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Climate change impacts on high elevation saguaro range expansion

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ABSTRACT

Severe freeze events have been identified as a primary limiting factor for the saguaro cactus at high elevations in the southwestern United States. With the observed increase in minimum temperatures, it may be expected that saguaros will expand their elevational range. To better understand the factors influencing potential range expansion, we developed a logistic regression model to help explain saguaro presence along its current uppermost elevation. We find that the occurrence of fire decreases the odds of saguaro presence by 78 percent. While less frequent freeze events could allow saguaros to push their current elevational limit, our model suggests that increased fire activity related to the establishment and spread of invasive species could inhibit this range expansion.

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1. Introduction

The saguaro cactus (*Carnegiea gigantea*) occurs in the Sonoran Desert, primarily in Sonora in Mexico and Arizona in the United States (Fig. 1). Saguaros are near the northeastern edge of their range in Saguaro National Park's Rincon Mountain District (RMD) in southern Arizona, where they are bounded at around 1400 m (4500 ft) in elevation (Niering et al., 1963).

The Rincon Mountains of Saguaro National Park are part of a larger system of mountains known as the Sky Islands or the Madrean Archipelago. These mountains showcase the relationship between elevation and biomes (Merriam and Steineger, 1890) by transitioning from one dominant vegetation type to another as elevation increases. The present study is focused on the elevational band in which saguaros disappear from the landscape alongside a shift in the dominant vegetation type from desert scrub to desert grassland around 1220 m (4000 ft) (Whittaker and Niering, 1965, 1975).

With increasing elevation, severe freeze events become more frequent and annual precipitation increases (Whittaker and Niering, 1965). This area is further characterized by more frequent fires compared to lower elevations which seldom burn because of insufficient fine fuel loads (Esque et al., 2004). Although saguaros have received intensive ecological study such as Steenbergh and Lowe's three volume series (1976, 1977, 1983) and long-term demographic studies spanning back to at least 1908 (Pierson and Turner, 1998; Pierson et al., 2013; Rodriguez-Buritica et al., 2013) there is relatively little information about saguaro ecology at the edge of its elevational range.

Freeze severity and duration have long been explored as limiting factors for saguaros in the northern extent of its range (Shreve, 1911). In the late 1930s widespread saguaro mortality in Saguaro National Monument (which became a national park in 1994) led to the initiation of many research studies examining the ecology and demographic characteristics of the species. From these studies, it now seems certain that the proximate cause of mortality in older, large individuals was a severe freeze event in 1937, while prolonged poor recruitment was probably due to the combined impacts of severe freeze, cattle grazing, and the removal of saguaros' nurse trees to fuel nearby lime kilns (Steenbergh and Lowe, 1977). Recruitment began to recover by the 1970s, however, in response to the park's restriction on wood-cutting in the 1930s and the gradual elimination of grazing. In addition, there were no major freeze events at low elevations in the park between 1978 and 2011. All of these conditions combined with several years of above average precipitation led to superb recruitment conditions for young saguaros through the 1980s and 1990s. A 2010 survey indicated a rebounding saguaro population which had doubled its numbers in many parts of the park (O'Brien et al., 2011).

With a surging saguaro population and decreasing freeze event frequency (Weiss and Overpeck, 2005) it could be expected that

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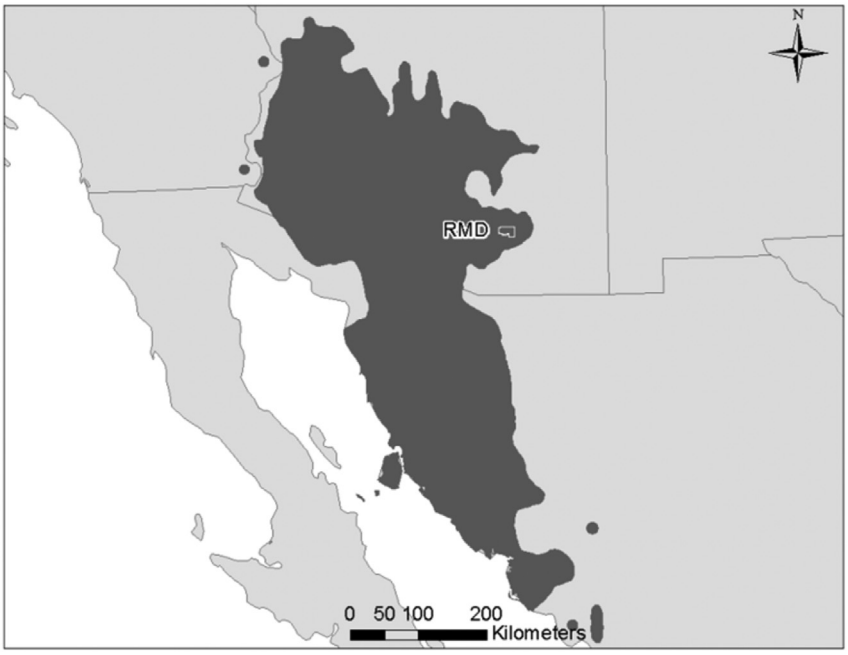

Fig. 1. Range of the saguaro (*Carnegiea gigantea*). The location of the Rincon Mountain District (RMD) of Saguaro National Park is indicated along the northeastern edge of the range. Data from Little (1976); digitized by USGS (2014).

saguaros might expand their current spatial and elevational distribution as observed with other species (Chen et al., 2011; Parmesan and Yohe, 2003; Tape et al., 2006; Walther et al., 2002). Climate change prediction models anticipate saguaro distributions to expand east and west of their current extent (Shafer et al., 2001).

In addition to the reduced frequency of freeze events, most climate change models predict generally hotter and drier conditions for the southwestern United States. Overall, temperatures are expected to increase one to two degrees Celsius by the middle of the twenty-first century (Barnett et al., 2004). Annual precipitation is estimated to decline 10 percent by 2100 (Christensen et al., 2007), principally driven by reductions in winter precipitation (Seager and Vecchi, 2010). Both temperature and precipitation predictions suggest that potential and actual evapotranspiration will increase dramatically, which is expected to foster the spread of many invasive species and increase the occurrence, extent, and severity of wildfire. The non-native perennial buffelgrass (*Pennisetum ciliare*) has been shown to rapidly convert desert scrub ecosystems to grass-dominated landscapes (Olsson et al., 2012), limiting the distribution of saguaros at higher elevations (Stevens and Falk, 2009). Fire activity is also increasing at these elevations in the desert Southwest (Esque et al., 2004), and saguaros are highly susceptible to fire (McLaughlin and Bowers, 1982; Wilson et al., 1996).

Decades of ecological and demographic research on saguaros indicate that future changes in saguaro range will be complex. Progress is being made in understanding how environmental stress affects species (Adams et al., 2009; Mueller et al., 2005) and their distribution (Shafer et al., 2001). Climate modeling for saguaros has projected a 500 km northward latitudinal shift and 600 m altitudinal increase in distribution for the population in the United States (Rehfeldt et al., 2006; Thomas et al., 2012). Our objective for this paper is to model the governing factors of saguaro presence at its current elevational limit, which may become a front for range expansion under changing climate conditions. We then evaluate this model in the context of predicted climate change in the southwestern United States to illuminate how saguaro populations may respond to changing climatic and ecological conditions at its upper elevational limit.

2. Materials and methods

Using one-foot resolution aerial imagery in a Geographic Information System (GIS), we identified locations of saguaros by searching for the distinct shape of their shadows in the image (Fig. 2). We located 71 saguaro shadows at high elevations across the RMD. On north-facing slopes, saguaro shadows were absent above 1158 m (3800 ft) elevation. On south-facing slopes, saguaro shadows were detected up to 1585 m (5200 ft). Based on this information, we selected an elevation band from 1067 m (3500 ft) to 1676 m (5500 ft) for our study area (see Fig. 3).

Within the study area, we selected plots stratified by fire history, solar insolation, and elevation. Using these strata, we randomly selected 120, 0.25 hectare (0.62 acre) plots using a GIS model. Between July 2010 and July 2011, we systematically searched all plots for saguaros in the field and recorded whether the species was present on the plot.

At the conclusion of the field work, we classified each plot with a binary value indicating the presence (1) or absence (0) of saguaros. We used this variable (*SAGUARO*) as the outcome variable in a logistic regression model. The general equation for a logistic regression model, where β represents the coefficients on x independent variables is:

$$g(x) = \beta_0+\beta_1 x_1+\beta_2 x_2+\beta_p x_p$$

Four independent variables known to influence saguaro distribution through microclimatic and other biophysical controls were utilized to predict saguaro presence in this model. These variables were *elev* (elevation in meters derived from a 50 m × 50 m DEM), *slope* (percent slope derived from a 50 m × 50 m DEM), *fire* (binary variable indicating whether a fire had occurred on the plot in the previous thirty years), and *solar* (solar insolation in WH/m^2 received at the plot on the winter solstice derived from a 50 m × 50 m DEM).