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Modeling Reproduction Influencers of an Endangered Oak

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Modeling Reproduction Influencers of an Endangered Oak

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ABSTRACT The endemic oak, *Quercus brandegeei* has been labeled as endangered by the IUCN Red List of Endangered Species due to its limited genetic diversity and lack of regeneration. The oak (*Quercus*) species is a keystone species in many parts of the world and has been facing various challenges to their survival (Westwood 2017) making efforts to support and protect endemic oaks all the more ecologically and socially imperative. There are challenges to identifying threats as there are many unknown characteristics of *Q. brandegeei's* biology that are essential to carrying out conservation efforts. To develop a greater understanding of the species, the study characterized the size distribution and population structure of *Q. brandegeei*, which may be connected to the predicted small number of reproducing individuals, responsible for the lack of regeneration. Following the analysis of population structure, 73% of the trees sampled showed evidence of reproduction and 55% of trees fall within a DBH size class greater than 50 cm, indicating a population consisting of reproducing adults. There were reproduction differences between population localities and regions. With the majority of individuals reproducing, generalized linear models were then used to identify environmental factors (location, precipitation, and temperature) that served as the strongest predictors of reproduction. The strongest predictive model revealed that a combination of location by region and total wet season precipitation during the year of production were significant factors in predicting whether or not individuals reproduced. These findings may help to determine the most effective locations for reintroduction of seedlings and areas to conduct *in situ* conservation efforts.

INTRODUCTION

The effects of anthropogenic activities and climate change have resulted in shifts within plant species distribution and reduced ecosystem resilience (Fordham et al. 2012). The decline of

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various species poses risks to the stability of many vulnerable ecosystems around the world. One way to help reverse this decline is to identify populations of endangered species and the reasons for their decline or lack of recruitment in hopes of using this knowledge to revive populations. *Quercus*, a prominent keystone species, is valuable to ecosystems across multiple continents and has experienced hinderances to natural recruitment linked to anthropogenic and climatic changes (Perea et al. 2017; O'Donnell et al. 2020).The oak genus is researched well in some regions, but there are still some members of the genus that have limited data and publications, specifically species located in mountainous regions of Mexico and southeastern United Sates (O'Donnell et al. 2020; Gerst et al. 2017).

Endemic species found in arid environments have a limited area of occurrence, making climate change a serious threat. A loss of their preferred habitat or changes that shift the regions where they can survive and reproduce can lead to species extinction. This highlights the need for conservation efforts designed for the specific condition of a threatened species and its location. Previous studies have determined that 175 out of 420 oak species were critically endangered or vulnerable (Westwood 2017). Of the species identified, 19% were found to be data deficient, one of which is *Quercus brandegeei*, a species endemic to Southern Baja California, Mexico.

Quercus brandegeei's current range is in an arid desert climate on sandy soils adjacent to ephemeral rivers as well as granitic mountains and associated washes near desert scrub (Denvir and Westwood 2016). The range of *Q. brandegeei* receives a mean annual precipitation of about 50 cm with the majority of rainfall during the summer months (ibid.; Blanchet et al. 2007). The genetic delineation of *Q. brandegeei* results from the formation of the Sea of Cortes, isolating it from mainland Mexico and decreasing its genetic variability (Cavender-Bares et al. 2015). Species fragmentation resulting from speciation, habitat loss, and the need for very specific conditions for individuals to become established increases the potential for extinction (Sgardeli et al. 2017). The already severe lack of regeneration serves as another indicator of a heightened probability of extinction (ibid.). The limited range of *Q. brandegeei* is compounded by other threats identified by Westwood and Alvarez-Clare (2019) including overexploitation, drought conditions, over-grazing by livestock and the potential overharvesting for charcoal and fuel wood (Denvir and Westwood 2016). This species provides services for both the people in the region and the organisms consuming its acorns.

Efforts to provide this species with favorable chances of survival need to include identifying determinants of reproduction. Methods and determinants of reproduction vary by species (Klimas et al. 2012) including reproduction strategies of oaks, ranging from individuals following masting events or cloning (Alfonso-Corrado et al. 2007). Masting events are difficult to time with some species following a two year precipitation regiment to allow for enough nutrients to initiate seed production, whereas others may follow precipitation patterns of the current year (Knops et al. 2007). A combination of the plant's internal nutrient storage and weather cues such as amount of precipitation have contributed to the onset of seed and fruit production, primarily in the case of woody and wind pollinated plants (Pearse et al. 2016). With various factors playing a role in reproduction, it is important to formulate statistical methods for identifying which may be more influential depending on the species.

Variation in seed production for *Q. brandegeei* may be partly due to the location of trees. Slopes facing either the gulf of California or the Pacific Ocean both present topographic and climatic differences (Arriaga and Leon 1989). Historically, these two areas have seen a difference in rainfall of about 204 mm; the Pacific region has yearly means of 507 mm compared with the Gulf area's yearly mean of 303 mm. The Pacific region also experiences colder temperatures (ibid.). Rainfall becomes a significant influencer to determining successful seed production due to the synchronicity of masting events occurring over large areas (Buechling et al. 2016), making a varying and drying climate in areas of *Q. brandegeei's* already small range possibly detrimental to its regeneration.

To better understand the population's condition, the overall population structure of the species was determined, specifically establishing the proper size class distribution for visualizing the number of juvenile and mature adults. Developing the most biologically appropriate size class to present population structure will assist with creating more viable models for a population's viability (Klimas et al. 2007). The appropriate type of curve used to represent the size class distribution of unmanaged and viable old growth forests depends on the species, with one of the more common curve shapes being the reversed j-shape indicating a greater presence of small class size trees than larger trees, following a negative exponential curve (Westphal et al. 2006). It is hypothesized that the size class distribution will be skewed with more trees in the larger size classes since there has been no observation of recent regeneration. As all trees observed by field researchers are at least 100 years old there should be evidence of reproduction in all size classes, however larger trees may also be storing nutrients to focus on maintaining their leaves, especially due to the exceedingly small amount of precipitation received in the region. It is hypothesized that there will be little to no reproducing individuals in the smaller size classes, indicating a possible DBH size threshold for mature reproducing adults, and the majority of individuals will not be reproducing possibly to conserve nutrients to support leaves throughout the year.

To test predictors of seed production, generalized linear models with a binomial distribution were used. Some of the predictor variables tested included: DBH, location, total precipitation, and minimum and maximum temperature during the dry and wet season of the year of production and the year previous. It is predicted that demographic variables such as DBH will not be strong predictors of seed production. While the relationship between size class and reproduction has been found in other studies, the lack of smaller size classes is likely to make demographic predictors less important. It is predicted that the model will be strengthened with the addition of climate factors such as precipitation and temperature and location. Differences in reproduction will likely be seen based on the region individual trees are located, which will again be primarily explained through precipitation of the current reproducing year and temperature.

METHODS

Data collection

Populations of *Q. brandegeei* were located and sampled using data from a previous phylogenic and biogeographic study of *Quercus* subsection *Virentis* conducted by Canvender-Bares et al. 2015. Field surveys were conducted by researchers to identify additional populations, resulting in the 11 populations identified in 4 different regions presented in Table 1.

Region	Locality
Gulf	Aserradero
North	Todos Santos
	Tejon
	Valle Perdido
	Puente San Antonio
	Canyon de Brecha
Pacific	Cultivo/Palmera
	La Alegria
	La Burrera
	Santo Domingo
South	Santa Anita

Table 1. The 11 populations are named based on the corresponding locality, which can also be associated with a specific region of Baja California Sur.

For each population, 10 to 20 trees were sampled by measuring diameter at breast height (DBH) and overall height for each stem. The demographic data provided by researchers included basal area for both individual trees and stems, evidence of reproduction (i.e. presence of acorns), and if the individual trees were located in or out of the Sierra de Laguna nature reserve. A total of 174 individual trees, comprised of 283 stems, were sampled.

Climate data was taken from the Mexican department of Environmental and Natural Resources provided by the Comission Nacional del Agua Servicio Meterologico National (CONAGUA). Using the map and coordinates of each sampled population provided by researchers and the Centro de Investigación Científica y de Educación Superior de Ensenada (CICESE).The closest weathers station to the sampled populations were identified by comparing the location of each population to the operating stations on the CICESE map. Nine stations were found to have the closest proximity to the 11 populations. From these stations data for daily average temperature, daily minimum average temperature, daily maximum average temperature was downloaded.

Using the data downloaded for daily precipitation, the total wet season rainfall for the year of production (2017) and the year prior (2016) was identified by plotting the total precipitation by month and identifying the 3 months with highest total precipitation for each population. The resulting wet season was found to take place during August through October. The dry season was much more difficult to distinguish as there is little to no rainfall during the majority of the year. Graphs of average monthly rainfall were again used, and spring was identified as the dry season, specifically months March through June. The daily precipitation for each of these months was summed and used as predictor variables.

Analysis

To determine the population structure of *Q. brandegeei*, the DBH of each multi-stemmed individual was aggregated using quadratic sum equation (Magarik et al. 2020; Snowden et al. 2002):

$$DBH_{ms} = \sqrt{\sum_{i=1}^{n} DBH_i^2} \qquad (1)$$

All of the DBH values for the individual trees (n=174) were categorized into 7 classes that increased by 15 cm intervals from 0-15cm as class 1 and 90+ cm as class 7 (see figure 1 for full range). Various bar charts displaying the count of reproducing individuals were then created using the 15 cm classes as well as the location of each population. To identify if DBH classes or different locations had significantly different numbers of reproducing individuals, DBH, population, location in or out of the nature reserve, and region were used a fixed factors and added to generalized linear models. The lowest AIC values produced were used to signify the presence of significant differences between groups.

Generalized linear models with a logit distribution were used to model presence/absence of seed production. Packages lattice and lme4 were used to run each model in RStudio. All possible predictor variables can be viewed in Appendix 1. Predictor variables with $p \leq 0.05$ were included in the model and AIC values were used to determine the best-fit model.

RESULTS

Demography

Trees were grouped based on their DBH in a way that represented the biological structure of the population. The mature population of trees suggests that the majority of individuals are at the age of reproductive capability and fall within larger size classes. Figure 1 shows that 77.5% of trees fall within the 30 to 40 cm DBH size class and larger.

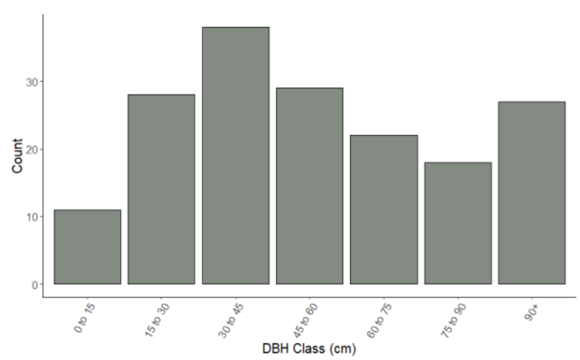

Figure 1. The entire population of *Q. brandegeei* sampled was placed into 7 DBH classes each spanning 15 cm intervals. The majority of trees have a DBH of 30 cm or larger.

Appendix 2 shows that there is evidence of reproduction, indicating reproductive maturity, in all size classes. Size class was not significant in determining whether individuals reproduced. When dbh class was added to the glm as a fixed factor, the change in AIC was less than 2 from 191.47 for the Null model and 191.19 for the

DBH classes when added as a fixed factor and dbh was not significant in determining reproductive status.

The count of reproducing individuals by region showed more variation in evidence of reproduction than by DBH class. The first location variable used to display the count of reproducing and non-reproducing individuals was the split by the 11 population named in Table 1. Appendix 3 displays the differences in the number of reproducing individuals based on the 11 populations. The resulting AIC value with population used as a fixed factor was 76.317, a significant drop in AIC compared to the null model, ideintifying significant differences in the number of reproducing individuals between populations. A noteworthy difference can be seen with Todos Santos which had no evidence of reproduction at the time compared to the rest of the population in the same region.

The difference in reproducing individuals can be clearly seen between populations, which was then followed by testing the differences in reproducing individuals by region. Figure 2 displays the count of reproducing and non-reproducing individuals. With region added to the model, the AIC value dropped to 144.71 which is a significant drop in AIC compared to the null model, displaying that location based on region has caused a difference in the number of reproducing individuals observed.

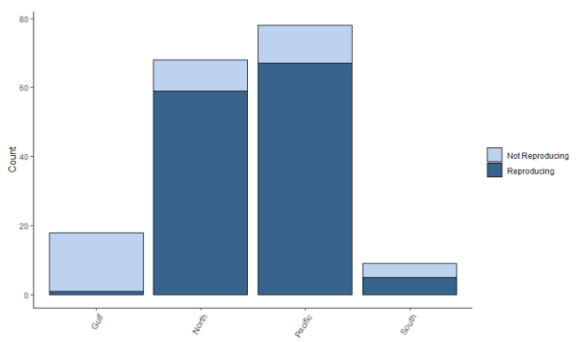

Figure 2. Reproduction based on region is displayed above with the Gulf region having the smallest number of reproducing individuals.

Predicting Reproduction

Climatic and location variables (listed in Appendix 1) were used as fixed variables to predict the presence of reproducing individuals. Appendix 4 shows the results from the best fit model and compares it to other models created. The delta AIC value of 0 identifies the first model as the strongest with both present year rainfall during the wet and dry seasons as well as the location within a specific region having the greatest ability to predict whether or not an individual reproduces.

Appendix 5 presents the predictive strength of each of the variables in the strongest model created with an AIC value of 74.708 which is the largest decrease from the null model with a value of 191.47. Each variable's estimate indicates the likelihood of reproduction occurring based on the presence of the specific variable.

Within the model, 4 of the variables were considered significant with a p-value of less than .05. These variables include: location in the gulf, north, and south region, as well as the presence of rainfall during the wet season. Trees located in the gulf region can be considered to have a 21.0% chance less of reproducing compared to the other regions. An individual being located in the North region also decreases the chance of reproduction by 9.86%. However, individuals present in the south region have an increased chance of reproducing by 6.54%. The final variable that increases the chances of reproducing is the presence of rainfall during the wet season, regardless of the location, which increases by .059%

DISCUSSION

As challenges to species recruitment and increasingly hostile climates expand throughout deserted areas, it is crucial to identify keystone species and link current conditions which may explain the barriers to a population being reproductively viable. In the case of *Q. brandegeei* all individuals are considered reproductively mature due to their age and evidence of reproduction across all DBH size classes (Appendix 2). The mature population can also be seen in the lack of new recruits – specifically shown in the absence of the usually expected, or healthy and sustainable structure of the reversed j-shaped curve (Westphal et al. 2006) for the DBH size distribution which would imply the presence of many smaller juvenile individuals. The graphs displaying the count of reproducing and non-reproducing individuals indicates that drivers for reproduction are not necessarily influenced by size or age.

Location was then used, specifically the location of the 11 populations, to identify possible patterns in reproduction, resulting in clear differences for the number of reproducing individuals within 5 populations: Aserradero, Canyon de Brecha, Puente San Antonio, Santa Anita, and Todos Santos. These differences are also seen between the 4 regions, with the Gulf region containing the least amount of reproducing individuals. Timing of reproduction can change between various species due to phenological differences, which Abrahamson and Layne (2003) found within mixed species oak forests in southern Florida. The possible phenological differences *within* the *Q. brandegeei* species may be indicated through the lack of reproducing individuals in the Gulf regions. Researchers had returned to the location later in the season and found more individuals with evidence of reproduction, revealing that climate characteristics may play a larger role in dictating reproduction in specific regions of Baja California Sur, and that the individual population are especially sensitive to those changes due to the very limited rainfall in the region.

The narrow rainy season in early autumn likely triggers the masting behavior of the 11 populations, with a slight deviation in timing for the population located in the Gulf region, which is to be expected as masting correlates with environmental cues like temperature or rainfall (Koenig et al. 2015). An indication of *Q. brandegeei's* sensitivity to rainfall specifically lies within the species' year long leaf lifespan (Cavender-Bares et al. 2015). Of all the oak species in the previous study conducted by Canvender-Bares et al. (2015), *Q. brandegeei* one had the smallest leaf area which is associated with the low mean annual precipitation.

Significant weather variables found in this study reflected the opposite of the findings in Koenig et al. (2015) which stated a significance in summer temperatures and summer rainfall presenting themselves as determinants of patterns of acorn production, where in this study, wet and dry season rainfall displayed the greatest potential in predicting reproduction with wet season rainfall being the only significant weather variable. The strongest model lacked the presence of temperature as a predictor variable of reproduction, indicating that if the temperature drops, but no rain falls, then there will not be a significant increase in the likelihood of reproduction. Abrahamson and Layne (2003) found that shrubby south Florida oaks are not affected by low winter temperatures, however there is evidence that rainfall levels do have a positive effect on acorn crop size.

The challenging environment of Q. brandegeei as well as the little knowledge of the species complicates identifying factors that may lead to being able to predict reproduction. The current understanding of what directly influences preproduction and masting in plants is also still not completely known (Pearse et al. 2016; Koenig et al. 2020 however rainfall and location can be considered significant predictors of reproduction for the species *Q. brandegeei* based on the evidence found.

A more detailed study on the climatic variation in the 4 regions of Baja California Sur, survey the water table near existing populations throughout the years, and long term and repeated surveys of both acorn density and the number of reproducing individuals would be beneficial to determining more concrete climatic and reproductive patterns of the species.

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Support for this project was provided by the McNair Scholars program offering a Summer Research Opportunity (SROP) as well as an independent research grant for the continuation of the project through the autumn. Funding for data collection was provided by The Moton Arboretum, Franklinia Foundation, and The Global Trees Campaign. Data was collected and provided by Dr. Jeannine Cavender-Bares (University of Minnesota), Audrey Denvir (The Morton Arboretum), and Dr. Antonio González-Rodríguez (Universidad Nacional Autonomo de Mexico). Thank you to our local collaborators at the Centro de Investigaciones Biológicas del Noroeste (CIBNOR), Dra. Aurora Breceda, and staff from the Sierra la Laguna Biosphere Reserve. I would like to thank my mentors, Dr. Christie Klimas and Dr. Silvia Alvarez-Clare for providing support and guidance throughout the entirety of this project, as well as my research team Maddie Fernandez, Carolyn Brinckwirth, and Daniel Pérez Morales for their collective support and collaboration. Lastly, thank you to my McNair mentors Rhea Bovee and Brittany Rivera for supporting me throughout the research process.

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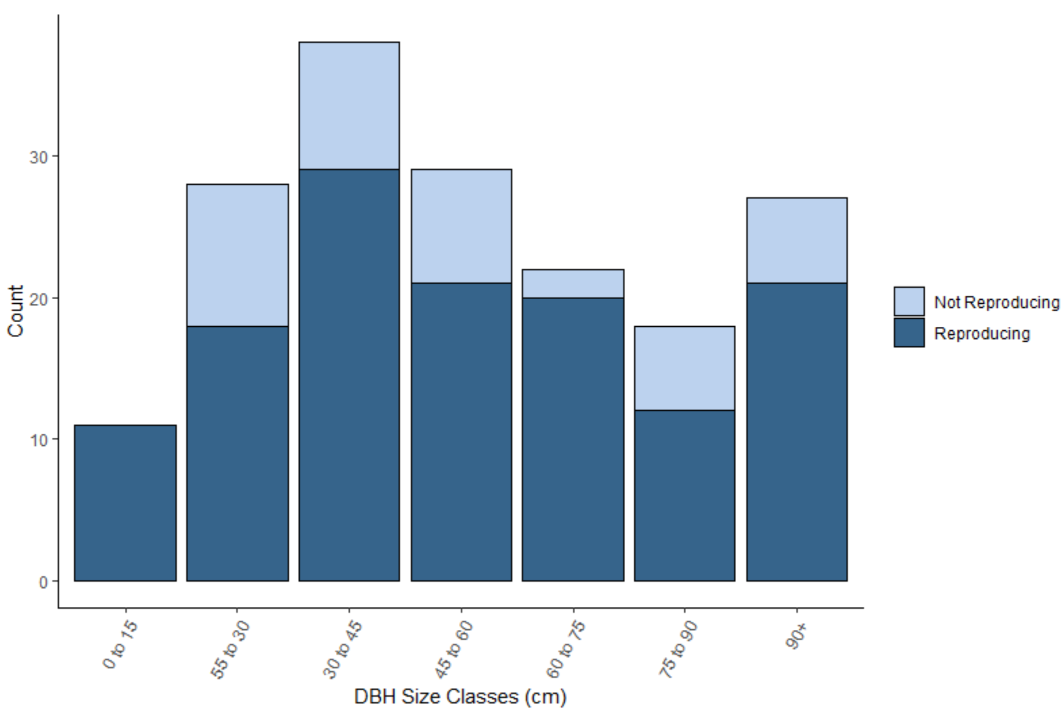
APPENDICES

Appendix 1.

Variable	Description
Reproducing	Presence/absence of acorns; data represented as 0 and 1's
DBH_class	Consists of the 15 cm size classes
Region	Pacifico, Norte, Golfo, Sur
In_reserve	In or out of the Sierra La Laguna Nature Reserve
Min_temp	Average Minimum Temperature 2017
Max_temp	Average Maximum Temperature 2017
Dry_rainfall	Total dry season precipitation: Spring April – June 2017
Wet_rainfall	Total wet season Precipitation: Late Summer Early Fall August – October 2017
Min_temp.1	Average Minimum Temperature 2016
Max_temp.1	Average Maximum Temperature 2016
Dry_rainfall.1	Total dry season precipitation: Spring April – June 2016
Wet_rainfall.1	Total wet season Precipitation: Late Summer Early Fall August – October 2016

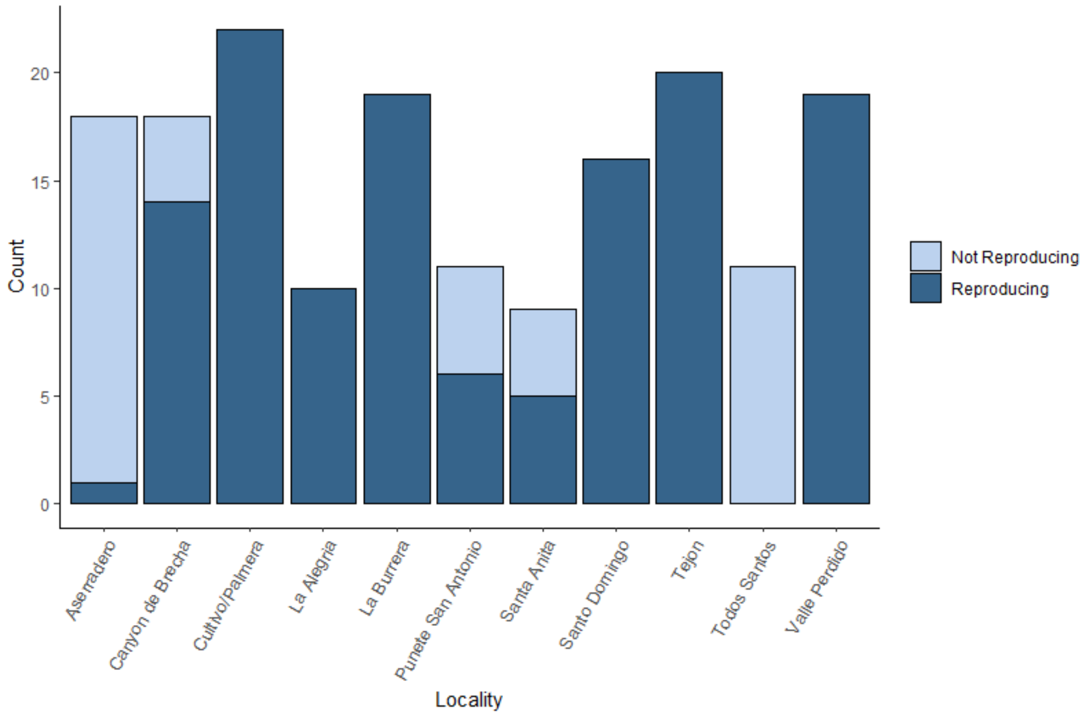
Note: Each of the variables listed above were used as fixed factors in the generalized linear models.

Appendix 2.



Note: Evidence of reproduction can be seen within all size classes and the number of reproducing individuals are not significantly different.

Appendix 3.



Note: Clear differences in the number of reproducing individuals are seen within 4 populations. Following the addition of locality into the generalized linear model, Aserradero, Canyon de Brecha, Punete San Antonio, and Santa Anita, had a significantly different number of reproducing individuals compared to the rest of the populations.

Appendix 4.

Model Variables	K	AIC_C	ΔAIC_C	ω_i
Region + Wet_Rainfall + Dry_Rainfall	6	73.233	0.00	0.746
Region + In_Reserve + Wet_Rainfall + Dry_Rainfall	7	75.387	0.253	0.254
Region + In_Reserve + Max_Temp + Wet_Rainfall	7	106.115	32.882	0
Region + In_Reserve + Wet_Rainfall	6	110.570	37.337	0
Region + In_Reserve + Dry_Rainfall	6	120.933	47.700	0
Region + In_Reserve + Max_Temp + Dry_Rainfall	7	122.689	49.455	0
Region + In_Reserve + Min_Temp	6	126.736	53.503	0
Region + In_Reserve + Max_Temp	6	126.836	53.603	0
Null	1	191.490	118.256	0

Note: The ΔAIC_C and AICc values for the models will the greatest predictive strength are compared using Akaike's weights. The strongest predictive model is displayed with a delta AIC value of 0, as the models weaken the ΔAIC_C value increases with the null model being the weakest. Each variable used in the original generalized linear model is included, with none of the precipitation or temperature variables from the year prior to reproduction are included in the strongest model.

Appendix 5.

Binomial Model: Predictors of Reproduction					
Formula: reproducing ~ region+ + wet_rainfall + dry_rainfall					
	Estimate	**Std. Error**	**Z value**	**Pr(>|z|)**	**Significance**
Gulf Region (intercept)	-21.03335	6.25238	-3.364	0.000768	***
North Region	-9.86168	4.85372	-2.032	0.042176	*
Pacific Region	2.91171	4.37499	0.666	0.505708	
South Region	6.53623	1.70271	3.839	0.000124	***
Wet Season Rainfall: Current Year	0.05888	0.01995	2.951	0.003166	**
Dry Season Rainfall: Current Year	24.58385	1458.508	0.017	0.986552	
AIC = 72.727; deviance = 60.727, degrees of freedom residuals = 167					

Note: AIC values were produced following the creation of each model. The number is arbitrary, although the smaller the value produced in comparison to the previous and null model, the stronger fit the predictors of reproduction are. Above is the strongest predictive model of reproduction.