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Final Report: Status of Barking Frog (*Craugastor augusti*) in New Mexico

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Introduction

The Barking Frog (*Craugastor augusti)* may be one of the most unique species in the United States and little is known about its ecology or conservation status (Schwalbe & Goldberg 2005). The species belongs to the tropical frog family (Craugastoridae), has direct development, and is the only representative of this family to reach New Mexico (Hedges et al. 2008). The species is also the only native frog in the southwestern U.S. to reproduce via direct development. There are five sub-species of *C. augusti*, three occur in Mexico, and two occur in the United States (*C. a. cactorum* in Arizona and *C. a. latrans* in Texas and New Mexico; referred to as *C. augusti* hereafter). The Texas-New Mexico subspecies is listed as a Species of Greatest Conservation Need in New Mexico.

Craugastor augusti is a habitat specialist and a secretive species, spending most of its life underground or in crevices of rocky outcrops. The secretive nature of this species is the likely reason very little is known about its ecology and conservation status (Schwalbe & Goldberg 2005). Rainfall appears to control much of the species activity, including breeding and dispersal, and because of this, it is considered an explosive breeder. Presumably the majority of its calling and reproduction occurs for a one to five-day period associated with thunderstorms between May and August (Radke 2001).

Numerous aspects of *C. augusti* ecology make it vulnerable to several threats. For instance, long-term changes in precipitation patterns from climate change can alter breeding and dispersal timing. Because *C. augusti* reproduces via direct development (i.e., does not require standing water for larval develop), it is necessary for eggs to remain moist during development (Streicher & Fujita 2014). Persistent drought and extreme dry periods can impact this species by creating dry soil conditions that can result in high rates of egg or froglet mortality (Jameson 1950; Streicher & Fujita 2014).

Habitat fragmentation and the species' small range also increase its threat risk. Because *C. augusti* is a habitat specialist, it is restricted to unique and isolated landscape features that include rocky escarpments and creosote flats with soft, gypsum soils (Degenhardt et al. 1996; Goldberg and Schwalbe 2004). Where *C. augusti* occur within these habitats, they can be abundant and easy to detect (Degenhardt et al. 1996; Schwalbe and Goldberg 2005), but alterations to an occupied area may irreparably damage these habitats. Within New Mexico, *C. augusti* has a small and disjunct distribution with little to no population connectivity (Degenhardt et al. 1996; Streicher et al. 2014), and loss of any suitable habitat can have severe population impacts.

The goal of this project was to determine the current status of known *C. augusti* populations and assess potential threats to the species. We conducted presence/absence surveys at known populations of *C. augusti* in southeastern New Mexico, as well as other (supplemental) localities where the species is predicted to occur based on habitat niche models. This report summarizes this effort, provides a niche model, an occupancy model, and recommendations for long-term monitoring.

Methods

Field Methods

We complied historical localities of *C. augusti* from published and gray-literature and museum records to establish sampling localities. We identified 20 unique sampling localities (later referred to as 'targeted sites') in New Mexico from a total of 550 locality records from 43 museum collections. In addition, we sampled 39 other sites (later referred to as 'supplemental sites') there were in the vicinity of known localities (within 30km) and had suitable habitat. This was done to determine if unrecorded populations occur within the study region. In total we sampled 59 unique sites.

Sampling began on 7 May 2015 and concluded on 28 August 2015. We conducted call surveys approximately every two-weeks or when weather conditions were expected to be ideal for frog calling activity (recent or concurrent rainfall). Rainfall is the best predictor of *C. augusti* calling activity, and sampling trips were planned according to rainfall events (Radke 2001).

We used standardized call surveys to assess calling intensity of frogs at both historical and supplemental sites. This method provides an assay of breeding male relative abundance and is ideal for assessing species presence or absence (Heyer et al. 1994). Sites were scored using a relative abundance metric: 0 = no frogs heard calling; 1 = individuals could be counted; 2 = calls overlapping but individuals can still be distinguished; 3 = full chorus, cannot distinguish individuals.

For each survey we recorded time of survey, air temperature, percent cloud cover, wind speed estimated from Beaufort Wind Scale, and moon cycle and percentage.
When appropriate, i.e. if frogs were calling on public and accessible lands, we conducted visual encounter surveys to locate frogs and collect chytridiomycosis swabs when possible.

Weather Data

We obtained mean monthly minimum and maximum temperature and precipitation data between 1980 and 2015 from eight weather stations within the range of *C. augusti* (Carlsbad, Carlsbad Airport, Bitter Lakes, Brantley Dam, Roswell Airport, Roswell, and NMSU). Data were acquired from the Western Regional Climate Center for this 35-year period (WRCC 2015). We calculated 35-year monthly mean minimum and maximum temperatures and monthly rainfall from January to December.

Activity time

We reviewed all published papers, agency reports, museum records, and public observations to determine the activity period of the species. We calculated the number of days per month the species has been observed in New Mexico from these records. This is an aggregation of all records ranging from 1944 to 2015 and provides a frequency histogram of the species' activity.

Niche Model

We compiled occurrence records for *C. augusti* in United States by querying large multi-institutional databases and online sources (e.g. iDigbio and Vertnet). We normalized the taxonomic designations and used openRefine software (http://openrefine.org) to further correct errors in geographic or taxonomic data associated with each occurrence. In addition, each record was considered for georeferencing (assignment of geographical coordinates) if only a verbatim description of a locality was assigned. We followed the same georeferencing protocols as those used by large-scale efforts for natural history museum collections of vertebrates (see http://www.vertnet.org) and relied on Geolocate software developed by Bart and Rios (http://www.museum.tulane.edu/geolocate/) for coordinate assignments. Only those records that had an error radius of less than 5km (thus fitting within an analysis cell) were considered fit for use and saved for further analyses.

To map suitable landscapes for *C. augusti*, we selected an algorithm based on maximum entropy (Maxent; Elith et al. 2010) because it is ideal for evaluating relationships between predictor variables and species whose occurrence is based on museum records that are presence-only data. We used Maxent's built-in functions for random seeds, background selection, cross-validation, and model averaging to calculate the level of habitat suitability for *C. augusti* (Phillips & Dudík 2008). This approach allowed us to determine those abiotic and biotic variables that best predict the occurrence of *C. augusti* in New Mexico from a set of variables we chose based on the species' ecology.

Occupancy Model

To estimate detectability associated with *C. augusti* occupancy, and ultimately estimate likelihood of occupancy at sites where no *C. augusti* were detected, we used the R package 'unmarked' (Fiske & Chandler 2011). We relied on the single-season model (MacKenzie et al. 2002) to account for imperfect detectability and to initially fit occurrence models with no linkage between abundance and detection. We then assessed models using a multimodel inference approach. When creating a priori models, we only relied on the variables that we considered to affect detectability and for which we had data for all sampling occasions. Those variables were: day of year, wind speed, observer, cloud cover; we treated those variables as observation covariates. We ranked competing models with Akaike Information Criterion by calculating differences between candidate models and the lowest AIC (Δi AIC) model. We used Akaike weight (w_i) for each model to guide selection of the most parsimonious model. Survey points that were within 500m meters of each other were considered the same for occupancy analyses.

Results

We performed a total of 104 call surveys and detected calls of *C. augusti* during nine of them. These nine positive detections represented six sites (Tables 1 and 2). The weather data for 2015 is incomplete, therefore figures presenting the data for this year stop at September. The study region received above average rainfall in May and July but below average rainfall in June and August (Fig 1A). With the exception of July at the Carlsbad station, the monsoon months received below average rainfall. There was little variation in mean monthly temperature in 2015 compared to the 35-year mean monthly measurements (Fig 1B).

Based on compiled observations, this species is most frequently observed between May and September with most records in July. This corresponds well with 35-year mean of monthly precipitation (Figure 2A) and mean monthly minimum and maximum temperatures (Figure 2B).

The niche model that best describes the distribution of *C. augusti* in New Mexico indicates that areas that are most suitable occur in the vicinity of Roswell and Carlsbad, but also near the Organ Mountains east of Las Cruces and on Crow Flats, north of Dell City, TX (Figures 3—7). Most important variables that drive the model of distribution are minimum winter temperatures, sum of monsoon precipitation (Jul-Sep), geologic features, minimum temperatures between March and October, and depth to any restrictive layer in soil (Table 3).

We detected *C. augusti* at six out of 23 historical areas where the species was documented. Overall naïve occupancy rate was near 0.25; however, models of occupancy indicate that time of year plays a significant role in detectability of the frog. According to the best occupancy model (Table 4), the highest probability of detection is near 0.7 at the beginning of the sampling season (Figure 8). We used a parametric bootstrap to check the adequacy of fit of the model based on detectability varying with time of year. We used a chi-squared test of model fit. We failed to reject the null hypothesis (null hypothesis being that the model computed from data is different from that computed on bootstrap samples), thus consider our best occupancy model to be useful for further surveys.

Discussion and conclusions

Despite the low number of sites where *C. augusti* was detected, it is promising to note that at least one detection occurred in each of the four "core" regions (Figures 4—7). The four regions are loosely described as areas near Roswell, Carlsbad, Dell City, TX and Las Cruces. Due to the limited activity period and secretive nature of this species, our observed occupancy is likely an underestimate.

Throughout our surveys, detectability appeared to be closely tied to the presence of recent rains or high humidity, consistent with the findings of Radke (2001). Due to the sporadic nature of rainfall during the active period, consistent sampling under ideal conditions was problematic. With the exception of Aguirre Springs, all occupied sites were similar in habitat type and were comprised of creosote flats with friable soil suitable for burrowing. The occupied site at Aguirre Springs is characterized by premontane habitat with large boulders, more similar to habitats occupied by *C. augusti cactorum* in Arizona.

The highest call intensities were observed at sites in proximity to riverine systems, such as those along the Pecos River near Bitter Lakes National Wildlife Refuge (NWR) and along the Black River near the Cottonwood Day Use Area. These sites may either harbor larger populations or allow for increased activity due to consistently higher humidity.

Recommendations

We found that six sites had calling activity in 2015 and this is likely an underestimate. Because of the species' secretive habits and explosive breeding strategy, this species is very difficult to sample. It is not possible to determine any population trends using data collected during a study based on a single year. To truly assess the status of this species and potential threats to its persistence, a long-term, multi-year sampling strategy is necessary. While this species poses many sampling problems, it is nevertheless possible to design a cost-effective protocol. The primary issue to effectively sample this species is being present during or immediately after rainfall events to maximize the potential of detection of calling individuals. To overcome this significant barrier, we suggest creating an interagency and local volunteer program for monitoring. Many *C. augusti* populations are located on State or Federal lands making it feasible to request that local land managers be in charge of conducting call surveys on these lands after rainfall events. In addition, coordination between agency personnel and local non-profits could promote species monitoring (Table 5).

Establishing a cooperative citizen science initiative would be the most effective way to monitor *C. augusti* in New Mexico. Recruiting and training local citizens that have an interest in natural history could provide systematic and temporally consistent data on species activity and status. For instance, volunteers could be assigned a route to sample when environmental conditions, i.e. rainfall events, are most suitable for *C. augusti* sampling. The benefit to this approach is that a small number of volunteers could collect a large amount of valuable data. Study sites could be established at localities identified historically such as Bitter Lake NWR, Brantley Lake State Park, Bottomless Lakes State Park, Organ Mountains National Recreation Area, and other scattered areas near Roswell and Carlsbad.

Data sheets and sampling protocols (Appendix) could be provided to volunteers. Volunteers can then scan data sheets and email them to New Mexico Department of Game and Fish (NMDGF). In addition, volunteers could report their observations to the iNaturalist and Herpmapper platforms, where NMDGF biologists can monitor the progress of data collection. This initiative would increase cooperation between agencies and local residents in monitoring a unique and enigmatic species in New Mexico.

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Table 1. Chronological list of field surveys for *Craugastor augusti* during 2015.

Site	*Date*	*Time*	*Detection*	*Call Intensity*	*Site Type*
Park's Ranch	7 May	2128-2133	-	0	Target
Brantley Lake	7 May	2256-2259	+	2	Target
Park's Ranch	8 May	2305-2358	+	1	Target
Crau-augu_17	9 May	2221-2224	-	0	Target
Crau-augu_28	16 June	2130-2133	+	3	Target
Crau-augu_17	16 June	2235-2238	-	0	Target
Crau-augu_15	17 June	0123-0200	-	0	Target
Crau-augu_27	17 June	2330-2355	-	0	Target
Crau-augu_10	21 June	2047-2050	-	0	Target
MSB 23896	21 June	2051-2054	-	0	Target
Crau-augu_19	21 June	2139-2140	+	3	Target
Bitter Lakes	21 June	2140-2143	+	3	Target
CRAU1	21 June	2030-2033	-	0	Suppl.
CRAU2	21 June	2035-2038	-	0	Suppl.
CRAU3	21 June	2039-2042	-	0	Suppl.
CRAU4	21 June	2217-2220	-	0	Suppl.
Crau-augu_29	25 June	2218-2242	-	0	Target
CRAU_6/25-1	25 June	2255-2258	-	0	Suppl.
Crau-augu_21	25 June	2322-2328	-	0	Target
CRAU_6/26-1	26 June	2324-2327	-	0	Suppl.
CRAAUG 2344	26 June	2344-2347	+	1	Suppl.
Crau-augu_27	26 June	2355-2358	-	0	Target
CRAAUG_6/27	27 June	0040-0044	-	0	Suppl.
CRAU-BML1	3 July	0014-0017	-	0	Suppl.
CRAUBRANT-1	3 July	2024-2027	-	0	Suppl.
CRAUBRANT-4	3 July	2038-2041	-	0	Suppl.
CRAUBRANT-2	3 July	2046-2049	-	0	Suppl.
CRAUBRANT-3	3 July	2052-2055	-	0	Suppl.
Crau-augu_9	3 July	2101-2104	-	0	Suppl.
Crau-augu_21	3 July	2118-2121	-	0	Suppl.
CRAU-Dark-Can-1	3 July	2159-2202	-	0	Suppl.
Crau-augu_28	3 July	2221-2224	-	0	Suppl.
Crau-augu_29	3 July	2310-2313	-	0	Suppl.
Co Rd F041-1	4 July	0001-0004	-	0	Suppl.
ELPA-4	4 July	2050-2053	-	0	Suppl.
ELPA-5	4 July	2101-2104	-	0	Suppl.
ELPA-1	4 July	2107-2110	-	0	Suppl.
ELPA-2	4 July	2119-2122	-	0	Suppl.
ELPA-7	4 July	2133-2136	-	0	Suppl.
ELPA-3	4 July	2145-2148	-	0	Suppl.
ELPA-6	4 July	2215-2218	-	0	Suppl.
ELPA-8	4 July	2220-2223	-	0	Suppl.
CF1 (Sr 506)	4 July	2230-2233	-	0	Suppl.
CF2 (Sr 506)	4 July	2234-2237	-	0	Suppl.
Crau-augu_27	4 July	2236-2339	-	0	Target
Sr 506-1	4 July	2301-2304	-	0	Suppl.
Sr 506-2	4 July	2308-2311	-	0	Suppl.

Sr 506-3	4 July	2314-2317	-	0	Suppl.
Crau-augu_20	11 July	2045-2048	-	0	Target
Baylor Can-1	11 July	2126-2129	-	0	Suppl.
Baylor Can-2	11 July	2132-2135	-	0	Suppl.
Baylor Can-3	11 July	2139-2142	-	0	Suppl.
Baylor Can-4	11 July	2145-2148	-	0	Suppl.
Oliver Lee-1	12 July	2101-2104	-	0	Suppl.
Oliver Lee-2	12 July	2129-2132	-	0	Suppl.
Crau-augu_20	12 July	2107-2110	-	0	Target
Crau-augu_20	12 July	2345-2348	+	1	Target
Crau-augu_10	17 July	0007-0010	-	0	Target
Crau-augu_12	17 July	0016-0019	-	0	Target
CRAU6	17 July	0026-0029	-	0	Suppl.
CRAU11	17 July	0034-0037	-	0	Suppl.
CRAU9	17 July	0056-0059	-	0	Suppl.
Crau-augu_19	17 July	2041-2044	-	0	Target
Crau-augu_6	17 July	2047-2050	-	0	Target
CRAU1	17 July	2056-2059	+	2	Suppl.
CRAU2	17 July	2101-2104	+	2	Suppl.
Crau-augu_5	17 July	2111-2114	-	0	Target
Crau-augu_8	17 July	2116-2119	-	0	Target
Crau-augu_4	17 July	2132-2135	-	0	Target
Crau-augu_26	17 July	2152-2155	-	0	Target
*Crau-augu_*	17 July	2217-2220	-	0	Target
CRAU4	17 July	2310-2313	-	0	Suppl.
CRAU10	17 July	2324-2327	-	0	Suppl.
CRAU1	17 July	2339-2342	-	0	Suppl.
CRAU2	17 July	2344-2347	-	0	Suppl.
CRAU3	17 July	2356-2359	-	0	Suppl.
Crau-augu_20	20 July	2049-2052	-	0	Target
Baylor Can-1	20 July	2127-2130	-	0	Suppl.
Baylor Can-2	20 July	2136-2139	-	0	Suppl.
Baylor Can-3	20 July	2144-2147	-	0	Suppl.
Baylor Can-4	20 July	2121-2154	-	0	Suppl.
Crau-augu_20	24 July	2049-2052	-	0	Target
Baylor Can-1	24 July	2127-2130	-	0	Suppl.
Baylor Can-2	24 July	2136-2139	-	0	Suppl.
Baylor Can-3	24 July	2144-2147	-	0	Suppl.
Baylor Can-4	24 July	2121-2154	-	0	Suppl.
Oliver Lee-1	25 July	2130-2133	-	0	Suppl.
Oliver Lee-2	25 July	2149-2152	-	0	Suppl.
Crau-augu_20	29 July	2049-2052	-	0	Target
Baylor Can-1	29 July	2115-2118	-	0	Suppl.
Baylor Can-2	29 July	2230-2233	-	0	Suppl.
Baylor Can-3	29 July	2237-2340	-	0	Suppl.
Baylor Can-4	29 July	2248-2251	-	0	Suppl.
Crau-augu_20	8 August	2115-2118	-	0	Target
Baylor Can-1	8 August	2201-2204	-	0	Suppl.
Baylor Can-2	8 August	2207-2210	-	0	Suppl.
Baylor Can-3	8 August	2214-2217	-	0	Suppl.
Baylor Can-4	8 August	2220-2223	-	0	Suppl.

BL-1	27 August	2106-2109	
Crau-augu_10	27 August	2116-2119	Target
Crau-augu_12	27 August	2130-2133	Target
Crau-augu_13	27 August	2149-2152	Target
Crau-augu_28	28 August	2311-2314	Target
Crau-augu_17	28 August	2331-2334	Target

Table 2. Summary of surveys and detections of *Craugastor augusti* during 2015 surveys.

Month	*# Surveys*	*# Detected*
May	4	2
June	19	4
July	70	3
August	11	0
TOTAL	**104**	**9**

Table 3. List of most important variables contributing to a mean of the five best species distribution models of *Craugastor augusti* based on records from the United States. Variables not listed accounted for less than 5% individually.

Variable	***Percent contribution***
Minimum temperature (Oct-Mar)	28.5
Sum of precipitation (Jul-Sep)	27.6
Rock type on landscape	12.2
Minimum temperature (Mar-Oct)	11.1
Depth to restrictive layer (in soil)	7.7

Table 4. Two models from analysis of *Craugastor augusti* occupancy in New Mexico based on 2015 surveys of targeted and supplemental historical localities. Models are ranked from lowest to highest AIC values. Number of parameters includes a parameter for estimated occupancy and detectability (thus a model with no covariates has two parameters).

Model	*Number of parameters*	*AIC*	*Δi AIC*	w_i
Day of year	3	57.86	0.00	0.974
No observation or site covariates	2	65.07	7.21	0.026

Table 5. List of agencies and non-profit organizations to contact for recruiting volunteers for long-term monitoring.

Name	*Location*	*Type*	*Website*
Friends of Bitter Lake National Wildlife Refuge	Roswell	Non-profit	http://www.friendsofbitterlake.com/
Bitter Lake National Wildlife Refuge	Roswell	Federal Agency	http://www.fws.gov/refuge/Bitter_Lake/
Carlsbad Caverns National Park	Carlsbad	Federal Agency	http://www.nps.gov/cave/index.htm
New Mexico Chapter Audubon Society	Albuquerque	Non-profit	http://nm.audubon.org/
J. Kenneth Smith Bird Sanctuary & Nature Center	Roswell	Non-profit	http://www.roswellbirds.org/
Bottomless Lakes State Park	Roswell	State Agency	http://www.emnrd.state.nm.us/SPD/bottomlesslakesstatepark.html
Brantley Lake State Park	Carlsbad	State Agency	http://www.emnrd.state.nm.us/SPD/brantleylakestatepark.html
Aguirre Springs (Bureau of Land Management)	Las Cruces	Federal Agency	http://www.blm.gov/nm/st/en/prog/recreation/las_cruces/aguirre_spring_campground.html
Organ Mountains – Desert Peaks National Monument	Las Cruces	Federal Agency	http://www.blm.gov/pgdata/content/nm/en/prog/NLCS/OMDP_NM.html

A.

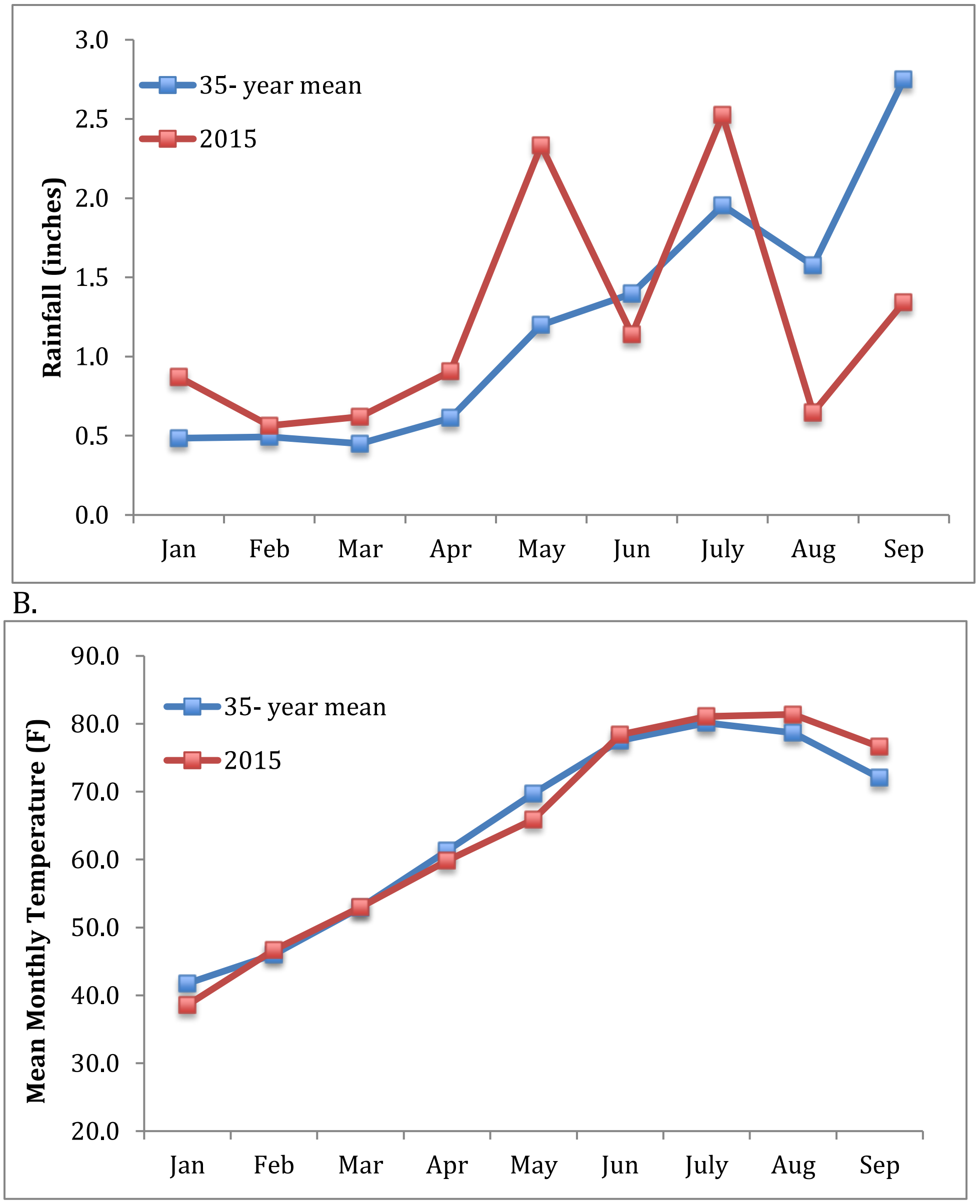
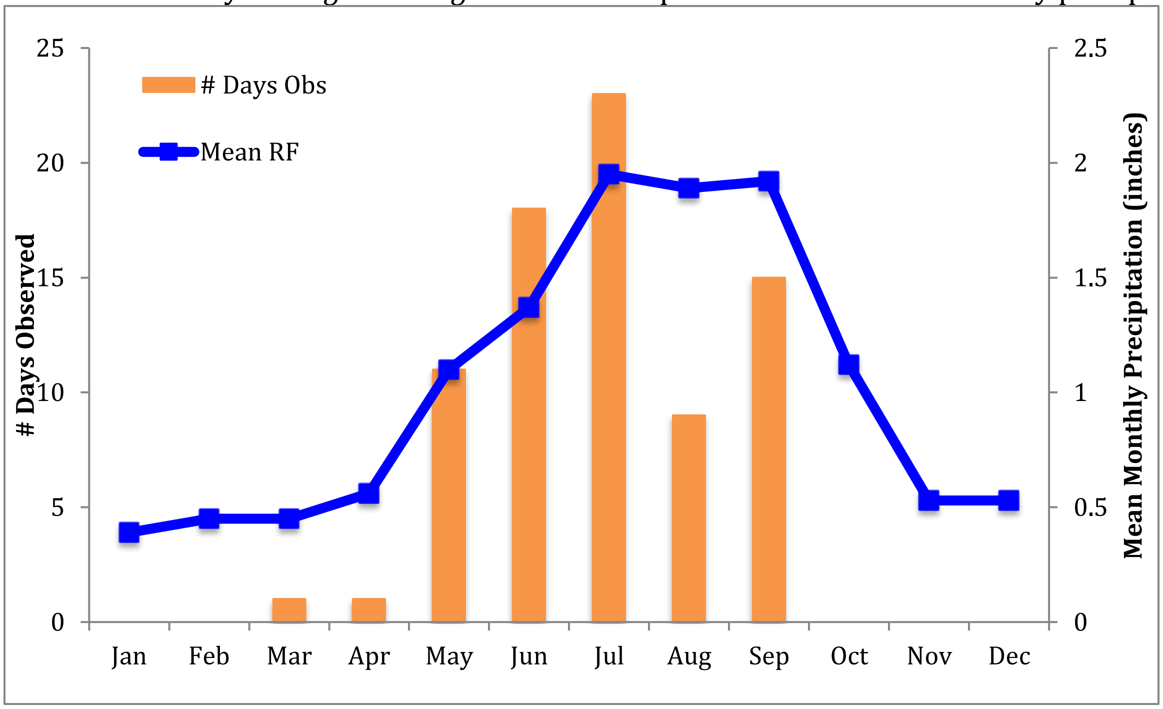


Figure 1. Monthly climatic summary calculated from eight regional weather stations. Blue line is 35-year monthly mean; red line is 2015 data for (A) mean monthly temperature and (B) monthly rainfall total.

A. Number of days *Craugastor augusti* observed per month vs. mean monthly precipitation.



B. Number of days *Craugastor augusti* observed per month vs. mean monthly minimum and maximum temperature.

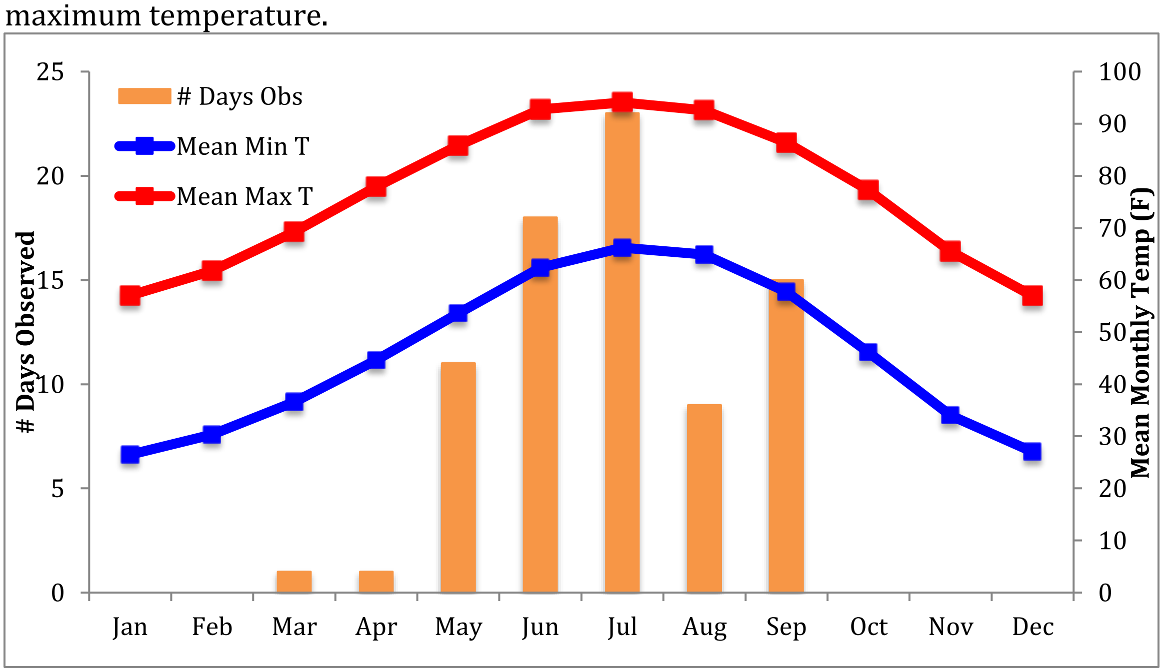


Figure 2. Frequency histogram summarizing the aggregated number of days per month *Craugastor augusti* has been observed. This includes all observations from 1944 to 2015. Climatic data represents 35-year monthly means (see text for details).

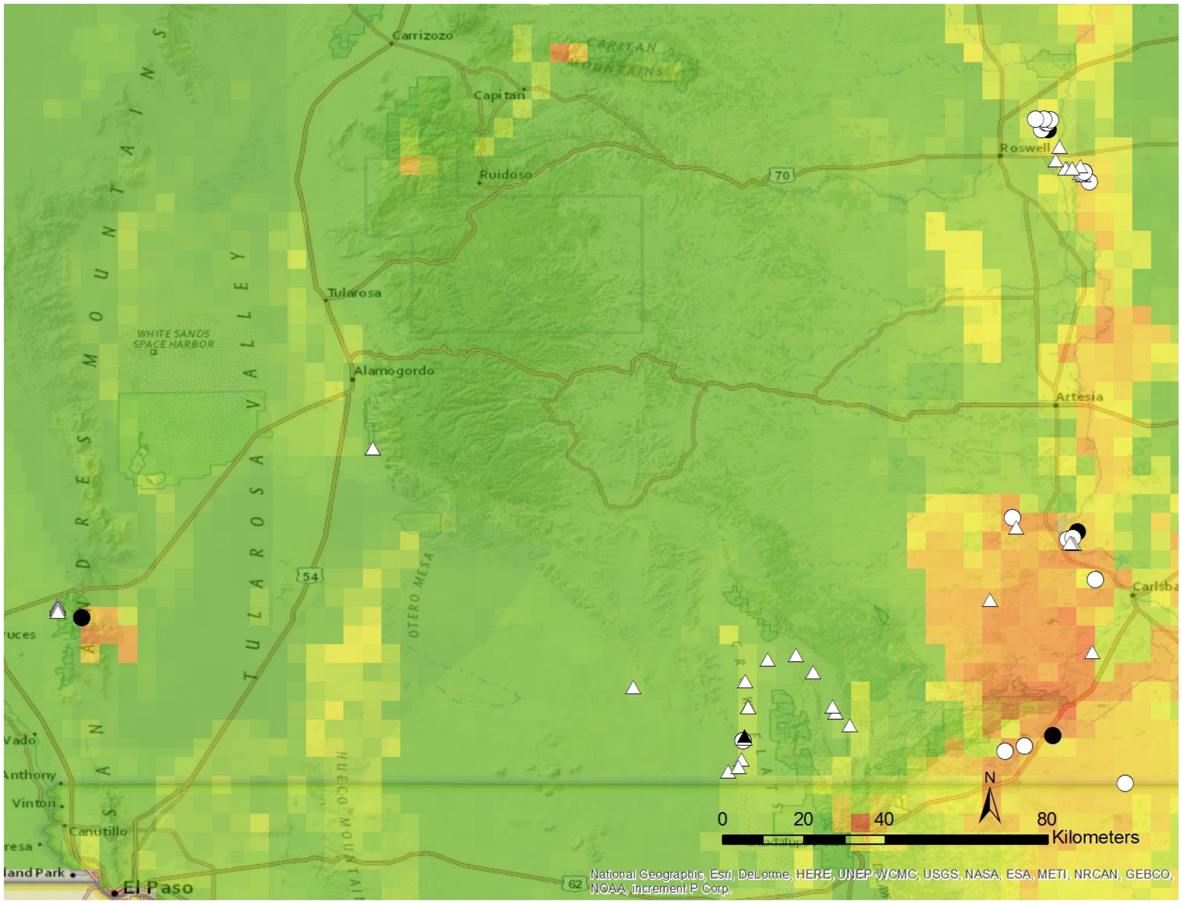


Figure 3. Map indicating localities sampled in this study in southeastern New Mexico overlayed on the best species distribution model for *Craugastor augusti*. Circles indicate targeted surveys while triangles indicate sites of supplemental surveys. Black-filled symbols indicate detection of species and white-filled symbols signify non-detection during a survey.

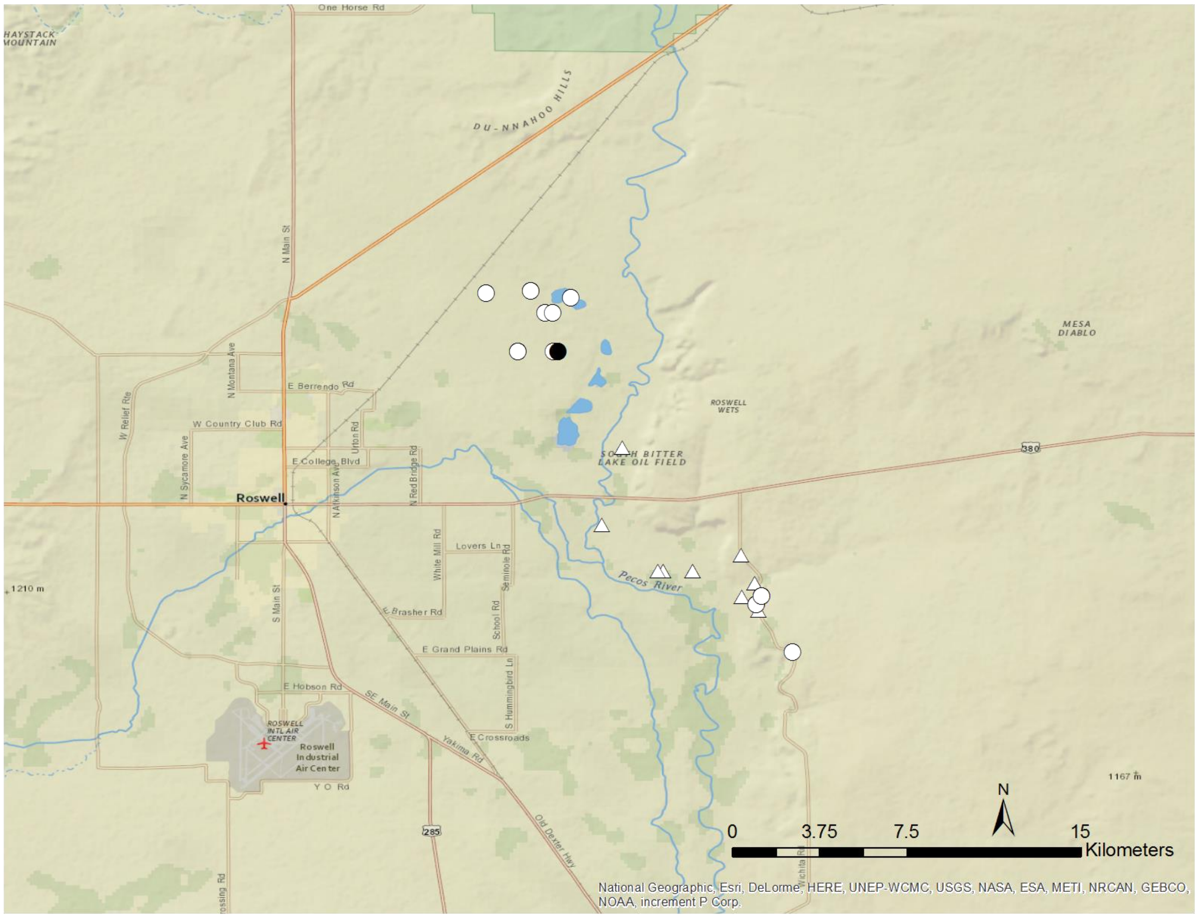


Figure 4. Map indicating localities sampled in this study near Roswell. Circles indicate targeted surveys while triangles indicate sites of supplemental surveys. Black-filled symbols indicate detection of *Craugastor augusti* and white-filled symbols signify non-detection during a survey.

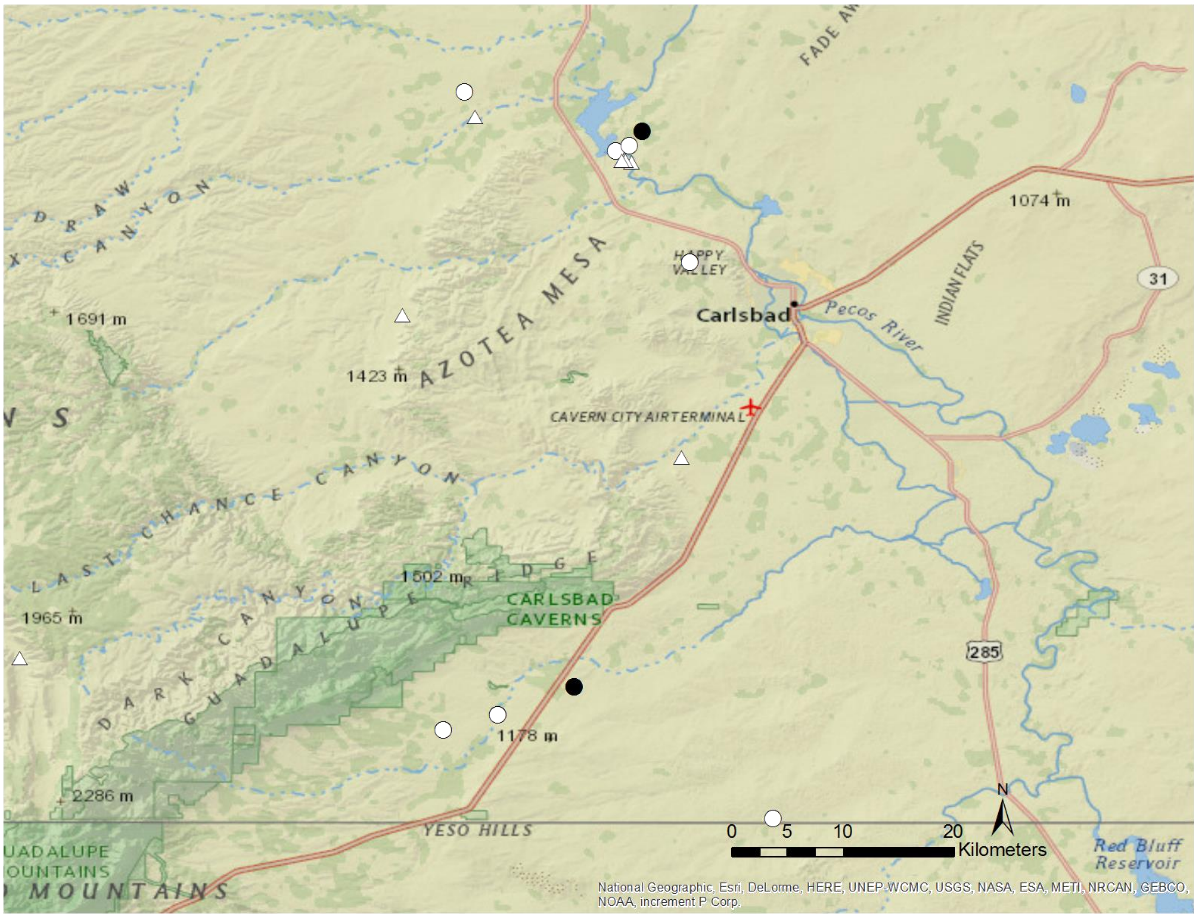


Figure 5. Map indicating localities sampled in this study near Carlsbad. Circles indicate targeted surveys while triangles indicate sites of supplemental surveys. Black-filled symbols indicate detection of *Craugastor augusti* and white-filled symbols signify non-detection during a survey.

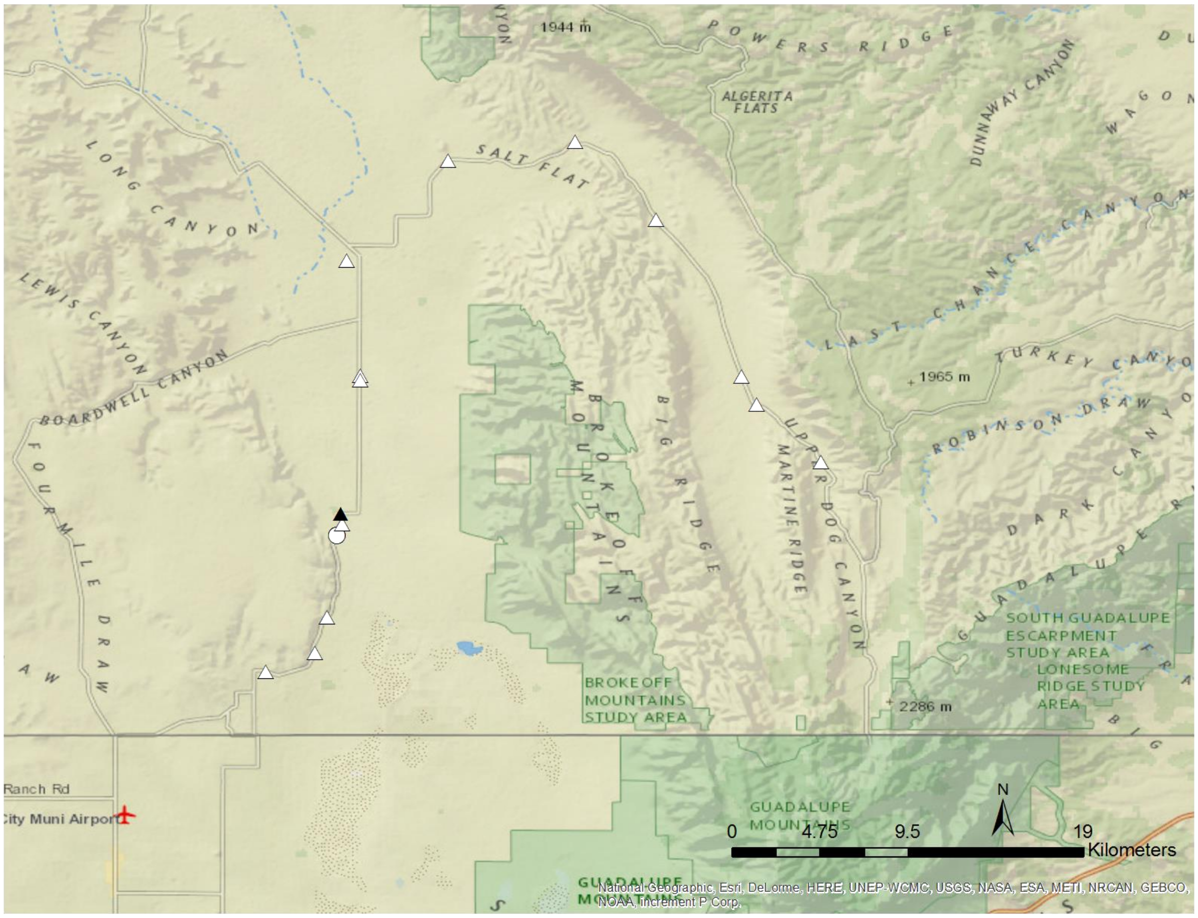


Figure 6. Map indicating localities sampled in this study near Dell City. Circles indicate targeted surveys while triangles indicate sites of supplemental surveys. Black-filled symbols indicate detection of *Craugastor augusti* and white-filled symbols signify non-detection during a survey.

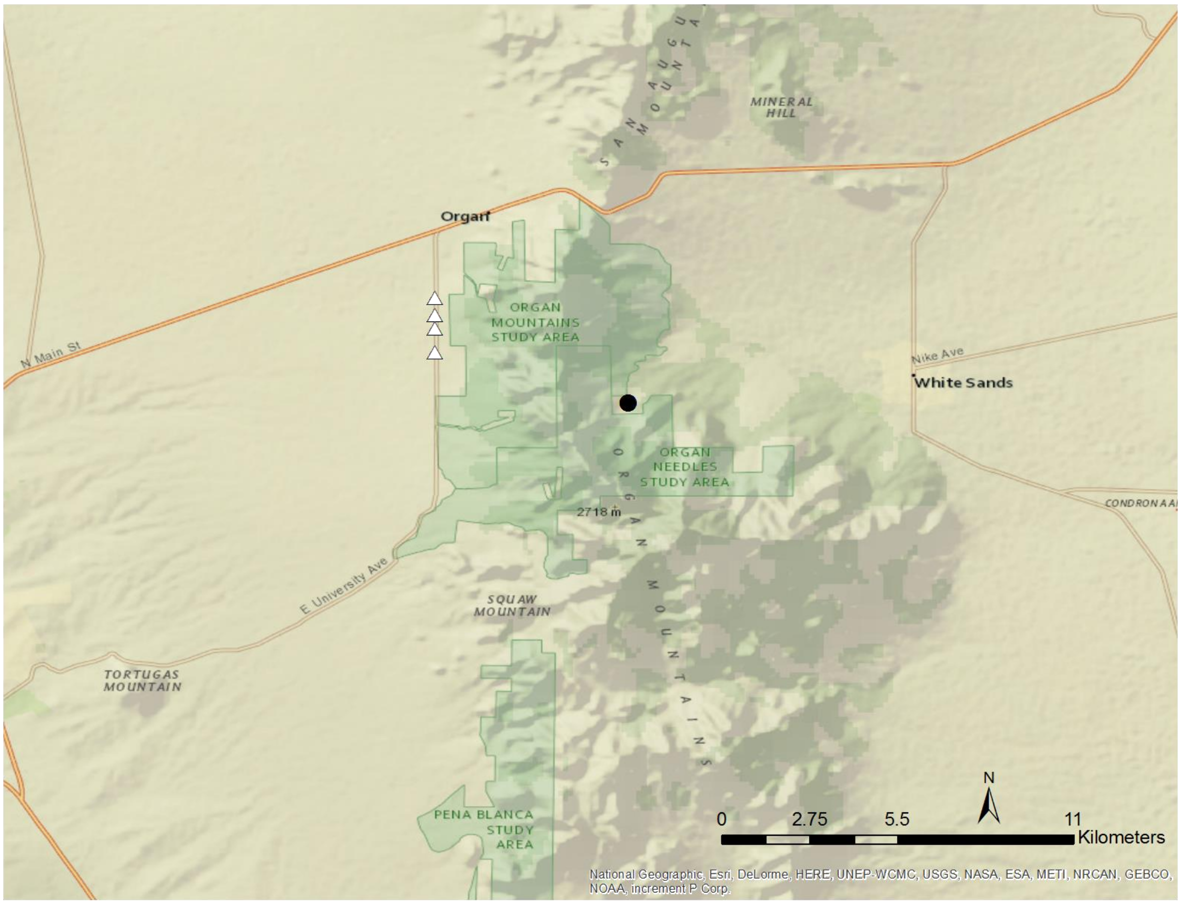


Figure 7. Map indicating localities sampled in this study near Las Cruces. Circles indicate targeted surveys while triangles indicate sites of supplemental surveys. Black-filled symbols indicate detection of *Craugastor augusti* and white-filled symbols signify non-detection during a survey.

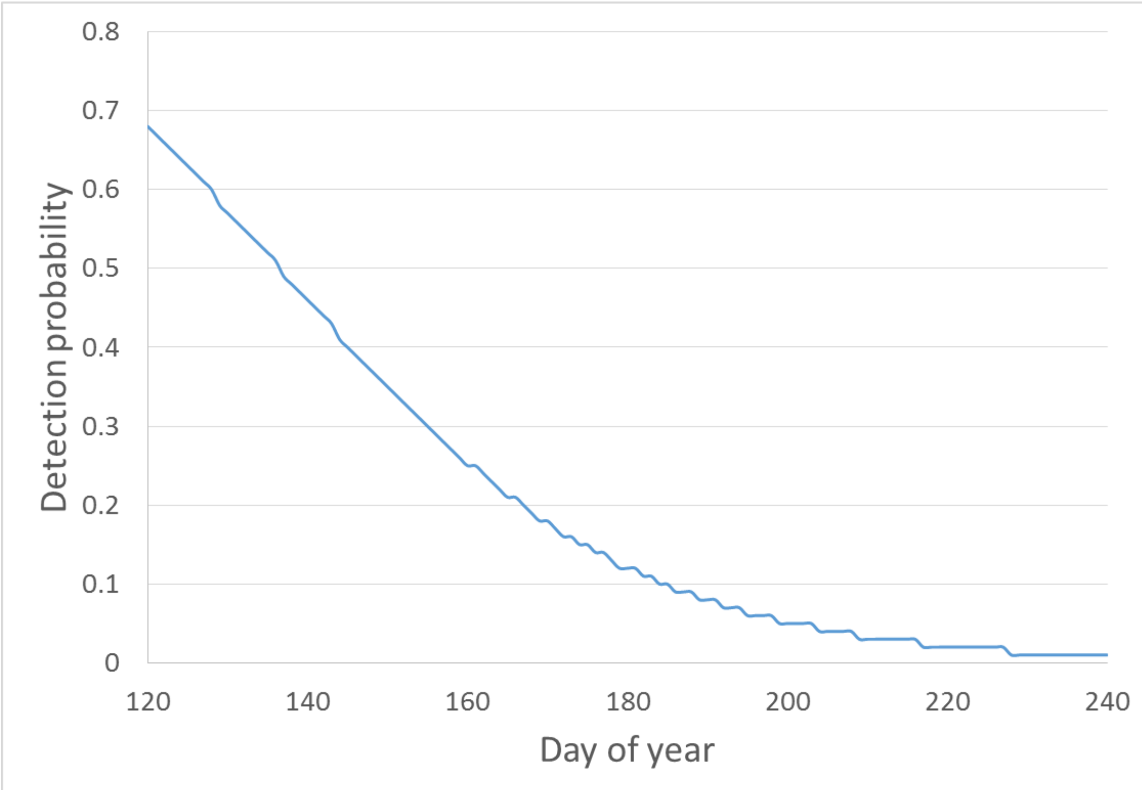


Figure 8. Estimated detection probability during this study's sampling period in 2015 for *Craugastor augusti* in New Mexico.