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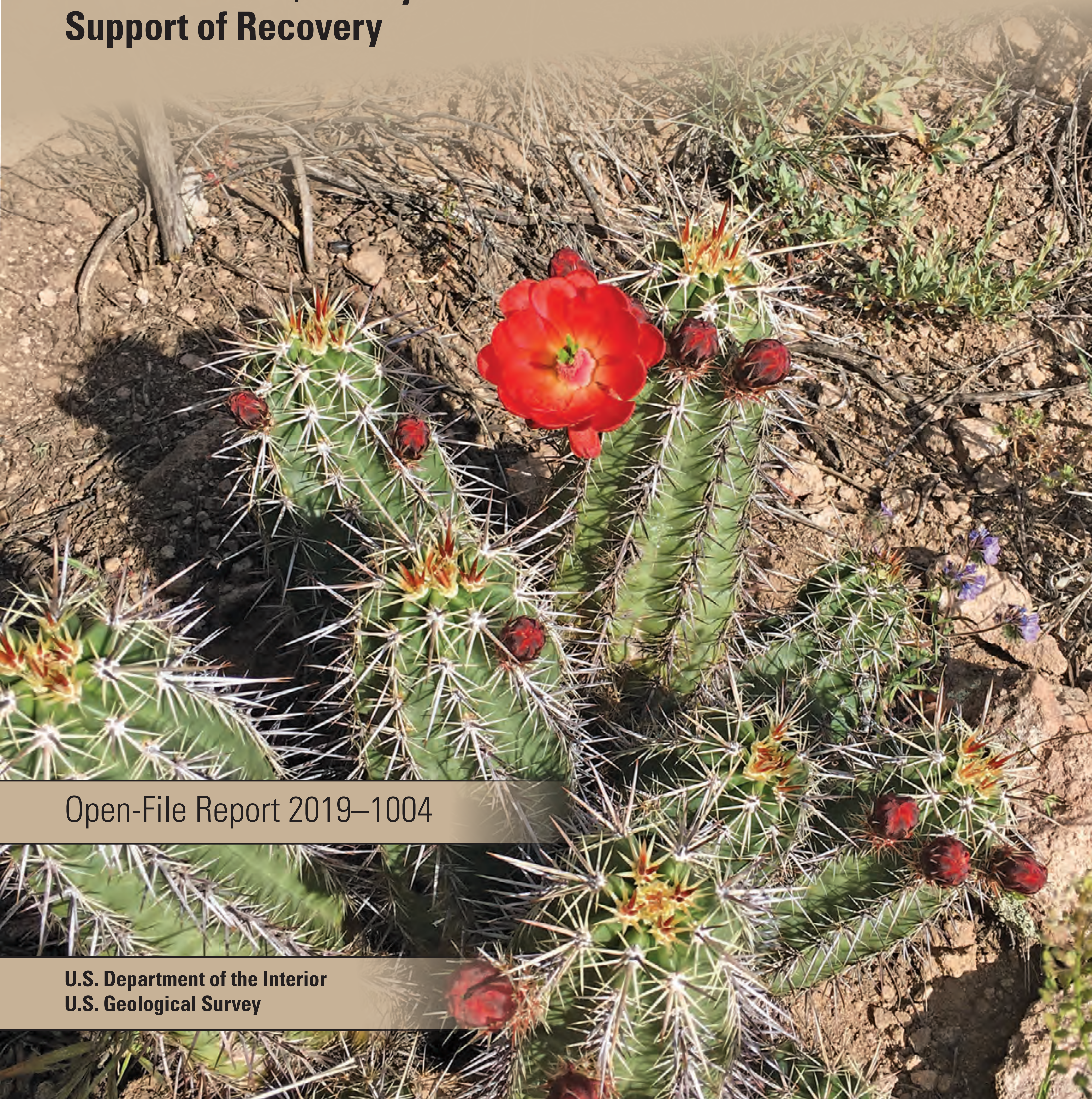
Arizona Hedgehog Cactus (*Echinocereus triglochidiatus* var. *arizonicus*)—A Systematic Data Assessment in Support of Recovery



Open-File Report 2019–1004

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph showing Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) along U.S. Route 60, Tonto National Forest, near Superior, Arizona, April 17, 2017. Photograph by Joshua Fife, Arizona Department of Transportation, used with permission.

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Preface

The Federally listed Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) occurs in a narrow range in Madrean woodlands and Interior Chaparral plant communities in Gila and Pinal counties in central Arizona. U.S. Fish and Wildlife biologists have recognized several activities that have resulted in habitat loss for the species and loss of individual cacti. In addition to road construction and road widening, the potential of further development of large copper mines within the range of the cactus prompted U.S. Fish and Wildlife biologists to approach the U.S. Geological Survey (USGS) for technical help in organizing and assessing existing survey and monitoring data for the Arizona hedgehog cactus. This Open-File Report describes the three tasks USGS ecologists undertook to compile and assess these existing data and includes a demographic analysis of monitoring data collected by environmental consultants for mining companies operating within the range of the Arizona hedgehog cactus.

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Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Area	
square meter (m^2)	10.76	square foot (ft^2)
hectare (ha)	2.471	acre
square kilometer (km^2)	2.471	acre

Abbreviations

AIC	Akaike's information criterion
AZGFD	Arizona Game and Fish Department
ΔAIC	Change in AIC
GIS	geographic information system
GLM	general linear model
GLS	generalized least squares
GPS	Global Positioning System
HDMS	Heritage Data Management System
IPM	Integral Projection Model
LTRE	Life Table Response Experiment
FWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator

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Abstract

The Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) is endemic to central Arizona in Gila and Pinal Counties, and has been federally listed as endangered by the U.S. Fish and Wildlife Service (FWS) since 1979. Mining, mineral exploration, and highway development have resulted in habitat degradation and loss of individual plants. Therefore, decreases in the population of the cactus are expected to continue. In response to a request from FWS to compile, evaluate, and synthesize data for the cactus, we identified and evaluated existing survey and monitoring data for the cactus and conducted a demographic analysis with suitable data.

Systematic surveys for the Arizona hedgehog cactus did not begin until the late 1970s. Early surveys generally were anecdotal descriptions of cactus populations and precisely georeferenced records of individual cactus occurrence did not occur until global positioning systems were widely used. Much of the georeferenced data have been collected by consultants for mining operations, the Arizona Department of Transportation, the U.S. Forest Service, and independent surveyors. Occurrence records have been compiled by the Arizona Game and Fish Department Heritage Data Management System, but submission of these data may be incomplete, and the attributes reported have varied among the contributing entities. The compilation and management of survey data is essential for field-based evidence of the size, distribution, and range extent of the cactus. In support of consistency in future survey data collection, this report makes several suggestions for future surveys.

Monitoring for the Arizona hedgehog cactus, defined as repeat observations of the status of cactus individuals, has been done by consulting companies for three mines. Demographic monitoring further involves marking individual cacti in consistently defined plots and recording the fate of each cacti through time, including birth, growth, reproduction, and death. We were able to use demographic monitoring data provided by two consulting companies to calculate survival and population growth rates, using several statistical approaches. Resulting models indicate that larger cacti, as measured by their number of stems, have greater survival rates. Larger individuals also had higher probability of producing more flowers. Small cacti had the lowest survivorship, with potentially only 15–20 percent reaching large size. Most populations monitored by the two companies were stable to increasing. However, there were differences in the growth rates among plots and some plots had negative population growth rates. The demographic monitoring data we used represented relatively dense populations of undisturbed cacti. Hence, overall positive population growth rates were not influenced by any large-scale

disturbances. Previous analyses with cacti and other species suggest that more than 10 years of data are necessary to accurately forecast long-term population trajectories. As the monitoring intervals we evaluated were shorter, they represent short-term dynamics only. Several suggestions are made in the report to improve collection of monitoring data to support evidence-based estimates of demographic characteristics of the Arizona hedgehog cactus.

Introduction

The endangered Arizona hedgehog cactus, (*Echinocereus triglochidiatus* var. *arizonicus*)[1] is a dark-green, multi-stemmed succulent with brilliant red claret-cup flowers. The Arizona hedgehog cactus is endemic to central Arizona in Gila and Pinal Counties, central Arizona (fig. 1), and occurs between approximately 3,200 to 5,200 ft (975 to 1,585 m) in the transition zone of the Mogollon Rim where floristic elements of upland Sonoran Desert, montane woodlands, and interior chaparral communities meet. Most documented Arizona hedgehog cactus occur on lands administered by the U.S. Forest Service (USFS).

The Arizona hedgehog cactus has been federally listed by the U.S. Fish and Wildlife Service (FWS) as endangered since 1979 (Cook, 1979). Draft recovery plans have been developed for the Arizona hedgehog cactus (Fletcher, 1984; Baker, 2013); however, a recovery plan has not been finalized. Mining, mineral exploration, and road construction and widening have resulted in habitat degradation and loss of individual plants (Philips and others, 1979; Viert 1996). Projects completed under Federal Section 7 consultation have resulted in the direct impact or loss of an estimated 3,247 Arizona hedgehog cactus and about 561 acres (227 ha) of occupied, suitable, and (or) potential habitat (K. Robertson, U.S. Fish and Wildlife Service, written commun., May 22, 2015). Decreases in the population of Arizona hedgehog cactus are expected to continue because of loss of suitable habitat. The taxon occurs within the footprint of current and proposed future mining activity and is near a major state highway undergoing widening.

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[1] The Integrated Taxonomic Information System (2018) and the Flora of North America Association (2018) no longer accept this nomenclature and instead recognize the variety as *Echinocereus arizonicus* Rose ex Orcutt. The Natural Resources Conservation Service PLANTS Database (Natural Resources Conservation Service, 2018) also no longer recognizes this nomenclature, instead recognizing the cactus as *E. coccineus* Engelm. var *arizonicus* (Rose ex Orcutt) D.J. Ferguson. Regional authors restrict the Arizona hedgehog cactus to *E. arizonicus* subsp. *arizonicus* (see Baker, 2011). Nevertheless, the species is legally listed in the Federal Register (Cook, 1979) as *E. triglochidiatus* var. *arizonicus*, the treatment described by Benson (1969), and the listing name has not been changed.

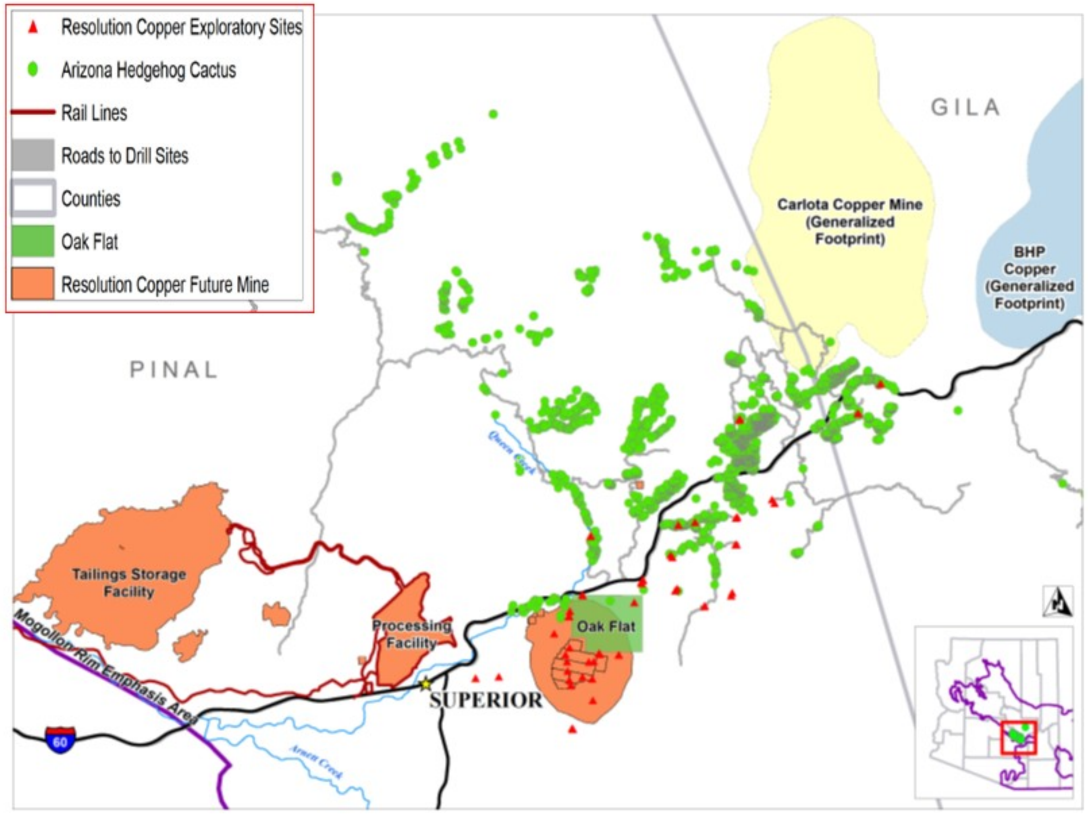

Figure 1. General location of reported Arizona hedgehog cacti in Pinal and Gila Counties, central Arizona and associated mining and cultural features. Range of the Arizona hedgehog cactus, although poorly described, is bisected by U.S. Route 60 and includes an active copper mining district. Cactus prefers cracks, fissures, and small spaces in bedrock and stabilized boulders, especially on Apache Leap Tuff (dactite) and Schultze granite (Cedar Creek Associates, 1994; Viert, 1996). Figure courtesy of K. Robertson, U.S. Fish and Wildlife Service.

Since the listing of Arizona hedgehog cactus as an endangered species, agencies, organizations, and individuals have collected survey data (documentation of cactus individuals and their location, usually at a single time or at the initiation of multi-year monitoring) and (or) monitoring data (repeat observations of the status of cactus individuals) for the species. For example, USFS staff have collected survey data on lands they steward, and consultants to mining companies have collected survey and monitoring data for plants in their project area. However, no established field survey or monitoring protocols yet exist for this cactus species. Full census of the species is difficult because of the rugged terrain in which the cactus grows, and the different methods of density estimates applied by various surveyors introduce unacceptable error for population estimation. Additionally, another cactus species, *E. santaritensis* (Baker, 2013), with a red claret-cup flower like the flower of the Arizona hedgehog cactus, occurs along the range periphery of the Arizona hedgehog cactus or is intermingled with Arizona hedgehog cactus. Fehlberg and others (2013) also noted that along the periphery of Arizona hedgehog cactus distribution were sites where cacti showed morphological characteristics of both *E. arizonicus* and *E. santaritensis* but that additional genetic research is needed to clarify the distinction between *E. arizonicus* and similar cacti. These taxonomic problems indicate the need for refinement of the Arizona hedgehog cactus range and that observers may mistakenly document these other cacti as Arizona hedgehog cactus, confounding survey data quality.

The FWS identified the need for compilation, evaluation, and synthesis of existing data for the Arizona hedgehog cactus to inform Section 7 consultations, the 5-year status review, and a finalized Arizona hedgehog cactus recovery plan. A U.S. Geological Survey (USGS)/FWS Quick Response project, funded in Federal fiscal year 2016, authorized the assistance and expertise of USGS ecologists to lead such an assessment. We organized the assessment methodologically to (1) identify and compile existing quantitative monitoring data, (2) evaluate and synthesize those data for the purposes of modeling the species demography, and (3) participate in a focus group that considers the field collection of Arizona hedgehog cactus data and reporting of those data. We report here the assessment findings as they relate to known Arizona hedgehog cactus spatial characteristics (for example, abundance and density) and temporal dynamics (for example, demography). We also discuss what these findings suggest for best practices in future surveys and monitoring efforts.

Methods

Task 1—Data Identification and Compilation

We obtained all available literature, reports, and data concerning the Arizona hedgehog cactus and identified those sources that provide quantitative information on the location of individual cacti or changes in the survival, productivity, or health of individual cacti. The FWS Arizona Ecological Services Field Office and consultants contracting with mining companies that were conducting activities within the expected range of the Arizona hedgehog cactus provided published literature and reports. We evaluated data collected by consultants for three mining companies and, when adequate, used the data for demographic analysis of the dynamics of the cactus population: Resolution Copper Mining (hereinafter "Resolution", collected by WestLand Resources, Inc. [hereinafter "WestLand"], Tucson, Arizona), Carlota Copper Company (hereinafter "Carlota", collected by Cedar Creek Associates [hereinafter "Cedar Creek"], Fort Collins, Colorado), and OMYA Arizona Inc. (hereinafter "OMYA", collected by Himes Consulting of Chandler, Arizona, and provided to the project by FWS). The Arizona Game and Fish Department (AZGFD) Heritage Data Management System (HDMS) staff provided location data current to October 2017.

Task 2—Data Evaluation and Synthesis

We evaluated the quantitative data identified in task 1 for (1) spatial and temporal extent, (2) method of data collection, and (3) data management standards, with special consideration of the potential use of the data for spatial extrapolation of Arizona hedgehog cactus distribution and density. For those datasets with adequate demographic monitoring data, we calculated population size, survival, reproduction, growth, and other demographic descriptors.

Demographic monitoring involves marking or mapping individuals in consistently defined monitoring units and monitoring the fate of individuals in all stages of the life cycle through time, including birth, growth, reproduction, and death (Elzinga and others, 1998). Accurate and precise measurement of vital rates, along with consistent identification of individuals, are prerequisite for developing demographic models to characterize the dynamics of populations. Based on our synthesis of available demographic data for Arizona hedgehog cactus, we selected data appropriate for developing a demographic model of population dynamics in the monitored populations (Cedar Creek Associates, 2009, 2010, 2011, 2012, 2014, 2015; WestLand Resources, Inc., 2010, 2012, 2014, 2016). Both datasets incorporated a consistent measure of individual size—the number of stems on an individual plant—that could be taken as the state variable in a size-based demographic model. Additionally, individual cacti were consistently tagged and relocated in 2-year census intervals, or occasionally in 1-year census intervals. Although flowering was not recorded at each census, a subset of flowering observations was available to establish a statistical relation between the size of cacti (number of stems) and their potential flower production. Finally, newly observed cacti were tagged and recorded at each monitoring census, allowing an estimate of recruitment into the populations.

We used the R package IPMpack version 2.1 (Metcalf and others, 2013; Merow and others, 2014) to fit Integral Projection Models (IPMs) separately for each dataset. IPMs are like matrix projection models and estimate population growth (λ) by combining individual regression models that predict vital rates (for example, growth, survival, fecundity) from a continuous-state variable such as size. The vital rate regressions are integrated in a discretized kernel (similar to a projection matrix) that predicts changes in the size distribution of individuals and their offspring from one census to the next, and typically are composed of a survival and growth component, *P*, and a fertility component, *F*. Estimates of deterministic (finite rate of increase) and stochastic (incorporating demographic and environmental variability) population growth rates (λ and λs), along with other measures such as elasticity (relative contribution of vital rates to population growth), can be obtained from the IPM kernel (Merow and others, 2014). IPMs improve upon matrix population models by eliminating the need to delineate discrete stages in a continuous-state variable, a step that can bias predictions (Salguero-Gómez and Plotkin, 2010), and by reducing the number of parameters that need to be estimated (Ellner and Rees, 2006). We used an IPM rather than a matrix model because there were no clear criteria by which to categorize Arizona hedgehog cactus into discrete size classes. Furthermore, IPMs can provide more accurate parameters for small datasets (Ellner and Rees, 2006).

Because WestLand personnel did not collect demographic data from plots (fig. 2) but instead along extended, interconnected linear transects (generally along both sides of unpaved roads), we pooled all individuals to construct a single IPM for the Arizona hedgehog cactus population at the Resolution site. Conversely, Cedar Creek personnel collected demographic data from 10 permanent monitoring plots at the Carlota site (fig. 3), and we retained these distinctions in our analyses, calculating overall pooled and plot-level IPMs. Because of the small sample size of cacti in one plot (Diversion Inlet, n=12), we did not construct an individual IPM for that dataset. However, we retained the individuals from Diversion Inlet in our pooled IPM.

We modeled survival during the census interval as a binomial general linear model (GLM) with size (number of stems) as the predictor. To model growth between censuses, we used a generalized least squares (GLS) regression with variance as an exponential function of size to account for a trend of increasing variability with increasing size. Because we did not have flowering data for all cacti in each census, we modeled individual fecundity values from available data (flower counts by WestLand in 2010 and 2016) as a combination of two GLM models. First, we modeled the probability of flowering based on the size of an individual as a binomial GLM (that is, logistic regression). Second, we modeled the predicted number of flowers that an individual could produce as a Poisson GLM, which is appropriate for count-based data. Finally, we calculated the establishment rate for a census as the total observed recruits divided by the total predicted reproductive effort (where reproductive effort is the modeled probability of flowering × the modeled number of flowers produced).

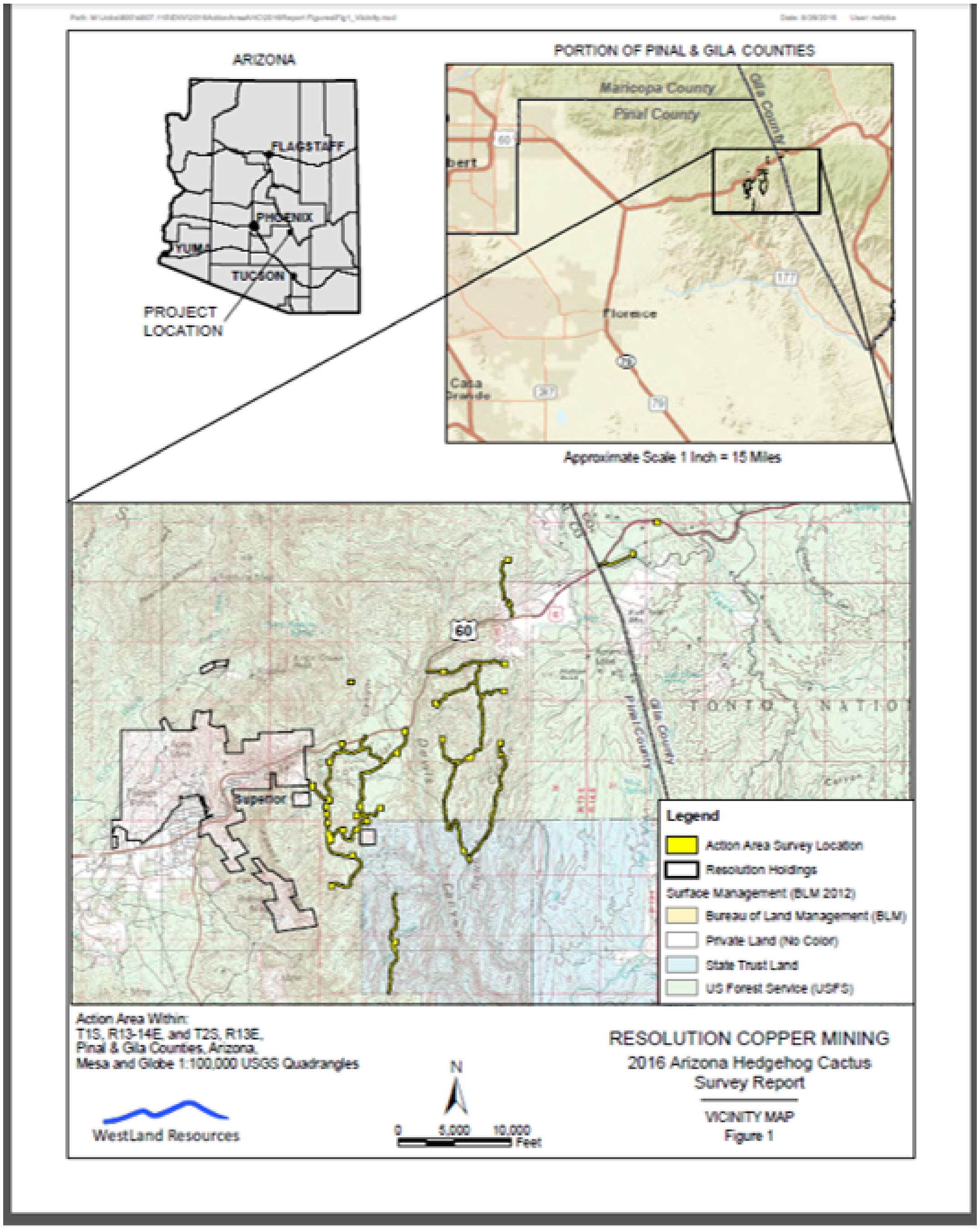

Figure 2. Arizona hedgehop cactus monitoring areas associated with Resolution Copper Mining monitoring (referenced as WestLand sites in text), central Arizona, 2016, indicated in green and yellow. Figure sourced from WestLand Resources, Inc. (2016).

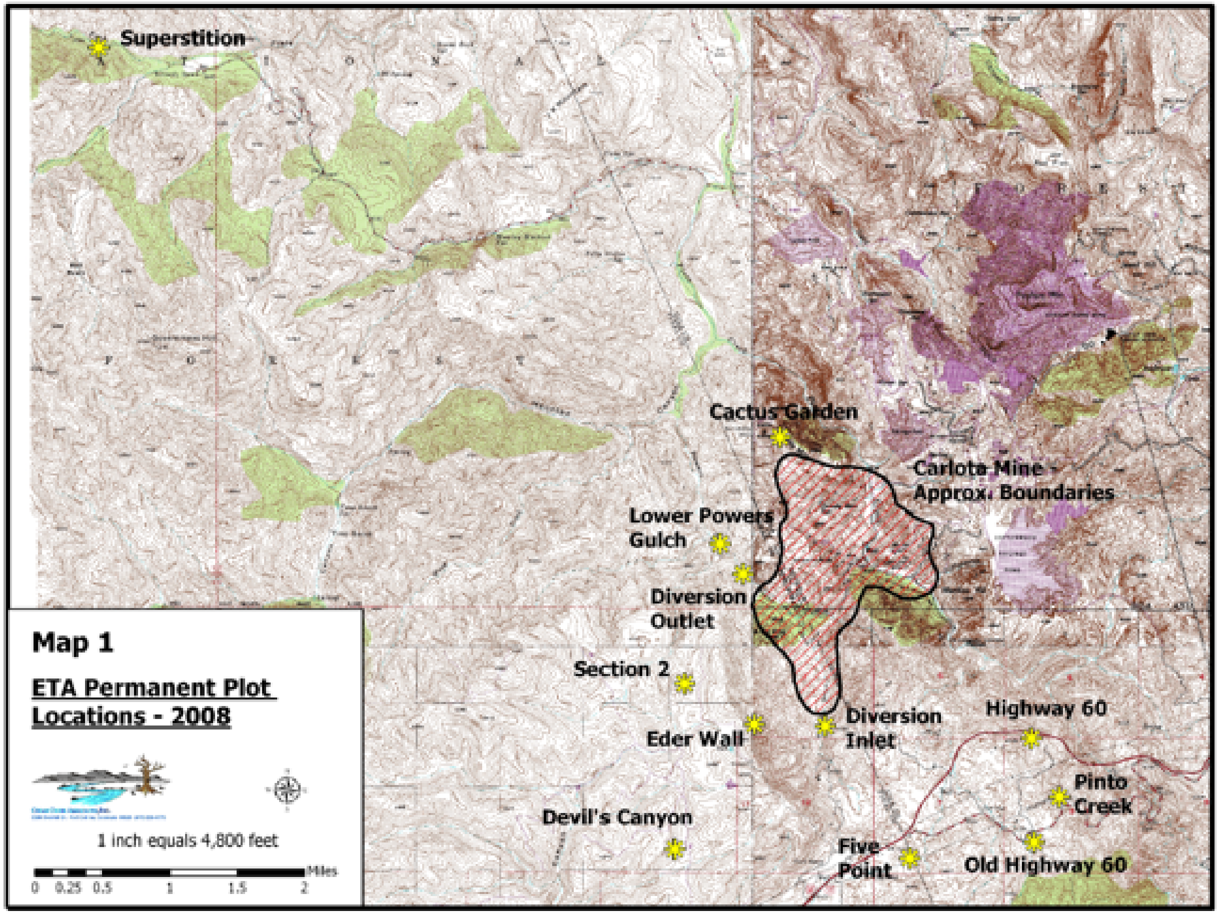

Figure 3. Location of Arizona hedgehop cactus (*Echinocereus triglochidiatus* var. *arizonicus* [ETA]) plots associated with Carlota Copper Company monitoring (referenced as Cedar Creek sites in text), central Arizona, 2008 (yellow star symbols). All plots except Cacti Garden were permanent monitoring plots and were used in the demographic analysis. Cacti Garden was an experimental plot established to measure cactus transplant success. The Division Outlet site on the figure is referred to as Diversion Outfall in the consultant's monitoring reports and in this report. Figure sourced from Cedar Creek Associates (2009).

There is an unknown level of uncertainty involved in identifying recruits for small cacti, as these are difficult to observe in the field and may not be noticed for several years. In terms of the existing data, WestLand personnel noted when cacti were newly observed but did not make specific determinations as to whether newly observed cacti were seedlings established between censuses. Cedar Creek personnel included a “seedling” category during monitoring, but the criteria for inclusion in this category are not described. For the purposes of this report, we define recruits as newly observed individuals in each census with one or two stems or those that were identified as “seedlings” by field observers. This criterion was meant to avoid misrepresenting newly observed adult cacti as seedlings. The full fecundity kernel for the IPM is described by the equation:

$$F(z', z) = P_{flower(z)} * F_{flowers(z)} * P_{establishment} * F_{recruit(z')}, \quad (1)$$

where z’ and z are the size distribution of individuals from the first census to the next,
$P_{flower(z)}$ is the probability of flowering as a function of size,
$F_{flowers(z)}$ describes the number of flowers produced by individuals as a function of their size,
$P_{establishment}$ is the establishment probability, and
$F_{recruit(z')}$ is the size distribution of recruits at the next census.

For all regression models that constitute the IPM, we evaluated quadratic and cubic functions of size and retained these terms if they resulted in a reduction in Akaike’s information criterion (AIC) (change in AIC [ΔAIC] ≥2) relative to a model without that term.

Based on the fitted IPMs, we extracted the predicted survivorship for an individual of size 1 to reach size 100 (that is, the fraction of the cohort surviving across the size range), along with the mean life expectancy for individuals along this size range. We used eigen-analysis of the discretized IPM kernel (integrated with the midpoint rule) to derive the deterministic population growth rate (λ; Caswell, 2001), and perturbations of vital rate regression parameters to calculate the sensitivity and elasticity of λ to these parameters (Rees and Rose, 2002; Merow and others, 2014). Elasticity is the proportional sensitivity of λ to changes in individual vital rates, and indicates which vital rates or size ranges have the most influence on λ. For comparison, we also calculated elasticities using a second technique—eigen-analysis of discretized IPM kernels—that enabled a visualization of the most influential cacti size ranges on λ.

Additionally, we quantified the uncertainty in λ by bootstrap sampling from the estimated parameter distributions of each vital rate regression, including growth, survival, and fecundity models (Ellner and Rees, 2006; Merow and others, 2014). For each vital rate model, we generated 1,000 bootstrap samples from the multivariate normal distribution. The IPM kernel and population statistics were recalculated for each sample, and from these we generated 95-percent confidence intervals for λ. Our procedure follows steps described in Merow and others (2014).

To characterize the differences in λ between plots (Cedar Creek data only) and to determine whether such differences affected the pooled estimate of λ, we used a Life Table Response Experiment (LTRE; Caswell, 2001) following the example in Merow and others (2014). LTREs decompose differences in λ owing to the variation in a treatment of interest—in this case, plot identity. This retrospective analysis of contributions to λ has the benefit of independence from the magnitude of the population growth rate, unlike elasticity (Silvertown and others, 1996). For the analysis, we took the mean IPM across all plots as the reference matrix, and the plot-level IPMs as the treatment matrices. We fit the LTRE using the R package “popbio” (Stubben and Milligan, 2007).

Several caveats should be recognized in our demographic analyses of available data for the Arizona hedgehog cactus. First, the data did not allow us to directly link reproductive effort (flowering and fruiting) with the size class distribution of cacti because flowering was not recorded for all individuals during each census. Rather, the relation between size and reproductive effort was modeled using a subset of flowering observations and subsequently extrapolated to the full dataset of cacti. This approach eliminates temporal variation in reproductive effort (that is, because the number of flowers produced is a static prediction based on size and not from actual observations), although overall fecundities are still bounded by the number of observed recruits at each census. For this reason, we do not report reproductive values for cacti based on their size. A second caveat is that difficulty in locating small cacti in the field, particularly along extended linear transects (WestLand data), could bias estimates of the recruitment rate. Seedlings may go unobserved for a period before they are large enough to be seen by observers. Therefore, newly observed cacti may sometimes constitute young adults rather than seedlings that became established during the census interval. This bias may be compounded by the 2-year census intervals used by WestLand and Cedar Creek, during which time seedlings could emerge and die off without being observed. For these reasons, we applied a size-based criterion to separate seedlings from previously unidentified adult cacti, but it is possible that both the seedling emergence and mortality rates are underestimated. Finally, the short temporal duration of monitoring (3–5 census periods for most plots and transects) likely precludes accurate forecasts of the minimum viable population size and stochastic population growth rates, which require longer monitoring periods (Doak and others, 2005; Shryock and others, 2014). Instead of providing such estimates, which are likely to be inaccurate, we report the deterministic population growth rates (λ) and do parametric bootstrapping of vital rate regressions to estimate the uncertainty in this parameter based on the available data.

Task 3—Focus Group

The Desert Botanical Garden in Phoenix, Arizona, organized and hosted an Arizona Hedgehog Cactus symposium at their location in Phoenix, Arizona on September 21, 2016. The 1-day event featured 12 speakers who have worked on different aspects of Arizona hedgehog cactus biology, ecology, and (or) conservation.

Data Assessment and Findings

Task 1—Data Identification and Compilation

Few publications on the Arizona hedgehog cactus are available in the peer-reviewed science literature (see Baker, 2006; Aslan, 2015) and these do not address the overall occurrence or population demography of the cactus. Species location data and monitoring results are available in consulting company and (or) agency reports submitted to the FWS and USFS, or data submitted to the AZGFD HDMS.

Task 2—Data Evaluation and Synthesis

Survey Data

Although Arizona hedgehog cactus were initially discovered and described by Orcutt in 1926 (specimen type from a site near Top of the World, Arizona, along U.S. Route 70), systematic surveys for Arizona hedgehog cactus appear to have begun in the late 1970s. Surveys initially described populations and their locations; however, the descriptions generally used anecdotal description and (or) topographic map identification of locations and locations of specific cacti were indeterminate. A non-exhaustive list of these surveys with qualitative location description is presented in table 1.

Georeferenced data of Arizona hedgehog cactus occurrences have been collected by consultants for major mining operations, the Arizona Department of Transportation for road-widening projects on U.S. Route 60, the USFS, and independent surveyors, often contracted for survey of specific areas for the cactus. Baker (2013) compiled georeferenced location data from existing reports and from his own georeferenced ground surveys. Additionally, Baker (2013) reviewed these existing occurrence records to correct for any records that may have incorrectly included reports of *E. santaritensis* as *E. triglochidiatus* var. *arizonicus*. Baker submitted these data to the AZGFD HDMS to include in their ongoing compilation of occurrence records for the Arizona hedgehog cactus.

The HDMS compiles all submitted occurrence records for the Arizona hedgehog cactus. As of October 2017, there were 6,769 records for Arizona hedgehog cactus in the database (Sabra Tonn, Heritage Data Management System Program Supervisor, written commun., December 27, 2017). Submittal of observation records is voluntary on the part of observers. Although the immediate listing of observations records does not include date of observation nor name of contributor, the HDMS documentation records provide additional data for each contributor submittal. It also is unknown whether some records may report on the same individual plant, but as contributed by different observers.

Table 1. Arizona hedgehog cactus surveys without georeferenced location data for individual cacti, central Arizona, 1977–96.

[Table describes major survey efforts but is not inclusive of all survey efforts]

Author	Date	Scope	Plants observed	Measurements
Wisner	1977	Unspecified hilltops, Unspecified portions of U.S. Route 60 and side roads including to Devil's Canyon	Not specified.	Only general descriptions.
Crosswhite	1979	Devils Canyon, Iron Canyon, between Pinal Ranch and Pinto Creek.	157	Original report not available. Reichenbacher (1986) used to describe scope and number of plants observed.
Philips and others	1979	Systemic search of 182 square kilometers.	155	First 20 plants in each of 3 populations measured for clump diameter, diameter largest stem, diameter smallest stem, and height smallest stem. Remaining plants measured for stem number, flowering and fruit number. Only averages reported. Density estimates provided by population.
Reichenbacher	1986	Proposed Magma Copper power transmission line (Magma Oak Flat power substation on south Side Queen Creek Canyon to Pinto Valley Corporation substation); areas deemed unsuitable habitat were only spot-checked or not checked; a total of 5.04 miles.	219	Summary of number of plants per corridor segment and density by acre.
Ralston	1994	Likely habitat within Pinal, Graham, Gila, and Greenlee Counties.	Number of individual plants not reported; author states no new populations located.	Individuals in 25-square-meter plots surveyed to determine density, # stems and flowers recorded for each individual in plot, in sparse areas individuals surveyed within 60-minute time interval
Viert	1996	Carlota Copper Company project area (no map or description of project area included in report).	1,150 measured, general observations on 1,000 additional specimens outside project area.	Habitat geology, rooting media, proximal vegetation, exposure to direct sun, stem status, borer insect damage, diameter of largest stem, number of ribs, number of stems, and density.

Well-documented spatial data can be used to refine models of species habitat requirements and to make estimates of the overall abundance and density of a species. Numerous survey reports have provided author observations on the abiotic habitat contexts in which Arizona hedgehog cactus occurs (Philips and others, 1979; Crosswhite, 1992; Cedar Creek Associates, 1994). Cedar Creek Associates (1994) described detailed geological associations of the Arizona hedgehog cactus based on non-georeferenced observations of 2,000 Arizona hedgehog cactus on the Carlota mine and surrounding areas. Spatial data representing the abiotic associations identified observationally could be used to spatially interpolate the location of suitable habitat for the Arizona hedgehog cactus if geographic information system (GIS) layers of appropriate resolution representing edaphic or other landscape properties within the Arizona hedgehog cactus distribution were available. Likewise, the existing georeferenced location data, and potentially well-described quantitative location data, for the Arizona hedgehog cactus provide training input on which to develop and test spatial interpolations. Although density estimates have been variously presented based on specific surveys (see Baker, 2013, for a summary of these estimates and his own estimate), these density estimates do not use spatial data to make specific map-based inferences on density. Additionally, the scarcity of "negative" survey data for Arizona hedgehog cactus confounds spatial interpolations of cactus abundance and density. A determination of the specific data needs to develop such interpolation and the availability of such spatial data were outside the scope of this assessment.

Monitoring Data

Resolution/WestLand Data

WestLand has done monitoring on a biyearly schedule beginning in 2010. Surveys have been done on approximately about 294 ha comprising 217 ha along roadways and 77 ha in association with drill pad sites (WestLand Resources, Inc., 2016; fig. 2). Results were reported by WestLand Resources, Inc. (2010, 2012, 2014, 2016).

The WestLand monitoring reports also describe their field methods for monitoring. Collection of field observations are targeted for peak flower bloom (April and early May) to maximize detection. Observations are made during each monitoring cycle on cacti previously tagged and georeferenced, and cacti newly observed within the observation area are added to the monitoring sample. Observations on several properties (table 2) are made for all Arizona hedgehog cactus monitored and other attribute observations are made on a sub-sample of the monitored Arizona hedgehog cactus. Monitoring findings are summarized in table 3.

Table 2. Plant properties of Arizona hedgehog cactus measured by WestLand Resources, Inc. for Resolution Copper Mining, central Arizona, 2010–16.

[**Symbols:** x, property measured; –, property not measured]

Plant property	2010	2012	2014	2016
Presence/absence	x	x	x	x
Number stems per plant	x	x	x	x
Height of stems per plant	x	New only	New only	New, subsample
Number of pups per plant	x	x	–	–
Width/height cluster	Subsample	–	–	–
Number buds per stem	x	–	–	In part
Number flowers per stem	x	–	–	In part
Number fruit per stem	x	–	–	–
Growth tubercles	–	Subsample	–	–
Increase areoles	–	–	Subsample	Subsample
Plant health	x	x	–	x

Table 3. Number of Arizona hedgehog cactus detected by WestLand Resources, Inc. for Resolution Copper Mining, central Arizona, 2010–16.

[**Abbreviation:** na, measurement not applicable for initial survey date]

Cactus status	2010	2012	2014	2016
Relocated live tagged	na	333	405	430
New tagged cacti (during monitoring)	346	72	44	32
New tagged from other field work	na	8	5	0
New tagged recruits[1]	na	26	0	0
Total monitored	346	439	454	462
Dead from previous monitoring	na	10	42	57
Missing from previous monitoring	na	3	4	11
Total loss	na	13	46	68

[1]New recruits considered less than 5 inches in stem height, only separated out in 2012.

Carlotta/Cedar Creek Data

Cedar Creek monitored the Arizona hedgehog cactus for Carlota on a yearly schedule beginning in 2007 (Cedar Creek Associates, 2009, 2010, 2011, 2012, 2014, 2015). In 2007 and 2008, Cedar Creek established permanent plots for long-term monitoring of the cactus (table 4). Two plots, Diversion Inlet and Diversion Outfall, were established in 2008 closest to mining activity for observing how Arizona hedgehog cactus near mine processing respond to sulfuric acid effects and were monitored annually from establishment through 2014. Eight permanent plots were established, five of which were reinstallations of plots initially established and measured in 1996 (Devil's Canyon, Five Point, Pinto Creek, Section 2, and Superstition). However, Cedar Creek notes that no comparison is possible between 1996 and reestablishment in 2007 and beyond for the Five Point plot because of missing Global Positioning System (GPS) data and changes in GPS technology. Cedar Creek monitored four of these plots on a biannual basis (2009, 2011, 2013, 2015). They monitored the Superstition plot in 2007, 2010, and 2012. The three additional permanent plots (Eder Wall, Highway 60, and Old Highway 60) were established in 2008 and have been monitored in 2010, 2012, and 2014.

Cedar Creek develops monitoring reports yearly; however, monitoring methods are not described in the reports. The following information on methods was obtained from Cedar Creek biologists (Jesse Dillon, Cedar Creek Associates, written commun., August 8, 2016):

> Each plot was created by establishing plot boundaries using four or six PVC pipes. The boundary points were collected on a sub-meter GPS and converted to a polygon to load on the sub-meter GPS for plot monitoring. Monitoring observations were conducted at least every other year in each plot. Monitoring consisted of biologists traversing the plot in a systematic manner to locate and collect data on all Arizona hedgehog cacti within the plot. GPS coordinates were collected at each cactus found in the plot. In addition, data regarding the age, size, health, and flowering were recorded and a photo was taken. Sub-meter GPS coordinates and photos are vital in relocation of these cacti in subsequent years. If a cactus was presumed missed in a previous monitoring event, it was indicated as such in the dataset.

For each monitoring cycle, Cedar Creek biologists verify the status of the monitored Arizona hedgehog cactus (mature, decadent dead, dead) and record the number of stems (termed "pods" on data sheets) and their status (live, damaged, dead).

Table 4. Number of live Arizona hedgehog cactus monitored in demographic plots by Cedar Creek Associates for Carlotta Copper Company, central Arizona, 2007–15.

[Total for reach year includes newly found cacti, not necessarily juveniles but undetected at the last monitoring event, as well as losses to death and (or) missed during monitoring. See appendix table 1.1 for additional details of yearly monitoring counts for Carlotta Copper Company. **Abbreviation**: na, monitoring measurements were not taken for plot in that year]

Location	2007	2008	2009	2010	2011	2012	2013	2014	2015
Devil's Canyon	26	na	29	na	31	na	36	na	33
Diversion Inlet	na	12	12	12	12	10	10	na	na
Diversion Outfall	na	59	57	66	69	71	72	68	na
Eder Wall	na	29	na	38	na	33	na	33	na
Five Point	75	na	82	na	84	na	84	na	84
Old Highway 60	na	34	na	32	na	31	na	28	na
Pinto Creek	26	na	28	na	32	na	32	na	33
Section 2	36	na	37	na	40	na	41	na	40
Superstition	34	na	na	41	na	38	na	na	na
US 60	na	25	na	25	na	26	na	26	na

OMYA/Himes Consulting Data

Himes Consulting made initial observations of Arizona hedgehog cactus along 3.3 mi of OMYA access road, running from U.S. Route 60 to their Superior limestone quarry. A base survey was done in May 2003 (no report available), May 2009 (Himes Consulting, 2009) and April 2011 (Himes Consulting, 2011). In 2009, 10-m-wide transects were walked or visually assessed on each side of the access route. Cacti locations from 2003 were assessed and, if an Arizona hedgehog cactus occurred within 30 m of the 2003 waypoint, the cactus was counted as alive. New cacti were recorded, and for all shoots and individual cactus, health was recorded (table 5). Monitored cacti were not tagged. These data were not used in the demographic analysis.

Table 5. Number of Arizona hedgehog cactus detected by Himes Consulting for OMYA Arizona Inc., central Arizona, 2003–13.

[**Abbreviation**: na, not applicable because measurement category did not apply during this year]

Cactus counted	2003	2009	2013
Base count	119	na	na
Relocated	na	62	118
New to this date[1]	na	59	34
Total alive	na	121	152
Dead/missing from last observation date	na	57	3

[1]Reports indicate that some new cacti may have been outside the 10-meter transect lines. In future work this should be avoided, or each new cactus should be individually documented to avoid confounding analysis.

Demographic Analysis

Vital Rates

Regression models indicated that both survival and size (number of stems) at the end of the census interval were significantly related to size at the start of the census, with larger individuals having greater survival (fig. 4). Growth was approximately linear across the size range of cacti (fig. 4). The flowering models indicated that both the probability of flowering and the predicted number of flowers increased significantly with size (that is, size measured as the number of stems per plant, fig. 5). Throughout the monitoring period, there were 61 reported mortalities along the WestLand transects (about 11 percent of 549 total monitored cacti; this includes several instances where a tag was relocated, and the cactus was no longer present) and 92 reported mortalities in the Cedar Creek plots (about 19 percent of 485 total cacti). These mortalities were offset by 99 recruits (defined as newly observed cacti with ≤2 stems) along WestLand transects and 105 recruits in Cedar Creek plots.

A total of 204 new cacti were located along WestLand transects following the initial census, along with 129 new cacti located within the Cedar Creek demographic plots. Subtracting from these totals cacti that met our definition for recruit size (≤2 stems), there were potentially 105 adult cacti located along the WestLand transects that were not identified in the first census, and 24 such individuals in Cedar Creek demographic plots. These individuals are large enough (≥3 stems) that they may have been alive at the start of monitoring, suggesting that the rate of undetected adult cacti in the initial census along the WestLand linear transects may have exceeded 15 percent, although this estimate could be lower depending on the growth rate of the cacti. The rates of undetected adult cacti in Cedar Creek plots were substantially lower (about 5-percent overall).

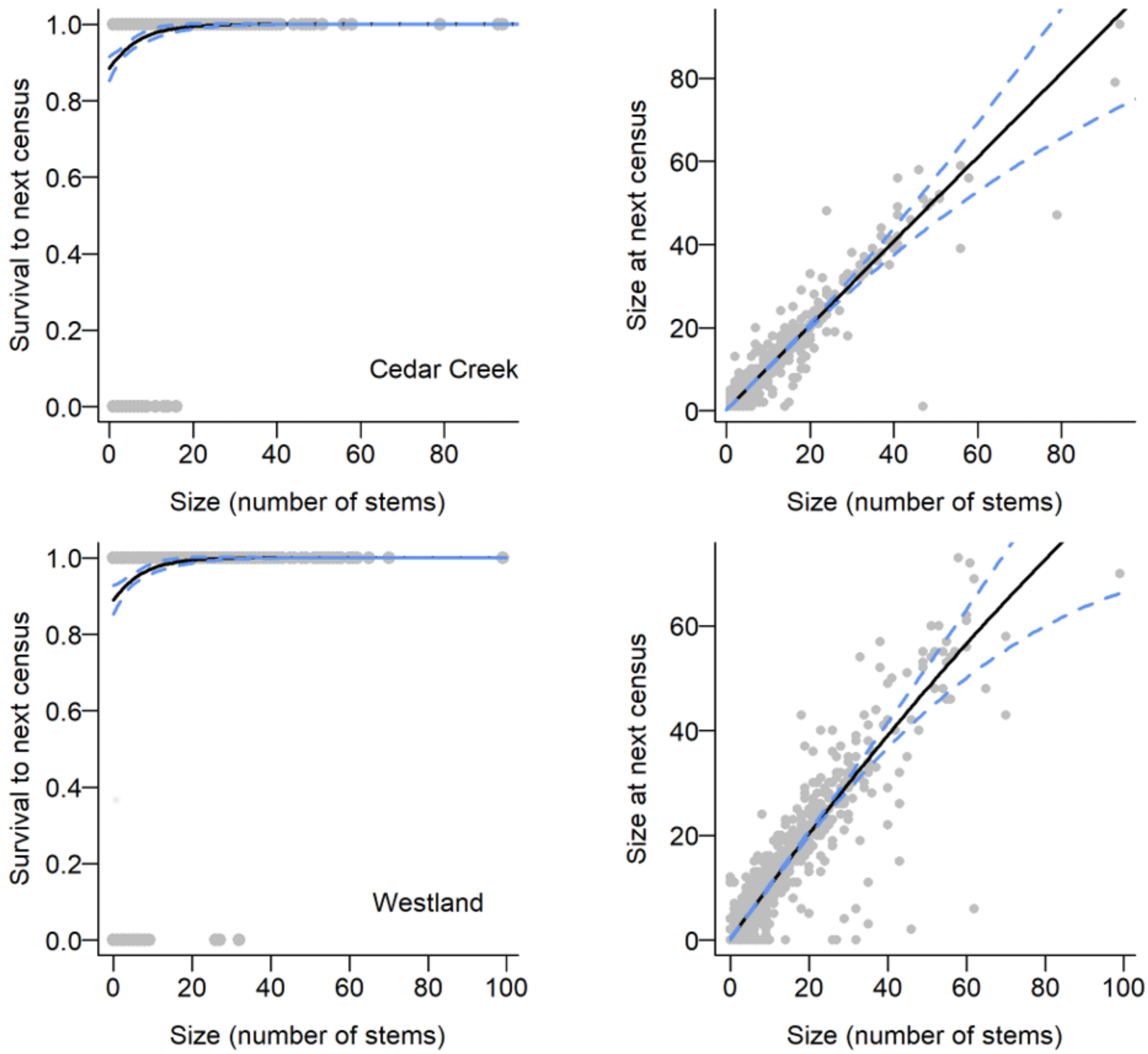

Figure 4. Binomial general linear models for survival and generalized least squares (GLS) models for growth of Arizona hedgehog cacti (*Echinocereus triglochidiatus* var. *arizonicus*) at Cedar Creek (top graphs) and WestLand (bottom graphs) sites (see figs. 2 and 3 for site locations), central Arizona. Size (number of stems) was taken as the explanatory variable for each model. GLS models treated variance as an exponential function of size to account for the increased variability among larger individuals. Dashed blue lines indicate the 95-percent confidence interval for model parameters. Although overall survival rates were high, smaller cacti had lower survivorship than larger cacti. Growth was predominantly linear between censuses, with somewhat higher variance for larger individuals.

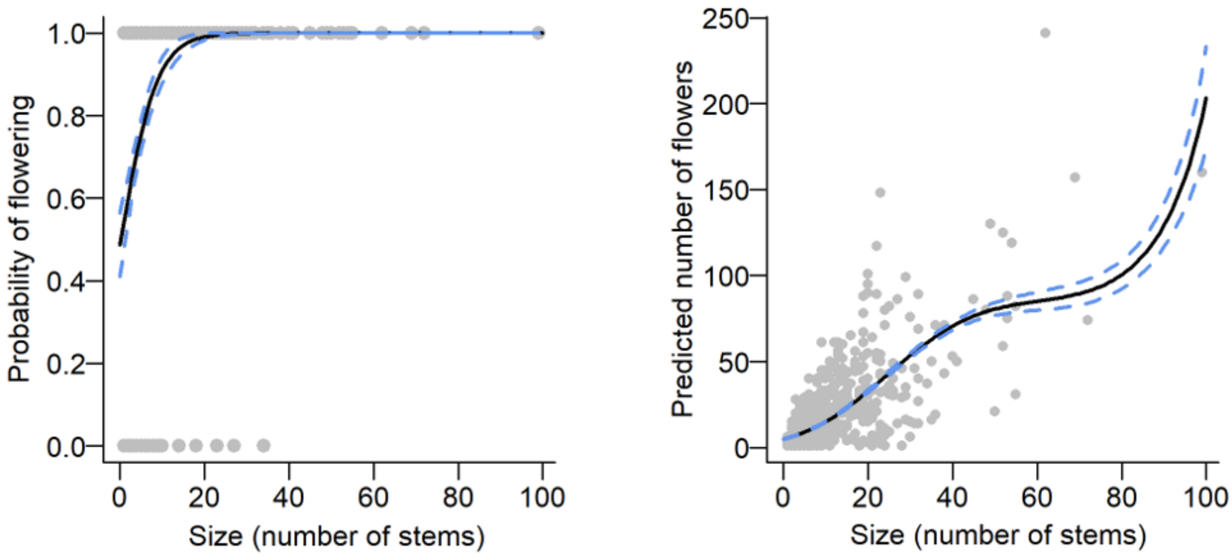

Figure 5. Probability of flowering for Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) based on the number of stems in a binomial general linear model (GLM) (left graph) and predicted number of flowers produced by an individual with a given number of stems (poisson GLM; right graph). Models are based on flower counts of cacti done in 2010 and 2016 by WestLand Resources Inc. and are not inclusive of all cacti in each census. Models indicate that larger cacti have a higher probability of flowering and tend to produce more overall flowers. Hence, larger individuals are likely to contribute more to fecundity (reproductive effort) than smaller individuals.

Integral Projection Models of Population Growth

Population growth rates for populations of Arizona hedgehog cacti monitored by WestLand and Cedar Creek were positive ($\lambda > 1$). The deterministic population growth rate for the pooled WestLand data was $\lambda = 1.022$, with a bootstrapped 95-percent confidence interval of 1.009–1.035 (fig. 6). For the pooled Cedar Creek data, λ also was positive (1.018), with a bootstrapped 95-percent confidence interval of 1.015–1.041 (fig. 6). Using the fitted IPM, we extracted survivorship curves for a hypothetical individual moving from size 1 to 100 (number of stems) as well as the mean life expectancy for cacti along this size range (fig. 7). Small cacti had the lowest survivorship, with 15–20 percent predicted to reach a size of 20 stems (fig. 7).

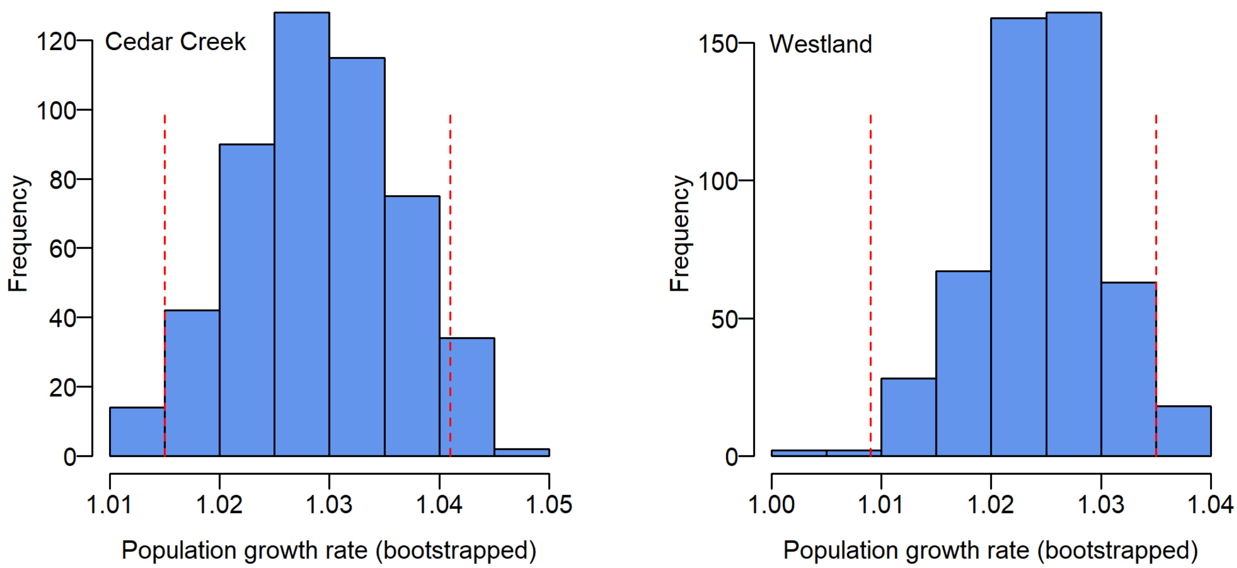

Figure 6. Distribution of population growth rates (λ) from a parametric bootstrap of Integral Projection Models for the Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) sampled at Cedar Creek and WestLand sites (see figs. 2 and 3 for site locations), central Arizona. Red vertical dashed lines indicate the 95-percent confidence interval for each simulation around estimates of λ. Simulations indicate that population growth remains positive after accounting for uncertainty in the regression models for each vital rate (growth, survival, and fecundity).

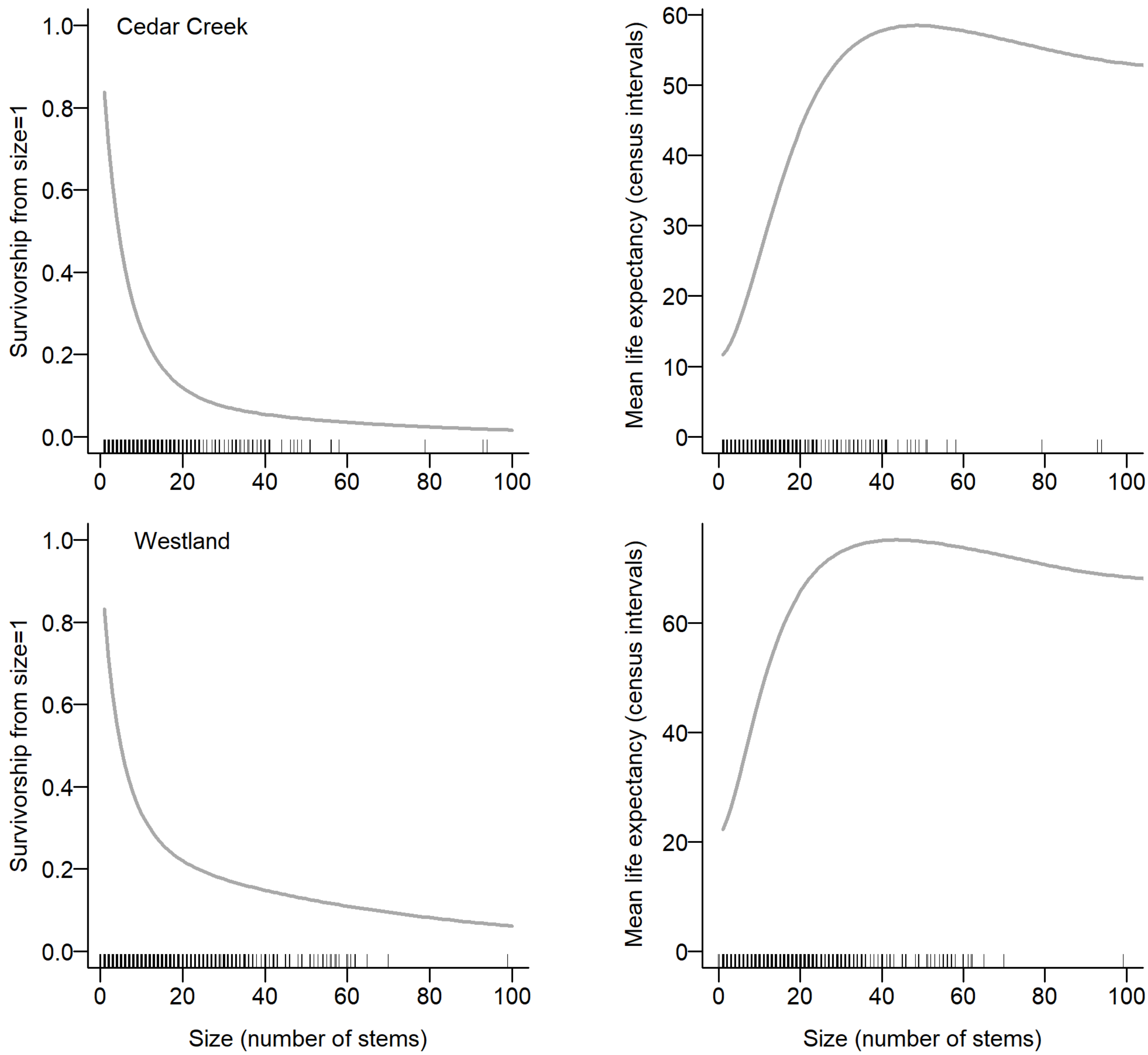

Figure 7. Survivorship and mean life expectancy derived from the survival and growth components of an Integral Projection Model for the Arizona hedgehog cactus (*Echinocereus triglochidiatus* var. *arizonicus*) at Cedar Creek (top graphs) and WestLand (bottom graphs) sites (see figs. 2 and 3 for site locations), central Arizona. Predicted survivorship is based on an individual with a starting size of 1 stem. Tick marks along the x-axes indicate the observed size distribution of cacti. Model indicates that smaller cacti have lower survivorship, with only 15–20 percent of individuals expected to reach a size of 20 stems. Similarly, the mean life expectancy (in census intervals) for cacti increases with their size.

Elasticity Analysis

Elasticity values derived through perturbations of regression model parameters indicated that small perturbations to the growth model had a larger effect on population growth (λ) than perturbations to the survival or fecundity parameters. This was true for both WestLand transects and Cedar Creek plots (table 6). Perturbation-based elasticity values for survival and fecundity were comparable, with the fecundity model slightly more influential in the WestLand IPM. Elasticities derived through eigen-analysis of the discretized IPM kernel (akin to a high-dimensional matrix model) showed a similar pattern, with survival and growth of small to mid-sized cacti most influential to λ (fig. 8). High elasticity values were centered along the diagonal of the plot, suggesting that individuals staying at approximately the same size between censuses (stasis) had a greater influence on λ than individuals with larger growth or shrinkage events (fig. 8).

Table 6. Elasticity values for vital Arizona hedgehog cactus survival, growth, and fecundity rates.

[Rates were calculated through perturbation of regression model parameters. Integral Projection Models (IPMs) included a binomial general linear model(GLM) for survival, a generalized least squares regression for growth, and binomial and Poisson GLMs for fecundity. Values indicate the proportional influence that changes in the regression model parameters for each vital rate have on population growth (λ). Larger elasticity values indicate that λ is more sensitive to changes in these model parameters. For both monitored sites, the growth model parameters had the largest proportional influence on λ. In IPMs, growth includes the stasis category, where individuals may stay the same size; hence, elasticity for growth is higher than for survival]

Vital rate	Cedar Creek Associates	WestLand Resources, Inc.
Survival	0.097	0.110
Growth	0.807	0.735
Fecundity	0.095	0.154

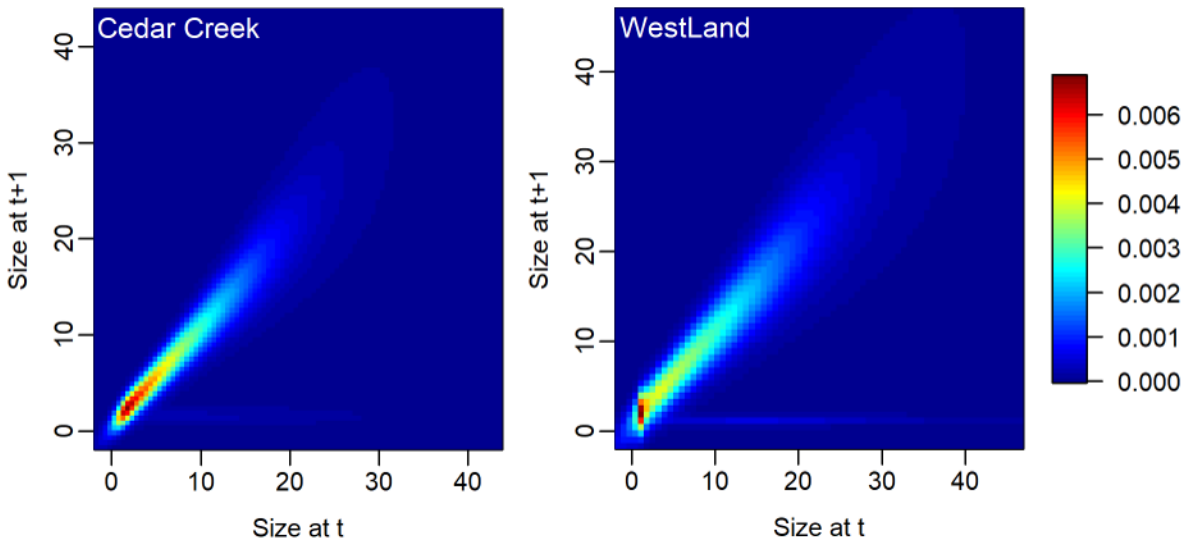

Figure 8. Elasticity values derived from eigen-analysis of discretized Integral Projection Model kernels for Cedar Creek Associates (left graph) and WestLand Resources, Inc. (right graph). Larger values (brighter colors) indicate greater proportional influence on population growth (λ) for cacti of a given size. The graphics indicate that survival and growth of small to medium-sized cacti (0–20 stems) had the largest proportional influence on λ at both monitored locations. Additionally, because the largest elasticity values are centered on the diagonal, this suggests that cacti surviving and staying at approximately the same size have the most influence on λ.

In previous studies incorporating matrix population models, cacti typically have had high elasticity values for stasis (surviving and staying in the same size class), but such estimates are largely dependent on the dimensions of the matrix model under consideration (Salguero-Gómez and Plotkin, 2010). In general, the fewer dimensions in a matrix model, the higher the elasticity value for stasis (that is, because fewer individuals are progressing or retrogressing between size classes defined at a wide size interval). IPM demographic models are dimensionless and, therefore, are not directly comparable to matrix projection models in terms of elasticity, as matrix models for cacti generally have used 3–10 size classes (COMPADRE Plant Matrix Database, version 4.0.1 [Max Planck Institute for Demographic Research, 2018]; Salguero-Gómez and others, 2015). The major difference between IPMs and matrix population models is that the growth model in IPMs effectively includes the stasis category because individuals may stay the same size, grow, or shrink in the regression model linking size between censuses. However, in matrix models, stasis generally is included as a component of the survival elasticity. Therefore, to directly compare elasticity values between IPMs and matrix population models, the growth and survival elasticity values must be combined in a single category.

The COMPADRE Plant Matrix Database (Salguero-Gómez and others, 2015) provides a compilation of all published matrix population models for plant species. We created a subset for this database that includes only species of Cactaceae as a basis of comparison to evaluate the Arizona hedgehog cactus pattern of elasticity values. For Cactaceae as a whole, the average elasticity for survival is 0.76, for growth is 0.17, and for fecundity is 0.06. The elasticity values of a matrix model differ from those of a IPM-based model because of the way size classes are combined. For this matrix model, combining the growth and survival categories results in an averaged combined elasticity of 0.94. Based on these estimates, the Arizona hedgehog cactus is in line with most cacti when elasticity values are calculated through the most common method (eigen-analysis). Arizona hedgehog cactus is close to the median elasticity value among all cacti for both reproduction and combined survival / growth (fig. 9). This suggests that the cactus follows a typical pattern where the persistence of individuals at or near the same size from year to year most influences population growth.

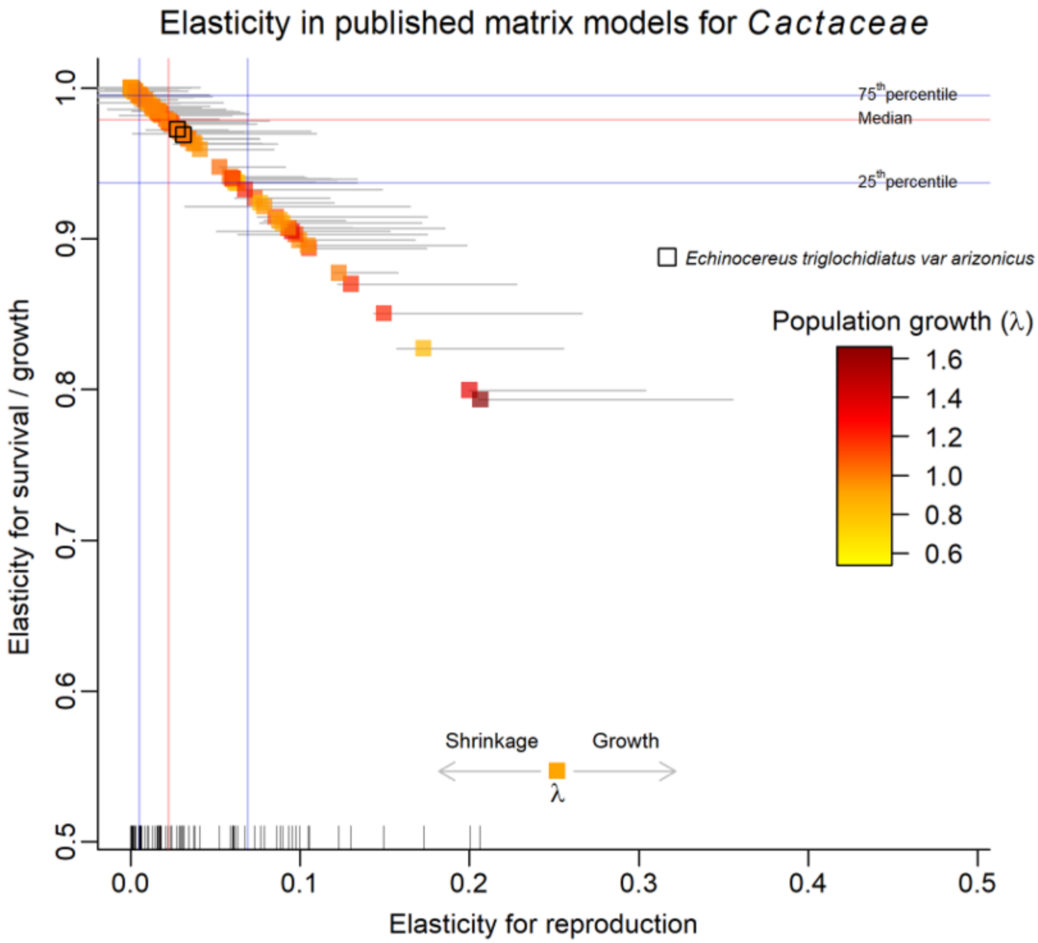

Figure 9. Published elasticity values derived from eigen-analysis of transition matrices for cacti in the COMPADRE plant matrix database (Max Planck Institute for Demographic Research, 2018). Elasticity is the proportional influence of a vital rate on the overall population growth rate (λ). We combined the growth and survival elasticities to create a valid comparison between the matrix models and our Integral Projection Model for Arizona hedgehog cactus. In the figure, combined elasticity for survival and growth is on the y-axis, and elasticity for reproduction is on the x-axis. Color of symbols matches the observed population growth (λ) for each matrix model. Horizontal gray lines represent elasticity values for growth and decline from each matrix, where available. Blue and red colored lines indicate the 25th percentile, median, and 75th percentile values for survival / growth and reproduction elasticities. Arizona hedgehog cactus (black squares) is near the median value for each measure.

Low elasticities for fecundity are commonly observed for plant species when λ is near 1 (Silvertown and others, 1996), as has been the case for most modeled cacti. However, this should not be taken to indicate that fecundity is unimportant for long-term population persistence. Fecundity often is the most variable vital rate, and its importance for long-term population maintenance is unlikely to be accounted for by short-term data (Shryock and others, 2014), particularly because cacti often show episodic recruitment (Godínez-Álvarez and others, 2003). High fecundity years are necessary to buffer populations against high mortality events, which may be more common than high fecundity years. Low elasticity values for fecundity may relate to the low frequencies of recruitment observed during the limited number of censuses available from monitoring (3–5 sampling episodes). Hence, the elasticity values could change if a high recruitment or mortality event is subsequently recorded during monitoring.

Life Table Response Experiment

The Life Table Response Experiment (LTRE) indicated that three plots reduced the overall pooled estimate of population growth (i.e., λ calculated with data from all plots combined), including Old Highway, Section 2, and Five Point (fig. 10). In contrast, the remaining plots increased the pooled estimate of population growth. This plot-level variation in demographic rates identified by the LTRE was corroborated separately by IPMs calculated at the plot level: three plots had negative population growth rates (Five point, -0.999; Old Highway 60, -0.903; Section 2, -0.989), whereas the remaining plots had positive population growth rates (Devil's Canyon, 1.057; Diversion Outfall, 1.032; Eder Wall, 1.053; Pinto Creek, 1.043; Superstition, 1.107; US 60, 1.031).

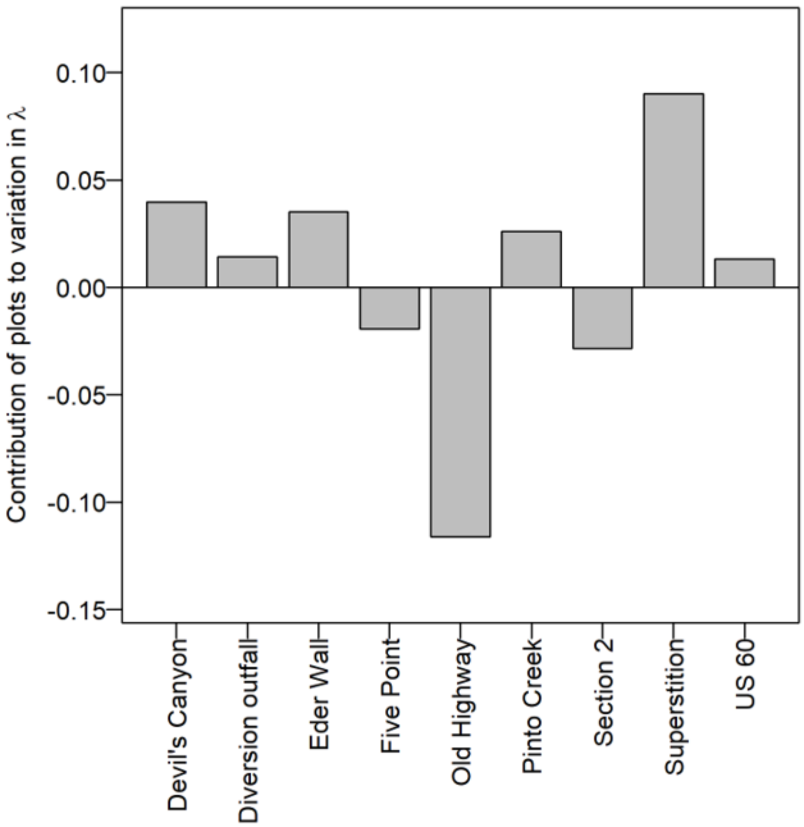

Figure 10. Life Table Response Experiment contrasting Cedar Creek Associates demographic plots in terms of their contribution to the pooled estimate of population growth (λ). Negative values indicate plots that decreased the pooled estimate of λ (overall population growth across all plots), whereas positive values indicate plots that increased the pooled estimate of λ. Three plots decreased the pooled estimate of population growth: Five Point, Old Highway, and Section 2.

Summary Demographic Analysis

We determined that most populations monitored by WestLand and Cedar Creek were stable to increasing ($\lambda > 1$). In the bootstrap simulations of model uncertainty, the deterministic population growth rate for these populations did not decrease to less than 1, the level at which a population is declining. However, spatial variability in population growth rates was observed among the demographic plots monitored by Cedar Creek (fig. 10). The cause of these apparent differences in population growth is worthy of future investigation; it is beyond the scope of this report. However, the three plots with negative population growth rates were not those established to monitor potential sulfuric acid impacts (Diversion Outfall and Diversion Inlet).

The demographic results presented here are based on relatively dense populations of undisturbed cacti. Although there are anecdotal observations of Arizona hedgehog cactus inhabiting disturbed patches such as roadsides (Cedar Creek Associates, 2009), our demographic models do not predict how populations may respond to sustained disturbance, such as the removal of large numbers of individuals. Instead, this report notes that the monitored populations had positive population growth in the absence of such large-scale disturbance.

As with other desert species, cacti populations typically are characterized by episodic recruitment and mortality events influenced by fluctuating environmental conditions (Drezner and Lazarus, 2008). For this reason, their population dynamics are difficult to characterize with short-term data, which often fail to capture rare but extreme events that shape long-term population trajectories (Miriti and others, 2007). Previous analyses with cacti (Shryock and others, 2014) and other species (Fieberg and Ellner, 2001; Doak and others, 2005) have suggested that more than 10 annual censuses are necessary to accurately forecast the stochastic population growth rate. Other measures based on stochastic projections, such as quasi extinction thresholds and estimates of minimum viable population size, also require large amounts of data. Although stochastic projections may be calculated with only a few censuses, the results will represent short-term dynamics observed during the monitoring period, leading to potentially inaccurate forecasts of future population trajectories (Fieberg and Ellner, 2001). The available data for Arizona hedgehog cactus, consisting of several biannual censuses for most cacti, are not sufficient to support forecasts of stochastic population growth rates or future population sizes. For this reason, we do not report such measures. Instead, we derived a 95-percent confidence interval for our estimates of deterministic population growth rates (fig. 6) as a function of the combined uncertainties in lower level vital rates (growth, survival, and fecundity) observed during the monitoring period.

Demographic monitoring done to date (2018) indicates that the Arizona hedgehog cactus shares many demographic characteristics with other cacti. Larger individuals have higher survivorship than smaller individuals, and a greater probability of producing more flowers. Seedling and young cacti often have lower survivorship than older cacti (Godínez-Álvarez and others, 2003). Although causes of mortality were not assessed for this report, frequently reported causes of mortality for seedling and young cacti include desiccation owing to drought (Drezner, 2004), insect damage (Miller and others, 2009), and herbivory (Shryock and others, 2014). Nurse plant associations commonly are recorded among cacti, wherein larger plants provide favorable microsites for seedlings and increase survival (Holland and others, 2013). However, it has not been established whether Arizona hedgehog cactus requires nurse plants for early establishment and survival, and such associations may not be constant across the lifespan of cacti (Drezner and Lazarus, 2008).

Survival and seedling establishment in Cactaceae frequently are linked with annual precipitation and summer maximum temperatures (Godínez-Álvarez and others, 2003; Drezner and Lazarus, 2008). Precipitation was less than average in south-central Arizona for 8 of the 10 years from 2007 to 2016 (National Oceanic and Atmospheric Administration, 2018), during which time the Arizona hedgehog cactus was monitored. However, the limited duration of monitoring (3–5 censuses) and biannual sampling scheme precludes establishing a statistical link between vital rates and climate.

Task 3—Focus Group

The Arizona Hedgehog Cactus Symposium was attended by 22 people (see agenda in appendix table 1.2). Presentations were made on the species taxonomic history (Kim McCue, Desert Botanical Garden), morphological studies (Marc Baker, private contractor), genetic studies (Shannon Fehlberg, Desert Botanical Garden), pollination studies (Clare Aslan, Northern Arizona University), salvage studies (Cathy Babcock and Mark Siegwarth, Boyce Thompson Arboretum), transplanting (Russell Waldron, SWCA Environmental Consultants), propagation (Jan Fox, WestLand Resources, Inc.), and monitoring (Jan Fox of WestLand Resources, Inc., and Jesse Dillon of Cedar Creek Associates). No formal notes or follow-up actions were developed.

Future Surveys and Monitoring

This assessment of existing data resources for the Arizona hedgehog cactus identifies potential actions to improve the quality and applicability of data derived from future surveys and monitoring of the cactus.

Survey Data

There is no mandate for submission of survey data for the Arizona hedgehog cactus to either the FWS and or HDMS. Nevertheless, the compilation and management of survey data are essential to any field-based determination of the range boundaries of the cactus and evidence-based estimate of its population density. Because the HDMS has an ongoing and permanent system for data compilation and archiving, this program of the AZGFD could be considered as a permanent repository with survey data going directly to the HDMS or to them through the FWS. Although the HDMS accepts occurrence records in any format, the HDMS provides these recommended data collection standards:

- Georeferenced coordinates for each observation—North American Datum of 1983 Universal Transverse Mercator zone 12 coordinate system; ideally one GPS coordinate record will be collected for each cactus, but if, this is not possible, then annotation should be made indicating the estimated number of cactus over a defined area. Submit data to the HDMS through a geographic information system (GIS) file or spreadsheet such as modified for plants from the HDMS Scientific Collecting License (Sabra Tonn, Heritage Data Management System Program Supervisor, written commun., May 30, 2018).
- Observation submissions include, at a minimum, who is doing the collecting, the date, as well as the georeferenced coordinates.

Negative-occurrence data are highly valuable in determining the distribution and habitat requirements for an endangered species. Negative-occurrence data consist of detailed descriptions and or GIS polygon depictions of areas surveyed where no cacti were found, accompanied by a description of the survey methodology sufficient to indicate the intensity of the survey. No repository is available for the collection of data or reports on negative-survey results for the Arizona hedgehog cactus, at the time of this report.

Because of the issues existing for taxonomic separation of the Arizona hedgehog cactus and either comingled *E. santaritensis* or cacti with traits of both, information gained by surveyors (particularly at the periphery of the range of the cactus) may be particularly useful in clarifying these taxonomic issues. Use of a vetted identification guide between the two species and documentation of cactus morphology with pictures could be encouraged, with a directive as to where this information could be submitted for compilation.

Demographic Monitoring

A key difficulty in establishing demographic monitoring for cacti is correctly identifying seedling establishment. For this reason, it is critical to establish exactly how many cacti exist in a monitoring unit at the time a demographic study is initiated. This may be easier to accomplish in a typical square plot of moderate size than along extended linear transects. Based on the data reviewed here, the rate of undetected cacti likely was higher along the linear, roadway transects monitored by WestLand than in the demographic plots monitored by Cedar Creek. Incorrectly establishing the number of plants in a demographic monitoring unit at the start of monitoring may lead to an overestimation of the recruitment rate for a species, particularly where recently emerged seedlings and young adults are similar in size, as is frequently the case with cacti. There are situations in which the type of monitoring done by WestLand would be preferable, such as establishing the total population size and (or) density in the study area. However, for accurate estimates of population dynamics and the population growth rate (λ), strict adherence to demographic monitoring protocols (consistent plot size, identifying and marking all individuals) is necessary.

For short- to moderate-lived plants, annual censuses are preferable to biannual censuses because an annual monitoring period is required to capture changes in vital rates. Census periods longer than 1 year are not typically recommended for demographic studies unless changes in adults of the monitored species are slow or seed germination is extremely rare (Elzinga and others, 1998). Most cacti (with the potential exception of large columnar species) do not fit into this category. Moreover, census periods longer than 1-year complicate estimates of fecundity for two reasons: (1) the appearance of seedlings may be missed in the year in which they emerge; and (2) an unknown amount of reproductive effort, including flowering and fruiting, is not recorded in the off-sample years. The measurement of reproductive effort forms the basis for estimating seedling establishment rates and the reproductive value of individuals. Finally, without annual measurements, it is difficult to establish links between vital rates (survival, flowering, seedling establishment) and environmental conditions that vary on an annual or seasonal basis, such as precipitation and temperature.

Several additional measurements were taken by WestLand and Cedar Creek that we considered beyond the scope of this report, as they did not help us to assess population dynamics. First, we did not assess visual measures of cacti health, as these are subjective judgements and are not typically used in demographic analyses. To be considered as an indicator in long-term population monitoring, such measures would have to be standardized among observers in a way that ensures consistent ratings. Second, we did not consider measurements of growth that were taken on subsets of cacti. Although these measurements could be used to estimate the age of individuals based on their size, such estimates are of questionable accuracy and vary based on the study site under consideration (Drezner and Lazarus, 2008). Moreover, establishing an age / size relation would require the height and (or) diameter of stems from all individuals, and these measurements were not reported at the Cedar Creek site. For our demographic model, we included the only measure of size (number of stems) that was consistently available across all monitored individuals. However, most previous demographic models of cacti have incorporated either stem diameter or height as the state variable.

In summary, we propose three changes to the existing monitoring framework to accurately capture demographic trends for the Arizona hedgehog cactus:

1. Sample on an annual rather than a biannual basis;
2. Record flowering and (or) fruiting effort each year cacti are sampled; and
3. Monitor cacti in plots that allow consistent detection of all individuals, including seedlings.

Standardized, long-term collection of monitoring data will provide the FWS, public land managers, and commercial interests with the best data to inform management decisions concerning Arizona hedgehog cactus and its supporting habitat. As the length of data collection increases, better assessment can be made of the response of the cactus to emerging threats such as wildfire and rapidly changing climate. Long-term monitoring—that is, 10 years or more—allow statistical linking of population events with specific drivers, such as climate events.

Acknowledgments

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Appendix 1. Details of Arizona Hedgehog Cactus Monitoring Counts and Agenda for Arizona Hedgehog Cactus Symposium

Table 1.1. Details of yearly Arizona hedgehog cactus monitoring counts for Carlotta Copper Company, central Arizona, 2007–15. Gray shaded cells indicate the first monitoring year for each permanent plot. Plot monitoring generally was undertaken every other year for all but the Diversion Inlet and Diversion Outfall plots, which were measured yearly.

[**Plot:** DC, Devil's Canyon; DI, Diversion Inlet; DO, Diversion Outfall; EW, Eder Wall; FP, Five Point; 60, Highway 60; OH, Old Highway 60; PC, Pinto Creek; S2, Section 2; SU, Superstition. **Abbreviations**: nd, no data available for cell measure; na, monitoring measurements were not taken for plot in that year.]

				2009			2010			2011			2012			2013			2014			2015		
Plot	Size (acres)	2007	2008	Continuing	New	Dead	Continuing	New	Dead	Continuing	New	Dead	Continuing	New	Dead	Continuing	New	Dead	Continuing	New	Dead	Continuing	New	Dead
DC	2.79	26	na	22	7	5	na	na	na	26	5	3	na	na	na	30	6	1	na	na	na	32	1	2
DI	nd	na	12	12	0	0	12	0	0	12	0	0	12	0	0	12	0	2	10	0	0	na	na	na
D0	2	na	59	57	0	2	55	11	2	66	3	0	68	3	1	72	1	1	66	0	6	na	na	na
EW	0.83	na	29	na	na	na	28	10	1	na	na	na	31	2	7	na	na	na	31	2	2	ba	na	na
FP	2.15	75	na	72	10	5	na	na	na	77	7	5	n		na	79	5	5	na	na	na	80	5	6
60	0.61	na	25	na	na	na	23	2	2	na	na	na	25	1	0	na	na	na	26	1	1	na	na	na
OH	6.04	na	34	na	na	na	26	6	8	na	na	na	28	3	4	na	na	na	28	0	3	na	na	na
PC	1.33	26	na	24	4	2	na	na	na	28	4	0	na	na	na	31	1	1	na	na	na	30	3	2
S2	1.61	36	na	34	3	2	na	na	na	35	5	4	na	na	na	39	2	1	na	na	na	39	1	2
SU	0.39	34	na	na	na	na	34	7	0	na	na	na	41	2	5	na	na	na	na	na	na	na	na	na

Table 1.2. Arizona Hedgehog Cactus Symposium Agenda, Phoenix Arizona, September 21, 2016.

Arizona Hedgehog Cactus Symposium
Desert Botanical Garden
Phoenix Arizona
Whiteman Conference Room
September 21, 2016
8:00am – 4:00pm

8:30am **Welcome and Introductions** – Kim McCue

(Presentations will be 10-15 min; discussion/questions 5-10 min)

Arizona hedgehog cactus Biology

8:50am	Taxonomic history – Kim McCue
9:10am	Morphological studies – Marc Baker
9:30am	Genetic studies – Shannon Fehlberg
9:50am	Video – Cactus conservation at the Desert Botanical Garden
10:00am	Pollination studies – Clare Aslan
10:20am	Break

Arizona hedgehog cactus Salvage and propagation

10:40am	Salvage – Cathy Babcock/Mark Siegwarth
11:00am	Transplanting – Russell Waldron
11:20am	Propagation – Jan Fox
11:40am	Discussion

Arizona hedgehog cactus Monitoring – Current status and future directions

12:00pm	Introduction – Kathryn Thomas
12:10pm	WestLand Resources highlights – Jan Fox
12:20pm	Cedar Creek Associates highlights – Jesse Dillon
12:30pm	**Lunch** and dialogue
1:30pm	Future directions for monitoring
2:30pm	**Research and Recovery** – Kathy Robertson
2:40pm	Future directions for research – gaps and goals
3:40pm	Closing and wrap up

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