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Climate change effects on southern California deserts

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ABSTRACT

Climate change has already affected southern California where regional increases in temperature and vegetation shifts have been observed. While all the CMIP5 temperature projections agree on a substantial level of warming throughout the year, there is fair bit of divergence in the magnitude and seasonality of projected changes in rainfall. While desert plants and animals are generally adapted to extreme conditions, some species may be approaching their physiological threshold. We calculated the climate velocity of both temperature and aridity (PPT/PET) in SE California to illustrate the spatial variability of climate projections and reported on the probable expansion of barren lands reducing current species survivorship. We used a vegetation model to illustrate both temporal and spatial shifts in land cover in response to changes in environmental conditions. Such information is useful to plan land use for renewable energy siting in the region.

1. Introduction

The Desert Renewable Energy Conservation Plan (DRECP), part of California's renewable energy planning efforts, is a collaborative effort between the California Energy Commission, California Department of Fish and Wildlife, the U.S. Bureau of Land Management, and the U.S. Fish and Wildlife Service. Its goal is to provide adequate protection and conservation to ~22.5 million acres of southeast California desert ecosystems, the state's largest and most intact natural landscape (Chornesky et al., 2015), while allowing for the development of renewable energy projects.

North American deserts are expected to become warmer at faster rates than other regions (Stahlschmidt et al., 2011). Climate projections from various sources agree that temperatures will increase in the southern California deserts by more than 2 °C by mid-century (Stralberg et al., 2009; Snyder and Sloan, 2005; Snyder et al., 2004; Bell et al., 2004) while observations are already showing a measurable warming that has occurred during the last 30 years (LaDochy et al., 2007). Desert plants and animals are generally adapted to extreme warm temperatures, but some species may be approaching their physiological threshold (e.g. Serra-Diaz et al., 2014). While some species may not experience increases in temperature-driven mortality, their survival may nonetheless be affected. For example, the sex determination of eggs laid by desert tortoise is affected by incubation temperature (Burke et al., 1996) and hatchling vigor can also be impacted by higher temperatures (Spotila et al., 1994).

Precipitation in North American deserts is low and varies temporally at both short (season) and longer (decade) time scales (Stahlschmidt et al., 2011). A review of recent publications focused on California (PRBO, 2011) illustrated the wide range of rainfall projections for both the Mojave and Sonoran Deserts for the 21st century: some GCMs project increases, some decreases in annual rainfall. Cayan et al. (2008) chose two climate futures that both simulated a summer monsoon, but the warmer GFDL projected an overall increase in precipitation while PCM projected a decrease under the A2 emission scenario. Furthermore, while climate projections from the 5th Coupled Model Intercomparison Project (CMIP5) generally agree with earlier projections from the 3rd CMIP in many areas of the world, projected winter precipitation by CMIP5 climate models generally increases over California. However projections for precipitation over southern California regions remain uncertain in the CMIP5 ensemble (Neelin et al., 2013). Given the degree of aridity in the region, even relatively modest changes are likely to have large ecological consequences and drought conditions are likely to get worse.

Recent studies have shown that climate change has already affected southern California where regional increases in temperature (LaDochy et al., 2007) and vegetation shifts (Guida, 2011;

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Kelly and Goulden, 2008) have been observed. Guida (2011) observed over the last 30 years (1979–2008) an increase of 1.5 °C in the average annual minimum temperature and a decrease of 3 cm in the average annual precipitation in the Newberry Mountains, on the southeastern corner of the Mojave Desert, near its transition to Sonoran conditions. Changes were more pronounced at high elevation and correlations between climate and species distributions suggested that species most reliant on higher precipitation were already migrating to higher elevations to adapt to on-going changes in climate (Guida, 2011). Similarly, Kelly and Goulden (2008) attributed to climate change the shifts in vegetation distribution they observed along the Deep Canyon Transect of Southern California's Santa Rosa Mountains between 1977 and 2007. While they associated mortality events to two extreme droughts, they also documented the upslope movement of the dominant species by approximately 60 m in 30 years and linked it to the increase in climate variability (particularly precipitation) and warming.

We report here on a series of climate analyses using the most recent IPCC projections for the region and describe the likely responses of the major vegetation types on the landscape. We used a velocity index to illustrates the rate and magnitude of change in the area, a barren index to describe the risk of soil erosion simply due to drought conditions, and results from a dynamic global vegetation model to illustrate overall potential vegetation dynamics in response to changes in temperature and precipitation regimes.

2. Methods

2.1. Study area

The DRECP region includes fractions of the Mojave and Sonoran deserts that occupy the lowest elevations on the eastern slopes of the southern Sierra Nevada and the mountains of southern California. Annual frost-free season ranges from 210 to 365 days in Mojave and Sonoran Deserts, respectively. Elevations range from below sea level in the Salton Sea Basin and Death Valley upward to 1,500 m along the Sierra Nevada. The Mojave Desert is an area of extreme temperatures with a mean July maximum of 47 °C (117 °F) in Death Valley but it is a high desert overall with elevations ranging between 600 and 1,200 m, consequently with lower minimum temperatures than the Sonoran desert. The Sonoran desert is the hottest North American desert in part because of its low elevation (<600 m).

Seasonal rainfall patterns vary substantially over the DRECP region. During winter, storms originating in the Pacific Ocean move inland and are pushed against the Coast Ranges or the Sierra Nevada mountains. This causes adiabatic cooling, condensation, and long-duration low-intensity rainfall over large areas. Despite the rain shadow from the Sierra Nevada, the Mojave Desert portion of the DRECP receives most of its rainfall from these winter storms. Summer weather is dominated by the North American monsoon where strong storm cells from the Gulf of Mexico move northwestward causing local cyclonic thunderstorms of short duration and high intensity (McMahon, 2000). The Peninsular Ranges create rain shadows for the Sonoran Desert, which displays a bimodal rainfall regime with 50% of its rainfall occurring during summer. Differences in seasonal rainfall, winter dominated in the Mojave and bimodal in the Sonoran, are sufficient to cause substantial differences in vegetation structure and floristic composition (McMahon, 2000) between the two deserts, with a transitional ecotone known for its species and genetic diversity (Wood et al., 2012).

2.2. Climate inputs

Historical climate data (1895–2010) were created and distributed by the PRISM group at Oregon State University (Daly et al., 2008). To match the scale of the future projections, they were upscaled to a 1/24° by taking the mean of the original 1/120° (~800 m) grid cells (Daly et al., 2008). Climate projections (2010–2100) from the 5th Coupled Model Intercomparison Project (CMIP5) had been downscaled to 1/24° (~4 km) using a method developed by Abatzoglou (2012) and provided through his web site (http://maca.northwestknowledge.net/). CMIP5 climate models include Earth System Models (ESMs) that represent the biosphere in more detail than most climate models (e.g. nitrogen cycle, dynamic vegetation, fire emissions). We looked at the 20 sets of downscaled climate projections and chose three that bracketed the full range of future precipitation for a similar level of warming over the DRECP region (Fig. A1).

The three models (MIROC5, CCSM4, and CanESM2) were ranked among the top 10 CMIP5 performers by Rupp et al. (2013) with respect to their ability to simulate historical climate for the west coast of the US and for their overall structural soundness. Each model projects a different precipitation future – one with approximately the same level of winter and summer precipitation as historical but somewhat drier overall (the 5th generation of the Model for Interdisciplinary Research on Climate, MIROC5), one with wetter winters than historical but similar annual moisture to historical (the Community Climate System Model, version 4.0, CCSM4), and an earth system model that projects both much wetter winters and summers than historical (the 2nd Generation Canadian Earth System Model, CanESM2). None of the top 10 CMIP5 future climates projected drier winters and wetter summers, so we did not consider such a scenario.

In the 5th Assessment Report for the Intergovernmental Panel for Climate Change (AR5), the storyline emission scenarios (Nakicenovic et al., 2000) were replaced by four Representative Concentration Pathways (RCPs) projecting the evolution of the concentration of atmospheric carbon dioxide over time. The RCPs (vanVuuren et al., 2011) were developed to simulate four levels of radiative forcing (2.6 W m^{-2}–8.5 W m^{-2} by 2100) resulting from different carbon dioxide concentration trajectories driven by diverse climate policies. We analyzed climate model results for the low RCP 4.5 and the more likely RCP 8.5.

2.3. Climate velocity

Based on the IPCC (2014) summary for policy makers, "*Climate velocity is defined as the rate of change in climate over time (*e.g., *°C/yr, if only temperature is considered) divided by the rate of change in climate over distance (*e.g., *°C/km, if only temperature is considered)* (Loarie et al., 2009; Dobrowski et al., 2013). *Climate velocity for temperature is low in mountainous areas because the change in temperature over short distances is large*." In low relief areas, climate velocity for temperature is generally high and can exceed 80 km/yr for the RCP 8.5 because the rate of change in temperature over distance is low.

Because it is expressed in units of distance over time, climate velocity provides a consistent and useful way to compare diverse measures of climate change. Previous analyses of climate change velocity have mostly focused on changes in temperature (e.g. Loarie et al., 2009). For the DRECP region, we calculated the climate velocity of a variety of climate variables including aridity, which is defined by UNEP (1992) as the ratio of annual precipitation (PPT) over annual average potential evapotranspiration (PET).

It seemed unlikely that an area that has already experienced high climate velocity in the past, will harbor species with a limited ability to keep up with a similar level of change, unless past changes were modest enough for the species to tolerate them or avoid them by using local refugia. We therefore decided to calculate the differences between historical and projected maximum climate velocity to provide maps that would show areas with climate stress levels that local species would have (or not) experienced historically. For each grid cell, we generated a time series of the velocity for the variable of interest (temperature and aridity) and, for specific periods of time including historical (1971–2000) and futures (2010–2039, 2040–2069, and 2070–2099), we picked the maximum velocity value. We then compared future to historical and mapped the differences.

2.4. Vegetation model

We used MC2 (Bachelet et al., 2015; Sheehan et al., 2015), the C++ version of the Dynamic Global Vegetation Model (DGVM) MC1 (e.g. Bachelet et al., 2001; Lenihan et al., 2008) to simulate vegetation shifts, changes in the biogeochemical cycles, and wildfire under historical and future conditions. The model does not simulate species, but broad vegetation types composed of combinations of woody and herbaceous lifeforms with varied leaf morphologies (needleleaf or broadleaf), phenologies (deciduous or evergreen) and physiological characteristics (C3, C4). The model uses 15-year average climate to define these lifeforms with climate-based rules (Daly et al., 2000). The model simulates competition between lifeforms for light, water, and nutrients, as well as the effects of disturbance (fire emissions, mortality) the results of which provide estimates of ecosystem productivity and carbon stocks that, compared to set thresholds, define the vegetation type every year.

We combined the vegetation types simulated by the DGVM into four broad categories to facilitate the interpretation of the simulation results. “Woody” corresponds to woody lifeform-dominated vegetation types, from dense woodlands to sparse shrublands. “Herbaceous” corresponds to herbaceous lifeform-dominated vegetation types that include grasses, sedges and forbs. “Desert” defines low to negligible productivity areas and is characterized by sparse woody and/or herbaceous cover. “Barren land” corresponds to bare rock and soil that do not allow plant growth. Because barren lands are sparse and simulated only under the driest of conditions (MIROC5) by the vegetation model, we created a “barren index” based on the percent time it was simulated as dominant for each pixel over a 30-year period.

The model simulates potential vegetation i.e. the vegetation that would occur on the landscape given local climate and soil conditions while ignoring land use legacies from human occupation. Consequently, simulation results for current conditions often disagree with reality, which limits our ability to validate our simulations. However, projected potential vegetation dynamics under future conditions provide valuable insights on how native vegetation may respond to climate change, whereas projections of future land use are highly uncertain. Moreover, relying on predicted changes in a particular species range (contraction or expansion) alone can bring surprises when an extreme climate event or pest outbreak extirpates such species, or if invasive or “climate refugee” species take over and modify ecosystem processes including disturbance (e.g. fire regime).

The model simulates carbon and nitrogen cycling at a monthly time step, allocating material among plant parts, multiple classes of leaf litter, and soil organic matter pools. Production is calculated monthly and is limited by temperature, soil water availability, nitrogen, and atmospheric CO_2 (Bachelet et al., 2001). The model also simulates actual and potential evapotranspiration (AET and PET) as well as soil water content to reflect water use by the vegetation. Live and dead plant material is interpreted as fuel categories (1, 10, 100, 1000 h) and their daily moisture is calculated to modulate fire occurrence and behavior (Lenihan et al., 2008). Potential fire behavior varies for each vegetation type, which affects fuel properties and realized wind speeds (higher for herbaceous than woody lifeform-dominated systems).

The MC2 model uses inputs on soil depth, texture, and bulk density as well as monthly precipitation, minimum and maximum temperatures, and vapor pressure. The model is initialized with a spinup method that ensures that the net carbon flux has stabilized with a realistic fire return interval for each vegetation type before starting to simulate 20th century conditions (Rogers et al., 2011).

3. Results

3.1. Climate projections

While we did not generate them, we performed analyses of the climate data to better understand the contemporary and future trends that might affect ecosystem resilience. All 20 CMIP5 models examined for this study show increases in minimum temperatures from historic conditions for the DRECP area with up to 2.7 °C under RCP 4.5 scenario and up to 3.5 °C under RCP 8.5 scenario (Fig. A2).

While projections of temperature change from the various climate models are fairly similar, precipitation projections from these same 20 models diverge in magnitude and seasonality particularly during summer and winter months (Fig. A3).

There is considerable variability and uncertainty in precipitation projections because California lies between high latitudes where climate models agree there will very likely be increases in precipitation and the subtropics where models agree there will be decreases (Neelin et al., 2013). Maloney et al. (2014) reported that, compared to CMIP3 models, CMIP5 projections show a southward shift of the transition zone between increasing and decreasing winter precipitation visible along the West coast of North America. This shift projects more moisture to parts of California according to many, but not all, climate models.

The three climate model projections (CanESM2, CCSM4, and MIROC5) we chose to study in more detail for the DRECP region show substantial warming, particularly during summer months over the entire area (Fig. 1). They project similar gradual increases in annual and seasonal temperature over the next century (2011–2100) with respect to historical conditions (1890–2011) over both the Mojave and, though warmer, the Sonoran areas (not shown here). The three climate models simulate increased precipitation during winter months over the entire area but the earth system model (CanESM2) simulates the greatest increase in winter and also a large increase in summer precipitation as well as in summer minimum temperature (Fig. 1).

Over the Mojave area in the DRECP region, the CanESM2 model projects increasing precipitation throughout the 21st century with a much wetter future overall despite a decline in spring and, to a lesser extent, Fall rains (Fig. 2). Both CCSM4 and MIROC5 models show little trend and very similar year-to-year variability to historical conditions, with higher winter precipitation under CCSM4 (Fig. 2).

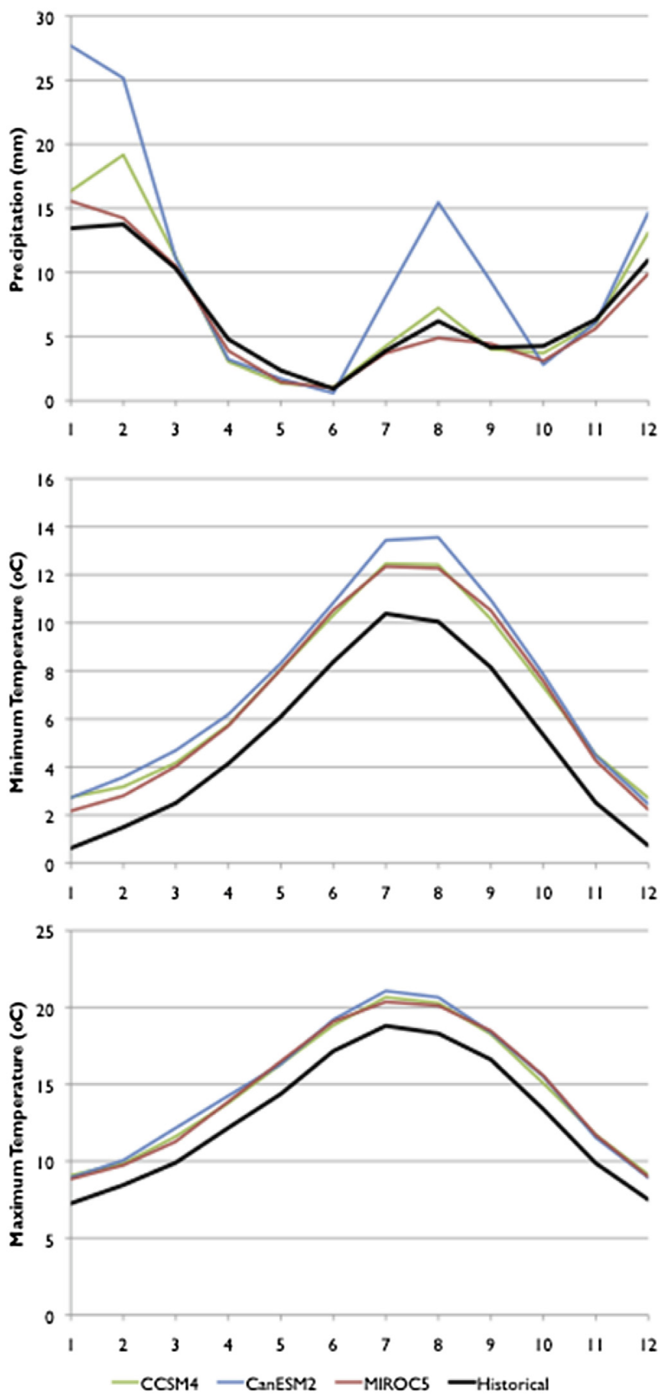

Fig. 1. Observed (1895–2010) and projected (2011–2100) monthly average precipitation, maximum and minimum temperature in the DRECP region from three CMIP5 climate models (CanESM2, CCSM4, and MIROC5) under RCP 8.5 downscaled by Abatzoglou (2012).

Results for the Sonoran portion of the landscape, which is generally drier than the Mojave, show comparable precipitation trends (Fig. 3) with the CanESM2 model simulating much wetter summers and winters. The MIROC5 model projects lower annual precipitation with a decrease in both summer and fall precipitation particularly during the 2nd half of the 21st century (Fig. 3). CCSM4 projections show similar magnitude of precipitation compared to historical with a shift toward higher winter contributions (Fig. 3).

3.2. Climate velocity

Dobrowski et al. (2013) state "*the use of climate change velocity is considered more biologically relevant (Ackerly et al., 2010) than the use of climate anomalies (simulated differences between future and current climate) as it accounts for regional changes in climate and the ability of topographic heterogeneity to buffer biota against these changes*".

In the DRECP region (Fig. 4), differences in the maximum velocity in mean temperature and aridity between historical and future conditions clearly show areas in the Sonoran where the maximum rates of change will exceed what local plants and animals have experienced in the recent past. Note that because aridity as defined by UNEP (1992) as the ratio of precipitation over PET, a decrease in the aridity index corresponds to an increase in water stress. In most cases, the change in maximum velocity of temperature and aridity is noted by mid-century and continues to late-century, but in the case of CCSM4 and CanESM2 mid century conditions are milder than either early or late 21st century.

3.3. Vegetation response

Because of winter rains, larger portions of the Mohave are dominated by woody lifeforms than in the drier Sonoran (Figs. 5 and 6). The herbaceous cover is also more extensive in the Mojave because of its generally greater soil surface water availability particularly in winter and spring. The Sonoran is dominated by desert vegetation where herbaceous plants can dominate during wetter years but that can also turn barren during particularly dry years (e.g. MIROC5 climate future for the 2nd half of the 21st century).

Under the wetter future projected by the Canadian earth system model (CanESM2), woody vegetation expands steadily with time in the Mojave but only slightly in the Sonoran where the evaporative demand is higher (Figs. 5 and 6). Desert and barren lifeforms decline in the Mojave by the end of the century while the increasing rains also cause the Sonoran to become progressively dominated by herbaceous vegetation.

The vegetation model under the CCSM4 future simulates modest increases in herbaceous cover and a decline in desert area in the Mojave (Figs. 5 and 6). Decadal variability appears less pronounced than during the historical period. Because of its projected increase in winter rain, the CCSM4 future also causes a large increase in herbaceous cover in the Sonoran at the expense of desert areas.

The warmer, somewhat drier future projected by MIROC5 promotes the persistence of the desert area with an increase in the extent of barren land in the Mojave, particularly after the 2050s (Figs. 5 and 6). The Sonoran desert is subject to an early period of herbaceous dominance with MIROC5 that is quickly followed by an increasing trend in desert and barren areas.

Each of the CMIP5 futures is characterized by a different spatial distribution of these aggregated potential vegetation categories. With the CanESM2 climate future, the wettest model of the three, the model simulated a steady decline in desert areas during the 21st century due to the expansion of the woody vegetation (woodlands and shrublands) driven by increased

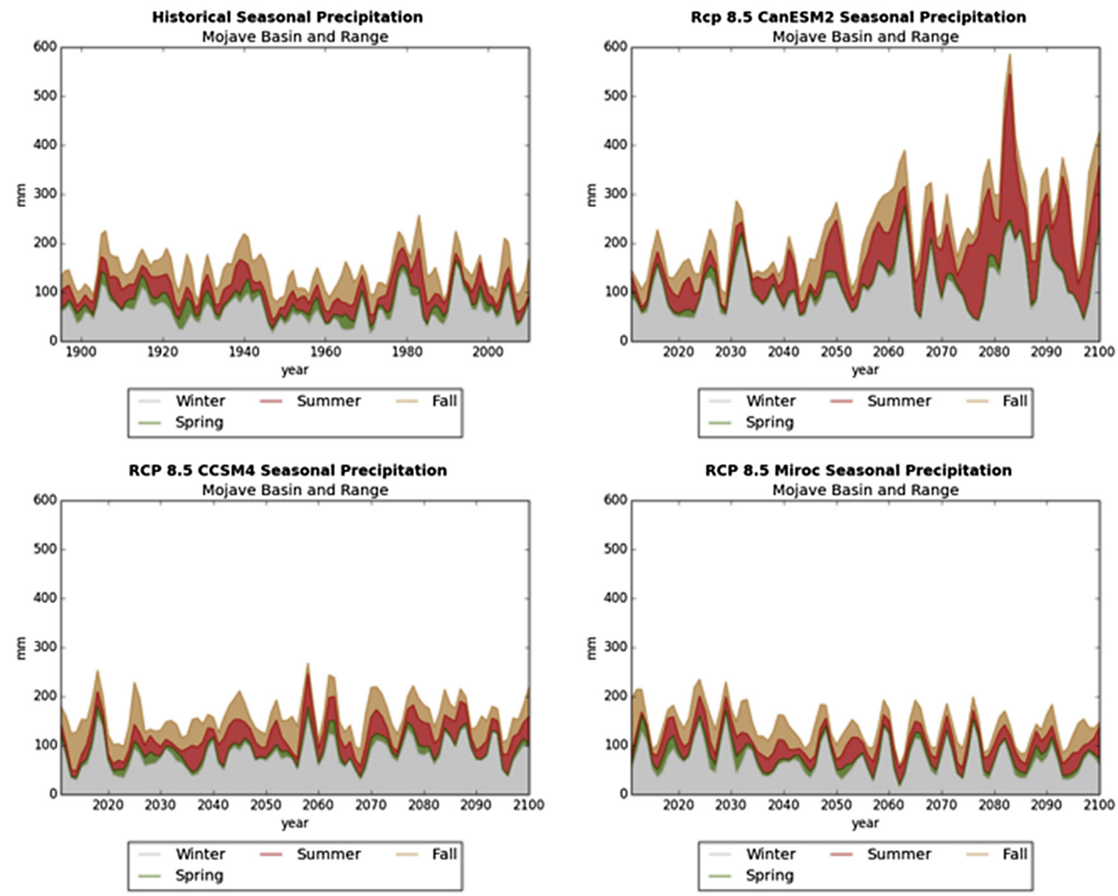

Fig. 2. Seasonal and annual precipitation for the Mojave portion of the DRECP for the historical (1895–2010) period from PRISM data (top left) and projected for the 21st century (2011–2100) by three CMIP5 models (CanESM2, CCSM4, and MIROC5) and downscaled by Abatzoglou (2012).

winter precipitation in the Mojave portion of the region (Fig. 7). The model simulated increases in herbaceous cover throughout the Sonoran simply caused by the general increase in annual precipitation. By the end of century, desert only persists in the driest locations, namely Death Valley and the lower Colorado Desert near Yuma, AZ.

The CCSM4 climate future, characterized by similar precipitation seasonality to that observed in the 20th century but with wetter winters and slightly wetter summers, causes a modest expansion of the woody vegetation by end of the century in the Mojave and large increases in herbaceous cover throughout the entire region, especially in the Sonoran (Fig. 7).

The MIROC5 climate future (the driest of the three) had the opposite effect causing substantial declines in herbaceous cover in the Mojave as soil water availability declines under warmer conditions (Fig. 7). Woody vegetation (shrubland) can expand because of its ability to access deeper water in the soil profile recharged during winter (increased winter rainfall even under MIROC5 future) and because of the simulated CO_2 fertilization effect whereby water use efficiency increases in step with the atmospheric CO_2 concentration. In the Sonoran portion of the DRECP, the desert expands at the expense of the herbaceous dominated systems while barren areas emerge at the extreme south.

Note that the maps (Fig. 7) illustrate the most frequent potential vegetation distribution for each grid cell during a particular time period (30 years) while the time series graphs (Figs. 5 and 6) show year-to-year variability in the area dominated by each vegetation category across the entire region.

With the wet CanESM2 climate future, there is an overall decline in the extent of barren land (Fig. 8), but certain areas (e.g., Death Valley) remain the most barren portions of the DRECP landscape. The CCSM4 climate future causes an early century decline in barren lands due to high precipitation levels in the earlier part of the 21st century but it is followed by a renewed mid-century expansion of barren areas, ending with conditions fairly similar to those found during the historical period (Fig. 8). As expected, the driest MIROC5 climate future causes an overall increase in the extent of barren land (Fig. 8).

4. Limitations and uncertainties

4.1. Uncertainty in climate projections

There have been many improvements made in climate change science modeling since the first assessment report for the Intergovernmental Panel for Climate change (Meehl et al., 2007) but many uncertainties remain, particularly with regard to precipitation. Geil et al. (2014) reviewed the CMIP5 projections to evaluate their skill at simulating the North American monsoon system,

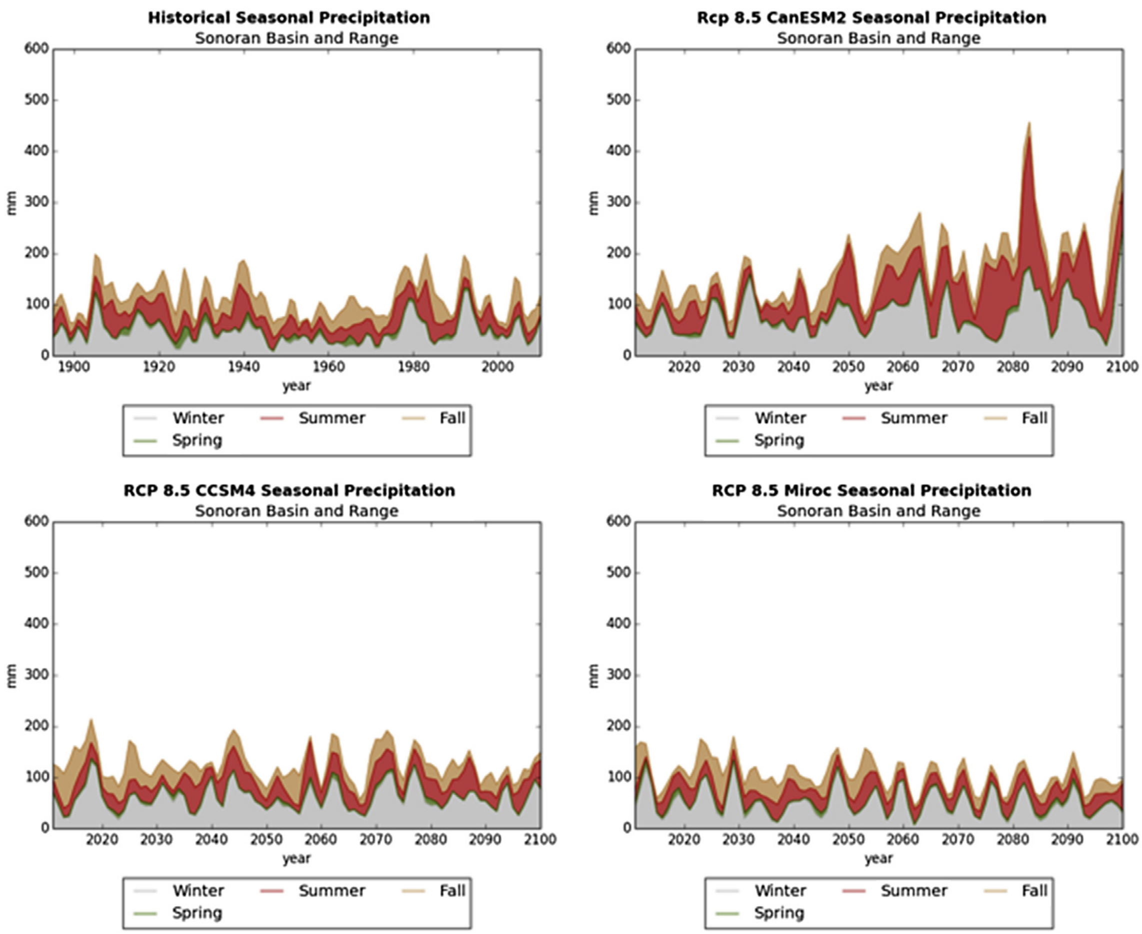

Fig. 3. Seasonal and annual precipitation for the Sonoran portion of the DRECP for the historical (1895–2010) period from PRISM data (top left) and for the 21st century (2011–2100) as simulated by three CMIP5 models (CanESM2, CCSM4, and MIROC5) and downscaled by Abatzoglou (2012).

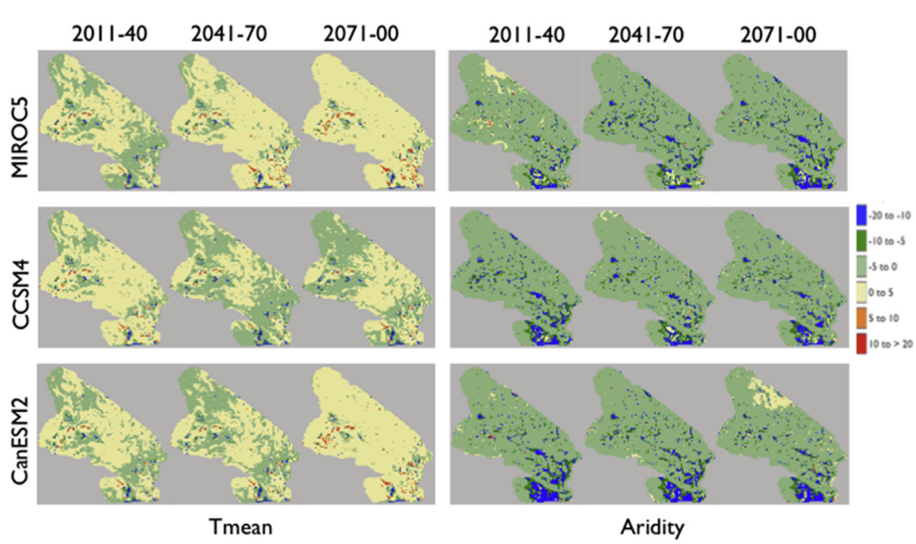

Fig. 4. Amount by which the projected maximum velocity (km yr^{-1}) for mean temperature and aridity (the ratio PET/PPT) over the DRECP area from three CMIP5 climate model projections (2.5 arc-minute resolution) under the RCP 8.5 emission scenario exceeds the maximum velocity during historical conditions (1971–2000) for three time periods 2010–2039, 2040–2069, and 2070–2099. Note that we capped velocity values at 20 km/yr. Red areas (on the left) will be experiencing greater maximum velocity in mean annual temperature than they have experienced in the past. On the other hand, the blue areas (on the right) will be experiencing greater maximum velocity in aridity than they have experienced in the past. (PET: potential evapotranspiration; PPT: precipitation). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

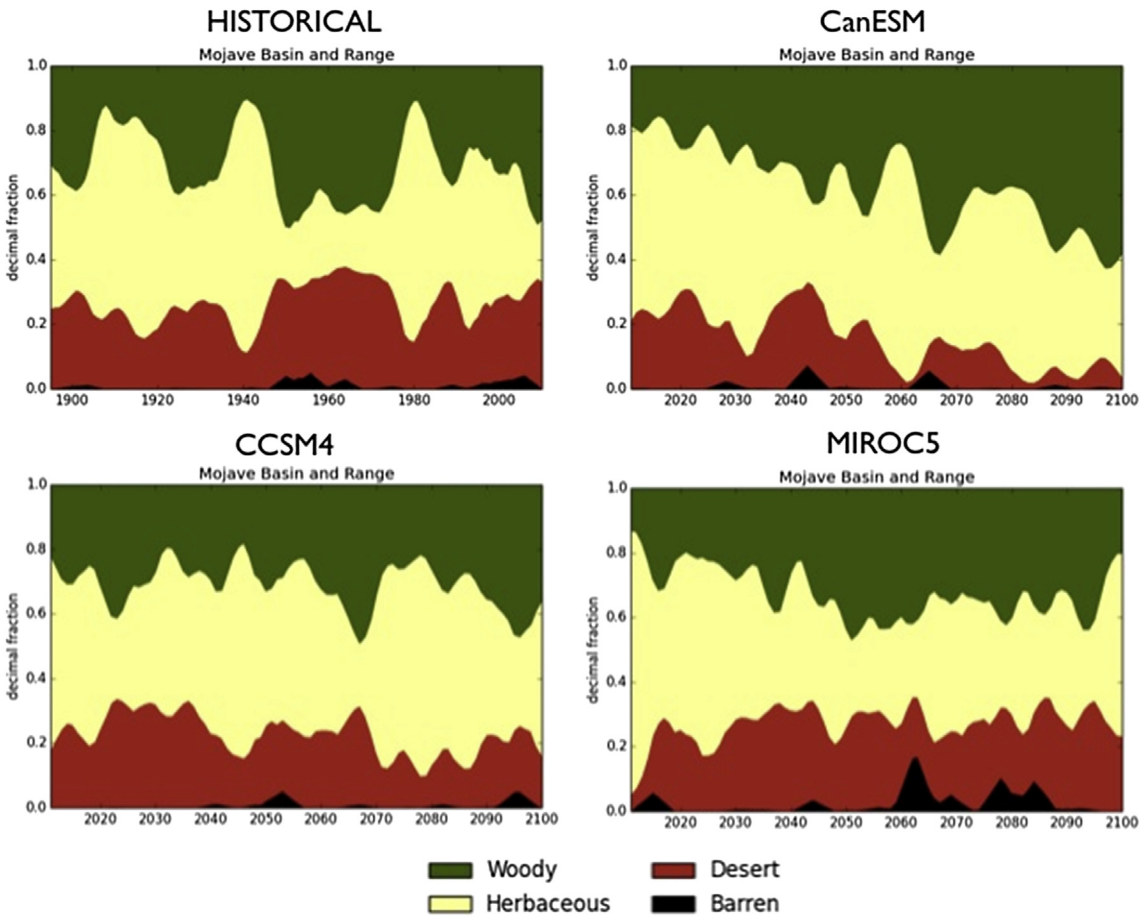

Fig. 5. Potential vegetation dynamics over the Mojave region of the DRECP for the historical (1895–2010) and future (2011–2100) periods simulated by the MC2 model as fractions of the entire DRECP area occupied by the various aggregated vegetation categories. The vegetation model was driven by three CMIP5 climate model projections (CanESM, CCSM4 and MIROC5) under RCP 8.5 downscaled by Abatzoglou (2012). A 15-year smoothing algorithm was used to display the model results. "Woody" corresponds to woody lifeform-dominated vegetation types, from dense woodlands to sparse shrublands. "Herbaceous" corresponds to herbaceous lifeform-dominated vegetation types that include grasses, sedges and forbs. "Desert" defines low to negligible productivity areas and is characterized by sparse woody and/or herbaceous cover. "Barren land" corresponds to bare rock or soil that do not allow plant growth.

which affects the fraction of precipitation received during summer primarily in the Sonoran. Results showed no improvement since CMIP3 in the magnitude of the mean annual cycle of precipitation but significant improvements in simulating the timing of the seasonal cycle. Geil et al. (2014) concluded that even the highest resolution models are still too coarse to capture small-scale topographically influenced processes that are key to realistically represent the monsoon.

Some decision makers argue that only historical information should be used and extrapolated in the future because of the uncertainty in climate projections. However climate processes are not stationary and the changes that are observed today may have never been recorded before (e.g. melting of the ice caps). Furthermore assuming we can simply use the past to effectively inform the future can promote vulnerability. On the other hand, expecting that new models will dramatically improve the accuracy of the projections is overly optimistic. Models should be considered as tools that describe the fundamental behavior of our planet with the best available science and help generate hypotheses by providing a range of plausible futures and identify gaps in our knowledge where their accuracy fails.

4.2. Climate data downscaling

GCMs were originally designed to simulate the earth's climate. Consequently their spatial resolution is coarse. Over time their resolution improved from the original ~500 km in the early 1990s to ~100 km in 2014 but it remains too coarse to be used for local assessments. Even the relatively fine scale of regional climate models (RCMs) remains too coarse at ~15–50 km to guide local management. A variety of downscaling methods have been used to provide finer scale climate information (Wilby et al., 1998; Díez et al., 2005). The earliest statistical downscaling method, the delta or anomaly method, uses the difference (or ratio for precipitation) between future and current GCM results to modify a "baseline" of observed long-term (30 years) average climate (e.g. Lenihan et al., 2008). A more sophisticated statistical downscaling method such as MACA (Abatzoglou, 2012) corrects the bias that may exist between climate model hindcasts of historical conditions and observations. Future projections are created assuming the bias will remain stable in the future. It is important to remember when using downscaled climate that, despite the fact that the information is now served at fine scale, the original in-

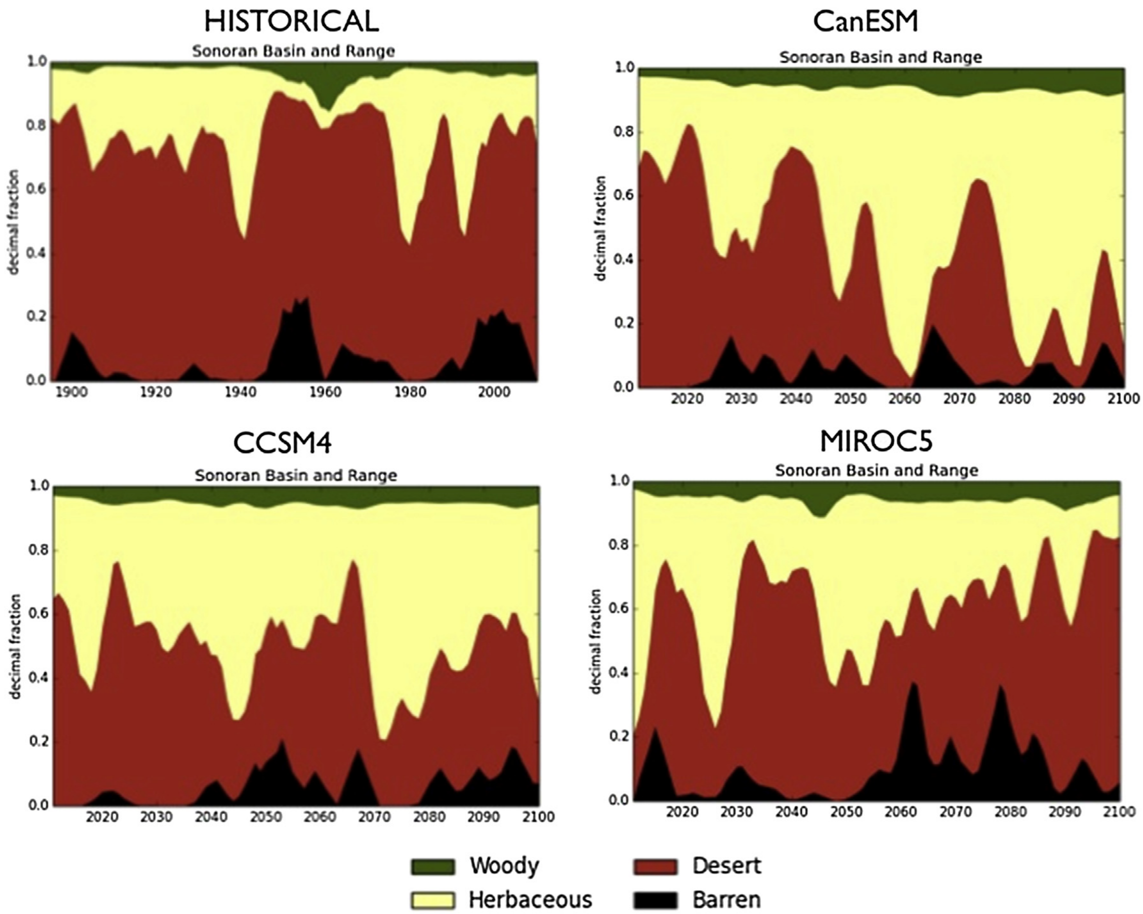

Fig. 6. Potential vegetation dynamics over the Sonoran region of the DRECP for the historical (1895–2010) and future (2011–2100) periods simulated by the MC2 model as fractions of the entire DRECP area occupied by the various aggregated vegetation categories. The vegetation model was driven by three CMIP5 climate model projections (CanESM, CCSM4 and MIROC5) under RCP 8.5 downscaled by Abatzoglou (2012). A 15-year smoothing algorithm was used to display the model results. "Woody" corresponds to woody lifeform-dominated vegetation types, from dense woodlands to sparse shrublands. "Herbaceous" corresponds to herbaceous lifeform-dominated vegetation types that include grasses, sedges and forbs. "Desert" defines low to negligible productivity areas and is characterized by sparse woody and/or herbaceous cover. "Barren land" corresponds to bare rock or soil that do not allow plant growth.

formation was generated at coarse scale and did not take into account local topography or landcover patchiness, and simply assumed each grid cell to be homogeneous. Downscaling methods may thus increase the precision but not the accuracy of the climate projections.

4.3. Gridded climate input and meteorological station network

The accuracy of climate models depends foremost on the availability of meteorological data. Ideally, weather stations should be well distributed across the landscape so that data interpolation between stations can provide reliable coverage at spatial resolutions comparable to model results. Unfortunately, the network of meteorological stations can be sparse where population density is low such as in the DRECP region and more stations can usually be found in easily accessible sites than in remote areas, just as in complex terrain more stations are usually located in valleys than on ridge tops. As a result, landscape heterogeneity may not be captured by the sparse network and will affect the reliability of climate model projections. When data are scarce, models trained on such data are less likely to produce robust simulations of current conditions, let alone project realistic futures.

4.4. Local climate refugia decoupled from regional warming

Another source of uncertainty results from the lack of fine-scale water features in the climate models. Because most climate models use coarse resolutions, smaller inland water features (springs, streams, ponds, playas) are not included and therefore the local microclimates they help create are not simulated. Moreover complex topographic features such as narrow canyons are also missed. As a result, fine scale information that includes these features will be important to identify refugia sites that may provide climate buffering opportunities (e.g. Dobrowski, 2010).

4.5. Soil water availability and vegetation response

In the MC2 DGVM, herbaceous lifeforms successfully compete with woody lifeforms for shallow soil moisture (often ephemeral) while woody lifeforms have access to water reserves deeper in the soil profile. This assumption seems to fit many observations throughout the world (e.g. Mordelet et al., 1997; Weltzin and McPherson, 1997). In the DRECP region, the survival of phreatophytic mesquite and the extirpation of the grasslands have been attributed to the shrub capacity to grow deeper roots as the water table dropped such as at Harper's well (California) which agrees

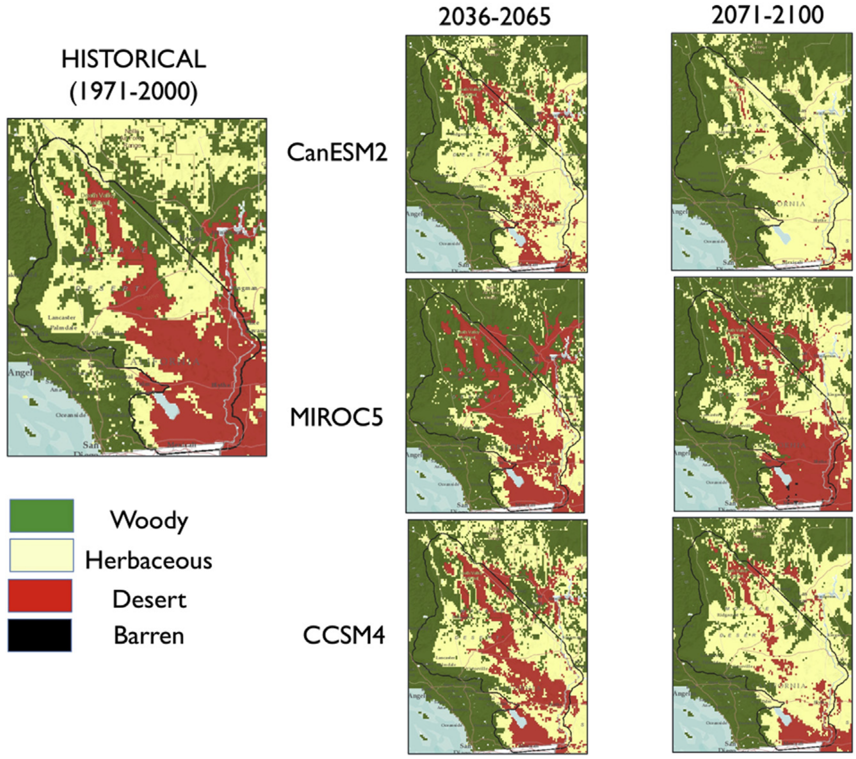

Fig. 7. Potential vegetation distribution simulated by the MC2 DGVM over the DRECP region for the historical (1971–2011) period using PRISM climate drivers and for two future periods (2036–2065 or mid-century – 2071–2100 – or late-century) using CanESM2, MIROC5 and CCSM4 future climates under RCP 8.5 downscaled by Abatzoglou (2012). "Woody" corresponds to woody lifeform-dominated vegetation types, from dense woodlands to sparse shrublands. "Herbaceous" corresponds to herbaceous lifeform-dominated vegetation types that include grasses, sedges and forbs. "Desert" defines low to negligible productivity areas and is characterized by sparse woody and/or herbaceous cover. "Barren land" corresponds to bare rock or soil that do not allow plant growth; it only occurs in a few places as dominant vegetation at the end of the century with MIROC5.

well with our model structure. Along the same lines the precipitation pulses in wet springs described by Moritz et al. (2012) can cause extensive blooms in the desert that are interpreted by our model as times of herbaceous expansion taking advantage of soil surface wetting.

4.6. CO_2 fertilization effect

A gap in our knowledge remains the controversial effect of CO_2 on plant species that were not studied in FACE experiments and in areas where nutrient limitation may reduce the CO_2 fertilization effect (e.g. Asshoff et al., 2006). A moderate CO_2 effect is included in the vegetation model to provide some mitigation of the warming and drying trends in the form of enhanced productivity and water use efficiency for woody lifeforms under drier conditions. This may cause the model to overestimate woody expansion as well as underestimate drought stress mortality.

4.7. Fire risk in the desert

In the last 2 decades of the 21st century, higher temperatures and evaporative demand have caused increases in fire frequency throughout the dry forests of the western US (Westerling et al., 2006). In California, further increases in temperature will likely cause more fires in the Sierra Nevada forests and in chaparral where high human population densities ensure abundant fire ignition sources. Desert areas with sparse vegetation, however, do not have a history of fire since fuel loads are low, and, more importantly, too discontinuous to carry a fire. Moritz et al. (2012) remarked that, in some deserts, fire activity has been increasing because of invasive herbaceous species (D'Antonio and Vitousek, 1992; Brooks et al., 2004) that are not represented in our simulations because their introduction is mostly due to human activities not represented in the model. Any future increases in annual precipitation could exacerbate the invasion and establishment of exotic grasses, although in desert areas such as the Sonoran, temperature increases will likely outweigh precipitation increases, reducing the likelihood of fuel build-up.

4.8. Land use and human footprint

The MC2 vegetation model was designed to simulate land without human intervention and thus results shown here did not include land use. The model has since been revised to include the direct human impacts on vegetation distribution and further analyses for the region will soon be available.

5. Conclusions

Monitoring and field research results have shown that vegetation worldwide is being affected by on-going climate change (e.g. Walther et al., 2002). Species are shifting to higher latitudes or different elevations to adapt to changes in their environment (e.g. Moritz et al., 2008; Harsch and Hille Ris Lambers, 2014). Paleoecology studies have shown that change is not new and that vegetation has shifted over geological time in response to past warming and precipitation changes (Guida, 2011; Moritz and Agudo, 2013). Current concern is that the changes observed today are occurring at a faster pace than ever before (e.g. Root et al., 2003). Recent studies have shown mortality among desert plants related to extended drought and warming (e.g. McAuliffe and Hamerlynck, 2010).

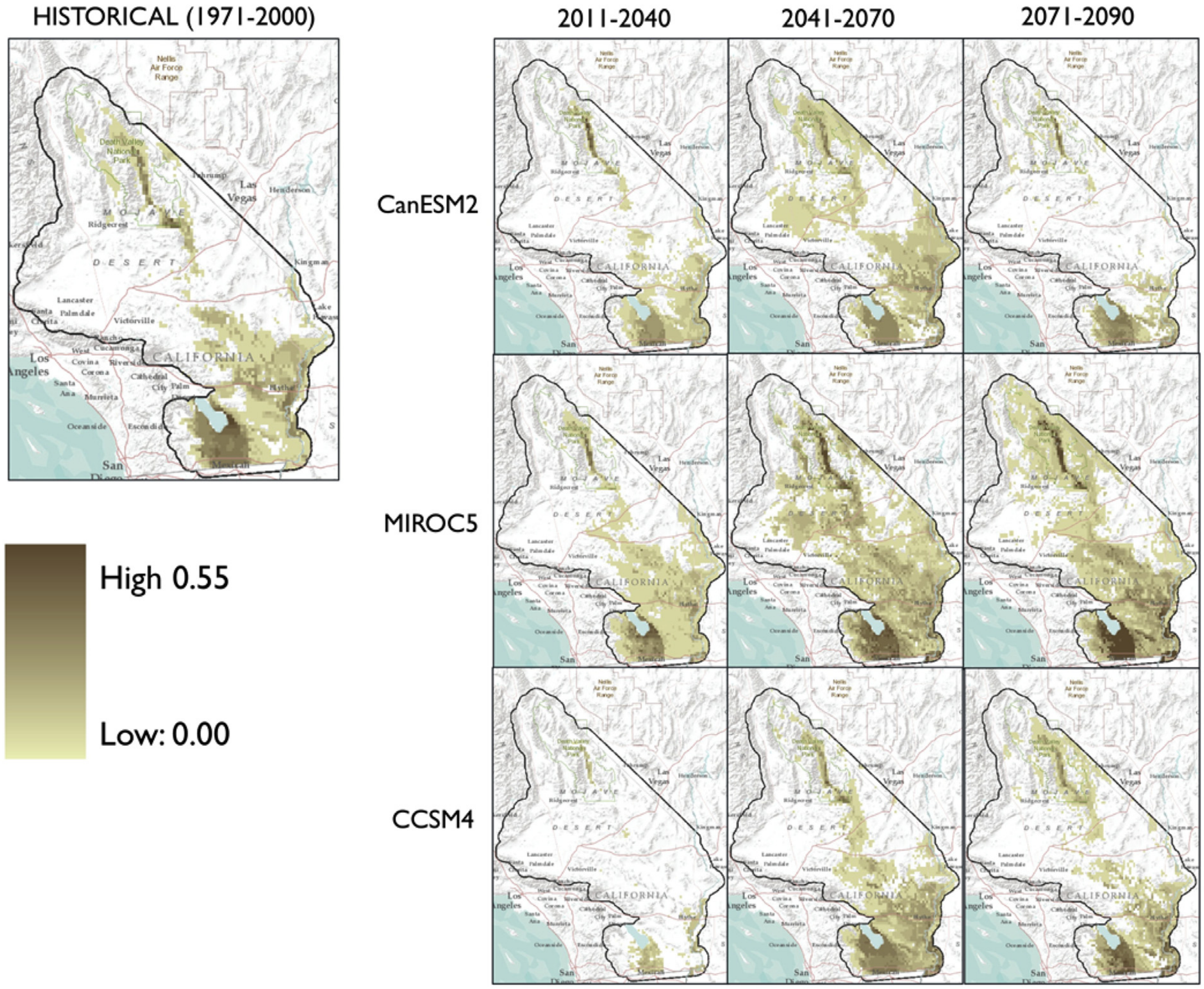

Fig. 8. Barren index based on MC2 DGVM results driven with CanESM2, MIROC5 and CCSM4 climate futures under RCP 8.5 downscaled by Abatzoglou (2012). The Barren index represents the percent time the category "barren land", i.e. no simulated productivity at all, was simulated as the dominant cover over a 30-year period. In all but one case (MIROC5; see a few "barren" pixels on Fig. 7) barren land was not simulated as the dominant cover (>50% of the time) with climate futures.

Changes in regional climate have been documented in southern California where temperatures are rising and precipitation variability is increasing while the snowpack is declining (Kelly and Goulden, 2008). Extreme heat and drought caused by climate change may exceed the survival thresholds of current desert dwellers. Maladapted resident plant species would degrade wildlife habitat and survivorship. Our study shows the effects three possible futures could have on the DRECP landscape both temporally and spatially. Projections of the magnitude and seasonality of precipitation regime are key to understanding the future of the area. The wetter of the three future projections, assuming an increase in water use efficiency further mitigating the increasing heat and evaporative demand, would allow woody lifeforms to expand in the Mohave while herbaceous vegetation would expand in the hotter Sonoran, reducing the extent of desert (as defined in our model) and barren land in the DRECP but also increasing fine fuel loads.

Finer scale analyses could identify possible climate refugia, i.e. landscape features that would buffer changes in climate, such as proximity to permanent sources of water or streams, shady valleys and north facing slopes, and warrant protection from development. In-depth research on the physiological thresholds of the desert species found in the area could also help identify those that are likely to be extirpated by heat waves or increased night-time temperatures and bring consideration to assisted migration of the most threatened species in the areas.

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Appendix

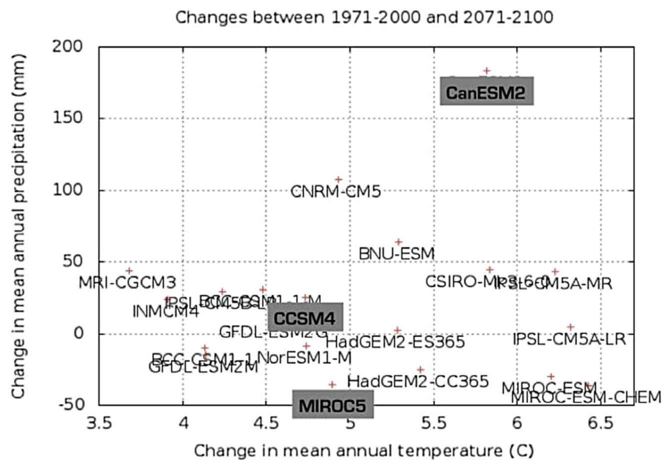

Fig. A1. CMIP5 climate projections (20 models out of 41, Rupp et al., 2013) of the change in mean annual temperature and precipitation between historical (1971–2000) and future (2071–2100) conditions. The three highlighted models were used for in-depth analyses over the DRECP study area. Mean historical precipitation (1949–2005) varied from 112 mm in the Sonoran and 185 mm in the Mojave ecoregions (Abatzoglou et al., 2009).

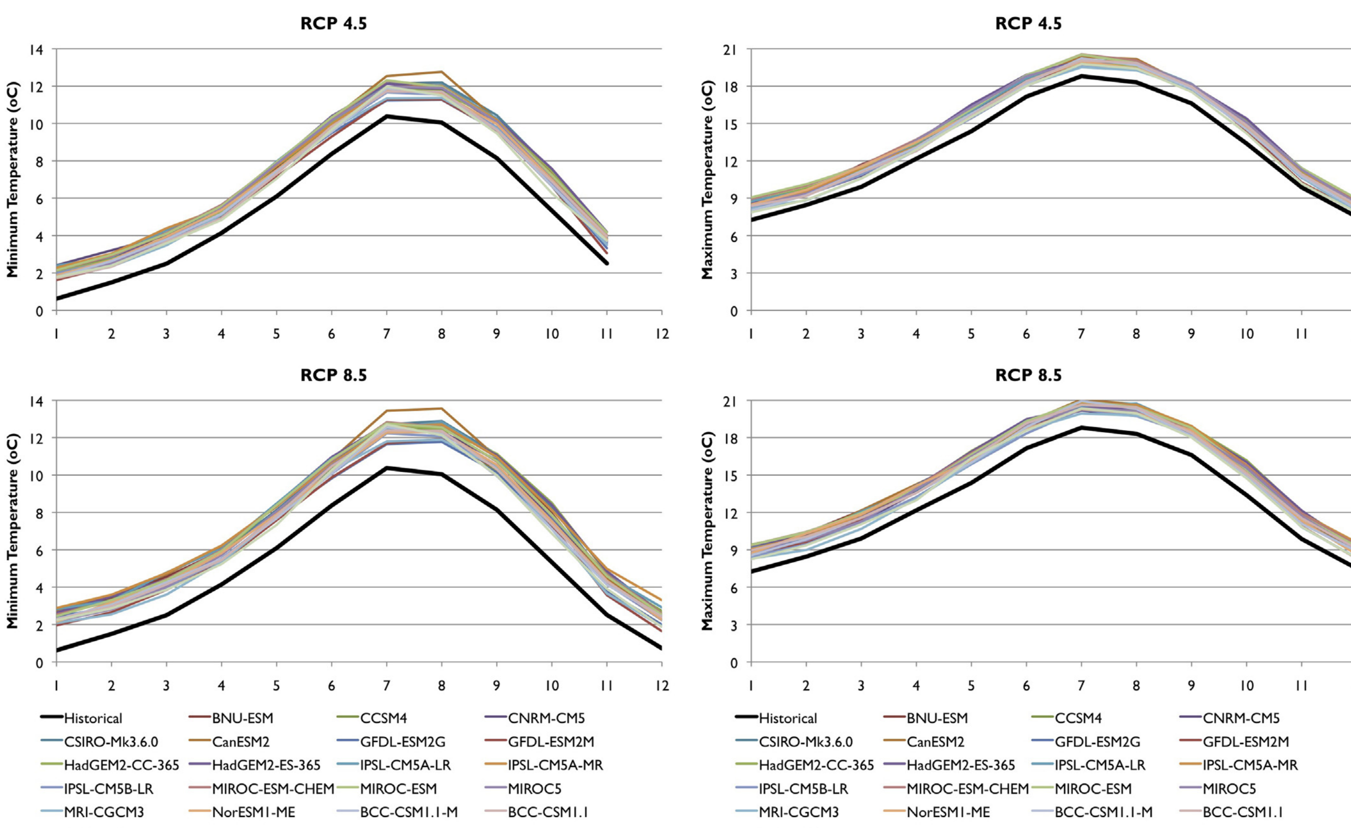

Fig. A2. Observed (1971–2000) and projected (2011–2100) minimum and maximum monthly temperature by 20 CMIP5 climate models for two RCP 4.5 (top) and 8.5 (bottom) emission scenarios in the DRECP region. Note the difference in scale for minimum (left) and maximum (right) temperature to facilitate visualization. Climate data from the various climate modeling teams were downloaded from the CMIP5 web site and downscaled by Abatzoglou (2012).

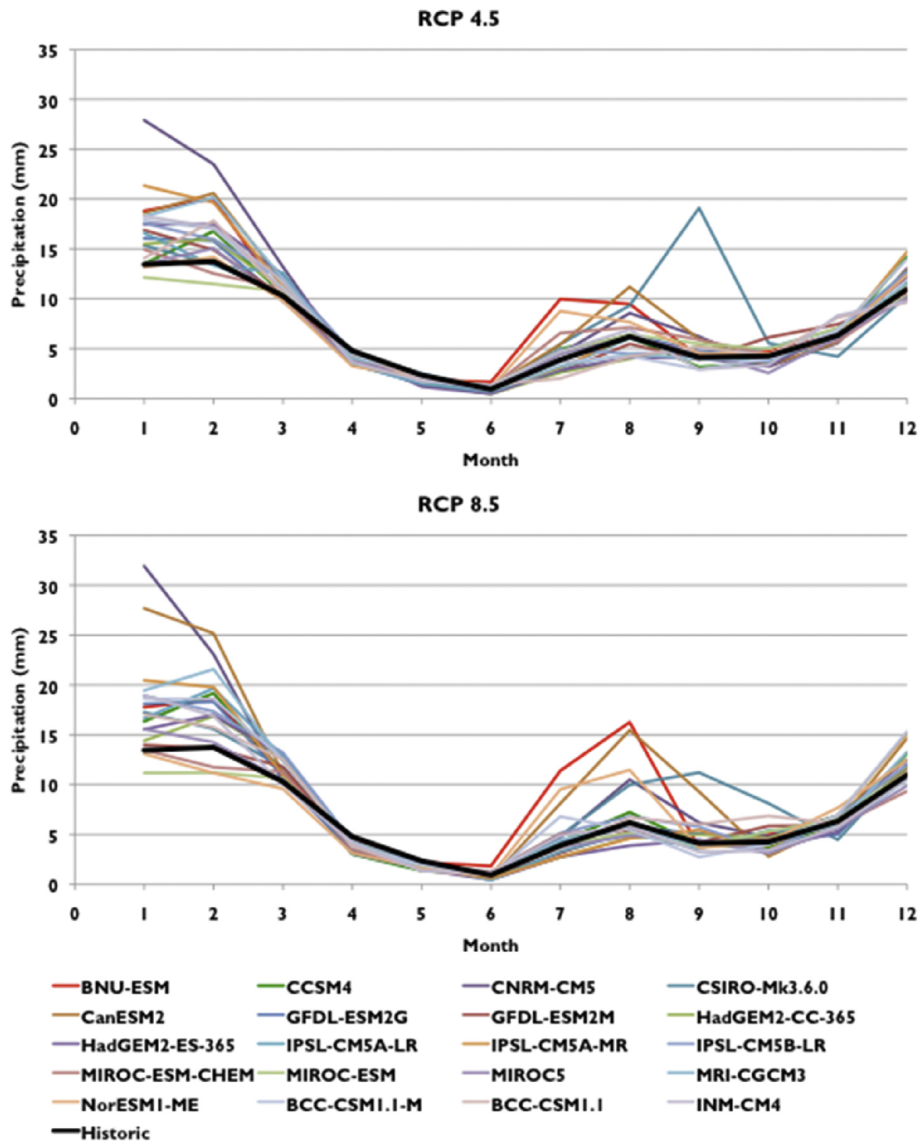

Fig. A3. Observed (1895–2010) and projected (2011–2100) monthly precipitation (mm) by 20 CMIP5 climate models for two RCP 4.5 (top) and 8.5 (bottom) emission scenarios in the DRECP region. Climate data from the various climate modeling teams were downloaded from the CMIP5 web site and downscaled by Abatzoglou (2012).

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