Transient Dynamics of Vegetation Response to Past and Future Climatic Changes in the Southwestern United States.

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Dying Joshua Tree at Lake Mead NRA, AZ (2004)

Introduction

Predicting the effect of major climatic changes on plant species requires knowing both the plant's climate tolerances and how rapidly it can shift geographically. The climatic tolerances of species can be modeled from its Twentieth Century range and then applied to predictions of future climates in order to plot areas of future potential survival. Unfortunately, in the topographically diverse southwestern U.S., models of future climate are of limited use unless they can be extrapolated to a meaningful landscape scale. In our research, we have modeled plant distributions, Twentieth Century climates, future climates, and future potential climate space for several plant species to a ~1 km grid scale. Our techniques need not only apply to plants, they could be adapted for any climate-dependant organism or process needing spatially detailed estimates.

Future plant distributions modeled from climate tolerances only represent areas where a species could potentially persist if it were already there, not areas where a species is likely to be. In order to distinguish this *potential* range from the *likely* range, we have designed spatial models incorporating the dynamics of change, especially migration. These models use fossil data showing a species response to past periods of rapidly warming climate. At the end of the Younger Dryas Period, 11,600 years ago, winter minimum temperatures rose at least 4 degrees C over a time span of less than 200 years. This abrupt temperature warming is the most recent analog in both pace and magnitude and for the changes expected in this region over the next 200 years.

Our results demonstrate dramatic differences for plant species in their ability to respond to changing climates. For example, two large desert succulents characteristic of the southwestern deserts respond in opposite ways to the projected changes in climate. The future potential range of Joshua Tree (*Yucca brevifolia*) is not only reduced and shifted northward by climate change, but the plant's lack of dispersal mechanisms should reduce its actual extent by at least 90%. In contrast, the future potential range of giant saguaro (*Carnegia gigantea*), expands in all directions from its current range, and the plant's dispersal, aided by numerous animal species, should ensure its capability to take advantage of much of this expanded range.

A Recent Analog for the Future

The most recent climatic warming of similar rate and magnitude to that expected over the next 200 years occurred from 11,700 to 11,500 years ago between the end of the Younger Dryas Period and the Early Holocene. At that time, the middle latitudes of western North America warmed about 4°C in less than 200 years as indicated by the red arrows on the paleoclimatic records shown below (Figure 1).

The abundant paleoecological records in the western United States, such as fossil pollen in lake sediments and plant parts in packrat middens, allow reconstruction of the ecological consequences of this rapid warming. Some plant species well adapted to the new climate expanded, while others such as Joshua Tree, contracted (Figure 4).

Some plant species with adaptations for rapid dispersal, such as herbs with wind-blown seeds, adjusted quickly in the past. But most later-successional species, such as trees and shrubs, took many thousands of years to fully equilibrate with the new Holocene climate. Non-wind-dispersed trees and shrubs that have been studied in detail have demonstrated average migration rates between 10 and 100 meters per year.

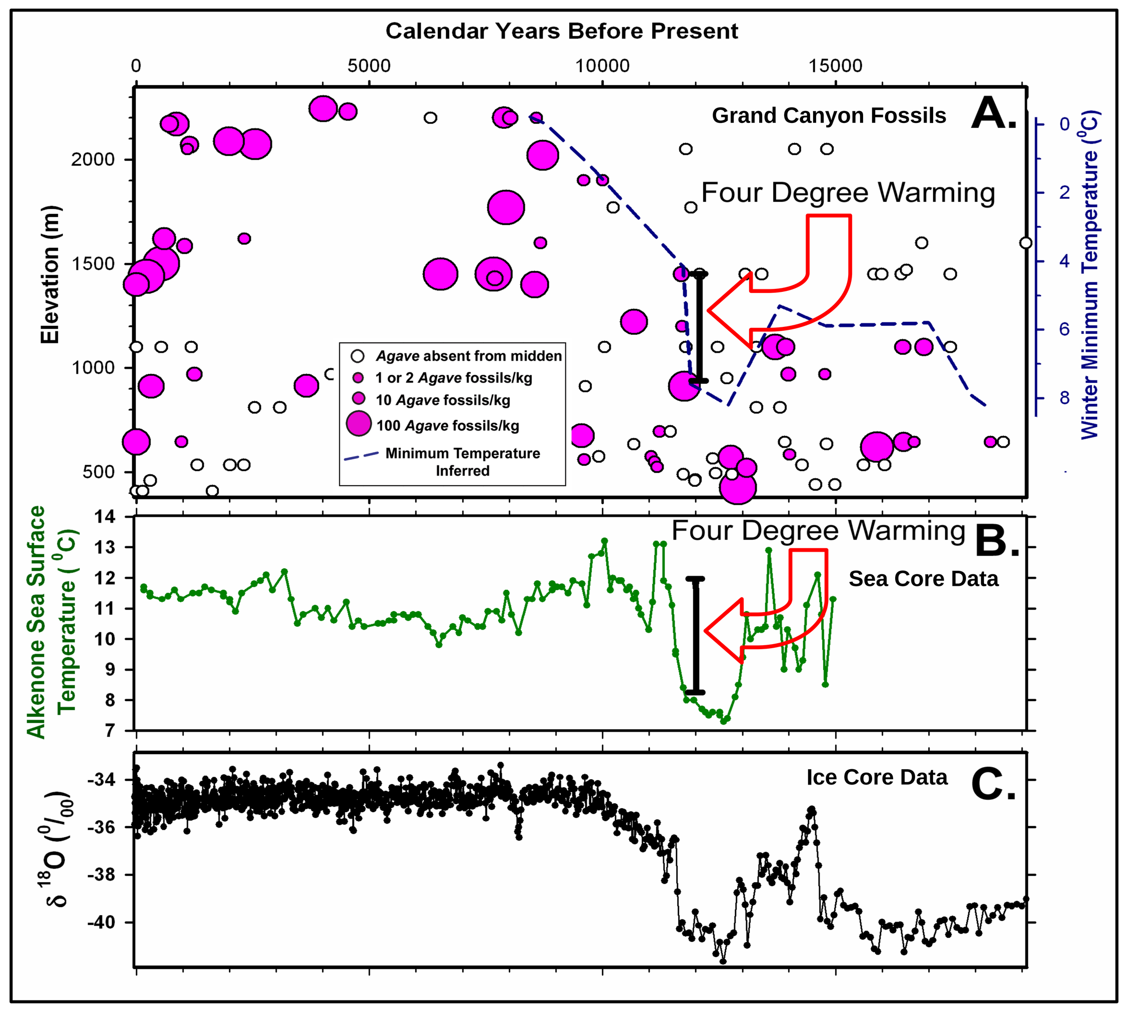


FIGURE 1.

A. The upper elevational limit of Utah agave (Agave utahensis) in the Grand Canyon, AZ, rose 600 m as temperatures increased. Fossil packrat middens containing Utah agave are shown as pink circles scaled to reflect concentration, while those without are shown as open circles. The inferred difference between today's winter minimum temperature and previous times is shown by the blue dashed line with the scale on the right (adapted from Cole and Arundel, 2005).

B. The mean annual sea surface temperature off of northern California is reconstructed using the chemistry of alkenones from sea core ODP 1019 (adapted from Barron et al., 2004).

C. Although the corresponding northern latitude temperature increase in Greenland as reflected by the oxygen isotopes from the GISP2 ice core is of greater rate and magnitude than the more southerly records, it occurs at the same time (adapted from Grootes and Stuiver, 1997).

Projecting Climate Models on the landscape

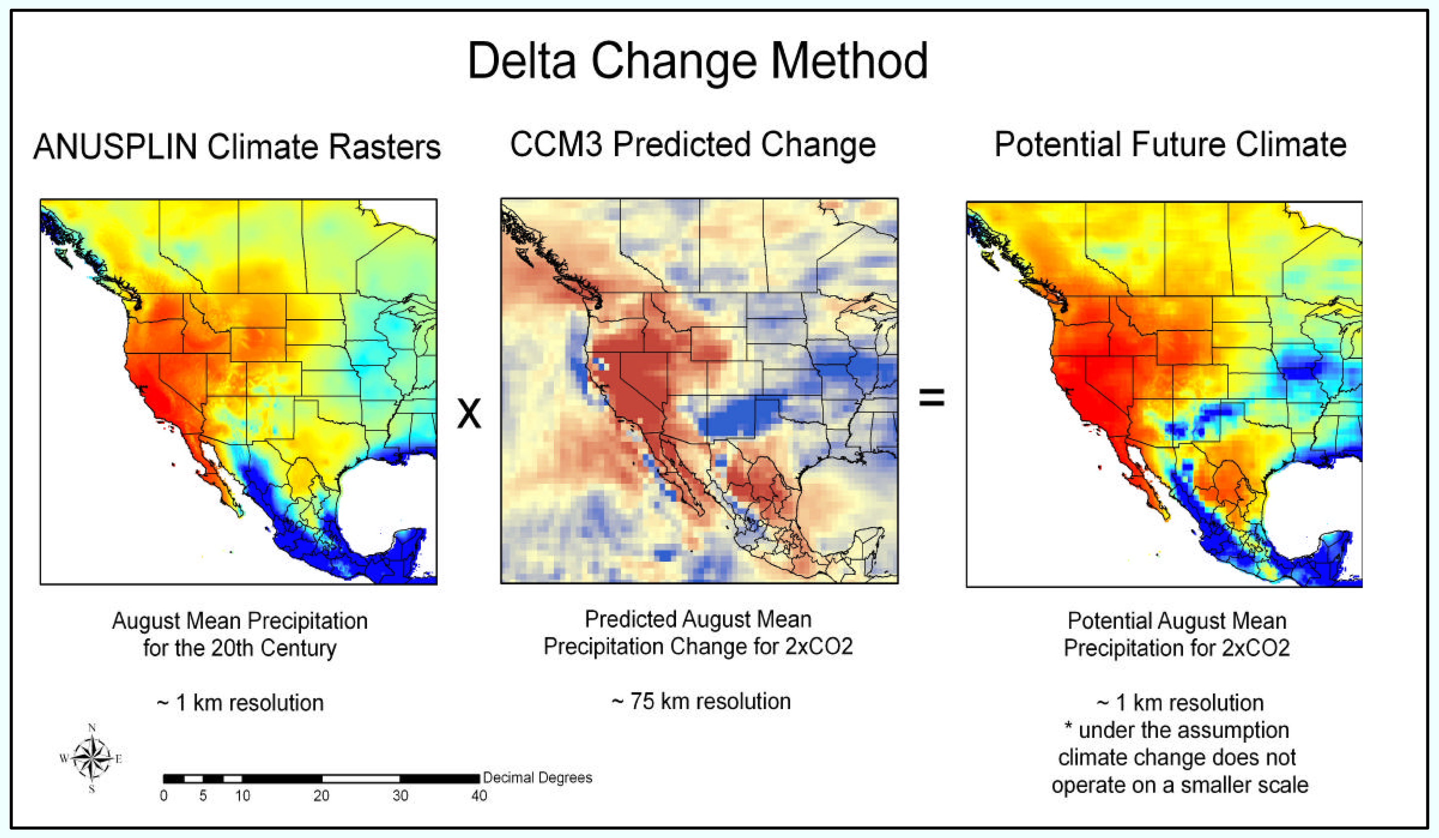


FIGURE 2 Making Global Atmospheric Circulation Models (GCMs) relevant to predicting the survival of individual plant species requires translating their results to scales relevant to population biology. The Delta-Change Method can be used to extrapolate regional-scale atmospheric results such as the 75 km CCM3 down to a 1 km landscape scale using digital elevation models (DEMs). This type of extrapolation is not only essential, but also reliable in topographically diverse regions such as the western United States. This is because the climatic differences within each region are primarily driven by regional topography, and the elevational differences between mountains and valleys will not be affected by global climate change. Twentieth Century 1 km climate rasters were generated using ANUSPLIN techniques (Arundel and Cole, 2003).

Predicting Plant Survival

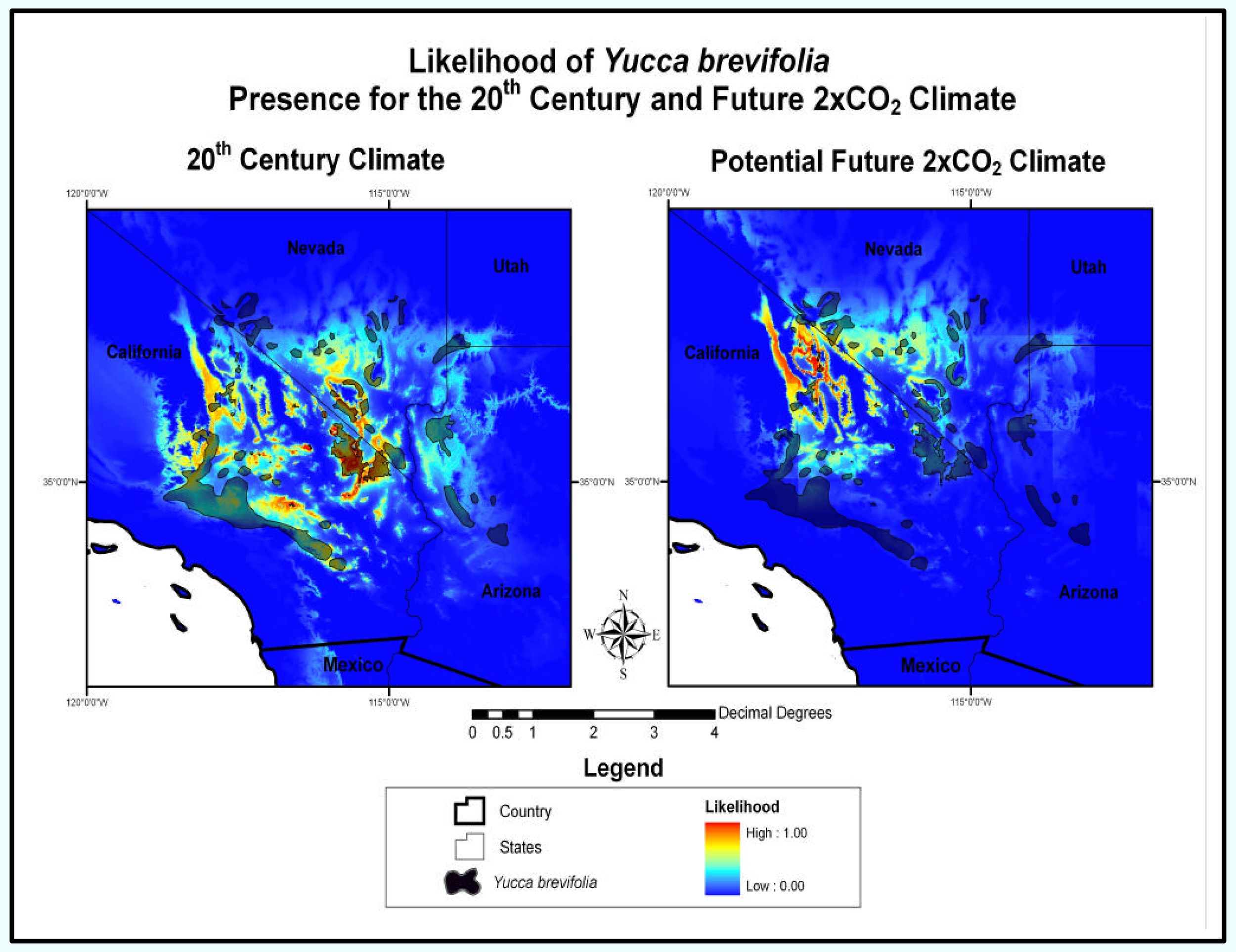
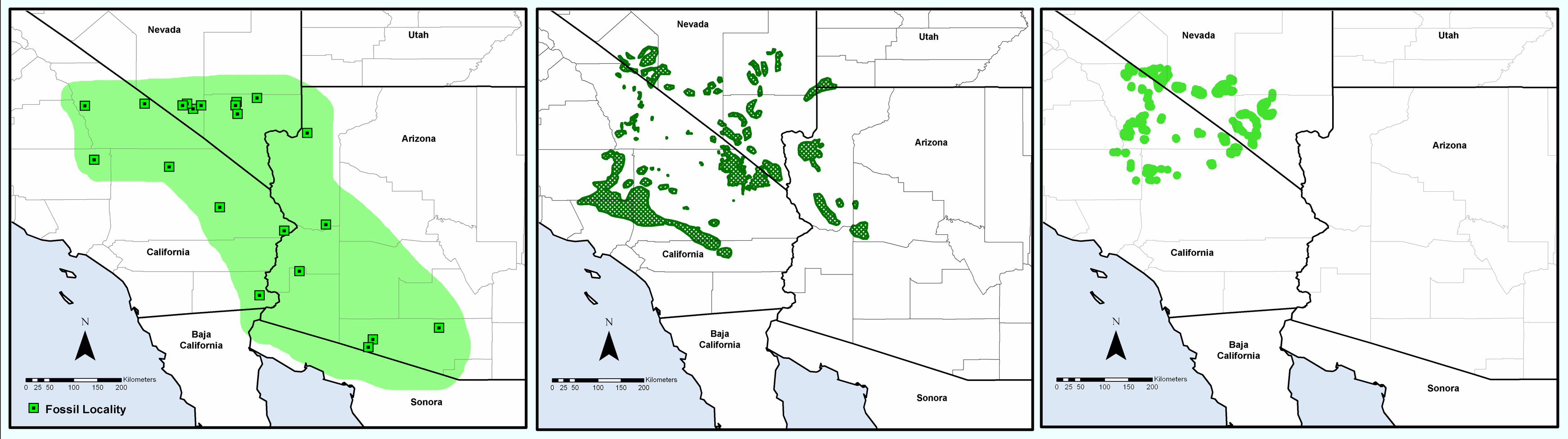


FIGURE 3 Predicting the survival of a plant under different climates requires modeling the probability of the species occurring under Twentieth Century Climate and applying this mathematical relationship to new climates. The figure shows our application of a climate model for Joshua Tree to GCM-predicted climates for the late Twentieth Century versus a future $2XCO_2$ climate. The probability surface was generated using a multiple quadratic logistic regression of the 7 most significant (of 20) climate variables for this species. The significance of climate limiters was determined using a new spatial analytical technique, ClimLim (Arundel 2004).



A. Ice-age Joshua Tree distribution (Green). Fossils from 11,600 to 20,000 year old packrat middens are shown as squares.

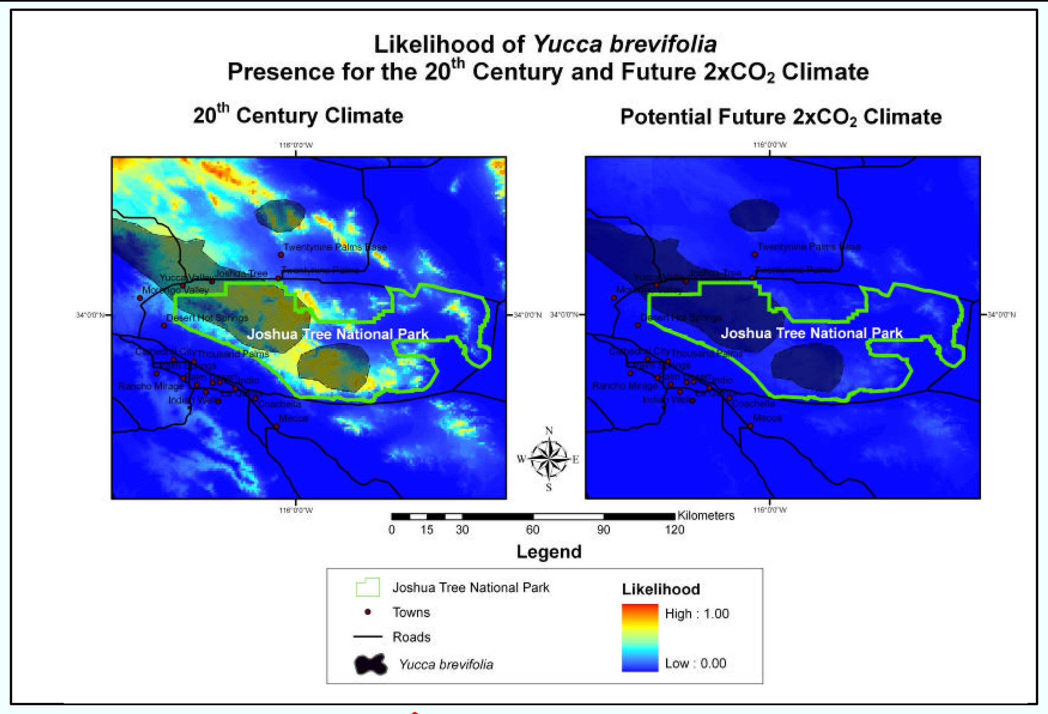
B. Twentieth Century Joshua Tree distribution (Green).

C. Likely twenty-first century Joshua Tree distribution (green). In order that these future stands remain visible at this scale, future migration rates were assumed to be 10 times actual observed rates.

FIGURE 4 The past, present, and future distributions of Joshua Tree (*Yucca brevifolia*) are depicted on these three maps. Although widely distributed across the Mojave and Sonoran Deserts during the late Pleistocene (A), Joshua Tree dramatically declined during the Holocene to its current limited extent (B). Its decline could be related to the extinction of the Shasta Ground Sloth (*Nothrotheriops shastensis*) about 13,000 years ago. Fossil ground sloth dung contains abundant seeds and fruits of Joshua Tree suggesting that the animal may have acted as a dispersal agent for the species. GCM models of $2xCO_2$ climates suggest a more limited climate zone for Joshua Tree that is shifted to the north by several hundred kilometers. Joshua Tree may have little migrational capability to adapt to new climates since its primarily mode of reproduction today is clonal and during the Holocene it migrated at less than 10 meters per year.

FIGURE 5.

Joshua Tree populations are already experiencing mortality in predicted areas such as Lake Mead, AZ (top right image on poster) and at Joshua Tree National Park, CA. Our $2xCO_2$ climate model suggests that it will be unable to persist much longer within Joshua Tree National Park (model comparison at right).

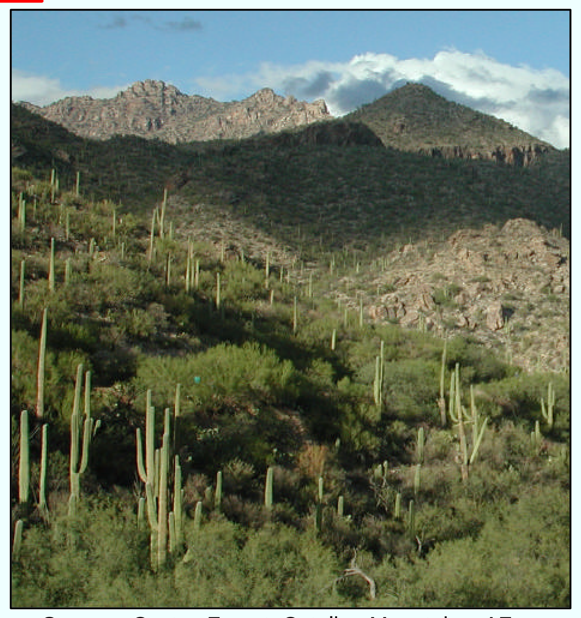


TWO EXAMPLES

Joshua Tree

Healthy Joshua Tree at Lake Mead NRA, AZ (1995)

Saguaro



Saguaro Cactus Forest, Catalina Mountains, AZ.

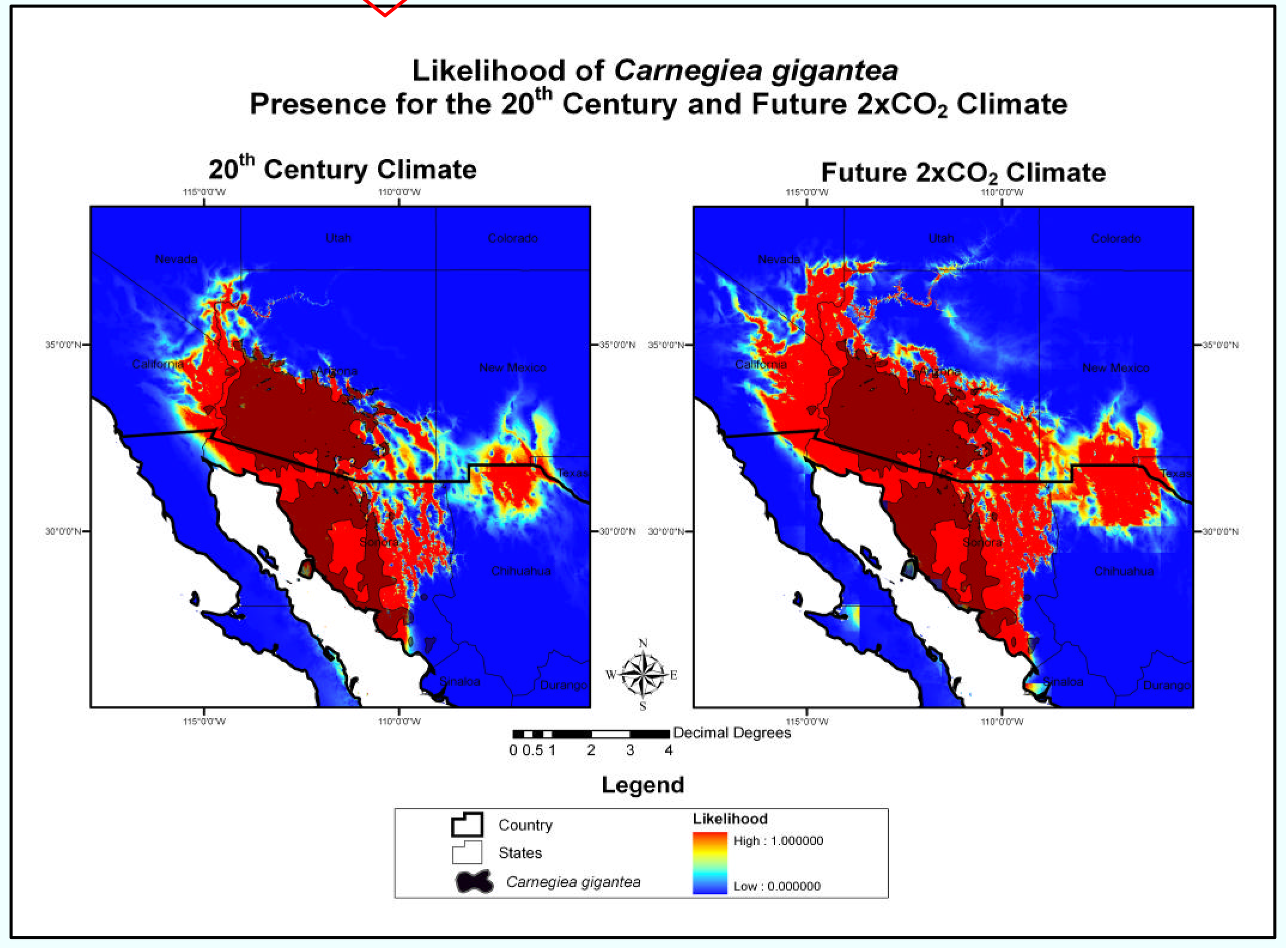


FIGURE 6

Unlike Joshua Tree, Giant Saguaro (*Carnegia gigantea*) should be able to expand its range in the future due to more favorable climates as well as effective animal seed dispersers for the species. This map only displays its *potential* distribution as determined by climate. Its likely future distribution can be better predicted by incorporating climate, fire, substrate, and migration into spatial models.

References

Arundel, S.T., and K.L. Cole. (2003). Digital climate coverages of North America. Electronic datasets of monthly maximum and minimum temperature and precipitation at a ~1km resolution available at: http://www.geog.nau.edu/global_change/climate_surfaces.html.

Arundel, S.T. (2004). Using Spatial Models to Establish Climatic Limiters of Plant Species' Distributions. Ecological Modelling 182: 159-181.

Barron, J. A., L. Huesser, T. Herbert, and M. Lyle. (2004). High-resolution climatic evolution of coastal northern California during the past 16,000 years. Paleoceanography 18: 1020.

Cole and Arundel (2005). Carbon isotopes from fossil packrat pellets and elevational movements of Utah Agave reveal Younger Dryas cold period in Grand Canyon, Arizona. Geology 33:713-716.

Grootes, P.M., and M. Stuiver. (1997). Oxygen 18/16 variability in Greenland snow and ice with 103 to 105-year time resolution. Journal of Geophysical Research 102:26455-26470.

Additional Maps and Information: http://www.usgs.nau.edu/global_change

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