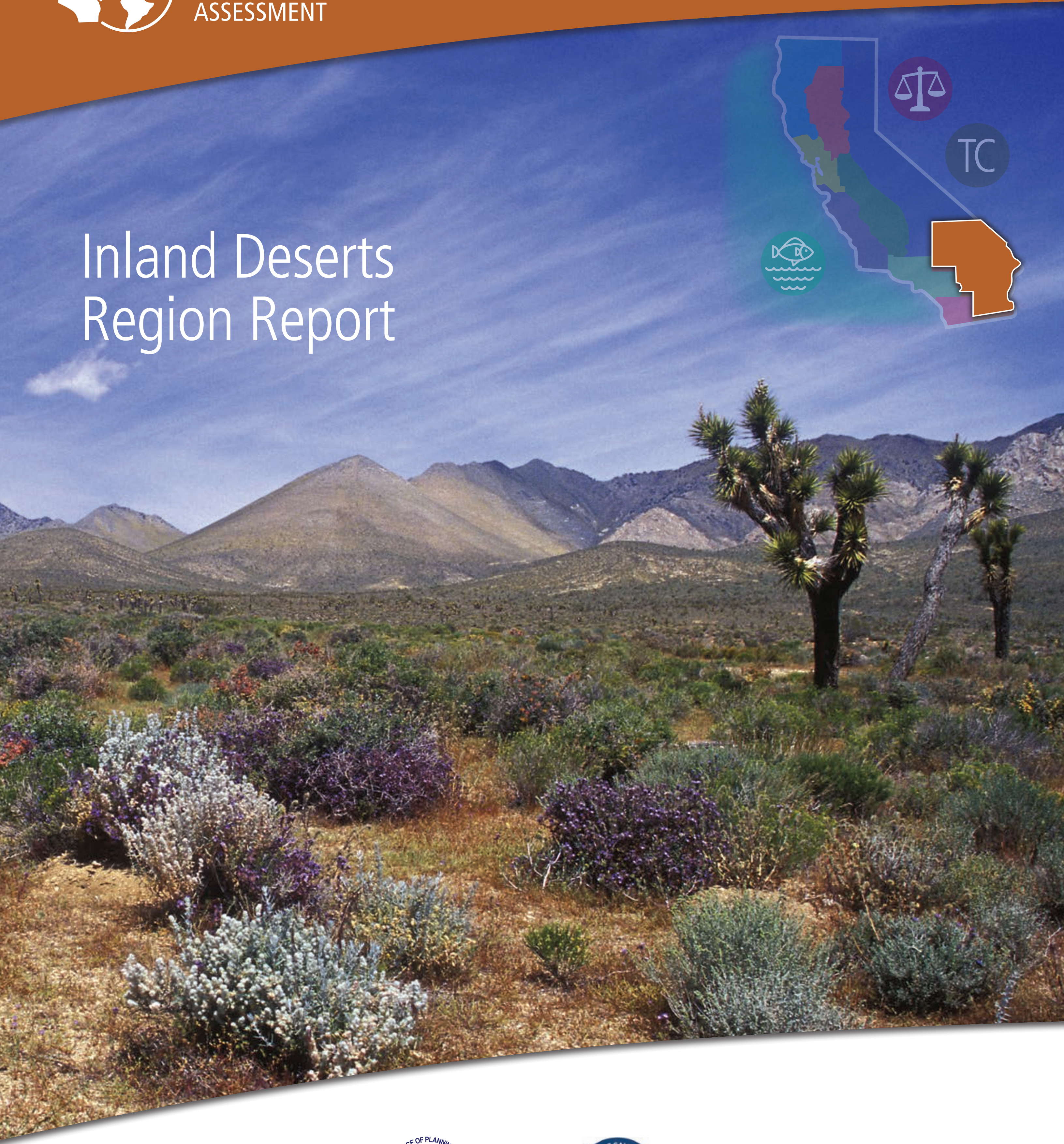
CALIFORNIA'S FOURTH
CLIMATE CHANGE
ASSESSMENT

Inland Deserts Region Report

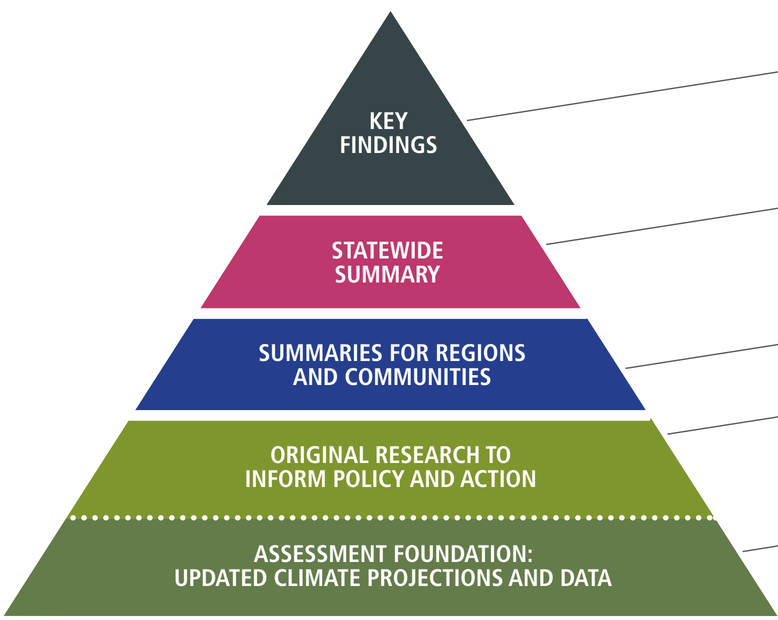


Coordinating Agencies:

Introduction to California's Fourth Climate Change Assessment

California is a global leader in using, investing in, and advancing research to set proactive climate change policy, and its Climate Change Assessments provide the scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. The Climate Change Assessments directly inform State policies, plans, programs, and guidance to promote effective and integrated action to safeguard California from climate change.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. This cutting-edge research initiative is comprised of a wide-ranging body of technical reports, including rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health. In addition, these technical reports have been distilled into summary reports and a brochure, allowing the public and decision-makers to easily access relevant findings from the Fourth Assessment.

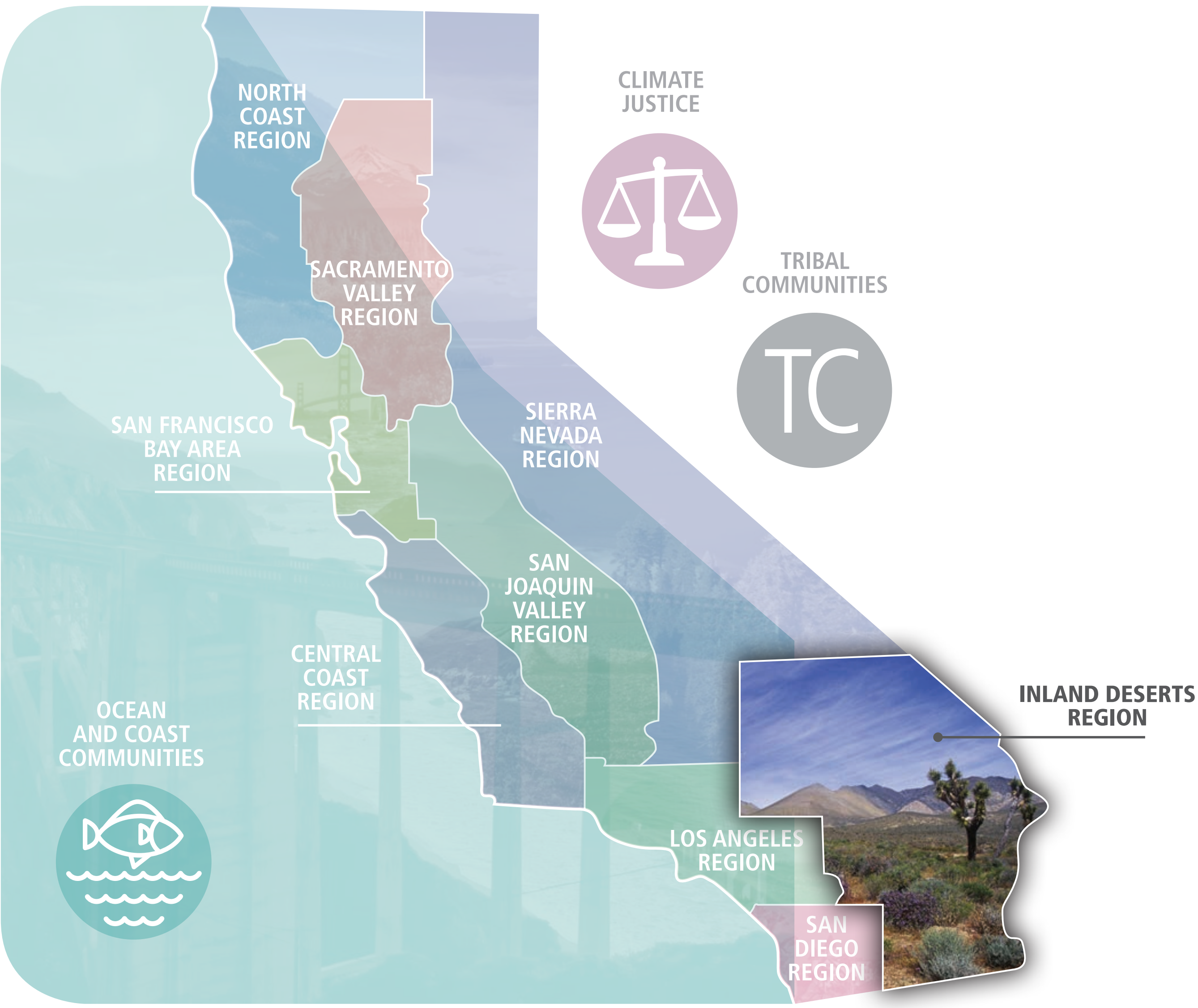


- A concise summary of the Fourth Assessment's most important findings and conclusions.
- An in-depth report on how California's people, built environment, and ecosystems will be impacted by climate change and how we can proactively adapt, based on the Fourth Assessment's findings.
- Reports summarizing Fourth Assessment findings to provide a state of the science for nine regions, the ocean and coast, tribal communities, and climate justice in California.
- Academic research that provides robust and detailed results on resilience and vulnerability to climate change.
- A shared foundation of updated climate change projections, data and ecosystem models developed for use by Assessment authors to permit cross-comparability of results and ensure the findings consider a robust range of future climate conditions. These data are available to the public via Cal-Adapt.org.

All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor as well as, where applicable, appropriate representation of the practitioners and stakeholders to whom each report applies.

For the full suite of Fourth Assessment research products, please visit: www.ClimateAssessment.ca.gov

Inland Deserts Region



The Inland Deserts Region Summary Report is part of a series of 12 assessments to support climate action by providing an overview of climate-related risks and adaptation strategies tailored to specific regions and themes. Produced as part of California's Fourth Climate Change Assessment as part of a pro bono initiative by leading climate experts, these summary reports translate the state of climate science into useful information for decision-makers and practitioners to catalyze action that will benefit regions, the ocean and coast, frontline communities, and tribal and indigenous communities.

The Inland Deserts Region Summary Report presents an overview of climate science, specific strategies to adapt to climate impacts, and key research gaps needed to spur additional progress on safeguarding the Inland Desert Region from climate change.

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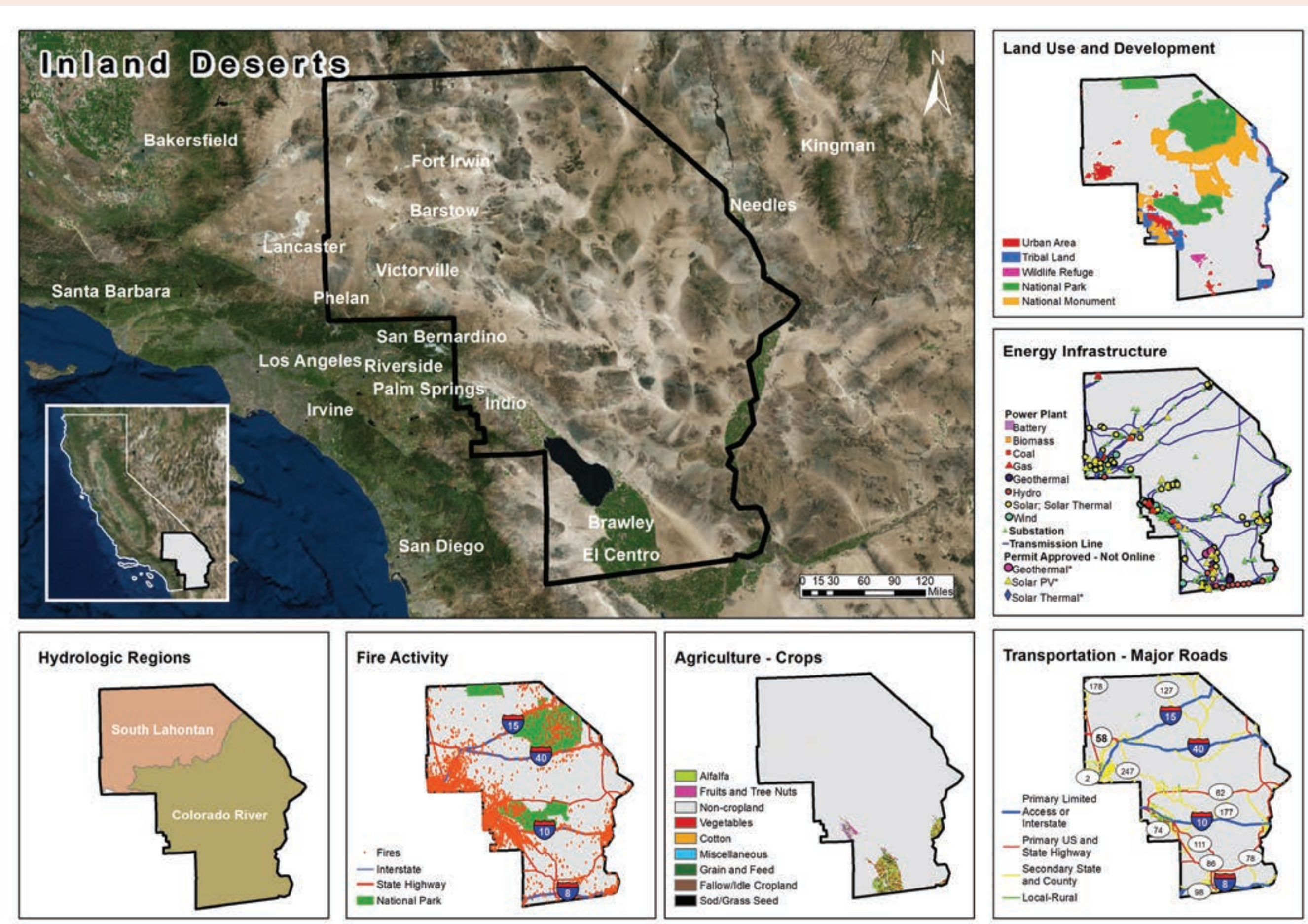
Executive Summary

The Inland Deserts region is the hottest and driest region of California, with a desert climate that varies primarily due to elevation. The region's climate is becoming more extreme, with daily average high temperatures projected to increase by up to 8-14ºF by the end of century. Rainfall rates are currently low (approximately 5 inches per year) and highly variable from year to year. This variability is projected to increase over the coming decades, with extreme drought and extreme wet events both becoming more common. In turn, increasing frequencies of these extreme events will increase the risk of flash flooding and wildfire, given the close relationship between precipitation variability and growth of invasive grasses that serve as the major fuel for wildfire in the region.

Physically, the region encompasses the Mojave and Sonoran deserts in the southeast corner of the state (Figure 1A). The domain includes all of Imperial County and the desert portions of Riverside and San Bernardino Counties. The region has about 1 million inhabitants, with 85% of those residing in urbanized areas including the Victor Valley in San Bernardino County (Victorville, Apple Valley, Hesperia), the Coachella Valley in Riverside County (Indio, Palm Springs, Palm Desert), and the El Centro Metropolitan Area in Imperial County (El Centro, Brawley, Calexico) [American Communities Survey estimated 2017 population]. In addition, the tribal lands of 12 different groups are contained in the region (Figure 1B). Future development will likely take place within and amongst these urbanized areas.

FIGURE 1



Satellite composite image of the Inland Deserts (A). Subplots B-G show geography and infrastructure in the region, including Land Use (B), Energy (C), Transportation (D), Agriculture (E), Fire Activity (F), and Watersheds (G).

Despite its sparse population, the region is important for protected lands, tourism, and agriculture. The region has the largest acreage of federally protected lands in the state (US BLM NLCS National Monuments and Conservation Areas)—7,448 square miles of National Parks and Monuments, including ecologically unique and sensitive ecosystems in Joshua Tree National Park and the Mojave Trails National Monument. It contains important wildlife refuges, including the Salton Sea. Biodiversity hotspots are found at high elevation, in oases, and sand dunes that provide a climatic refuge against extreme heat and aridity that characterizes sandy lowland areas (bajadas). These hotspots are threatened by climate change as well as other land-use pressures, and identifying and protecting appropriate climate refugia is likely to be the best strategy for conservation.

Tourism in the region derives from proximity to these protected lands and is a direct result of the region's climate. The Coachella Valley is a major tourist destination that developed in the 1950s as a warm-weather winter retreat for residents of cold, snowy climates. Tourism is the number one contributor to the Coachella Valley's economy. The close relationship between tourism and climate may make the region's economy uniquely vulnerable to the effects of climate change.

Crops cover 4% of land area in the region, primarily in the Imperial Valley (Figure 1E). While crop coverage may seem low in the region as a whole, it belies the importance of agriculture to the fully agrarian Imperial Valley, the Palo Verde Valley along the Colorado River, and the southeastern portion of the Coachella Valley adjacent to the Salton Sea. Agriculture is the primary economic driver of the Imperial and Palo Verde Valleys, and is second only to tourism in the Coachella Valley. Because its warm climate enables winter harvests, the Imperial Valley is a major source of winter fruits and vegetables for the U.S. and abroad. Other important crops include forage and fodder such as alfalfa and hay. Already at the high temperature limit for agriculture globally, climate change will bring additional heat stress to field crops, livestock, and the health of farm workers. Agriculture in the valleys is nearly completely irrigation dependent, and demand will likely increase with rising evapotranspiration rates under a warmer climate. Currently, the Imperial Valley has the highest per capita water consumption in the state due to its water-intensive agriculture, relatively low population, and senior water rights to the Colorado River. Potential climate-driven reductions to Colorado River flow and competing water needs in other regions pose another threat to agriculture.

Like much of California, many of the effects of climate change will be mediated through climate-driven stress to water supply and quality. Land use patterns in the region are highly dependent on water availability, and competing needs for water amongst urban development, agriculture, and natural ecosystems. High variability amongst climate model predictions of future rainfall rates make projections of future water availability highly uncertain; however, climate warming will dry soils and increase the risk of severe drought.

Much of the region is challenged by high poverty and unemployment rates and low educational attainment levels, making the residents more vulnerable to the effects of climate change. Imperial County has a poverty rate of 23%, making it the 5th highest poverty county in the state (CA Budget Project/US Census). Riverside and San Bernardino Counties also have poverty rates above the state average (15.6 and 17.6% respectively, vs. 14.7% statewide). The extreme heat projected for the region is likely to threaten this vulnerable population directly through heat-related illness, and indirectly through strain on infrastructure and via changing levels of air pollution and disease. Increasing climate extremes—extreme high temperatures, likelihood of flash flooding, and wildfire risk—will stress transportation and energy infrastructure currently in place, and will increase energy demand for cooling. Population growth and urbanization in the region, expected to be higher here than for the state as a whole, is likely to exacerbate strains on infrastructure, land use, and water supply, and may increase wildland-urban interface areas that could potentially lead to more wildfire activity without careful planning that takes these issues into account.

In addition to climate-sensitive tourism and agriculture, other industries important to the region are based on the relatively inexpensive land costs compared to nearby coastal areas. These include real estate development and construction, renewable energy development, logistics and warehousing, and correctional facilities. Climate change mitigation policies implemented over the past decade have had a net positive economic impact on the region, mainly through construction of new renewable energy sources (Jones et al., 2017). These new renewable energy sources are a key part of attaining statewide greenhouse gas reduction goals while providing future energy supply. While beneficial for the economy and for greenhouse gas mitigation, development of renewable energy poses a threat to sensitive ecosystems that are contracting in size due to higher temperatures and more severe drought, and to competing land uses, including agriculture and recreation.

A major geographic feature of the region is the Salton Sea, the state's largest lake, which is maintained by inflows from agricultural runoff. Future environmental quality of the region is highly dependent on the fate of the Salton Sea, which is currently threatened by diminishing levels of inflows from agricultural runoff. As the Sea shrinks, the increasingly exposed playa (dry lakebed) is likely to become a major source of dust, polluting the air of the region and potentially of areas beyond. The region already suffers from high rates of childhood asthma and cardiovascular disease thought to be linked to dust emissions from the Sea (Imperial County Public Health, 2016), making increased playa dust emissions of particular concern in terms of human health and environmental justice. Climate change will exacerbate water supply and quality issues that hamper efforts to restore the Sea, and will place additional stress on environmental quality, habitat, and public health challenges related to the shrinking Sea.

A general summary of climate risks facing the California's Inland Deserts region include:

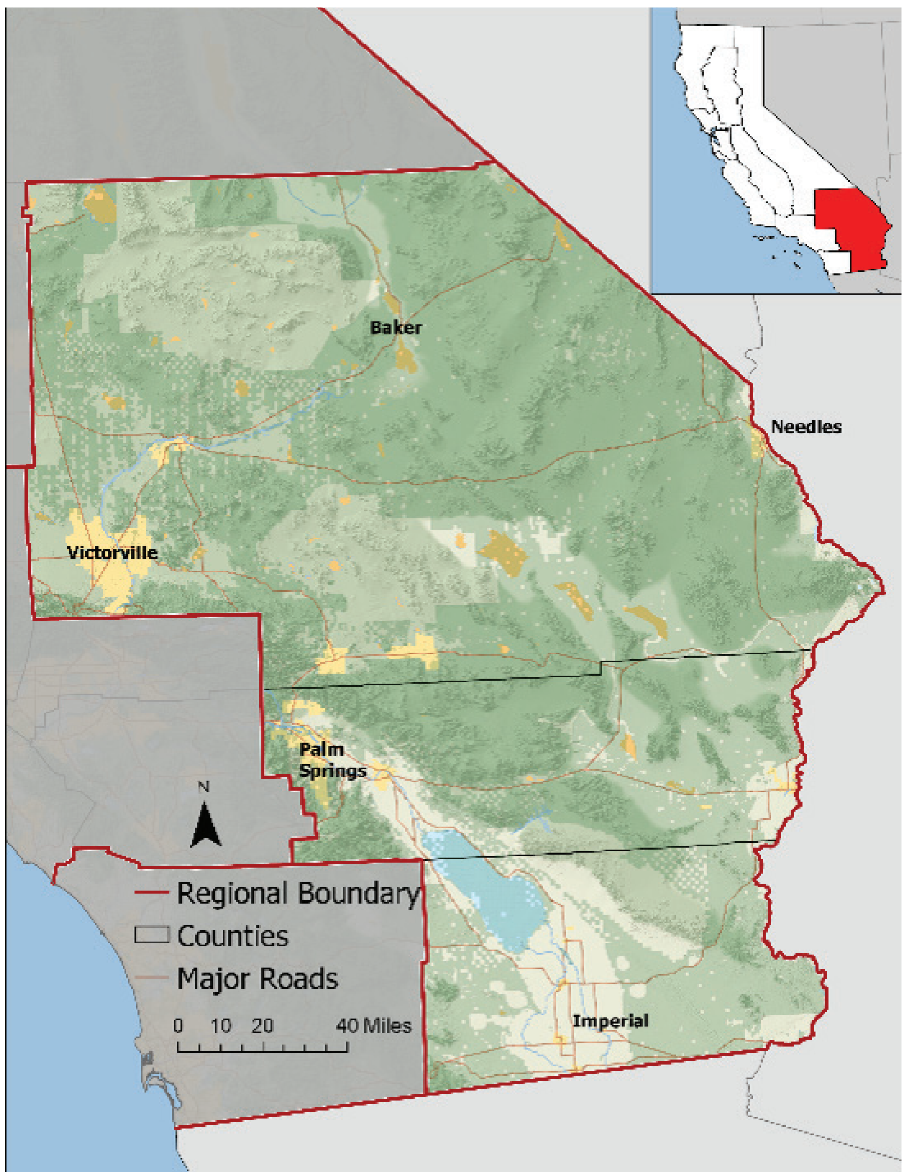
- Extremely high maximum temperatures are expected to occur in the Inland Deserts.
- The fate of the Salton Sea is a critical determinant of future environmental quality.
- Renewable energy development will have big impacts on the economy and infrastructure.
- Continuing current land use/development patterns (i.e., housing development in the region to compensate for lack of development on the coast) will require increased energy for cooling to compensate for a rise in extremely high temperatures.
- Higher temperatures will exacerbate water stress in an already very water-limited region.
- Changing water availability is a key determinant of the future for ecological and agricultural systems.
- Population in the Inland Deserts is highly vulnerable to the effects of climate change.
- Tourism is a major economic driver that is likely to be threatened by a changing climate.

Table of Contents

Introduction

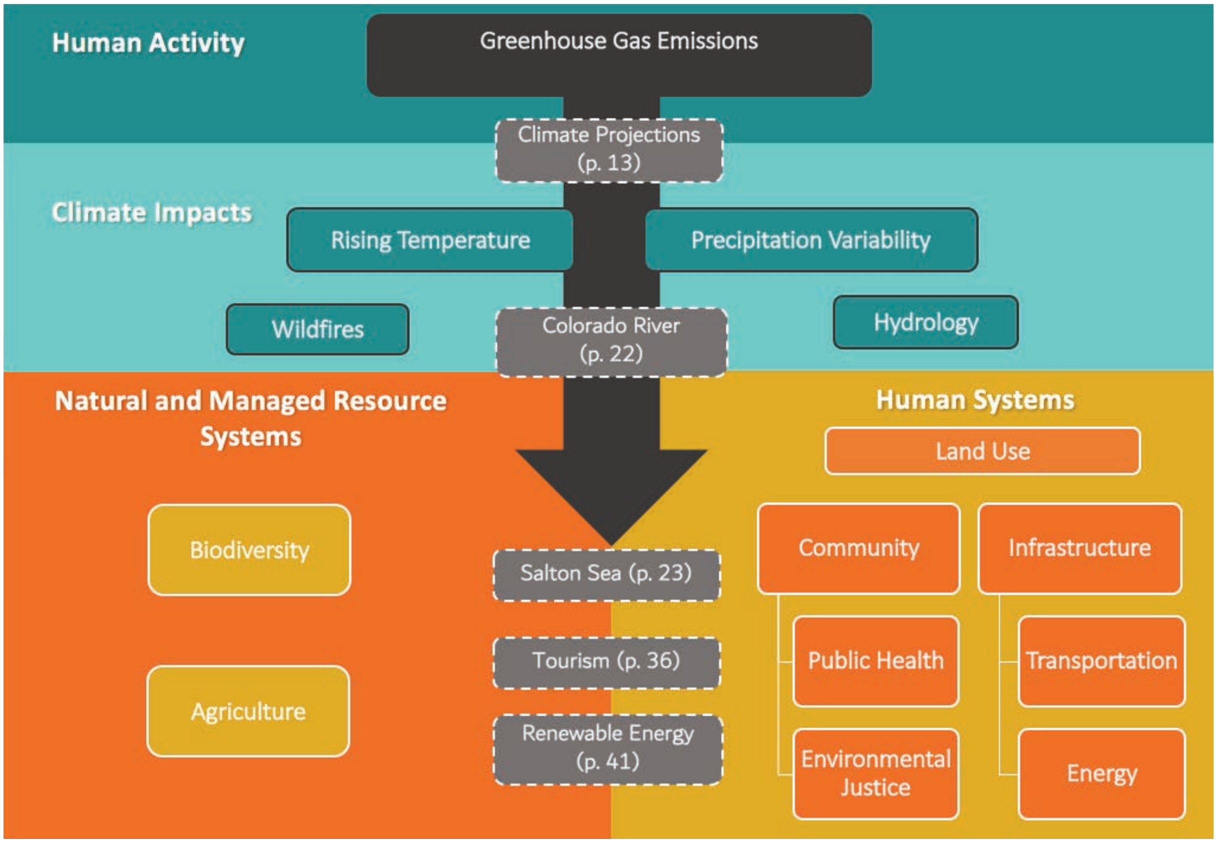
The Inland Deserts of California are comprised of the Mojave and Sonoran deserts in the southeast corner of California (Figure 2). The region includes all of Imperial County and the desert portions of Riverside and San Bernardino Counties. In this report, we summarize the major climate change risks for natural, managed, and human systems in the region, drawing on peer-reviewed literature, government reports, and other reports that contribute to California's Fourth Climate Change Assessment. In addition to synthesizing the state of knowledge, we identify adaptation options that can help lessen the impact of climate change in the region. The report is organized into 3 sections (Figure 3). Section 1 (Inland Deserts Physical Climate) describes the projected climate of the region to the end of the 21st century, along with direct impacts of climate on wildfires and hydrology of the Inland Deserts. Section 2 (Natural and Managed Resource Systems) addresses climate change effects on natural and managed resource systems, including biodiversity and agriculture. Section 3 (Human Systems) explores climate change effects on human systems, including land use decisions, risks to infrastructure, and the vulnerability of Inland Desert communities. Finally, section 4 (Research Needs) identifies knowledge gaps where future research can contribute an improved understanding of climate change impacts and adaptation strategies for Inland Deserts.

FIGURE 2



Inland Deserts. Source: Jim Thorne.

FIGURE 3

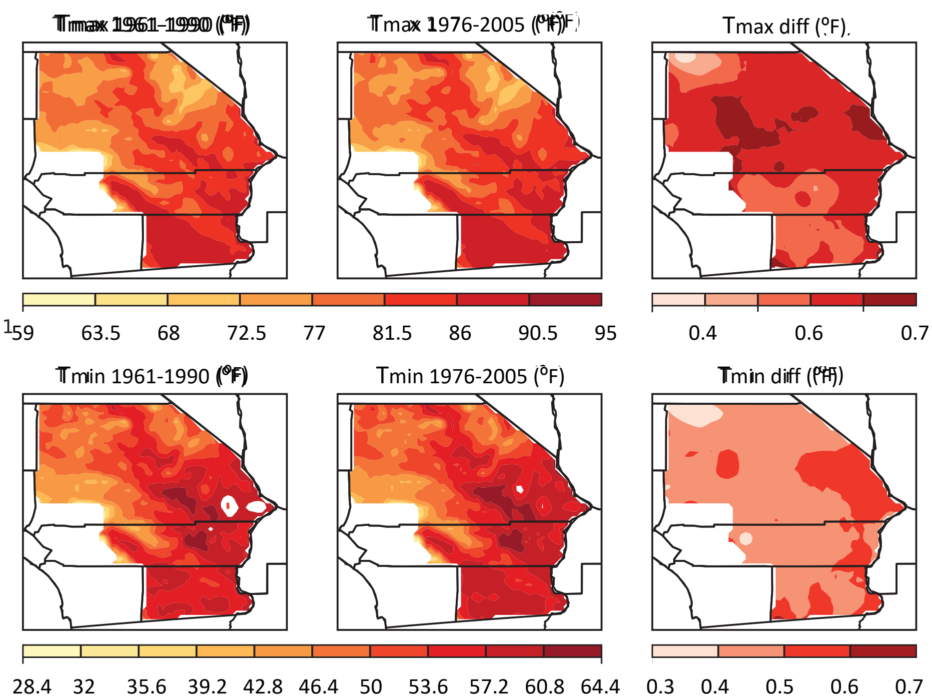


Greenhouse gases emitted by human activities have a direct effect on climate, including temperature and precipitation amounts and seasonality. In turn, these climatic drivers affect wildfires and hydrology, and indirectly impact natural and managed resource systems, and human systems including land use, community, and infrastructure.

Inland Deserts Physical Climate

In this section, we describe the direct impacts of climate change on temperature and precipitation projections in the Inland Deserts over the 21st century. These climate changes have important consequences for wildfire by changing the type, amount, and connectivity of vegetation that fuel fire intensity and spread. Climate change will also affect hydrology and water supplies in the region, which strongly depend on future precipitation amounts and variability. Of particular importance is how climate change will affect the flow of the Colorado River, which is the major water supply for most of the region.

FIGURE 4



Distribution and changes to daily temperature extremes in the Inland Deserts in the second half of the 20th century. Top panels: Average daily maximum temperature (°F), and bottom panels: average daily minimum temperature for 1961-1990 (left), 1976-2005 (middle) and difference between these periods (right). Source: Neil Berg, UCLA.

The Inland Deserts of California have an extremely warm and dry climate that is becoming even more extreme with climate change. Average high temperatures average 81°F across the region, with very hot, dry summers (average July highs 99°F-109°F) and warm, dry winters (average December lows 30-44°F). Rainfall averages just 5 inches per year, but annual totals are highly variable. Spatially, the climate varies primarily with elevation (Figure 4). The Mojave Desert is the relatively cooler high desert (Köppen Climate Class BWk: cold desert), while the Sonoran is the hotter low desert (Köppen Climate Class BWh: hot desert). Climate change has already increased temperatures in the region. Over the second half of the 20th century, daily maximum temperatures warmed by 0.4-0.7 °F, comparing 1976-2005 with 1961-1990 (Figure 4). It is extremely likely that increased levels of greenhouse gases in atmosphere due to human activities are responsible for warming over this period (IPCC, 2014).

Scientific Basis for Climate Change Projections

Greenhouse gases, such as carbon dioxide and methane, trap heat in Earth's atmosphere. Levels of these greenhouse gases have increased since the Industrial Revolution, and in particular since the 1950s, due to human activities such as fossil fuel burning. 21st century climate will depend on future emissions of greenhouse gases, which in turn depends on human decisions over the next several decades (IPCC, 2014).

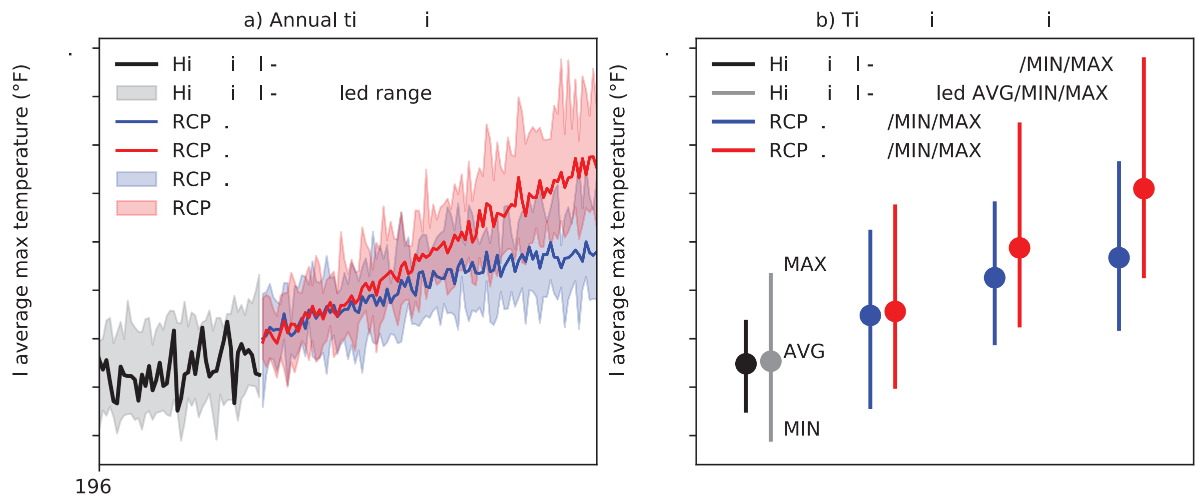
Predictions of future climate requires that future levels of greenhouse gases are estimated in a systematic way. Projections of future greenhouse gas emissions are called Representative Concentration Pathways (RCPs), and are based on future scenarios of global population, economics, energy and land use, technology, and policy (van Vuuren et al., 2011).

Climate projections given in this report are based on two RCPs: RCP 4.5, a moderate emissions pathway requiring greenhouse gas mitigation, and RCP 8.5, a "business-as-usual" scenario that extends current emission trends forward in time. These RCP emissions were used in 10 global climate models that best simulate aspects of California's climate to project climate conditions out to 2100 (Pierce et al., 2018). Projections of temperature and precipitation were downscaled to ~6 km (Pierce et al., 2014), and are presented here for the Inland Deserts. These data and accompanying visualizations are freely available at www.cal-adapt.org.

21st Century Climate Projections

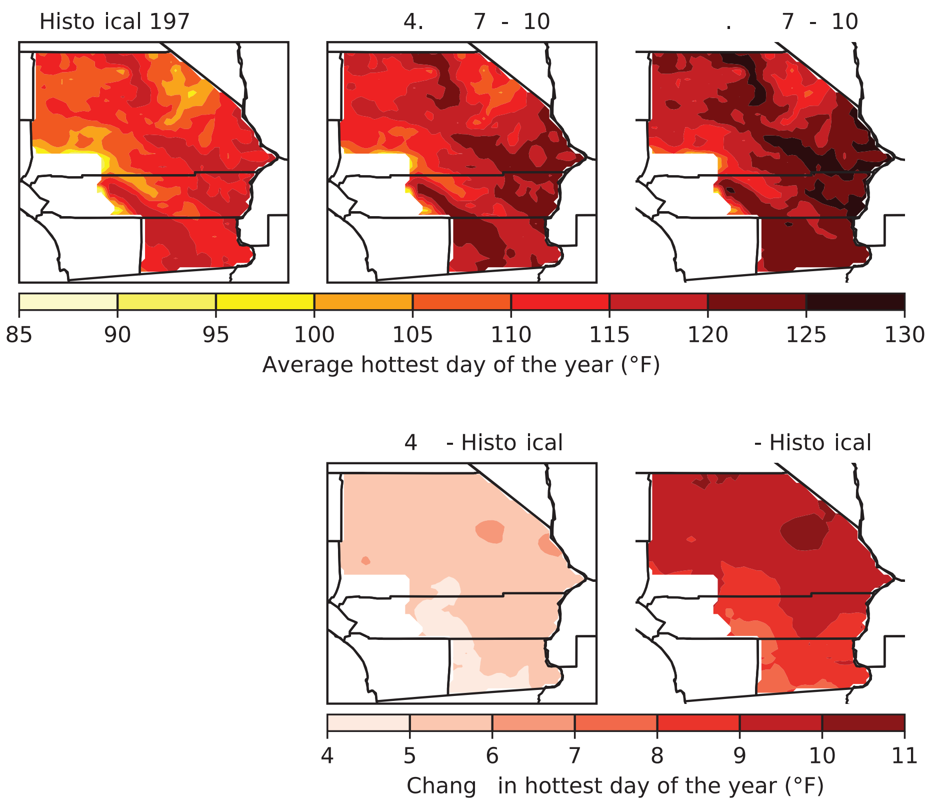
California's Inland Deserts are known for extreme heat, which will only become more extreme in the future. Daily maximum temperatures are projected to increase by +5-6°F for 2006-2039, by +6-10°F for 2040-2069, and +8-14°F for 2070-2100 on average for the region, with ranges depending on future greenhouse gas emissions (Figure 5). Historically, the hottest day of the year ranges from the high 90s (°F) at upper elevations to >115°F in eastern low desert regions. By the end of the 21st century, these hot extremes are projected to rise by at least +6°F, and up to +9°F on average, depending on future greenhouse gas emissions (RCP 4.5 and RCP 8.5, respectively; Figure 6). The region also has a high frequency of extremely hot days, defined as temperatures >95°F, averaging 90 per year in the Mojave, and 135 per year in Palm Springs during the 1981-2000 period (Sun et al., 2015). Climate change is expected to increase the frequency of >95°F days, with projection of up to 141 days in the Mojave, and 179 days—half the year—in Palm Springs by the end of the 21st Century under RCP 8.5 (Sun et al., 2015).

FIGURE 5



Historical (black) and projected annual average maximum temperature in the Inland Deserts for two emission scenarios (RCP 4.5: blue, RCP 8.5: red). Panel a: Annual Time Series: Solid lines show model averages, and shaded areas show modeled ranges. Panel b: Three decade summaries: Circle markers show model averages, and error bars show modeled ranges. Source: Neil Berg, UCLA.

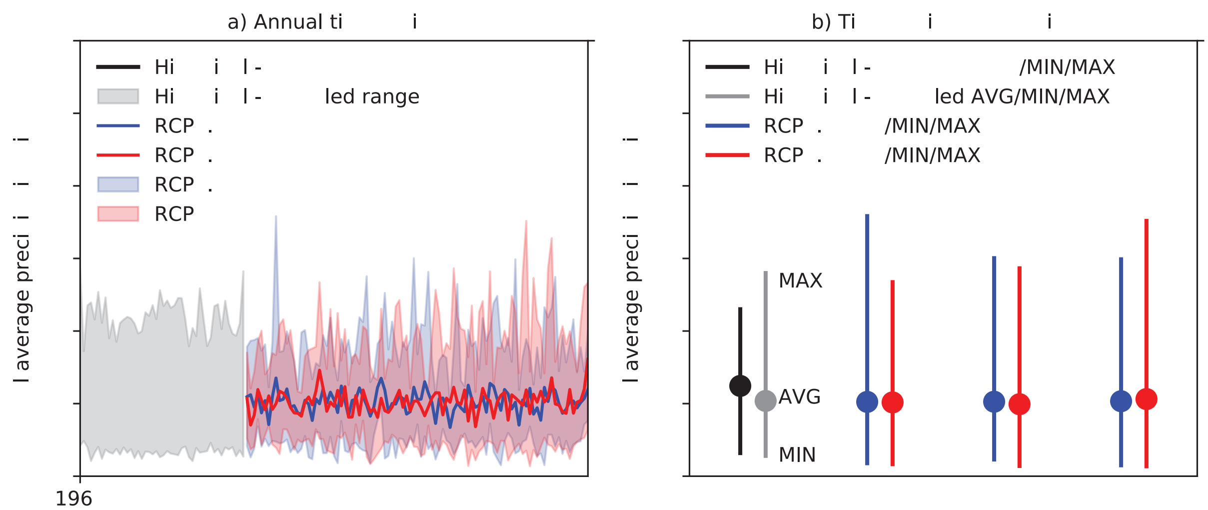
FIGURE 6



Average hottest day of the year (ºF) across the Inland Deserts for historical observations (1976-2005) and modeled end of century (2070-2100) for RCP 4.5 and RCP 8.5 scenarios (top panels), and change in the temperature of the hottest day of the year at the end of century for RCP 4.5 and RCP 8.5 (bottom panels). Source: Neil Berg, UCLA

In addition to these hot extremes, low temperature extremes warmed over the 20th century by 0.3-0.6ºF (1976-2005 period compared to 1961-1990; Figure 4). 21st century projections also show warming of daily minimum temperatures, albeit less than for daily high temperatures, ranging from +0-1ºF for 2006-2039, +3-4ºF for 2040-2069, and +4-7ºF for 2070-2100 (Figure 5). This change is particularly relevant for high elevation areas that currently experience minimum temperatures below freezing (≤32ºF). During 1981-2000, NOAA records indicate that Victorville (2,726' elevation) experienced 44 days a year of freezing temperature, but this number is projected to decline to 9 days per year midcentury, and to 2 days by the end of century (Sun et al., 2015).

FIGURE 7

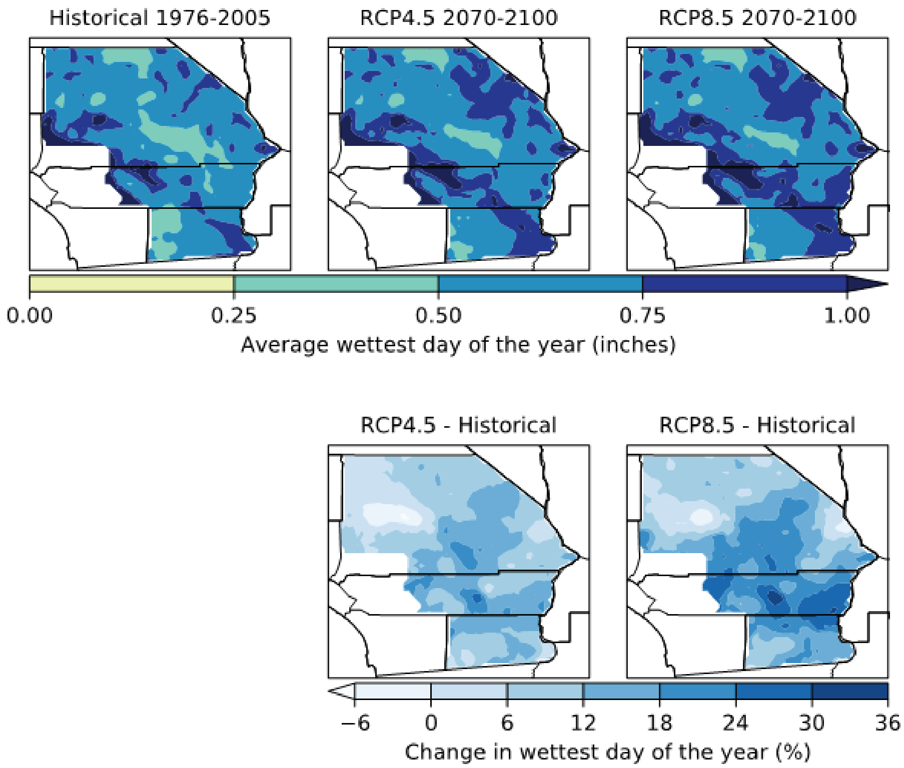


Historical (black) and projected annual average precipitation in the Inland Deserts for two different emission scenarios (RCP 4.5: blue, RCP 8.5: red). Panel a: Annual Time Series: Solid lines show model averages, and shaded areas show modeled ranges. Panel b: 3 decade summaries: Circle markers show model averages, and error bars show modeled ranges. Source: Neil Berg, UCLA.

Historically, precipitation in the region is highly variable, averaging around 5 inches per year, with rainfall some years as low as 1½ inches and as high as 10¾ inches over the 1950-2005 period (Figure 7). There is also large spatial variation in precipitation rates across the region driven by elevation and location, with averages ranging from 3 inches per year to roughly 8 inches per year (Figure 8). Projecting climate impacts on precipitation is highly uncertain in California, in particular for annual rainfall totals in the Inland Deserts (Allen and Luptowitz, 2017). For the suite of downscaled climate models used in this assessment, there is little projected change in average rainfall each year to the end of the 21st century (<10%), even under different emission scenarios (Figure 7). However, projections reveal an increase in inter-annual precipitation variability, with reductions in minimum annual precipitation of up to 50% and increases in maximum annual precipitation of 40-65% by the end of the 21st century (Figure 7).

Precipitation in the Inland Deserts occurs during two seasons. In the winter, large scale global circulations occasionally bring extratropical cyclones from the northern and eastern Pacific region. These storms are responsible for most of the annual rainfall across the desert region, with February typically being the wettest month. Winter precipitation increases with elevation and decreases going from north to south, and west to east. In the summer, global circulations reverse, allowing the North American Monsoon to periodically drift westward into this portion of the state (Hereford et al., 2006). Historically, summer monsoon precipitation falls primarily in July, August, and September (Tubbs, 1972). The monsoonal rains account for about 30% of precipitation over the eastern deserts, decreasing to around 15% in the western Mojave.

FIGURE 8



Average wettest day of the year (inches) across the Inland Deserts for historical observations (1976-2005) and modeled end of century (2070-2100) for RCP 4.5 and RCP 8.5 scenarios (top panels), and percent change in wettest day of the year at the end of century for RCP 4.5 and RCP 8.5 (bottom panels). Source: Neil Berg, UCLA.

These seasonal patterns of precipitation may also change with the climate. As winter and summer precipitation have different climatic drivers, current research suggests these phenomena will be affected differently by climate change. Winter precipitation (falling mainly in December, January, and February) is projected to increase over the region due to warming of the tropical Pacific according to roughly half of the current generation of climate models (Allen and Luptowitz, 2017). In contrast, summer monsoonal precipitation is thought to decrease by up to 40% (Pascale et al., 2017). While it is difficult to predict precipitation changes in the region, higher temperatures mean the atmosphere will be capable of carrying more water vapor, thus increasing evaporative demand on already scarce water supplies and decreasing soil moisture. High interannual and interdecadal variability along with the difficulty of simulating future sea surface temperatures pose challenges to precipitation simulations in current climate models (Pascale et al., 2017). Better prediction of precipitation trends and seasonality is an important area where future research is needed.

Over most of the region, the wettest day of the year is projected to increase by as much as 30% in some areas by 2100 (Figure 8). The combination of more intense rainfall events and drier soils in an already very dry region will increase the probability of flash floods. Dry soils are poor absorbers of rainfall, causing high runoff rates. Moreover, infrequent rainfall increases the possibility of debris flow of accumulated material such as dead vegetation and rocks during flash flood events (Reid et al., 1994). Because of the dry climate, infrastructure is generally not designed to handle large flows of water that may be generated in a flash flood event—for example, many roads cross dry creek beds without bridges—making intense rainfall events a large risk here than in wetter areas.

Projected Fire Activity through 2100

The combination of low annual precipitation amounts and high precipitation variability from year to year often results in discontinuous fuel beds (i.e. the horizontal and vertical spacing of fuels over a given area) across this portion of California. The Mojave Desert flora within these fuel beds is mainly comprised of annual grasses and shrubs such as manzanita, California buckwheat, and desert holly, while higher elevations are favorable habitats for juniper pine, sagebrush and some white fir. The Joshua tree is iconic and is a common flora across much of the Mojave, particularly over the southern Mojave (Figure 9). Various species of cacti are home to this portion of California but are more prevalent over the southeast portions of the Inland Deserts. Within the desert ecosystem, fuels have the most significant contribution to the overall fire regime (Brooks at el., 2004).

FIGURE 9

Joshua tree against a smoke plume from the 2015 Lake fire burning near Yucca Valley. The same region burned in 2006 during the Sawtooth Complex Fire. Source: Kurt Miller, Riverside Press-Enterprise/SCNG, https://www.pe.com/2015/06/25/pioneertown-desert-community-still-shaken-by-sawtooth-blaze-now-frets-over-lake-fire/

Consequently, fire activity is highly variable from year to year depending on the amount of loading, continuity, and vertical arrangement of the fuels that are present. A brief analysis was performed on historical fire data across the region that consisted of 9,784 records which spanned the years 1992 to 2015 (Short, 2017). Displaying the dataset graphically reveals that most of the fire activity is clustered around the national forests, in and near the more populated areas, and along major transportation corridors such as interstates and railroads (Figure 1F), illustrating that most of the fire activity in the region is human related. Specifically, 22% of the fires were caused by equipment use, 30% were attributed to miscellaneous causes, and 37% were related to various other causes, with only 10% started by lightning (Table 1). However, lightning played a disproportionately large role in the ignition of extremely large fires; it was cited as the cause for 40% of the fires that were 500 acres or more. While many incidents are covered at the initial attack stage, these larger fires require additional resources from outside the area, thus making them more costly to suppress.

TABLE 1. CAUSES OF FIRE IGNITIONS FOR 1992-2015.

Data from Short, 2017.

CAUSE	NUMBER	%
Miscellaneous	2,998	31%
Equipment Use	2,109	22%
Lightning	978	10%
Missing/Undefined	806	8%
Arson	743	8%
Children	562	6%
Smoking	516	5%
Debris Burning	477	5%
Campfire	419	4%
Railroad	64	1%
Fireworks	52	1%
Powerline	48	0%
Structure	12	0%

Perhaps the most significant meteorological effect of climate change would be the potential for a weaker North American Monsoon signal over the Desert Southwest (Pascale et al., 2017). Some climate models project lower precipitation amounts during the summer months in the coming decades. Since lightning is responsible for igniting nearly half the large fires that are listed in our database, a diminished monsoon influence would suggest potentially fewer starts due to lightning.

Projected warmer and periodically drier conditions during the next 80 years may increase the risk for more severe drought (Pierce et al., 2015). Although an increase in average temperatures will probably have little impact on fire activity, changes to the frequency, amount, and spatial distribution of annual precipitation could have dramatic effects on future amounts and types of desert vegetation. It has been suggested that the changing climate has fostered the advancing invasion of non-native grasses which has led to increased fire activity in recent years (Brooks and Matchett, 2006, Figure 10). However, the 1992-2015 record of fires in the region shows no distinct trend in large fires (>500 acres), which could imply that non-native grasses have limited influence on fire activity in this region. Despite a drier climate outlook for the remainder of this century, variability of precipitation from year to year will govern the length and severity of fire season through fuel loads.

FIGURE 10

The 2006 Sawtooth Fire as it moves through the desert landscape. Source: photo taken near Mocking Bird Ln, Morongo Valley by Taya Lynn Gray of the Desert Sun newspaper.

One major factor to consider when addressing the propagation of wildfire is wind. The Inland Deserts have a number of well-known high wind prone areas such as the San Gorgonio (Banning) Pass, which serves as the gateway to the Coachella Valley, and the Cajon Pass leading to the Victor Valley. Prevailing wind directions over these areas are generally from the west, except in the Colorado River Valley where the majority of wind comes from the south. Winds across these areas are strongest during the evening and overnight hours mainly from April through September (Fisk, 2008). The stronger winds that frequently occur in these areas play a vital role in the spread of wildfires, particularly in areas where vegetation is sparse. It is important to note in our discussion of wind that we are not referencing "Santa Ana Winds", which mainly affect the coastal and mountain areas of Southern California to the west of this region (Rolinski et al., 2016).

Speculation on how wind speed may be influenced by climate change is difficult to ascertain. Since the majority of these desert winds, particularly during the summer, are thermally driven, it is plausible that there would be an upward trend in velocity. The projection of higher temperatures would imply a stronger temperature gradient between the coast and the interior of California, which would subsequently enhance onshore flow during the afternoon and evening hours, especially over the western sections of the Inland Deserts. However, the current generation of climate models only projects subtle (5-10%) changes in wind speeds (Kulkarni & Huang, 2014). Future research is required to ascertain the effect of climate change on winds in the region.

As 60% of the cause of large fires are related to human activity, climate-driven changes in human population of the region, human behavior, and transportation infrastructure and activity are likely to have a large effect on future fire activity. How these various factors evolve in the coming years will dictate the kind of fire activity that occurs across this portion of the state. As an adaptation strategy, residents and visitors to the region need to be informed of the risk of human ignitions of wildfires despite the perception that deserts are not susceptible to fires. Further research that better elucidates the relationship between climate change and risk of ignition from human activity is needed.

The Colorado River: Key Water Resource for Development of Inland Deserts

The Colorado River is the lifeblood of agriculture and urban development in the Inland Deserts, supplying the vast majority of water resources to the Imperial, Coachella, and Palo Verde Valleys. Colorado River flows supply around 3.5 million acre-feet of water to the region, with drainage and runoff waters from agriculture feeding into and maintaining the Salton Sea. The Colorado River is also an important water resource for approximately 40 million people in six U.S. states in addition to California, and in Mexico. In most years, the entire flow of the river is consumed for human uses. Allocations of river water are governed by seniority of water rights, with California as a senior rights holder, and major agreements, including the 1922 Colorado River compact, the 1944 US-Mexico treaty, and amendments to both. However, these allocations were made based on high streamflow volumes during a historically wet period in the early 20th century, so river water has been over-allocated much of the time since. This shortfall has worsened with reduced streamflow during the 2000-2012 drought, the driest period in recorded history (U.S. Bureau of Reclamation, 2012), and will likely worsen with further 21st century climate change (Vano et al., 2012). Increasing evapotranspiration is projected to reduce Colorado River flows by 20-30% at mid-century, and 35-55% at end-century (Udall and Overpeck, 2017). As a result, less water will be available for human use across the entire Colorado River Basin. Furthermore, the amount of precipitation falling as snow in the region is projected to decline substantially, which impacts timing of streamflow, with implications for downstream users (Wi et al., 2012).

In addition to climate change pressures, increasing municipal use demands have already put additional pressure on irrigation districts to reduce agricultural water use. The 2003 Quantification Settlement Agreement identified a pathway for California to reduce its reliance on Colorado River water to its legal allocation, 4.4 million acre-feet, via water conservation and land fallowing schemes. These schemes transfer water from agricultural uses in the Inland Deserts to growing municipal populations in coastal Southern California served by the Metropolitan Water District and the San Diego County Water Authority. However, this "conserved" agricultural water reduces drainage inflows to the Salton Sea and, consequently, will cause significant ecosystem damages and health impacts to local communities due to a shrinking, increasingly saline Salton Sea. The potential political pressure for additional water use reduction in the Inland Deserts will likely depend on the magnitude of increased future demands elsewhere in the Colorado River basin and in coastal Southern California as well as the magnitude of future reductions in Colorado River flow.

The Salton Sea

The Salton Sea, located below sea level in Riverside and Imperial counties, is California's largest lake by surface area (> 340 square miles). It is ecologically important as a rest stop for millions of migratory birds along the Pacific Flyway, and a year-round habitat for several endangered and sensitive species, including the desert pupfish, Yuma clapper rail, and burrowing owl (Audubon California, 2016; U.S. Fish and Wildlife Services, 2011). Formed in its most recent state in the early 1900s due to a dam break along the Colorado River, this terminal lake was maintained by inflows consisting mostly of runoff emanating from irrigated farmland around the Sea. Since its formation, the Sea's water quality has been in a slow decline due to the accumulation of salts and pollutants. This decline accelerated in 2018 with cessation of water transfers to the Sea resulting from competing demands on water from the Colorado River. Agricultural runoff is also declining due to large transfers of Colorado River water from the Imperial Valley to urban users in coastal Southern California under the 2003 Quantification Settlement Agreement.

Reductions in agricultural runoff to the Salton Sea pose a hazard for public health and the region's economy, in addition to destroying the Sea's ecological benefits. As inflows are reduced, the shrinking Sea leaves exposed lakebed (playa) that is a source of airborne dust causing severe air quality impacts on the region (Frie et al., 2017). Increasing dust and potential toxic airborne emissions may lead to major environmental justice issues for the vulnerable population living nearby through increased asthma and respiratory illness. High levels of dust also threaten the region's economic drivers, tourism and development.

Over the next dozen years, inflow volumes will decrease by 40%, leaving 100 square miles of exposed playa, and increasing salinity by threefold (Cohen, 2014). Higher salinity levels threaten fish and birds that currently depend on the Salton Sea habitat. The estimated public damages of a continual decline of the Sea have been estimated at between $11 and $70 billion over the next 30 years (Cohen, 2014). These estimates cover impacts including increased respiratory illness associated with higher airborne particulates levels emitted from exposed playa, decreased property values, decreased recreation, and the loss of wildlife habitat. Climate change poses an additional threat not included in these assessments, including increasing evapotranspiration rates, and possible changes in agricultural water management inputs and Colorado River allocations to the region. Climate change will exacerbate stresses to the limited water supply feeding the Sea and may accelerate the pace of decline. Currently, there are no comprehensive restoration projects in place (Salton Sea Restoration Renewable Energy Initiative, 2015).

Hydrologic Assessment: Current Status and Future Challenges for Adaptation to Climate Change

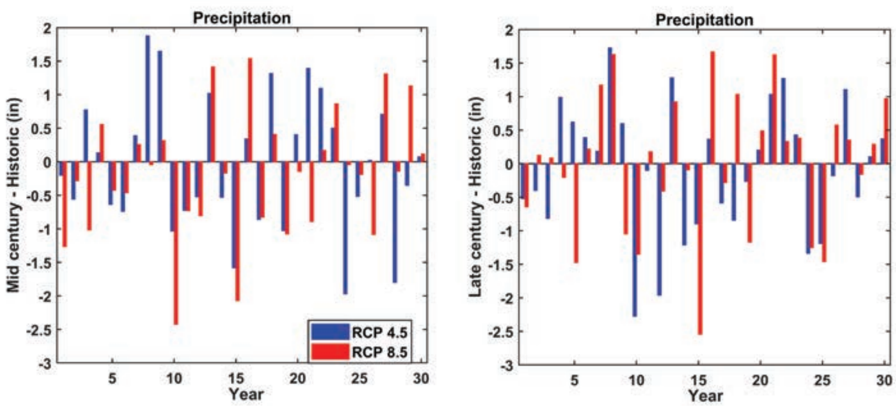
The Inland Deserts encompasses two main hydrologic regions of the state. These include the Colorado River hydrologic region and the southern portion of south Lahontan hydrologic region, with 92% and 39% of their areas located in this region respectively (Figure 1G). The Colorado River hydrologic region is the largest water user in California based on 1996-2005 data, at a rate of 379 gallons per capita per day. Surface water provides 91% of its water supply. Groundwater is the primary water supply in the south Lahontan hydrologic region, providing 66% of the region's water supply (California Department of Water Resources, 2013a).

The Colorado River Region has a subtropical desert climate. The northern part of this region includes Mojave Desert and San Bernardino and San Jacinto mountains with peaks higher than 10,000 ft above the sea level, as well as the Sonoran Desert. The Sonoran Desert is comprised of the Salton Sea, California's largest lake as measured in surface area, and significant irrigated land within the Imperial, Palo Verde, and Coachella Valleys (California Department of Water Resources, 2013b). Agriculture is the main land use in the Imperial Valley, and Colorado River water delivered through the All-American Canal is the main water source for this region. The Coachella Valley contains most of the urban areas within this region, and its main water source is Colorado River water transported by Coachella canals as well as groundwater. There are 64 groundwater basins in this region. According to the California State Groundwater Elevation Monitoring Program (CASGEM) basin prioritization, only the Indio and San Gorgonio Pass sub-basins of Coachella Groundwater Basin are classified as high priority basins, meaning that government and water agencies should reduce groundwater depletion in these sub-basins and determine sustainable pumping rates. Land subsidence has occurred in some areas as a result of high intensity pumping. Currently, water levels in the Salton Sea are primarily maintained by agricultural tailwater and runoff, with some contributions from urban wastewater flows. Salton Sea water levels are in decline due to water rights transfers away from the region (see Salton Sea sidebar) as well as below average precipitation in recent years and decreases in return flows from both local irrigated agriculture and surface flows from Mexico. As the Sea is a terminal lake, rising salinity levels are a significant concern.

The South Lahontan hydrologic region (Figure 1G) has an arid climate with mean annual precipitation of 8.2 inches (1981-2010). Surface water resources include ephemeral and intermittent streams and waterways that mostly flow during summer thunderstorms. The winter season is typically cool and dry. Groundwater resources for the South Lahontan hydrologic region are mainly supplied by the alluvial aquifers composed of sand and gravel or finer sediments. In areas near the mountains and foothills, fractured rock aquifers exist which typically have less capacity than the alluvial aquifers. The Los Angeles Aqueduct is the major water facility in this region (California Department of Water Resources, 2013c). The Mojave River watershed is one of the major watersheds of South Lahontan hydrologic region that is fully contained in the Inland Deserts domain. This watershed is amongst the most populated areas of the South Lahontan hydrologic region, with 66% of its water supplied by groundwater. This dependence on groundwater is expected to increase in the future as surface water supplies become limited due to recent and projected severe droughts. According to the CASGEM basin prioritization, the western portion of the Mojave River watershed is classified as a high priority basin. Lowering of groundwater levels in recent years has impacted important wetland and riparian communities in this region; efforts are underway to restore these important habitats (California Department of Water Resources, 2013c).

Future changes in water availability are assessed by comparing projected precipitation, surface runoff, and potential recharge with historic values. Historical annual precipitation from 1951-1980 is about 5 inches per year, with projections indicating a decline to 3.9 inches per year by the end of 21st century. While there are no significant differences between the projected 30-year mean annual precipitation and the historic period from the 10 global climate models (GCMs) considered to be most representative of the California climate (ACCESS1-0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5), there is a considerable year-to-year variability among the GCMs and RCP scenarios. Differences in the direction of precipitation changes relative to the historic period are strongly dependent on future emissions scenarios (RCPs; Figure 11). Projected mean annual precipitation from these 10 GCMs mostly representative of the California climate indicate that 50% of the years in the mid-century period (2035-2064) will be drier than historic conditions (1951-1980) based on the RCP4.5 simulations. However, RCP 8.5 simulations illustrate a drier mid-century and a wetter late century period relative to historic conditions. These variabilities among the GCMs ensemble averages complicate water resources planning.

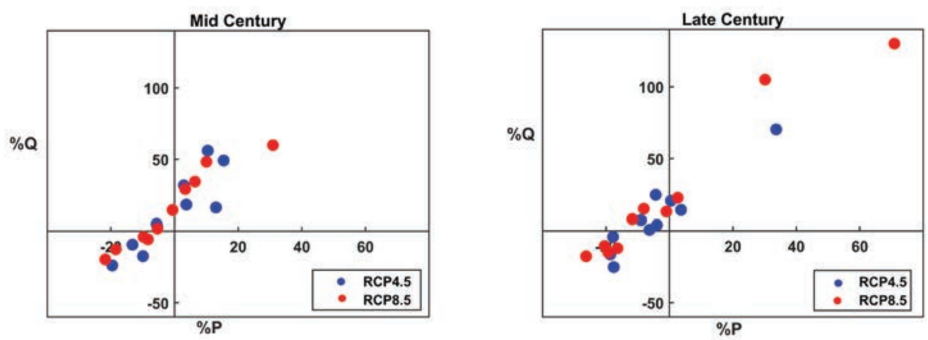
FIGURE 11



Relative annual differences between the ensemble annual mean precipitation from 10 GCMs and historic precipitation. The historic period corresponds to 1951-1980, the mid-century period to 2035-2064 and the late century period to 2070-2090.

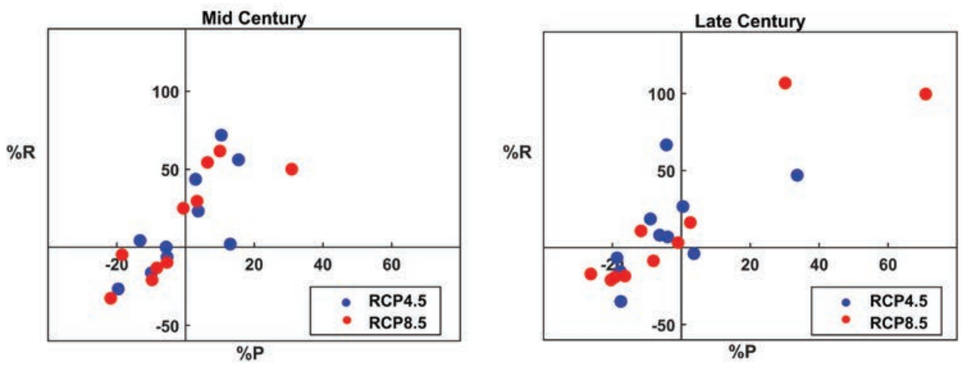
Variabilitiy in precipitation projections further translate to relative changes in surface runoff simulated by the Variable Infiltration Capacity (VIC) model, which has been widely used for climate change impact assessments. Previous investigations have shown that subsurface runoff simulations from VIC can be used as proxy for groundwater recharge (Niraula et al., 2017a). In the Inland Deserts, changes in 30-year mean annual surface runoff is linearly related to changes in precipitation amount relative to the historic period (Figure 12). While there is no clear consistency in the magnitude and direction of surface runoff among multiple GCMs at mid-century, almost all simulations converge to a drier than average surface runoff by end-century.

FIGURE 12



Percent changes in 30-year mean annual surface runoff (%Q) and precipitation (%P) from 10 GCMs relative to the historic condition. The historic period corresponds to 1951-1980; mid-century period to 2035-2064; and the late century period to 2070-2090.

FIGURE 13



Percent changes in 30-year mean annual recharge (%R) and precipitation (%P) from 10 GCMs relative to the historic condition. The historic period corresponds to 1951-1980, the mid-century period to 2035-2064 and the late century period to 2070-2090.

Subsurface runoff simulated by the VIC model was used as a proxy for potential recharge similar to the methods used by Niraula et al. (2017b). While changes in the 30-year mean annual recharge are mostly consistent with the projected changes in precipitation relative to the historic period, in some cases during the mid-century, increases in recharge were projected despite decreases in precipitation relative to the historic mean. There is more scatter in the relationship between 30-year mean recharge and precipitation compared to the relationship of surface runoff and precipitation (Figure 13). Future changes in the magnitude and direction of changes in runoff and recharge depend mostly on the precipitation rate, which is highly variable amongst GCMs (Figures 12, 13). Another source of uncertainty is related to the incomplete representation of land surfaces in the VIC model. It should be noted that these simulations only illustrate changes in surface runoff and potential recharge as a function of changes in precipitation and temperature. The role of human activities and how they change in response to future changes in the climate are not considered.

Various strategies have been implemented and are being considered as adaptation options for robust water resource management. The focus for water managers—both within the Inland Deserts and the state—will be to address future increases in water scarcity, which is defined as the degree to which demand exceeds supply. With respect to suplly management, the region is heavily reliant on imported water from the State Water Project and the Colorado River, but also on groundwater recharged from local sources and precipitation.

Since new freshwater supplies are unlikely to be appropriated on a permanent basis, the region must, and is, considering augmenting these current supplies through a number of avenues. To this end, the region is pursuing strategies such as recycling of treated municipal wastewater, capture and recycling stormwater, recharge and conjunctive use of ground water, desalinization of brackish groundwater, and the reuse of agricultural runoff.

In addition to these measures, water agencies within the region are increasing their cooperation to manage water more efficiently. As an example, a number of water agencies within the Inland Deserts have partnered in a joint project to manage their aquifers as a connected system in which dry year yields can be shared, and coordinated efforts have arisen to improve habitat for the Santa Ana Sucker fish species and to remove the invasive reed *Arundo donax* (SACCUP, 2017). Alternatively, the main wholesale water provider continues to develop long-term water sharing agreements with irrigation districts to ensure that water moves to its highest valued uses and to cover basic human needs during extreme droughts and periods of shortage (MWD, 2017).

On the demand side, the region has invested significantly in water conservation efforts. More effective water pricing structures, rebate programs for water conservation technologies, and education programs are part of the strategy to improve water use in the region. These strategies are particularly important given expected increases in the region's population. There is reason to believe significant gains in addressing water scarcity can be achieved by looking at the declining trend in per capita water use since the 1990s in the region. One area with significant possibilities for water savings is in urban outdoor conservation. More than 50% of the water used by households is for outdoor watering, with much of the indoor use already benefiting from decades of conservation efforts. In response, agencies are spending significant resources—time, money, personnel—to identify and encourage efforts by homeowners and business to reduce their outdoor water use.

Finally, the region is investing significantly in effective and efficient storage. While surface water storage will be limited in the region given lack of land for such purposes, groundwater storage and improved management will likely provide significant opportunities to the region to decouple water supply availability to yearly surface water deliveries. Future climate change impact assessment research in this region should implement integrated groundwater-land surface models to simulate dynamic feedback processes between land cover condition, groundwater flow, and surface runoff in response to changes in climate and changes in human water use.

Natural and Managed Resource Systems

In this section, we describe the effects of projected climate change on agriculture and ecosystems. Agriculture is the primary economic driver in the Imperial and Palo Verde Valleys, and is second only to tourism in the Coachella Valley. The region is a major source of winter fruits and vegetables. The region also has a large acreage of federally protected lands (U.S. Bureau of Land Management National Conservation Lands), including nearly 7500 square miles of National Parks and Monuments. This includes ecologically unique and sensitive ecosystems in Joshua Tree National Park and the Mojave Trails National Monument that are also tourist draws for the region. High biodiversity in the region is a product of localized refuges from climatic extremes that will likely contract as the climate warms. Both agriculture and natural systems are uniquely adapted to the already extreme climate of the Inland Deserts and serve as a model for how other regions of the state might respond to a warmer, drier climate.

Agriculture

The agricultural valleys of the Inland Deserts are some of the hottest agricultural regions in the world, with maximum summer temperatures that can reach 122°F. These extreme temperatures are project to increase by up to +8ºF by the end of the century under RCP 8.5. The number of extreme heat days per year, with maximum temperature greater than 112°F, are predicted to increase from ~10 to more than 80. The major crops in the region are forage crops (alfalfa, Sudan grass, and Bermuda grass) and winter vegetable crops. Alfalfa, a crop with a C3 photosynthetic pathway, already shows heat stress and reduced yields during the warmest periods (Ottman and Mostafa, 2014). Less is known about the effect of extreme heat on other forage crops like Sudan and Bermuda grass, which use the C4 photosynthetic pathway. C4 crops also have a significant advantage in higher physiological water use efficiency. Recent studies of C4 energy crops show little evidence of reduced photosynthesis at the highest observed temperatures, thus biomass production could be maintained even as water stress increases (Oikawa et al., 2015). However, excessive temperatures can cause seed abortion of crops such as sorghum during the grain filling period (Nguyen et al., 2013). High temperatures can also substantially increase the risk of scalding in flood irrigated crops (Hutmacher et al., 2001).

Besides summer heat, the relatively minimal risk of winter frost in the region's agricultural valleys could diminish even further under climate change. Most of these valleys are currently in the US Department of Agriculture's plant hardiness zone of 10a or warmer (planthardiness.ars.usda.gov) which implies an extreme minimum temperature of 30°F or warmer. If the threat of frost were removed, crops that are highly intolerant of frost could become new candidate crops for cultivation in the Inland Deserts in winter.

Along with crops, another major face of agriculture is cattle production, both on grazing lands and in feedlots in the Palo Verde and Imperial Valleys. The feedlot cattle are often steers from dairy operations in California's Central Valley. Shade and sprinkling water to provide evaporative cooling are often used to successfully mitigate heat stress, but studies have shown contradictory impacts of sprinkling on animal weight gain and feed efficiency (Morrison et al., 1973; Correa-Calderón et al., 2010). Different cattle breeds have varying susceptibility to heat and ability to acclimatize, but commonly used dairy breeds (such as Holsteins) are recognized to be more heat-sensitive (Blackshaw & Blackshaw, 1994). Along with increases in temperature, potential increases in humidity may be important for cattle production as humidity increases mammal heat stress and reduces the effectiveness of evaporative cooling measures such as sprinkling. Besides animal health, potential impacts on farm workers needs to be considered for summer workers. One mitigating factor in the Inland Deserts, unlike other parts of California, is that the main demand for farm labor occurs during the cooler winter vegetable season. Temperature changes may also exacerbate insect, weed, and other pest problems for humans, animals, and crops due to the potential for increased insect, pathogen, and weed growth under higher temperatures (Rosenzweig et al., 2001).

Agriculture is also vulnerable to increased stress to water supplies and extreme high temperatures under projected 21st century climate change. Agriculture in the region is nearly completely dependent on irrigation, primarily by water from the Colorado River. The Colorado is said to be the most litigated river on Earth, and much has been written about contested water rights for this overallocated resource that will only become more scarce and precious in the future. Inland Desert valleys are already one of the hottest agricultural regions in the world, and essentially serve as a model for what many other agricultural regions will face in the future with respect to heat tolerance and high salinity soils. Much research about temperature effects on agriculture has taken place here, but projected warming will take this region far past what it has experienced in the past.

Water for irrigation is critical to agriculture in the Inland Deserts, which have too little precipitation to support crops apart from marginal grazing lands. Precipitation in major agricultural valleys of the region is under 4 inches per year; climate change models under the RCP 8.5 scenario show wide relative variance in precipitation (0.5-8 inches/year), but all scenarios show that the major valleys retain their hyper-aridity (CalAdapt). The hydrologic scenarios show an increase in reference evapotranspiration, representing meteorological evaporative demand, of 2-4% by 2100 (CalAdapt). These increases in evapotranspiration will increase crop water demand, but this will depend on the type of crop grown. For some crops, such as alfalfa and winter vegetables, rising atmospheric carbon dioxide levels that cause climate change may also improve plant water use efficiency (Gago et al., 2014), but this is not relevant for the sorghum varieties that comprise most of the forage crops in the region since they have a C4 photosynthetic pathway.

The vast majority of irrigation water in the Inland Deserts comes from the over-allocated Colorado River, which is likely to see major streamflow reductions in the 21st century (see Colorado River sidebar). While irrigation districts that supply water to the region have some of the most senior water rights on the Colorado River (e.g., the Imperial Irrigation District, the Palo Verde Irrigation District, and the Coachella Valley Irrigation District), reduced streamflow may put additional pressure on these water suppliers to reduce their water use to alleviate shortfalls elsewhere in the Colorado River basin, especially if less than 7.5 million acre-feet are available for the US portion of the Colorado River Basin (MacDonnell et al., 1995). Efforts to reduce water use have already occurred, primarily with the Quantification Settlement Agreement that reduced Imperial Irrigation District use, regulated Coachella Irrigation District use, and implemented fallowing within the Palo Verde Irrigation District (Anderson, 2004; Hanak, 2003).

Along with the major agricultural valleys, there are smaller, isolated agricultural areas in the Inland Deserts, primarily in the alluvial regions of the Mojave Desert, that are irrigated primarily with groundwater. While small in area, they are isolated from other agricultural regions and can support cultivation of high-value, organic food crops (Jansen & Vellema, 2004). The water supplies for these isolated areas may be limited if climate change reduces the intensity and frequency of aquifer recharge during wet years. Besides reduced quantity, agricultural water quality may decrease under climate change as well. Water salinity is strongly and inversely correlated with stream flow in the Colorado River (Spahr, 2000). Irrigation districts in the region are in the downstream reaches of the Colorado, and thus experience higher salinity. As salinity of irrigation water rises, additional water will need to be leached through the soil profile to avoid deleterious yield losses (Grismer, 1990), which will reduce the water use efficiency of agricultural systems in the region. Reuse of urban waste water that has higher salinity may also have an effect if that water is applied to agriculture (Glenn et al., 2009).

In addition to direct effects of climate on water supply, there are several non-climate issues that intersect with agricultural water use. These factors that may independently respond to climate change, indirectly affecting agriculture through changed water supply. First, urbanization of the agricultural valleys of the Inland Deserts competes with agriculture for both land and water. The populations in the Palo Verde, Coachella, and Imperial Valleys have increased by more than 20% per decade recently (US Census), and now exceed 600,000 people. The water needs of new urban development depends greatly on landscaping choices, and water used for indoor use can be reused for other purposes following secondary and tertiary treatment. Second, there is a potential for additional water transfers away from the region. Despite senior water rights of irrigation districts in the Inland Deserts for Colorado River water, serious shortages in the lower Colorado River Basin could cause some curtailment of current water allocations to the region during droughts or possibly the need to transfer water to urban water districts outside of the region. Finally, restoration of the Salton Sea could affect water availability for agriculture, depending on the desired physical and ecological condition of the Sea, which depends directly on the quantity and quality of water flowing in (Glenn et al., 1999; Kjelland & Swannack, 2018). If the Salton Sea continues to shrink, potential agricultural impacts include crop damage from dust storms from the exposed playa (Abuduwaili et al., 2015) and health impacts on cattle in feedlots close to the sea.

There are a number of adaptation options that can maintain agricultural productivity in the Inland Deserts in the face of reduced water supply and extreme heat expected with 21st century climate change. Drip irrigation, despite higher initial capital costs, can increase yields in forage crops compared to furrow or flood irrigation with the same evapotranspiration rates (Hutmacher et al., 1992). For vegetable and crops with sparser canopies, drip irrigation can reduce water losses by minimizing soil evaporation (Ayars et al., 2015). Deficit irrigation of alfalfa during summer can conserve water during periods of peak evaporative demand (Hanson et al., 2007), but may affect yields if not carefully implemented. While reduced yields are undesirable for farmers, alfalfa yields during extremely hot periods are already reduced by heat stress, and yields can recover quickly if the crop is well developed and the applied stress is not too severe. Conversion of forage crops from alfalfa to C4 pathway crops can result in increased water use efficiency and biomass production with similar evapotranspiration rates (Anderson, 2010).

Alternately, changing the planting date of crops might reduce water use by minimizing full canopy cover during periods of peak evaporative demand. For vegetable crops, the impact of changing crop season on agricultural markets needs to be considered. Crops that arrive earlier or later in the season may command lower prices due to competition from other regions. Switching to salt-tolerant crops that can be irrigated with drainage water or urban waste water is possible if water use regulations are appropriately modified and technical safeguards are in place to protect crop, soil, and human health (Rahman et al., 2016; Rhoades et al., 1988a; Rhoades et al., 1988b). However, market acceptance and crop quality of salt-tolerant crops is a substantial unknown. Changing crop timing is also likely to be of limited benefit for perennial crops including citrus, dates, and grapes.

While more efficient water use and water reuse are adaptation options, careful management of salinity of applied water is crucial for protecting soils and aquifer health in the Coachella and Palo Verde Valleys, as groundwater can be used in both of these regions (Harter, 2015). Moreover, improvements in irrigation and on-farm water use efficiency, both due to management changes and increased evaporative demand from climate change, will accelerate the Salton Sea's decline, unless other mitigation water is provided, due to the increased salinity of drainage water entering the sea.

Further research is needed to project the impacts of higher temperatures on agriculture in the Inland Deserts. As the region already has some of the warmest climate agricultural systems in the world, there are no good analogues for potential changes under future climate scenarios. Research is needed on how current crops will fare under future climate, as resilience of crops and animal production systems to future temperatures is a key unknown. The tradeoffs between increasing evaporative demand and improved plant water use efficiency on controlling plant water consumption needs to be evaluated holistically. It is currently an open question as to whether breeding programs can help develop more heat-tolerant cultivars and whether there are cost-effective cooling strategies to help reduce stress and production losses in feedlot cattle. Along with heat-tolerance, new information on the impact of crop management practices and cultivars on water use is needed. Specifically, further research needs to examine how crop yields change with reduced amount and quality of irrigation water, how this varies over a season, and how much water can be saved by changing the timing of crop cycles.

More research is needed to better understand the risks of a changing water supply to the Inland Deserts in the 21st century. Projections of water supply require improved understanding of how external demands for Colorado River water will change, particularly with respect to pressure on Inland Desert irrigation districts to transfer water to coastal Southern California. Climate effects on water supply and quality must also be considered for better understanding of the requirements of restoration of the Salton Sea given that the amount and quality of agricultural drainage water will be altered by a changing climate and changing agricultural practices. Finally, work is needed on modeling and understanding different types of agricultural systems in the region that can maintain agricultural productivity (in terms of crop yield, quality, agricultural employment and revenues, etc.) while using less water.

Biodiversity and Ecosystems

Contrary to popular perception of deserts as a desolate wasteland, the deserts of southeastern California are in fact a biodiversity "hotspot" (Kraft et al., 2014). The California deserts comprise 28% of the state and include 37% of California's plant species (Figure 14). The rich biodiversity of these deserts is a product of both geography and topography; here, both the cooler Mojave Desert and the hotter low-elevation subset of the Sonoran Desert, the Colorado Desert, transition across a boundary extending from just north of Palm Springs and northeast to Needles. Additionally, the Baja California Peninsula bioregion extends into California along the Peninsular Mountain Range, through Anza Borrego State Park to its

FIGURE 14

Desert wildflowers.

northern terminus near Palm Springs. Each of these bioregions brings with it a characteristic flora and fauna. The Mojave Desert includes at least 1,409 plant species, 20 of which are endemic to that bioregion and 51 found nowhere else in California (Raven and Axelrod, 1977; Baldwin et al., 2002). The Colorado Desert includes at least 709 plant species; seven are endemic to this bioregion, with 100 species found nowhere else in California (Raven and Axelrod, 1977; Baldwin et al., 2002). These numbers are conservative—new varieties and species are being identified each year. Patterns of high biodiversity go beyond plants. A region that includes the northern part of the Peninsular Mountain range, the southwestern edge of the Mojave Desert, and the northwestern edge of the Colorado Desert, includes 33 species of native lizards, more than any similar sized area in all of North America [33 species] (Barrows et al., 2013).

The highway corridors of Interstate Highways 8, 10, 15 and 40 across the California deserts are often zones of low biodiversity, whereas the desert region's biodiversity is concentrated in the isolated mountain ranges ("sky islands") where somewhat cooler and relatively wetter climates occur (Kraft, 2014), at isolated springs, oases, and rare river courses (such as the Mojave and Amargosa Rivers), and on sand dunes. The two factors explaining these biodiversity hotspots are isolation and the occurrence of conditions that can buffer species from the harsh heat and aridity otherwise characterizing these deserts. Even sand dunes often hold more moisture than the surrounding coarser bajada sands. Unlike coarser sands or finer silts, aeolian sands absorb and hold onto rainfall for long periods at levels readily accessible to plant roots and burrowing mammals, lizards, snakes, and arthropods (Seely, 1991; Lei, 2004; Rosenthal et al., 2005). If species evolve adaptations to deal with the scouring, wind-blown sand that creates and maintains dunes, their populations can and do thrive there. Burrowing just a few tens of centimeters below the dune surface, creatures can enter a cooler zone of near-100% humidity and therefore survive through the summer droughts. Every dune system in the deserts of southeastern California includes plants, arthropods, and/or lizards that occur nowhere else in the world.

A warming and likely drier climate, with more intense and prolonged droughts, would clearly stress populations anywhere. For those species already near their presumed physiological limits living in deserts, there is reason for concern for common iconic desert species as well as for narrow endemic ones. Joshua Trees, *Yucca brevifolia*, are one such iconic, widespread Mojave Desert species (Figure 15). Using models to predict the future distribution of species under expected warmer conditions, Cole et al. (2011) concluded Joshua Trees in California and Arizona could likely be largely extinct by the end of this century due to the effects of modern climate change. Using comparable methods, but at a much finer scale and focusing on Joshua Tree National Park, models constructed by Barrows and Murphy-Mariscal (2012) similarly identified increasing levels of unsuitable habitat where

FIGURE 15

Joshua trees *(Yucca brevifolia)* are an iconic Mojave Desert species.

these trees currently occur. However, rather than extinction, the models also identified small areas of climate refugia (10% of their current distribution), where this species could continue to sustain populations in the Park. That more optimistic prediction has received support from on-the-ground measurements of patterns of seedling recruitment; recruitment is highest and most consistent in those same areas shown to be climate refugia in the models. In contrast, Joshua Tree seedling recruitment has been poor to non-existent for several decades in areas beyond these climate refugia. Outside of Joshua Tree National Park, high recruitment and expanding populations of Joshua trees at higher elevations and latitudes indicate distributional shifts consistent with a sensitivity to increasingly warmer and drier conditions.

Agassiz's desert tortoise, *Gopherus agassizii,* is yet another iconic and widespread species of the California Deserts (Figure 16). This region has many competing human land uses that can, at local scales, compromise and potentially cause local extinction of these federally threatened tortoises (Lovich and Bainbridge, 1999; Averill-Murray et al., 2012). However, risks associated with climate change extend beyond local scales, encompassing the entire range of this species. Modeling the response of this species to anticipated modern climate changes levels, Barrows (2011) identified a precipitous decline in suitable habitat if temperatures continue to increase and precipitation declines. Just 7% of the tortoise's current habitat would still be suitable within Joshua Tree National Park. That 7% represents potential climate refugia where the tortoises may still be able to sustain small populations. Using a similar modeling approach to predict tortoise impacts from climate change for the US Marine Corps Air and Ground Combat Center (MCAGCC) in Twentynine Palms, a region north of Joshua Tree National Park, a more optimistic 40% of suitable habitat would remain in climate refugia (Barrows et al., 2016). Validating these predictions with real on-the-ground data is more challenging for tortoises than for Joshua Trees, as young tortoises are notoriously difficult to find and therefore survey. Nevertheless, Lovich et al. (2014) reported a dramatic decline in tortoises within the National Park, a landscape protected from land uses that could otherwise cause tortoise declines. The tortoise decline occurred over the past two decades, a period associated with persistent drought and warming consistent that presage future climate conditions.

FIGURE 16

Agassiz's desert tortoise *(Gopherus agassizii)*.

Joshua Trees and desert tortoises are presented here as examples because of their iconic nature and because of the detailed research done on these species. People will take notice if either are lost to extinction. However, for the vast number of desert species, we lack such information. Almost certainly some will be more resilient to the effects of climate change, while other will be more sensitive (e.g., Wu et al., 2018). Identifying and protecting climate refugia may be the best opportunity to stem widespread climate-related extinctions in southeastern California's desert region. The climate buffering noted for sites that are desert biodiversity hotspots is an indication that they too are acting as climate refugia. High species richness and genetic diversity (Harrison and Noss, 2017) and endemism (Sandel et al., 2011) are characteristics of climate refugia, as are sustainable populations with on-going successful recruitment. However, modern climate change is just one of several threats they face; as such it is critical that within these potential refugia other anthropogenic stressors are eliminated or managed (i.e. Abella and Berry, 2016; Berry et al., 2014).

Pumping water from desert aquifers that may be supplying critical water to desert springs, oases, and rivers is an on-going concern. Without that water, the refugial capacity of these sites could dry up as well. Invasive plants represent another threat. To the extent that those weeds out compete and displace native plants, important food for vegetarian tortoises may be lost. Invasive plants also fuel wildfires in desert areas where the native desert plants, such as Joshua Trees, have little or no evolutionary history for adapting to fire, and so lack a capacity to survive intense fires. Invasive weeds and the fires they fuel are particularly problematic within the airflow corridors extending from the Los Angeles basin out onto the desert landscape. Those corridors carry nitrogen-laden smog, which then falls onto the desert soils, acting like a fertilizer that provides a competitive edge to non-native invasive grasses, to the detriment of the native flora (Rao et al., 2014). As anthropogenic stressors layer upon California's rich desert biodiversity, extinction risk is heightened. However, the benefits of identifying and protecting climate refugia can go beyond the reduction of climate effects; they represent relatively finite targets for focused management of weeds, fires, and water resources, thereby increasing the resiliency of the plants and animals therein.

Tourism in the Coachella Valley

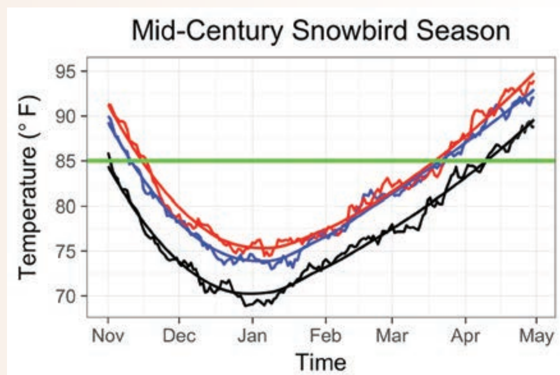
The Coachella Valley hosts thousands of out-of-state visitors every year. Tourism is the number one contributor to the local economy, generating 50,000 jobs and more than $6.4 billion annually. Climate change poses a threat to the tourism in the Coachella Valley as mild winter temperatures are expected to warm, and as the length of the mild temperature period contracts. The seasonal influx of visitors lasts typically during the time when the daily maximum temperature ranges 70-85°, roughly from November to May, with the season's peak in March. This period of visitors is often called the "Snowbird Season" because of the large number of visitors who come to escape cold and snowy winter climates in their hometowns.

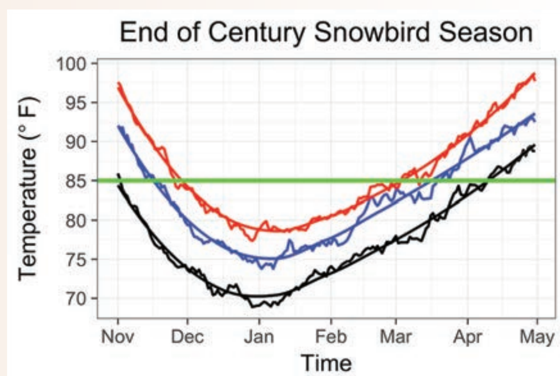
The Snowbird Season is an obvious economic driver, as employment and business revenue peak during this time. Jobs in tourism-related occupations such as accommodation, food services, waste management, arts, recreation, and entertainment decline significantly during the months outside of the Snowbird Season. These data show that tourism is the main driver for seasonal economic patterns in the Coachella Valley (CVEP, 2016).

This highly seasonal tourism may make the region economically vulnerable to climate change. With hotter winters to come, so-called "snowbirds" may be less inclined to visit the region due to both push and pull factors. That is, the Coachella Valley may be too hot for their liking or their hometowns may not be cold enough to make them want to leave. If temperature is a factor that tourists consider when they decide whether or not to visit the Coachella Valley, this could be a big blow to the local economy.

Climate projections from 4 models downscaled to the region suggests that the Snowbird Season, measured as number of days with high temperatures in the range of 70-85°, will be reduced from its historical length of ~5.5 months to around 4.5 months at mid-century, and to 3.5-4 months by the end of this century. By the end of the century, this represents a reduction of 25-33% in days with favorable temperatures for outdoor activities that are popular tourist attractions in the Coachella Valley, such as golf, tennis, and the Palm Springs Tramway.

Other main attractions in the Valley such as the Coachella Valley Music and Arts Festival, Stagecoach, The Palm Springs International Film Festival, and BNP Paribas Open attract many visitors annually. These major events will be affected by extreme heat, particularly since much of them take place outdoors. The venues will have to either shift their dates or provide more cooling infrastructure to accommodate their guests.





Historical and model projections of daily maximum temperature in Indio during Snowbird Season (Nov.-May) at mid- and end-century (historical: black, RCP 4.5: blue, RCP 8.5: red)

Human Systems

This section addresses the effects of climate change on human systems, encompassing land use, infrastructure, and human communities. The Inland Deserts have around 1 million inhabitants, with 85% living in urbanized areas including the Victor Valley in San Bernardino County (Victorville, Apple Valley, Hesperia), the Coachella Valley in Riverside County (Indio, Palm Springs, Palm Desert), and the El Centro Metropolitan Area in Imperial County (El Centro, Brawley, Calexico) [American Communities Survey estimated 2017 population]. Tribal lands of 12 different groups are contained in the region (Figure 1B). More information how already-occurring and projected climate change impacts disproportionately affect California's Tribal and Indigenous Communities may be found in the Fourth Assessment "Tribal and Indigenous Communities Summary Report"). In addition to agriculture, the major economic drivers are tourism; transportation, logistics, and warehousing; and real estate development, which includes housing and renewable energy. Land use is divided between natural and managed lands and those designated for the energy and transportation infrastructure that drive these industries. Use of land for renewable energy development is expected to grow in importance to meet California's climate change goals. Projected extremes in temperature and precipitation pose a threat to energy and transportation infrastructure, but these can be mitigated with careful planning. On the other hand, people and communities may be more vulnerable to climate change. Residents of the Inland Deserts are particularly vulnerable because of high poverty and unemployment rates, along with low educational attainment levels compared to state averages. The deterioration of the Salton Sea will additionally burden the population with worsening public health. Indeed, the fate of the Salton Sea will have a major negative impact on the region and will become a critical environmental justice issue for the State of California as a whole if it continues on its current trajectory of decline. A plan for the restoration of the Salton Sea is critically needed and will lessen the impact of many other climate-driven hardships that the region faces.

Land Use and Community Development

Land use decisions determine the impact of development on the environment, while in turn the environment shapes the type and form of development possible. Climate change affects land use both through changing patterns of development with the intent to minimize greenhouse gas emissions that cause climate change, and by directly altering the environment that shaped existing development patterns. Climate change affects not only public and private land use decisions, but is mediated by changing water availability and usage, and energy choices (Dale et al., 2011). In the Inland Deserts, water availability plays a fundamental role in determining the environment, society, and development. Climate change is likely to alter water availability in the region, with wide-ranging impacts on individuals and communities, industries and institutions, and entire ecosystems. Energy choices in the context of climate change, namely the drive toward emissions-reducing renewable energy sources, have become another fundamental driver of land use in the Inland Deserts.

Climate change is transforming land use priorities in the Inland Deserts under the California Renewables Portfolio Standard (RPS), which requires that 50% of electricity come from renewable sources by 2030 (Penn, 2017). The San Gorgonio Pass Wind Farm is California's third largest source of wind energy (Figure 17), with more than 2,000 turbines producing nearly 700 MW of power in 2015 (California Wind Energy Association, 2017). The Inland Deserts lead the state in solar power production and installation that includes investment in solar panel manufacturing and installation (Steinberg, 2014; Sullivan, 2017). In 2014, the Ivanpah Solar Electric Generating System in the Mojave Desert was the largest in the world, although that honor passed to India two years later (Al Jazeera, 2016). Renewable energy facilities as well as the land, roads, and transmission corridors necessary to transmit and distribute electricity constrain land use options and have important tradeoffs with natural environments.

FIGURE 17

Wind turbines near the San Gorgonio Pass

Yet the drive towards more renewable energy, as a response to California's climate change mitigation policy, can conflict with other land use goals, such as wildlife protection. Research addressing natural ecosystem impacts has suggested that future developments can and should be sited in more developed areas (Hernandez et al., 2015; Turney and Fthenakis, 2011). The Desert Renewable Energy Conservation Plan (https://www.drecp.org/), developed by a collaboration of state and federal agencies with the involvement of local stakeholders has the goal of conserving desert ecosystems in California while facilitating siting and permitting of renewable energy projects (see sidebar on Impact of Renewable Energy Development).

In addition to wildlife protection, development of land for renewable energy also competes with other uses of land such as for recreation and agriculture (Moore-O'Leary et al., 2017). Decisions to invest resources on energy production may reduce the money and space available to preserve open space, manage parks, and to invest in conventional and urban farm projects. In the Inland Deserts, only marginal or abandoned farm land in the Imperial Valley has been slated for utility-scale solar power development to date (Imperial County Planning & Development Services Department Cluster: Solar Power Project Draft Environmental Impact Report). Yet, as renewables become a larger fraction of California's energy portfolio, there is likely to be greater conflict on what might be considered less marginal land.

Increased adoption of renewable energy will help the region reduce its carbon footprint, albeit at some cost to future land use decisions and environmental services. In contrast, other land uses such as urbanization and agriculture are the most significant sources of climate change due to human activity, and account for the bulk of the region's greenhouse gas emissions (Kalnay and Cai, 2003, 2004; U.S. Environmental Protection Agency, 2015). Urban areas account for as much as 80 percent of carbon emissions since 2008 (World Bank, 2018). In California, the majority of these emissions come from passenger vehicles. Since the mid-1980s, urbanization has surpassed land use for farming, grazing, and water resources in Inland Southern California (Chen et al., 2010). This urbanization trend is expected to continue, with state population projections showing future development around existing urban centers (Fourth California Climate Assessment Statewide Report, 2018).

Future land use planning of these expanding and developing urban centers will play a major role influencing the region's ability to reduce greenhouse gas emissions. These considerations are already included in California law, such as with the 2008's Sustainable Communities and Climate Protection Act (SB 375, 2008), which requires cities and counties to implement sustainable land use plans that reduce regional emissions from passenger vehicles in order to access statewide transportation funds. Specifically, each of California's Metropolitan Planning Organizations must develop and implement a Sustainable Communities Strategy as part of its Regional Transportation Plan. In the Inland Deserts, this role is played by the Southern California Association of Governments (SCAG). The region's current Regional Transportation Plan/Sustainable Communities Strategy, developed in cooperation with local governments, county transportation commissions, tribal governments, non-profit organizations, and businesses and local stakeholders throughout the six counties of Southern California, seeks to "[balance] future mobility and housing needs with economic, environmental and public health goals" (SCAG, 2016, Chapter 5). These land use strategies emphasize higher density, mixed-use, and transit-oriented development to encourage public and active transportation, which simultaneously reduce greenhouse emissions and increase physical activity and opportunities for social interactions (Maibach et al., 2008; Rissel, 2009). Improving access to efficient public transportation and other alternatives to automobile travel— both of which are targeted in the general as well as climate action plans of Inland Desert cities and the structure of subregional governments— is crticial to reducing greenhouse gas emissions throughout the Inland Deserts, and are also a means to improve public health (Ahern, 2011; Aylett, 2015; Carter et al., 2015; Flint, 2018).

The land use element of a general plan guides the physical development of city or sub-region, including greenhouse gas emissions associated with residential, retail, and industrial development. The land use elements designed to manage growth and development in the Inland Deserts emphasize transition to renewable energy, especially solar, urban infill where possible, improved access to effective public transit, reliance on drought-tolerant landscaping, and increased resilience to climate-related emergencies, including extended droughts and wildfires (Imperial County Planning and Development Services, 2015; Riverside County Planning Department, 2017). These plans do not identify the specific actions that counties, sub-regional governance organizations, or cities will take to adapt to climate change; those are made in Climate Action Plans.

Climate Action Plans specify the activities that a state, county, sub-regional organization, or city will undertake to reduce greenhouse gas emissions and otherwise adapt to a changing climate. In addition to the SCAG Regional Transportation Plan/Sustainable Communities Strategy, which anticipates significant declines in greenhouse gas emissions (SCAG, 2016), climate action plans developed by Riverside and San Bernardino counties and many of the region's cities detail strategies for reducing greenhouse gas emissions associated with energy production and use, waste water treatment and solid waste disposal, manufacturing, transportation, and agriculture (Riverside County, 2015; San Bernardino County, 2014; WRCOG, 2014). Overall, these documents support Smart Growth, a development approach that favors higher densities, mixed use buildings, and public transit to reduce sprawl, improve environmental quality, and encourage community engagement. The success of these plans, which are consistent with California's SB 375 (Benfield, 2012) that directs governments to coordinate their investments in transportation, land use, and housing to minimize emissions and environmental impacts, are evident in the region's investment in solar energy, public and active transportation, and infill development rather than further expansion of housing into the Wildland-Urban Interface. Solar energy investment is expected to benefit the region's economy by supporting the region's energy independence, especially in the case of emergency, and generating jobs with middle class earnings potential (Jones et al., 2017).

A significant concern the region is confronting is development within the Wildland-Urban Interface, the zone where human development meets or intermixes with wildland fuel (Stein et al., 2018). Today, more than one-third of new development occurs in the Wildland-Urban Interface, with California leading the nation (U.S. Department of Agriculture-Forest Service, 2015). To address this issue, the region's smart growth strategies emphasize urban/suburban infill, a development strategy that limis opportunities for people to live in the Wildland-Urban Interface, thereby reducing the potential damages and risk surrounding wildfires. Regarding those who already live in areas vulnerable to wildfires, community participation, which the region has "in abundance," as noted in Guzman (2018), is central to best practices for managing the Wildland-Urban Interface and reducing the damages associated with wildfire (Lachapelle and McCool, 2012). "Best practices" in addressing wildlife in these vulnerable areas include incorporating defensible space around properities and emergency preparation, actions that are essential to mitigating property damage and loss of life that can be caused by wildfires. The success of these efforts to address wildfire risk, and more generally to promote sustainable development and to adapt to climate change depend on many factors, including community participation and awareness (perhaps facilitated through online and ad hoc dissemination strategies and education forums regarding best practices), quality data available that elected officials, policymakers, and community members can use to better inform their decisions, and the flexibility and capacity to develop and implement evidence-based strategies to increase climate resilience (Fisichelli et al., 2016; Hallegate, 2009; Hunt et al., 2011; Shulte and Miller, 2010). This challenge may be complicated by political as well public resistance to climate change adaptation strategies.

Of course, the ability of the community, agencies, and governments to make informed decisions, and implement scientifically sound climate action plans, depends critically on the quality of the data and science available, with recognition that there may be significant heterogeneity across cities or regions in how to best address climate change due to natural, social, economic, or demographic differences. Recent meta-analyses of local climate action plans and related subnational planning for climate change adaptation (see Moser and Ekstrom, 2010; Tang et al., 2010) suggest that there is considerable variation among climate action plans.

To best aid communities and decision makers in their efforts to continually update their climate action plans based on sound science, efforts and commitments are needed to develop consistent data sources and methods of analysis. Such efforts will facilitate both the comparison and assessment of climate change adaptation strategies, and perhaps increase regional coordination and cooperation. There has to be increased consideration (and science) into the effects of climate-induced heat waves, droughts and floods, and wildfires on natural ecosystems. The Inland Deserts region is vast, covering expansive deserts, uninhabited mountain ranges, rural settlements in the east, and both large and small agricultural areas. Most of the focus to date in the region has been on the impacts to plants and wildlife that might be impacted by renewable energy production and wildfire threats. While a focus on plants and wildlife should not wane,

Impact of Renewable Energy Development

The Inland Deserts are set to play a major role in California's energy future through development of new utility-scale renewable energy capacity that will supply California's energy needs while minimizing greenhouse gas emissions. The Inland Deserts have a strong competitive advantage for production of renewable energy because of abundant solar and wind resources, geothermal resources at the Salton Sea, proximity to demand centers and transmission infrastructure, and relatively inexpensive land available in large parcels (Jones et al., 2017; EES Consulting, 2013). Twenty-nine renewable energy projects (out of a statewide total of 150) have been granted permits in the region (CEC REAT Projections). Most of these projects are utility-scale solar energy systems, particularly those using solar photovoltaic panels mounted on steel and aluminum structures. In addition to reducing greenhouse gas emissions, solar energy improves air quality when it replaces fossil fuel burning. Carefully sited solar farms can reclaim degraded land, such as is taking place on abandoned farmland in the Imperial Valley (Imperial County Planning & Development Services Department Cluster: Solar Power Project Draft Environmental Impact Report: ftp://ftp.co.imperial.ca.us/icpds/eir/cluster-Isolar). Energy storage technologies can also support clean energy goals by reducing greenhouse gas emissions by delivering stored renewable energy, reducing demand for peak electrical generation from natural gas peaking plants, improving the reliability of the electrical transmission and distribution grid, and increasing the efficiency of existing infrastructure to meet energy system demands. In the Inland Deserts, operational energy storage systems are electrochemical (e.g., batteries) (California Energy Commission – Tracking Progress Report, http://www.energy.ca.gov/renewables/tracking_progress/documents/energy_storage.pdf). Imperial County, for example, is home to a 30-megawatt, 20-megawatt-hour lithium-ion battery energy storage system that helps the grid accommodate power from two large solar energy projects, SunPeak 2 and Midway III.

However, development of renewable energy, even on desert lands, involves trade-offs between ecological, political, and socioeconomic values (Moore-O'Leary et al., 2017). Specifically, avian mortality (birds and bats), death of insects, disruption to wildlife and habitat—such as that of the desert tortoise—are concerns due to large amount of land needed, dry cooling systems, effects due to other construction, operation and maintenance, proximity of power plants to protected areas including rare and endangered species habitat. In an effort consider these competing issues, the Desert Renewable Energy Conservation Plan (DRECP) was developed to ensure the conservation of desert ecosystems in light of renewable energy projects in California. This landscape-scale planning effort is a collaboration between the U.S. Bureau of Land Management, California Energy Commission, U.S. Fish and Wildlife Service, and California Department of Fish and Wildlife, with input from local stakeholders, that covers 22.5 million acres of California. A primary objective of the DRECP is to conserve sensitive desert resources by meeting climate adaptation requirements for desert wildlife and identifying sensitive ecosystems and species. For example, the DRECP streamlines the renewable energy permitting process by identifying lands closed to renewable energy, such as those designated as California Desert National Conservation Lands, Areas of Critical Environmental Concern, National Scenic and Historic Trail management corridors, and wildlife allocations. Specifically, in the Inland Deserts, the counties of Imperial, Riverside, and San Bernardino—along with the counties of Los Angeles and Inyo—were granted a Renewable Energy Conservation Planning Grant (RECPG) from the Energy Commission to effectively plan and promote renewable energy projects that align well with federal, state, and local renewable energy and conservation goals.

more research is needed on ways to mitigation and adapt to the health effects of climate change. Finally, there has to be increased development and dissemination of disaster-preparedness plans. Climate change adaptation planning emphasizes making transitions to renewable energy, public transit, etc. affordable at the expense of preparing the region for the real threat of drought, increased fresh food costs, wildfire, and deadly heat waves (Pierce et al., 2008; United States EPA, 2016). Failure to address these threats may be tied up in policymakers' reluctance to embrace climate science in a relatively conservative region. Yet disaster preparedness need not require accepting climate science; for example, measures can involve preparing for drought and wildfire as we do for earthquakes by improving infrastructure, limiting where people can live, preparation kits, and drills specific to the Inland Deserts region (Boulter et al., 2013; Lloyd et al., 2017).

Energy

Energy supply and demand in the Inland Deserts will be sensitive to rising temperatures projected with 21st century climate change, in addition to concurrent changes in population, technology, and policy. Climate change will affect energy supply because higher temperatures reduce production capability by decreasing capacity and efficiency of electricity production, transmission and distribution systems. At the same time, higher temperatures will increase electricity demand for air conditioning, which will become particularly necessary for human well-being in the Inland Deserts, a region of already extremely high temperatures. These effects are important considerations for energy development planning in the region.

Energy generation in the Inland Deserts is currently being transformed by a transition from fossil fuel to renewable energy sources required under the California Renewables Portfolio Standard (RPS). The RPS requires that 50% of retail electricity sales come from renewable sources by 2030 and is a major component of California's climate change mitigation strategy. Construction of new renewable energy generation infrastructure in the Inland Deserts— mainly solar photovoltaic (PV) and solar thermal systems— has already begun to replace natural gas power plants as the primary electricity source. Many new utility-scale renewable energy projects have come online since 2010, and more are proposed for the region, which will turn the region from a net electricity importer to an exporter, with a substantial positive effect on the region's economy (Jones et al., 2017). While likely to be effective at reducing greenhouse gas emissions from electricity generation, utility-scale renewable energy in the region could have cross-cutting, potentially negative, effects on some

TABLE 2.

PRIMARY ENERGY SOURCE (TOTAL ELECTRICITY CONSUMPTION*)	SOUTHERN CALIFORNIA EDISON (85,448 GWH)	IMPERIAL IRRIGATION DISTRICT (3,385 GWH)	OTHER ELECTRIC UTILITIES (424 GWH)
Coal	0%	14%	21%
Hydro	6%	4%	6%
Natural gas	19%	35%	1%
Nuclear	6%	3%	5%
Renewable	28%	28%	17%
Biomass & biowaste	1%	10%	0%
Geothermal	7%	3%	8%
Eligible hydroelectric	0%	8%	0%
Solar	10%	7%	1%
Wind	10%	0%	7%
Other	0%	0%	1%
Unspecified**	41%	16%	50%

Primary energy sources by utility provider in the Inland Deserts in 2016. Please note that the values for total electricity consumption and primary energy sources represent the entire region served by each individual electrical utility. The "Other Electric Utilities" refers to the City of Needles, City of Banning, Victorville Municipal Utility Services, Anza Electric Co-op, and Bear Valley Electric Service. (Source: California Energy Commission, Utility Annual Power Content Labels for 2016 (http://www.energy.ca.gov/pcl/labels/))

* Total electricity consumption data is for the year 2016 (Source: California Energy Commission, Electricity Consumption by Entity (http://www.ecdms.energy.ca.gov/elecbyutil.aspx))

** "Unspecified" sources of power refers to transactions of electricity that are not traceable to specific generation sources.

aspects of ecology and human systems in the Inland Deserts without careful planning to minimize and mitigate these effects (see sidebar "Impact of Renewable Energy Development").

Finally, the Inland Deserts region is likely to experience large increases in energy demand as the climate warms due to extreme high temperatures. Compared to the state as a whole, the region has higher than average transportation fuel use, and lower than average per capita income, meaning that it is more vulnerable to possible increases in the cost of energy (electricity and transportation fuel). Nevertheless, energy-related climate change mitigation policies have had a net positive impact on the economies of Riverside and San Bernardino Counties between 2010-2016, and the positive impact is expected to continue (Jones et al., 2017).

The major sources of electricity in the Inland Deserts are provided by Southern California Edison (SCE) and Imperial Irrigation District (IID) (Table 2). Meanwhile, five other electrical utilities serve the remainder of the region, including the City of Needles, City of Banning, Victorville Municipal Utility Services, Anza Electric Co-op, and Bear Valley Electric Service. The current electricity generation mix in the region is composed of both in-state and out-of-state electricity generated from fossil fuels and renewable sources of energy (Figure 1C). Most of the electricity in region is generated from fossil fuel combustion (coal and natural gas) and from unspecified sources of energy, which are transactions of electricity that are untraceable to specific sources. However, the largest providers of electricity (SCE and IID) in the region use close to 30% renewable energy (biomass/biowaste, geothermal, small hydroelectricity generation, solar, wind).

Southern California currently imports electricity from out of state via major transmission lines, most of which pass through the Inland Deserts region (Sathaye et al., 2012). A large fraction of this energy comes from coal, which California is eliminating from its energy supply mix as part of efforts to decrease greenhouse gas emissions (Mahone et al., 2018). Nevertheless, out of state imports of electricity and transmission through the region will likely still be necessary in the future with increasing utilization of renewable energy sources. Supplies of wind and other renewables from out of state are abundant at times when local solar power is insufficient and will be needed to overcome the mismatch in the timing of peak energy demand versus energy supplied from local renewable sources (CEC, 2017).

Currently, a total of 166 operating power plants exist in the Inland Deserts region and use a variety of energy sources to generate 8.6 gigawatts of power (https://cecgis-caenergy.opendata.arcgis.com/datasets/california-power-plant). Some of the power stations burn natural gas, while others use renewable energy sources, including solar, wind, biomass, hydropower, and geothermal energy (Figure 1C). In this region, there are six natural gas power plants (2709 MW). Approximately 95% of the power plants in this region are fueled by renewable sources, including 94 solar/solar thermal (4034 MW), 33 wind (943 MW), 1 biomass (54 MW), 10 hydropower (124 MW), and 20 geothermal power plants (718 MW). This shift toward renewables, driven by the RPS, has led to replacement of older fossil fuel power plants by new renewable sources (Jones et al., 2017). Of the 150 permitted renewable energy projects statewide, 29 of them are located in the Inland Deserts (https://cecgis-caenergy.opendata.arcgis.com/datasets/california-renewable-energy-action-team-reat-projects). These 29 plants, 90% fueled by solar energy and 10% by geothermal sources, are estimated to produce up to 2.4 gigawatts of energy.

Increasing temperatures will reduce the efficiency of energy generation by natural gas fired power plants and solar photovoltaic systems. For a combined cycle natural gas fired power plants in the Inland Deserts, power output is reduced by 0.14-0.25% per °F above 96°F for wet and dry cooling systems, respectively (Maulbetsch and DiFilippo, 2006). For photovoltaic systems, voltage output is reduced linearly with temperature. Reductions have been reported as 0.21-0.25% per °F warming; however, the relationship between power loss and increased temperature will vary among systems depending on the material and other system properties (Fouad et al., 2017). In contrast, concentrated solar thermal systems, such as the Ivanpah Solar Power Facility (392 MW) located in the northeast corner of the Inland Deserts region, increase efficiency with rising ambient temperatures. Projecting the combined effects of warming and changes in radiation due to air pollution using CMIP5 models up to mid-century, Wild et al. (2017) found no net change in power output from concentrated solar in southern California.

In addition to electricity generation, the region has infrastructure for distribution and storage of electricity that will also be vulnerable to climate change. A little over 4,900 miles of transmission lines exist in the region (https://cecgis-caenergy.opendata.arcgis.com/datasets/california-electric-transmission-line). These transmission lines currently serve an important role transmitting imported electricity from out of state into the population centers of southern California. This will likely continue with further development of renewable energy in the Inland Deserts and out-of-state. Transmission lines are vulnerable to warming because high temperatures can damage lines, leading to capacity losses around 0.8% per °F of warming when conductor temperature rises above the design limit of 176°F (equivalent to an air temperature of 100°F) (Sathaye et al., 2012).

Electric substations then convert high voltage electricity to lower voltage that is suitable for homes and industrial purposes. There are 262 operational electric substations in the region, and three proposed substations (https://cecgis-caenergy.opendata.arcgis.com/datasets/california-electric-substation). Voltage transformers are a critical component vulnerable to climate change, since heat causes energy loss and increases the rate of transformer failure (Gao et al., 2017). Transformer capacity is sensitive to ambient temperature conditions at the time of peak load (Sathaye et al., 2012) and decreases roughly 0.4% for every 1°F increase of ambient temperature above 86°F (Li et al., 2005). Using climate model projections, Sathaye et al. (2012) project a 1.5-5% reduction in regional peak load capability by mid-century, and a 2-3% reduction by end of century.

As a whole, California's current residential electricity consumption is 2,333 kWh per capita. Meanwhile, the energy demand by residents of Inland Desert counties of Imperial, Riverside, and San Bernardino is 2,679 kWh per capita (http://ecdms.energy.ca.gov/elecbycounty.aspx). Both per capita and total electricity demand in the region are expected to increase with climate change and population growth. Population in Imperial, Riverside, and San Bernardino counties is projected to increase close to 70% by the year 2100 along with increased land use development (California Department of Finance, 2016). Per capita energy use will go up as increased penetration of residential air conditioning will play a vital role in ensuring the adaptation of the growing population in this region to a warming climate (Sailor & Pavlova, 2003; Auffhammer & Aroonruengsawat, 2011). By the end of the century, the non-coastal portions of Southern California are projected to experience the largest increases in household electricity demand in the state (Auffhammer, 2018). Parts of the Inland Deserts will require increases of up to 2.5 and 3.4% in electricity demand by mid-century, and 10.6 and 29% under RCP 4.5 and 8.5, respectively (Auffhammer, 2018).

Future research and adaptation planning is needed to address energy challenges due to 21st century climate change in four areas. First, as electricity generation transitions to renewable sources, a more nuanced analysis of the costs and benefits of different types of renewable energy sources under a warming climate is needed. Specifically, more attention is needed to comparing trade-offs between distributed generation, such as rooftop solar and local storage, with utility-scale solar energy with traditional transmission and distribution pathways. Some of the negative effects of utility-scale renewable energy may be partially mitigated by the additional generation of distributed renewable energy. Second, better predictions of the impacts of climate change on energy supply and reliability are needed for this region in particular, with a focus on the electricity consumption of disadvantaged communities, and on vulnerability and resilience of current and proposed power system equipment to ensure a reliable supply given temperature projections. Furthermore, increased utilization of renewable energy will also require new research on coordinating the operations of distributed generation and solar and wind energy resources to deliver a steady energy supply, including microgrids and energy storage systems. Third, with the increasing adoption of smart sensor technology such as advanced metering infrastructure, big data analytics are critically needed to improve energy efficiency, reduce emissions, and enhance the security of the smart power grids under a changing climate. Last but not the least, there is an urgent need to study electric vehicle sharing and coordinated charging strategies to improve air quality and reduce transportation costs by leveraging the electric grid infrastructure.

FIGURE 18

Bridge washout along I-10 near Desert Center, July 2015.

Transportation

California has a large multi-modal transportation system, consisting of thousands of miles of roadways and railways, several seaports, airports and transit systems, as well as extensive biking and walking networks. This large transportation network is critical to millions of travelers and for the efficient movement of goods. The Inland Deserts region includes most of Caltrans District 8, the largest of 12 statewide Caltrans districts that covers approximately 28,650 square miles of land, and the Imperial County part of Caltrans District 11. Within District 8, there are four major interstates and 32 state routes totaling 7,200 lane miles.

In the last several years, the impacts of climate change on transportation has been a topic of high interest. In 2015, the Transportation Research Board (part of the National Academies, see www.trb.org) formed a Transportation Systems Resilience Section consisting of committees on infrastructure protection, business continuity and disaster logistics, and emergency evacuation research. There have been several specific workshops on these topics and a research roadmap is currently being developed. The impacts of climate change on transportation consist of three main areas: 1) impacts on transportation infrastructure; 2) impacts on travel behavior; and 3) impacts on goods movement and supply chain business continuity.

It is clear that transportation infrastructure such as roadways (highways, arterial roads, residential streets, etc.), bridge supports, railways, seaports, and airports are all potentially at increased risk due to severe storms, flash floods, higher temperatures, and increased wildfire risk (Radke et al., 2018). As an example, in July 2015 a bridge over a desert wash collapsed during a major flash flood near Desert Center (Figure 18). As a result, bridges like this are being rebuilt with deeper foundations, with the expectation that flash floods will increase in frequency due to climate change. Wildfires can also directly affect the transportation infrastructure, literally melting pavement and buckling concrete. Debris flows or mudslides can also wash out or damage transportation infrastructure.

Temperature extremes are also increasing within the Inland Deserts (see "Regional Climate Projections," Figures 4, 5). In general, these higher temperature extremes do not necessarily have a strong effect on transportation, except when temperatures are so high, that airplanes may be restricted on being able to take off and land. This is dependent on a number of factors, including airport altitude, runway length, type of aircraft and payload. As an example, many flights were cancelled at several southwest US airports during June 2017 when temperatures exceeded 119 °F (https://www.washingtonpost.com/news/capital-weather-gang/wp/2017/06/20/its-so-hot-in-phoenix-that-airplanes-cant-fly/?noredirect=on&utm_term=.63bea31f7125).

In addition to the direct effects on transportation infrastructure, extreme weather events can cause major disruptions in normal everyday travel. When parts of the transportation infrastructure fail, then typical travel routes for both passenger travel and goods movement may be affected. In recent years, the California Department of Transportation has set up Traffic Management Centers (TMCs) around the state to provide roadway information to the public; as an example, Caltrans District 8's TMC can be accessed at http://www.dot.ca.gov/dist8/tmc/. In addition to providing real-time information on lane- and road-closures, it also offers rerouting information, future conditions on the roadways, and other information. This allows travelers to choose different routes to avoid travel delays, congestion, and other related problems. In the extreme cases of a major disaster where evacuations are required, the TMC and related websites can also provide evacuation routes and related information. There are a variety of examples of the effectiveness of these TMCs over the last several years. A good example for the Inland Deserts region was the re-routing of traffic along the I-10 freeway during the bridge washout incident in July 2015 (Figure 18).

Beyond re-routing and evacuations that may be related to climate change and extreme weather events, it is unclear whether actual travel behavior changes due to higher temperature extremes. Most current vehicles have robust climate controls; therefore, there is little evidence that people change their travel behavior (e.g., deciding to make a trip, trip departure times, trip route) due to extreme heat. However, when the extreme heat is combined with traveling on roads with significant road grade, more vehicle breakdowns along the roadside have been recorded, potentially affecting traffic operations.

Transportation is often thought of as simply trips made by typical passenger vehicles. However, perhaps just as important is the goods movement system. Southern California is home to two major seaports (Port of Long Beach and Port of Los Angeles) that process approximately 43% of all the goods entering the United States. In addition to the ports, there is a sophisticated system of goods movement that include railyards, transfer stations, trucking fleets, rail systems, and distribution warehouses. All of these are vulnerable to transportation disruptions due to climate change and extreme weather events. Missed shipments can drastically affect material supply, the manufacturing process, and the distribution of the finished goods. Any disruption can have a deep effect on the economic vitality of the region and on the livelihood of many businesses (Radke et al., 2018). As a result, many companies are engaged now in resiliency planning and preparation to mitigate these potential effects due to transportation disruptions.

Inland Southern California plays an important role in the goods movement and supply chain business continuity. This region is home to a large and expanding number of warehouses and distribution centers, a critical link for goods movement and manufacturing. In addition to addressing re-routing issues described in the previous section made by trucks, companies are now eliminating "weak-links" in their transportation system, seeking out multiple modes of good movement and delivery.

There are a variety of actions that can and should take place in order to adapt to climate change and mitigate its impacts. In terms of transportation infrastructure, more resilient structures should be built, including bridges, ramps, and drainage systems. In many cases, actions are already being taken to fortify structures susceptible to flooding. For example, bridges such as the one along the I-10, described above, are being rebuilt with deeper and stronger footings. Use of materials with a higher heat tolerance should be considered during the next repaving cycles to increase resilience to extreme heat events. Barriers and diversions can be built along roads to protect critical locations from potential mudslides.

California has already set up effective traffic management centers to deal with strategy development and for disseminating information to travelers during infrastructure failures or disruptions. These traffic management centers should continue to embrace new techniques in "intelligent traffic management", including:

- Innovative monitoring solutions that use traffic and roadway sensing to improve situational awareness among travelers.
- Advanced traffic routing methods (e.g., distributed routing algorithms) that can be utilized during extreme weather events, which may result in isolated road closures all the way up to full blown evacuations.
- Innovative traffic control techniques that can potentially change traffic signal timing and ramp metering.

For goods movement and supply chain management, businesses should continue to identify risks and impacts associated with supply chain disruptions. Based on this assessment, action plans can be developed to minimize these disruptions through redundant pathways. For Inland Southern California, the majority of the distribution warehouses were developed and located in an ad-hoc manner based on land prices and availability. It would be valuable for regional planners to now examine the warehousing and distribution system as a whole and identify weaknesses. Based on this analysis, specific roadway and management techniques could be developed to increase the resiliency of current goods movement system in the Inland Deserts.

There are a number of specific research needs and knowledge gaps, specifically on the relationship between climate change and transportation as a whole. Specific research questions include: 1) improving our understanding of the linkages between climate change events and traffic operations, where numerous "what-if" case studies can be carried out to determine how we can improve traffic operations to increase resiliency; 2) improving our understanding of the linkages between climate change events and travel behavior; to date, there are no solid studies showing how people change their travel habits based not just on disruptive weather events, but on extended extreme heat; this also pertains to goods movement; and 3) improving how transportation agencies (e.g. Caltrans District 8) interact with city traffic managers and private-sector entities during extreme weather events.

Public Health: Vulnerability and Adaptation Options

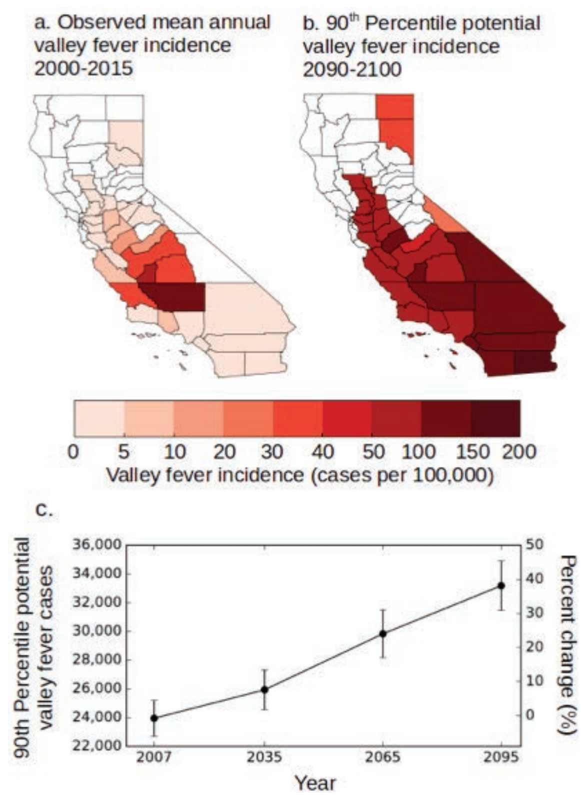
Within the Inland Deserts region, climate change is poised to increase multiple public health vulnerabilities by exacerbating environmental risks to health and well-being while also compromising the capacity to address risks. Direct effects of increasing temperatures within the region, already characterized by extreme heat, could include increased risk of rapid and lethal health consequences as well as chronic degradation in well-being (Kostas and Hajat, 2008). Indirectly, climate change is expected to interact with other global change drivers and exacerbate health vulnerabilities associated with air pollution and disease (Patz et al., 2005). Climate changes in the Inland Deserts may degrade or add strain to health-related infrastructure, including electricity, water delivery, and transportation. Spatial and demographic variability in climate-related health risks also have high potential for increasing environmental justice issues, with greater predicted warming impacts in low income and minority communities (Tayyebi and Jenerette, 2016). Differences in the availability of air conditioning and other mitigation measures can further exacerbate these differences in heat vulnerability among communities (Harlan et al., 2006; Jenerette et al., 2016). In preparing and adapting to future climate warming, a suite of uncertainties may lead to alternate public health futures. The fate of the Salton Sea in particular, which may be affected by climate change, could have a large effect on public health in the region.

Heat-related health impacts are associated with increases in both chronic and peak exposure to high temperatures (Basu, 2009; Ostro et al., 2011; Sherbakov et al., 2018). High temperatures can have extensive health impacts ranging from degraded quality of life to mortality (Kovats and Hajat, 2008). These negative health effects can result both from increased average temperatures and increased intensity and duration of acute heat waves. The projected increases in daytime high temperatures for the Inland Deserts are associated with increasing risk from a diverse set of respiratory and pulmonary health consequences, as well as the aggravation of other health conditions (Patz, 2007; McMicheal et al., 2007). The specific mechanisms linking high temperatures to the resulting health impacts are an active area of research, and translating outdoor meteorological conditions to physiological warming and health vulnerabilities is an ongoing research challenge (Hondula et al., 2014; Harlan et al., 2014).

In measuring environmental temperature and impacts to health, two metrics are commonly evaluated: air temperature and surface temperature. Air temperature is a widely used metric of environmental temperature representing conditions in shaded locations, and has been repeatedly found to influence human health through many heat-related illnesses (Kalkstein, 1991; Hondula and Barnett, 2014; Harlan et al., 2014). The influence of air temperature on heat-related illness is frequently related to elevated nighttime temperatures, as projected increases in minimum temperatures reduces a person's ability to recover during sleep from high daytime temperatures. A second temperature metric, surface temperature (frequently defined as land surface temperature) is measured as the emission of long-wave infrared radiation from a surface primarily viewed from thermal cameras or satellite platforms (Voogt and Oke, 2003). Surface temperatures have also been shown to directly correlate with heat-related health incidents (Laaidi et al., 2012; Vanos, 2015; Jenerette et al., 2016), and are more closely related to negative health outcomes than air temperature (Jenerette et al., 2016). These two metrics provide alternate windows into temperature-related health threat: air temperature is measured continuously but only from a limited number of locations, while surface temperature measure by satellite provide extensive spatial coverage but only limited timing of available temperature. Resolving the uncertainties in the drivers of spatial and temporal variation for both air temperature and land surface temperature will contribute to a more robust understanding of the drivers of climate change related heat impacts.

In addition to direct effects of warming on public health vulnerability, climate change in the Inland Deserts is also likely to exacerbate air quality-driven health impacts (Jacob and Winter, 2009). Increasing temperatures and more drought conditions may increase concentrations of ozone and particulates (West et al., 2016; West et al., 2017). Specifically, formation of ground-level ozone generally increases with temperature (Cardelino and Chamedies, 1990), so warming is expected to increase harmful surface ozone levels. Emissions of the ozone precursor NO_x from agricultural soils may also increase with higher temperatures, further enhancing ozone production (Oikawa et al., 2015). Climate change may also increase exposure to particulates resulting both from increased dust and fire. More severe and frequent drought and high temperature conditions could increase dust production from the extensive desert regions (Engelstaedter et al., 2006) as has been implicated for the Owens Lake region in southern California (Borlina and Renno, 2017). Increasing fire frequency can create recurring air quality degradation events leading to respiratory health effects and growing evidence of increased risks of all-cause mortality (Reid et al., 2016). Increased air emissions from an expanded playa of the Salton Sea may also add to these air quality problems.

FIGURE 19



Observed and projected increase in Valley Fever incidence by county for (a) 2000-2015, and (b) 2090-2100 under RCP 8.5. Source: Gorris, Zender et al., in prep

Simultaneous with increasing health risks associated with climate changes, the capacity to cope with risks may also be compromised. Public health infrastructure associated with both electricity and water distribution may be compromised by climate change effects on those systems. With increasing temperatures, electricity demands for cooling increase, which can increase the risk of blackouts (Gao et al., 2018). In turn, electricity failure during heat waves may lead to widespread heat-related health impacts. Water distribution may also be impacted by climate change. Warming can increase water demand and decrease water availability, stressing water distribution systems. Climate change may also increase risks from infectious disease in the Inland Deserts. Mosquito borne diseases are expected to increase in prevalence with climate change (Gould and Higgs, 2009). Coccidioidomycosis, the fungal pathogen responsible for Valley Fever, may also increase in response to climate change due to warming and more variable precipitation patterns (Gorris et al., 2018, Figure 19).

Across most of these health risks, the consequences of climate change-induced health vulnerability are poised to magnify environmental justice concerns (Harlan et al., 2006). The Inland Deserts already have large disparities in wealth and heat risk (Tayyebi and Jenerette et al., 2016). Urbanized regions include some highly affluent neighborhoods featuring extensive outdoor irrigation supporting lush vegetation and cooler microclimates. Other urbanized neighborhoods contain extensive poverty, with limited irrigation and vegetation. Within the agricultural regions that are home to very disadvantaged communities, exposure to health risks may be higher, given that most farm workers perform strenuous labor outside in high temperature conditions and may be exposed to higher levels of atmospheric pollutants from agricultural activities. The increased health risks from climate change may exacerbate these differences.

Several strategies may help the Inland Deserts adapt to climate change by mitigating these health vulnerabilities. The increased use of urban vegetation may provide a buffer against higher maximum temperatures through vegetation-derived cooling (Jenerette et al., 2016); however, this strategy generally requires sustained water inputs, which may also be at risk given increasing water shortage predicted for the region. Better planning for increased peak electricity use and water demand can increase resilience of critical public infrastructure to climate change. Resource conservation efforts may also limit potential increases in infrastructure demand. Strengthening social networks may also provide added coping capacity to reduce climate change related health impacts. Climate effects on air quality can be minimized by reducing ozone precursors, both from on-road and agricultural sources, and reducing wind-blown particulates in general throughout the region and specifically in response to the shrinking Salton Sea. In alleviating climate change impacts to health vulnerability in the Inland Deserts, multiple strategies will be needed to address the breadth potential health impacts.

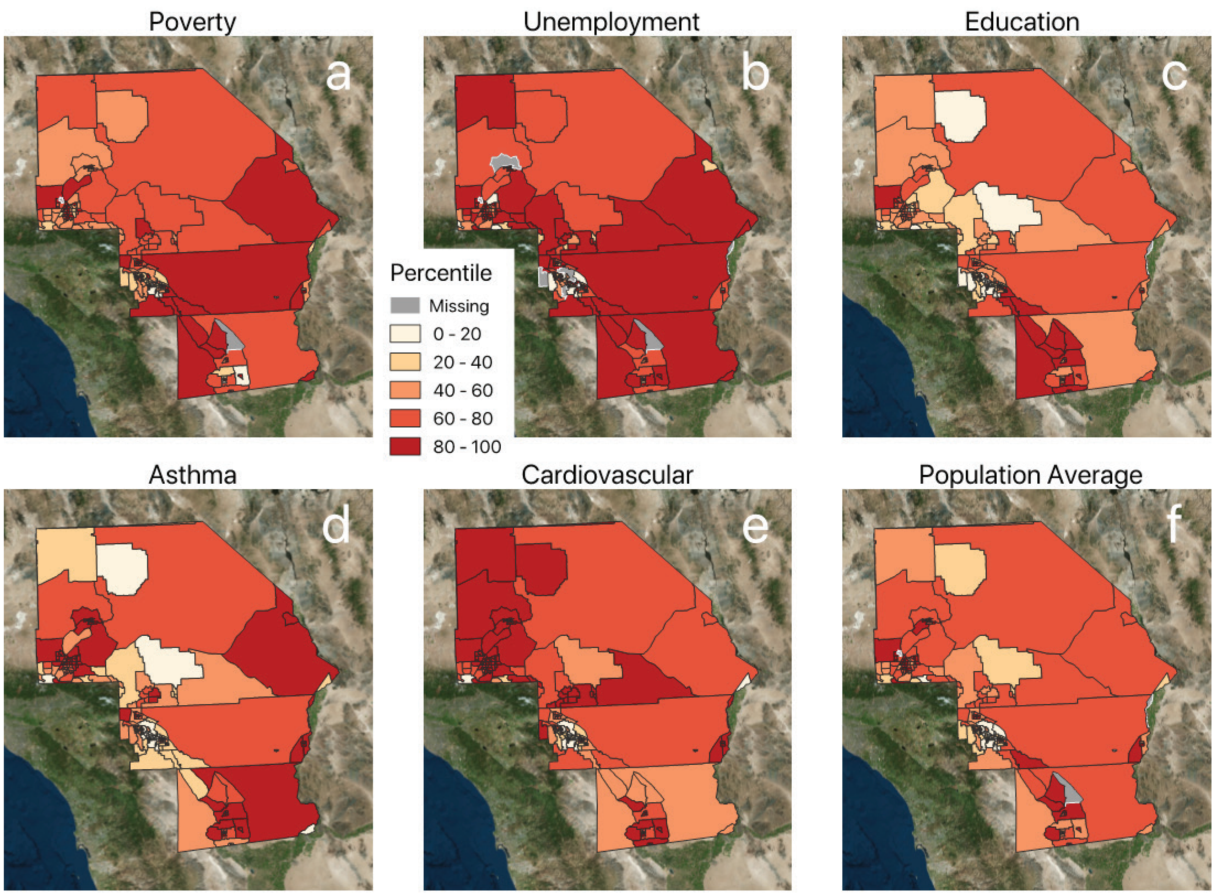
Further research could reduce the uncertainty in the effectiveness of these public health adaptations. A crucial uncertainty is the fate of the Salton Sea – both in terms of the water quality and from increasingly exposed playa sediments. Degraded water quality in the remaining sea may lead to increased emissions of the toxic gas hydrogen sulfide (H_2S) due to mass fish mortality, leading to noxious odors throughout the region. Toxic pollutants in the Salton Sea sediments may have a large potential for emissions during high wind events. Outside of the Salton Sea, abandonment of agricultural lands may lead to dust emissions from soils contaminated with pesticides and other residues. These legacies of contamination need further study to characterize the distribution of contaminants and assess the potential health impacts. Changing vegetation cover in natural and managed lands due to changing water availability may also pose a stress that is not well understood. In the end, translating environmental health risks associated with climate change to specific health vulnerabilities has large uncertainties. With increased coping capacity and public infrastructure, some of the health risks can be mitigated. However, the implications of coping-based strategies will need foresight to avoid enhancing environmental injustice.

Environmental Justice

The impacts of environmental changes such as those expected with climate change in the Inland Deserts are not uniformly distributed across communities and population demographics. Health impacts associated with air pollution, for example, are typically most severe for specific at-risk populations, such as young children, senior citizens, and those already suffering from respiratory or cardiovascular disease. Many other factors can further influence the ability of any given group of people to successfully adapt to the local effects of environmental changes, including socio-economic status, mobility, employment opportunities, and language barriers. Collectively, analyzing and mitigating the disproportionate effects of climate change depending on these types of factors is an important environmental justice concern, and one that has been an increasingly highlighted policy priority within the state of California. For more information on Statewide environmental justice issues, please refer to the companion Fourth Assessment Climate Justice report (Climate Justice Summary Report 2018).

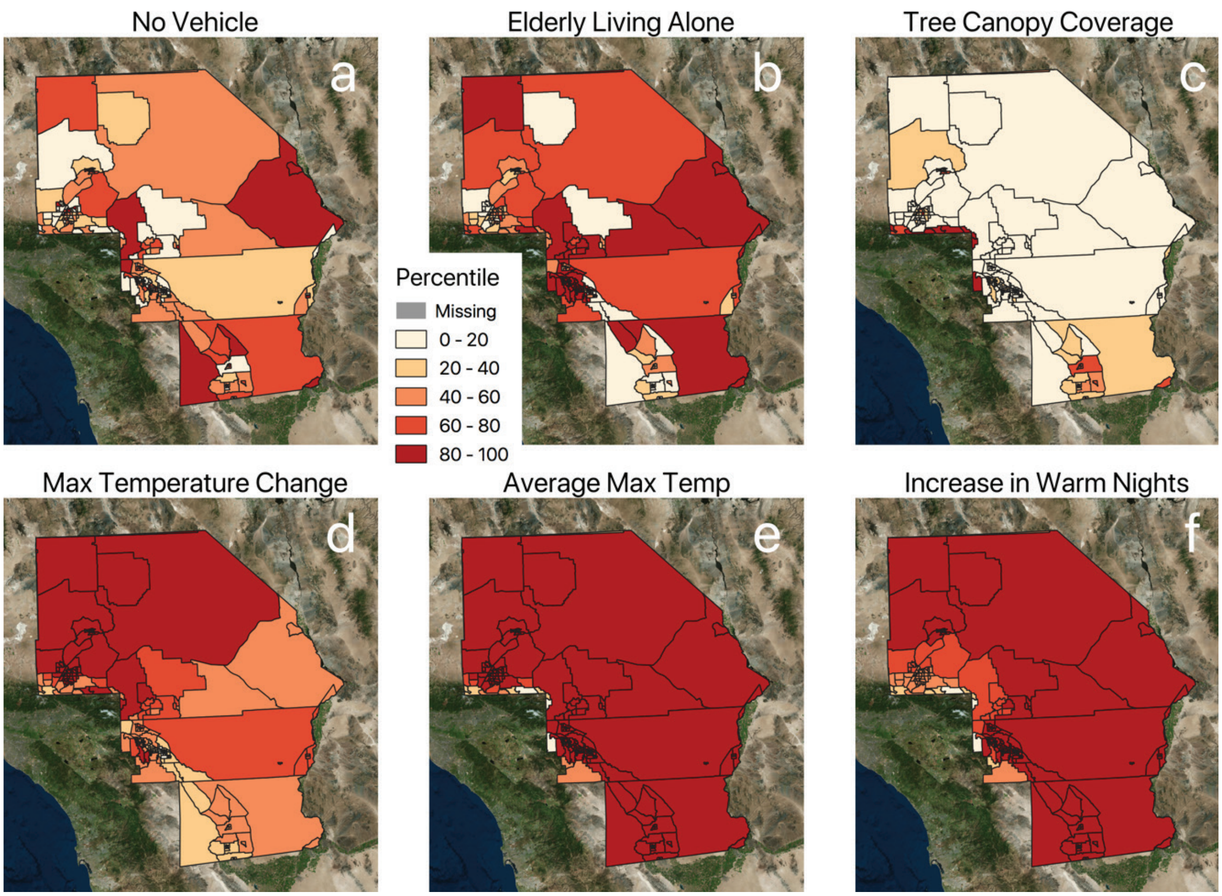
The Inland Deserts of California shows signs of disproportionate vulnerability to climate change through multiple demographic and environmental metrics currently in use. CalEnviroScreen, a data product of California's Office of Environmental Health Hazard Assessment (OEHHA), reveals a disproportionate number of census blocks in the Inland Desert region that rank in the upper quintiles for population vulnerability metrics such as poverty, unemployment, education, and existing incidence rates of asthma and cardiovascular disease (Figure 20). Combined, these metrics highlight some of the ways in which Inland Deserts residents in particular may struggle to respond to increasing challenges related to climate change relative to populations with greater resources and resilience. The Environmental Justice Screening Method, another tool used for the identification of at-risk communities on a regional scale, supports and extends the results of the CalEnviroScreen metrics, underscoring the importance of addressing resilience disparities within regional communities when planning for future environmental problems (Sadd et al., 2011). To estimate climate change vulnerability, the Environmental Justice Screening Method examines 7 indicators related to heat stress, including economic, social, and environmental factors (Figure 21). The resulting Climate Change Vulnerability metric reveals unique spatial patterns of climate-related risks: while metrics measuring current vulnerability to environmental health risks are concentrated almost entirely within the greater Los Angeles area of southern California, the climate-focused vulnerability metrics highlight the vulnerability of Inland Desert residents relative to those of more urban areas. In particular, Inland Deserts have some census tracts with a high proportion of the population with no vehicle, and who are elderly and living alone. There is also a low proportion of tree canopy that can provide a cooler microclimate in residential areas. Extending and responding to these and other risks associated with future climate change will require a careful examination of individual community resiliencies and vulnerabilities, enabling policies that can mitigate the disproportionate negative effects of climate change on at-risk groups.

FIGURE 20



Population vulnerability estimated by census-block quintile for poverty (a), unemployment (b), low educational attainment (c), asthma rates (d), cardiovascular disease rates (e), and population average risk (f). Source: CalEnviroScreen.

FIGURE 21



Climate change vulnerability estimated by census-block quintile for percent of households with no vehicle (a), population of elderly living alone (b), tree canopy coverage (c), changing in maximum monthly average temperature change from 2000s to 2050s (d), average maximum monthly temperature in 2050s (e), and increase in warm nights for 2000s to 2050s (f). Source: Environmental Justice Screening Method.

Research Needs

Because of the central role of water resources to the endurance of human and natural biological systems in the Inland Deserts, it is clear the uncertainty in the amount and seasonality of future precipitation complicates predictions about the future of the region. More robust climate model simulations of intra- and interannual precipitation would provide broad support for improved projections in other areas, since precipitation governs runoff and groundwater recharge rates, and development of fuel beds that control risk of severe wildfire. Another critical need for better understanding of future water resources is integration of surface and groundwater modeling, allowing simulations of the relationship between future climate, land cover, groundwater recharge, and surface runoff in response to climate change and human decisions.

Apart from physical drivers of water availability, there are also important questions about potential changes to water rights under climate change. For example, how would extreme reductions in Colorado River flows affect current water allocations? Similarly, the future of the Salton Sea is pivotal to the well-being of humans and ecosystems, but in the face of inaction, critical research questions remain. What kind of governance solution would it take to halt the shrinking of the Sea? What volume of fresh water is needed to maximize outcomes, and from where might this water come? How much will climate change exacerbate Salton Sea shrinkage rates? How severe are the public health risks from the Salton Sea within and beyond the region given different restoration scenarios?

The strength of the future economy of the Inland Deserts will likely depend on the development of robust renewable energy supplies that reduce greenhouse gases and air pollution. In order to realize this future while minimizing negative impact to other systems, research into the tradeoffs between distributed generation and utility-scale renewables that considers climate change effects on system infrastructure is needed. Development of smart sensor technology, microgrids, and efficient forms of energy storage will also be critical. Ideally, this will involve pilot demonstrations of these new technologies.

Continued strength of the tourism sector depends on a better understanding of the strength of the link between tourist decisions about where and when to travel to the Inland Deserts, and local climate conditions at their destination. Research on the link between travel behavior and temperature will also be useful for improved adaptation and resilience of the transportation sector.

More research is needed to identify community specific adaptation and mitigation strategies that are most appropriate for this region. Further research on the mechanisms of heat stress and its interactions with other health vulnerabilities may reveal new strategies to ameliorate the effects of extremely high temperatures on public health. How do spatial and temporal variability of air or land surface temperature affect the impact of heat on health, and can such information be used to mitigate this threat? Ways in which climate adaptation and mitigation strategies can be used in tandem to ameliorate current environmental justice issues and stresses should be explored, such as optimizing local climate in disadvantaged neighborhoods with combinations of solar panels and vegetation. Also, more research is needed to understand the future of urban development in the region given the expectation of extremely high temperatures in the region paired with climate impacts to other regions from which migrations to the Inland Deserts can be expected, such as loss of habitable land in coastal areas due to sea level rise.

Inland Desert valleys are already one of the hottest agricultural regions in the world, and essentially serve as a model for what many other agricultural regions will face in the future with respect to heat tolerance and high salinity soils. Much research about temperature effects on agriculture has taken place here, but projected warming will take this region far past what it has experienced previously. More research about crop and animal response to higher temperatures, and ways to increase resilience is greatly needed. This may include research about the effectiveness of different cultivars, water application, crop planting cycles, and new models that better represent vegetation response to heat and elevated carbon dioxide levels.

While the climate refugia approach has been well studied for charismatic desert species such as the Joshua tree and the desert tortoise, such information is lacking for most desert species. Research to identify and protect refugia for a broader suite of endemic desert species could reveal the best adaptation options for these ecosystems as a whole.

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