result in the discovery of a new population, and they may be prime sites for reintroduction if properly managed. We may be able to employ and engage citizen scientists or amateur botanists to conduct surveys of these species when official botanists cannot. This will help us to begin to establish more sites, in accordance with all recovery plans. No plants besides FELI have protected populations outside the park. Maderas del Carmen is a protected area in Mexico, so at least the known population that still exists there is on protected land. We need to include Black Gap Wildlife Management Area and Big Bend Ranch State Park in the conversations about surveying and reintroduction.

Additional research

Further research on these species is critical to their success. Unfortunately, little outside funded research of these species has been done. Research needs include: (a) the collection of population-level demographic data, combined with population models to determine the current growth rate and long-term stability of each population; (b) surveys of potential habitat to locate additional populations; (c) better estimates of the global abundance of each species; (d) better understanding of habitat requirements and propagation methods to support the establishment of new populations; and (f) research to determine probable effects of climate change on each species. Because populations of these species are small and isolated, they may suffer from loss of genetic diversity. Population genetic studies could provide information to guide captive breeding and construction of new populations. It would also be prudent to bank the seeds of each species.

Collaboration

Cooperative partnerships between government agencies, private conservation organizations, and landowners will be crucial in the coming decades if we hope to conserve these species. In addition to cooperating with law enforcement agents, mentioned above, cooperation with the Mexican government, Mexican conservation organizations, and Mexican conservation biologists would be very valuable. Cooperation with private land owners in the US, in Brewster, Presidio, Terrell, and Culberson Counties, would help preserve this species where they occur on private land in the US. Finally, developing greater public support for the conservation and preservation of these species - and other native plant species and communities - would be of great value. Directly engaging with the public, for example by holding workshops and outreach events, would help raise public awareness of their needs.

Conclusion

At last estimate, between 18,000 and 55,000 species become extinct per year (UNEP 2007). It is now believed that 30 to 50% of all species could be headed towards extinction by the mid-21st century (Thomas *et al*. 2004). Sadly, over 31% of all cactus species are threatened with extinction (IUCN 2015). Understanding biodiversity and preventing biodiversity loss have become major foci among scientists in an effort to save as many species as possible. Unfortunately, time and resources are limiting factors. I hope that this study will be of use in this endeavor. In particular, I hope it will be of use in the search for additional populations and in planning for establishing new populations.

Data access

The raw data with spatial coordinates, the final GIS database, and other supplemental materials are available to researchers and others with verified, valid needs for it from Big Bend NP. You may also contact Dr. Norma Fowler, University of Texas at Austin, to request a copy. These data are not provided in this report because of the ongoing problem of poaching

Appendix A: Figures

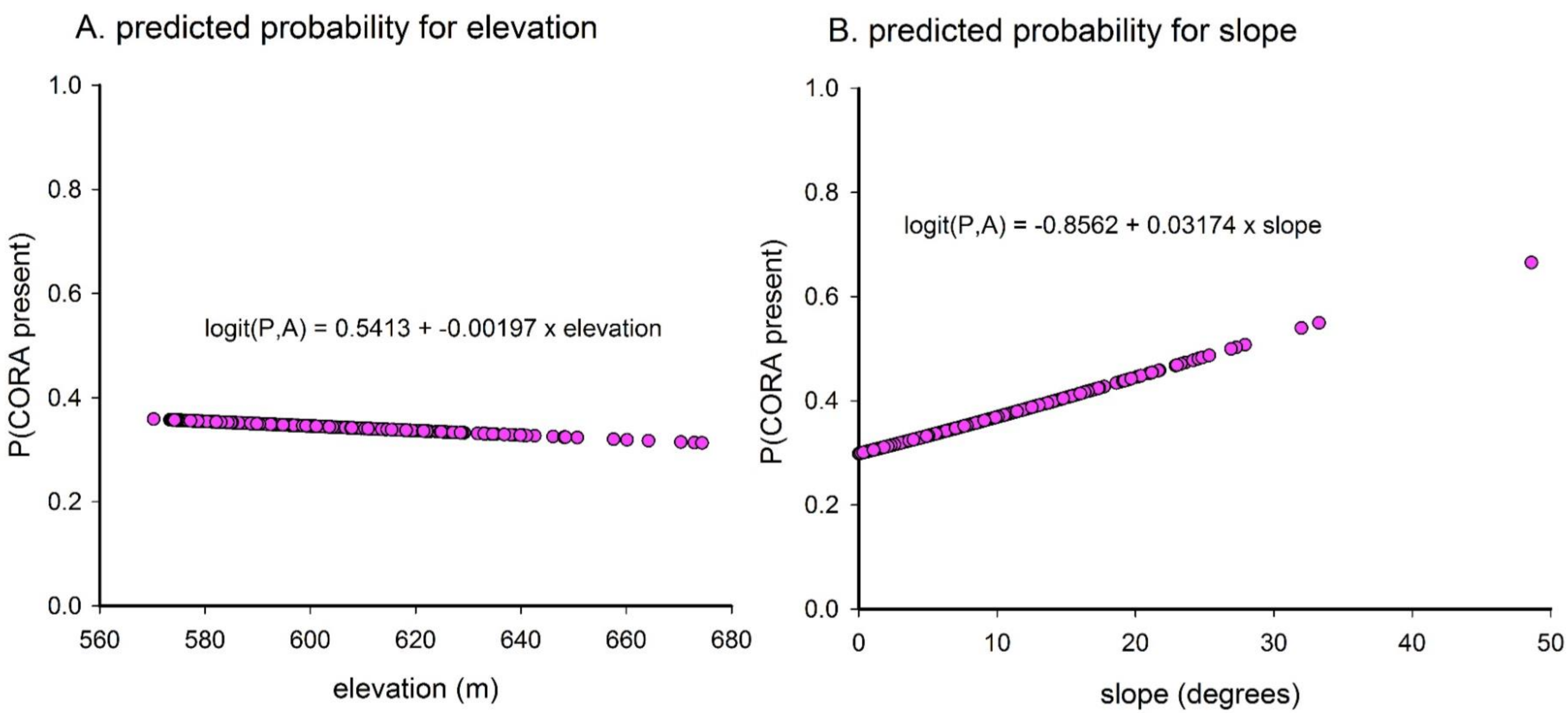


Figure 1. Results of analyses of *Coryphantha ramillosa* subsp. *ramillosa* presence-absence data. (A) Elevation did not have a significant effect on the probability of CORA presence at a point (p = 0.672); (B) Points on steeper slopes were more likely to have a CORA plant present (p = 0.0137). Each point represents one plant location or one pseudo-absence in the data set.

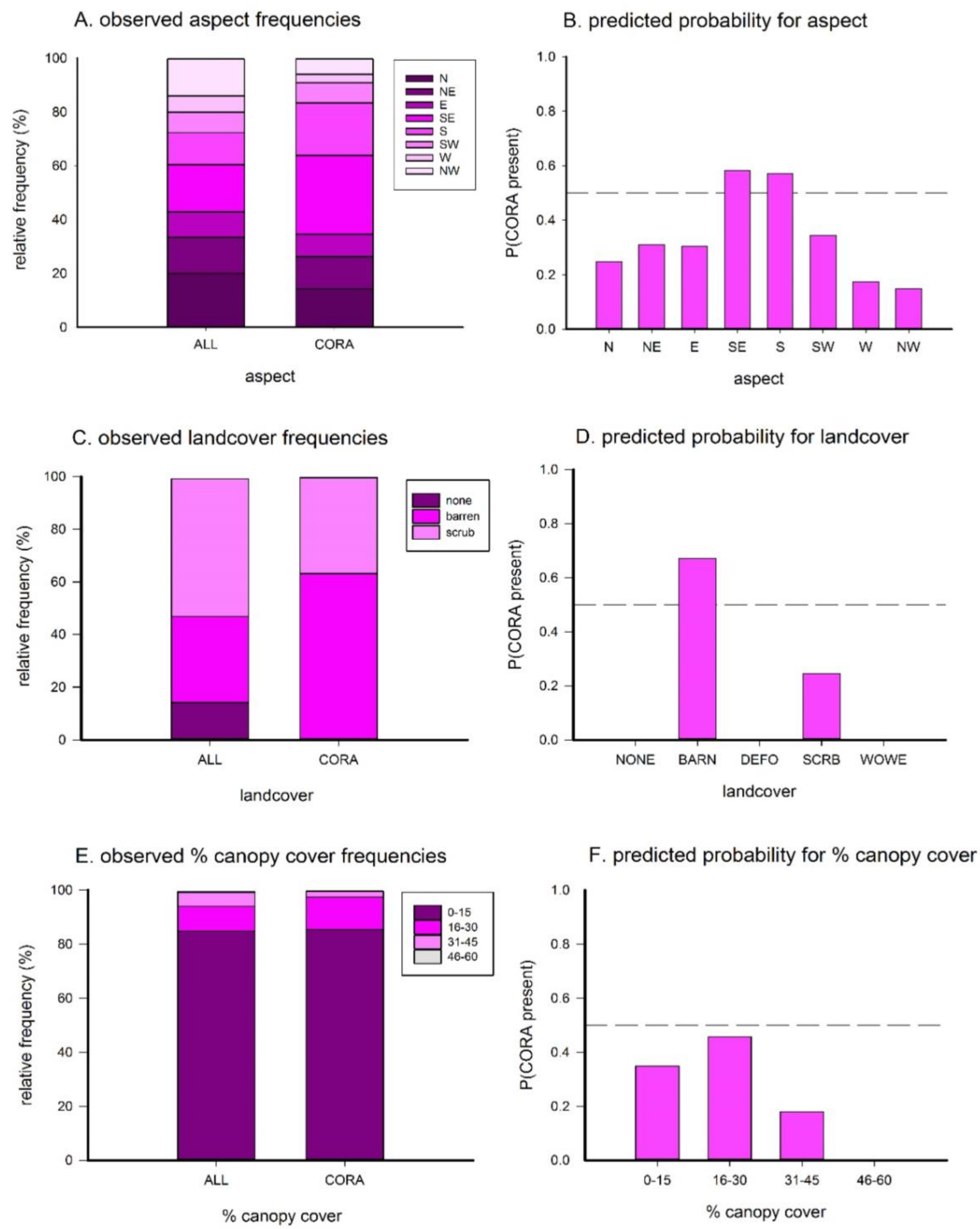


Figure 2. *Coryphantha ramillosa* subsp. *ramillosa*: results for aspect, % canopy cover, and landcover. A, C, E: composition of the site and of points with CORA present. Left bar: site (both presence and pseudo-absence points); right bar: only points with CORA present. B, D, F: results of analyses of *Coryphantha ramillosa* subsp. *ramillosa* presence-absence data. Bars represent the predicted probability of a point in each category having a CORA plant. (NONE = no landcover data; BARN = barren; DEFO = deciduous forest; SCRB = scrubland; WOWE = woody wetlands)

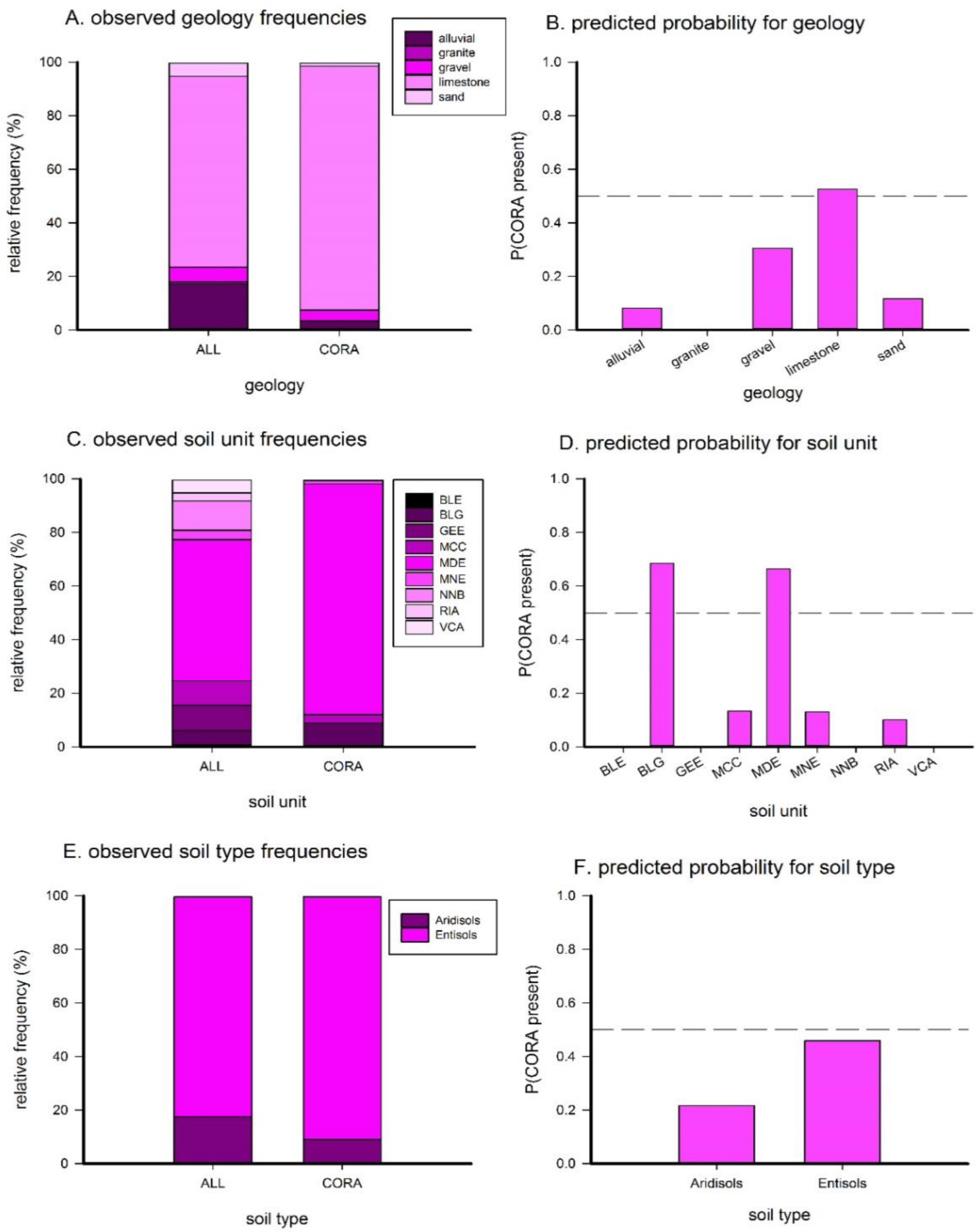


Figure 3. *Coryphantha ramillosa* subsp. *ramillosa*: results for geology, soil unit, and soil type. A, C, E: composition of the site and of points with CORA present. Left bar: site (both presence and pseudo-absence points); right bar: only points with CORA present. B, D, F: results of analyses of *Coryphantha ramillosa* subsp. *ramillosa* presence-absence data. Bars represent the predicted probability of a point in each category having a CORA plant. (BLE = Blackgap-Rock outcrop complex (10-30% slopes); BLG = Blackgap-Rock outcrop complex (20-70% slopes); GEE = Geefour silty clay; MCC = Mariscal very channery loam; MDE = Mariscal-Rock outcrop complex; MNE = Mariscal-Terlingua complex; NNB = Ninepoint clay loam; RIA = Riverwash and Pantera soils; VCA = Vincente, Lomapelona, and Castolon soils)

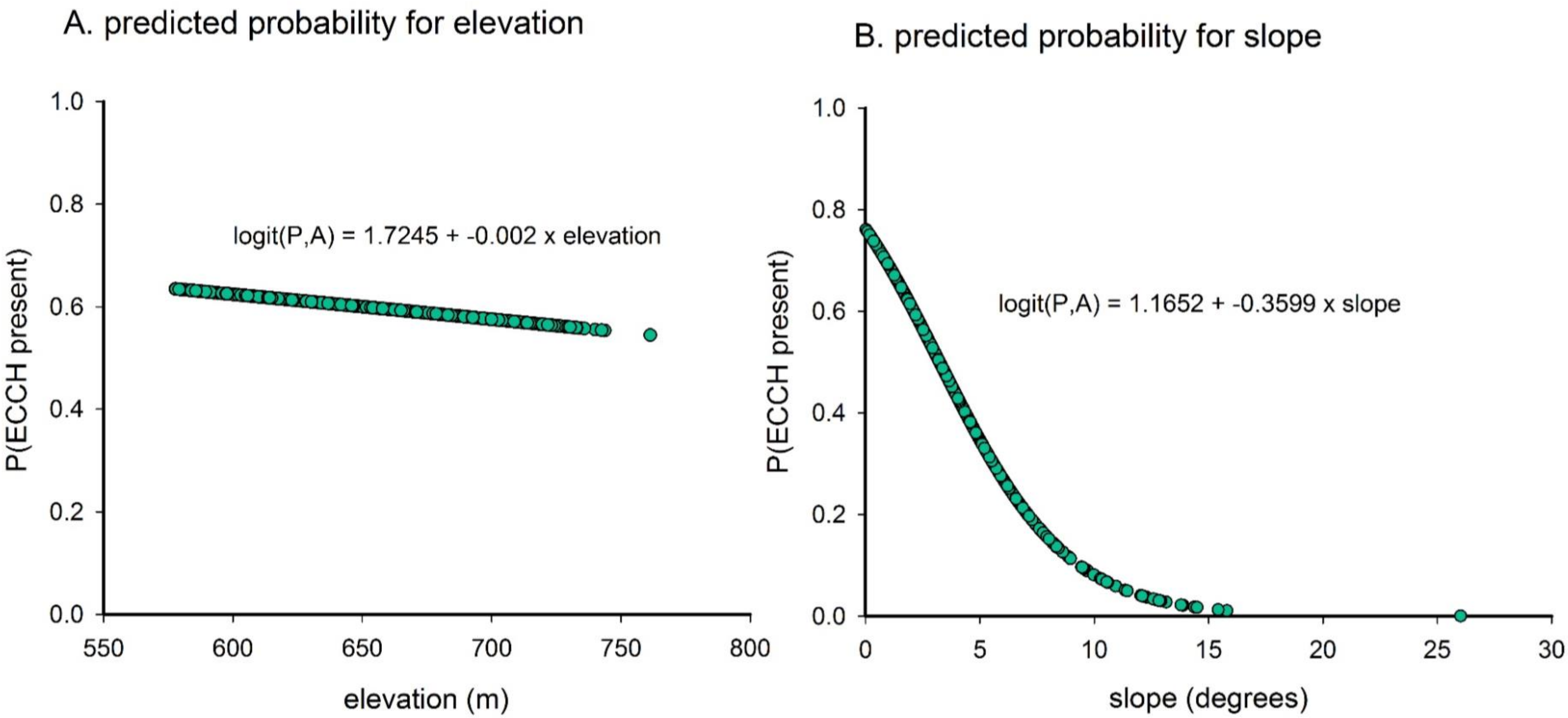


Figure 4. Results of analyses of *Echinocereus chisoensis* var. *chisoensis* presence-absence data. (A) Elevation did not have a significant effect on the probability of ECCH presence (p = 0.0959); (B) Points on less steep slopes were more likely to have an ECCH plant present (p < 0.0001). Each point represents one plant location or one pseudo-absence in the data set.

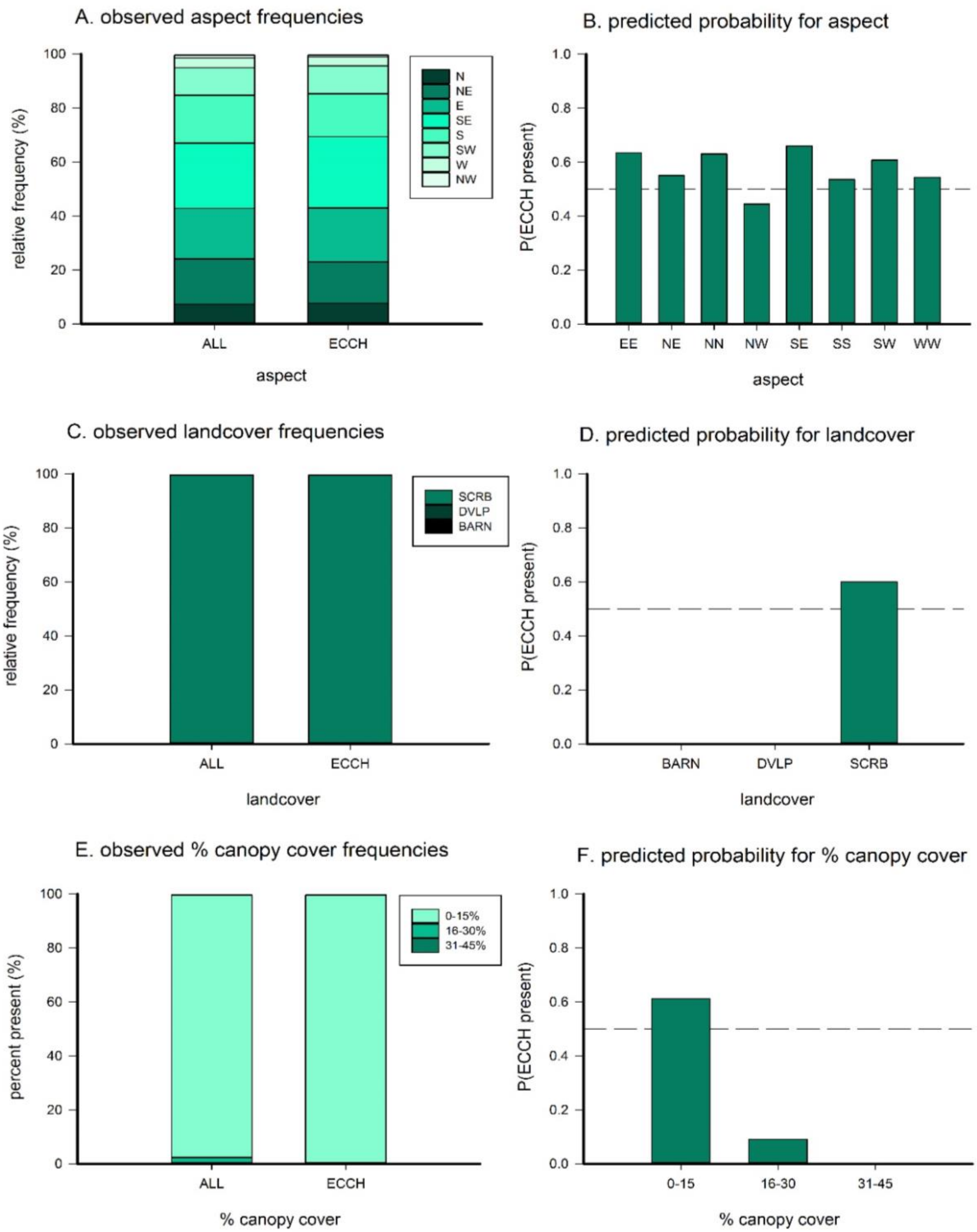


Figure 5. *Echinocereus chisoensis* var. *chisoensis*: results for aspect, % canopy cover, and landcover. A, C, E: composition of the site and of points with ECCH present. Left bar: site (both presence and pseudo-absence points); right bar: only points with ECCH present. B, D, F: results of analyses of *Echinocereus chisoensis* var. *chisoensis* presence-absence data. Bars represent the predicted probability of a point in each category having an ECCH plant. (BARN = barren; DVLP = developed land; SCRB = scrubland)

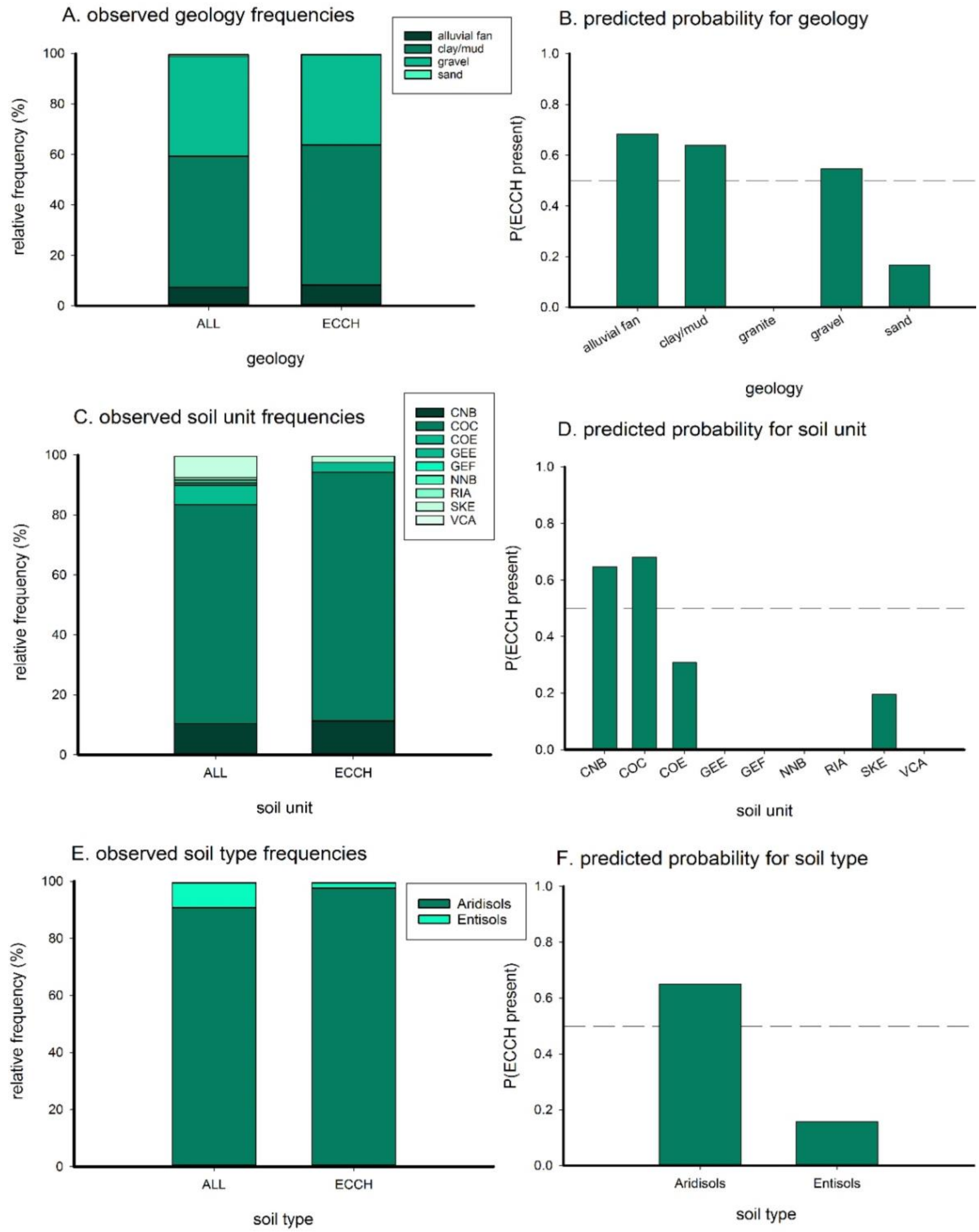


Figure 6. *Echinocereus chisoensis* var. *chisoensis*: results for geology, soil unit, and soil type. A, C, E: composition of the site and of points with ECCH present. Left bar: site (both presence and pseudo-absence points); right bar: only points with ECCH present. B, D, F: results of analyses of *Echinocereus chisoensis* var. *chisoensis* presence-absence data. Bars represent the predicted probability of a point in each category having an ECCH plant. (CNB = Chillon very gravelly fine sandy loam; COC = Corazones very gravelly sandy loam (1-8% slopes); COE = Corazones very gravelly sandy loam (1-30% slopes); GEE = Geefour silty clay (3-20% slopes); GEF = Geefour silty clay (10-45% slopes); NNB = Ninepoint clay loam; RIA = Riverwash and Pantera soils; SKE = Solis-Rock outcrop complex; VCA = Vincente, Lomapelona, and Castolon soils)

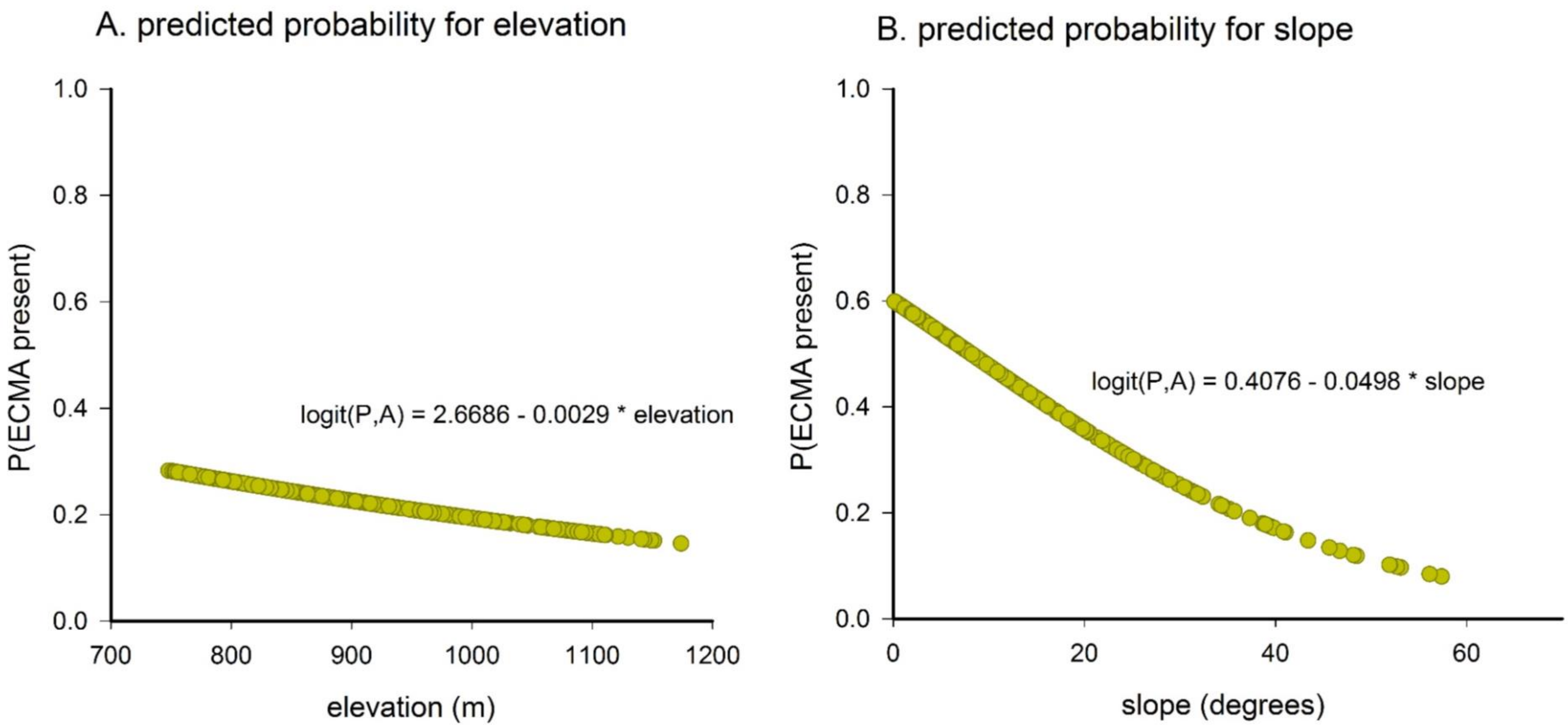


Figure 7. Results of analyses of *Echinomastus mariposensis* presence-absence data. (A) Points found at lower elevations were more likely to have an ECMA plant present ($p < 0.0001$); (B) Points on less steep slopes were more likely to have ECMA present ($p < 0.0001$). Each point represents one plant location or one pseudo-absence in the data set.

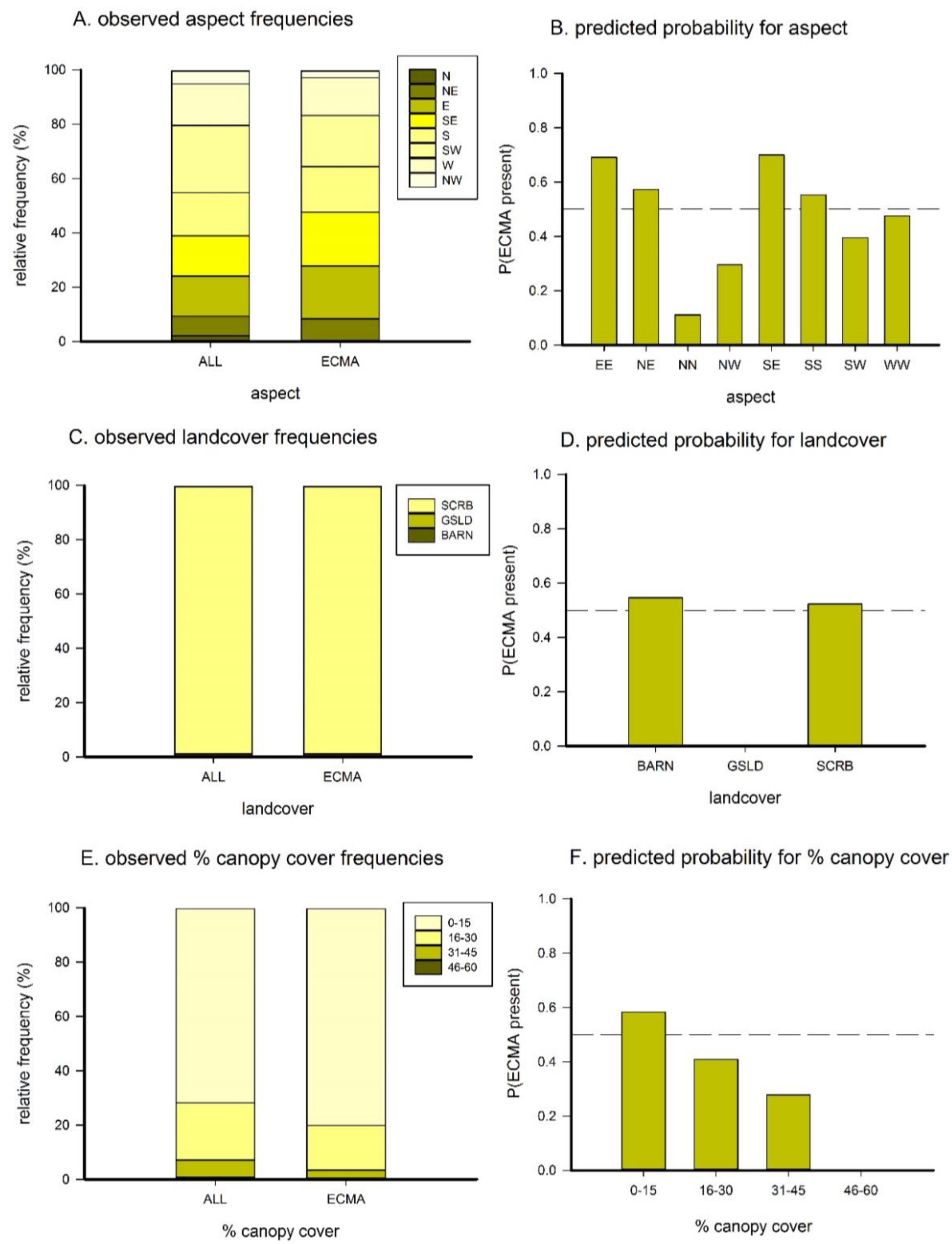


Figure 8. *Echinomastus mariposensis*: results for aspect, % canopy cover, and landcover. A, C, E: composition of the site and of points with ECMA present. Left bar: site (both presence and pseudo-absence points); right bar: only points with ECMA present. B, D, F: results of analyses of *Echinomastus mariposensis* presence-absence data. Bars represent the predicted probability of a point in each category having an ECMA plant. (BARN = barren; GSLD = grassland; SCRB = scrubland)

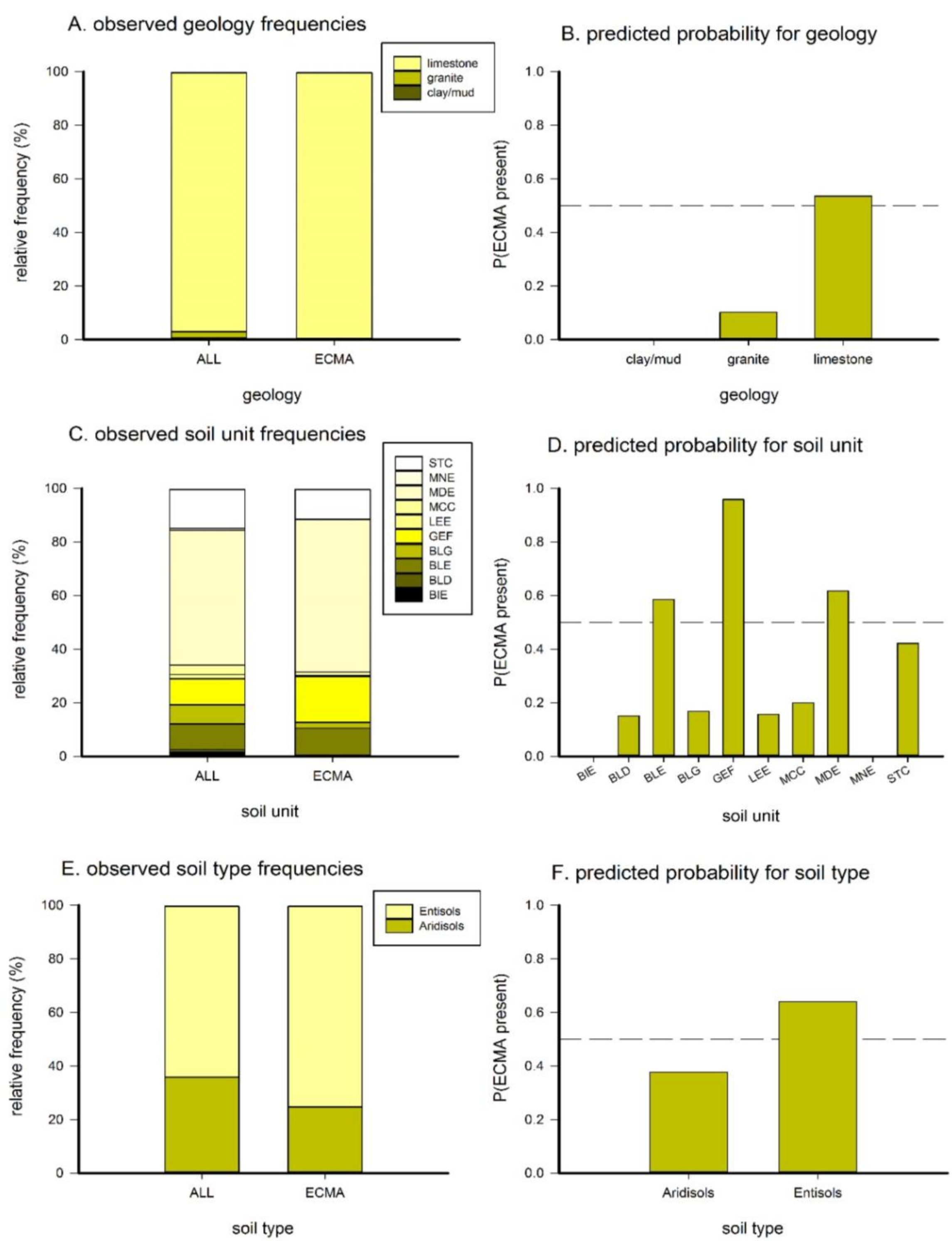


Figure 9. *Echinomastus mariposensis*: results for geology, soil unit, and soil type. A, C, E: composition of the site and of points with ECMA present. Left bar: site (both presence and pseudo-absence points); right bar: only points with ECMA present. B, D, F: results of analyses of *Echinomastus mariposensis* presence-absence data. Bars represent the predicted probability of a point in each category having an ECMA plant. (BIE = Bissett-Rock outcrop complex; BLD = Blackgap-Rock outcrop complex (1-16% slopes); BLE = Blackgap-Rock outcrop complex (10-30% slopes); GEF = Geefour silty clay (10-45% slopes); LEE = Leyva-Rock outcrop complex; MCC = Mariscal very channery loam; MDE = Mariscal-Rock outcrop complex; MNE = Mariscal-Terlingua complex; STC = Strawhouse-Stillwell complex)

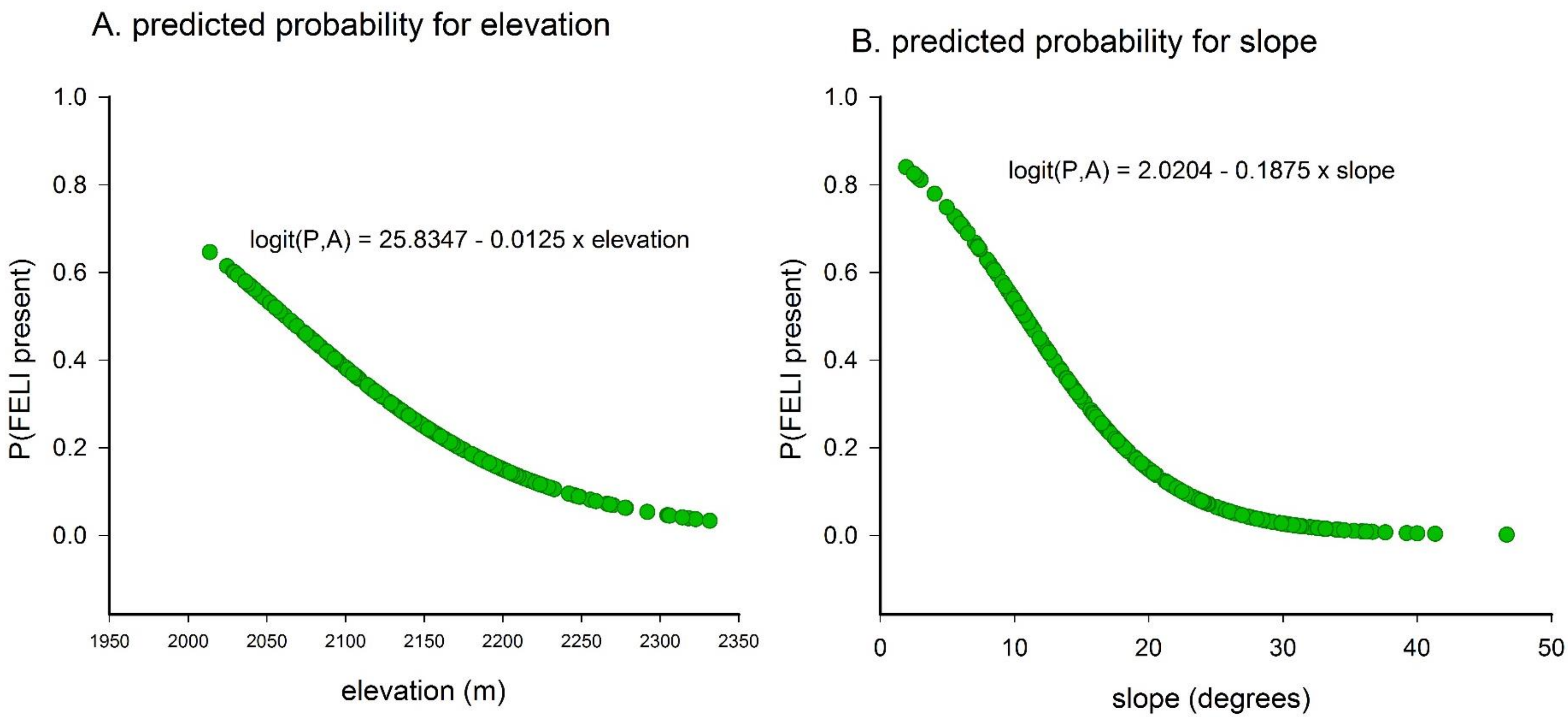


Figure 10. Results of analyses of *Festuca ligulata* presence-absence data. (A) Points at lower elevations were more likely to have a FELI plant present ($p < 0.0001$); (B) Points on less steep slopes were more likely to have a FELI plant present ($p < 0.0001$). Each point represents one plant location or one pseudo-absence in the data set.

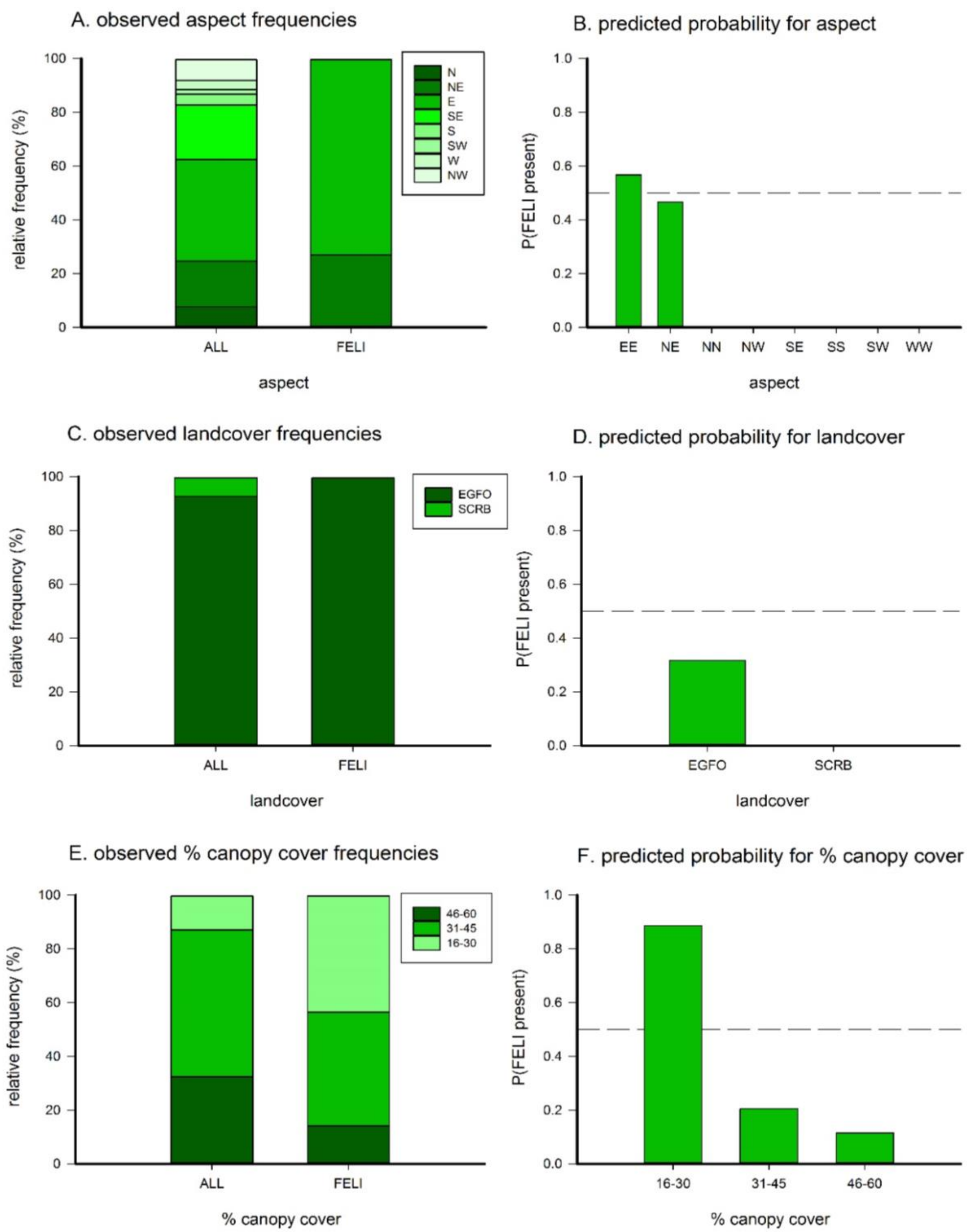


Figure 11. *Festuca ligulata*: results for aspect, % canopy cover, and landcover. A, C, E: composition of the site and of points with FELI present. Left bar: site (both presence and pseudo-absence points); right bar: only points with FELI present. B, D, F: results of analyses of *Festuca ligulata* presence-absence data. Bars represent the predicted probability of a point in each category having an FELI plant. (EGFO = evergreen forest; SCRB = scrubland)

Appendix B: Tables

Table 1. The four target species. Nomenclature follows Correll (1970) and Poole (207).

Scientific name	USDA Code	Common names	Previous scientific name(s)	Current federal status
Coryphantha ramillosa subsp. *ramillosa* Cutak	CORA7	**Bunched cory cactus** Whiskerbush Whiskerbush pincushion cactus Big Bend cory cactus Big Bend mammillaria	*Mammillaria ramillosa* Weniger	Threatened
Echinocereus chisoensis var. *chisoensis* Marsh	ECCH2	**Chisos Mountain hedgehog cactus** Chisos hedgehog cactus Chisos hedgehog Chisos pitaya	*Echinocereus metornii* Frank *Echinocereus chisoensis* subs. *fobeanus* Oehme *Echinocereus reichenbachii* var. *chisoensis* Benson	Threatened
Echinomastus mariposensis Hester	ECMA2	**Lloyd's mariposa cactus** Lloyd's fishhook cactus Golfball cactus Silver column cactus Mariposa cactus Mariposa Lloyd's cactus Mariposa viszagita Biznaga-bola de mariposa (Spanish)	*Neolloydia mariposensis* Benson *Sclerocactus mariposensis* Taylor *Pediocactus mariposensis* Halda *Echinocactus mariposensis* Weniger	Threatened
Festuca ligulata Swallen	FELI	**Guadalupe fescue** Guadalupe Mountains fescue	N/A	Endangered

Table 2. Table of predictor variables used in SAS analyses of presence and pseudo-absence points.

Variable	Variable name	Variable ID	Kind	Values	Units	Possible values	Dataset	Source
1	elevation	ELEV_M	Numerical	Range of continuous values	meters	~500-2200 meters	Digital Elevation Model (DEM)	Earth Explorer, USGS
2	slope	SLOPE_DEG	Numerical	Range of continuous values	degrees	~0-50˚	Digital Elevation Model (DEM)	Earth Explorer, USGS
3	aspect	ASPECT_NAME	Categorical	Cardinal directions	none	N, NE, E, SE, S, SW, W, NW	Digital Elevation Model (DEM)	Earth Explorer, USGS
4	landcover	LC_WDLD	Categorical	Landcover types	none	BARN (barren), DEFO (deciduous forest), etc.	National Landcover Dataset (NLCD)	TNRIS, TWDB
5	% canopy cover	CAN_%	Categorical	Categories of % canopy cover	percent	1 (0-15%), 2 (16-30%), 3 (31-45%), 4 (46-60%)	National Landcover Dataset (NLCD)	TNRIS, TWDB
6	geology	ROCKTYPE1	Categorical	Name of rock type	none	Limestone, alluvial fan, gravel, etc.	Texas geological map data	Mineral Resources, USGS
7	soil unit	MUSYM	Categorical	Name of primary soil unit	none	MDE, BDE, GEE, etc.	Soil map units	Web Soil Survey, SSURGO, NRCS, USDA
8	soil type	S_ORD	Categorical	Name of primary soil type	none	Entisols, Mollisols, Aridisols, etc.	Soil map units	Web Soil Survey, SSURGO, NRCS, USDA

Table 3. Plant species commonly found growing near each of the target species. Species in bold were confirmed at a field site in Aug. 2016 or March 2017. Associated species information for CORA from Heil *et al*. (1985); for ECCH, USFWS (1993); for ECMA, Anderson and Schmalzel (1997); for FELI, USFWS (2016a).

Species	Associated Species
CORA	***Agave lechuguilla* (lechuguilla)** ***Ariocarpus fissuratus* (living rock cactus)** ***Coryphantha echinus* (sea urchin cactus)** ***Coryphantha macromeris* (beehive cactus)** *Cylindropuntia leptocaulis* (desert Christmas cactus) ***Cylindropuntia schottii* (dog cholla)** ***Echinocactus horizonthalonius* (Turk's head cactus)** ***Echinocereus stramineus* (strawberry hedgehog cactus)** *Echinomastus warnockii* (Warnock's fishhook cactus) *Escobaria duncanii* (Duncan pincushion cactus) ***Euphorbia antisyphilitica* (candelilla)** ***Ferocactus hamatacanthus* (Texas barrel cactus)** ***Fouquieria splendens* (ocotillo)** ***Jatropha dioica* (leatherstem)** *Krameria erecta* (pima rhatany) ***Larrea tridentata* (creosote bush)** *Mammillaria lasiacantha* (lacespine nipple cactus) ***Opuntia engelmannii* (desert pricklypear)** *Opuntia imbricata* (cane cholla) *Opuntia rufida* (blind prickly pear) ***Selaginella lepidophyllas* (resurrection plant)** *Vachellia constricta* (whitethorn acacia)
ECCH	***Agave lechuguilla* (lechuguilla)** ***Coryphantha echinus* (sea urchin cactus)** ***Coryphantha macromeris* (beehive cactus)** ***Cylindropuntia leptocaulis* (desert Christmas cactus)** ***Cylindropuntia schottii* (dog cholla)** *Echinocactus horizonthalonius* (Turk's head cactus) ***Echinocereus dasyacanthus* (Texas rainbow cactus)** *Echinocereus stramineus* (strawberry hedgehog cactus) *Echinomastus warnockii* (Warnock's fishhook cactus) ***Fouquieria splendens* (ocotillo)** ***Jatropha dioica* (leatherstem)** ***Larrea tridentata* (creosote bush)** *Leucophyllum frutescens* (cenizo) *Opuntia engelmannii* (desert prickly pear) ***Opuntia macrocentra* (purple pricklypear)** *Opuntia rufida* (blind pricklypear)

	Vachellia constricta (whitethorn acacia)
ECMA	***Agave lechuguilla* (lechuguilla)** ***Ariocarpus fissuratus* (living rock cactus)** *Bouteloua ramose* (chino grama grass) *Buddleja marrubiifolia* (woolly butterflybush) *Calliandra conferta* (Rio Grande stickpea) ***Coryphantha echinus* (sea urchin cactus)** ***Dasylirion leiophyllum* (green sotol)** *Dasyochloa pulchella* (low woollygrass) ***Echinocactus horizonthalonius* (Turk's head cactus)** ***Epithelantha bokei* (pingpong ball cactus)** ***Euphorbia antisyphilitica* (candelilla)** ***Fouquieria splendens* (ocotillo)** *Hechtia texensis* (Texas false agave) ***Jatropha dioica* (leatherstem)** *Krameria erecta* (pima rhatany) ***Larrea tridentata* (creosote bush)** ***Leucophyllum candidum* (Big Bend silverleaf)** ***Mammillaria lasiacantha* (lacespine nipple cactus)** *Mammillaria pottsii* (fox-tail cactus) ***Opuntia engelmannii* (desert pricklypear)** ***Salvia dorrii* (desert sage)** *Selaginella* spp. (spike moss) ***Tiquilia greggii* (plumed crinklemat)**
FELI	***Acer grandidentatum* (bigtooth maple)** ***Agave americana* (century plant)** ***Cupressus arizonica* (Arizona cypress)** ***Dasylirion leiophyllum* (green sotol)** *Juniperus deppeana* (alligator juniper) ***Juniperus flaccida* (drooping juniper)** ***Muhlenbergia* spp. (muhly grass)** *Pinus arizonica* (Arizona pine) ***Pinus cembroides* (Mexican pinyon)** *Pinus strobiformis* (southwestern white pine) ***Piptochaetium fimbriatum* (pinyon ricegrass)** ***Pseudotsuga menziesii* (Douglas fir)** ***Quercus gravesii* (Chisos red oak)** ***Quercus grisea* (gray oak)** ***Quercus hypoleaucoides* (silverleaf oak)** *Quercus laceyi* (lacey oak) *Salvia regla* (mountain sage)

Table 4. Average value of each climate variable for each species.

Variable	CORA	ECCH	ECMA	FELI
elevation (m)	595.32	648.57	863.73	2113.11
slope (degrees)	7.67	1.66	5.56	12.06
max. temp (°C)	30.56	30.16	28.32	18.54
min. temp. (°C)	12.22	12.28	11.82	7.19
avg. precip. (cm)	25.40	26.64	30.02	55.75

Table 5. Most common geology and soil characteristics for all four species. Data from the USGS (Mineral Resources) and USDA (Natural Resources Conservation Service).

Variable	CORA	ECCH	ECMA	FELI
rocktype1	Limestone	Clay or mud	Limestone	Rhyolite
rocktype2	Shale	Sandstone	Shale	Ash-flow tuff
rocktype3	Mudstone; siltstone	Coal	Mudstone; siltstone	Lava flow; volcanic breccia (agglomerate); vitrophyre
orig_label	Kbo	Kag	Kbo	Os
unit_age	Late Cretaceous	Late Cretaceous	Late Cretaceous	Oligocene
total_lith	Sedimentary Carbonate Limestone	Unconsolidated Fine-detrital Clay	Sedimentary Carbonate Limestone	Igneous Volcanic Felsic-volcanic Rhyolite
low_lith	Limestone	Clay	Limestone	Rhyolite
lith_form	Bed	Bed	Bed	Pyroclastic, ash-flow
full_max	Phanerozoic Mesozoic Cretaceous Early-Cretaceous	Phanerozoic Mesozoic Cretaceous Early-Cretaceous	Phanerozoic Mesozoic Cretaceous Early-Cretaceous	Phanerozoic Cenozoic Tertiary-Paleogene Early-Oligocene
full_min	Phanerozoic Mesozoic Cretaceous Late-Cretaceous	Phanerozoic Mesozoic Cretaceous Late-Cretaceous	Phanerozoic Mesozoic Cretaceous Late-Cretaceous	Phanerozoic Cenozoic Tertiary-Paleogene Early-Oligocene
max_ma	145.5	145.5	145.5	33.9
min_ma	65.5	65.5	65.5	28.4
unit_name	Bouquillas Formation	Aguja Formation	Bouquillas Formation	South Rim Formation from Pine Canyon Caldera
unit_com	In Western part of Trans-Pecos, Texas, Eastern part of Trans-Pecos, Texas and High	Clay, sandstone, and lignite. Upper-continental deposits up to 268 m thick. Argillaceous	In Western part of Trans-Pecos, Texas, Eastern part of Trans-Pecos, Texas and High	Pine Canyon Rhyolite, brown to gray, densely welded multiple cooling units of peralkaline

	Plains- limestone, marl and shale. Upper part-interbedded marl and shale; lower part-limestone, silty to sandy, flaggy, dark grayish orange near base; marine megafossils	sandstone cross-bedded clay in part calcar; freshwater limestone scarce; a few lignite beds. Vertebrate fossils and petrified wood common.	Plains- limestone, marl and shale. Upper part-interbedded marl and shale; lower part-limestone, silty to sandy, flaggy, dark grayish orange near base; marine megafossils	rhyolitic ash-flow tuff, at least 300 m thick within the caldera, rocks lying between the Pine
musym	MDE	COC	MDE	PUF
muname	Mariscal-Rock outcrop complex, 5-30% slopes	Corazones, very gravelly sandy loam, 1-8% slopes	Mariscal-Rock outcrop complex, 5-30% slopes	Puerta-Madrone-Lazarus complex, 20-45% slopes
taxorder	Entisols	Aridisols	Entisols	Mollisols
flodfreqdc	None	None	None	None
drclasswet	Well drained	Well drained	Well drained	Well drained
runoff	Very high	Low	Very high	Very high
geomdesc	Hills on plateaus	Pediments, piedmont slopes	Hills on plateaus	Mountain slopes, mountains
taxclname	Loamy-skeletal Carbonatic Hyperthermic Lithic Ustic Torriorthents	Loamy-skeletal Mixed Hyperthermic Ustic Haplocalcids	Loamy-skeletal Carbonatic Hyperthermic Lithic Ustic Torriorthents	Clayey-skeletal Smectitic Mesic Alfic Lithic Argiustolls

Table 6. Field observation data for *Coryphantha ramillosa* subsp. *ramillosa* from March 2017.

Species	Date	Elevation (m)	Flowers	Fruits	Diameter (cm)	Visible damage	Vigor	Notes
CORA1	3/13/2017	584.61	0	4	5.68	none	very dry	Sticking out of limestone at ~35˚ angle; on top of ledge; about 0.61m from *F. splendens*
CORA2	3/13/2017	597.10	0	0	6.35	none	dry	At the edge of limestone cliff at ~55˚ angle; 0.78m away from *L. tridentata* and *C. schottii*
CORA3	3/13/2017	597.23	0	0	10.12	none	healthy	"Perfect specimen"; coming out of limestone crack at ~70˚ angle; 0.48m from *L. tridentata*
CORA4	3/13/2017	599.85	0	0	5.08	none	healthy	At the very edge of limestone cliff at ~45˚ angle; 0.34m away from *E. stramineus* and *L. tridentata*
CORA5	3/13/2017	598.32	0	0	5.46	none	very dry	In limestone crack at about ~30˚angle; very close to edge of cliff; 0.29m from *E. dasyacanthus*; 2 dead individuals
CORA6	3/13/2017	584.91	0	0	6.25	none	dry	In limestone at ~45˚ angle; 0.66m away from *L. tridentata* and *F. splendens*
CORA7	3/13/2017	580.03	0	0	5.94	none	dry	Near limestone ledge at ~45˚ angle; next to *L. tridentata*
CORA8	3/13/2017	580.64	0	0	7.62	none	healthy	On edge of limestone cliff at ~45˚ angle; 0.55m away from *L. tridentata*
CORA9	3/13/2017	589.18	0	0	7.56	none	very dry	~45˚ angle on top of limestone ledge; 0.73m away from *E. dasyacanthus* and *E. stramineus*; 1 dead individual nearby
CORA10	3/13/2017	593.14	0	0	5.02	none	very dry	On top of limestone ridge at ~30˚ angle; 0.15m from *L. tridentata*

Table 7. Results from generalized linear models for *Coryphantha ramillosa* subsp. *ramillosa*.

Variables	N	-2 Log Likelihood	AIC	Pearson Chi-Square / DF	Num DF	Den DF	F Value	Pr > F
elevation	766	989.08	993.08	1.00	1	764	0.18	0.6720
slope	766	983.14	987.14	1.00	1	764	0.0137	**0.0137**
aspect	766	901.74	917.74	1.01	7	756	11.19	**<0.0001**
landcover	766	761.80	771.80	0.85	3	761	2810.54	**<0.0001**
% canopy cover	766	974.29	982.29	1.00	3	762	2.70	**0.0445**
geology	646	767.86	777.86	1.00	4	641	16.51	**<0.0001**
soil unit	654	562.08	580.08	0.75	8	645	8.60	**<0.0001**
soil type	634	837.39	841.39	1.00	1	632	20.72	**<0.0001**

Table 8. Field observation data for *Echinocereus chisoensis* var. *chisoensis* from March 2017.

Species	Date	Elevation (m)	Flowers	Fruits	Height (cm)	Visible damage	Vigor	Notes
ECCH1	3/13/2017	621.18	12	0	15.13	none	healthy	Has 6 distinct stems; surrounded by dead *L. tridentata* and *C. schottii* (nurse plants); on desert pavement bajada; on very flat surface
ECCH2	3/13/2017	621.03	7	0	10.97	none	healthy	Has two distinct stems; surrounded by dead *C. schottii* and *L. tridentata* (may have been nurse plant); on desert pavement bajada; very flat surface
ECCH3	3/13/2017	621.49	2	0	13.54	yes	healthy	One stem; visible damage (possible rabbit or mice bites); surrounded by *C. schottii* and *L. tridentata*, but fully exposed (doesn't have clear nurse plant); desert pavement bajada; very flat surface
ECCH4	3/13/2017	622.40	7	0	21.00	none	healthy	Six stems; surrounded by *C. schottii* and two large *L. tridentata* (nurse plants); desert pavement bajada; very flat
ECCH5	3/13/2017	622.49	4	0	12.62	yes	dry	Two stems; surrounded by *C. schottii* and very large *L. tridentata* (nurse plants); desert pavement bajada; very flat
ECCH6	3/13/2017	621.49	4	0	7.67	yes	very dry	Four stems; visible damage (possible rabbit or mice bite marks); no nurse plant (fully exposed); dead *C. schottii* around base of plant; desert pavement bajada; very flat
ECCH7	3/13/2017	626.06	6	0	13.92	none	healthy	Three stems; in the middle of large *L. tridentata* (nurse plant); desert pavement bajada; very flat
ECCH8	3/13/2017	623.32	7	0	18.06	none	dry	Two large stems; in the middle of dead *L. tridentata* (possible nurse plant); desert pavement bajada; very flat
ECCH9	3/13/2017	622.10	24	0	25.41	none	healthy	Very large individual; 6 stems; in the middle of large *L. tridentata* (nurse plant); desert pavement bajada; very flat
ECCH10	3/13/2017	621.79	7	0	17.17	none	healthy	Five stems; surrounded by *L. tridentata* and *C. schottii* (nurse plants); desert pavement bajada; very flat

Table 9. Results from generalized linear models for *Echinocereus chisoensis* var. *chisoensis*.

Variables	**N**	**-2 Log Likelihood**	**AIC**	**Pearson Chi-Square / DF**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
elevation	2500	3362.28	3366.28	1.00	1	2498	2.78	0.0959
slope	2500	3137.96	3141.96	0.99	1	2498	170.36	**<0.0001**
aspect	2498	3333.50	3349.50	1.00	7	2490	4.07	**0.0002**
landcover	2500	3361.39	3367.39	1.00	2	2497	0	0.9994
% canopy cover	2500	3294.81	3300.81	1.00	2	2497	17.17	**<0.0001**
geology	2500	3309.54	3319.54	1.00	4	2495	10.70	**<0.0001**
soil unit	2500	3005.64	3023.64	0.98	7	2491	918.11	**<0.0001**
soil type	2482	3117.18	3121.18	1.00	1	2480	151.18	**<0.0001**

Table 10. Field observation data for *Echinomastus mariposensis* from March 2017.

Species	Date	Elevation (m)	Flowers	Fruits	Diameter (cm)	Visible damage	Vigor	Notes
ECMA1	3/14/2017	780.90	2	2	2.54	none	healthy	Under a dead *L. tridentata*; surrounded by small limestone rocks; ~4.5m from the road; near *A. lechuguilla* and *S. dorrii*.
ECMA2	3/14/2017	782.73	0	0	3.30	none	healthy	Next to dead *A. lechuguilla* and live *S. dorrii*; no fruits or flowers; ~7.5m from road
ECMA3	3/14/2017	787.91	1	1	3.81	none	healthy	Near *E. horizonthalonius*, *S. dorrii*, and *E. antisyphilitica*; ~15m from road on top of limestone ridge
ECMA4	3/14/2017	784.86	0	5	3.43	none	healthy	Underneath dead *S. dorrii*; near *A. lechuguilla* and *L. tridentata*; on top of limestone ridge; ~30.5m from road
ECMA5	3/14/2017	787.60	1	0	3.56	none	healthy	"Perfect specimen"; under dead *A. lechuguilla*; near *F. splendens* and *S. dorrii*; on top of limestone ledge; ~15m from road
ECMA6	3/14/2017	784.25	1	6	6.35	none	healthy	Near *O. engelmannii*, *L. tridentata*, and *S. dorrii*; on limestone ledge; ~7.5m from road
ECMA7	3/14/2017	783.95	0	6	7.62	none	healthy	Under dead *S. dorrii*; ~6m from road on the side of a limestone hill; near *F. splendens*
ECMA8	3/14/2017	779.98	0	4	5.08	none	dry	In gulch that lead to creek bed; in between two large limestone rocks; ~15.5m from road; next to *E. antisyphilitica*
ECMA9	3/14/2017	781.51	0	4	7.87	none	healthy	On the side of the road; in loose, limestone gravel; next to *E. horizonthalonius* and dead *L. tridentata*
ECMA10	3/14/2017	789.99	0	0	5.08	none	very dry	On the side of the road; in loose, limestone gravel; next to *L. tridentata*

Table 11. Results from generalized linear models for *Echinomastus mariposensis*.

Variables	N	-2 Log Likelihood	AIC	Pearson Chi-Square / DF	Num DF	Den DF	F Value	Pr > F
elevation	2094	2846.46	2850.46	1.00	1	2092	50.95	**<0.0001**
slope	2094	2850.68	2854.68	1.00	1	2092	41.30	**<0.0001**
aspect	2092	2722.87	2738.87	1.00	7	2084	21.55	**<0.0001**
landcover	2094	2897.15	2903.15	1.00	2	2091	0.02	0.9766
% canopy cover	2091	2794.10	2802.10	0.99	3	2087	24.43	**<0.0001**
geology	2094	2838.75	2844.75	1.00	2	2091	11.96	**<0.0001**
soil unit	2004	2320.46	2340.46	0.98	9	1994	24.80	**<0.0001**
soil type	2004	2632.45	2636.45	1.00	1	2002	124.34	**<0.0001**

Table 12. Field observation data for *Festuca ligulata* from March 2017.

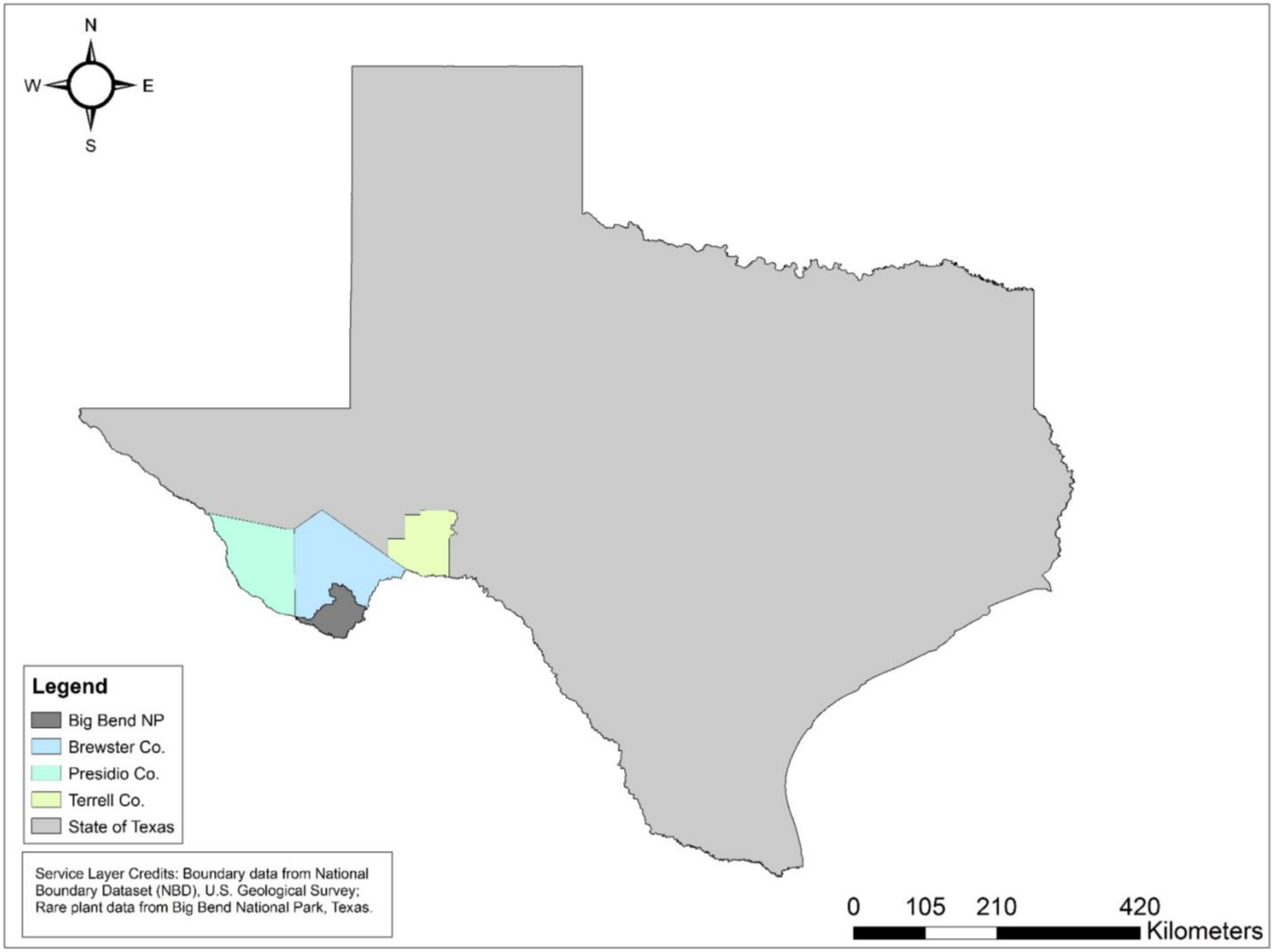
Species	Date	Elevation (m)	Inflorescence	Seeds	Height (cm)	Visible damage	Vigor	Notes
FELI1	3/15/2017	2099.16	0	0	30.48	none	dry	50% green; 45˚ angle on side of hill; under *J. flaccida* tree; near *D. leiophyllum*; *A. americana*; near very large rhyolite boulder; 6 tillers
FELI2	3/15/2017	2094.28	0	0	29.57	none	healthy	60% green; 15% angle; under *Q. gravesii* tree and *P. cembroides* saplings; still has part of dead inflorescence; large rhyolite boulders nearby; 6 tillers
FELI3	3/15/2017	2096.72	0	0	24.33	none	healthy	75% green; 20% angle; under *J. flaccida*, *P. cembroides*, and *Q. gravesii* saplings; near *A. americana*; very small individual; only 2 tillers
FELI4	3/15/2017	2088.49	0	0	42.67	none	very dry	30% green; 45% angle; under *Q. gravesii* tree and *P. cembroides* saplings; near *D. leiophyllum* still has part of dead inflorescence; large rhyolite boulders nearby; 3 tillers
FELI5	3/15/2017	2091.84	0	0	39.62	none	healthy	75% green; 45% angle; under *Q. gravesii* tree and *P. cembroides* saplings; near *A. americana*; large rhyolite boulders nearby; 5 tillers

Table 13. Results from generalized linear models for *Festuca ligulata*. Geology, soil unit, and soil type did not differ between presence and absence points, so no analyses could be performed.

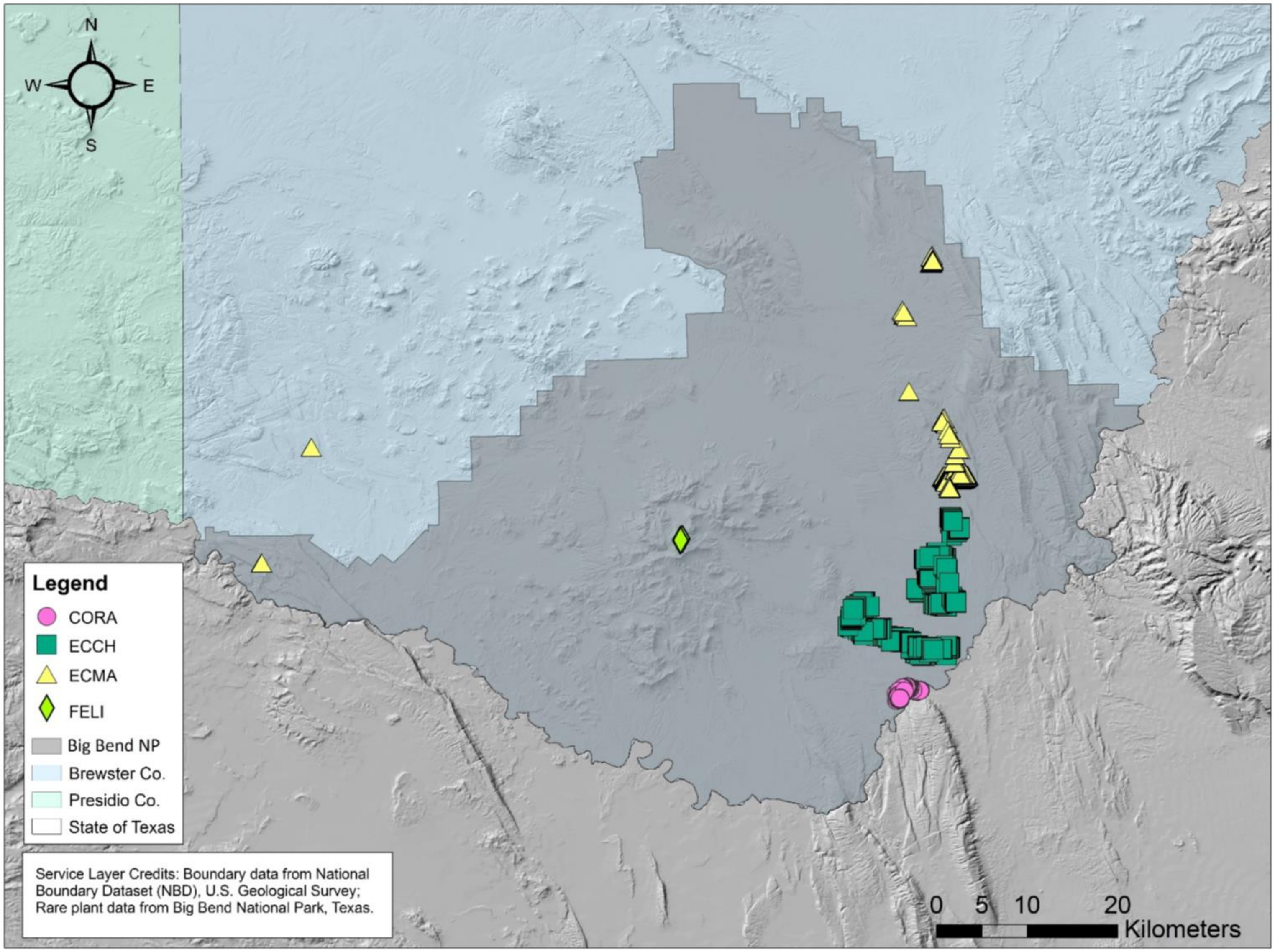
Variables	N	-2 Log Likelihood	AIC	Pearson Chi-Square / DF	Num DF	Den DF	F Value	Pr > F
elevation	354	396.27	400.27	0.91	1	352	26.81	<**0.0001**
slope	354	339.40	343.40	0.81	1	352	53.20	<**0.0001**
aspect	354	266.25	282.25	0.56	6	346	10.28	**0.0465**
landcover	354	409.77	413.77	0.93	1	352	0	0.9749
% canopy cover	269	235.71	241.71	1.01	2	266	22.12	<**0.0001**
geology	–	–	–	–	–	–	–	–
soil unit	–	–	–	–	–	–	–	–
soil type	–	–	–	–	–	–	–	–

Appendix C: Maps

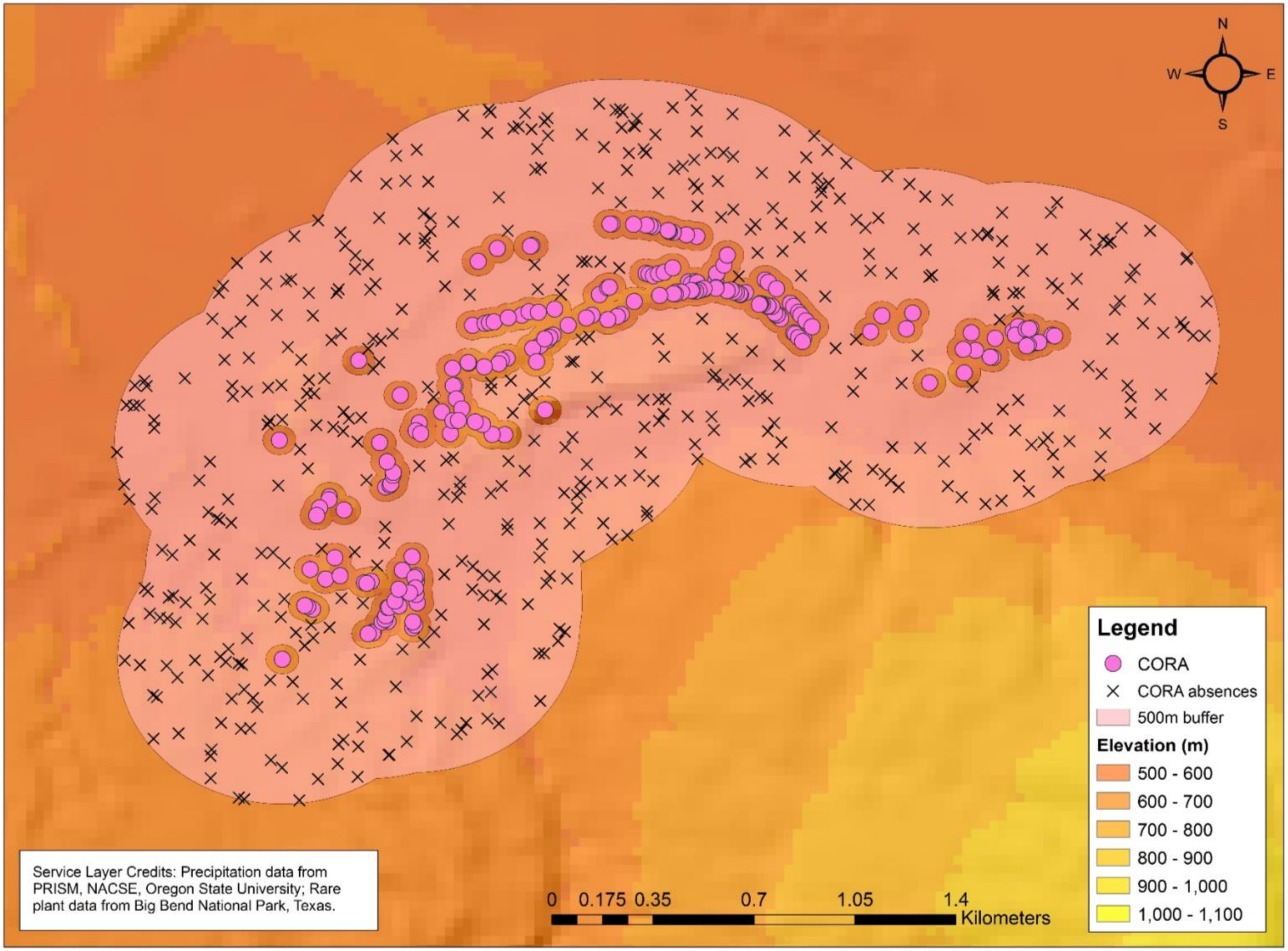
Map 1. Map of the Big Bend Region within the state of Texas.



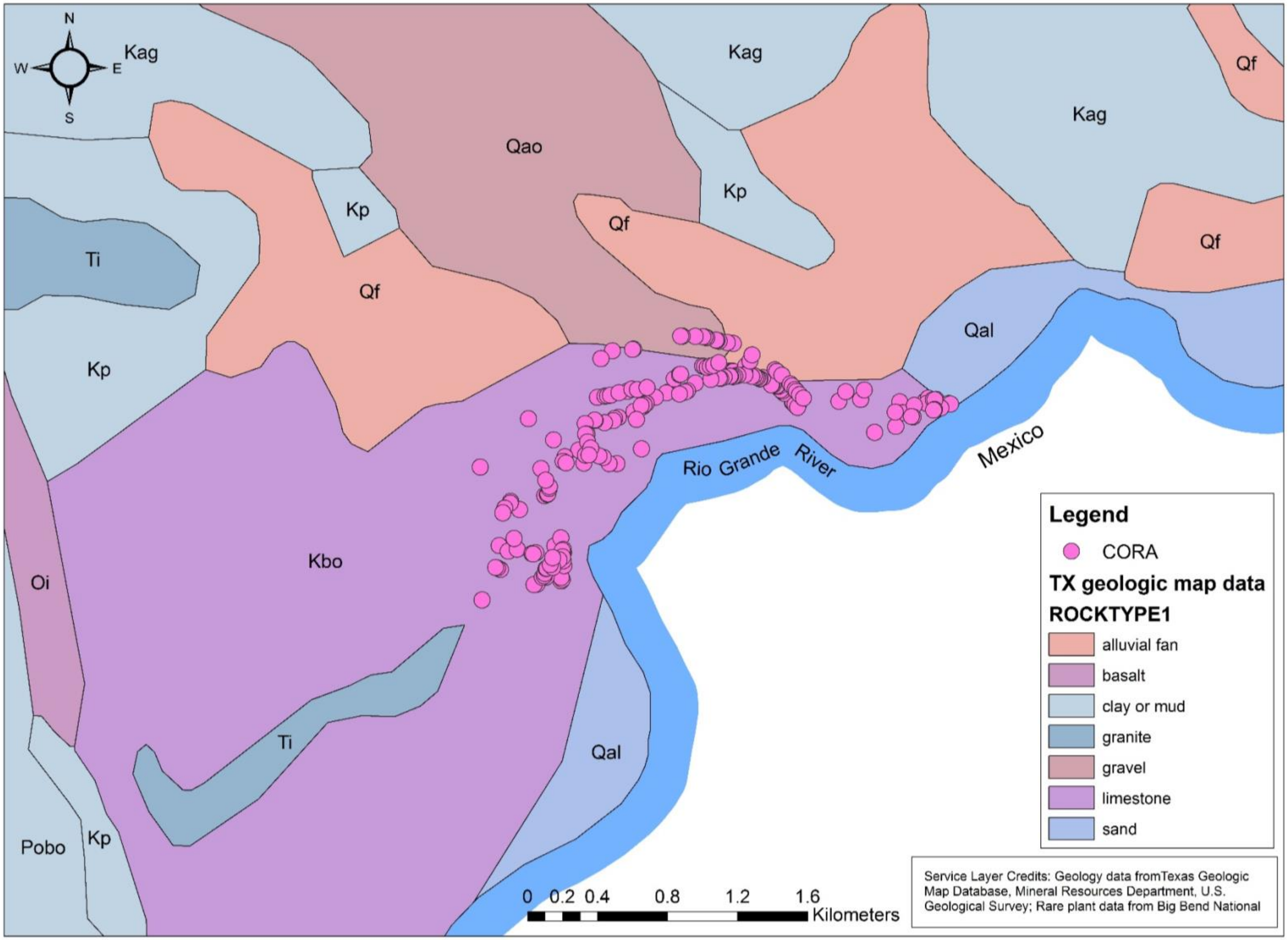
Map 2. Big Bend National Park and the occurrences of the four target species.



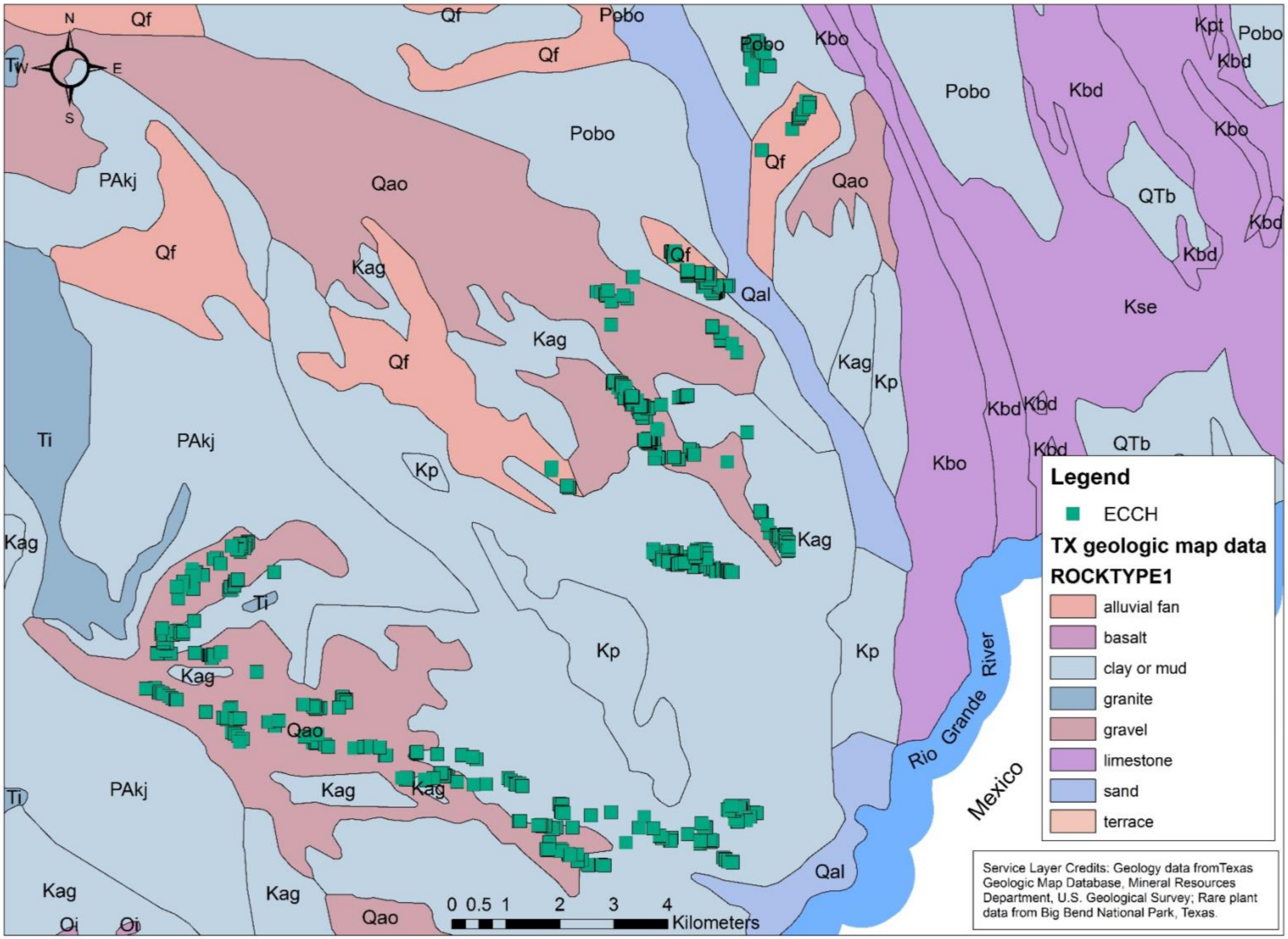
Map 3. Example of 500-meter buffer and pseudo-absence points created in ArcGIS. These are the ones created for CORA.



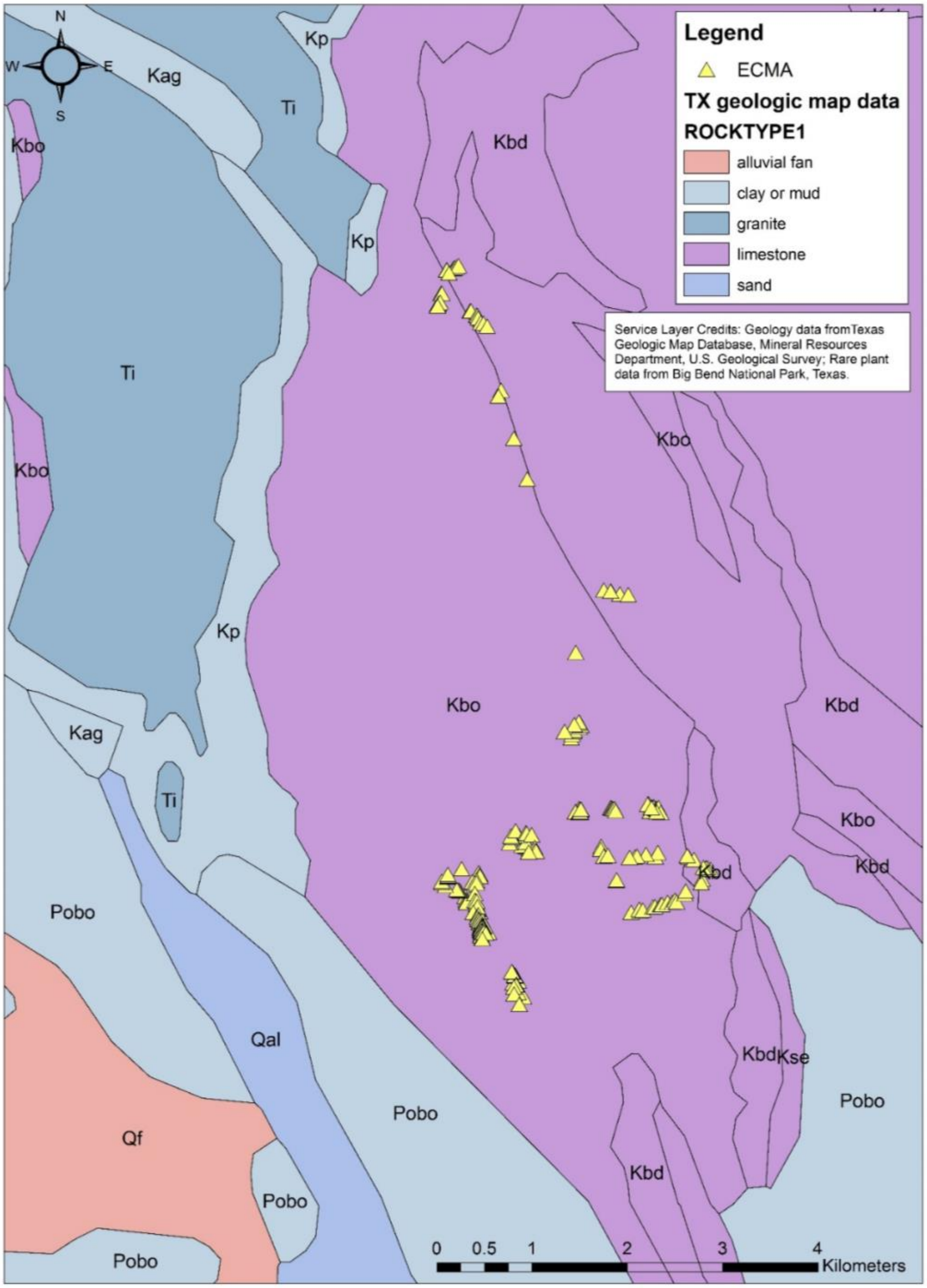
Map 4. Geological map and presence points for *Coryphantha ramillosa* subsp. *ramillosa*



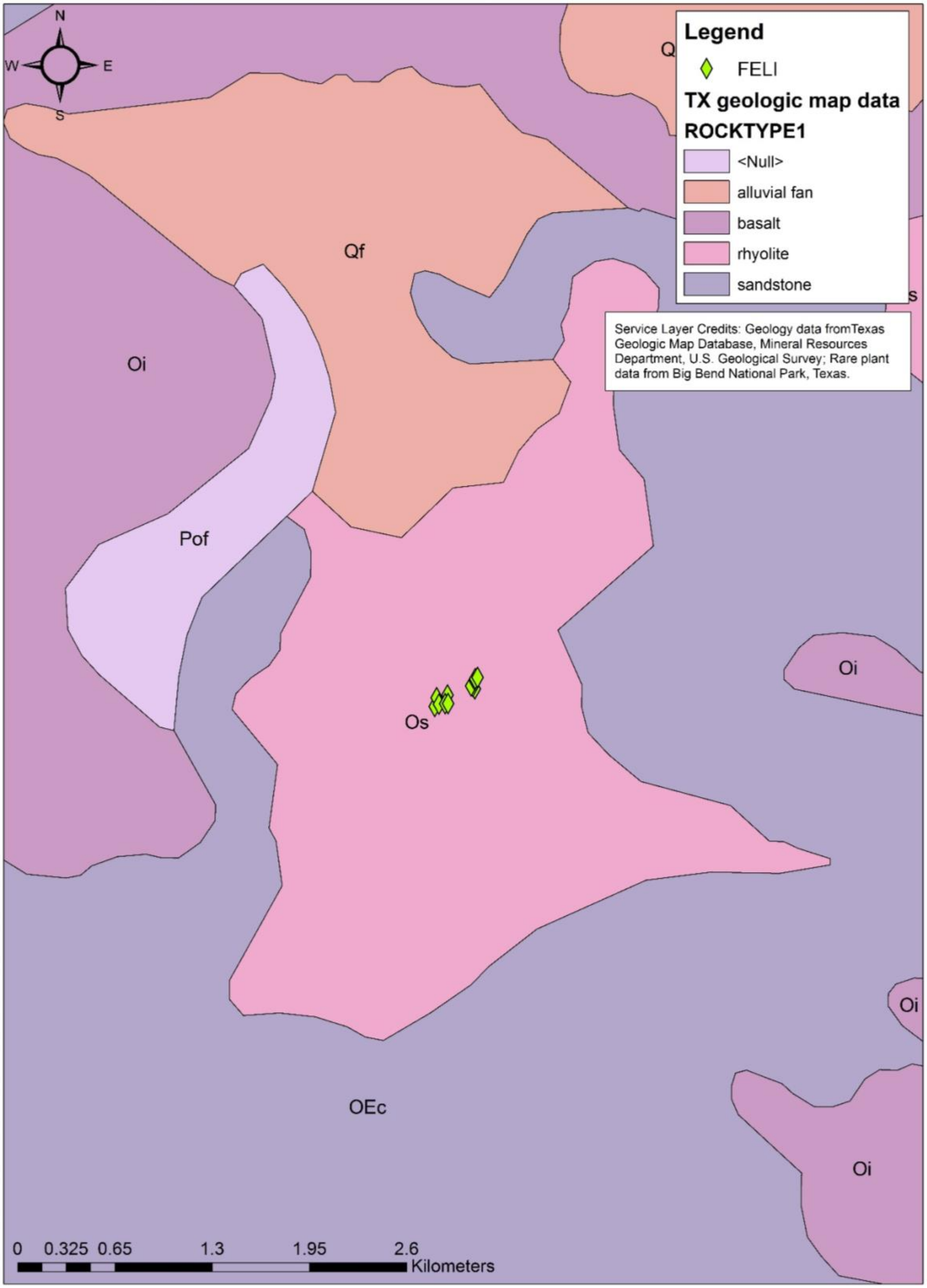
Map 5. Geological map and presence points for *Echinocereus chisoensis* var. *chisoensis*.



Map 6. Geological map and presence points for *Echinomastus mariposensis*.



Map 7. Geological map and presence points for *Festuca ligulata*.



Appendix D. Photos

Photo 1. Limestone cliffs near Rooney's Place where CORA is found (Aug. 2016).

Photo 2. Lower alluvium-filled valleys near CORA site (Aug. 2016).

Photo 3. The invasive *Cenchrus ciliaris* (buffelgrass) near the CORA site (Aug. 2016).

Photo 4. Top of limestone cliffs where CORA can normally be found (Aug. 2016).

Photo 5. CORA in limestone at ~45˚ angle (March 2017).

Photo 6. CORA flowering (Aug. 2016).

Photo 7. Two very dry, desiccated CORA plants (March 2017).

Photo 8. Vegetation at the ECCH site (Aug. 2016).

Photo 9. The invasive *Cenchrus ciliaris* (buffelgrass) near the ECCH site (Aug. 2016).

Photo 10. ECCH in the center of its nurse plant, *Larrea tridentata* (creosote) (March 2017).

Photo 11. ECCH surrounded by *Cylindropuntia schottii* (dog cholla) (March 2017).

Photo 12. Dark green, hydrated ECCH (Aug. 2016).

Photo 13. Healthy ECCH individual (March 2017).

Photo 14. ECCH flowering (March 2017).

Photo 15. Vegetation and geology at the ECMA site (March 2017).

Photo 16. ECMA on a very flat limestone surface (March 2017).

Photo 17. This ECMA was small, roughly the size of a golfball (March 2017).

Photo 18. ECMA flowering (March 2017).

Photo 19. ECMA flowering, up close (March 2017).

Photo 20. ECMA fruit (March 2017).

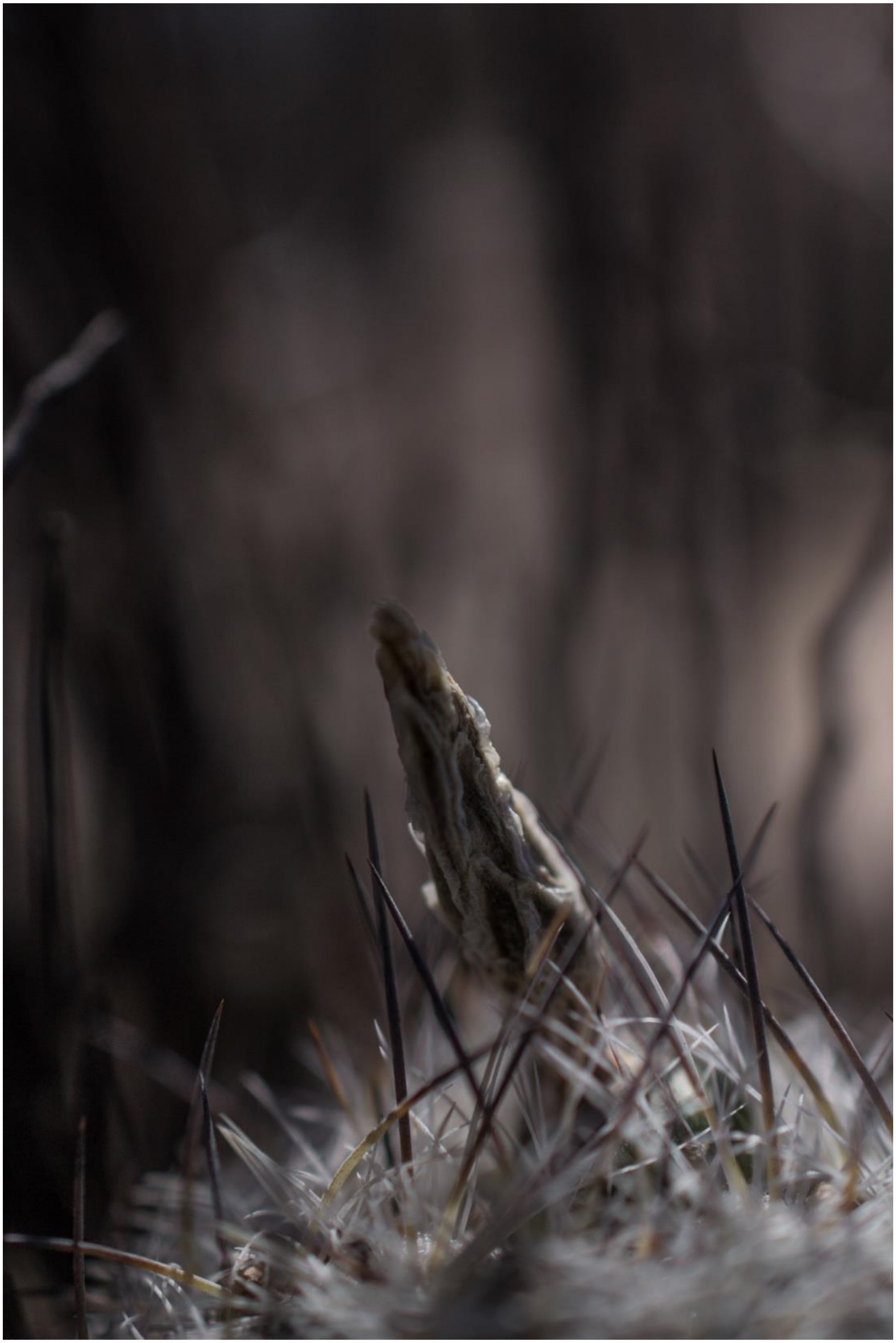


Photo 21. Leaf litter next to FELI (March 2017).

Photo 22. FELI site during large rain event (Aug. 2016).

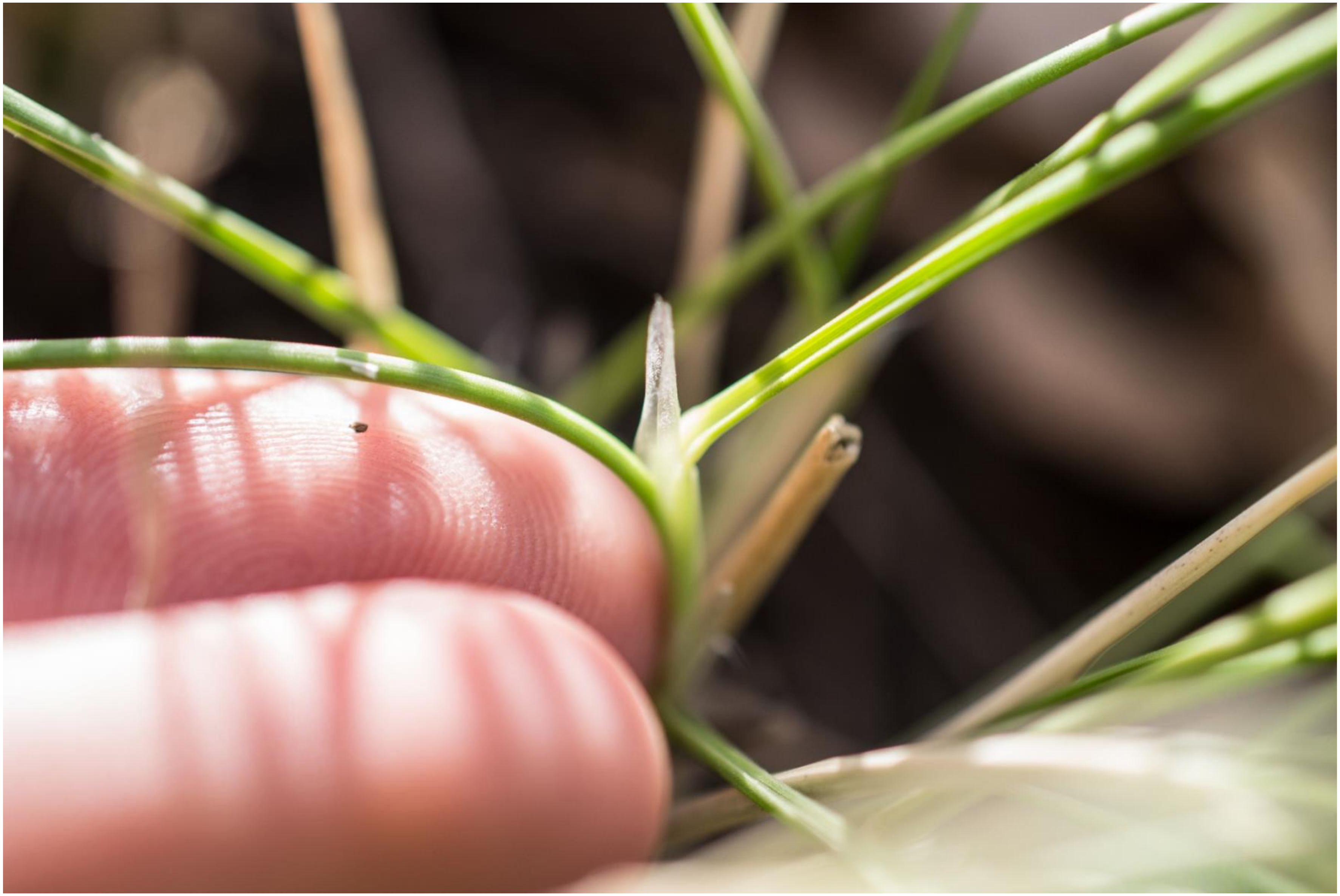
Photo 23. FELI inflorescence (Aug. 2016).

Photo 24. FELI inflorescence (Aug. 2016).

Photo 25. Talus slopes of Boot Canyon where FELI can be found (March 2017).

Photo 26. FELI found near Pinnacles Trail (March 2017).

Photo 27. FELI ligule (March 2017).



Glossary

CORA – *Coryphantha ramillosa* subsp. *ramillosa*, Bunched cory cactus

DEM – Digital elevation model

ECCH – *Echinocereus chisoensis* var. *chisoensis*, Chisos Mountain hedgehog cactus

ECMA – *Echinomastus mariposensis*, Lloyd's mariposa cactus

ESRI – Environmental Systems Research Institute

FELI – *Festuca ligulata*, Guadalupe fescue

GCS – Geographic coordinate system

GIS – Geographic information system

GLIMMIX – Generalized linear mixed models

GPS – Global positioning system

IUCN – International Union for Conservation of Nature

NAD – North American Datum

NLCD – National Landcover Database

NP – National Park

NPS – The National Park Service

NRCS – Natural Resources Conservation Service

OSU – Oregon State University

PRISM – Parameter-elevation Regressions on Independent Slopes Model

SAS – Statistical Analysis System

SSURGO – Soil Survey Geographic Database

subsp. – subspecies

TNC – The Nature Conservancy

TNRIS – Texas Natural Resources Information System

TPWD – Texas Parks and Wildlife Department

TWDB – Texas Water Development Board

USDA – United States Department of Agriculture

USFWS – United States Fish and Wildlife Service

USGS – United States Geological Survey

var. – variety

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Vita

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