SAN DIEGO COUNTY ECOSYSTEMS: ECOLOGICAL IMPACTS OF CLIMATE CHANGE ON A BIODIVERSITY HOTSPOT

A Report for:

California's Fourth Climate Change Assessment

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

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. It includes research to develop 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.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report contributes to resilience in the areas of biodiversity and habitat by considering how projected changes in climate may affect San Diego's diverse and unique landscape as well as how boundary organizations can collaborate across jurisdictions and disciplines to accomplish landscape-scale planning and conservation.

ABSTRACT

The diverse ecosystems, habitats, plants, and animals in the San Diego County region will be impacted by climatic shifts in multifold ways due to current and future variability, along with other factors including habitat loss and fragmentation, land use shifts, and changing fire regimes. While home to a major metropolitan area, San Diego County still hosts expanses of native and preserved habitats where management and conservation action could be greatly enhanced through science-based assessments and planning for climate change and increased climate variability. Projections of climate change in the region include warming by 4-9° F on average, and a 15-25% decrease in fall and spring precipitation with an increase in variability resulting in more frequent and intense droughts punctuated by increasingly rare yet extreme precipitation and flooding events. In addition, an increase in fire events and potential lessening of coastal marine influence may also affect San Diego's ecosystems. Climate warming superimposed upon the pronounced spatially-varying temperature in the San Diego region will likely be associated with range shifts for many species resulting in novel community assemblages and biotic interactions and could create phenological mismatches. More frequent and intense heat waves may disproportionately affect younger age classes and reduce reproductive and survival rates of species sensitive to temperature extremes. With increasingly variable precipitation, drought may occur more frequently due to increased occurrence of dry days and could intensify because of warmer temperatures. Since drought disproportionately affects some species, these projected changes may cause structural changes to ecosystems. Santa Ana winds, occurring during increasingly dry fall months, would create ideal fire conditions. Coastal low clouds and fog along San Diego's coast buffer this zone from the effects of warming and drying through shading and cooling. Although these marine stratus clouds will remain a presence, future changes in this phenomenon are uncertain. The spatial and temporal scales at which climate variations and change operate must be considered to build resilience into natural systems. Effective conservation actions will need to build on ongoing efforts focused on landscape-scale planning rather than more traditional single-species approaches. To carry this out will require cross-jurisdictional, multidisciplinary collaboration by scientists, policy-makers, planners, land managers, and the broader conservation community, which has a decades-long history of accomplishment in San Diego County.

Keywords: biodiversity, climate, ecology, ecosystem, management, San Diego, Southern California

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HIGHLIGHTS

- San Diego County is part of a biologically diverse and unique landscape that will be impacted in multifold ways due to current and future climatic variability.
- This assessment of the state of the science is critical to understanding the vulnerability of systems and allowing partners to take stock of the state of knowledge about potential climate impacts at the regional level.
- Climate warming superimposed upon the pronounced spatially-varying temperature in the San Diego region will likely be associated with range shifts for many species resulting in novel community assemblages and biotic interactions.
- More frequent and more intense heat waves may disproportionately affect younger age classes and reduce reproductive and survival rates of species sensitive to temperature extremes. Warming temperatures may also create phenological mismatches.
- The region's precipitation regime is projected to become more variable with more dry days and more dry years. However, the few extremely heavy precipitation events, increased over historical levels, could result in increased flooding and occasional wet years.
- Drought may occur more frequently due to increased occurrence of dry days and could intensify because of warmer temperatures. Since drought disproportionately affects some species, these projected changes may cause structural changes to ecosystems.
- Annually, the occurrence of Santa Ana winds during increasingly dry fall months would create ideal fire conditions. Longer dry spells and decreased precipitation in fall may extend fire season into the winter, increasing the risk of Santa Ana wind-driven fires. Regardless of climatic shifts, people will remain the major driver of fires in San Diego.
- Coastal low clouds and fog buffer warming and drying along the coast through shading and cooling. Although these marine stratus clouds will remain a presence, future changes in this phenomenon are uncertain, so the degree to which this will ameliorate the impacts of warming and drying is unknown.
- The spatial and temporal scales at which climate variations and change operate must be considered to build resilience into natural systems. Effective conservation actions will need landscape-scale planning rather than more traditional single-species approaches. To carry this out will require cross-jurisdictional, multidisciplinary efforts by scientists, policy-makers, planners, land managers, and the broader conservation community.
- Boundary spanning organizations like the Climate Science Alliance-South Coast can advance climate adaptation planning by providing opportunities to translate science into actions, forge new and expanded partnerships, and catalyze innovative, large-scale actions needed to build long-term resilience to climate change.

WEB LINKS

An executive summary of this report is available on the Climate Science Alliance website:
http://www.climatesciencealliance.org/sdc-ecosystems-report
http://www.climatesciencealliance.org/climatesummit

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1: Introduction to San Diego's Climate and Ecosystems[1]

Amber D. Pairis, Udara Abeysekera, John M. Randall, Megan K. Jennings, Julie Kalansky, and Dan Cayan

The mediterranean-type ecosystems of California, characterized by warm, dry summers and relatively cool, wet winters, are some of the most ecologically diverse systems outside of the tropics (Cowling et al. 1996). Within this region, the California Floristic Province (CFP), which spans from southwestern Oregon to northwestern Baja California, west of the crest of the Cascade, Sierra Nevada, Transverse, and Peninsular mountain ranges, is largely coincident with this mediterranean-type climate zone. The CFP is recognized as one of the world's biodiversity hotspots (Stein et al. 2000a, Burge et al. 2016) with high rates of species richness and diversity among both plants and animals. Within the CFP, the San Diego region is particularly diverse, hosting a wide range of habitats, vegetation types, and species.

The San Diego region's high level of diversity is, in part, the result of the complex physiographic and climatic structure within the short distance from the sea to mountain crest. The San Diego region is also at the interface of two ecoregions. As such, it is the northern range limit for a number of species endemic to the Baja California Peninsula and conversely, the southern terminus for a number of more northerly ranging species. The distances between ecotones, or transitional regions between ecosystems, in this region are relatively short and changes in mean climate conditions could displace entire ecosystem zones. The region may already be experiencing climate change impacts through drought-driven ecosystem effects including widespread shrub (Venturas et al. 2016) and tree mortality (Freeman et al. 2017, Minnich et al. 2016). Although it is not possible to say with certainty that the recent droughts are a result of climate change, ecosystem responses to them provide a window into projected changes under future climate scenarios. We use these examples and others in this document in order to characterize potential species and ecosystem effects of climate change. In the near term, within 20-30 years, ecosystems in the region will be most threatened by landscape changes, disturbances, and fragmentation due to urban development and fire. In the longer term, climate variability will compound those stressors with significantly warmer temperatures, more variable precipitation regimes resulting in occasional high-intensity flooding and more frequent and prolonged droughts, and more destructive fires due to drought and increased ignitions/fuel availability. The region's characteristic coastal fog and low clouds may act as a buffer against the warmer and drier conditions, but projections of how fog and low cloud cover may change in the future are highly uncertain. Although the region's species and ecosystems have adapted to a precipitation regime with greater year-to-year variability than nearly

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[1] Suggested section citation: Pairis, Amber D., Udara Abeysekera, John M. Randall, Megan K. Jennings, Julie Kalansky, and Dan Cayan. 2018. Introduction to San Diego's Climate and Ecosystems. Pages 1 - 11 *in:* Jennings, M.K., D. Cayan, J. Kalansky, A.D. Pairis et al. ***San Diego County ecosystems: ecological impacts of climate change on a biodiversity hotspot***. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: EXT-CCC4A-2018-010

anywhere else in the United States (Dettinger et al. 2011), they will be challenged as average temperatures rise and the precipitation regime is propelled to even greater variability.

1.1 Impetus for this Assessment: Building off 20+ years of Conservation Planning

Geographically, San Diego County's ecoregions are remarkable in accommodating a wide range of habitats and climatic regimes (Figure 1.1). The County extends 70 miles (roughly 115 km) west to east, encompassing the cool waters of the Pacific, chaparral-covered foothills, > 6,000 ft (> 1,800 m) forested crests of the Peninsular Ranges, and the low elevation western Sonoran Desert. To the south, the international border with Mexico can interfere with and even block the south-north movement of many plants and animals, particularly where sections of border fence have been constructed. Ecologically, the county is known for a high species richness (Figure 1.2) boasting more taxa of plants and mammals than any other in the United States (Rebman and Simpson 2014, Tremor et al. 2017). San Diego County is home to thousands of species including ~200 taxa of plants and animals that are considered at-risk (California Department of Fish and Wildlife 2017), and 30 different vegetation types that can be broadly classified into nine different categories (Table 1.1).

San Diego County's diverse ecological landscape is also home to a human population estimated at 3.3 million in 2015, the second largest county-wide population in California behind Los Angeles County, and fifth largest in the entire nation (U.S. Census Bureau 2017). Most of the human population lives in the western third of the county, the majority of which falls within the San Diego metropolitan area, one of the largest in the nation. Situated immediately to the south is the metropolitan area of Tijuana, Mexico, which is home to another 1.7 million people (Secretaría de Desarrollo Social 2015). According to the decennial U.S. Census, San Diego County's population has increased rapidly for over a century, growing at rates of 30%-90% in every decade of the 20th century and of over 10% thus far in each of the first two decades of the 21st century.

Not surprisingly, the rapid development and growth in human population in San Diego County has degraded large areas of habitat, shifted land use patterns, and expanded development into San Diego's backcountry (Figure 1.3), which has imperiled many of the region's distinctive and endemic species. As a result, San Diego's communities of conservation planners, natural resource managers, and developers were among the first in the nation to come together to collaborate on the planning and implementation of a regional habitat conservation plan. This resulted in a strategy to create networks of linked conserved areas through federal Habitat Conservation Plans (HCPs), and state Natural Community Conservation Plans (NCCPs). Since the mid-1990s, most new land conservation efforts in San Diego County have been tied to these plans. Landscape connectivity is a particularly important component of the design of these reserve systems when it comes to addressing climate variability. Interconnected networks of habitat will be required by many species to move to suitable areas as the climate changes and their current ranges become inhospitable (Heller and Zavaleta 2009, Association of Fish and Wildlife Agencies 2012).

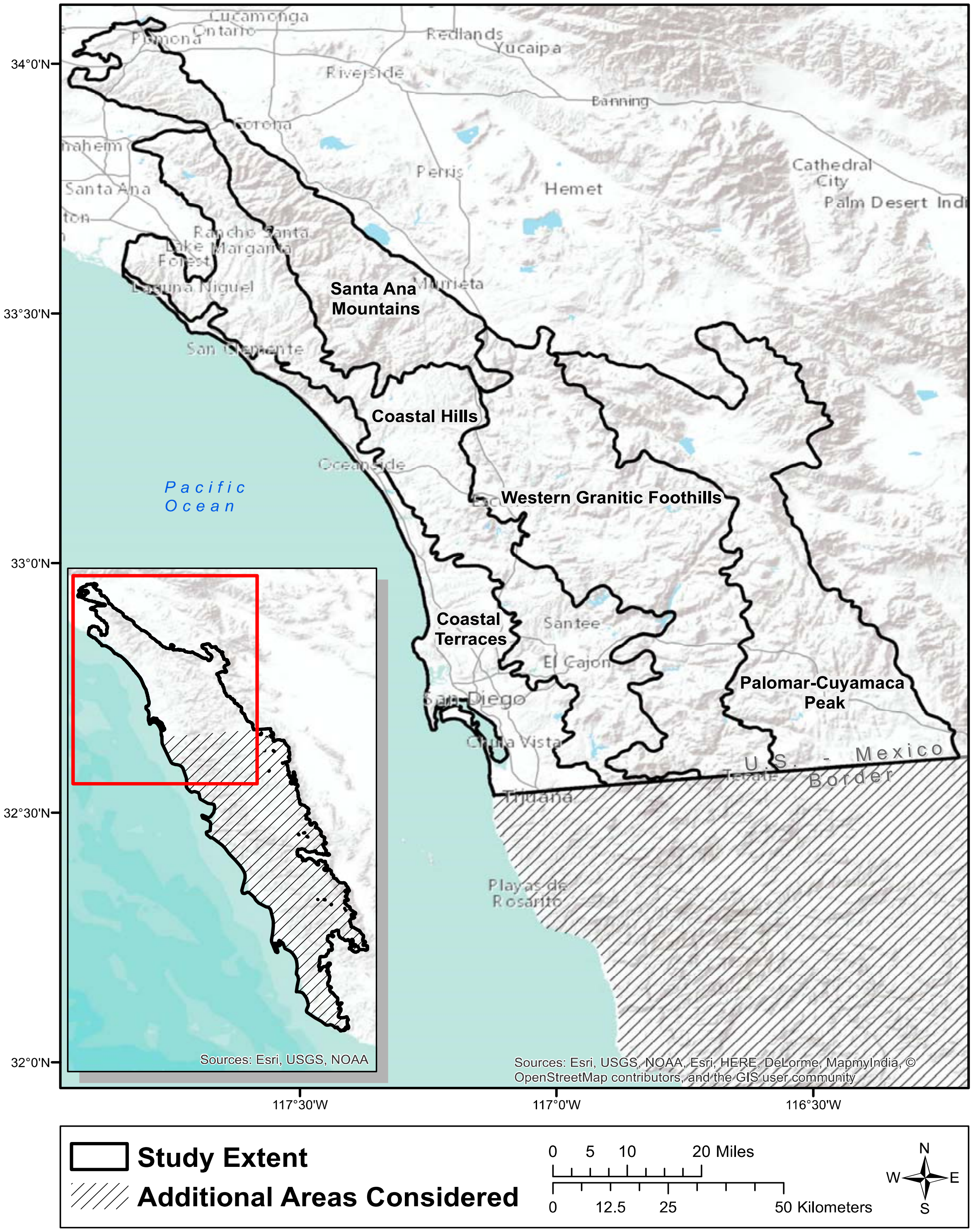

Figure 1.1: Map of the study area encompassing the greater San Diego region. Labeled ecoregional subsections (U.S. Forest Service 2007) represent a diversity of ecotypes, distance to coast, and elevation within the region.

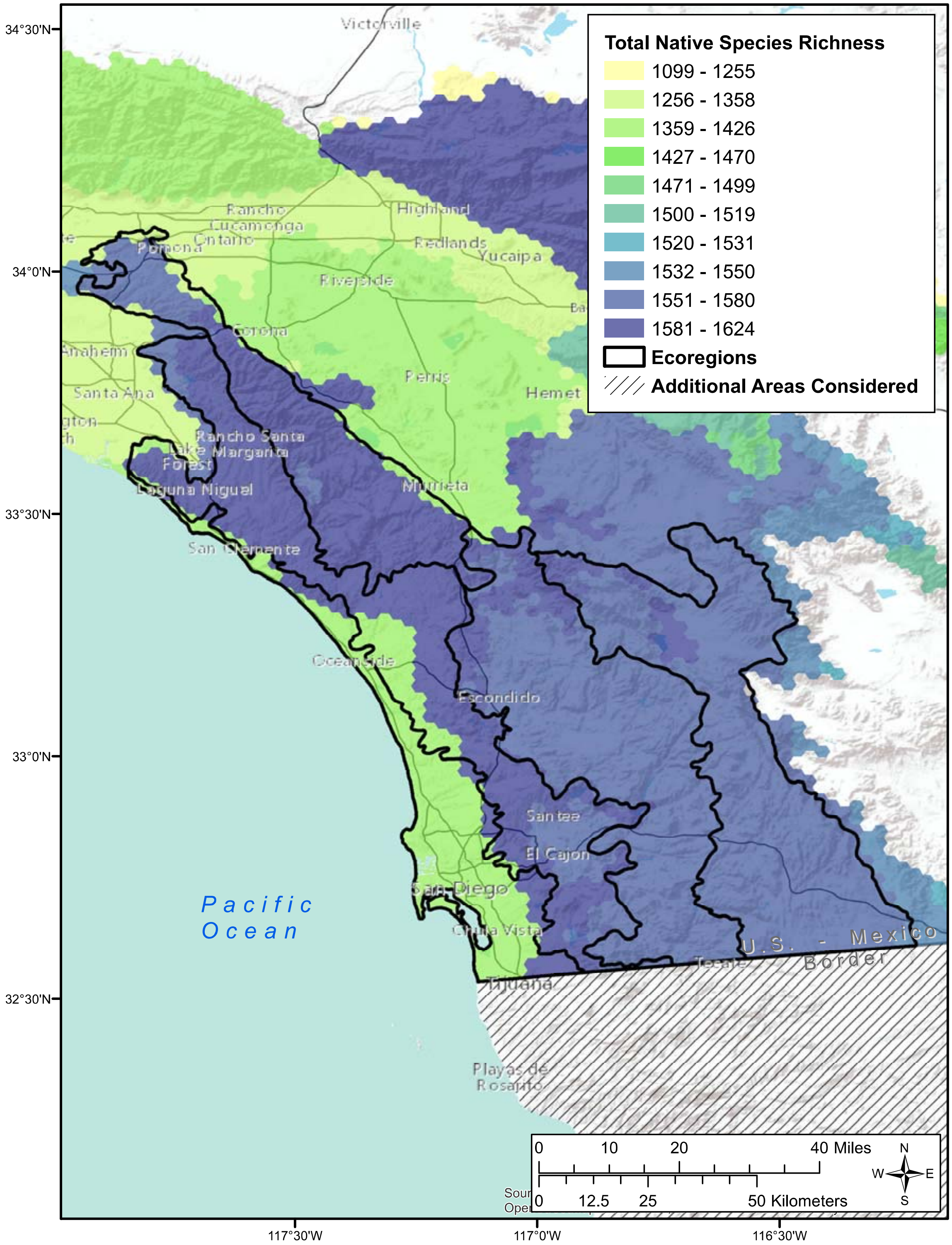

Figure 1.2: Map of total native species richness for all plant and vertebrate faunal taxa from the California Department of Fish and Wildlife's Areas of Conservation Emphasis II mapping efforts (California Department of Fish and Wildlife 2015). Ecoregional subsection boundaries (U.S. Forest Service 2007) are displayed to identify how richness varies in San Diego's different ecosystems.

Table 1.1: Nine major vegetation/land cover types mapped in the San Diego study region calculated by categorizing Wildlife Habitat Relationship types from statewide vegetation data (CALFIRE Fire and Resource Assesment Program [FRAP] 2015). Protected area calculations were based on compiled data from the San Diego Association of Governments (2017) and the California Protected Area Database (GreenInfo Network 2017).

Vegetation Type	Area mi^2 (km^2)	Percent area	Protected area mi^2 (km^2)	Percent protected
Agriculture	156.1 (404.3)	4.1%	9.6 (24.9)	0.7%
Barren	20.7 (53.7)	0.5%	5.2 (13.5)	0.4%
Chaparral	1,498.3 (3,881.6)	39.2%	860.5 (2,229.4)	58.9%
Coastal scrub	546.8 (1,416.5)	14.3%	240.0 (621.8)	16.4%
Coniferous forest	47.6 (123.2)	1.2%	34.7 (89.9)	2.4%
Grassland/Meadow	413.4 (1,071.1)	10.8%	130.6 (338.4)	8.9%
Oak/Hardwood Forest	243.6 (631.1)	6.4%	88.9 (230.4)	6.1%
Riparian forest	71.2 (184.4)	1.9%	29.6 (76.6)	2.0%
Urban	783.0 (2,028.5)	20.5%	34.4 (89.2)	2.4%
Wetland	37.6 (97.5)	1.0%	27.6 (71.6)	1.9%
Total Area	3,818.3 (9,891.9)	100%	1,461.3 (3,785.7)	38.3%

The development and establishment of these landscape conservation planning efforts for the San Diego region also led to the establishment of robust relationships among planning jurisdictions, land management entities, researchers, and the broader conservation planning community. These relationships can now serve as a framework for realizing conservation action to build climate resilience into San Diego's natural landscapes. A more recently established component of this planning and management community is the San Diego Management and Monitoring Program (SDMMP), which was created in 2008. The SDMMP coordinates regional monitoring and management across four NCCP areas in western San Diego County in a collaborative effort involving over 115 partners, including local jurisdictions that own and manage conserved lands, state and federal agencies, academic and research organizations, nonprofit organizations, and other stakeholders. This coordination is centered on a strategic management plan, Management and Monitoring Strategic Plan for Conserved Lands in Western San Diego County: A Strategic Habitat Conservation Roadmap (MSP Roadmap), that covers 111 species, 11 vegetation communities and 13 threat categories as well as prioritized management and monitoring objectives for a 5-year planning period. This strategic plan includes a section on the threat of climate change as well as a monitoring and management approach to address the threats of climate change. These efforts and approaches are important to note in considering how to further address climate change impacts on San Diego's ecosystems, but could benefit from broader collaboration and cooperation among researchers, planners, managers, and others to expand the scope of climate adaptation efforts across the San Diego region, both geographically and ecologically. The Climate Science Alliance – South Coast has strived to help fill that need for broader cooperation and partnerships beyond the original NCCP framework.

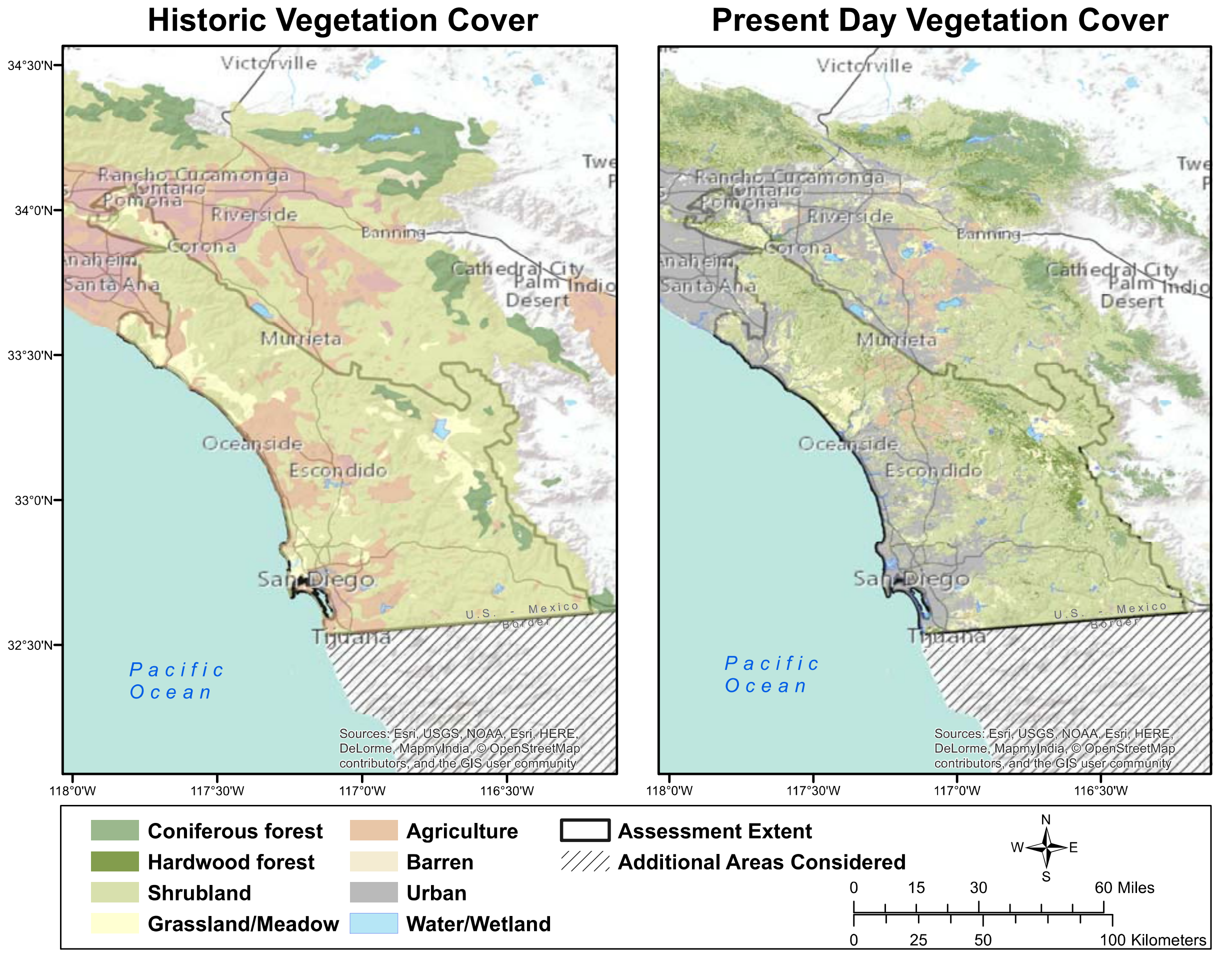

Figure 1.3: Change in distribution of urbanization, agricultural lands, and natural vegetation types between the 1930s Wieslander Vegetation Type Mapping project (Thorne and Le 2016) and present day statewide vegetation data (CALFIRE FRAP 2015).

1.2 Assessing Climate Shifts and Ecological Impacts

This assessment is an overview of the existing science on projected climate for the San Diego region by the end of the century and summarizes the state of our current knowledge on associated ecological impacts. To evaluate regionally-specific climatic shifts, we relied on downscaled climate data created for California's Fourth Climate Change Assessment. We then conducted a literature review to identify the types of ecological impacts that might be expected in the face of climate variability. When possible, the reviews focused on regionally-specific examples from Southern California or San Diego County although the examination of prior data and studies was not exhaustive and primarily focused on peer-reviewed literature, technical reports, and data that were publicly available and readily accessible. Where there are gaps in ecological knowledge from the Southern California region, then the assessment utilized studies and models from other regions and systems to consider how those impacts might manifest in San Diego's ecosystems.

1.2.1 Study Area

The study area (Figure 1.1) in this assessment contains a complex overlay of topography from the Pacific coast to interior mountains. The area's mediterranean-type climate, characterized by highly variable precipitation, strong seasonality, and coastal low level clouds (Dettinger et al. 2011, Clemesha et al. 2016) strongly influences the resident biological palette. The focus of our study is the San Diego region's mountains, foothills, valleys, and the coastal zone (Figure 1.2). The montane ecoregion includes the Peninsular Range Mountains as well as the Santa Ana Mountains. The granitic foothills lie just west of the crest of the Peninsular Range and the coastal hills and terraces are situated between the Pacific Ocean and the foothills that extend from San Diego's southern border with Mexico north to the San Joaquin Hills in Orange County. For the sake of brevity, we refer to this as the San Diego County region throughout the report. In addition, we compare impacts and management of the northwestern portion of Baja California, Mexico that borders San Diego in our analyses, though with less detail than our primary focal area. Northwestern Baja California and San Diego County share many species and ecosystems whose ranges may shift northward and to higher elevations as changes play out across the landscape. The marine and coastal ecosystems of San Diego, while a vital component of the region's biology, have a unique complement of species and face distinct challenges from the terrestrial realm, so are not included in this assessment. Similarly, the Colorado region of the Sonoran desert that falls within San Diego's Anza Borrego Desert State Park, the largest state park in California, was also omitted from the report because it has previously been addressed in assessments with similar ecotypes such as the Mojave Desert and the remainder of the Sonoran Desert (Archer and Predick 2008, Gremer et al. 2015, Cameron et al. 2017).

1.2.2 Climate Data

Aligned with the California Fourth Climate Change Assessment, this review will consider two future scenarios: 1) Representative Concentration Pathway (RCP) 4.5, a mitigated greenhouse gas (GHG) emission scenario that would limit warming to under 3.6˚ F (2˚C), and 2) RCP 8.5, a business as usual scenario. The projections for mid-century (2040-2069) will focus on RCP 8.5 and the projections for end of century (2070-2100) will include both RCP 8.5 and RCP 4.5. The two scenarios are relatively similar through the middle of the century with RCP 4.5 and 8.5, differing by ~ 1.5˚F, whereas by end of century the greater accumulation of atmospheric GHG's causes the RCP 8.5 scenario to warm considerably more (by 3-4˚F) than RCP 4.5. Results shown here include those derived from an ensemble of 32 global climate models (GCMs) or those 10 models that have been selected by a California Department of Water Resources appointed advisory group (Cayan and Tyree 2015) and by the California Fourth Climate Change Assessment (Pierce et al. 2018) as being the most representative models for California. The output from these models has been downscaled using the Localized Constructed Analogs (LOCA) statistical downscaling method (Pierce et al. 2014). The number of models will be specified in the figure caption.

1.3 Translating Climate Science

Given the San Diego region's history of conservation planning, it is uniquely poised to demonstrate how the intersection of monitoring, research, and combined efforts by scientists and planners can promote effective long-term planning. Sustained, long-term collaboration is needed to conserve biodiversity and allow species and habitats to adapt to climate change and shift over time. However, the spatial and temporal scales at which climate impacts must be considered to build resilience into natural systems require landscape-scale planning rather than the single-species approaches which have historically driven conservation action in the region. Building resilience into San Diego's ecosystems is a challenge that will likely require collaborative efforts by policy-makers, planners, land managers, and the broader conservation community. There is a growing imperative for multidisciplinary assessments, scenario evaluations, and other comprehensive science-based strategies to inform management and conservation actions. It is becoming increasingly important for researchers to play a more prominent role in the dissemination of their research in ways that are actionable given the existing regulatory, economic, and social context in which land managers work (Enquist et al. 2017).

In light of this, a group of ecologists and climatologists, under the umbrella of the Climate Science Alliance-South Coast, sought to conduct a review of regionally-specific climate information paired with knowledge of local species and habitats that are at risk due to climate variability and other stressors. This collaboration is unusual in that the project was developed without a mandate or funding, but solely out of a desire to articulate risks that had not previously been made available to conservation planners and land managers. The overarching goal of this collaborative effort was to present a needed assessment of the San Diego region's ecosystems and natural resource futures, and to take stock of the implications of climate change with consideration for other stressors.

The synthesis here is not fine-scale or focused on single-species issues and therefore, not meant to be prescriptive. However, we hope it can be used to help inform management targets and approaches and promote proactive management and planning for a range of climate scenarios. While many land managers currently focus on strategies to resist change, this body of analysis advocates for management actions that build resilience in the short-term with an eye towards transformation as climate variability manifests in various ways across the landscape. Specifically, it highlights needs for continuous monitoring and assessment of climate changes and management goals, recognizing that managing for the near-term, and particularly a focus in individual species, may hamper our ability to promote resilience of the region's ecosystems into the future.

The sections that make up this assessment articulate the likely climatic changes expected, or already being observed, within the study area and provide a pathway for supporting and informing management planning and actions. Each section describes future changes of important climate or climate-driven elements, including temperature, precipitation, fire, and fog and examines how and why these phenomena and other co-stressors might affect ecological factors including resource availability, habitat stability, and species' behavior and biology. In gauging these effects, this assessment describes the region's unique diversity of ecosystems, habitats, plants, and animals, as well as their susceptibility to impacts from climate variability and relevant anthropogenic drivers that may be exacerbated by a changing climate (e.g., urban growth, land use shifts, and fire regimes).

1.4 Climate Impact Summaries

Below we briefly describe some key climate changes and associated impacts to San Diego ecosystems that are covered in more detail in the following sections. In addition, we highlight some prominent knowledge and monitoring gaps identified in each section. A more complete list can be found at the end of each section. The summary section includes a discussion of the interaction of the various climate variables to amplify or mitigate impacts as well as a table to summarize the knowledge and monitoring gaps.

1.4.1 The Effects of Temperature Variability and Change on San Diego's Species and Ecosystems

As for the State of California and most of the globe, climate change is expected to warm the San Diego region substantially over the coming decades. Recent climate models project that, by the end of the 21st Century, annual average temperatures will increase by about 4-6 °F under the RCP 4.5 scenario, or 7-9 °F under RCP 8.5 (Cayan et al. 2013, Pierce et al. 2013, Pachauri et al. 2014). The early form of these changes is likely already appearing in San Diego County with warmer average temperatures and more frequent and intense heat waves. Although there is still uncertainty about how individual species might respond to a warmer climate, observations from other settings suggest that warming will shift species to range higher in elevation and northward in latitude and advance phenological stages earlier (Hughes 2000, Cayan et al. 2001, Walther et al. 2002, Parmesan and Yohe 2003). These changes in species' distributions and life cycles may also increase the prevalence of invasive plants, animals, and pathogens in the region (Dukes and Mooney 1999). Several unknowns remain, including the physiological impacts of heat waves and changes in humidity to plants and animals, and the impacts of temperature shifts on population dynamics. Improved monitoring to determine what makes climate refugia effective for conservation is an important multidisciplinary research area that should include land managers.

1.4.2 Precipitation and Drought in San Diego County

A warming climate will increase the atmospheric water vapor, estimated under theoretical principles to be 7% per 1.8 °F of warming (Trenberth 2011). Climate models demonstrate that concomitant changes in atmospheric circulation will increase the number of dry days and thereby increase drought occurrence and severity in mediterranean-type climate regions, including Southern California (Polade et al. 2015, Berg and Hall 2015). Occasionally, however, this changed climate will likely intensify extreme precipitation events as storms tap the moistened atmosphere (Prudhomme et al. 2014, Polade et al. 2017). Together these opposing mechanisms appear to yield only small overall changes in long-term annual precipitation, which would continue (increasingly) to be highly variable and strongly dependent on extreme events (Pierce et al. 2013, IPCC 2014, Polade et al. 2017). Overall, projections suggest an increasing climatic water deficit (Stephenson 1998) wherein the available water from soil moisture is increasingly unable to satisfy the evaporative demand (Thorne et al. 2015). These changes in precipitation regime and drought have the potential to cause structural changes to ecosystems by affecting certain species more negatively than others (Venturas et al. 2016). Understanding how changes in the precipitation regime will affect the bioavailability of water in the soil at shallow and deep levels as well as stream flow requires improved observations and calibrated hydrological models for the region.

1.4.3 San Diego Wildfires: Drivers of Change and Future Outlook

Wildfire conditions in the San Diego region are most severe during Santa Ana events, which combine low humidity and strong winds with already dry natural fuels. Although humans are and will remain the primary driver of fire ignitions in the region, climate change threatens to aggravate fire risk through changes in the precipitation regime, which is projected to cause drying during spring and fall, as well as through higher temperatures which would decrease fuel moisture. During extreme years, drought-induced shrub and tree mortality can also increase fire risk and lead to extreme fire behavior. Extended dry seasons may be particularly significant if they persist into late fall and winter when Santa Ana winds are most common (Guzman-Morales et al. 2016a), creating conditions that are prime for large, fast-moving fires. In addition, because humans have been the cause of the largest and most damaging fires in southern California (Syphard and Keeley 2015), increasing urbanization in the region will increase fire risk as roads and housing spread into wildland margins. The potential for shorter recurrence of fire in the same location and drier climate during post-fire periods may inhibit species and ecosystem recovery, leading to “type conversion” of shrubland ecosystems to non-native annual grasslands (Zedler et al. 1983, Syphard et al. 2007b, Keeley and Brennan 2012).

1.4.4 Impacts and Influences of Coastal Low Clouds and Fog on Biodiversity in San Diego

One of the San Diego region’s defining characteristics is the coast-to-inland contrast imposed by a frequent ocean cloud shield of coastal low clouds and fog (CLCF), known colloquially as the marine layer (Vanderplank and Ezcurra 2016). CLCF often provide shade and moisture for the region’s coastal margin, driving, at least in part, faunal activity and species dynamics along the coast (Dawson 1998, D’Antonio et al. 2002, Baguskas et al. 2014). Both oceanic and atmospheric effects are important to CLCF formation, so predicting how CLCF may be altered in a changing climate is challenging, making future projections highly uncertain (Clemesha et al. 2016a). Research on the impacts of CLCF on the region’s ecosystems is limited. However, a new CLCF dataset may foster expanded regional research in this area. Understanding the role of CLCF in ecosystem dynamics is important because CLCF may buffer warmer and drier conditions in the region.

1.4.5 Conservation and Management for San Diego’s Future Climate

There is a long and continuing history of land and natural resource conservation planning and action in San Diego County. Although there are a number of efforts underway to begin integrating climate-focused monitoring and research into ongoing land conservation and management activities, they must be expanded and have yet to be fully incorporated into planning and management actions to address and mitigate climate impacts. Specifically, the spatial and temporal scales at which climate impacts must be considered to build resilience into our natural systems require landscape-scale planning that is best addressed in a cooperative, cross-jurisdictional approach. Long-term monitoring and adaptive management will be critical to managing species and ecosystems into the future, and adaptation and scenario planning will also play a role. In light of projected growing impacts of climate change, it is likely that management goals may warrant re-evaluation, recognizing that managing for the near-term, particularly single-species management, may hamper abilities to build resilience into vulnerable ecosystems (Boitani et al. 2007).

We intend for this report to provide a strong foundation for future multidisciplinary collaborations between climatologists, ecologists, land managers, conservation and land-use planners, and policymakers. The information contained herein summarizes the current understanding of climate regime on biodiversity and potential future impacts on the rich biodiversity of the San Diego region and highlights the unique opportunities for the region to be a leader in adaptive management under a non-stationary climate regime.

2: The Effects of Temperature Variability and Change on San Diego's Species and Ecosystems[2]

Authors: Megan K. Jennings, Kristen Guirguis, Dawn M. Lawson, Eric D. Stein, and Sula E. Vanderplank

2.1 Background and Current Conditions

San Diego County spans starkly different climate zones where desert conditions are found a short distance east of a mild coastal climate. The California Floristic Province, of which San Diego County is a part, is the most biodiverse region in the United States (Stein et al. 2000b, Myers et al. 2000, Burge et al. 2016). In particular, San Diego County, with its wide range of native species that inhabit the coast, foothills, mountains, desert, and border region has more imperiled species than any other county in the nation (Dobson et al. 1997). Organisms living within 10-20 mi (20-30 km) of the coast are acclimated to a generally temperate mediterranean-type climate, while those native to inland valleys and deserts are more acclimated to the temperature extremes the region experiences. The coastal zone is characterized by relatively cool days and mild nights. During summer, average daily maximum temperatures in the interior valleys are about 15 °F hotter than at the coast. In some parts of the interior valleys average summer maximum temperatures exceed 95 °F (35 ºC) while average coastal maximum

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[2] Suggested section citation: Jennings, Megan, Kristen Guirguis, Dawn M. Lawson, Eric D. Stein, and Sula Vanderplank. 2018. The Effects of Temperature Variability and Change on San Diego's Species and Ecosystems. Pages 11-29 *in:* Jennings, M.K., D. Cayan, J. Kalansky, A.D. Pairis et al. ***San Diego County ecosystems: ecological impacts of climate change on a biodiversity hotspot***. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: EXT-CCC4A-2018-010

temperatures are below 80 °F (26.6 °C). At night, the dry conditions in the interior valleys promote nighttime cooling, whereas coastal cloud cover helps to keep coastal temperatures mild. In winter, average coastal and desert temperatures are more similar than in summer. However, there are notable differences in the amount of day-to-day variability. The coldest winter temperatures are observed in the highest elevations where average nighttime winter temperatures are below freezing (Figure 2.1).

Temperatures at the coast are moderated by the cool waters of the Pacific Ocean. During the summer, the coast is often protected during the day from extreme heat by seasonally persistent coastal low clouds and fog (CLCF, colloquially known as the “marine layer”; see Section 5.1). However, clear days still occur and when they do, the coast can experience temperatures that may be closer to the warmer inland region. The frequency distribution of daily maximum temperatures along the coast is strongly skewed, with a long warm “tail,” indicating the potential for very hot temperatures relative to the mean climate on extreme days. This is partly due to the variability of marine layer clouds (see Section 5.1), which modulate temperatures in portions of the coastal margin that are affected by the atmospheric marine layer (Iacobellis and Cayan 2013) and when absent, can leave the coast unprotected during inland heat waves (Clemesha et al. 2017).

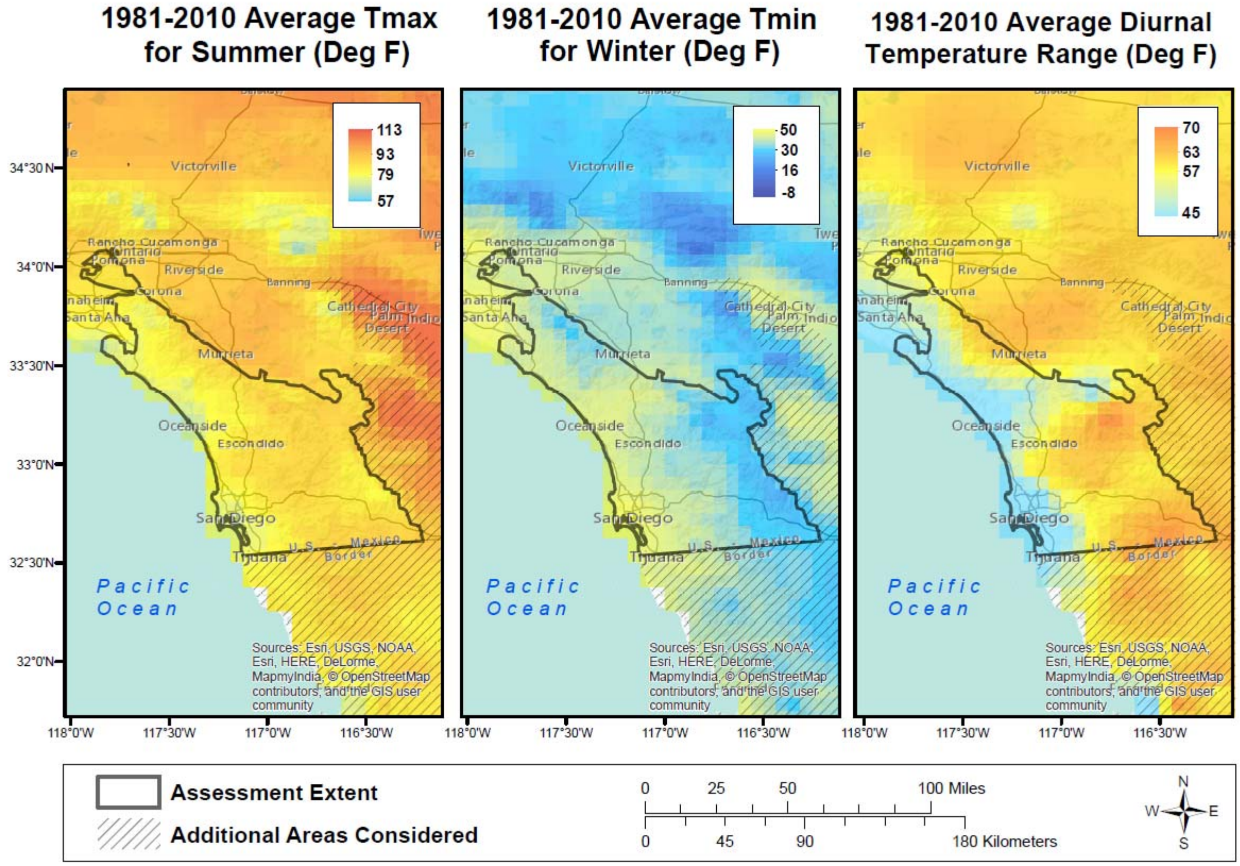

Figure 2.1: The San Diego region study area with historic maximum temperature for summer (left), minimum temperature for winter (center), and average annual diurnal temperature range (right).

Heat waves can also occur during Santa Ana winds (see Section 4.2.2), which are common during September and October, but may occur at other times of year too, and can bring very hot temperatures relative to the typical maritime climate. The highest temperatures along the coast generally are associated with Santa Ana winds that occur during the early or late part of the warm season. Nearly 50% of hot days along the coast (days over 85 ºF [29 ºC]) that occur in May are due to Santa Ana events. In October, Santa Ana events account for over 70% of hot days. Early-season heat waves have been shown to be particularly significant in terms of human health because they occur before the population has had a chance to acclimate to summertime warm weather (Basu and Samet 2002, Ebi et al. 2004, Guirguis et al. 2014).

In this section, we review projections of mean temperature and temperature extremes for the future and examine the impacts this may have on San Diego's ecosystems and species. We then conduct a literature review to identify the types of ecological impacts that might be expected in the face of increasing mean annual temperature, increasing severity and frequency of heat waves, and reduced number of freeze days. When possible, this review focuses on regionally-specific examples from southern California or San Diego County. Where there are gaps in the regional ecological knowledge, studies and models from other regions and systems were considered to determine how impacts might manifest in San Diego's ecosystems. In some cases, it is difficult to disentangle the effects of shifting or increasing variability in temperature from those of altered precipitation patterns. However, as there is greater confidence in temperature projections, we present these impacts separately and encourage additional research into ecological responses to these climate drivers both independently and together.

2.2 Shifts in Mean Temperature

Climate change is expected to raise yearly average temperatures by about 4-6 ºF (~2.2-3.3 ºC) by the end of the century under the RCP 4.5 scenario or 7-9 ºF (3.6-5 ºC) under RCP 8.5 (Figure 2.2). The greatest increase is projected for the fall season where some parts of San Diego show a temperature increase of >10 ºF (>5.6 ºC). To understand the ecological impacts of not only the trajectory and extent of change in mean temperature, but also the rate of change, more studies are utilizing climate velocity as a metric (Carroll et al. 2015). Climate velocity can be measured as the change in temperature per unit of time (e.g., degrees per decade or century). To more specifically assess the degree of impact to suites of species, velocity has also been measured in the units of distance per unit of time needed to maintain a stable climatic environment (Hamann et al. 2015), which can be helpful in determining how quickly species may need to move to stay in similar climatic conditions (Loarie et al. 2009). In San Diego County, the rate of change from the present to the end of the century, under either the RCP 4.5 or 8.5 scenario, is likely to be most rapid along the southern coast (AdaptWest Project 2015).

2.2.1 Range Shifts

Range shifts or contractions are expected for many species of plants and animals in response to changes in temperature and other climatic variables. Most often, shifts are expected at the edge of range extents toward cooler environments where future temperatures will resemble those of the current climate in the present-day range of a species. Species' shifts up in elevation and to higher latitudes with increasing temperatures have been widely reported across taxonomic groups both within California (Moritz et al. 2008, Tingley et al. 2012, Wolf et al. 2016) and globally (Chen et al. 2011). So, in general, climate change is anticipated to drive species' ranges upslope to higher elevations or northerly to higher latitudes (Loarie et al. 2008, Rapacciuolo et al. 2014), but the diversity of terrain and variability in climate across California may support biogeographic shifts that do not follow those expectations (Rapacciuolo et al. 2014). Specifically, in coastal southern California, there is a primary temperature gradient where winter low temperatures are higher at the coast and lower inland that can overcome the typical gradient of declining temperatures with increasing elevation and result in lower winter low temperatures at lower elevation in the coastal zone (Davis et al. 2007). Thus, in regions like San Diego, movement towards the coast (Loarie et al. 2008, Langham et al. 2015), where temperatures are relatively mild, may occur for some species where development and habitat fragmentation have not limited connectivity to these areas. Using elevation as a surrogate for temperature in these landscapes could obscure the biological effects of climate change (Monleon and Lintz 2015). In addition, species range shifts can be masked by disturbance history (e.g., fire), habitat fragmentation, and persistence of adults in long lived plant species where the climate is unsuitable for seedling recruitment (Murphy et al. 2010). The difficulty in detection and causal attribution of range shifts combined with uncertainty about their direction makes it difficult to plan for managing and maintaining populations under climate change. Because of its complex landscape, there is potential that the San Diego region may have more opportunities for species to shift and adapt to changing conditions. However, habitat fragmentation and loss, especially within the concentrated development along San Diego's coastal region will limit the opportunities for coastward range shifts.

The coastal sage and chaparral vegetation communities that dominate the landscape in southern California extend southward into Baja California, Mexico by approximately 155 mi (250 km), at which point there is an ecoregional boundary. It is these ecotones and boundary regions where community shifts may be most likely. Both chaparral and coastal sage scrub are expected to experience a high degree of exposure to climatic shifts in the future under high emissions scenarios, regardless of climate model, particularly in the coastal and foothill zones (Thorne et al. 2016). This exposure may affect up to 68% of the land area in the greater Los Angeles and San Diego regions where vegetation may be highly impacted by the end of the century under RCP 8.5, the future emissions scenario in line with current levels (Thorne et al. 2017). Predictions of change in the coastal sage scrub vegetation types common in coastal San Diego County include large scale declines in species richness in the South Coast ecoregion due to both climatic shifts as well as land use changes that affect dispersal and overall habitat availability (Riordan and Rundel 2009). This and other prior modeling efforts suggest that temperature is a key factor in determining the distribution of shrubland community species (Franklin 1998). In comparing the response of shrub distribution across the four southern California National Forests to climatic and terrain variables, mean minimum temperature of the coldest month and mean maximum temperature of the warmest month were the most important climatic variables (Franklin 1998). This suggests that range shifts of vegetation communities under climate change in San Diego will be primarily driven through temperature, although fine-scale shifts in distribution could emerge from changes in precipitation regimes. In fact, it is the combination of temperature, specifically maximum temperature of the warmest month, and precipitation that drive patterns of distribution for several species of manzanita (*Arctostaphylos*) in the San Diego region (Franklin 1998, Vasey et al. 2012, Villarreal 2012; Figure 2.3). Physiological evidence supports this correlation as well, as species within the genus *Arctostaphylos* have been shown to vary with respect to resistance to water stress (Vasey 2012).

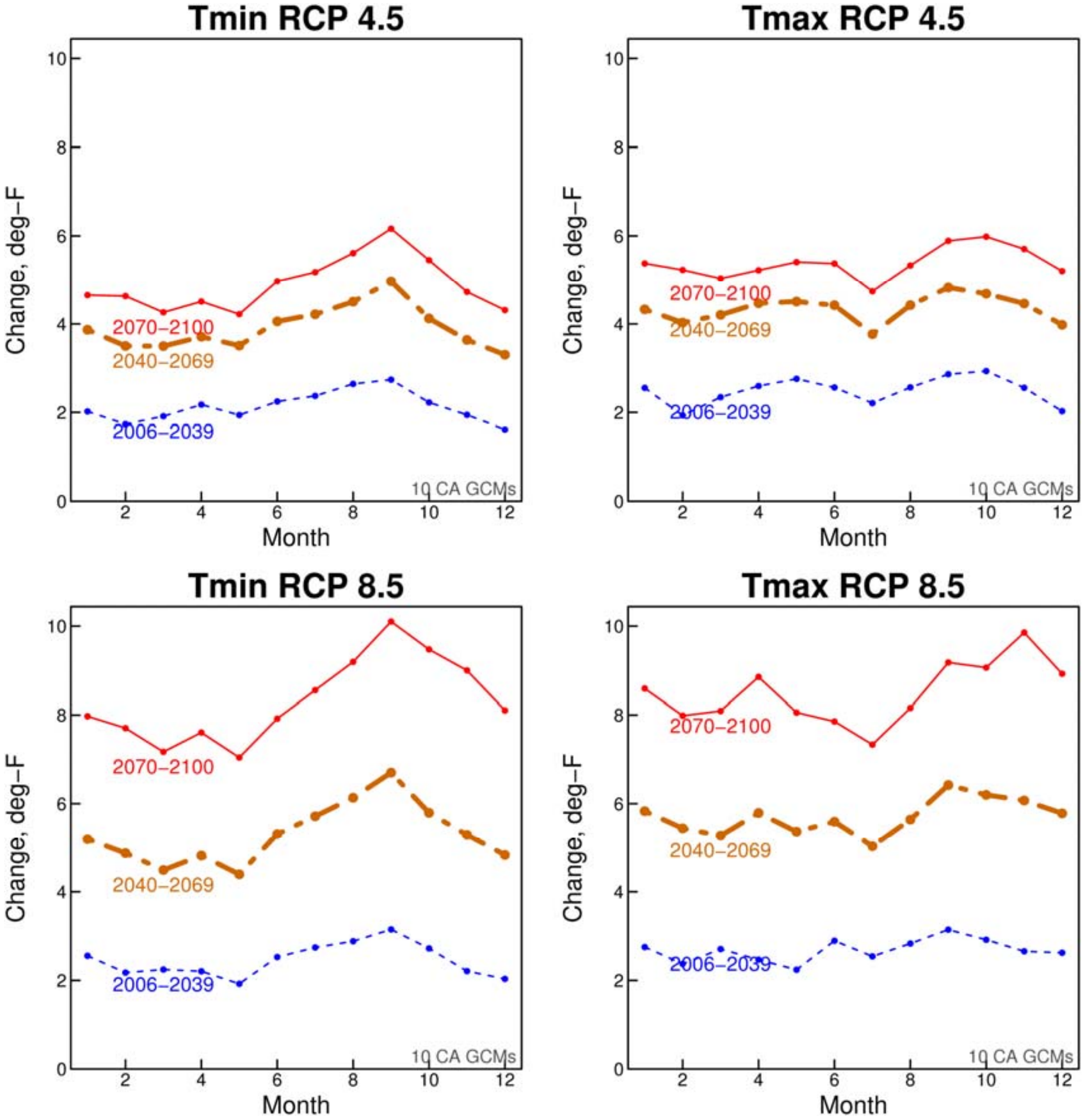

Figure 2.2: Projected shifts in temperature, based on the 10 GCMs used in the Fourth Assessment, over the annual cycle displayed as minimum and maximum temperatures under RCP 4.5 and RCP 8.5 in three future periods: 2006-2039 (blue dotted line), 2040-2069 (brown dashed line), 2070-2100 (red solid line).

Increased air temperatures also result in higher water temperatures for streams and estuaries, affecting their biological communities, particularly in regions like San Diego where relatively shallow systems are more susceptible to heating. Many cold-water-dependent species may already be at the limit of their habitat ranges in the study area. Examples may include the southern steelhead (*Onchorynchus mykiss*), formerly found throughout southern California, now found only in the northern extent of the study region and farther north, and the California newt (*Taricha torosa*), found only in stream segments with more persistent water such as San Mateo Creek at the border of San Diego and Orange Counties, and the San Diego River including tributaries such as Boulder Creek. Overall warming, reduced duration of persistence of cold water habitat, or loss of thermal stratification in ponds, lakes, and estuaries may reduce breeding and rearing habitat and threaten cold-water refugia during warm weather as has been described for the Pacific northwest (Ebersole et al. 2001) and the Sierra Nevada (Null et al. 2012). This may result in range contraction due to the loss of critical niches, despite the overall stream, lake, or estuary habitat remaining present. For example, Jaeger et al. (2014) predicted that, in the southwestern U.S., warming and drying will increase stream intermittency by up to 20%. Increases in dry channel reaches will reduce stream network connectivity and limit the opportunity for native fishes to access spawning habitats and seasonally available refuges.

For rare or endemic species that only occur in San Diego County and neighboring areas, temperature increases may alter habitat suitability, driving species' ranges out of the study area or even resulting in extirpation. The federally endangered quino checkerspot butterfly (*Euphydryas editha quino*) was one of the first narrow endemic species in the region for which a range shift in response to climate change has been observed (Parmesan 1996, Parmesan et al. 1999, 2015). Until recently, it was unclear what was driving elevational shifts in the species' range, but more recent research has pointed to warming temperatures as the likely driver (Parmesan et al. 2015). The diverse endemic plants of the San Diego region, and the California Floristic Province in general, are also particularly susceptible to projected climatic shifts. Scenario models of endemics project large-scale range contractions and shifts, particularly toward high elevation mountains where climate refugia may exist (Loarie et al. 2008). Conversely, species that currently occur in Baja California but not San Diego may move northward into the County, becoming components of novel, or no-analog, plant communities.

For some maritime scrub species primarily distributed in northwestern Baja California, climatic shifts projected for the end of the 21st century may result in a loss of suitability at the southern extent of species' ranges. It is unclear whether these species (e.g., *Aesculus parryi, Bergerocactus emoryi, Rosa minutifolia*) will be able to shift northward (Riordan 2013). Although climatic conditions may be similar north of the border, there are other constraints on dispersal and establishment that will limit the range and number of plant species that may colonize the San Diego region. Both range contraction and range shifts may split up San Diego's existing plant communities, constituting new assemblages of species and resulting in novel interactions among species (Loarie et al. 2008). Unfortunately, the region's flora is more likely to be dominated by contractions rather than shifts or expansions due to dispersal limitations.

The shifts in biotic interactions resulting from climatic changes may have synergistic effects that are important to consider (Russell et al. 2012), particularly when individual plants or vegetation communities are altered. Shifts in environmental conditions can change the availability and suitability of habitat for animal species, especially habitat specialists that rely on particular plant species or assemblages. These species may lose habitat, be forced to follow the shifting ranges of the plants they need, or both. Distribution models of two sensitive southern California wildlife species, the California gnatcatcher (*Polioptila californica californica*) and the quino checkerspot butterfly, overpredicted suitable habitat under future conditions when biotic interactions were not modeled (Preston et al. 2008). For the quino checkerspot, combined abiotic and biotic models predicted a 98-100% loss in suitable habitat under warming varying from 3-5 °F (1.7-2.8 °C) or precipitation shifts at either end of the spectrum (50% and 150%; Preston et al. 2008). The California gnatcatcher models showed similar declines in habitat suitability under altered climatic conditions, but the species was less sensitive to change than the butterfly (Preston et al. 2008). This highlights the importance of considering not only climatic variables in future modeling but shifts in biotic interactions under change models.

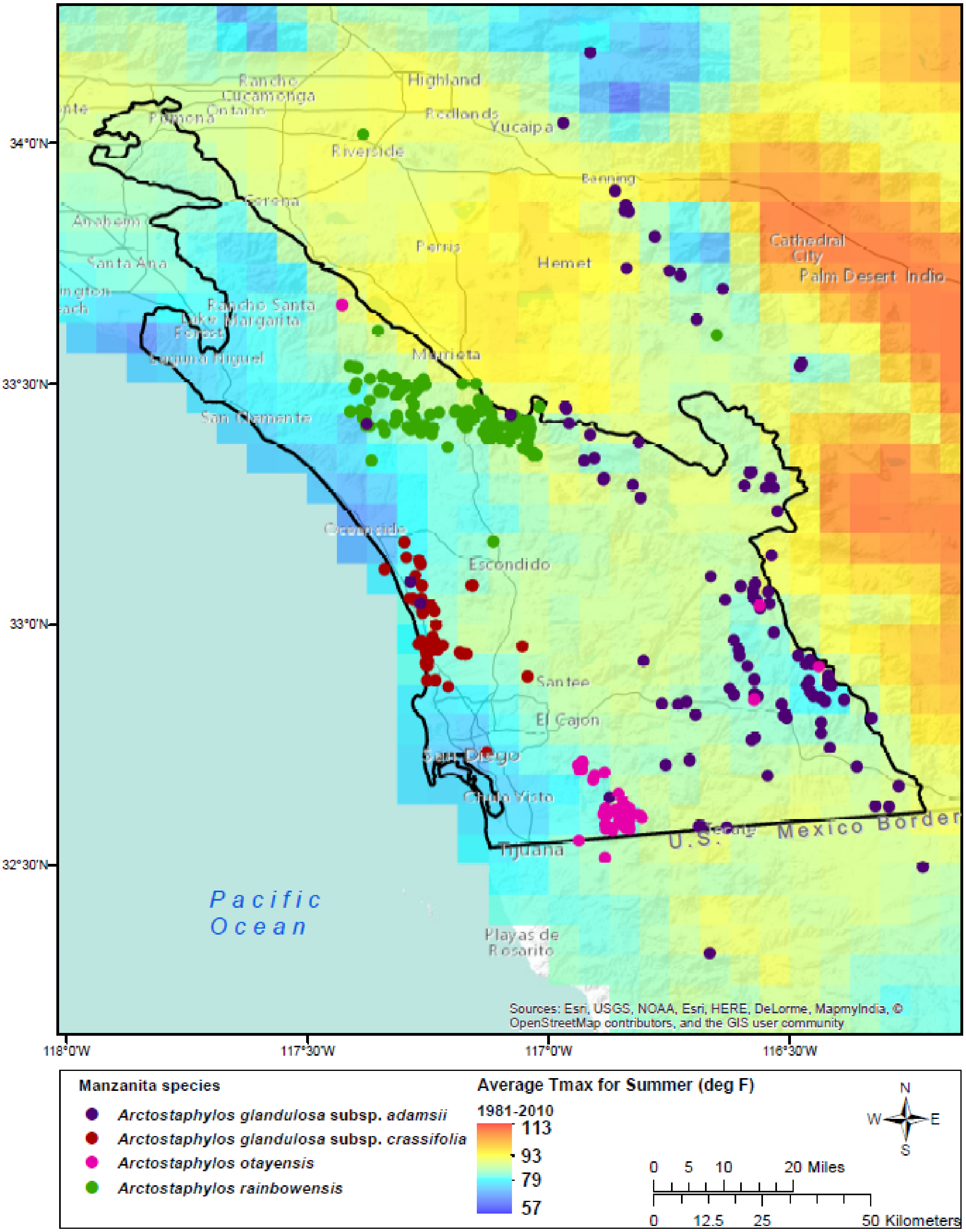

Figure 2.3: Occurrence data for four species of manzanita (*Arctostaphylos glandulosa ssp. glandulosa, A. g. ssp. adamsii, A. otayensis*, and *A. rainbowensis*; Global Biodiversity Information Facility 2017) in the San Diego region with respect to the distribution of maximum temperatures during the warmest months.

Temperature shifts are also expected to result in changes in the interactions of pathogens and of invasive species with susceptible populations of native species. Just as with managed species and habitats, pathogens are expected to shift ranges, many of them into novel environments with temperate climates. In some cases, the range of vectors will expand, which has happened with the *Aedes aegypti* mosquito, the insect vector primarily responsible for the spread of diseases like Zika virus, dengue fever, and chikungunya (Brown et al. 2017). Whether the individuals at the expanding edge of the range will be carriers of pathogens is unknown, as is an understanding of whether the virulence of pathogens will change with increased temperatures and expanded range extents. The expansion of pathogens can pose a risk not only to humans, but also to wild populations. For example, West Nile Virus, which has caused large-scale declines in the populations of several bird species (LaDeau et al. 2007) and infections and death in people, is expected to increase in the inland portions of the south coast by 2050 (Harrigan et al. 2014) unless control measures are taken. Pathogens affecting plants may also spread such as the insect-fungus complex, the polyphagous shothole borer (*Euwallacea* sp.) and *Fusarium* fungus that has recently caused large-scale death of a wide variety of native and agricultural tree species. Riparian tree species such as willow (*Salix* spp.) and sycamore (*Platanus racemosa*) have been particularly hard-hit in San Diego and other parts of southern California (Umeda et al. 2016) and are likely impacting nesting habitat for federally protected species like the southwestern willow flycatcher (*Empidonax traillii extimus*) and least Bell's vireo (*Vireo bellii pusillus*).

The impact of invasive species is also more likely in some systems under increased temperatures. These impacts may be realized through invasion pathways such that mechanisms for spread, invasion by new species, shifts in impacts, changes in distribution, and efficacy of control may be affected (Hellman et al. 2008). In aquatic environments, the lack of cold extremes may enhance the ability of some species to invade, expand, or to exert competitive or predatory pressure on native species (Rahel and Olden 2008). In San Diego County, this has already occurred as the shallow waters of many stream environments have experienced an increase in populations of warm water fish like sunfish into historically cold-water habitats. Increased weed incursion into native plant communities is also likely under increased temperature regimes (Dark 2004, Hellman et al. 2008).

2.2.2 Predicting Shifts

One way to predict how, in the absence of empirical data, ecological communities may respond to climate change is to identify traits of the species or species groups most likely to be susceptible to temperature changes. The response of both populations and individual species will depend on intrinsic factors like biology and life history traits as well as extrinsic factors such as exposure to changes in climate, disturbances, or habitat loss and fragmentation. The extrinsic factors are largely dependent on the range and biogeography of a species. The intrinsic characteristics can be separated into sensitivity and adaptive capacity (Foden et al. 2013). Lower trophic level communities, such as algae and benthic invertebrates, respond to temperature changes based on traits such as endemism, micro-endemism, temperature preference, altitudinal preference, and stream zonation preference. Modeled responses to projected climate change in Europe suggest that distributions of temperature-sensitive invertebrate communities have the potential to shift entire stream ecosystems (Hershkovitz et al. 2015). Higher trophic level life history traits relating to sensitivity include slow life history, large home ranges (Purvis et al. 2000), habitat specialization, narrow environmental tolerances, and rarity, while the ability to respond through adaptation may be hampered by poor dispersal potential and low evolutionary potential (Foden et al. 2013).

For example, species with shorter life spans are likely to be more susceptible to the negative effects of climatic variability than long-lived species (Morris et al. 2008). For short-lived plants, reproductive rates may be most impacted, whereas for animals, survival and reproductive rates are expected to be affected most by climate variability (Morris et al. 2008). However, the direction and degree of impact is dependent on the species and their relative sensitivity to shifting climatic variables (Muths et al. 2017). In the San Diego region, this could be particularly significant for rare and federally listed species that are short-lived such as the Laguna Mountains skipper (*Pyrgus ruralis lagunae*) and Hermes copper butterfly (*Lycanea hermes*), or annual plants that are narrow endemics such as the San Diego thornmint (*Acanthamintha ilicifolia*). The impacts to annual plants can be buffered by long-lived seed, such as the population of Orcutt's spineflower (*Chorizanthe orcuttiana*) which was rediscovered on Point Loma after 20 years (Lawson unpublished data). But for those annuals with short-lived seeds, the impacts may be more significant. Although most modeling of habitat suitability under shifting climatic conditions focuses on a single life stage (Russell et al. 2012), specifically the adult life stages in a population, reproduction and survival to reproductive maturity are the demographic variables most likely to be affected by these changes. This has been demonstrated in black oak (*Quercus kelloggii*), where seedling establishment was found to be most sensitive to the maximum temperature in August and also associated with water-year climatic water deficit with projections for reduced establishment windows in the future and associated population declines (Davis et al. 2016). Temperature in combination with precipitation is a very important driver of annual plant population dynamics, although the optimal values, timing, and interactions between them are species specific (Levine et al. 2008, Lawson 2011).

2.2.3 Adaptive Capacity

Generally, species' responses to disturbances and climatic shifts are defined by their adaptive capacity, such that species with a greater evolutionary potential or plasticity of ecological responses will have a higher capacity to adapt to environmental changes (Williams et al. 2008b). Though difficult to measure directly, adaptive capacity can often be measured indirectly through evaluation of dispersal ability and habitat specialization, which may indicate sensitivity to threats and stressors (Williams et al. 2008b, Glick et al. 2011, Gardali et al. 2012). This is currently a focal topic with respect to climate change but plays a role in how species respond to stochastic events such as wildfires, disease, and floods, and also to permanent changes like habitat loss and fragmentation. In the San Diego region, the Peninsular Range is an important source of genetic divergence in vertebrate and invertebrate species (Vandergast et al. 2008). This suggests that the region has relatively high capacity for evolutionary adaptation to climate change. But, that capacity may be limited by the rate of change in climatic shifts. If those shifts outpace the rate of evolution, then the persistence of many populations and species is at risk, particularly species that do not demonstrate an ability to behaviorally adapt or move. Nonetheless, protecting regions of genetic diversity and divergence are two important strategies for adaptation and resilience of natural systems.

2.3 Temperature Extremes

2.3.1 Heat Waves and Tolerance Thresholds

Climate change is already affecting California, and San Diego County, with more frequent and intense heat waves. Heat waves in the region have also become more humid, with warmer nighttime temperatures (Gershunov et al. 2009, Gershunov and Guirguis 2012). This reduced cooling at night means that humans and animals get less relief from the daytime heat, which historically occurred. High humidity can exacerbate the impacts of heat on health (Steadman 1984, Karl and Knight 1997, Sheridan and Kalkstein 2004). In California, the strongest health impacts from recent heat waves have been found at the coast (Knowlton et al. 2009, Gershunov et al. 2011, Guirguis et al. 2014), where residents are used to relatively mild temperatures and are not well acclimated to heat.

Along with long-term averages, temperature extremes would also increase (Gershunov and Guirguis 2012, Gershunov et al. 2013).The background climate warming will increase the frequency, duration, and intensity of heat waves, as measured against historical thresholds (Figure 2.4). Historically, the average hottest day per year was in the range of 90-100 ºF (32-38 ºC) at the coast and 105-115 ºF (40.5-46 ºC) in the deserts. Under RCP 8.5, the average hottest day per year is projected to increase to 100-110 ºF (32-43 ºC) and 110-125 ºF (43-51.6 ºC), respectively.

Importantly, changes in the probability of heat waves do not directly follow changes in background warming, because the processes that determine daily variability and drive heat waves differ throughout the region. This is shown through temperature probability density functions (PDF), which indicate how frequently heat waves of various intensity occur. Different locations across the region have asymmetric PDF shapes that vary considerably. Locations with less variance, or shorter warm tails, would see a greater increase in heat wave probability than would locations with larger variance, and longer warm tails, under the same amount of warming (Guirguis et al. 2017). For maximum temperatures, coastal locations (San Diego International Airport [SD ITL Airport], Figure 2.4a) exhibit long warm tails, whereas inland locations (Cuyamaca, Figure 2.4c) exhibit short warm tails. Under the same amount of warming, these differences in PDF shape would result in higher heat wave probability for Cuyamaca than for SD ITL Airport because, at Cuyamaca, the higher-density portion of the PDF is shifted over the historical 95th percentile threshold. The minimum temperature distributions (Figures 2.4d-f) exhibit a smaller variance than is observed for maximum temperature at all locations, especially at the coast. Under the same amount of background warming, minimum temperature heat wave probabilities would increase more than maximum temperature because high-density portions of the PDF cross the historical heat wave threshold. The result of shifting the minimum temperature PDFs is dramatic at SD ITL Airport (Figure 2.4d) and Miramar (Figure 2.4e) where, with background warming of 6 °F, approximately half of summer days would qualify as a heat wave (51% and 46%, respectively).

How marine layer clouds and Santa Ana winds may change in the future is not well understood and thus how heat wave frequency may be altered in the future is highly uncertain. Multi-year shifts have been observed in marine-layer clouds (Schwartz et al. 2014) and Santa Ana winds (Guzman-Morales et al. 2016) but long-term trends have not been detected. Although changes in Santa Ana winds in a changing climate are uncertain overall (see Section 4.2.2), the one change we can be reasonably certain of is that Santa Ana winds will get warmer. It is also worth noting that Santa Ana wind-driven coastal heat waves are responsible for the hottest temperatures recorded at the coast.

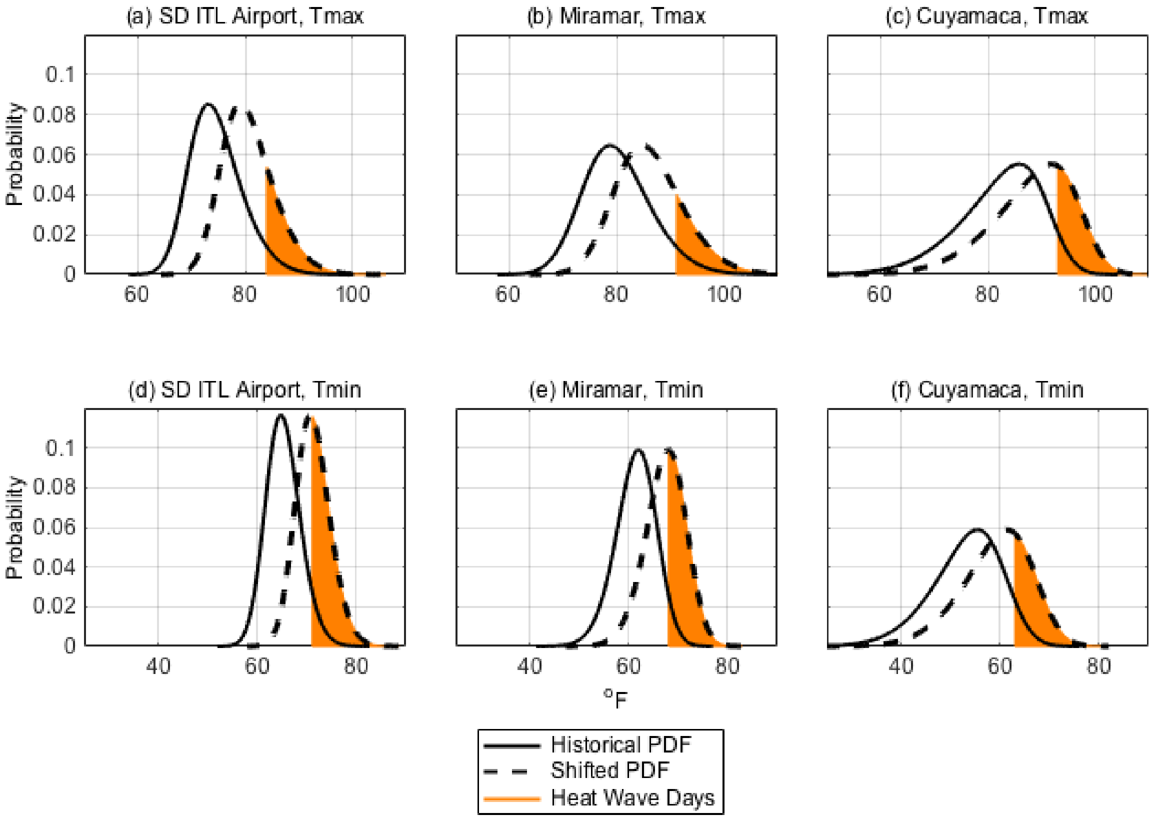

Figure 2.4: Distribution of historic extremes temperatures at coastal (SD ITL Airport; a&d), inland (Miramar; b&e), and montane (Cuyamaca; c&f) weather stations. Probability density functions are displayed for both maximum temperature (Tmax; a-c) and minimum temperature (Tmin; d-f).

For some species, although a general increase in mean temperature will result in range shifts and reduction of habitat suitability, it is extremes (i.e., heat waves) that will exceed physiological thresholds for temperature tolerance. The impacts of heat waves on human populations have been well documented (e.g., Basu 2009, Anderson and Bell 2011, Gasparrini et al. 2015). Generally, the effects are greatest in segments of the population that are older, younger, and those that have compromised health (e.g., Basu 2009, Basu and Malig 2011, Oudin Åström et al. 2011). Animal populations are expected to have similar responses to heat waves as human populations although there is far less evidence for the direct or indirect impacts on plants and animals than for humans. The impacts of heat wave events have been documented in domestic livestock during several extreme events such as the summer of 2006 and most recently, July of 2017, that resulted in large scale mortality across several counties (Carr 2017).

In wild populations, extreme temperatures can result in direct mortality, particularly to more sensitive segments of populations such as young and old age classes with the former having a greater effect on population trends as reproductive rates and survival to reproductive age may be limited or significantly reduced by these events. For example, a study of house sparrows in Europe detected an increase in reproductive output with mean temperature but extreme events resulted in reduced body mass and morphometrics of young (Pipoly et al. 2013). The limits and range of impacts of these extremes are largely unknown for most species. However, habitat suitability models of climatic niche envelopes that include projections for future suitability under climatic shifts can provide some insight. For the big-eared woodrat (*Neotoma macrotis*), a dense shrubland associate, habitat modeling has shown a response to both winter minimum and summer maximum temperature thresholds. Under GFDL climate projections for the end of the century, temperatures are expected to exceed these thresholds, severely limiting suitability for the species in the future (Lawson unpublished data). This sensitivity to temperatures beyond estimated thresholds may be driven by physiological limitations or energetic costs. In a congeneric species, the desert woodrat (*Neotoma lepida*), activity was significantly reduced when temperatures in Death Valley exceeded 107.6ºF (42 ºC), potentially limiting resource gathering (Murray and Smith 2012).

In very few cases, the sensitivity to temperature thresholds has been linked to direct impacts on individuals, populations, and species. Localized extinctions of *Sceloporus* lizards documented in Mexico were empirically correlated with extreme temperatures. These temperatures were hypothesized to have exceeded a critical thermal maximum for the studied species, leading to deaths and eventually local extirpations (Sinervo et al. 2010), a finding which could be particularly important for San Diego’s diversity of herpetofauna. The type of thermal tolerance restriction has also been incorporated into population models to investigate how these limits may affect demographic rates and population dynamics. The California spotted owl (*Strix occidentalis occidentalis*) has previously been identified as being sensitive to temperature and selecting nest stands with suitable microclimates (Barrows and Barrows 1978, Barrows 1981). Further research suggested that the species has a thermal tolerance threshold of 98.6 ºF (37 ºC) that would limit fecundity and survival (Weathers et al. 2001). However, this threshold is often exceeded in the southern portion of the species’ range in the Transverse and Peninsular ranges of southern California where the species persists. In future scenarios, that threshold is more likely to be met and/or exceeded (Figure 2.5). Modeling of California spotted owl fecundity and apparent survival in the San Bernardino Mountains, just northeast of our study area, suggests that the owls that inhabit southern California are more limited by precipitation, particularly drought events and preceding year precipitation, than temperature extremes (LaHaye et al. 2004). This finding emphasizes the importance of understanding whether there is variation in thresholds among populations and plasticity in responses by individuals experiencing temperatures beyond physiological thresholds measured in some locations.

The in-stream environment is another location where temperature thresholds for various species have been documented in southern California. Specifically, the federally protected southern steelhead (*Onchorynchus mykiss*) is known to have an upper temperature threshold of 77 ºF (25 ºC; Hokanson et al. 1977, Jobling 1981, Bjornn and Reiser 1991) which is often exceeded at the southern extent of their range in southern California. During extreme daytime temperatures, trout may move to deeper pools or areas where cool groundwater seeps may provide a refugium. However, these areas often have low dissolved oxygen, which can be lethal, just as temperature > 77 ºF (> 25 ºC) can be for the species (Matthews and Berg 1997). Although some species demonstrate plasticity to extremes through behavioral avoidance, as described above for the steelhead, the timing and severity of these extremes can drive the severity of impacts. For the federally endangered arroyo toad (*Anaxyrus californicus*) found in the San Diego region, estivation, or burrowing, is a common response to avoid high temperatures and desiccation during hot, dry summers (Ramirez 2003). However, because the species breeds in relatively shallow, slow moving streams, eggs or tadpoles may be more susceptible to early heat waves (Perry et al. 2012) that can quickly raise the temperature in shallow water beyond lethal levels.

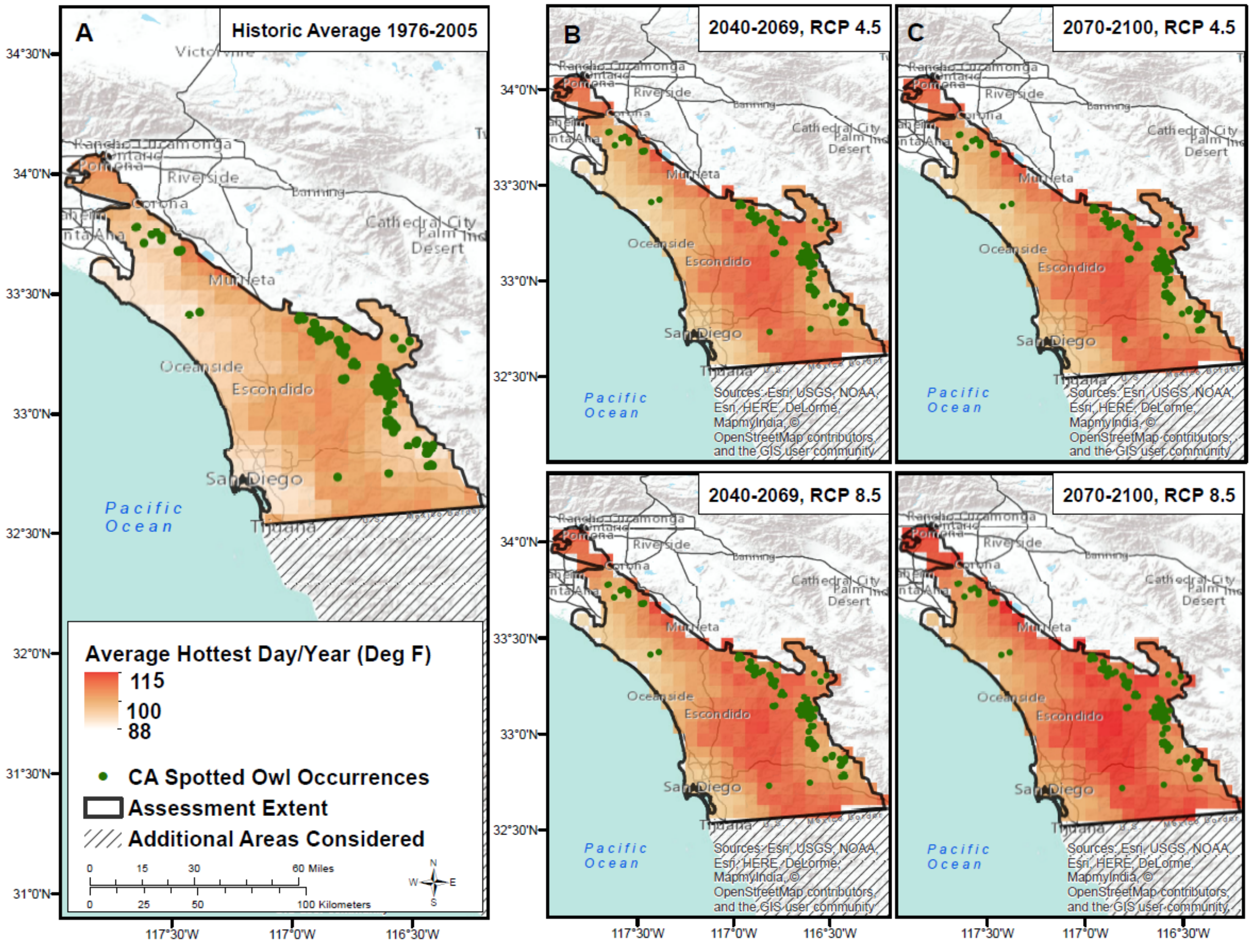

Figure 2.5: Extreme warm temperatures represented by the average hottest day per year in a) the historic time period, b) mid-century, and c) end of century under RCP 4.5 and RCP 8.5 emissions scenarios. Occurrence data for the California spotted owl (California Department of Fish and Wildlife 2017a) are overlaid to illustrate exposure to a thermal threshold of 98.6º F (37º C).

2.3.2 Shifts in Minimum Temperatures

Heat waves are only one end of the temperature spectrum. Climate change will also increase winter temperatures meaning that winters will be warmer in general, with fewer freeze days in the high elevation regions. In terms of cold extremes, there is evidence that mid-latitude anticyclones responsible for cold outbreaks in the southwest are becoming more frequent, meaning that future cold extremes could occur as frequently as in the past (Favre and Gershunov 2009). However, as temperatures continue to rise towards the end of the century, the likelihood of temperatures falling below thresholds used to identify cold extremes today will be much less likely (Gershunov et al. 2013).

Mediterranean climates are known for drought stress and fire, but due to their mild climates, the importance of winter low temperatures on plant distributions may be underestimated. In fact, variation in response to freezing is likely to be as important as drought and fire response in explaining plant distributions (Langan et al. 1997). Resistance to freezing depends on xylem conduit diameter (larger diameter, less resistance) (Jacobsen et al. 2007) and drought stress increases vulnerability to damage by frost (Ewers et al. 2003, Pratt et al. 2005). While seasonal drought occurs at the warmest time of the year reducing the likelihood of interactions between drought and cold stress, both extended seasonal drought and multi-year drought can result in winter drought stress when plants are most likely to experience freezing temperatures. Under these conditions of simultaneous drought and freezing temperatures, plants experience greater tissue damage and mortality.

Winter freezing tolerance can help explain both broad geographic and local microsite distributions (Boorse et al. 1998, Ewers et al. 2003). The influence of cold tolerance on plant distributions is exemplified by two sets of woody plants: 1) *Malosma laurina* and the related *Rhus ovata*, and 2) species within the genus *Ceanothus* (Figure 2.6). *R. ovata* has a higher frost tolerance with smaller xylem conduits and more frost tolerant leaf tissue than *M. laurina*. It occurs in more inland locations where winter lows are colder than the more coastal sites where *M. laurina* is found. Periodic cold snaps result in striking landscape level displays of dead *M. laurina* leaf tissue towards the colder margins of its distribution reflecting both micro and broad climate patterns (Davis et al. 2007).

Observational and experimental evidence link species distributions within the *Ceanothus* genus to differences in low temperature tolerance. Species distributions in southern California were found to be segregated along elevational gradients (Nicholson 1993) which are strongly correlated with temperature (Franklin 1998). In addition, experimental evidence has demonstrated the influence of winter low temperatures on the distribution of species within the *Ceanothus* genus (Ewers et al. 2003).

Changes in winter low temperatures anticipated under projected climate change are thus likely to influence both these sets of species and the communities of which they are a part. In the genus *Ceanothus*, abrupt species turnover with little commingling suggests that, in addition to climate, interspecific competition is important in determining these species' distributions (Nicholson 1993). As described above, because biotic interactions such as competition are important in defining the distributions we see today, it is not clear how these species might fare competitively in novel ecological associations that may form. These changes may also affect other conservation targets. For example, *M. laurina*-dominated coastal sage scrub is less suitable for the federally threatened California gnatcatcher (U.S. Department of the Navy [USDON] 2016). Increasing winter low temperatures could result in more suitable habitat for *M. laurina* across the landscape. Populations could be further increased by anticipated changes under climate change and increasing human population size (e.g. increased drought and fire risk) that favor *M. laurina* and further reduce suitable habitat for the California gnatcatcher.

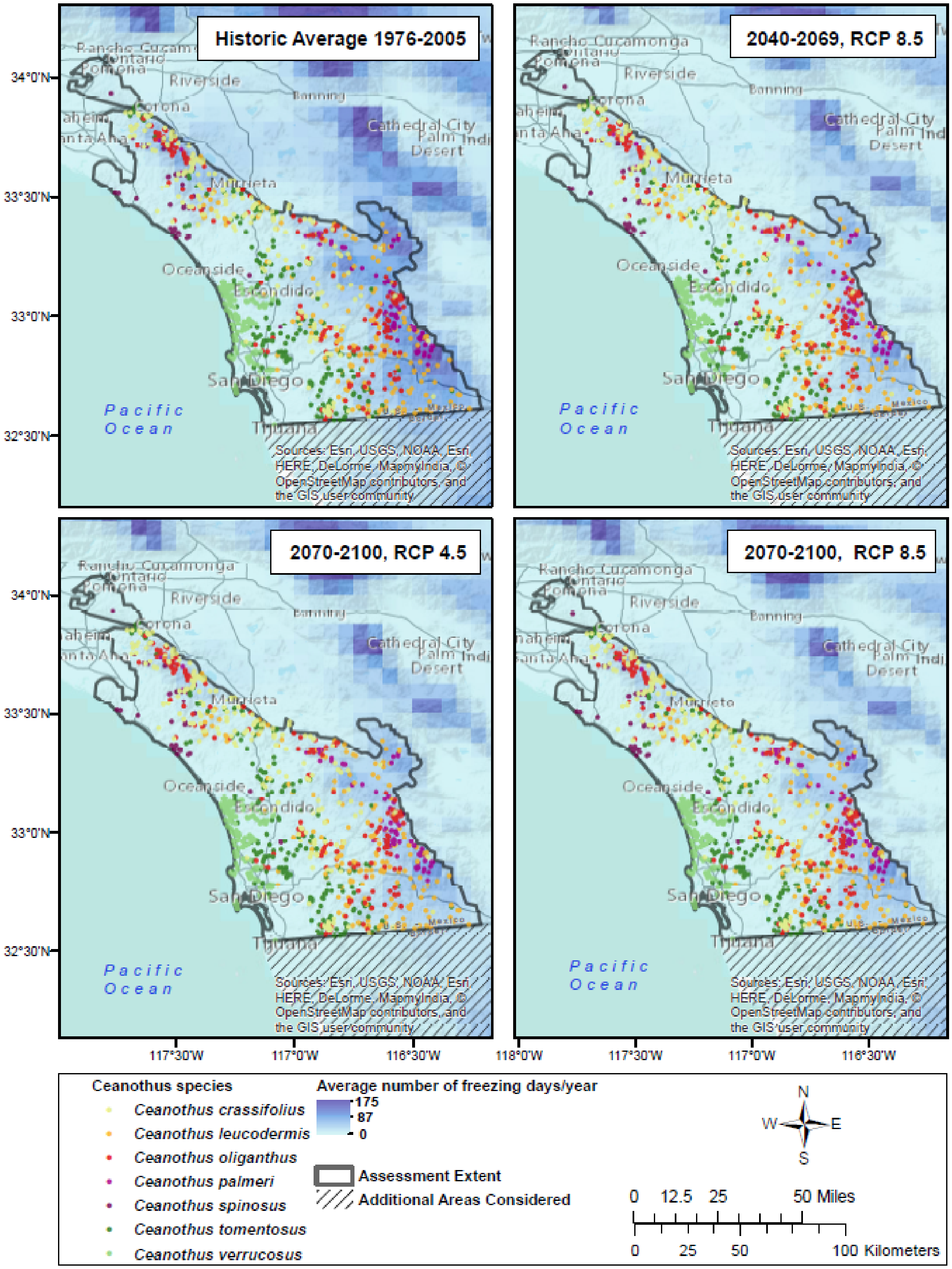

Figure 2.6: Distribution of extreme low temperatures for observed historic (upper left) and projected future climate conditions at mid-century (upper right) and the end of the century (bottom panels) in the San Diego region represented by number of days below freezing. Occurrences of species in the genus *Ceanothus* (Lawson 2009, Consortium of California Herbaria 2016) are included to illustrate the role of low temperatures in niche partitioning for the genus.

2.4 Timing

Shifts in temperature and temperature extremes may also result in altered timing of ecological phenomena like flowering, emergence of insects, and onset of breeding for many species. Over the last several decades, the arrival of migratory songbirds to breeding habitats and onset of nesting has trended earlier elsewhere in California (Macmynowski et al. 2007, Socolar et al. 2017). For many of these species, there is evidence that this trend is associated with climate (Macmynowski et al. 2007) and it has been suggested it is more likely monthly maxima and minima rather than mean annual temperatures that are the primary drivers behind these shifts (Field et al. 2016). In many plants, the timing of germination, leafing, and flowering is also shifting earlier. Specifically, those that flower in the early part of the season have been shown to be most sensitive to temperature (Wolkovich et al. 2012). *In situ* observations have revealed that phenological advances are drastically underpredicted in warming experiments (Wolkovich et al. 2012), highlighting the need to conduct monitoring and field studies to understand the full scope of phenological shifts. This information can be critically important for tracking how these phenological changes can result in mismatches in key biotic relationships like pollination; give competitive advantage to some species over others, particularly invasive species; or affect the synchronization of activities like breeding with availability of food resources. For many of San Diego’s rare plants, the breadth and importance of pollinators is unknown, making it difficult to assess whether phenological shifts may impact population persistence. In these cases, collecting baseline information about key ecological processes is the first step toward tracking and mitigating the impacts of climatic shifts on our natural systems.

Increases in the variability of temperature and shifts in timing of extremes and other fluctuations can also affect native systems. For many aquatic species, the onset of breeding is typically triggered by warming temperatures that reach a minimum threshold. Timing changes can trigger earlier emergence of insect larvae and more prolonged and extensive algal blooms, both of which can influence overall productivity of instream communities (Poff et al. 2002, Hamilton et al. 2008). This is particularly true for species of salmonids and amphibians like the arroyo toad. However, once breeding is initiated, temperatures must remain below maximum thresholds to allow for maturation in the fish and survival to metamorphosis in amphibians (Bancroft et al. 2008).

2.5 Refugia as an Adaptation Strategy

Planning for refugia is an oft cited strategy for designing conservation and land management strategies that will be resilient to climate change. Looking to the past for evidence of historic refugia through phylogeography and the fossil record has been one approach to tracking how species have responded through past climatic shifts (Gavin et al. 2014). In comparison, identifying future climate refugia is challenging for several reasons: first and foremost, the difference between the scale at which climate data are modeled and what is needed to identify refugia. Dynamic downscaling can offer the higher resolution data that are needed to identify refugia but is computationally intensive and not feasible to run at the regional level to allow for landscape-scale planning with respect to climate refugia. Secondly, there is also a question of what constitutes a refugium. Projections of temperatures into the future may lend themselves to identifying thermal refugia, but the variability in precipitation projections, both within a model and between climate models, make it more difficult to distinguish where precipitation refugia may occur.

One example of refugia emerging from local-scale patterns is from the Pacific coast of northern Baja California, Mexico. The influence of the relatively cold California current along the coast results in a heavy marine layer of low coastal fog that is highly stable and may sit over the land for days at a time (Vanderplank 2011). The effect of the cold current is strongest inland during the warmer months of the year and therefore fogs are most prevalent during those months, buffering the evapotranspiration balance until the winter months. Unique habitats have been identified within this region — namely the Maritime Succulent Scrub, noted for its high numbers of rosette-forming taxa that harvest moisture from the heavy coastal fogs (Rundel et al. 1972, Martorell and Ezcurra 2002). There are also small areas of Maritime Chaparral that favor non-sprouting chaparral species adapted to longer intervals between fire cycles and increased moisture from fog than inland areas. The low relief coastal plain between Ensenada and El Rosario is an area of exceptionally high endemism in the state of Baja California (Riemann and Ezcurra 2007, Garcillán et al. 2010). As an area with a relatively strong climate gradient, this region may be key to species migrations under changing climate regimes. The area seems to be a hotbed of speciation and an important future species refugium since the coastal fog mitigates some of the changing precipitation and temperature patterns (Minnich 2007).

Another approach is to investigate historic weather data and examine those for the location of microclimates that may be buffered from projected climatic extremes. The assumption with this approach is that microclimates created by topographic and air flow patterns will remain and that currently cool areas will maintain cooler conditions than the surrounding environments. In Figure 2.7, we have mapped historic mean temperature from PRISM (www.prism.oregonstate.edu) data between 1994 and 2015. Here, coarse-scale patterns of climatic trends suggest the coasts will be buffered from some temperature extremes, likely because of the marine influence in these areas. In addition, the montane regions of our study area do not experience the full range of extremes given the elevational relief in these areas. In contrast, the valley and foothill regions may be more susceptible to temperature extremes and those may be the areas in our study region where identifying local-scale temperature refugia may be beneficial for planning and management efforts. Although these data are still collected at a coarser scale than necessary to identify microclimates at the management- or preserve-level, they can be used as a first pass to target areas for monitoring to guide the selection of locations for future restoration, translocation, or acquisition targets. However, further study and additional, in-depth monitoring and modeling are needed to better understand potential temperature refugia prior to prioritizing these future actions. For example, deploying small, inexpensive temperature loggers across several potential study areas for a year could provide much more fine scale data and site-specific information about temperature refugia than could be gleaned from downscaled global climate models.

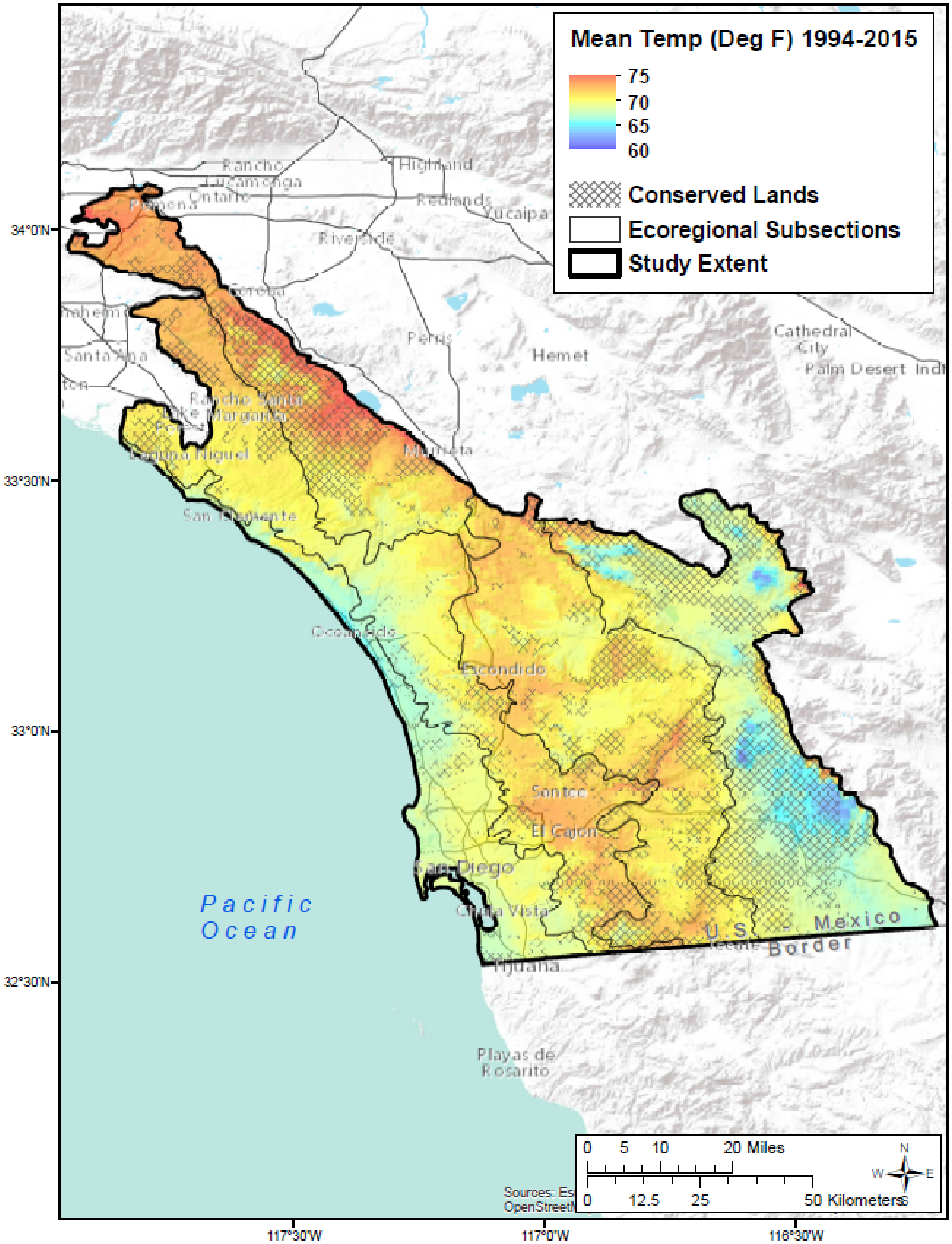

Figure 2.7: Map of potential temperature refugia across the region based on historic PRISM data of temperature averaged over the period from 1994 to 2015. Hatched areas represent conserved lands (SANDAG 2017, GreenInfo Network 2017).

2.6 Knowledge and Information Gaps

- The physiological impacts of heat waves and how humidity during the heat wave impacts species remain largely unknown.
- Species' genotypic and phenotypic adaptive variation in temperature tolerance.
- Modeling of biotic interactions for a broader range of species to better understand the interaction between climate, habitat elements, populations, and interspecific interactions.
- Several questions remain regarding climate refugia: What constitutes a refugium? How large does a refugium have to be to be effective? Over what time scales are refugia effective? What are metrics to determine if a refugium is effective? Lastly, how can this information be applied to management strategies?
- Further research into the impacts of temperature shifts, particularly temperature extremes, on demographic parameters and population dynamics.

2.6.1 Monitoring Needs

- Local scale temperature monitoring to inform adaptive management and site selection for habitat management or restoration projects to increase likelihood of success.
- Tracking of populations with range extent limits within or adjacent to the region to detect change.
- Phenology and population trend monitoring to identify when asynchrony is likely to lead to cascading ecological impacts (e.g., loss of pollination services).
- Increased spatial resolution of temperature observations would provide initial data to determine where climate refugia may be located and the respective size. Then, through ecological modeling, the effectiveness of the different variables can be examined.

3: Precipitation and Drought in San Diego County[3]

Authors: Julie Kalansky, Dan Cayan, Dawn M. Lawson, Eric D. Stein, and David W. Pierce

3.1 Current Precipitation Regime and Ecosystems

3.1.1 Precipitation Climatology Influence on Habitats and Adaptations

The San Diego County region has a mediterranean-type climate, wherein more than 80% of its annual precipitation occurs between the cooler November and April months (Figure 3.1). In addition to this markedly seasonal structure, the year-to-year variability in southern California is higher than anywhere else in the continental United States (Dettinger et al. 2011). Large spatial variability adds to the complexity of the climate regime in the region (Figure 3.2). The mean annual precipitation ranges widely, between approximately 8-36 in (200-900 mm), with most differences resulting from topographic influences. The topography changes dramatically over short distances. For example, there are only 30-45 mi (~50-75 km) between the coast and mountains. Although coastal areas have cooler summers, they typically receive less precipitation than inland locations, often causing them to be more xeric, or drier. Species and communities are able to persist in the face of highly variable precipitation because some features of the environment (e.g., groundwater reserves) buffer the variability and/or species have specific adaptations (e.g., bet-hedging life history strategies) to avoid or tolerate moisture deficit. As long as the interval between precipitation events does not exceed the longevity of long-lived dormant life stages, bet-hedging species may be less sensitive to projected changes than species in buffered systems as discussed below.

Shrublands are the most extensive vegetation type in San Diego County. There are two primary shrub communities: chaparral (dominated by evergreen species) and coastal sage scrub (dominated by drought deciduous species). These two communities array along an aridity gradient with coastal sage scrub on drier sites such as south facing slopes and at lower elevations and chaparral in more mesic sites (Mooney and Parsons 1973, Poole and Miller 1975). The shrublands are biologically diverse with high levels of endemism and numerous species with restricted ranges (Cowling et al. 1996). Shrubland plants have developed a wide range of adaptations to survive the seasonal summer drought and the high year-to-year variability in moisture availability. These adaptations fall into two main categories: drought stress avoidance and drought stress tolerance. Avoidance strategies include deciduous leaves that drop during drought stress thereby reducing moisture loss, and more extensive root systems that can obtain more water during drought. In addition, species can avoid drought by establishing seedlings during years with favorable moisture conditions. Tolerance strategies include stomatal control, cavitation resistance (water conduits are less susceptible to breakage under drought stress), and the ability to successfully establish after fire even during multi-year drought conditions.

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[3] Suggested section citation: Kalansky, Julie, Daniel Cayan, Dawn M. Lawson, Eric D. Stein, and David W. Pierce. 2018. Precipitation and Drought in San Diego County. Pages 30 - 48 *in:* Jennings, M.K., D. Cayan, J. Kalansky, A.D. Pairis et al. ***San Diego County ecosystems: ecological impacts of climate change on a biodiversity hotspot***. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: EXT-CCC4A-2018-010

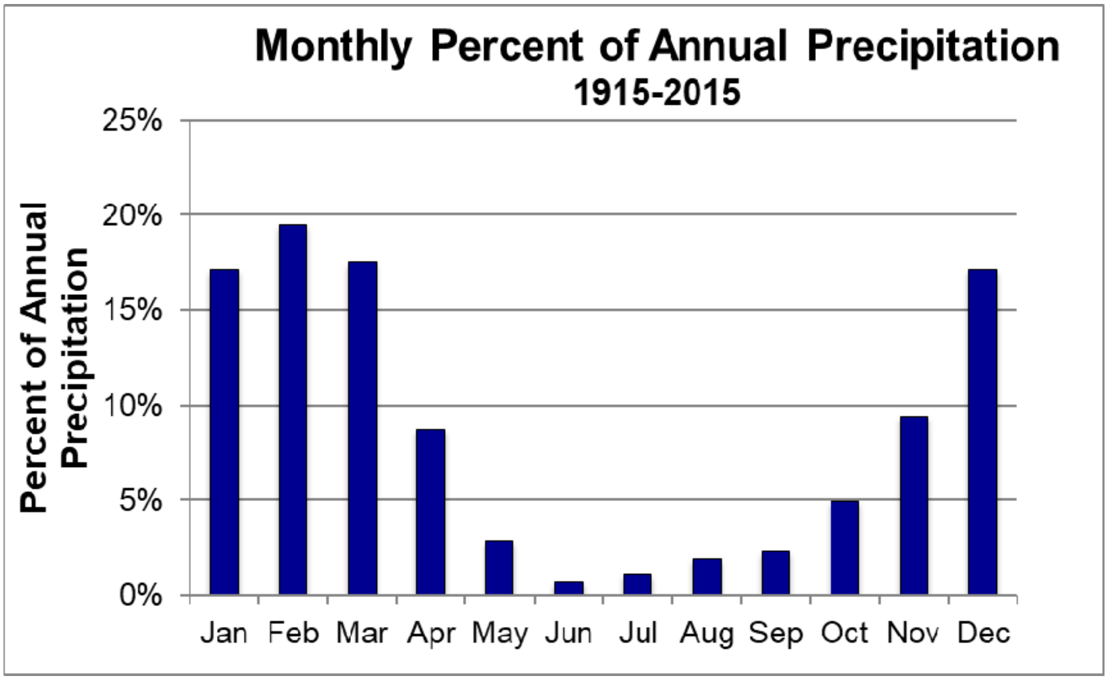

Figure 3.1: The monthly contribution to annual rainfall over the study region average of 1915-2015 using data from Livneh et al. (2015).

While analysis at the species level has utility for certain specific requirements (e.g., importance of California sagebrush to the federally threatened California gnatcatcher), the analysis at the functional group level provides a simplified perspective on community composition. Functional types refer to groups of species with similar ecological function and in a given community there can be multiple functional classifications. For example, as described above we can think of shrubland plants as either drought tolerators or drought avoiders. Drought tolerators include species with drought tolerant seedlings (less vulnerable to cavitation) that are very successful at post-fire establishment but adults that are more susceptible to mortality under drought (because of smaller root systems). Drought avoiders, conversely, are species that avoid drought stress. They have lower resistance to cavitation and almost no post-fire seedling survival but exhibit greater adult survival in fire free intervals due to more extensive root systems. In San Diego County shrublands, these functional groups also align with another functional classification, familiar to many, that is based on a mode of post-fire regeneration. This classification separates species into three groups: obligate seeders (fire kills all adults and regeneration is from soil stored seed), obligate resprouters (plants are top killed and post-fire regeneration comes from lignotubers), and facultative seeders (plants resprout and seedlings reestablish after fire). Obligate seeders are drought avoiders while obligate resprouters are drought tolerators, and facultative seeders are intermediate (Venturas et al. 2016). In San Diego County these species represent both widespread and limited distribution taxa. Obligate seeders include the widespread buckbrush (*Ceanothus cuneatus*) and the narrowly distributed wart-stemmed ceanothus (*Ceanothus verrucosus*). Obligate resprouters include the widespread toyon (*Heteromeles arbutifolia)* and the narrowly distributed Nuttal's scrub oak (*Quercus dumosa*). Facultative seeders include the widespread chamise (*Adenostoma fasciulatum)* and the narrowly distributed Encinitas baccharis (*Baccharis vanessea*) (USFWS 2011).

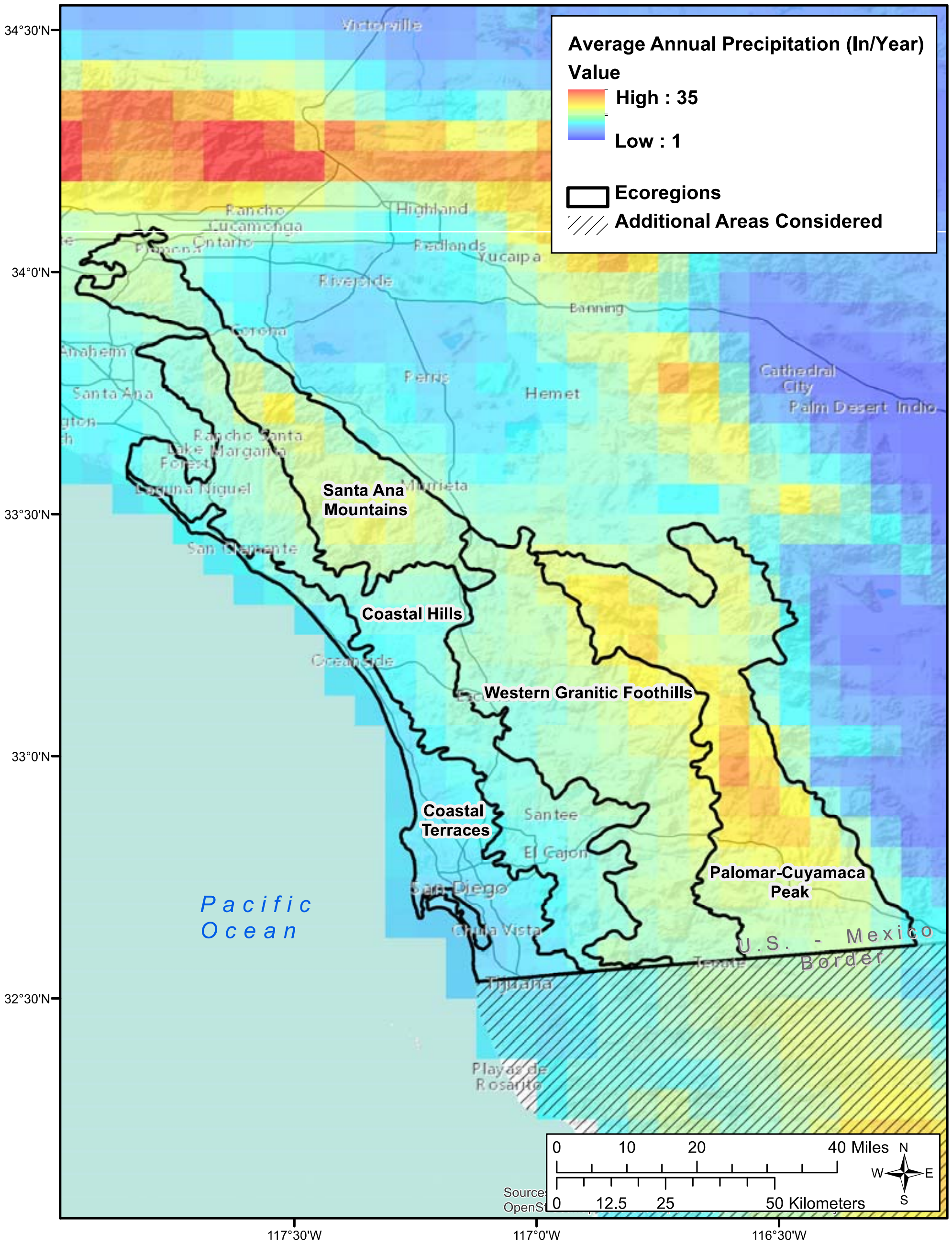

Figure 3.2: Annual precipitation from 1915-2015 (Livneh et al. 2015) with ecoregional subsections (U.S. Forest Service 2007) overlaid.

The strongly seasonal precipitation regime also creates unique microhabitats in the region, wherein a primary example is vernal pools. Vernal pools are temporary ponds that fill during the wet season on sites with impermeable soil layers. Unlike groundwater dependent systems they have no year-to-year water storage and thus their hydrological function is not compromised by long-term drought. This may confer greater resilience to climate change but this does not mean that climate change does not pose threats. Vernal pools are characterized by hydrological extremes from complete inundation in the winter to desiccation in the summer and as a consequence have developed an endemic biota capable of surviving these conditions (Zedler 1990, Simovich 1998). In San Diego County, there are 4 state and 7 federally listed threatened and endangered species that depend on vernal pools (City of San Diego 2017). The depth and duration of ponding are key characteristics of vernal pool hydrology and important drivers of vernal pool plant populations (Bauder et al. 2009). They vary widely from years with no ponding to years of extensive inundation. This variability is controlled by the timing, amount, and intensity of precipitation (Bauder 1989, 2005, Black et al. 2016) and micro-topography within and near pools (Emery et al. 2009). This makes vernal pools sensitive to anthropogenic physical disturbances that reduce watershed size and thus alter pool hydrology. Both the flora and fauna of vernal pools have adapted to this variability with long lived dormant life stages (seeds and cysts) that persist in the soil (Simovich and Hathaway 1997, Bliss and Zedler 1998). While seed and cyst longevity is poorly documented for vernal pools, both have been shown to persist for multiple years if environmental conditions do not favor hatching (Simovich and Hathaway 1997, Black and Zedler unpublished data). Maximum longevity may be much longer based on other highly variable environments where bet-hedging strategies result in propagule dormancy (Fox et al. 2006) but annual mortality is not negligible. Projected increases in precipitation intensity under climate change (Section 3.2) means that pools will likely continue to fill and dormant life stages will emerge and reproduce. However, projected decreases in the frequency of winter rain events and increases in long-term drought will increase the probability that diapausing crustaceans will go extinct in some pools, particularly those that have historically been filling only in high precipitation years (A. Bohonak pers. com.). Vernal pools have been described as resistant to floral invasions (Collinge et al. 2011) and in fact invasive upland annual grasses do appear to be controlled in vernal pools where there are high levels of inundation (Bliss and Zedler 1998, Black et al. 2016). However, Zedler and Black (2004) describe the invasion of San Diego county vernal pools by *Agrostis avenacea,* a native of ephemeral wetlands in Australia. They conclude that the lack of large-scale invasion may be due to the fact that most invaders in surrounding grasslands are upland species rather than an inherent resistance to invasion of vernal pools. Changes in the annual timing of precipitation (for example, more frequent summer storms) may also promote the establishment of crustacean species that have not historically been found in San Diego's vernal pools (A. Bohanak pers. com.) and/or alter the composition of native crustacean communities (e.g., summer ponding would be favorable to *Branchinecta lindahli* but not *B. sandiegonensis* due to higher water temperatures; M. Simovich pers. com.).

Population demographics of annual plants that avoid seasonal drought by over-summering as seed are highly responsive to year-to-year variability and within-season variation in the timing and distribution of precipitation (Pitt and Heady 1978, Levine et al. 2008, Lawson 2011b). Many annual plants have long-lived dormant seed that ensure there are sufficient seeds to germinate during favorable years and thus buffer their populations from high interannual variability (Fox et al. 2006). Temperature, in addition to precipitation, often plays a critical role in germination, survival, and ultimately seed production although effects are species specific (Pitt and Heady 1978). San Diego spine flower, (*Chorizanthe orcuttiana*), an endangered species found in coastal chaparral communities of San Diego County, may experience recruitment failure during drought. In an evaluation of its population dynamics, the single best predictor of population size was January and February precipitation (r^2=0.83) and explanatory power increased significantly when temperature was included (r^2=0.97) (Lawson 2011b). Within-season droughts, defined as periods of no rain within the rainy season, can also have adverse effects on annual plant populations when initial rains stimulate germination and subsequent subseasonal droughts result in mortality before seed production (Pitt and Heady 1978, Russi et al. 1992). Thus, while changes to total annual rainfall exerts a strong influence, other variations in precipitation characteristics, including changes in frequency, timing, or intensity of individual events may impact plant and animal communities in the San Diego region.

There are numerous other examples illustrating how the biota in San Diego County respond to the region's highly seasonal climate. Amphibians such as the Pacific slender salamander (*Batrachoseps pacificus*) and the arroyo toad (*Anaxyrus californicus*) become dormant (estivation), during June or July, and then become active again after the first fall rain (Cunningham 1960, Mitrovich et al. 2011). Both these species strive to complete their breeding season before the landscape becomes desiccated, whereupon they enter estivation. Similarly, the California mouse, (*Peromyscus californicus*) breeds during winter, which is also thought to be a strategy designed to take advantage of water availability (Nelson et al. 1995). Impacts of drought years on birds often operate through "bottom-up" mechanisms via forage and food limitations (Bolger et al. 2005, Cruz-McDonnell and Wolf 2016).

3.1.2 Extreme Events and Riparian Ecosystems

Similar to other California regions, the high year-to-year variability of precipitation in San Diego County is heavily affected by extreme precipitation events (Figure 3.3). The wettest days, defined here as those at or exceeding the 95th percentile of wet days, explain 80% of the year-to-year variability (Dettinger and Cayan 2014). Most of the heaviest events occur during winter, although the region occasionally experiences a few high rainfall events from tropical storms or convective rainfall patterns during late summer and early fall (Figure 3.4). During winter, many of the extreme precipitation events arise during "atmospheric river" storms that are fed by long and often narrow streams of water vapor transported from the Pacific Ocean. When uplifted by the mountains and other rising topography in the region, these produce many of San Diego County's extreme winter precipitation events (Dettinger et al. 2011). In cataloging atmospheric rivers and precipitation in the region, Gershunov et al. (2017) showed that three quarters of the heaviest (at or exceeding 95th percentile) of wet days have occurred during atmospheric rivers. Other large precipitation events occur during closed lows, which are cyclonic circulating wind systems that form to the south from the strong westerly wind stream, and which sometimes "park" over southern California for two days or longer.

Heavy precipitation events have great impacts on the stream and riparian systems in the region, whose historical record can be described as a series of intermittent pulses (e.g., Figure 3.5). Stream flows can vary by over 50-fold during the course of a season and by several hundred percent between years (Figure 3.5). Riparian systems in southern California are thus characterized by a disturbance regime that has created complex habitats and ecological feedbacks. Many species in these systems rely on seasonal peak flows to support breeding and rearing (Lytle and Poff 2004). For example, a number of spawning fish and amphibians depend on substantial flows or ponding patterns during a particular seasonal time window (Pearl et al. 2005, Mitrovich et al. 2011). Moreover, seasonal and occasional very wet years with strong flood flows, erosion, and sediment fluxes and deposition affect channel and floodplain morphology, which sustains and enriches habitat types across the floodplain (Beechie et al. 2010). High daily stream flows are most often pre-conditioned by precipitation in prior weeks sufficient to wet the land surface. Periodic stream channel scour events are critical to preventing senescence and providing a mix of age stands critical to the life history of many riparian dependent species (Faber et al. 1989). Many of the healthiest streams are located in the eastern part of the study region (Figure 3.6), in large part because the areas surrounding the stream are less developed.

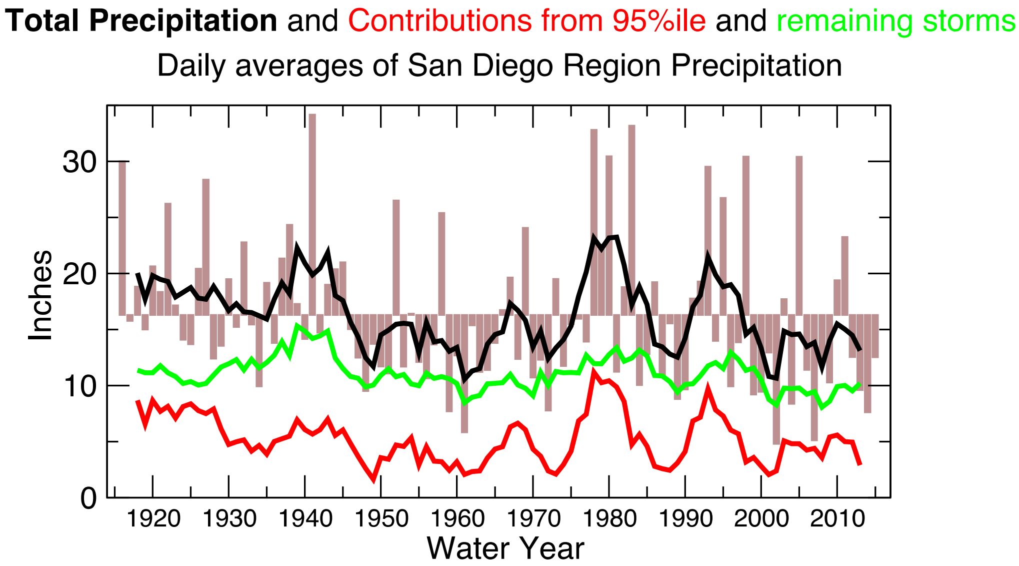

Figure 3.3: Precipitation events at and above the 95th percentile of daily amounts contribute 40% of the annual total and a major portion (80%) of the year-to-year precipitation in the San Diego study region. Brown bars are water year precipitation totals and the black line is the five-year running mean of the water year total precipitation. The red lines are contributions to annual total precipitation by events at or above 95th percentile of daily precipitation and the green lines are those less than 95th percentile. Figure courtesy of M. Dettinger, after Dettinger and Cayan, 2014. Data from Livneh et al. (2015) was averaged over the study extent.

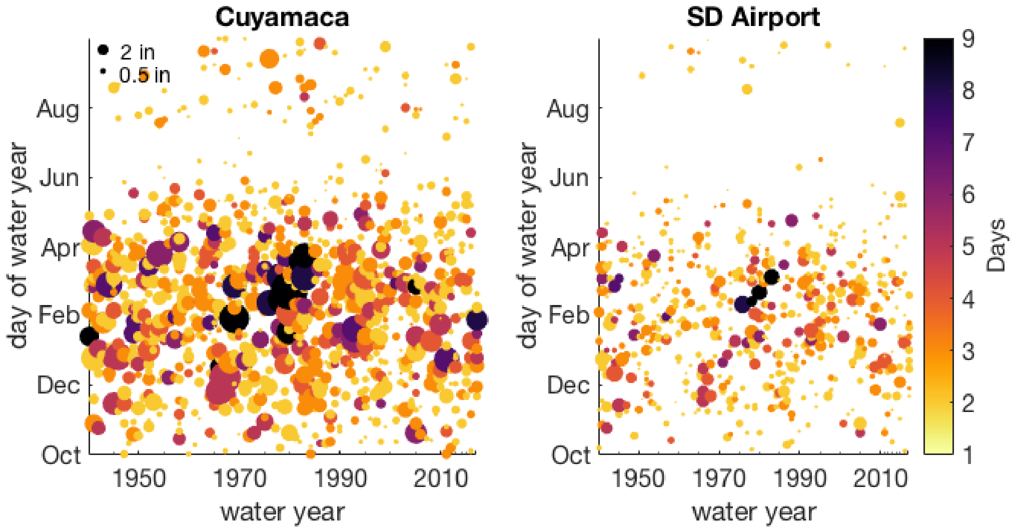

Figure 3.4: Occurrence of storms greater than 0.5 in (13 mm) (circles) from weather station records at Cuyamaca, located in the Laguna Mountains, and at the San Diego airport near the Pacific coast. Circle size represents the amount of precipitation and the color represents the number of continuous days of rain. The largest events have mostly occurred between November and March, though some occurred in late summer and early fall.

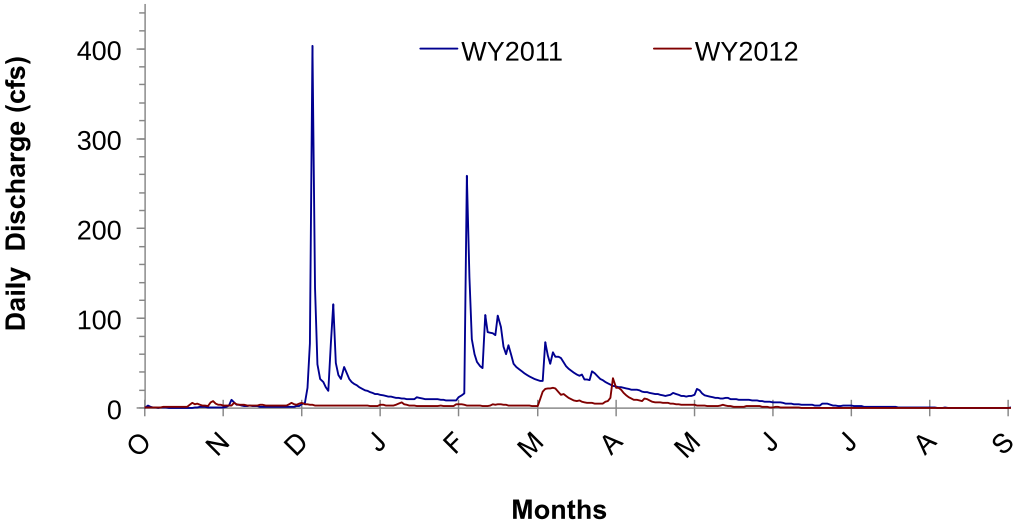

Figure 3.5: Daily discharge in cubic feet per second (cfs) from Sweetwater River, United States Geological Survey (USGS) gauge 11015000, which has headwaters in the Cuyamaca Mountains and drains to San Diego Bay. The flows shown are during a relatively wet year, 2011, and a relatively dry year, 2012.

Although the large natural variability of precipitation is a major controlling factor of stream flow characteristics, management decisions over the last 75-100 years have also had large impacts on riparian systems. Urban and agricultural development has converted naturally intermittent streams to streams with perennial or near-perennial flow such as in Peñasquitos Creek (White and Greer 2006). Some of these "perennialized" streams now support sensitive species or species that may be sensitive to climate change. Some of these species are already threatened or endangered, including the least Bell's Vireo. Increased recycling of treated wastewater for potable and non-potable uses and storm water capture through Low Impact Development and regional Best Management Practices (BMPs) designed to reduce pollution associated with urban runoff are reducing stream flows to more historical levels. However, these reductions may decrease the resiliency of "naturalized" aquatic dependent species by making them more vulnerable to dry conditions expected to occur under changing rainfall patterns.

Recent events such as the unusually wet heavy precipitation years of 2005, 2011, and 2017 and the droughts of 2001-2004, 2007-2010 and 2012-2015 exemplify the highly variable climate of southern California. The extremely warm dry years of 2014 and 2015 may be analogues of future drought events which will likely be exacerbated by warmer temperatures (Griffin and Anchukaitis 2014, Diffenbaugh et al. 2015). The recent wet winter of 2017, whose total precipitation was dominated by one or two highly productive storm events, may also provide a glimpse of how climate change may impact ecosystems in the region. By combining climate projections for the region, information learned from the recent events, and recent literature, we will discuss potential impacts of projected precipitation changes to the ecosystem. For consistency with the California Fourth Climate Assessment, all model projections use LOCA statistically downscaled data (Pierce et al. 2014).

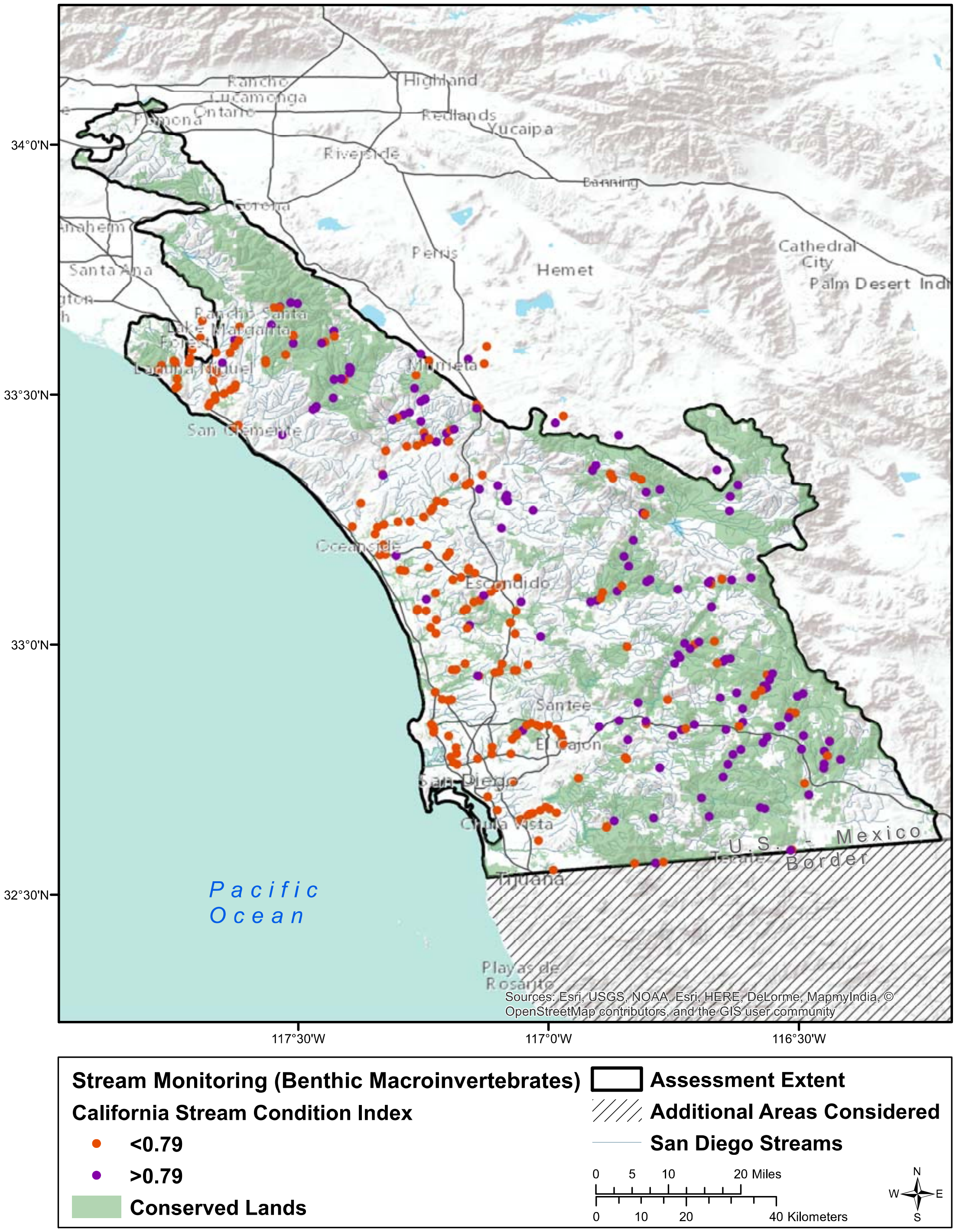

Figure 3.6: The California Steam Condition Index, CSCI, indicates the health of the stream based on benthic invertebrates (State Water Resources Control Board 2018). The score ranges from 0 to 1, with 1 indicating a healthier stream. The 0.79 cut-off represents the top ten percentile healthiest streams in California (Mazor et al. 2016). Many of the healthier streams, dark purple circles, are in eastern, less urbanized regions. Conserved lands data from the San Diego Association of Governments (2017) and the California Protected Areas Database (GreenInfo Network 2017).

3.2 Increases in Annual Drought Intensity and Frequency

By mid-21st century GCMs project that the subtropical zone expands poleward to the extent that precipitation occurrences in southern California are inhibited. Thus, even though projections indicate that occasional very wet days are projected to become more intense, the number of days with precipitation become fewer (Polade et al. 2014, 2017). This shift toward fewer rainy days would lead to years with increased numbers of dry days, and hence to an increase in the number of dry years. A collection of 10 GCMs exhibit this shift in daily and annual precipitation and also a tendency for runs of multiple years with deficit precipitation (Figure 3.7, bottom). The driest 5-years (also driest 1-, 3-, and 7- years, not shown) in a 31-year moving window are projected to become drier, especially under the higher RCP 8.5 GHG scenario. The intensification of dry spells is driven by an increase in the number of individual dry years, shown in Figure 3.7, (top) by the number of years whose annual precipitation falls below the 20th and 5th percentile of historical annual amounts. Again, increasing numbers of dry years is greater for the higher greenhouse gas (GHG) scenario, RCP 8.5.

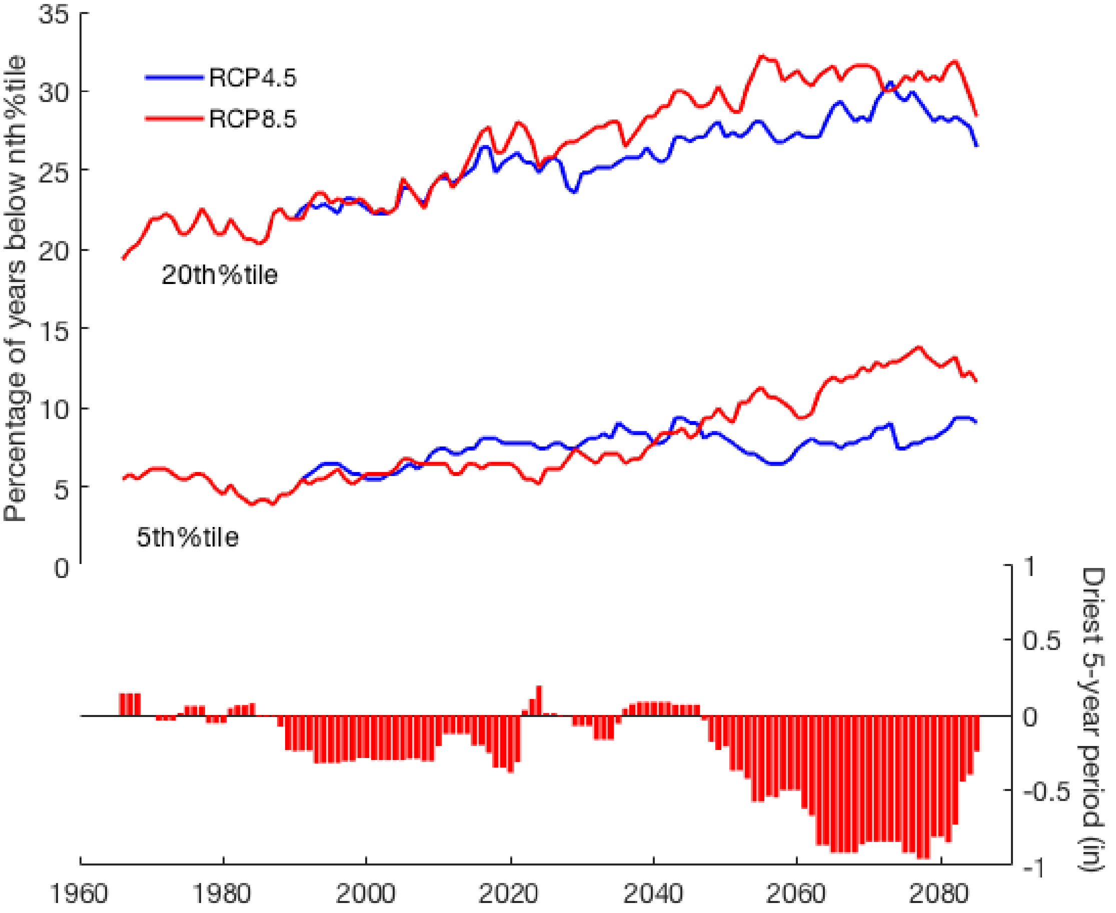

Figure 3.7: (Top) The percent of years in a 31-year sliding window that are below the 20th and 5th percentile thresholds averaged from a set of 10 RCP 4.5 (blue) and 10 RCP 8.5 (red) climate change simulations. (Bottom) Departure from average of the driest 5-years in a 31-year sliding window for RCP 8.5 (right). The anomaly is based on the average driest 5-years within the historical period.

Future dry spells during an overall warmer climate are a concern for San Diego County ecosystems. As noted above, the region's precipitation varies considerably within years and from year to year, and also has experienced large multi-year fluctuations. For example, within the last 101 years (Livneh et al. 2015), the driest 4-year period (1999-2002) dipped to 53% of historical long-term average and the driest 20-year period (1953-1972) precipitation fell to 80% of historical average.

To investigate future dry spells, a model projected 20-year drought was identified. This exercise considered simulations from several global climate models that have been selected for water resources climate change assessment (Cayan and Tyree, 2015) and also by the multi-institutional team who are preparing the California Fourth Climate Change Assessment, a 20-year drought was identified during the 2060-2079 period of the HadGEM2-ES RCP 8.5 GCM. The analysis considers the potential exacerbation of drought due to the increased dryness caused by changes in temperatures are very likely to increase throughout the 21st century and would increase losses of moisture from the land surface (Cayan et al. 2010, Diffenbaugh et al. 2015, Ault et al. 2016).

The selection of the simulated 20-year drought was made from statistically downscaled GCM output over San Diego County, which was used as input to the Variable Infiltration Capacity (VIC) land surface model to estimate hydrologically important variables including soil moisture, runoff, water loss from plants, and surface moisture and heat fluxes. Downscaling was accomplished using the LOCA technique (Pierce et al. 2014) in support of the California Fourth Climate Assessment. The LOCA downscaled data and the simulated drought episodes that were considered were developed from GCMs covering 1950-2005 for the historical period and 2006-2100 for two future climate projections using medium (RCP 4.5) and high (RCP 8.5) greenhouse gas and aerosol emissions scenarios.

The 20-year dry spell, along with the envelope of meteorological and hydrological measures from the 10 California GCMs is shown in Figure 3.8. As expected under the identification process, precipitation is generally low throughout the 20-year drought period, albeit with variations from very dry to somewhat greater than historical average. Overall, precipitation over the period is 79% of the historical median amount, nearly the same as the lowest 20-year average precipitation observed historically. Runoff closely mimics precipitation in its deflections through the 20-year period, but runoff is reduced to 57% of its historical median in comparison to the 79% precipitation reduction. Soil moisture on June 1 (total soil column moisture from the VIC model) also fluctuates but exhibits a significant decline from beginning to end of the 20-year dry spell. In part, this is likely the effect of increasing temperature more than 5 °F, because soil moisture during the long arid season trends downward as climate warms. All variables recover to the 10-model envelope median within a few years after the 20-year dry spell. Overall, the model simulations show growing impact in drying the landscape as climate warms caused by increased moisture deficits, wherein the atmospheric demand for moisture increasingly exceeds the amount available from the land surface via evaporation or transpiration (Williams et al. 2015b). If such a drought were to occur earlier in the 21st Century, the landscape would still be affected but of course not quite as extremely as during the warmer later period.

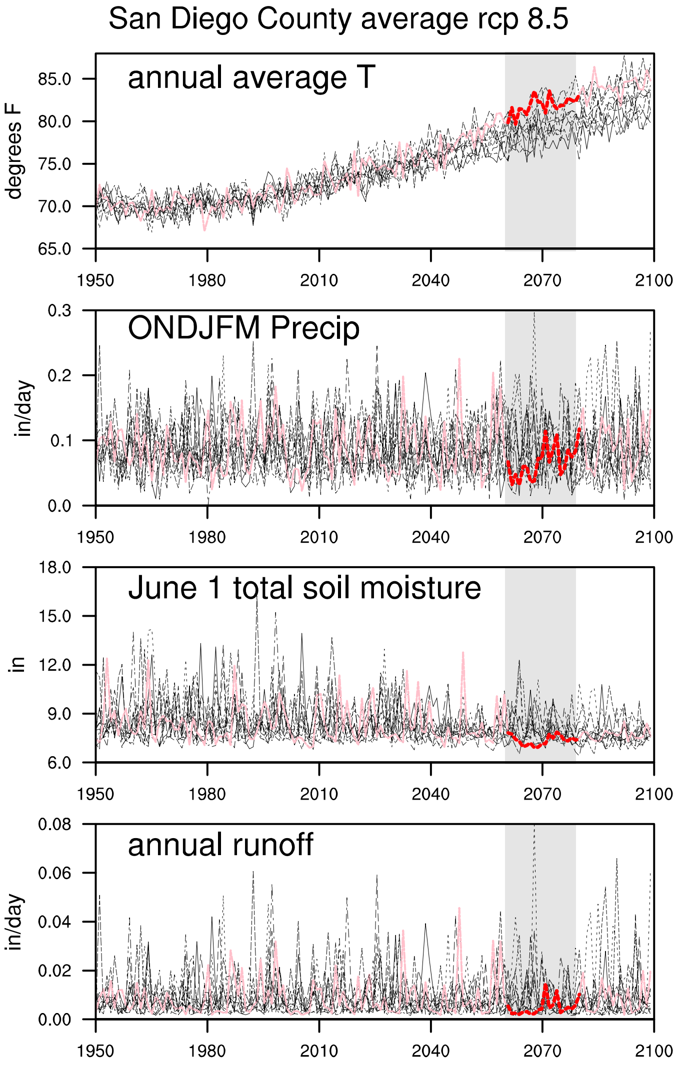

Figure 3.8. The 20-year extreme drought scenario relative to the other 10 California GCMs. The extreme drought is indicated by the grey shading. The precipitation is 79% of historical (2nd from top) but the run-off is only 57% of historical median (bottom), which is a result of the warmer temperatures (top).

Extreme drought has the potential to change ecological community composition and structure at the landscape scale in part because drought operates at a larger spatial scale than other disturbances such as fire. Although refuges likely occur where drought is mediated by local conditions such as fog (Kirkpatrick and Hutchinson 1980, Baguskas et al. 2014), shifts in composition and structure can occur through differential susceptibility of co-occurring species to drought or by making some species more susceptible to attack by pests or pathogens. In shrublands, extreme drought in the absence of fire could potentially shift stand species composition to favor deeper-rooted species (Venturas et al. 2016). Thus, while fire is the main driver of stand compositional changes (see Section 4), drought could also restructure communities. Drought interacts with fire because post-fire patterns of species establishment are strongly influenced by pre-fire patterns of individual plants in a stand. These patterns could be perpetuated by fire (Odion and Davis 2000). Additionally, drought may act in concert with other stressors, such as invasive species and nitrogen deposition, to cause community change (Cox et al. 2014, Pivovaroff et al. 2016). An example of this is thought to be the influence of periodic severe droughts in combination with grazing to influence the shift from native to exotic grassland in the 1800s over large areas of California (Burcham 1956).

Severe drought can also cause stress that makes trees vulnerable to insect attack (Allen et al. 2010), as was reported during the recent (2012-2016) drought in the form of several localized areas of rapid oak mortality in southern California. The oak deaths are thought to be a result of drought and attack by secondary wood borers and native ambrosia beetles (California Forest Pest Council 2015, Lawson et al. 2017a) and may also involve fungal attack (Aguirre et al. 2018). These insects typically don't attack healthy trees, so drought stress likely predisposed them to attack. Oak mortality is usually a decades-long process characterized by leaf thinning and branch loss (Jenkins and Pallardy 1995). However, beginning in 2015 on Marine Corps Base, Camp Pendleton in San Diego County, trees with full, dense, canopies appeared to have died over a single growing season (Lawson et al. 2017b). This uncharacteristic mortality was observed as a full canopy transitioning from dark green to pale green/tan leaves within a year. These trees have not resprouted either from the canopy or base as is typical of this species when damaged. Mortality continued through 2016. At two sites on Camp Pendleton the increase in recently dead oak trees (*Quercus agrifolia*) was approximately 500% or more (n=103 and 159) in 2016 compared to 2015. No sign of goldspotted oak borer (GSOB) was found in the trees. This level of oak mortality is unusual. In extensive, long-term oak studies on Camp Pendleton from 1986 through 2011, no evidence of previous large scale oak mortality was detected (Lawson 1993, 2015). It is possible that this phenomenon would have been more widespread in San Diego County in 2015 and 2016 had the GSOB not killed so many trees in other areas of the County. While the GSOB is not more likely to select drought-stressed trees for oviposition (Coleman and Seybold 2011), fewer trees on the landscape would mean lower competition for deep soil moisture. If indeed this rapid mortality is a result of long-term drought and ambrosia beetle attack, mortality may decrease rapidly with the higher levels of rainfall in the winter of 2016/2017. In addition, conifer tree die-offs resulting from recent (2002-2005) drought stress and insect attacks have been documented in (Freeman et al. 2017) and near (Minnich et al. 2016) the study area.

Beyond the importance of oak woodlands to biodiversity (Ohmann and Mayer 1987), climate impacts on oaks also have important cultural implications for the tribal communities in the San Diego region. There are few parallels to the oak tree when it comes to plants of cultural significance for tribal communities in San Diego. From a practical standpoint, oak trees provided an extraordinarily abundant and nutritious source of food in the form of acorns. A single tree could provide hundreds of pounds of acorns, which could be gathered and stored for months, thereby making subsistence horticulture unnecessary, and allowing California Indian tribes to develop complex economies and political structures of the type more typically associated with agricultural societies. But oak trees are more than practical; they are a symbol of life, growth, and the cycle of the seasons. California Indians venerate the oak tree because it is the very basis of their survival.

Annual plants, particularly winter annuals which germinate with the onset of the rainy season and set seed prior to the dry season are particularly resistant to drought. However, their response to drought is complex and depends on multiple factors including seedbank longevity, phenology (e.g. timing of germination, flowering and seed production), precipitation and temperature requirements, and interspecific competition so that it is not possible to generalize the response to drought of all winter annuals. The annual life history itself is an adaptation to regular seasonal drought. For longer term drought, the organismal point of view means that, what is harmful for one species may have a neutral or positive effect on another. The timing and intensity of precipitation, in combination with temperature, drives annual plant population dynamics including germination, flowering, and seed set, and the optimal configuration of these factors varies among species (Pitt and Heady 1978, Bowers 2005). Second, long-lived seedbanks can be an important bet-hedging strategy where only a fraction of viable seeds germinate when conditions are good (Clauss and Venable 2000). This means that if post-germination conditions result in plant death before reproduction, a seedbank persists. These two factors influence interspecific competition and can result in annual plant community composition varying widely year to year (Pitt and Heady 1978). A change in the patterns of variability (e.g. increasing numbers of dry years and/or increasing length of dry periods) mediated by interspecific competition will likely affect composition of annual communities. However, extirpation may not be common because temporal heterogeneity, discussed above, and microscale spatial heterogeneity result in refugia for annual species of differing requirements (Brooks and Berry 2006, Rao et al. 2011).

The literature on the impacts of extended drought or increased drying over long periods on vernal pools is limited. However, adaptation to high variability and frequent drought through bet-hedging strategies (Simovich and Hathaway 1997) suggests that vernal pools may not be as vulnerable to the projected increase in drought as other ecosystems (but see Section 3.1.1), provided the extent of their watersheds are not physically disturbed or altered so that they are sufficient to maintain the depth and duration of ponding. The vernal pools that are part of the City of San Diego's Habitat Conservation Plan will provide data to better understand the vulnerabilities of this ecosystem to future droughts.

There have been several studies that indicate bird species are negatively impacted by drought. A study of four bird species during 2002 and 2003 indicate a strong response to drought. Wrentit (*Chamaea fasciata*), spotted towhee (*Pipilo maculatus*), California towhee (*P. crissalis*), and rufous-crowned sparrow (*Aimophila ruficeps*), are all dependent on coastal sage scrub for habitat. In 2002, a drought year, these species experienced a significant decline in reproductive success with only a 1.8% success rate. This low success was attributed to a lack of food availability as arthropod abundance was extremely low as a result of the drought (Bolger et al. 2005). However, another study of wrentit during 2002 that supplemented food growth also showed later egg laying data and reduced the length of the breeding seasons suggesting that environmental conditions provide cues to the species as to when to breed and food supply may be a secondary factor (Preston and Rotenberry 2006). Other studies throughout the southwest have indicated negative impacts of drought on bird species reproductive success including greater roadrunner (*Geococcyx californianus*), ash-throated flycatcher (*Myiarchus cinerascens*), mourning dove (*Zenaida macroura*), Costa's hummingbird (*Calypte costae*), house finch (*Haemorhous mexicanus*), Crissal thrasher (*Toxostoma crissale*) and burrowing owl (*Athene cunicularia*) (McCreedy and van Riper 2014, Cruz-McDonnell and Wolf 2016). Given the impacts of drought on reproductive success, increased frequency and severity of drought may significantly affect bird populations in the region.

3.3 Intensification of Seasonal Drought

Another aspect of projected intensification of droughts is that GCMs indicate seasonal summer drought in Southern California may become more prolonged due to drying in the spring and fall shoulders of the traditional cool season rainy period. From the GCMs, spring precipitation decreases considerably, by approximately 20% during the mid-21st century and approximately 25% by the end of the century under RCP 8.5 (Figure 3.9). Fall precipitation decreases by approximately 15% during mid-century and approximately 20% by the end of the century (not shown). Under RCP 8.5 the spring precipitation decline, combined with effects of warming, result in progressive declines in spring soil moisture (Figure 3.10), amounting to 10-15% decreases by late 21st century. Adding to the seasonal drying is an increase in the region's already high excess demand for moisture from the land surface by the atmosphere, called the "climatic water moisture deficit" (Stephenson, 1998), a measure that is physiologically meaningful to plants and correlates with the distribution of vegetation types across the landscape. Under RCP 8.5 the climatic water deficit over San Diego County rises over the 21st century, reaching 5-25% increases by late-21st century (shown in Section 4 – Figure 4.4).

For many plant communities, spring is the time of largest increases in biomass due to the availability of moisture as well as the longer daylight hours (Parker et al. 2016). Thus, the projected spring drying has the potential to limit the growth of plants during their primary growing season. In terms of management, the implications of the spring drying remain uncertain because it is not known how a wide range of species will react to the spring drying or if it is significant enough to cause structural changes within an ecosystem. The largest implication for the fall drying is the extended fire season during the seasonal window of Santa Ana winds, which have caused the most devastating wildfires. Wildfires and their impacts are discussed in more detail in the Section 4.

The impacts of the change hydroperiod will have immense effects on intermittent and ephemeral streams in terms of reduced richness and disruption of breeding and dispersal patterns of invertebrates, fish, and amphibians whose life histories are tuned to cues associated with seasonal flow and inundation patterns (Brooks 2009). Blaustein et al. (2010) similarly predicts that climate change will adversely affect amphibian populations by altering survival, growth, reproduction, and dispersal capabilities, influencing food availability, predator-prey relationships, and competitive interactions, and by increasing susceptibility to pathogens. Examples of species in the region whose reproduction could be impacted include both the arroyo toad and Pacific slender salamander, which go into estivation as the landscape dries. Coupling the current monitoring of arroyo toad populations conducted by the United States Geological Survey (USGS) with additional data on hydrologic conditions might provide insight into future climate impacts. Further, earlier stream drying may promote formation of macroalgal mats and eutrophication locally or downstream, impacting the overall habitat. However, currently empirical observations are limited on how the changes in the timing of precipitation will affect amphibians and reptiles. Nonetheless, given the strong responses of individual freshwater organisms to temperature and flow, it is reasonable to assume that the projected future changes are likely to have considerable effects on the geographical distributions of freshwater organisms and the overall health of biological communities.

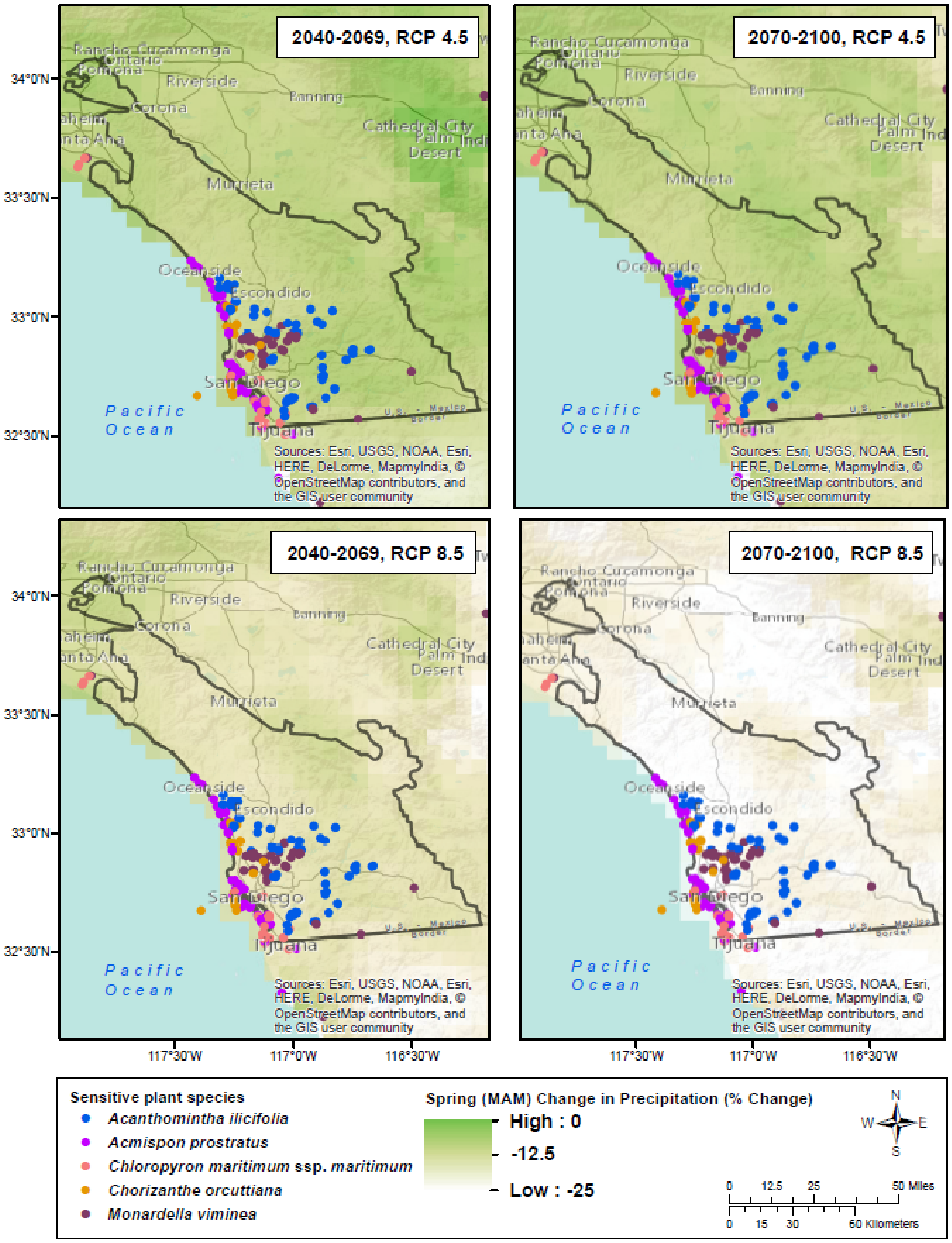

Figure 3.9: The percent change in spring (March-May) precipitation relative to the historical global climate model runs from 1976-2005. The figures on the left are averaged during mid-century (2040-2069) and the figures on the right are averaged at the end of the century (2070-2100). Top figures are under the RCP 4.5 scenario and bottom are the RCP 8.5 scenario. Overlaid are compiled species occurrence data (County of San Diego 2016, Global Biodiversity Information Facility 2017b, San Diego Management and Monitoring Program 2017) of select rare, threatened, or endangered plants (*Acanthomintha ilicifolia* [San Diego thorn mint], *Acmispon prostratus* [Nuttall's acmispon], *Chloropyron maritimum* [Salt march bird's beak], *Chorizanthe orcuttiana* [San Diego spine flower], *Monardella viminea* [Willowy monardella]).

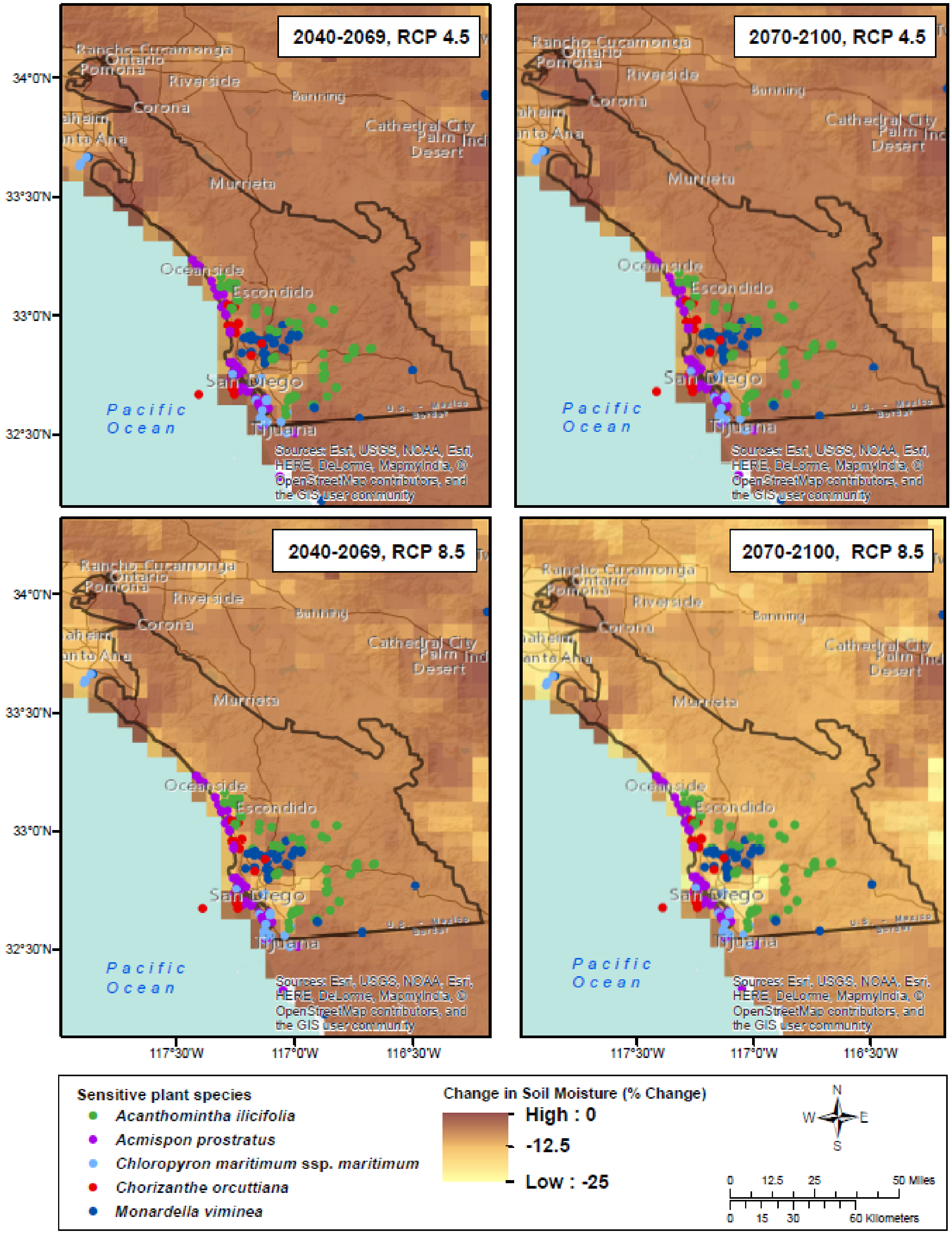

Figure 3.10: Same as figure 3.9, but for spring soil moisture.

3.4 Precipitation Extremes

The drying that is projected with increased drought intensity and longer seasonal dry periods is offset with a projected increase in the wettest days, representing an increase in precipitation variability. At the end of the century (2070-2100), the wettest day of the year is projected to increase by 15-25% percent under RCP 4.5 and 20-30% under RCP 8.5 (Figure 3.11). Less frequent and occasionally stronger storms might result in more precipitation flushed out to the Pacific and less retained by the soil and biosphere. The future bioavailability of water as a result of this precipitation regime change is a knowledge gap. The impacts of specific extreme events are most likely to affect intermittent, ephemeral, and headwater streams, such as those common to the San Diego region (e.g., upper San Diego River, upper San Luis Rey River) (Dhungel et al. 2016). Habitat shifts may result in less stabilizing streamside vegetation and increased erosion (Archer and Predick 2008). Shifts away from streamside riparian zones may also change the nature of allochthonous input, which in turn can reduce net primary productivity and result in a shift in the invertebrate community (Heino et al. 2009). For example, Martinez et al. (2015) suggests that as streams become more intermittent, there will be a decrease in the shredder functional group of freshwater macroinvertebrates, which in turn will reduce the availability of downstream detritus food sources for zooplankton and fish.

3.5 Knowledge and Information Gaps

- More research and improved hydrological modeling is needed to understand how changes in precipitation regimes will affect the bioavailability of water. Improved observations, data sharing, and coordination of instrumentation deployment related to stream flow, soil moisture, and other hydrological measures are needed to track changes and to evaluate and verify hydrological models.
- Drought thresholds need to be identified (see Section 4 on fire for a more detailed discussion) that can lead to structural change in ecosystems because of the more severe impacts to specific functional groups.
- Conduct monitoring and research projects that fill knowledge gaps about the effects of extreme dry season as well as multi-year droughts on individual species and ecosystem structure and function. This understanding should be coupled with considerations of changing water use practices and the cumulative effect on ecologically important flows.
- Improved understanding of the effects of a more variable precipitation regime and resultant altered streamflow, sediment transport, and stream temperature on stream health. Efforts to fill this gap should be coordinated with other data collection efforts, including the USGS study on aseasonal flows.

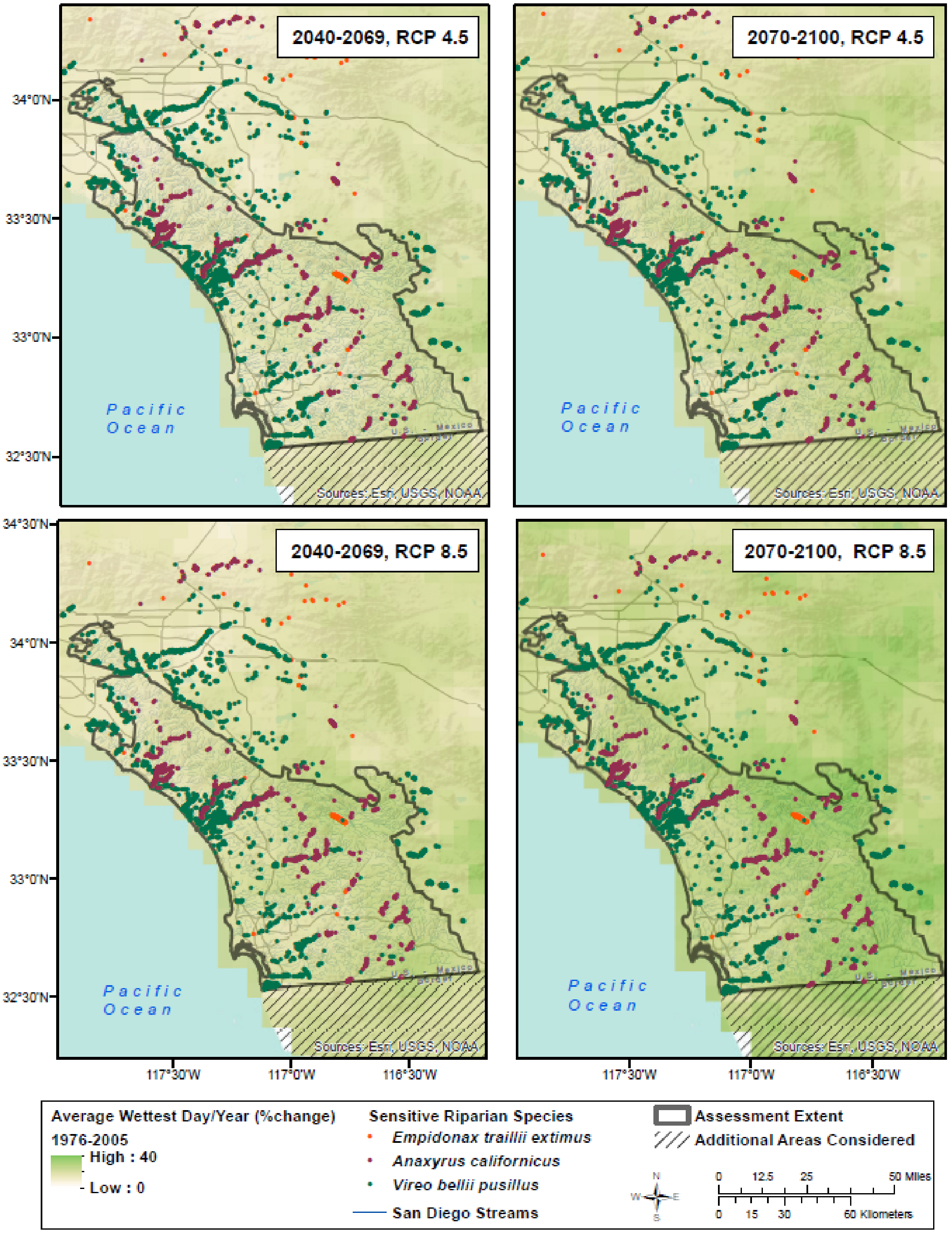

Figure 3.11: Change in the average wettest day per year at the end of the century, 2070-2100. The top figures are shown as increase, and the bottom figures are shown as percent. The middle panel is under RCP 4.5 and right is under RCP 8.5. Overlay with occurrence data for select sensitive riparian species (*Empidonax traillili extimus* [southwestern willow flycatcher], *Anaxyrus califoricus* [arroyo toad] and *Vireo bellii pusillus* [least Bell's vireo]; U.S. Fish and Wildlife Service 2016).

3.5.1 Monitoring Needs

- Coordinate weather and soil moisture monitoring across the region at sufficient spatial density to understand conditions affecting plant and animal communities across representative transects of San Diego County to understand sensitivity, resilience, and possible refugia to extreme events and climate change.
- Continue to develop a more extensive soil moisture monitoring network, with emphasis on deep levels whose moisture is crucial to some species in avoiding drought impacts. Monitoring locations should be coordinated with existing species and vegetation monitoring.
- Continue to support the current stream gauges and strategically install new stream gauges throughout the region.
- Coordinate among existing and proposed monitoring programs to support assessments of climate change effects. For example, enhancing the State Water Board's Surface Water Ambient Monitoring Program (SWAMP) to include sentinel site (i.e., indicator site) considered vulnerable to climate change and pairing that information with indicator species monitoring through SDMMP partners (e.g., amphibians or fish expected to be sensitive to climate change effects) could be a useful collaboration.

A benefit of the naturally highly variable climate in the region is that it provides a laboratory to better understand how ecosystems will respond to the more variable climate projected in the future. Therefore, once long-term and continuous monitoring begins, it could provide a wealth of knowledge to understand how an even more variable climate would impact ecosystems in the region. This information could then provide scientifically based information for conservation planning and land management.

4: San Diego Wildfires: Drivers of Change and Future Outlook[4]

Authors: Alexandra D. Syphard, Alexander Gershunov, Dawn M. Lawson, Hiram Rivera Huerta, Janin Guzman-Morales, and Megan K. Jennings

4.1 Introduction

Wildfire is one of the most important yet complex drivers of ecological function and biodiversity in San Diego County. As in other mediterranean-type ecosystems, fire is a natural ecosystem process that shapes the structure and distribution of the region's diverse plant communities, and in turn, the habitat for the region's animal species. Evidence via charcoal deposits and fire-adapted plant life history traits suggests that fire has been a predictable component of the landscape for millennia (Weide 1968, Keeley 1986, Keeley et al. 2011). Nevertheless, its occurrence, distribution, and ecological and social impact have evolved substantially over time.

The fire regime in San Diego County — that is, the characteristic size, frequency, intensity, and seasonality of wildfires — has changed in response to both climatic and anthropogenic factors. Until recently, large, high-intensity fires occurred regularly but infrequently within the county, on the order of once or twice a century (Keeley and Syphard 2018). This relatively infrequent occurrence of historical fires is due largely to the low frequency of natural ignition sources. Lightning-ignited fires rarely occur at the coast, with lightning strike density increasing toward the interior mountain ranges. Given that most lightning strikes occur in summer, shortly after winter rains, less than 5% typically result in a fire (Keeley 1982). Thus, it is believed that, before the arrival of human settlers, coastal shrublands only burned when a summer-ignited lightning fire persisted in the eastern mountains until Santa Ana winds in autumn carried it downslope toward the coast (Keeley and Zedler 2009).

The most extensive vegetation type in the county is chaparral, which is a biologically diverse plant community composed of several hundred shrub and sub-shrub species, often forming a mosaic pattern interspersed with drought-deciduous sage scrub, oak woodland, grassland, or coniferous forests (Keeley 2000, Keeley and Syphard 2018). Because of the mediterranean climate (cool, wet winters and hot, dry summers) and the flammability of many chaparral species, this vegetation is highly fire-prone. In particular, these shrublands tend to have low decomposition rates, high dead-to-live fuel ratios, dense community structure, and low fuel moisture (Christensen 1985, Bond and Van Wilgen 1996). The semi-deciduous coastal sage scrub

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[4] Suggested section citation: Syphard, Alexandra D., Alexander Gershunov, Dawn M. Lawson, Hiram Rivera Huerta, Janin Guzman-Morales, and Megan K. Jennings. 2018. San Diego Wildfires: Drivers of Change and Future Outlook. Pages 49 - 69 *in:* Jennings, M.K., D. Cayan, J. Kalansky, A.D. Pairis et al. ***San Diego County ecosystems: ecological impacts of climate change on a biodiversity hotspot***. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: EXT-CCC4A-2018-010

that dominates lower elevations shares many of the same flammability traits as chaparral (Figure 4.1), but has different life history characteristics and post-fire response strategies (Westman and O'Leary 1986).

In a given year, the fire season typically begins several months after the last rains, when plant growth has stopped and live fuel moisture has dropped, and ends with the onset of the winter rainy season (Sugihara et al. 2006, Dennison and Moritz 2009). Typically by May or June, fire danger is high and fuel moisture in San Diego County shrublands is low enough to support fires that spread rapidly (Weise et al. 1998, Dennison et al. 2008, Lawson et al. 2017b), although, in the absence of strong winds, fire agencies are typically able to contain and extinguish them. The season when most large fires occur and most of the land area burns begins in the fall when Santa Ana winds start up. Large fire events are almost always associated with extreme fire weather, and not only are these fires responsible for the vast majority of areas burned (Moritz 1997, Mensing et al. 1999), but these weather-driven large fire events are those where the vast majority of structures and human lives are lost (Keeley et al. 2013). The end of fire season can be variable year-to-year based on the extent of seasonal and longer-term drought and Santa Ana winds.

Figure 4.1: The drought-deciduous shrub species, California sagebrush (*Artemisia californica*), which is a dominant species in coastal sage scrub, is highly flammable when leaves die off to conserve water and energy during dry periods (photo credit Dawn M. Lawson).

Beginning in the middle Holocene, a large number of Native American groups settled in the region, and intentional burning became a widespread management practice, with deliberate burning of woody shrublands to convert them to herbaceous vegetation (Anderson and Byrd 1998). Subsequent settlement by people of European descent, beginning around 200 years ago, resulted in a wider variety and larger distribution of human-caused fire ignitions. The concurrent introduction of European grasses and forbs contributed to further fire- and disturbance-driven conversion of shrubland to herbaceous vegetation (Keeley 2004).

In the 20th century, human population growth skyrocketed in the county, and with it came massive expansion in urban development. As a result, human-caused ignitions have increased dramatically, both in number and in spatial extent. The resulting increase in fire frequency has altered the natural fire regime such that much of the landscape is burning at return intervals that are uncharacteristically short relative to pre-Euro-American settlement conditions (Safford and Van de Water 2014) (Figure 4.2). For example, areas that once burned every 30-150 years are in some cases re-burning within a 10-year period. Although the frequency and spatial pattern of fires have changed in response to population growth and urban expansion, the overall seasonality and severity, as well as the mean area burned, have remained relatively consistent (Keeley and Syphard 2016).

Although the majority of vegetation in San Diego County is dominated by shrublands, there are pockets of montane conifer forests dominating the highest elevations of the Transverse and Peninsular Ranges. Like other dry mixed-conifer ("yellow pine") forests in the western U.S. (Allen et al. 2002), some of these areas have suffered an increasing risk of stand replacing crown fires because 20th century fire suppression allowed the establishment of shade-tolerant understory conifers as ladder fuels. Unlike the natural fire regime of periodic crown fire in chaparral and coastal sage scrub, lightning-ignited fires were historically common in these interior, high-elevation forests, and they supported frequent, low-intensity surface fires, essentially experiencing altered fire regimes in the opposite direction of those in the shrublands (Wells et al. 2004). The Cedar Fire in 2003 burned through some of these forested lands at high intensity, resulting in high-severity, stand-replacing crown fire with extensive tree mortality (Franklin et al. 2006), particularly in areas where fire suppression had effectively excluded fire from the coniferous forest landscape for nearly a century. In the absence of a seed source for coniferous species, these communities have shifted to shrublands and oak woodlands which regenerated from basal resprouts or dormant seed banks (Goforth and Minnich 2008).

While periodic wildfire has played an evolutionary role in shaping the plant communities and ecology of the region, too-frequent fire, as experienced in the last several decades, threatens the ecological integrity of the region. Unlike the situation in montane conifer forests described above, repeated wildfires, at intervals too short to allow recovery of native vegetation, facilitate the conversion of native shrublands to weedy annual grasses, forming a positive feedback cycle that could irreversibly eliminate some of the region's rich biodiversity, and evidence suggests that widespread vegetation change has been occurring in recent decades (Syphard et al. 2018). Wildfire also threatens human lives and property due to the growing interface between residential communities and wildland vegetation; thousands of structures have been destroyed in recent decades (Syphard et al. 2012), numerous lives among firefighters and residents have been lost, and health impacted along the densely populated coastal zone from smoke (Delfino et al. 2009) blown tens of miles westward by the same Santa Ana winds that fan the fires in the hilly backcountry.

Given the unique combination of factors that shape the modern-day fire regime in the region, the potential effect of climate change on fire is nuanced, with the role of climate being different than it is in other parts of the state. As much as climate change is a concern for future wildfire patterns, the role of humans will be critical in determining whether people and wildfire can sustainably coexist in the future, while simultaneously conserving the natural heritage of the region.

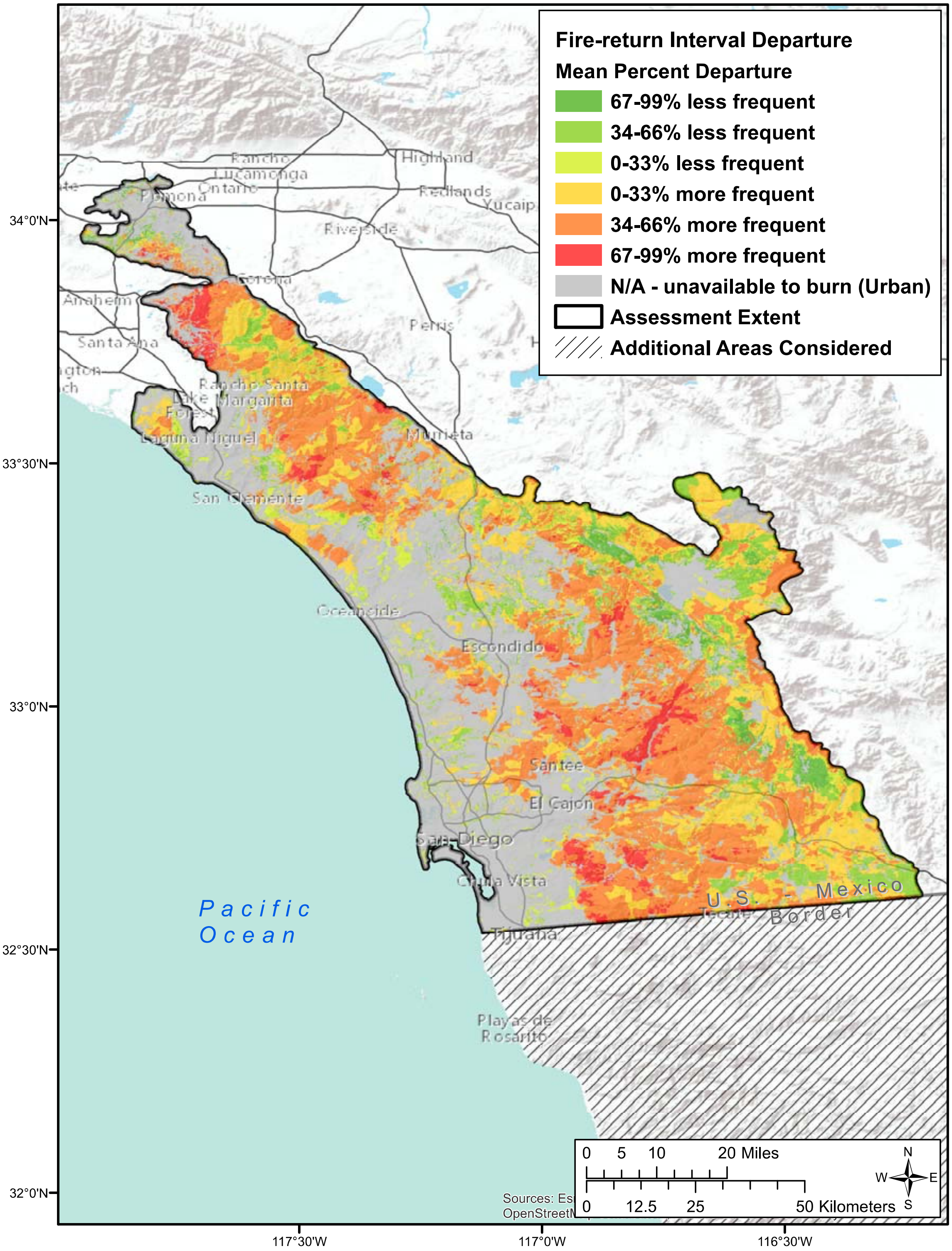

Figure 4.2: Map of study area with mean percent fire return interval departure (Safford and Van de Water 2014). Values range from 67-99% less frequent fire than historic return intervals for a given vegetation type in dark green to 67-99% more frequent than historic intervals in red where repeated fires have burned in short succession.

In this section, we describe the role of climate and fire-weather in driving fire activity in the San Diego region, in addition to the critical role that humans play in igniting and managing fire. After providing historical context, we summarize the current science with regards to future projections and how fire patterns may be altered in the future as a result of multiple changing drivers, including climate, land use, vegetation change, and decision-making.

4.2 Climatic Influences on Wildfire

4.2.1 Fire-Climate Relationships

Research on historical relationships between annual fire activity and seasonal climate variation shows divergent patterns geographically (Keeley and Syphard 2015, 2016, 2017, Syphard et al. 2017). In California, montane forested landscapes show strong relationships between annual fluctuations in temperature and precipitation with area burned, but these are seasonally dependent, with spring and summer temperatures being most critical. In lower-elevation coastal and foothill-dominated regions, like most of the land area in San Diego County, there has been little or no increase in fire activity associated with hotter and drier conditions (Keeley and Syphard 2015, 2016, 2017). This is likely because seasonal conditions are already prime for extreme fire behavior every year given the mediterranean climate regime of hot, dry summers followed by Santa Ana wind conditions. It would be difficult to get significantly more fire-prone in early fall before the first rains, but easier in late fall, winter, and spring, as we suggest below.

Although variability in current-year temperature and precipitation have not strongly influenced fire activity, one climatic variable that has become important in recent years is high prior-year precipitation. This is likely due to its role in promoting higher abundance of annual grasses that, once dry, become extremely ignition-prone in the subsequent year. Although this variable was not significantly tied to fire in the early 20th century, its current role may be due to the increased conversion of woody shrublands to grasslands in southern California (Syphard et al. 2018, Syphard et al. unpublished data), and may also signify an increasing influence of grass on the area's fire regime. This relationship between prior-year precipitation and fire has been found in other grasslands and savannas where fire activity is fuel-limited (Littell et al. 2009, Pilliod et al. 2017, Syphard et al. 2017).

4.2.2 Fire Weather and Climate: Santa Ana Winds and Precipitation Regime

Santa Ana winds represent strong episodic reversals of the more common westerly on-shore winds over southern California. Easterly Santa Ana winds are associated with clear, dry, and mild weather along the coast, with intensified offshore flow concentrated on the lee slopes of coastal topography such as the Santa Ana and Laguna Mountains. There is a common confusion between Santa Ana winds and Chinook or foehn-type winds, which are rain-shadow winds with very different origins from Santa Anas. Technically, Santa Ana winds are "katabatic" downslope winds that accelerate under the force of gravity as they descend the lee slopes of coastal mountains. Because dense cold air over the elevated Great Basin is a required source of Santa Ana winds, they are most frequent in winter and do not occur in summer (Figure 4.3). The Santa Ana season typically starts in October, when fuel moisture is at its driest. A spark in parched vegetation under this strong, gusty, dry wind causes wildfires that are extremely difficult if not impossible to control (Syphard et al. 2012). This explains the timing of the peak of the traditional southern California wildfire season — October — when the Santa Ana season starts and before the first rain storms of winter.

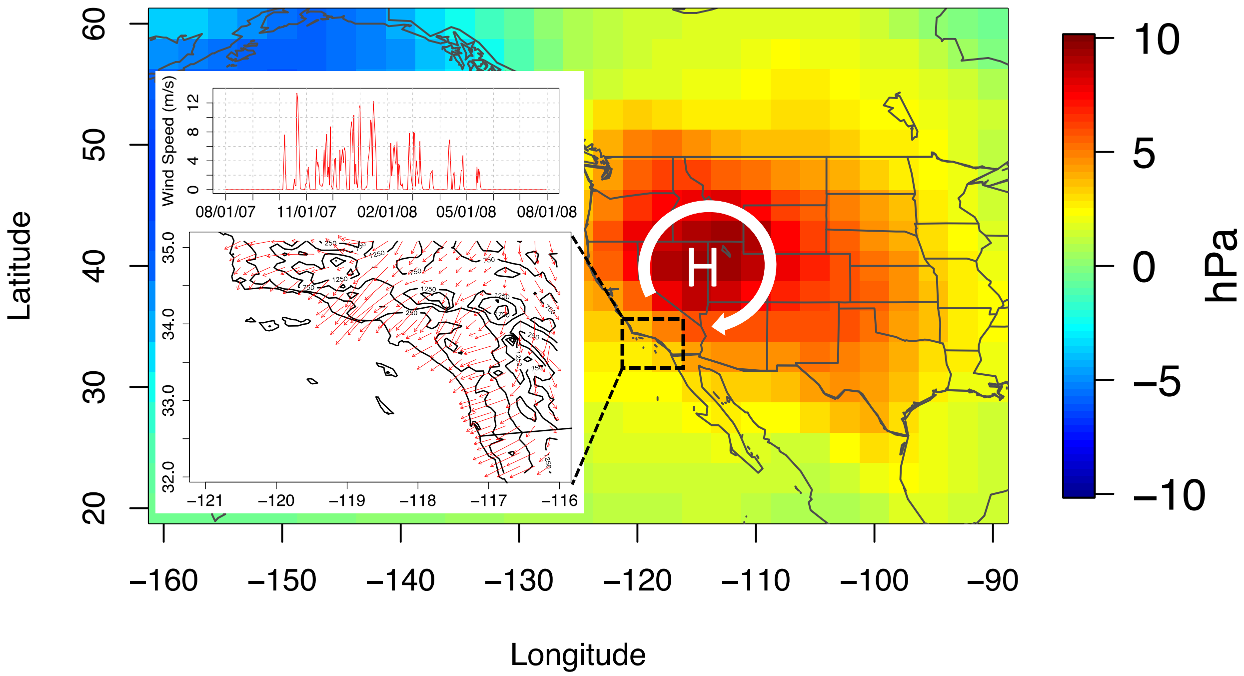

Figure 4.3: Sea Level Pressure anomaly composite for all Santa Ana wind days identified in a period of 65 years (1948-2012). The white arrow on the North America map shows the large-scale circulation around the High-pressure center. The resulting north-northeasterly flow over southern California is depicted in the inset map as the mean wind field during all Santa Ana days. The upper panel time series shows the regional mean speed of Santa Ana winds for the 2007-2008 (Aug-Jul) season.

Rooted in a cold airmass, Santa Ana winds warm and dry on their way downslope to become very warm and dry as they blow across much of coastal southern California and the northern part of Northern Baja California, Mexico. Santa Ana winds are caused partially by a high-pressure system (High) that is large-scale (synoptic-scale, over 500 miles) and centered approximately over the Great Basin. The Great Basin High (sometime referred to as the Four Corner High) has been traditionally viewed as the only cause of Santa Ana winds (e.g., Raphael 2003), by producing the north-easterly offshore winds over the high desert. However, the necessary and sufficient condition is of local thermodynamic origin — a temperature gradient between the cold desert air over the Great Basin and the warm air over the Pacific Ocean at the same altitude (Hughes and Hall 2010). This temperature gradient causes a localized offshore pressure gradient near the surface, which generates a katabatic surface wind flowing through gaps in topography and accelerating downslope on its way towards the coast (Figure 4.3). Katabatic wind is driven by gravity as cold dense air drains down a slope. A reservoir of cold dense air in the high desert of the Great Basin is therefore required for Santa Ana winds to develop. Santa Ana winds become relatively drier as the blowing air warms by compression (adiabatically, at the rate of 5.5 °F/1000 feet) on its descent from the elevated Great Basin (~4000-foot-high desert) towards sea level.

Concerning possible changes in Santa Ana winds, Hughes et al. (2011) examined a 30-year record of observed and projected Santa Ana winds, concluding that the disproportionate future warming of the Great Basin compared to the warming of the coastal zone will result in weaker

Santa Ana activity, claiming that this trend is already detectable. However, Guzman-Morales et al. (2016), who examined the longest and most comprehensive record of Santa Ana winds available (65 years), showed a slight increase in extreme Santa Ana activity attributed to natural causes, namely the 1970s shift in the Pacific Decadal Oscillation. Otherwise, the detailed results show no change in Santa Ana wind activity in a 65-year record, a result that strongly contradicts that of Hughes et al. (2011). Future behavior of Santa Ana winds is, therefore, a topic for future research. The only expectation that seems likely at this point is that Santa Ana winds will become warmer in a warmer climate, as suggested by Hughes et al. (2011). So, the warming Santa Anas may become more desiccating yet, and they will continue to be most frequent in December.

The other part of the climate story concerns fuel dryness, which is driven mainly by precipitation or lack thereof (see Section 3.2). Such increasing volatility in the delivery of precipitation is associated with lengthening dry periods that make it more likely for fuels to remain dry in the traditional winter wet season that coincides with the peak Santa Ana wind season. For this reason, even if Santa Ana wind climatology does not significantly change, the fire season of southern California may be expected to expand more frequently into winter and spring. The late season Santa Ana winds of May 2014 exemplified this possibility when they fanned wildfires in the Santa Monica Mountains of Los Angeles in late spring following a historically dry winter.

In December 2017, high prior-year precipitation produced robust growth of annual grasses, which was then followed by a lack of precipitation and extended dry conditions late into the season. These fuel conditions, coupled with extended, severe Santa Ana winds and co-occurring ignitions resulted in multiple, fast-moving wildfires breaking out across the region. At the writing of this report, more than a dozen fires ignited and burned in San Diego, Riverside, San Bernardino, Los Angeles, Ventura, and Santa Barbara Counties. This includes the > 280,000-acre Thomas Fire in Ventura and Santa Barbara Counties, in addition to the 4,100 acres burned in San Diego County's Lilac Fire. The Thomas Fire has now become the largest fire in California recorded history, and the large size of this fire may also be due to fuel dieback created during the California drought of 2012–2015 (see below, Keeley and Zedler 2009). We note that research is needed on how Santa Ana winds themselves impact fuel dryness in the short-term.

4.2.3 Drought

The climate in San Diego County is characterized by both seasonal and extended, multi-year drought as discussed in the previous section. Amplification of either of these characteristic drought patterns could have significant effects on area burned through their effects on dead fuels and fuel moisture, both of which are key drivers of fire propagation and spread (Stonex et al. 2004). Increased proportion of dead fuels can support fire behavior that is very difficult to control including rapid spread at both the flame front and from spot fires ahead of the fire front created by windborne fire brands (Keeley and Zedler 2009).

As discussed earlier, extension of the seasonal drought that characterizes the fire season later into the fall and winter means that low live fuel moisture could more frequently coincide with Santa Ana winds creating conditions that support megafires. In addition, more frequent, longer, or more intense multi-year droughts could also increase the number of megafires in the region because they result in vegetation dieback (Figure 4.4; Pratt et al. 2014, Venturas et al. 2016) which increases the proportion of dead fuels in a stand (Keeley and Zedler 2009).

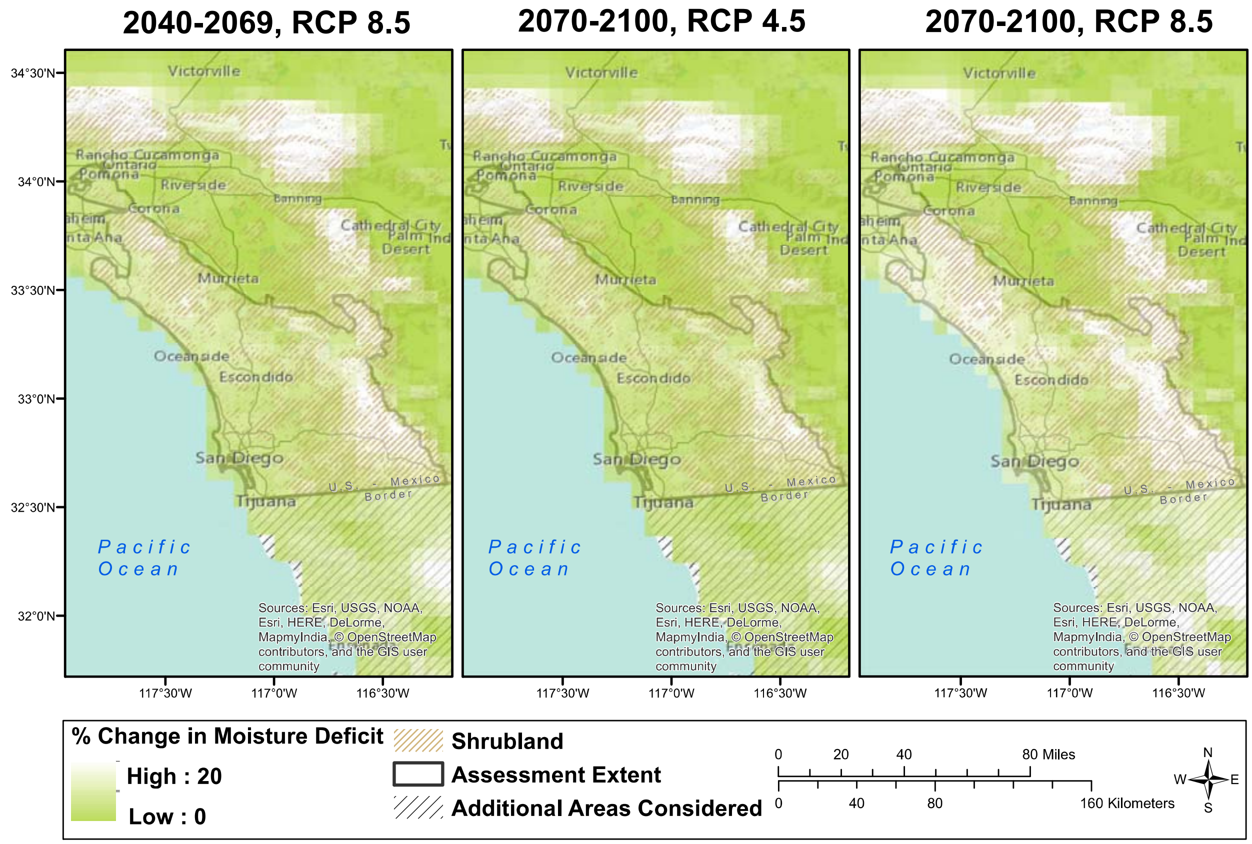

Figure 4.4: Map of climatic water deficit (CWD) in the San Diego region and shrubland vegetation types (CALFIRE FRAP 2015), where a lack of available moisture during extended droughts is most likely to result in vegetation dieback that will greatly increase fire risk. The scenarios shown are the scenarios that the California Fourth Climate Change Assessment recommends, RCP 8.5 until mid-century and both RCP 4.5 and 8.5 at the end of century.

While drought as described above results in increased fire hazard, at some point along the aridity gradient there could be insufficient moisture to support vegetative growth so that the system becomes fuel limited and fire activity declines. These effects would likely be complex and vary geographically depending on biophysical context. Regardless, model projections suggest that the potential effect of warmer and drier climate decreasing fire activity would not be anticipated before 2070-2099 (Batllori et al. 2013).

4.3 Human Influence on Wildfire

4.3.1 Fire Ignitions

Although seasonal variation of temperature and precipitation has not been significantly correlated with fire activity in San Diego County, fire activity is significantly limited by ignitions. That is, despite the fact that Santa Ana winds and extreme fire-weather create ideal fire conditions every year, a resulting megafire will only occur if an ignition coincides in space and time with a wind-driven weather event. In San Diego County, more than 95% of the ignitions are caused by humans (Syphard et al. 2007b); and because highly flammable shrublands and grasslands are closely juxtaposed with human habitations, fire regimes are and will continue to be most strongly controlled by anthropogenic impacts. Humans can affect wildfire patterns in a number of ways, from starting fires to managing fires (e.g., prescribed fire, fuel treatment, or fire suppression), and via changes in the abundance and continuity of fuel through land use decisions.

With the enormous population growth and exurban expansion in San Diego County, increased fire ignitions and the changing spatial pattern of ignitions have had the strongest effect on the fire regime (Safford and Van de Water 2014). Despite skyrocketing ignitions throughout most of the 20th century (Keeley et al. 1999, Syphard et al. 2007b), ignition frequency has started to level off in southern California (Keeley and Syphard unpublished data). Studies have shown that ignition frequency and area burned are often uncorrelated and controlled by different factors (Batllori et al. 2013, Hudspith et al. 2017), and accordingly, the mean area burned across southern California has not oscillated as dynamically as ignition patterns. This is likely in some part due to the effect of fire suppression in helping to offset the dramatic increase in number of fires. Above all, the most critical factor to consider in the near future is the timing and placement of ignitions (Syphard and Keeley 2015), particularly if dry conditions extend further into the winter when Santa Ana winds are most frequent.

Studies have shown that ignition patterns are non-random in San Diego County (Syphard and Keeley 2015) and because of this, prevention strategies could be customized to target the locations, causes, and timing of the most catastrophic events. In recent years, equipment-caused fires have been the most numerous, and they also accounted for most of the area burned, followed closely by the area burned by power lines (Syphard and Keeley 2015). Given the importance of these fire causes, efforts could be made to restrict the use of certain equipment in areas or times of the year where those fires are most likely to ignite. Most area burned by both of these sources occurred in October, generally in coincidence with Santa Ana wind season.

4.3.2 Housing Development

Housing development patterns and proximity to human infrastructure like roads are also significant correlates of fire frequency and area burned, with the highest levels of fire activity occurring at low-to-intermediate levels of development (Keeley 2005b, Syphard et al. 2007b, 2009, Archibald et al. 2010, Mann et al. 2016), which is also where most houses are destroyed by wildfire (Syphard et al. 2012). The reason for this nonlinear relationship is that, especially in places where most fires are human-caused, there are few people in remote landscapes to start fires, and there is little available fuel to burn in intensely developed areas. At low- to intermediate- housing density, houses are generally more exposed to wildfire, and dispersed housing is more challenging for firefighters to defend. Dispersed housing is also contributing to escalating fire suppression expenses (Gude et al. 2013). Although landscapes with larger areas of Wildland-Urban Interface (WUI) are generally most fire-prone (Radeloff et al. 2005), there is also a risk to homes that are spaced too closely together, especially if the building construction materials of those homes is flammable (Syphard et al. 2016). In a number of recent devastating fire events, including the October 2017 Tubbs Fire, substantial structure-to-structure fire spread has occurred, such that the homes provided even more fuel to propagate the fires than the surrounding vegetation (Mell et al. 2010).

In southern California, as well as other mediterranean ecosystems across the world, high fire frequency has been linked with intermediate levels of population density, such as those areas east of the coastal cities in San Diego County (Syphard et al. 2009); and the role of housing pattern and location has been identified as the most important risk factor for structure loss to wildfires across the continental U.S. (Alexandre et al. 2016). In fact, human-caused ignitions are now responsible for an average of 84% of the wildfires across the U.S. (Balch et al. 2017).

In addition to increased fire frequency, exurban development provides conduits for invasive species to expand into wildland vegetation, either through soil disturbance, planting of grass in residential areas, or via mechanical fuel reduction activities that are, ironically, designed to control fires (Merriam et al. 2006, Gavier-Pizarro et al. 2010, Brennan and Keeley 2015).

Despite the clear link between housing patterns and structure loss, the majority of fire-management actions are focused on prescribed fire, fuel treatments, or other types of vegetation manipulation. Nevertheless, simulation modeling studies have shown that land use planning decisions could significantly reduce future structure loss to wildfire (Syphard et al. 2013, Butsic et al. 2017). Furthermore, there are land-use planning decisions, either through zoning, or by private land acquisition that could be mutually beneficial in terms of fire risk reduction and biodiversity conservation (Syphard et al. 2016). In particular, preventing development (or purchasing conservation lands) in areas that are either highly fire-prone or have high species richness may provide maximal benefits for both objectives.

4.4 Fuels and Vegetation Change

4.4.1 The Role of Fuel in Shrubland Fires

The two primary characteristics of vegetation (fuels) in driving fire behavior are moisture and abundance. For example, in many forested ecosystems, fire activity tends to be highest in areas with moderate-intermediate precipitation and temperature conditions because both fuel moisture and abundance conditions are favorable for fire (Pausas and Ribeiro 2013, Whitman et al. 2015). In the non-forested areas of San Diego County, however, fire activity is predominantly a weather-driven phenomenon. That is, unlike other systems, fuel age is not a limiting factor during severe fire-weather conditions (Moritz 2003, Keeley et al. 2004, Moritz et al. 2004, Keeley and Zedler 2009, Price et al. 2012). This is evidenced by the sometimes extraordinarily short intervals that occur between fires. For example, the large fire events of 2007 resulted in nearly 74,000 acres (~30,000 ha) of overlap with the four-year-old recovering vegetation that burned in the 2003 Cedar Fire. There is also evidence that the 2017 Thomas Fire has burned across multiple areas of recent prescription burns.

4.4.2 Fuel Moisture

Fuel moisture plays a significant role in the ignition and spread of wildland fires (Krawchuk and Moritz 2011). It is generally divided into two major categories based on whether the fuels are live or dead. Because moisture must be vaporized before fuels can burn and fires propagate, variations in live fuel moisture (LFM) have a significant effect on fire behavior and spread (Pyne 1996). While the effect of fuel moisture on fire hazard is non-linear, thresholds exist above which: 1) fire hazard becomes extreme and 2) further decreases in fuel moisture do not increase fire hazard appreciably (Schoenberg et al. 2003). For example, Dennison et al. (2008) identified a LFM threshold for chamise (*Adenostoma fasciculatum*) chaparral in the Santa Monica Mountains, Los Angeles County, below which large (>2200 acres or 890 ha) fires are much more likely.

Live fuel moisture peaks in the spring, declines rapidly until the end of the spring or early summer, then declines slowly over the summer, bottoming out in late summer/fall and recovering after the onset of winter rains, although the actual timing of these events varies widely among years and sites (Lawson et al. 2017b). While fire behavior is driven by more than

LFM, there is a general relationship between live fuel moisture and fire behavior. Typically by May-June, fire danger is high and fuel moisture in San Diego County shrublands is low enough to support fires that spread rapidly (Weise et al. 1998, Dennison et al. 2008, Lawson et al. 2017b), although in the absence of strong winds, fire agencies are typically able to contain and extinguish them (Syphard et al. 2011, 2012).

Dead fuels of all sizes are extremely important in fire behavior, with small-diameter dead fuels often carrying a fire (Stonex et al. 2004). Dead fuel is sensitive to short-term weather conditions and is classified by the expected time lag to reach two-thirds of equilibrium with the local environment (Table 4.1). Coastal sage scrub is particularly flammable because of the pattern of seasonal leaf and small stem mortality in drought deciduous shrubs (Gray and Schlesinger 1981, Lawson unpublished data). Leaf and small stem mortality result in fine dead 1-hour fuels (less than 0.25 inch in diameter) being suspended throughout the canopy from late spring through the onset of winter rains. This dead fuel architecture means that drought deciduous shrubs can burn explosively even under normal weather conditions.

Table 4.1: Dead fuel moisture time lag classification system as defined by the U.S. Forest Service Wildland Fire Assessment System.

Time lag	Fuel size (diameter in in)	Determination
1-hr	1/4"	Fine flashy fuels (e.g., grasses) that respond quickly to weather changes. Computed from observation time temperature, humidity, and cloudiness.
10-hr	1/4-1"	Computed from observation time temperature, humidity, and cloudiness. Or can be an observed value, from a standard set of "10-Hr Fuel Sticks" that are weighed as part of the fire weather observation.
100-hr	1-3"	Computed from 24-hour average boundary condition composed of day length, hours of rain, and daily temperature/humidity ranges.
1000-hr	3-8"	Computed from a 7-day average boundary condition composed of day length, hours of rain, and daily temperature/humidity ranges.

4.4.1 Vegetation-Type Conversion

Vegetation-type conversion, or a shift in the primary physiognomic or functional groups of species that comprise vegetation communities in response to disturbance, is a serious concern in southern California. Type conversion threatens both shrublands (e.g., Zedler et al. 1983, Syphard et al. 2007b, Keeley and Brennan 2012) and coniferous forests (Franklin et al. 2006, Goforth and Minnich 2008). Both are adapted to wildfire but while shrublands evolved to sustain periodic stand replacing crown fires (Keeley and Safford 2016), coniferous forests rely on a pattern of frequent understory burns that prevent fuel build up that could lead to stand replacing fires (van Wagtendonk and Fites-Kaufman 2006). In both systems, resilience is compromised and type conversion is promoted when fires occur outside characteristic frequency (Figure 4.2), but for different reasons. Conifers don't regenerate after stand replacing crown fires because their seed source (e.g., mature trees) is lost and subdominant shrubs (with long lived seedbanks) and oaks (that are able to sprout basal buds) take over (Goforth and Minnich 2008). With overly frequent fires, shrublands are unable to fully regenerate seed and bud banks between fires to support post-fire recovery. Under these conditions, non-native annual grasses increase in dominance and further promote short fire intervals leading to increasing annual grass dominance (Brooks 2003, Keeley and Brennan 2012). These changes in fire regime have been driven by anthropogenic factors—high levels of ignitions in shrublands and fire suppression in forests—independent of climate change, but changing temperature and precipitation regimes, ultimately affecting both evapotranspirative demand and the bioavailability of water, pose additional threats to the resilience of these systems (McKenzie et al. 2009, Venturas et al. 2016). A wildfire that kills mature individuals may reveal climate change impacts to species ranges where the climate no longer supports juvenile recruitment sufficient to repopulate the stand. Further, given the distributions of these montane vegetation types follow elevational and climatic gradients, the upslope lean (Breshears et al. 2008a) of individual species and entire vegetation communities in response to shifting climatic conditions may be hastened by wildfire in the transitional zones between shrublands and forest types. While an important part of the biodiversity of our region, coniferous forests make up only 1.2% of the land area, thus the remainder of this section focuses on shrublands which make up over half of our study area (Table 1.1).

Shrubland type conversion includes shifts in functional type; for example, shrubs that resprout in response to fire (obligate resprouters) may increase at the expense of shrubs with fire-stimulated seed (obligate or facultative seeders); or, shrubs may be replaced with herbaceous species (primarily non-native grasses and forbs; Figure 4.5). In this highly biodiverse region (Myers et al. 2000) characteristic bird, mammal, and insect communities mostly align with shrub cover and thus the loss of shrub cover also represents a loss of those associated species (Diffendorfer et al. 2007) and represents impacts that can have global significance (Cowling et al. 1996).

Figure 4.5: Examples of shrubland systems that are intact (left), degraded (center), and completely converted to non-native annual grassland vegetation type (right) (left and center photo credits Dawn M. Lawson, right photo credit ACS Habitat Management).

The term type conversion implies some degree of stability or permanence in the vegetation change. Whether or not these shifts in vegetation type represent true ecological thresholds has important implications for conservation policy and management. Ecological thresholds are tipping points where the relationships between drivers and ecological properties change from linear to non-linear so that a small change in the driver results in a much larger change in the ecological response than at other places along the response curve (Briske et al. 2005). Shifts across true ecological thresholds exhibit stability and are permanent or difficult to reverse (Suding and Hobbs 2009, Sasaki et al. 2015). On a practical level, assuming threshold dynamics where they don't occur could lead to use of expensive intervention to avoid crossing a threshold that doesn't exist; alternatively, if unidentified thresholds do exist, cost-effective opportunities to prevent ecosystem damage could be missed (Bestelmeyer 2006, Suding and Hobbs 2009).

Much is known about the disturbance, degradation, and recovery dynamics in coastal sage scrub and chaparral (Diffendorfer et al. 2002). In short, the naturally fire-prone climate and vegetation supports a disturbance-based system where persistent seed and bud banks, and highly drought-resistant post-fire resprouts and seedlings promote vegetation recovery after periodic stand replacing wildfire. Woody species establishment in long fire free periods is episodic and patchy (Keeley and Safford 2016).

An altered fire regime, particularly increases in fire frequency beyond historical levels, is the primary driver of type conversion, but it also acts in concert with other disturbances, most significantly invasive grasses (Keeley 2006), but also grazing (Hedrick 1951), physical disturbance such as cultivated agriculture (Stylinski and Allen 1999), nitrogen deposition (Cox et al. 2014, Pivovaroff et al. 2016), extreme drought (Pratt et al. 2014), and in the future, potentially climate change (Lawson et al. 2010). Type conversion from shrubland to grassland occurs when fires recur before seed and bud banks have had time to regenerate sufficiently to repopulate a stand (Zedler 1995). Invasive annual grasses which have naturalized throughout this system promote the grass-fire cycle (Brooks 2003, Keeley and Brennan 2012) in a positive feedback loop where short-interval fire is fostered by a more continuous, highly flammable fine fuel load. In addition, invasive grasses impair shrub seedling recruitment through competition for light and moisture (Pitt and Heady 1978, Eliason and Allen 1997). Type conversion to shrublands dominated by obligate resprouters also happens as a result of short fire intervals (Lucas et al. 2017) or by extreme drought (Venturas et al. 2016). Finally, chaparral shrublands may also convert to drought-deciduous coastal sage scrub in transition to a full shift to grassland (Syphard et al. 2007a, 2018).

Although fire has been the main driver of stand compositional changes, drought could also restructure communities. Because drought operates at a larger spatial scale than fire, extreme drought, even in the absence of fire, could potentially shift stand species composition to favor deeper-rooted species (Venturas et al. 2016) with large effects across the landscape. Then, because post-fire patterns of species establishment are strongly influenced by pre-fire patterns of individual plants in a stand, these patterns could be perpetuated by fire (Odion and Davis 2000).

A number of studies have documented vegetation shifts from coastal sage scrub to grassland, with both fire frequency and nitrogen deposition implicated (Minnich and Dezzani 1998, Talluto and Suding 2008, Cox et al. 2014). In addition, chaparral conversion to grasslands after repeated fires has also been documented in many localized studies (e.g., Zedler et al. 1983, Haidinger and Keeley 1993, Jacobsen and Davis 2004, Keeley and Brennan 2012, Lippitt et al. 2013), although widespread vegetation change is still under investigation (e.g., Meng et al. 2014, Halsey and Syphard 2015, Syphard et al. 2018). Further evidence of thresholds and alternate stable states comes from studies of short fire intervals and recovery from cultivation. In the mid-1900s fire was used to "type convert" shrublands to grasslands to increase forage for livestock (Sampson 1944, Hedrick 1951). Where shrublands have been disturbed by cultivation, recovery is slow (Tierra Data Systems 2002) or does not occur at all (Stylinski and Allen 1999), even after the cultivation has ceased.

While understanding permanence of state changes has important policy and management implications, it is generally poorly defined for most systems (Deangelis and Waterhouse 1987, Hughes et al. 2013). For coastal sage scrub and chaparral, the reversibility of state changes and the rate that they are reversed appears to vary over their geographic range. There is evidence in the literature of both reversible (DeSimone and Zedler 1999, Tierra Data Systems 2002, Gressard 2012), and apparently irreversible state changes (Minnich and Dezzani 1998, Stylinski and Allen 1999, Tierra Data Systems 2002). Invasive grasses may create difficult to reverse but not permanent shifts by changing competitive relationships so that resources such as water and space are unavailable to native woody species (Pitt and Heady 1978, Eliason and Allen 1997). Because shrub seed dispersal is limited, if patches of annual grasses without shrubs are large (e.g., > 15-30 ft [~5-10 m]), natural recolonization can be a lengthy multi-generational process (Williams et al. 1987). Other drivers in addition to fire and invasive annual grasses that are anticipated to affect threshold dynamics include weather patterns that influence moisture availability (Williams et al. 1987), and anthropogenic nitrogen deposition (Cox et al. 2014). Stands maintained in degraded states by repeated disturbances (Gressard 2012) do not necessarily reflect the presence of thresholds if recovery is not delayed once the disturbance stops.

Increased drought under climate change may interact with fire and invasive species to reinforce type conversion, particularly with increased nitrogen deposition (Kimball et al. 2014). In stands recovering from fire, extreme drought may increase post-fire mortality of highly drought tolerant resprouts and obligate seeder seedlings (Jacobsen et al. 2007, Pratt et al. 2014). In long fire-free intervals, type conversion may be reinforced during droughts through reduced seedling establishment and increased adult mortality. Seedling establishment is episodic and patchy under these conditions and the deeper soil moisture that supports adult shrubs may not be available. More frequent, intense, or longer drought in combination with competition from invasive grasses may reduce the frequency of years with appropriate quantity and distribution of precipitation to support seedling establishment and recruitment to larger size classes (Pitt and Heady 1978, Canadel and Zedler 1994, Eliason and Allen 1997). This change could be reinforced by shortening life spans if extreme drought that reduces available deep soil moisture results in increased adult mortality (Venturas et al. 2016).

4.5 Ecological and Social Consequences of Changing Fire Regimes

In addition to the vegetation changes resulting from altered fire regimes, changes in fire patterns have broader implications for biodiversity and ecosystem integrity. Many wildlife species that occur in the mediterranean-type ecosystems of southern California have adapted to wildfires. Wildlife exhibit differential responses to wildfires depending on the availability of refugia and species' mobility, which determine their susceptibility to impacts from the direct effects of the fire. Habitat and diet breadth, population size and growth rates, and landscape connectivity can affect post-fire colonization and overall resilience to these types of stochastic events. For example, during a fire, many burrowing small mammals like kangaroo rats (*Dipodomys* sp.) or species that estivate, like the arroyo toad (*Anaxyrus californicus*) escape the passing flame front underground and can thrive in the post-fire environment. Arroyo toad burrowing habitat may benefit from the clearing of riparian vegetation and the pulse of fresh sediment from the first rains after a fire (Madden-Smith et al. 2005), and species like southern California's endangered Stephens' kangaroo rat (*Dipodomys stephensi*) prefer the open ground that facilitates movement (Diffendorfer et al. 2012, van Mantgem et al. 2015). However, other species have faced greater challenges after very large fires in southern California. The rare Hermes copper butterfly (*Lycaena hermes*), endemic to southern California and Baja California, Mexico, has experienced post-fire extirpation of a number of populations in San Diego County. Although their larval host plant, the spiny redberry (*Rhamnus crocea*) has recovered in burned areas, the remaining populations may be too distant for the species to recolonize (Marschalek and Klein 2010). The coastal cactus wren (*Campylorhynchus brunneicapillus*) has also been affected by the compounding effects of habitat loss, degradation, and fires with a loss of genetic connectivity associated with habitat fragmentation and genetic bottleneck signals attributable to wildfire events (Barr et al. 2015). The dusky footed woodrat (*Neotoma macrotis)* is another species subject to patch extirpation that must recolonize after fire (Wirtz et al. 1988, Schwilk and Keeley 1998). Recolonization however, even for species such as the woodrat with the ability to disperse relatively long distances, can be substantially impeded by road networks and habitat fragmentation (Bolger et al. 1997, McGregor et al. 2008).

While some research efforts in southern California have taken advantage of the natural experiment presented by San Diego's 2003 and 2007 wildfires to gather information about bird (Mendelsohn et al. 2008), small mammal (Brehme et al. 2011, Diffendorfer et al. 2012), large mammal (Schuette et al. 2014), and herpetofauna (Rochester et al. 2010) response to wildfire, there is much to learn about individual- and population-level responses, in particular as they relate to increasing fire frequency. Understanding the effects of shifting fire regimes on wildlife where frequent fire may result in conversion of shrublands to grass-dominated habitats (Keeley 2005a, Keeley and Brennan 2012) is a significant challenge. There is evidence of the effect of increasing fire frequency on some species, such as the iconic coastal sage scrub species, the threatened California gnatcatcher (*Polioptila californica californica*). Already threatened by habitat loss and fragmentation in the coastal regions of southern California, frequent fires have degraded habitat for the gnatcatcher (Winchell and Doherty 2014) as California sagebrush (*Artemisia californica*), laurel sumac (*Malosma laurina*), and white sage (*Salvia apiana*), key habitat elements for the bird, have been replaced by non-native annual grasses after repeated fires. Habitat specialists and small species are not the only species subject to the impacts of increasing fire frequency. Despite the fact that mountain lions (*Puma concolor*) are highly mobile and often able to escape from fires, the species is potentially at risk from vegetation-type conversion (Jennings et al. 2016). Although this species may tolerate grasslands when moving between habitats (Zeller et al. 2014), fragmentation between San Diego County and the Santa Ana Mountains to the north has limited gene flow and resulted in inbreeding for the southern California population (Ernest et al. 2014), a situation which further habitat degradation could exacerbate. The impacts of increasing fire frequency and associated vegetation-type conversion on landscape connectivity are largely unknown for many species but pose a potential threat to the networks of conserved lands in the region (Figure 4.6).

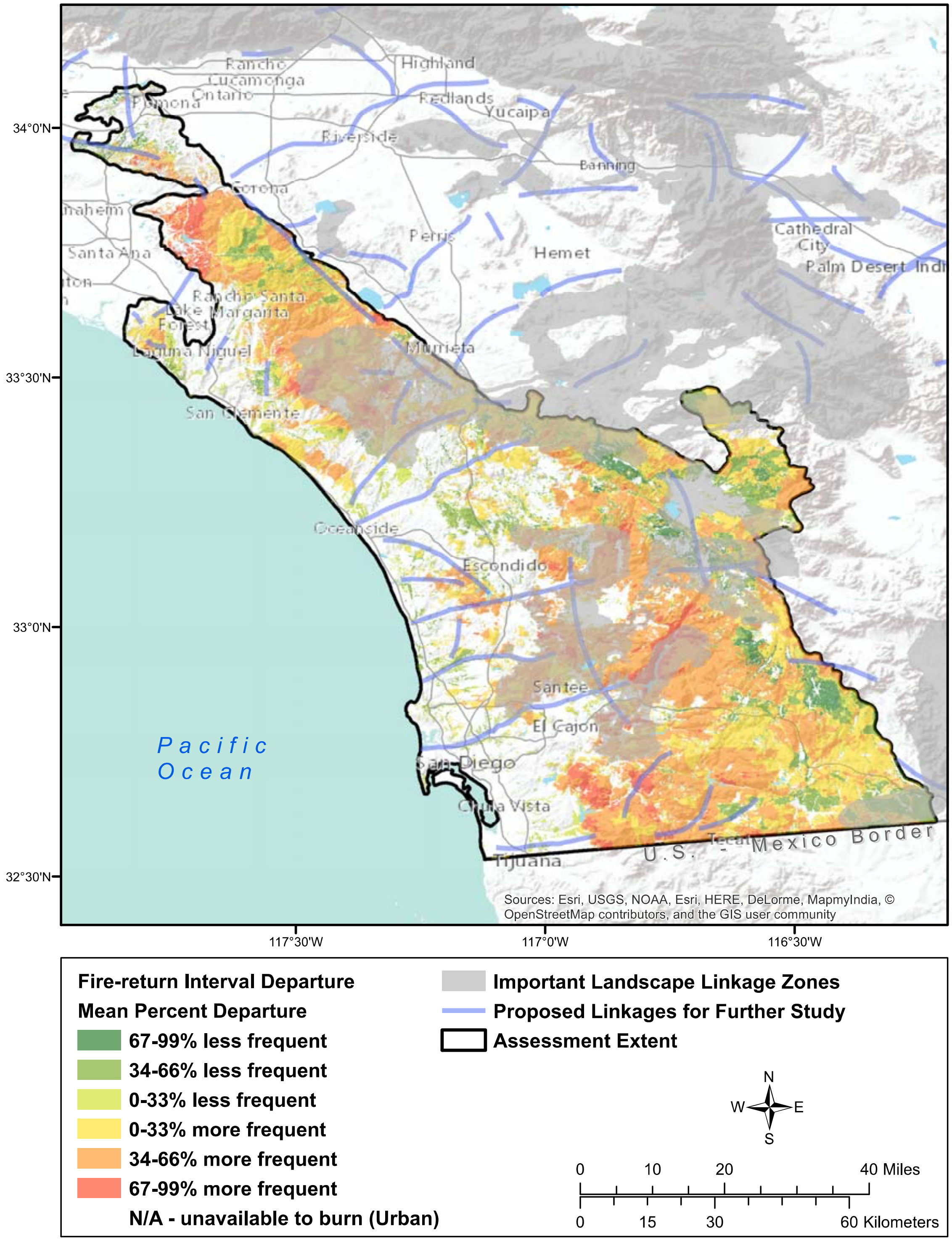

Figure 4.6: Map of fire-return interval departure (Safford and Van de Water 2014) in the region with an overlay of important areas for landscape connectivity. Yellow, orange, and red denote areas that have burned too frequently and are at risk of vegetation-type conversion. Gray areas signify proposed landscape linkages identified through prior research (South Coast Wildlands 2008, Spencer et al. 2010, Jennings and Zeller 2017) and blue sticks are proposed linkages for further study (Penrod et al. 2001).

In addition to terrestrial vegetation and fauna, wildfire also affects water quality and aquatic fish and benthic macroinvertebrate species, largely via its impacts to vegetation and soils within regional watersheds (Rehn et al. 2011). Although many aquatic species show signs of recovery several years after fire, more permanent changes in vegetation structure, i.e., from woody shrublands to grasslands, may cause long-term impacts to physical and hydrological properties of soil (Martinez-Fernandez et al. 1995, Williamson et al. 2004), water quality, and reservoir infilling (Hubbert et al. 2012). Woody shrublands are also better at sequestering carbon than grasses (Petrie et al. 2015).

As the number of large wildfires increases, so do costs to human lives and property. For example, the fires in 2003 and 2007 resulted in unprecedented numbers of structures and lives lost (Keeley et al. 2009, Syphard et al. 2012). However, the fire-weather conditions and size of the fires were not unprecedented (Keeley and Zedler 2009). The growing problem is the amount of WUI, or residential development that is now adjacent to and intermixed with wildland vegetation (Radeloff et al. 2005), which has been growing at an alarming rate (Hammer et al. 2009, Radeloff et al. 2018). A historical comparison of fire perimeters and urban development from the decade of the 1940s with the decade of the 2000s shows that, while area burned increased slightly (36%) in coastal San Diego County, urban development increased more than 800% (Figure 4.7). Thus, whereas no lives or structures were destroyed by fire in the 1940s, more than 5,000 homes were destroyed in the 2000s, along with 15 lives lost.

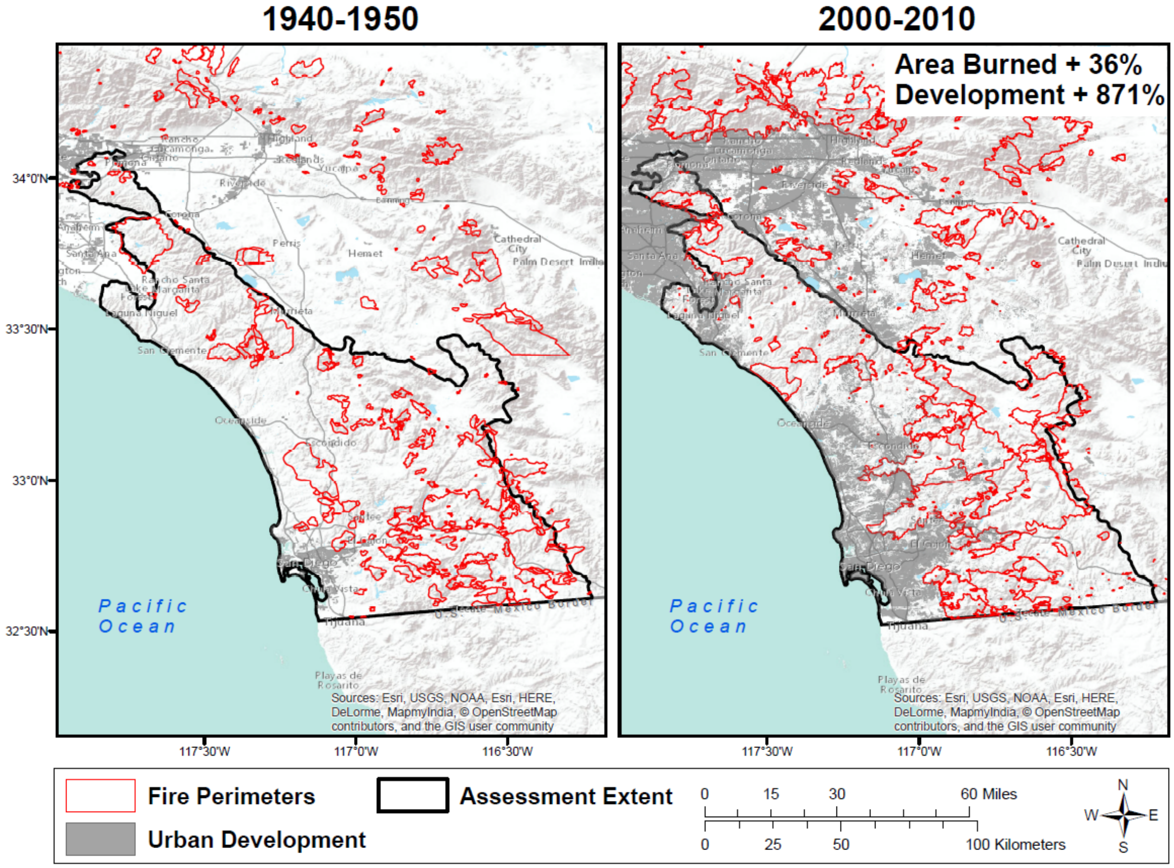

Figure 4.7: Size and distribution of fires (CALFIRE FRAP 2017) and urban development in the San Diego region during two periods: 1940-1950 (left panel), and 2000-2010 (right panel).

4.6 Fire Ecology and Management in Baja California

In contrast to the history of fire suppression and management in the United States that spans more than a century, fire management was initiated in Mexico during the 1970s by the Secretary of Agriculture and Hydraulic Resources (SARH), whose functions would be eventually transferred to the National Forestry Commission (CONAFOR), which was instituted in 2001 (Del Angel-Mobarak 2012). Since 1980, the Mexican Forest Service has received technical support and wildfire response training from the U.S. Forest Service (USFS), as well as from the Canadian and Spanish governments (Rodríguez-Trejo et al. 2011). During the early 2000s, fire policies and practices were defined and reformed through meetings and workshops during which priority was place on research needs to fill information gaps that would enable fire to become an essential part of management programs based on ecological principles (Rodríguez-Trejo et al. 2011). These changes in Mexico were primarily driven by the changes in the U.S. policy after recognizing the negative impacts of fire suppression on forest health (https://www.fs.fed.us/fire/). In addition, these meetings aimed to educate and train new generations to recognize the importance of fire in ecological management (Myers 2006). As a result, methods and techniques were agreed upon for the use of fire in forests and agricultural lands (Semarnat and Sagarpa 2009), as well as the National Program of Protected Natural Areas (Conanp and Semarnat 2007) where natural fire regimes in Natural Protected Areas (NPAs) are recognized and promoted. In 2011, the National Commission for Natural Protected Areas (Conanp and Semarnat 2007) published the strategies and guidelines for fire management in NPAs, which specifies the implementation of Forest Fire Protection Programs and the maintenance of ecologically acceptable fire regimes.

The region that comprises the northern portion of the state of Baja California (BC), in Mexico and the southern portion of California (CA), in the United States, spanning the U.S.-Mexico border, is within the CFP and as such, contains similar species and ecosystems. Because of these ecological similarities, this area can be used to contrast the impacts of the patterns of land use, which have been largely influenced by economic events linked to the United States (Ojeda-Revah and Espejel-Carbajal 2008), on fire regimes. Significant changes in vegetation have occurred over the last 150 years, with the largest changes on the north end of BC. This area is associated with population increases in urban areas, the migration of people to the border zone, and industrial and tourist activities that consume large quantities of water and energy (Antonio et al. 2008). The state of Baja California has one of the highest incidences of forest fires in Mexico (Sepúlveda-Betancourt et al. 1999). In recent years (2010-2015), an average of 196 forest fires have occurred and approximately 47,000 acres (~19,000 ha) have been affected annually (CONAFOR 2015). The causes of these fires are diverse, but just as in the San Diego region, human activity has been the primary ignition source in recent years (Delgadillo-Rodriguez 1998, Rodríguez-Trejo et al. 2011, CONAFOR 2015). Most incidences of forest fires from 2002-2015 have been documented close to urban areas (in the transboundary belt) and along roads connecting rural areas (Minnich et al. 1993). This pattern of fires located along bordering roads and nearby areas, which are mainly comprised of chaparral and scrub vegetation (Miguel-Barrera 2014, Rivera-Huerta 2017), is evident in the CONAFOR annual reports. The other primary ignition source for the region is in the montane regions of BC, in the Sierra de Juárez and the Sierra San Pedro Mártir, where the natural ignition source is lightning during summer.

The onset of fire season in Baja California is similar to that of the San Diego region, but it has been reported that 90% of fire scars appear in the early annual growth, suggesting that fires more often take place during the early summer (June-August) (Stephens et al. 2003, Skinner et al. 2008). As in the U.S., fire suppression efforts in BC are focused on systematic approaches to locate and extinguish fires in the first attack. These practices and the research of scars and history of fire in SSPM show sites that have not burned since 1950, similar to San Diego's montane ecosystems. If this trend continues, fuel accumulation will be greater, and the effects on the trend and severity too, so Baja California could experience the same effects that are currently being observed in California by the practice of suppression (Skinner et al. 2008). Several floristic and vegetation studies have been carried out over the last fifteen years in the Sierra San Pedro Mártir National Park (SSPMNP), (Thorne et al. 2010), including forest structure and mortality (Stephens and Gill 2005, Dunbar-Irwin and Safford 2016), fire history (Stephens et al. 2003, Skinner et al. 2008, Rivera-Huerta et al. 2016), forest disease (Maloney and Rizzo 2002), fuel loads and snags (Stephens 2004), post-fire regeneration (Stephens and Fry 2005), fire spatial patterns (Minnich et al. 2000, Stephens et al. 2008), and fire patterns and severity trends (Rivera-Huerta et al. 2016). Similar to the reference conditions at the beginning of the nineteenth century (Leiberg 1902), these studies describe a possible reference ecosystem that maintains its physical, structural, and fire characteristics (<20 years) of low to moderate severity, with mature individuals in an open forest. These studies describe the current conditions of the SSPMNP and also expose the possible consequences of the suppression of fire ignited by lightning—the main cause of wildfires in both San Diego and Baja California's montane conifer systems.

4.7 Moving into the Future

As we move into the future, Santa Ana winds during intensified and seasonally-extended drought may lead to increased potential for fall and winter megafire events. Combined with increasing human-caused ignitions associated with continued urban development, or further type conversion from woody shrubs to flammable herbaceous vegetation, some challenging management decisions will need to be made to allow people and fire to coexist while maintaining the county's natural resources.

Given that San Diego County currently suffers from an excess of wildfire, management strategies focused on prescription burning in San Diego's shrubland systems, as promoted for some forested regions, would only worsen the ecological impact of fire. Furthermore, regional research shows that wildfire and prescribed fire do little to limit subsequent fires (Price et al. 2012) and therefore may have limited effectiveness at reducing fire overall or at protecting communities. Other research on the role of fuel breaks in controlling large fire events in southern California suggests that mechanical fuel reduction has limited effectiveness for controlling large, weather-driven fires, but that strategically placed fuel breaks adjacent to communities may provide safe firefighter access to defend communities (Syphard et al. 2011, 2012, Penman et al. 2014). Nevertheless, fuel breaks and mechanical treatments such as mastication may have serious ecological consequences, such as furthering the spread of invasive grasses (Merriam et al. 2006, Brennan and Keeley 2015, Keeley and Syphard 2018). Therefore, trade-offs should be carefully considered when planning the design, location, and extent of vegetation management.

Although vegetation management in non-forested landscapes negatively impacts ecological resources and may have limited effectiveness at controlling weather-driven fires, studies in San

Diego County have shown that homeowner property preparation in terms of building construction and design and defensible space may significantly reduce the risk of a home being destroyed in a wildfire (Cohen 2004, Quarles et al. 2010, Syphard et al. 2014, 2016). However, while defensible space does provide significant protection, there is no added benefit of treating areas farther than 110 yards (100 m) from the property, even on steep slopes (Syphard et al. 2016).

When considering both local- and landscape-scale factors relative to their role in home loss, studies consistently show that the most significant factor explaining whether a home is destroyed is its location and arrangement relative to other homes on the landscape (Syphard et al. 2012, Alexandre et al. 2015, 2016). Research has also shown that land use decision-making, either via zoning for housing growth, or through the prioritization of where to purchase private land for conservation, could significantly reduce not only fire risk to humans, but also result in better ecological outcomes (Syphard et al. 2013, 2016, Butsic et al. 2017). This is not only because dispersed development patterns in the eastern portion of the county result in more habitat loss and fragmentation, but reducing sprawl in favor of compact, clustered, higher-density development could also reduce the overall amount of fire in the region as well as the number of fires that start closer to the origin of Santa Ana winds.

Ignition prevention efforts may also be highly effective as part of a comprehensive fire management program. For example, a number of prevention measures could be considered in the region, such as red flag warnings during severe fire weather to restrict equipment use during those times; road hardening projects to reduce ignitions started next to roads; restrictions on recreational activities during severe fire weather; and general education programs and outreach campaigns. Another measure that could prevent powerline-ignited fires would be to place powerlines underground. Although such measures are unpopular with utility companies, powerline-ignited fires often contribute to some of the most devastating human losses from wildfire (like those in San Diego County in 2007 and in northern California in 2017, and this relationship has been established in other parts of the world as well (Mitchell 2013).

4.8 Knowledge and Information Gaps

- Cost-benefit analyses and prioritization of where and when to conduct fire management strategies to optimize fire risk reduction with biodiversity conservation.
- The role of extended drought on fuel die-back, and contribution to increased area burned under Santa Ana winds.
- Interactions between drought and vegetation-type conversion in increasing landscape flammability.
- The conditions under which powerline-caused fires are most likely to occur and whether vegetation clearing is as effective as other strategies to reduce ignitions under severe weather conditions.
- The potential for short-term fuel drying under Santa Ana winds.
- The role of population growth and urban expansion relative to climate and vegetation change in driving future fire activity.

4.8.1 Monitoring Needs

- Quantification of the extent and rate of vegetation-type conversion across the region, and the primary drivers of this vegetation change.
- Vegetation dieback following extended droughts.
- Evaluating the practice of defensible space to ensure that homeowners are conducting it properly and sufficiently, but not excessively in a way that creates large-scale habitat conversion to unirrigated, flammable grasses.
- Improving the tracking of ignition sources to improve upon the large percentage of unknown sources and to better design prevention programs.
- Field studies to monitor and understand the potential for drought to impede recovery of native shrublands.

5: Impacts and Influences of Coastal Low Clouds and Fog on Biodiversity in San Diego[5]

Authors: Dawn M. Lawson, Rachel E.S. Clemesha, Sula E. Vanderplank, Alexander Gershunov, and Dan Cayan

5.1 Introduction

San Diego's mediterranean climate is characterized by a regular summer drought which, along the coast, can be offset by moisture and shading from coastal low clouds and fog (CLCF). The commonly used local terms "May Gray" and "June Gloom" attest to the seasonally persistent nature and horizontally uniform appearance of these stratiform ("layer") clouds. The blanket-like clouds (stratus, stratocumulus, and colloquially marine layer) reduce daytime maximum temperatures and when fog occurs (i.e., the cloud base meets Earth's surface) provide an incremental moisture source (Figure 5.1). While there are few studies (peer reviewed or gray literature) specifically from San Diego and the California Floristic Province (CFP) portion of Baja California, the broader literature points to a highly important role for CLCF in local ecosystem function, particularly in the moderation of seasonal and multi-year drought (Dawson 1998, D'Antonio et al. 2002, Baguskas et al. 2014). The effects are strongest near the coast,

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decreasing with inland progression (Vanderplank and Ezcurra 2016). The paucity of studies investigating the influence of CLCF is a reflection of the difficulty in quantifying it. Recent work in remote sensing has resulted in the publication of a spatial data set of CLCF (Clemesha et al. 2016a) and site scale instrumentation have resulted in multiple options for CLCF monitoring (Vasey et al. 2012b, Weiss-Penzias et al. 2012, Vanderplank and Ezcurra 2016, Bassiouni et al. 2017, Baguskas et al. 2018) both of which should facilitate incorporation of CLCF into ecological studies.

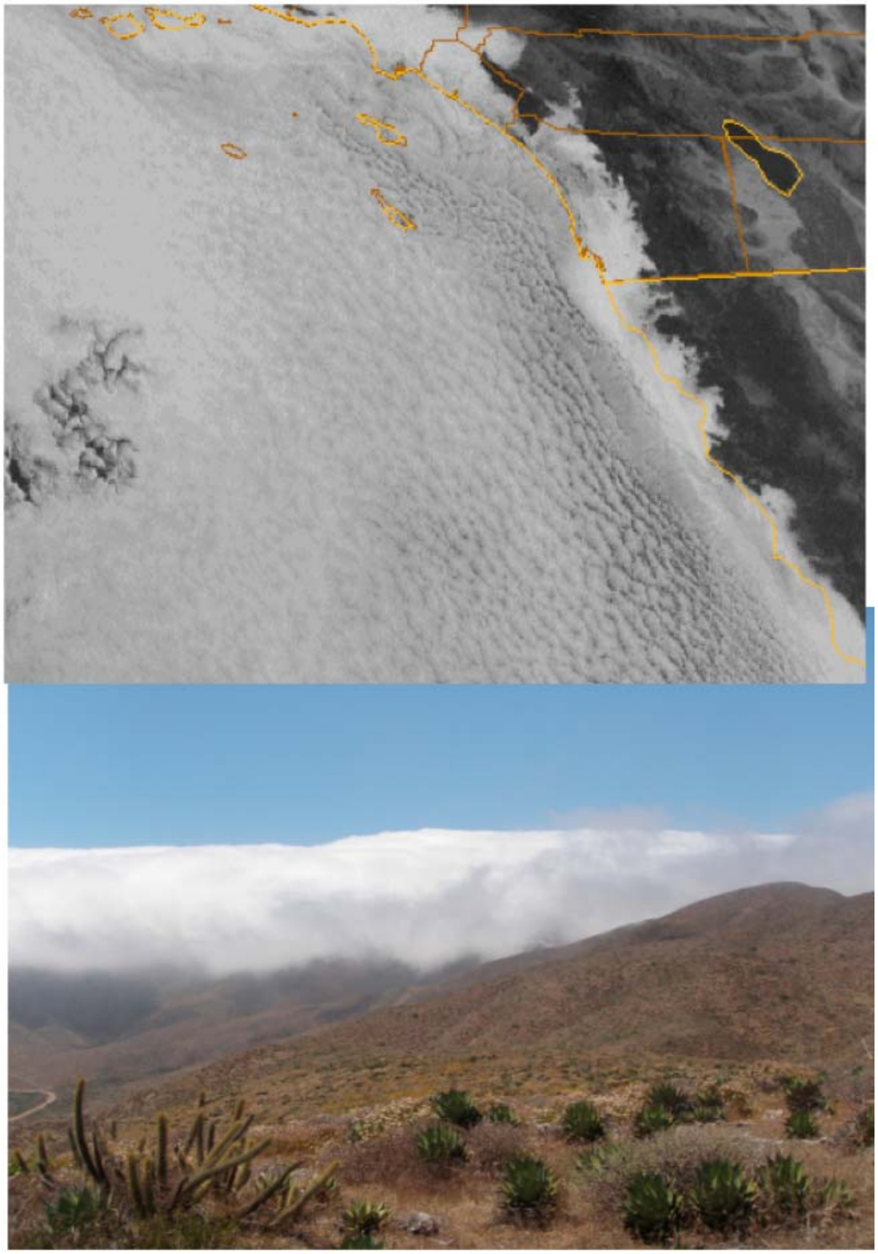


Figure 5.1: Examples of CLCF as viewed from the satellite GO ES-West (top NOAA 2018) and in the field in Baja California. Yellow lines depict county boundaries in California and the coast of Baja California (bottom photo credit Sula Vanderplank).

CLCF occurrence responds to a combination of global and regional climate features as well as local topography. Some observations show declines in California CLCF, but these haven't been linked to anthropogenic climate change with certainty (Williams et al. 2015a). Since possible changes in CLCF are uncertain, but continued warming is very likely, CLCF may help buffer warming and drying along the coastal plain through shading and cooling. For the purpose of this section, much of our knowledge of dry season coastal low clouds and fog (CLCF) variability in San Diego County will be extracted from the satellite record of Clemesha et al. (2016) and thus, we will consider CLCF to describe all low stratiform clouds together (stratus, stratocumulus, and fog). Where important known differences between low cloud and fog exist, e.g., in physical influences on the environment, we will address differences and potential limitations of the current state of the knowledge.

5.2 How Does CLCF Form Regionally?

Coastal low clouds form under a low-level temperature inversion wherein temperature increases rather than decreases with height in the troposphere (Figure 5.2; Lilly 1968, Pilié et al. 1979). This stable inversion acts as a lid, capping upward vertical mixing of cool, moist marine air. Formation of stratiform cloud occurs when the upper parts of the capped moist surface layer reach saturation. Along our coast, this temperature inversion is set-up seasonally by the interaction between the relatively cool California coastal sea surface temperature (SST) and the warm, dry descending air of the North Pacific High (Schwartz 2015). The North Pacific High is a result of the global scale Hadley circulation—the largest circulation system of the earth's atmosphere—in which air rises near the warm equator and sinks (large-scale subsidence) in the subtropics. The sinking air warms by compression (adiabatically) as it descends providing the contrast and cap to the cool marine air. This subtropical subsidence, broadly speaking, is the defining seasonal feature of our mediterranean climate—it is the reason for our rainless summers.

Formation mechanisms for fog specifically include: subsidence-forced lowering of the stratus layer (Koračin et al. 2001), lowering of stratus cloud base alone and thus a thickening of the stratus to the surface (e.g., Pilié et al. 1979), and an evolution from clear skies to fog and then to a lifted stratus deck (Leipper 1994, 1995). Although several mechanisms exist, the relative frequencies of occurrence of each mechanism compared to the others is unknown (Koračin et al. 2001).

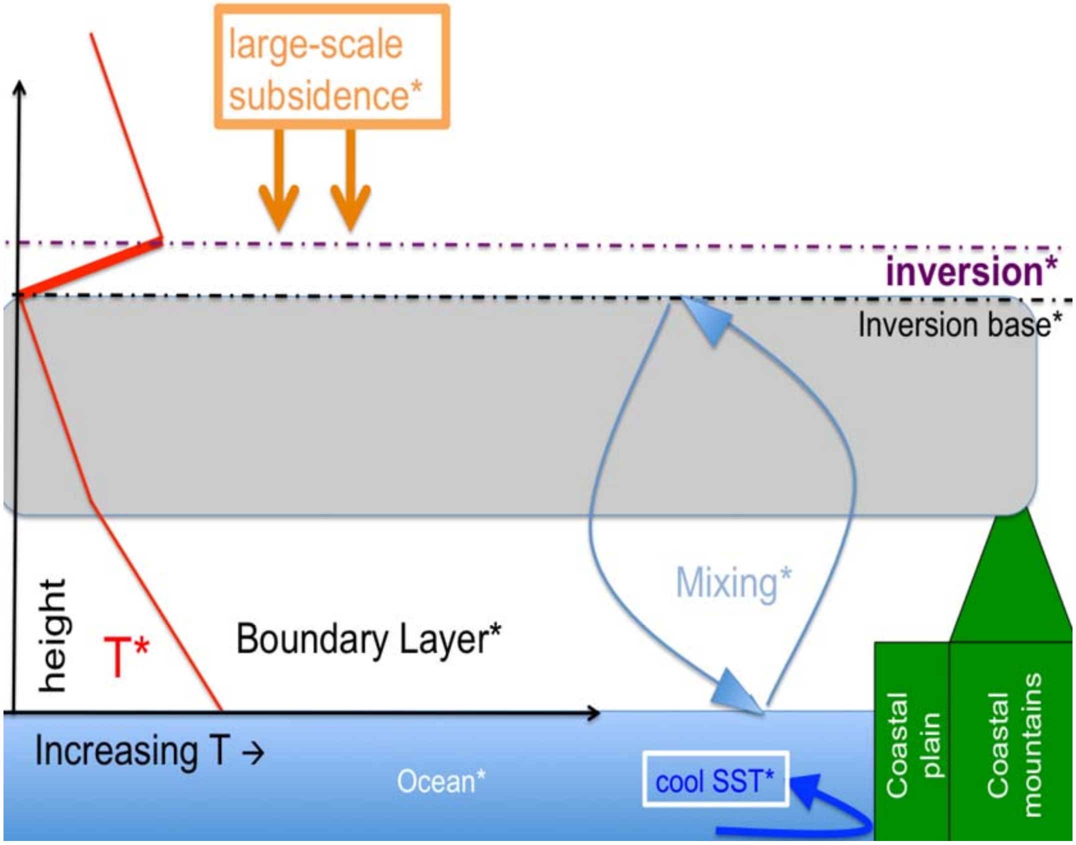


Figure 5.2: Idealized and simplified schematic showing the subtropical marine boundary layer structure with profile of temperature (T). A coastal low cloud is depicted in gray. Clouds with bases below 2 km are commonly defined as low clouds worldwide (Curry and Webster 1989, Houze 1993). In coastal California, a lower threshold of 1 km is often used (Iacobellis and Cayan 2013, Schwartz et al. 2014, Williams et al. 2015a). Technically, fog is a cloud whose base touches the Earth's surface (Houze 1993). Given this definition of fog, two observers, one at higher elevation in the coastal mountains and one at lower elevation on the coastal plain, may correctly identify the same feature as fog and stratus, respectively. Asterisks (*) denote factors expected to (or already observed to) change with anthropogenic climate change. Although topography won't be altered, anthropogenic land surface changes have already been shown to reduce fog (Williams et al. 2015a).

5.3 What Does CLCF Do to the Environment?

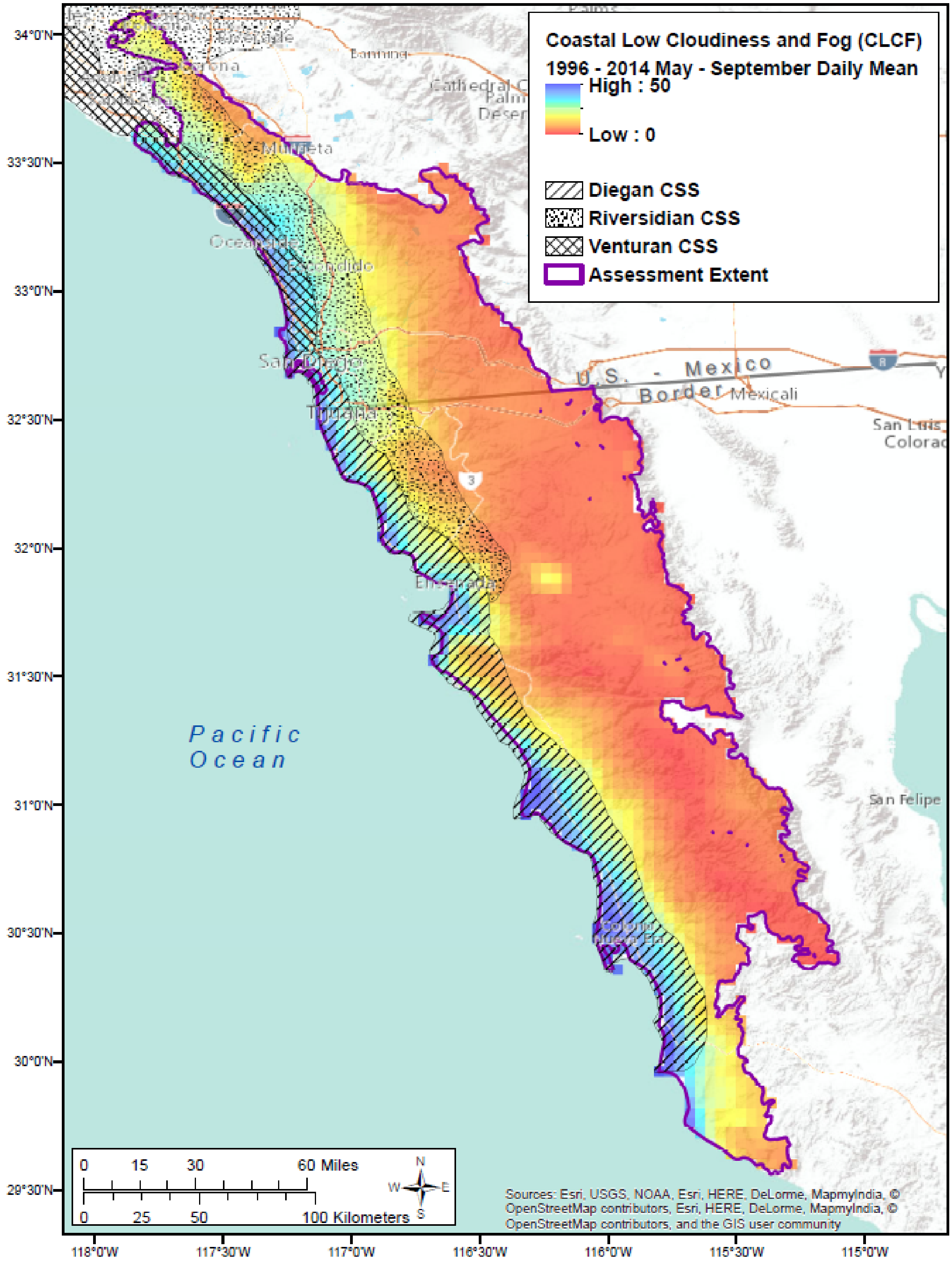
Table 5.1: Summary of CLCF impacts the environmental temperature, light, and moisture.

Variable	Impact of CLCF	Mechanism
Temperature		
Daytime maximum temperature	Reduced	Shading: Reduction of incoming solar radiation by cloud reflection
Nighttime minimum temperature	Increased	Blanket effect: Interception of infrared radiation and radiation back to surface reduces nighttime

Variable	Impact of CLCF	Mechanism
		radiative cooling
Diurnal Temperature Range	Decreased	Both mechanisms above
Light		
Total Solar Input	Reduced	Shading: High albedo of CLCF reflects incoming solar radiation
Diffuse Light	Increased	Light that does pass through CLCF is scattered
Moisture		
Evapotranspiration	Reduced	Shading
Direct Water Inputs	Increased (for ground/plant level fog only)	Interception of aerosolized water droplets, and either direct uptake through leaf tissue or concentration into larger droplets that add to soil moisture
Humidity	Increased	Low cloud overhead reduces daytime atmospheric drying; ground/plant level fog represents saturated conditions, i.e.,100% relative humidity (RH)

5.4 CLCF in San Diego

As can be expected for low clouds with an origin in marine-influenced air, there is a gradient towards the coast in CLCF presence with inland penetration limited by topography and distance from the coast. Figure 5.3 shows the long-term summer average of daily CLCF derived from a satellite record. On average for May-September at the immediate coast, for example in La Jolla, CLCF is present about 45% of the time, while less than 30 mi (~50 km) inland of La Jolla this value drops to about 15%. The gradient is even tighter in Orange County where the Santa Ana Mountains block the low clouds. Within the summer (May-September), the timing of the cloudiest time of the season varies across coastal California and occurs earlier in the south (Clemesha et al. 2016a). CLCF peaks in May and June along northern Baja and the southern California coast (Figure 5.4) and in late July/early August in northern California. Even though the curves are similar (Figure 5.4), the relationship between CLCF and daytime maximum temperatures (Tmax) is complex. CLCF is just one of several factors that affects Tmax (CLCF reduces solar input), so while the Tmax curve is consistent along the California coast, timing of peak CLCF varies (Clemesha et al. 2016a). Thus, if CLCF were to change under climate change the modulation of daytime temperatures may be altered. The low cloud cover also modulates heat wave expression at the coast (Clemesha et al. 2017). A striking recent example occurred on June 20, 2017; during all-time record-breaking heat in the San Diego County deserts (reaching 124 °F), coastal Del Mar was almost 60 °F cooler.



Sources: Esri, USGS, NOAA, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 5.3: Average Summer (May-September) CLCF between 1996- 2014. Coastal sage scrub data from Axelrod 1978.

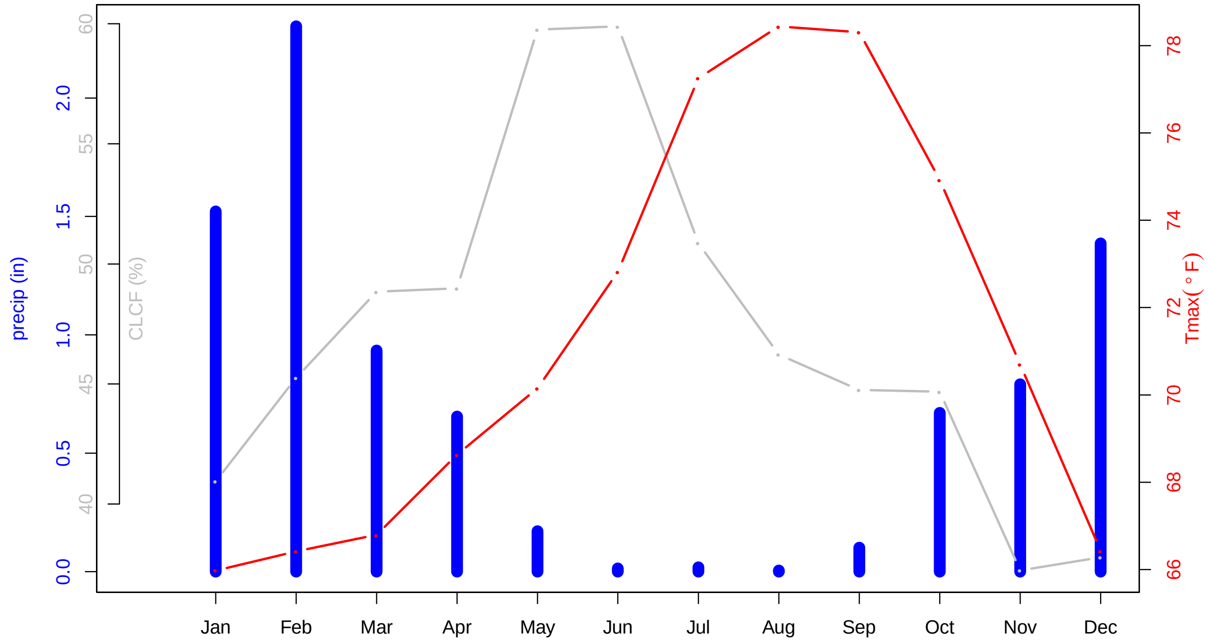


Figure 5.4: Monthly averages of low cloud presence from airport records, precipitation and daytime maximum temperature near the San Diego airport show the presence of CLCF during the hot, dry summer.

Within 10 mi (16.5 km) of the coast in San Diego County low clouds occur more than 30% of each summer day on average. The inland extent of CLCF also varies seasonally with a wider swath of San Diego consistently impacted by low clouds in May and June (the zone covered 30% of the time reaches over 20 mi [32 km] inland) and, as the summer proceeds, the low cloud cover contracts to the coast. At the immediate coast the clouds tend to be the most persistent in June when they are typically present over 50% of the time on average. Year-to-year variability is also strong. For example, Figure 5.5 contrasts May 2014, an exceptionally cloud-free month, with the anomalously cloudy May 2001. Although July tends to mark the beginning of the sunny season, July 2010 was an unusually cloudy month at the coast. Airport records suggest it was the cloudiest July at the San Diego airport in approximately 50 years. Cooler nighttime temperatures often lead to the formation and inland expansion of CLCF. The farthest inland extent of CLCF occurs in the early morning and the cloud deck typically recedes towards the coast later in the day due to daytime warming, drying and mixing processes (Ghonima et al. 2016, Wu et al. 2018).

What dictates the temporal and spatial variably of CLCF as described above? These low clouds are sensitive to the subtropical subsidence, which makes for warm, dry air in the free troposphere above the cloud deck. In addition to atmospheric conditions, oceanic and terrestrial conditions also play their parts. Analyses of airport records reveal that interannual to multidecadal variability of SST in southern California, and indeed along the whole west coast of the U.S., is negatively related to SST (Johnstone et al. 2010, Schwartz et al. 2014). As a recent case study, the anomalously clear summer of 2014 occurred during historically warm SST associated with the “blob” of warm SST off the Pacific northwest coast (Bond et al. 2015), while the gloomy summer of 2010 was associated with notably cold coastal waters. At the seasonal timescale, both atmospheric and oceanic components of lower tropospheric stability (LTS) are at play in driving the CLCF seasonal structure. The northward march of cloudiness over summer is related to the northward migration of lower stratospheric stability (Clemesha et al. 2016a). On daily time scales, CLCF variability is most strongly correlated to changes in stability of the lower atmosphere upwind of the CLCF region, reflecting a balancing act between stability and subsidence overhead. Intra-day changes and the spatial patterns of CLCF clearing are sensitive to cloud thickness and local elevation (Ghonima et al. 2016, Wu et al. 2018).

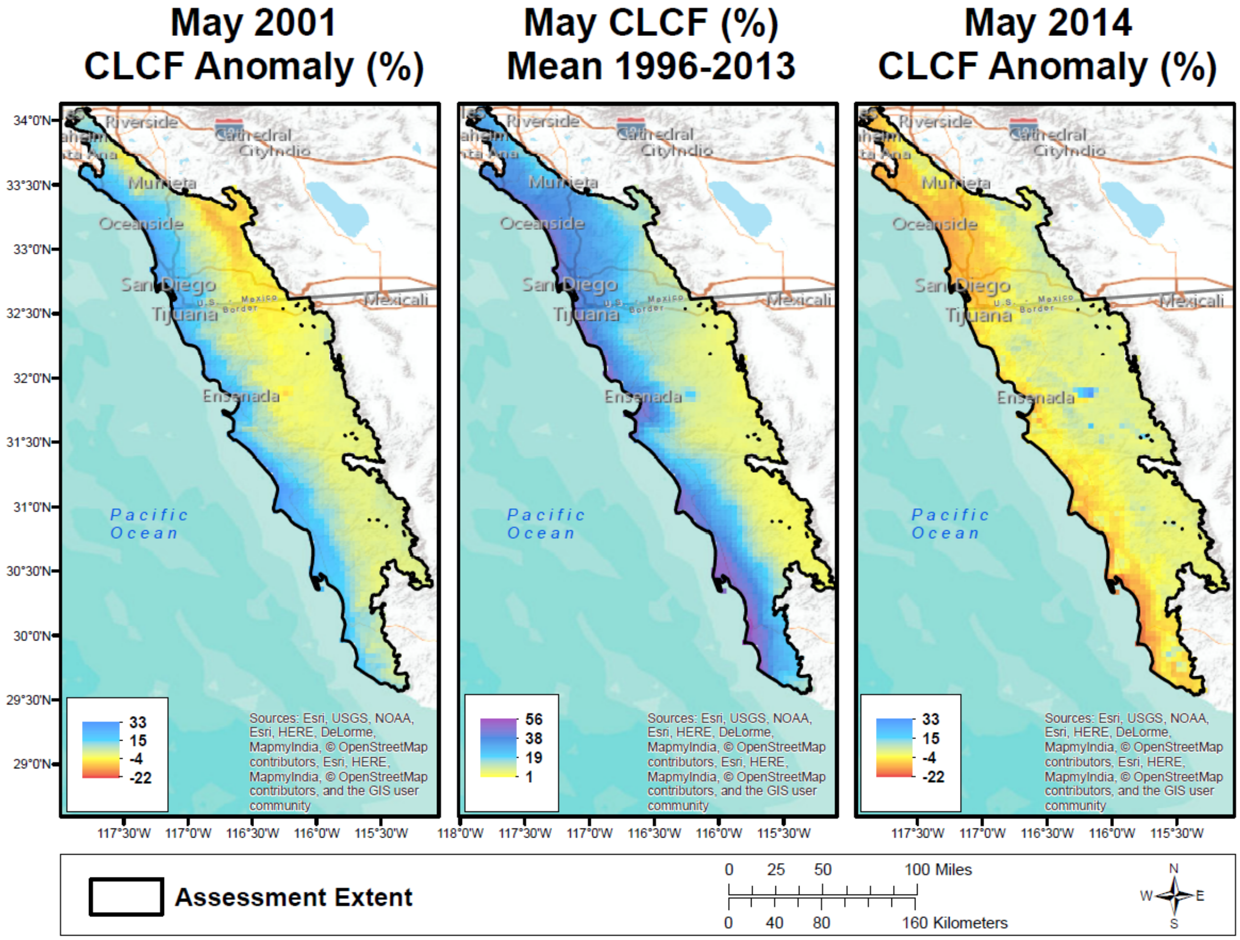


Figure 5.5: An example of interannual variability. Anomalies from the long-term May mean (middle) for May 2001 (left), and May 2014 (right) are shown.

5.5 The Future of CLCF Along the San Diego County Coast

Some recent studies have reported declines in California low cloud and fog, but these have not been linked to global anthropogenic climate change. Decreasing trends in annual dense fog frequency in the Los Angeles region have been observed (Witiw and LaDochy 2008, LaDochy and Witiw 2012). Johnstone et al. (2010) inferred a 33% reduction in fog for northern California over the last century, but this reduction was not necessarily driven by anthropogenic climate change and may be attributed to natural atmospheric variability (Johnstone and Mantua 2014). Williams et al. (2015a) found a trend toward increased cloud base height and a corresponding loss of fog in southern California that is attributed to urbanization. Schwartz et al. (2014)

observed decadal fluctuations and a slight but statistically significant decrease in summertime low cloudiness at airports along the west coast from 1950–2012. This broad scale variability was linked to multi-year fluctuations in sea surface temperature over the north Pacific, and the decline in recent years was related to a tendency for anomalously warm SST in the eastern north Pacific during recent decades.

How will CLCF along the San Diego County coast respond to climate change? Definitive answers await more research and continued observations, but it is possible to speculate how some of the major atmospheric and ocean drivers of CLCF (e.g., Schwartz 2015) may change (see Fig. 5.2 and caption). Considering large scale atmospheric processes, observations and model experiments indicate that the sinking motion that stabilizes the low-level inversion along the California coast may become more persistent due to broad scale expansion of subtropical subsidence (Lu et al. 2007). This process, which would broaden the North Pacific subtropical high-pressure belt, could result in a longer CLCF season, and is also likely related to a projected decline in precipitation during autumn and springtime in California (see Section 3). Other controlling processes that may be altered as the climate changes include strengthened inversions (Caldwell et al. 2013). There is considerable interest in bright open ocean stratocumulus cloud decks because of their impact on the global radiation budget, and Qu et al. (2014) find "medium overall confidence low cloud cover will decrease" according to climate model simulations. At low latitudes, Bretherton (2015) also expects a reduction of cloud cover in the future warmer climate. Likewise, Myers and Norris (2016) attribute less projected low cloud cover as a result of the opposing impacts of increased SST and increased atmospheric stability.

The southern California coastal region includes several additional factors which could be altered under climate change -- e.g., the impact of upwelling on sea surface temperature (SST), the influence of warming land on the lower atmosphere boundary structure, and the interaction of terrestrial/anthropogenic aerosols on cloud microphysics. Snyder et al. (2003) found intensified coastal upwelling in response to strengthened northerly winds. O'Brien (2011) found that climate change projections of northern California fog from a regional climate model "hints at a slight decline in the future" with high uncertainty (Torregrosa et al. 2014). Several decades of observations (Johnstone et al. 2010, Schwartz et al. 2014) and a recent study of land use change by Williams et al. (2015a) report decreases in southern California fog driven by urbanization. These studies and observational results underscore the sensitivity of CLCF to multiple factors and emphasize how changes in CLCF are the net result of sometimes competing influences. Thus far, observations and climate model simulations provide more evidence for future decreases than increases in CLCF. Although the uncertainty in projected changes in CLCF is high, there is much more certainty in projected warming and through their effects on shading and cooling, CLCF, if not substantially reduced, could buffer these warming effects (Williams et al. 2015b, Fischer et al. 2016).

5.6 Effects of CLCF on Biodiversity

Through effects on ecosystem water balance, low clouds and fog are important drivers of species dynamics and ecosystem function in diverse ecosystems worldwide from montane cloud forests to coastal regions (Dawson 1998, D'Antonio et al. 2002, Cáceres et al. 2007, Vasey et al. 2012a, Fischer et al. 2016, Oladi et al. 2017). But, while scientific studies on use of fog water by plants have been ongoing for hundreds of years (Stone 1957), it wasn't until the mid-20th century that evidence of the importance of fog inputs to a variety of ecosystems began to accumulate. Initially the focus was on fog drip to the soil surface from plant canopies intercepting aerosolized water (Oberlander 1956, Parsons 1960, Vogelmann et al. 1968). More recent work has used isotopic analysis to quantify the fog water inputs during the dry season or prolonged droughts to a wide variety of ecological communities and focused on the processes whereby low clouds and fog influence water balance through shading and foliar uptake of fog water in addition to fog drip (Burgess and Dawson 2004, Corbin et al. 2005, Emery and Lesage 2015).

Fog drip supports a diverse range of taxa including plants, animals, and microbes (Manzoni et al. 2012) and ecosystem processes including nutrient mineralization and carbon cycling (Carbone et al. 2013). In addition to fog drip, direct foliar uptake of fog water is important even where fog water is insufficient to change soil moisture (Breshears et al. 2008b). Shading reduces solar input and thus thermal loading and ultimately evapotranspirative stress on plants (Fischer et al. 2009) and heat stress on animals (Henschel and Seely 2008). Most work to date has been done in systems with higher levels of CLCF. However, and importantly when considering ecosystem effects in much of coastal San Diego County and CFP Baja California, even where the levels of moisture in CLCF are insufficient to change soil moisture, species and community effects can be significant (Breshears et al. 2008b).

Fog water can constitute a significant input to the hydrological regime (Pryet et al. 2012) and in some locales result in more water than rainfall (Dawson 1998). In arid systems, low clouds and fog during the regular dry season or prolonged drought can be particularly influential to ecological communities due to their contribution to the hydrological regime and effects on ambient temperature when moisture is most limiting (Breshears et al. 2008b, Fischer et al. 2009, Cassana et al. 2016, Oladi et al. 2017). Specifically, in mediterranean-type climate regions, most perennial plants are primarily sustained by water from winter rains, but moisture and shading from summer CLCF is remarkably important and can influence population dynamics, individual growth, and abundance (Corbin et al. 2005, Johnstone et al. 2010, Oladi et al. 2017).

Fog water input can be highly variable spatially depending on the size and characteristics of plant canopies, topography, and position with respect to other plant and topographic features that precipitate fog water out of the atmosphere (Oberlander 1956, Johnstone et al. 2010). Depending on the effects of climate change on low clouds, CLCF-supported mesic microenvironments could serve as important refugia for species under climate change (McLaughlin et al. 2017; also see Section 2.5). In areas close to the coast CLCF appear to be important in mitigating fire hazard (Lawson et al. 2017b, Emery et al. 2018, Williams et al. 2018). Recently, Williams et al. (2018) found burned area in coastal southern California to be inversely correlated with stratus frequency. Summer atmospheric water potential (PSI atm), a surrogate for fog (Loik pers. com.), was found to have a significant effect on both dead and live fuel moisture, emphasizing its importance in controlling fire hazard. Even a small increase in fine dead fuel moisture can result in significant changes in fire behavior (see Section 4.4.2).

5.6.1 Influence of Low Clouds and Fog on Biodiversity

5.6.1.1 Plants

CLCF influences the water budget by water addition through uptake of fog drip by shallow roots, foliar uptake of fog water, and reduction in water loss by shading (Figure 5.6). Below, we discuss ways that plants use fog water (fog drip and foliar uptake) and the positive influence (and to a lesser degree negative influence) of shading. We review the effect of CLCF on phenology (time of flowering) and plant demographics (recruitment, mortality, and fecundity). These effects on individuals and populations ultimately influence interspecific competition and species ranges. We provide illustrative examples of these patterns and processes, although mechanistic details for specific cases are often lacking. We use examples from San Diego and CFP Baja where available but, due to the dearth of region-specific literature, we also cite the broader literature to create a fuller picture of how CLCF likely influences biodiversity and ecosystems in our region.

Figure 5.6: Fog adapted life forms, *Agave sebastiana* (lower left, left photo) and *Pinus radiata var. cedrosensis* (upper left, left photo) (photo credit Sula Vanderplank) and fog water precipitating on cactus spines (right photo) (photo credit MC1 Eli J. Medelin).

Fog drip. One of the ways plants access fog water is through a process known as fog drip where fog condenses on leaves and stems and drips onto the ground where it is taken up by shallow fine root systems (Louw and Seely 1980, Corbin et al. 2005, Emery 2016). Many of the local endemic plants of San Diego and northwest Baja California correspond to fog-adapted life-forms with high efficiency in intercepting aerosolized water droplets. These life-forms include succulent rosettes (*Dudleya* spp., *Agave shawii*) that reveal trade-offs between leaf shape and size, and densely-spined cacti (*Bergerocactus emoryi*) that effectively capture fog water on their dense, long, narrow spines (Martorell and Ezcurra 2007, Vanderplank and Ezcurra 2016). Pine trees, such as the local Torrey pine (*Pinus torreyana*), are also efficient fog harvesters, with their needles dripping fog down to the soil surface (Fischer et al. 2009). Many others, however, such as California sage brush (*Artemisia californica*) while not specifically adapted to enhance fog capture, do so nonetheless when conditions are right (Emery and Lesage 2015).

Foliar uptake. The direct absorption of water deposited on plant leaves is another way that plants use fog water (Burgess and Dawson 2004, Cassana et al. 2016, Emery 2016). Even when this is associated with insufficient water to change soil moisture, the potential benefits can be important and include reducing drought related mortality by rehydrating plant tissue and increasing carbon fixation (Burgess and Dawson 2004, Breshears et al. 2008b, Cassana et al. 2016, Oladi et al. 2017). Foliar uptake happens when the plant–atmosphere water potential gradient is reversed so that water potential is higher in the air around the plant than in the plant tissue (Emery 2016). The mechanisms involved include stomatal transport (Burkhardt 2010) and specialized structures such as trichomes (Benzing et al. 1976) and epidermal hydathodes

(Martin and Von Willert 2000). The ability to utilize fog water in this way is species-specific and involves trade-offs. For example, increased foliar water uptake ability is correlated with lower stomatal control and consequent lower resilience to drought (Johnstone et al. 2010, Emery 2016). An additional trade-off is that, for areas that receive most of their fog at night, plants can lose moisture without the benefit of carbon uptake to support photosynthesis (Burgess and Dawson 2004). Recent research has shown that both drought deciduous and evergreen coastal sage and chaparral species take up fog water deposited on leaves (Emery and Lesage 2015, Emery 2016), although the drought deciduous species likely benefit more and some evergreen species are unable to use fog water (Emery 2016). Other life forms including lichens with green algae are able to take up water at air humidity above 96% (Lange et al. 1994).

Timing of flowering. The consequent reduction in evaporative stress appears to stabilize timing of flowering in more coastal sites. In the CFP of Baja California, the spring-to-fall seasonal flowering gradient is driven by moisture availability (Vanderplank and Ezcurra 2016). This general trend varies significantly from site to site. Coastal sites with a stronger influence of CLCF showed lower variances in timing of flowering than sites further inland. Available moisture derived both from rain and fog seems to control phenology in the region, but fog in particular (perhaps because it is present during the seasonal drought) seems to play an extremely important role in variation between sites. Vanderplank & Ezcurra (2016) found a significant negative correlation between fall-to-spring phenological variation and mean relative humidity in their study of phenological variation across the CFP-desert ecotone. Their data show that spatial and seasonal variation in flowering are dampened by the proximity to the coast (the drier, more inland sites showed stronger seasonality than the more mesic coastal sites). The coastal sites showed lower flowering intensity in spring compared to inland sites but maintained some flowering during summer when inland sites were largely dormant, showing that seasonality of flowering is buffered by coastal (foggy) conditions. These lengthier flowering periods reduce synchronicity and pulsing, which in turn can shift pollination/predation balances.

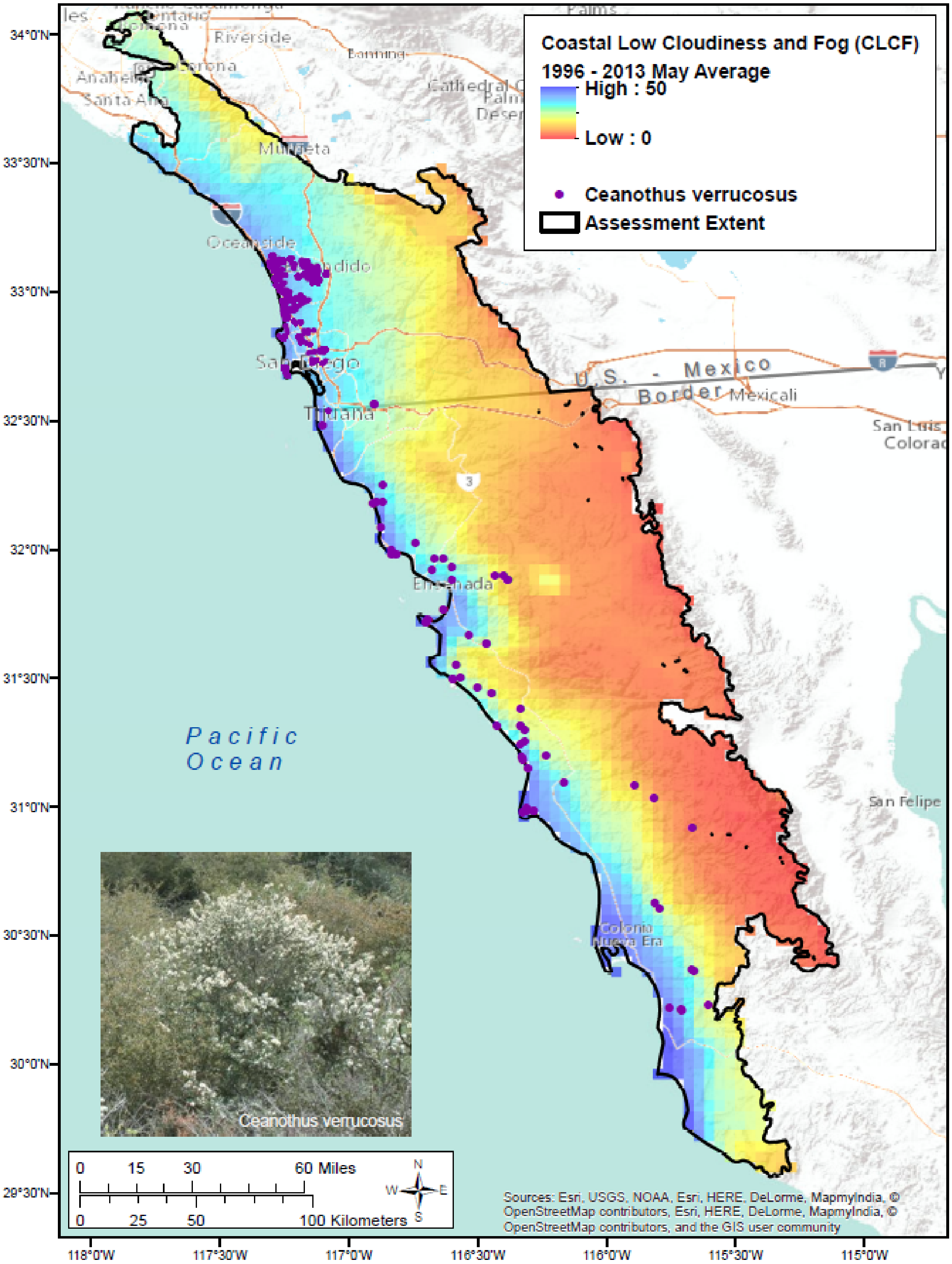
Plant productivity. Plant growth is regulated by carbon uptake and water loss trade-offs. CLCF can provide water during active growth periods and mitigate the effects of seasonal and long-term drought on plant productivity (Burgess and Dawson 2004, Fischer et al. 2016, Fyllas et al. 2017, Oladi et al. 2017). However, while low clouds reduce drought stress (Williams et al. 2008a, Fischer et al. 2009) they also reduce incoming photosynthetically active radiation (Carbone et al. 2013), although this is rarely limiting in southern California. In addition, water use efficiency, the amount of CO_2 assimilated per unit of water loss, is reduced by clouds (Williams et al. 2008a, Fischer et al. 2009). In spite of these trade-offs and while woody species in mediterranean-type climate ecosystems are primarily supported by winter rains, a number of studies have shown higher growth rates in woody species that also experience low clouds and fog during the dry season (Burgess and Dawson 2004, Fischer et al. 2016, Oladi et al. 2017).

Plant demographics. Particularly during the summer drought but also during long-term drought, contributions to the hydrological regime from fog water and reductions in evapotranspirative demand from cloud cover can have significant effects on plant demographics including survival, growth, and consequent recruitment to larger size classes, reproduction, and overall population size.

CLCF is an important driver of mortality and recruitment. Water stress is a primary driver of plant mortality (Allen et al. 2010). By improving plant water status (Baguskas et al. 2016), CLCF can reduce mortality associated with hydraulic failure (Baguskas et al. 2014) and promote growth (Corbin and D'Antonio 2004). While both juveniles and adults benefit from fog water, larger plants with more extensive root systems are buffered from drought through access to deeper, more reliable soil water. Survival through the first several summers is an important rate-limiting step in perennial plant establishment in mediterranean-type climate ecosystems (Frazer and Davis 1988, Thomas and Davis 1989). CLCF both through direct water input (Baguskas et al. 2016) and shading (Berry and Smith 2012, Berry et al. 2014) is likely to increase juvenile survival rates by supporting growth, allowing young plants to reach the more reliable deeper soil water resources sooner. In drought, deciduous species such as *Artemisia californica* CLCF may delay leaf drop, which is triggered by increasing drought stress (Gray and Schlesinger 1981). If the effects of low clouds and fog allow the plants to retain their leaves marginally longer they can potentially achieve a net carbon gain over plants that lose their leaves earlier (McDowell 2011).

Summer CLCF also supports higher reproductive output. Vanderplank & Ezcurra (2016) showed an increase in flowering in sites that experienced low clouds and fog over more inland sites. In addition, more rapid growth promoted by CLCF can lead to earlier reproduction because reproductive output in plants is more often associated with size than age (Harper 1977). Lawson (2011) documented seed production in the maritime chaparral shrub *Ceanothus verrucosus* in 1.5-year-old plants at Bernardo Mountain in San Diego County, where CLCF is common. *C. verrucosus* is an obligate seeding shrub where fire kills all adults and it must reproduce from seed. This finding was notable because the species is vulnerable to short fire intervals because it typically takes years for seedbanks to re-establish (Zedler 1995). Repeat fire prior to seed bank replenishment can lead to severe population decline. Early onset of seed production would reduce the vulnerability to population decline and patch extinction from short fire intervals.

Plant species ranges. The influence of CLCF on plant demographics and phenology affect interspecific competition (Corbin and D'Antonio 2004) and species ranges (Fischer et al. 2016). As such, a number of species are limited to areas with CLCF. The bishop pine was once widespread, the populations at its southernmost edge on Santa Cruz Island are supported by fog (Fischer et al. 2009). Wart-stemmed Ceanothus (*Ceanothus verrucosus*), a narrow range endemic, is limited to areas of relatively high CLCF in San Diego County and CFP Baja California (Figure 5.7) possibly due to the marine influence on winter low temperatures (Lawson et al. 2010). The southernmost extreme of the CFP, along the coast in Baja California, is home to coastal sage scrub in areas of very low precipitation. It is generally accepted that this southernmost ecotone of the CFP is largely maintained by CLCF which reduces daytime temperatures and increases humidity (Axelrod 1978, Raven and Axelrod 1978). In the coastal plain, CLCF appears to buffer the low winter rainfall regime, promoting the growth of "nebulophytes" (rosette-forming plants that are able to capture fog) (Rundel et al. 1972, Martorell and Ezcurra 2002). CLCF plays a critically important role in the extension of the southern and inland range limits of many CFP species by ameliorating the lack of rainfall in this gradient.



Sources: Esri, USGS, NOAA, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 5.7: Distribution of wart-stemmed ceanothus (*Ceanothus verrucosus*) and CLCF. Wart-stemmed ceanothus is a highly visible component of chaparral when flowering around February of each year (inset picture). Distribution data from San Diego Natural History Museum (2017), California Department of Fish and Wildlife (2015), Lawson (2009).

Floristic diversity. High floristic diversity in both coastal sage scrub and maritime chaparral has been linked to CLCF (Axelrod 1978, Vasey et al. 2014). In coastal sage scrub this is reflected in the diversity of the three coastal sage subtypes within the study region: Diegan, Venturan, and Riversidian Scrub types (Figure 5.3). These three subtypes grow in complete proximity to one another yet show surprising differences in species composition. The two coastal subtypes (Diegan and Venturan) are more diverse than the inland (Riversidian) subtype. This is reflected in a floristic similarity of 61% between Diegan and more northerly but still coastal Venturan Scrub (with 29 of the 51 dominant taxa extending north), but only 32% between Diegan and its inland counterpart Riversidian (with only 12 of the 51 dominant taxa being found away from the coast). Axelrod (1978) attributes these differences entirely to climate. He concludes there is no other obvious driver for the dramatic differences in species composition. His work shows that differences in mean annual temperature range throughout the year separates these three CSS subtypes, with Diegan having the lowest range, and Riversidian the highest. Since it is the shift in the range of temperatures (not mean annual temperature, which is very similar for all three), this vegetation type appears to be particularly susceptible to temperature extremes which are buffered by CLCF, allowing coastal vegetation to harbor many more species, and unique assemblages in the Diegan scrub (Caso et al. 2007, Richerson and Lum 2008, Vanderplank 2013, Vanderplank and Ezcurra 2016). This suggests that CSS is a vegetation type particularly reliant on CLCF (Figures 5.3 and 5.8).

Figure 5.8: Fog-shrouded coastal sage scrub in northern San Diego County (photo credit MC1 Eli J. Medelin).

Similarly to CSS, maritime chaparral comprises higher diversity in coastal locations. Evidence of the influence of CLCF on floristic diversity in maritime chaparral comes from central California. Vasey et al. (2014) measured floristic diversity on a coastal to inland gradient using mid-morning cloud frequency (Williams et al. 2008a) plus a number of climate variables associated with CLCF to evaluate its influence. They found higher diversity in coastal locations compared to more inland chaparral species assemblages and concluded that it appeared to be driven by summer moisture availability.

5.6.1.2 Fauna

Less is known about the effects of CLCF on fauna but a review of the literature reveals collection of aerosolized water by a number of different mechanisms and reduction of heat stress and shows a wide range of effects from flight behavior in birds, to timing of nesting, nesting success, and behavior in different taxa.

Birds. Humidity has been anecdotally documented to affect nesting time and clutching repeats of the California quail in Baja California (Vanderplank unpublished data). Sandhill crane flight behavior differs when fog covers roost sites, leading to reduced flight distances and increased circling. In foggy conditions, increased circling can increase collision risk with powerlines and other hazards (Kirsch et al. 2015, Murphy et al. 2016). Birds have also been noted to adjust their nest architecture in response to humidity; therefore, CLCF may impact both migratory and nesting birds in coastal San Diego (Botero-Delgadillo et al. 2017).

Reptiles. Moisture-harvesting lizards, such as the Australian thorny devil (*Moloch horridus*), have special skin structures, comprising a micro-structured surface with capillary channels in between imbricate overlapping scales, that enable the lizard to collect water by capillarity and transport it to the mouth for ingestion. Possible sources include rainfall, puddles, dew, fog condensation on the skin, or absorption from moist sand (Murray et al. 2016). In contrast, various other lizards and snakes use water droplets from advective fog condensation, rain, sleet, or snow without specialized structures, simply by licking it up (Louw 1972, Repp and Schuett 2008).

Insects. Fog likely influences insect abundance, distribution, and movement in the environment. Palmisano and Fox (1997) found that cool, foggy summers plus a generally low annual rainfall restricted to winters (e.g., in coastal central California) reduce insect abundance. Insect abundance may increase in coastal central California during less foggy summers. Another way that atmospheric water influences insect communities analogous to foliar leaf absorption is through passive absorption of water vapor. Passive absorption of atmospheric water is very common in arthropods and correspondingly, relative humidity is one of the factors that influences the activity pattern of surface-active arthropods in the Namib desert, and difference in humidity between microhabitats may affect arthropod distribution (Henschel and Seely 2008). Different mechanisms to utilize aerosolized water have also been found in other arthropods, e.g. the oral water vapor uptake system of the Californian desert cockroach *Arenivaga* (Edney 1966). Fog can also influence communication between individuals. It can act as a signal reflector which can interfere with or significantly attenuate sound waves, particularly if they are set into vibration by the sound and thus absorb power (Pye 1971, Bennet-Clark 1998).

Faunal diversity. Moisture availability promotes faunal diversity. The amazing wealth of insects found in damp sites attracts numerous predators including insectivorous reptiles and amphibians, insectivorous bats, birds, and mammals (Louw 1972, Henschel and Seely 2008, Kirsch et al. 2015). Areas that are beginning to dry and leave mineral deposits and salts on the soil surface are important sources of minerals for many organisms, including butterflies and larger animals like mule deer. Small mammals like shrews are largely insectivorous and, in turn, are predated by carnivorous creatures such as owls and coyotes. Cool, moist areas may form the basis for peaks in regional biodiversity. The humid air and damp microsites extend the active period for many creatures, reptiles in particular. The cooler air allows them to be active for a greater period of the year, reducing hibernation times and extending their ecosystem function well into the dry season.

Even in a hyperarid environment there are a number of ways for organisms to obtain atmospheric water, namely a) location in moist micro-environments, b) drinking from wet surfaces during dew or fog, c) consumption of moistened food, d) collecting fog water on the body, and e) absorbing water vapor. Both (d) and (e) involve some special adaptations, notably fog-basking, and formation of high osmotic pressure (Henschel and Seely 2008).

5.6.1.3. Community Impacts (Interspecific Interactions)

Individual species' ability and effectiveness at utilizing fog water is highly variable (Emery and Lesage 2015) with many trade-offs. This combined with high spatial and temporal variation in the presence and intensity of CLCF results in a complex web of effects across the landscape. This variation influences interspecific interactions and ultimately species distributions, species assemblages, and ultimately biodiversity (Fischer et al. 2009). The following are two examples of interspecific interactions (synchrony and pulsing) influenced by CLCF. There are undoubtedly many more.

The influence of CLCF on flowering timing and insect populations can influence mutualisms and predation. The study of Vanderplank and Ezcurra (2016) in CFP Baja California shows the effect of CLCF on synchrony of flowering, with populations nearer the coast in foggier conditions exhibiting lower synchrony. A recent study on the timing of anthesis in *Erigeron glaucus* showed that even in species with strong seasonality of flowering, within populations, the degree of flowering synchronicity has a significant impact on both pollination success and seed survival (English-Loeb and Karban 1992). Low synchrony (low levels of flowering throughout a long flowering season) may help some individuals avoid temporal bouts of predation from specific insects, but dense and simultaneous floral displays (Figure 5.9) may be the most effective in terms of recruiting pollen vectors. These findings are echoed across several studies that show earlier or peak flowering to attract pollinators and later or non-synchronous flowering to attract seed predators (Elzinga et al. 2007).

The mitigation of summer drought by CLCF can also alter competition. Annual plant species over-summer as seed to avoid the summer drought, whereas perennial plants must use a number of strategies including fog water usage to survive. Native perennial grass species (Figure 5.10) are better able to compete with invasive annual grasses at coastal locations with higher CLCF than in inland sites without CLCF (Corbin et al. 2005). While fog and low clouds can tip the balance in favor of perennial native coastal sage scrub species over exotic annual grasses, in systems where perennial invasives are important, dry season fog and low clouds assists them as well. In northern California coastal native perennial grasslands, low clouds and fog benefit both invasive and native perennial grasses (Corbin et al. 2005, Corbin and D'Antonio 2010, Clary 2012).

Figure 5.9: ***Agave sebastiana*****, flowering in the heavy fog on Cedros Island. Fog can affect both pollination and floral predation, reducing both (photo credit Sula Vanderplank).**

Figure 5.10: Native perennial grasses resprouting during summer drought supported by CLCF (photo credit Dawn M. Lawson).

5.7 Conclusions and Needs for Further Research

This review shows the importance of CLCF in species and community dynamics and importance in ecosystem processes (hydrological cycle and fire). It interacts with other elements of the hydrological cycle, importantly providing drought relief in coastal areas during the hot, dry mediterranean summer. While initial work on understanding its ecosystem effects in California focused on the more mesic northern California coastal redwood forests with substantial summer CLCF (Oberlander 1956, Parsons 1960, Dawson 1998), more recent work has examined diverse ecosystems and species including grasslands, shrublands, and forests in the central coast and Channel Islands (Corbin et al. 2005, Clary 2012, Vasey et al. 2012a, Baguskas et al. 2014, Emery and Lesage 2015, Emery 2016, Fischer et al. 2016). This work has shown that even in sites and plant communities with less consistent fog water input, fog has important ecological implications influencing species distributions (Corbin et al. 2005, Vasey et al. 2012a), woody plant mortality (Baguskas et al. 2014, 2016, Fischer et al. 2016), and carbon cycling (Carbone et al. 2013).

We don't yet know the long-term-future of CLCF under climate change. If it stays the same, it could buffer other anticipated impacts of climate change; if it decreases, a number of adverse ecosystem effects could occur. Water stress from declining CLCF could result in shrinking populations and ranges for many species and alter community composition in favor of species that are more able to cope with water stress. There is potential for genetic bottlenecking and extinction in plants if fog shortens flowering times and shifts phenology and pollination. The impacts of disturbance could increase if post disturbance recovery is impaired by reduced recruitment and survival. Simultaneously, these factors may also reduce natural resources management strategy (e.g., plant community restoration) effectiveness or increase costs.

While the body of literature on CLCF has built substantially, our understanding of the role of fog and its local effects on ecological patterns and processes is limited. Difficulty in instrumentation, and until recently (Clemesha et al. 2016a, Torregrosa et al. 2016, Rastogi et al. 2016) a lack of spatial data has resulted in CLCF being factored into scientific research in coarse ways using surrogates such as distance from the coast (Keeley et al. 2005), atmospheric water potential (Lawson et al. 2017b), and humidity (Vanderplank and Ezcurra 2016). While useful, these substitutes have their limitations. Distance from the coast doesn't take the effect of topography on distribution of CLCF, and atmospheric water potential and humidity don't factor in the effect of shading from clouds. Table 5.2 summarizes the effects of CLCF on biodiversity.

Fog is very important in ecosystem functioning in San Diego and CFP Baja California. However, our understanding of the role of fog and its impacts on a local scale are limited, and in urgent need of further study. Understanding how fog influences species and ecosystems under the current climate is critical to our ability to effectively engage in adaptive management to respond to climate change in our region.

Recent developments in instrumentation and remote sensing have made CLCF data much more accessible. Instrumentation options include simple leaf wetness sensors that detect the presence of moisture on a flat surface, to more sophisticated devices such as passive harp-style collectors, active fog collectors, pyranometers, and time series analysis of photos (Vasey et al. 2012b, Weiss-Penzias et al. 2012, Vanderplank and Ezcurra 2016, Bassiouni et al. 2017, Baguskas et al.

2018). Analytical approaches to create spatial CLCF data sets using remote sensing have resulted in the availability of spatial data sets (Clemesha et al. 2016 - http://tenaya.ucsd.edu/~rclemesha/data.html; Rastogi et al. 2016, Torregrosa et al. 2016). These advances have reduced barriers to including CLCF in research projects which is anticipated to promote increased research into the role of CLCF in ecological communities.

Table 5.2: Influence and implications of CLCF on biological resources in San Diego County and CFP Baja

Category	Description
Ecosystem processes	CLCF influences the hydrological cycle, increasing moisture availability by reducing evapotranspirative demand and when fog is present, adding moisture.
Ecosystem processes	CLCF can influence fire hazard through effects to both live and dead wildland fire fuel moisture.
Ecosystem process	CLCF can influence the carbon cycle by stimulating microbial communities.
Primary biological effect	Fog provides moisture during the seasonal and multi-year drought that can directly be used by plants and animals.
Primary biological effect	CLCF influences animal behavior.
Primary biological effect	CLCF influences population demographics—longevity, fecundity, phenology, and pollination.
Primary biological effect	The ability to utilize CLCF and its effect on individual species is species-specific thus its presence influences species competition.
Adaptation Planning Implication	CLCF is a controlling biogeographical factor (species and community distributions).
Management Planning Implication	CLCF influences plant species demographics and thus may explain spatial variation in plant community response to disturbance (e.g., type conversion from shrublands to grasslands) and plant community restoration success. As a result, it is anticipated to be useful in natural resources management planning.
Adaptation Planning Implication	CLCF may create climatic refugia.

Data is available at http://tenaya.ucsd.edu/~rclemesha/data.html.

Most of the pioneering research of fog impacts on biodiversity has been conducted in other regions of the world, and much remains to be tested and documented in our own backyard. There are many opportunities to incorporate CLCF into research and management in the San

Diego region. The following are broad categories of research where further investigation is urgently needed:

- Correlating local CLCF data to existing biological data, especially using long-term datasets. This may include behavioral and ecological data on plants and animals and also natural history and distribution data that can be correlated to CLCF characteristics (e.g., daily frequency, biological lag periods, multi-day persistence, timing of CLCF season, diurnal clearing patterns, and cloud base height).
- Including CLCF data and fog data capture in future study designs.
- Further applied research linking management implications to the presence and extent of CLCF. Monitoring and analysis to test hypotheses and support local decision-making and research can greatly inform adaptive management strategies.
- Gathering data on species' responses to low clouds and fog. Studies on individual species or groups of organisms will greatly inform our understanding of local ecosystem dynamics. This kind of research could be expanded to include citizen science and perhaps an iNaturalist platform where people record observations on foggy days, or a similar way of crowdsourcing data.
- The design of new studies that address CLCF impacts on the biology of San Diego County will fill valuable holes in our local knowledge of CLCF impacts.
- Land managers can incorporate CLCF into management planning and adaptive management (e.g., restoration efforts, out-plantings and projecting natural disturbance, and project effects on conservation targets) by using spatial data sets derived from remote sensing (Clemesha et al. 2016a) and for north and central California (Torregrosa et al. 2016) and/or adding fog instrumentation to weather stations.
- Citizen science crowdsourced data — e.g., query iNaturalist by foggy days versus non-foggy days.
- Teachers and classrooms
- NASA's Students' Cloud Observations online scool.larc.nasa.gov/
- Take a photo of a cloud—the website coastclouds.com allows you to post a georeferenced photo of a cloud and see the satellite animation and a map of the location.
- Ecosystem services—heat mitigation for human populations.

6: Conservation and Management for San Diego's Future Climate[6]

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6.1 Introduction

Southern California is a biodiversity hotspot situated in a highly urbanized landscape with a growing population. The most immediate threats to the region's ecosystems and rich biodiversity are urbanization, land use change, and changing water management practices. However, climate change will act synergistically to exacerbate existing stressors and bring new impacts to a landscape already compromised by fire, invasive species, and habitat loss and fragmentation. San Diego County has a long history of landscape-scale conservation and management, yet current management has not yet fully evolved to the point where climate adaptation strategies are being fully integrated into on-the-ground actions and planning. In addition, management goals and approaches that are required to address near-term, regulatory requirements for single-species management may hamper the ability to build resilience to climate change and variability into the future. Fortunately, for a quarter century San Diego has also been on the forefront of landscape conservation planning with the aim of creating a network of protected areas. It is both this history of action and the network of relationships that have been established in the process of building San Diego's conservation network that present an opportunity for the region to again step up as a conservation leader in the face of a changing climate. The policies and management actions which have guided urban development and the creation of protected area networks in tandem can be tuned to address climate change impacts as well. In San Diego, these actions have been advanced through federal Habitat Conservation Plans and the State of California's Natural Community Conservation Plans as well as Special Area Management Planning and Integrated Water Resource Management Program watershed plans for aquatic resources. These regulatory tools offer the framework to address both the prevailing threat of habitat loss and fragmentation as well as the compounding stressors of shifts in climate and increased climate variability.

In the preceding sections, we reviewed the current state of science and knowledge about the projected shifts in climate and climate variability and the likely impacts they will have on ecosystems in the San Diego region. In this section, we discuss the challenges and opportunities for addressing the impacts of climate shifts and variability in the context of San Diego's history and experience in conservation policy and land management. We review the current state of

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conservation policy and management in the region and explore aspects of climate smart strategies that could be integrated into existing approaches. Resilience can be an ambiguous and misunderstood term that can hinder adaptation planning and projects as resilience holds different meanings for different stakeholders (Fisichelli et al. 2016). Here, we focus on three distinct responses to change: 1) resistance, 2) accommodation, and 3) transformation or directed change (Fisichelli et al. 2016). By establishing complementary management actions that utilize all three of these strategies to both minimize or ameliorate the harmful effects of urbanization and climate change on ecosystems, San Diego can be at the forefront of conservation planning and management.

6.2 History of Regional Conservation Planning

Since the end of World War II, southern California has undergone rapid urbanization whereby large expanses of natural habitat were converted into small fragmented islands surrounded by development. Despite this history of urbanization, large portions of San Diego County have been set aside in conservation status (Figure 6.1). The County's first and largest open spaces were designated at the turn of the 20th century with the establishment of the Cleveland National Forest. The land was originally conserved through protection of the 50,000-acre (200 square km) Trabuco Cañón Forest Reserve in the Santa Ana Mountains, followed by the 700,000-acre San Jacinto Forest Reserve. In 1908, the reserves were combined to form the Cleveland National Forest, which today encompasses a total of 465,000 acres in San Diego, Orange, and southern Riverside Counties. Land conservation in the region continued throughout the century in pulses such as the designation of State Parks lands in the 1930s (e.g., Anza Borrego Desert State Park created in 1932; Cuyamaca Rancho State Park created in 1933; Torrey Pines State Natural Reserve, first protected in 1899 and designated a state reserve in 1956); and regional parks in the 1960s and 1970s. Anza Borrego Desert State Park alone encompasses over one-fifth of San Diego County's land area; at over 600,000 acres (2,430 square km) it is California's largest state park, and the nation's second largest state protected area outside of Alaska.

In contrast, San Diego County's human population has increased more than two-fold in just the last 45 years from 1.4 million in 1970 to 3.3 million in 2015 (U.S. Census Bureau 2015), a faster growth rate than experienced in other urbanized areas of southern California such as Los Angeles and Orange Counties. The population is expected to increase by another 25% by mid-century to a population of 4.14 million people. Despite the pace of urban growth in the region, over 46% of San Diego County's land area is currently in some form of protected status, including working landscapes such as military facilities and conservation easements, with a goal of 55% by 2050, according to the San Diego Association of Governments' 'San Diego Forward' Plan (SANDAG 2015). Although these trajectories appear to be at odds with one another, it is San Diego's commitment to conserving its varied ecosystems and rich ecological diversity that have made it a proving ground for many conservation strategies and implementation. The ownership of the San Diego region's conserved lands is diverse, ranging from federal, state, and local governments to conservation non-profits to private property owners with conservation easements, all of whom have unique management goals and approaches. However, a unifying theme across the landscape, regardless of ownership, has been a focus on the ecosystems and species at greatest risk.

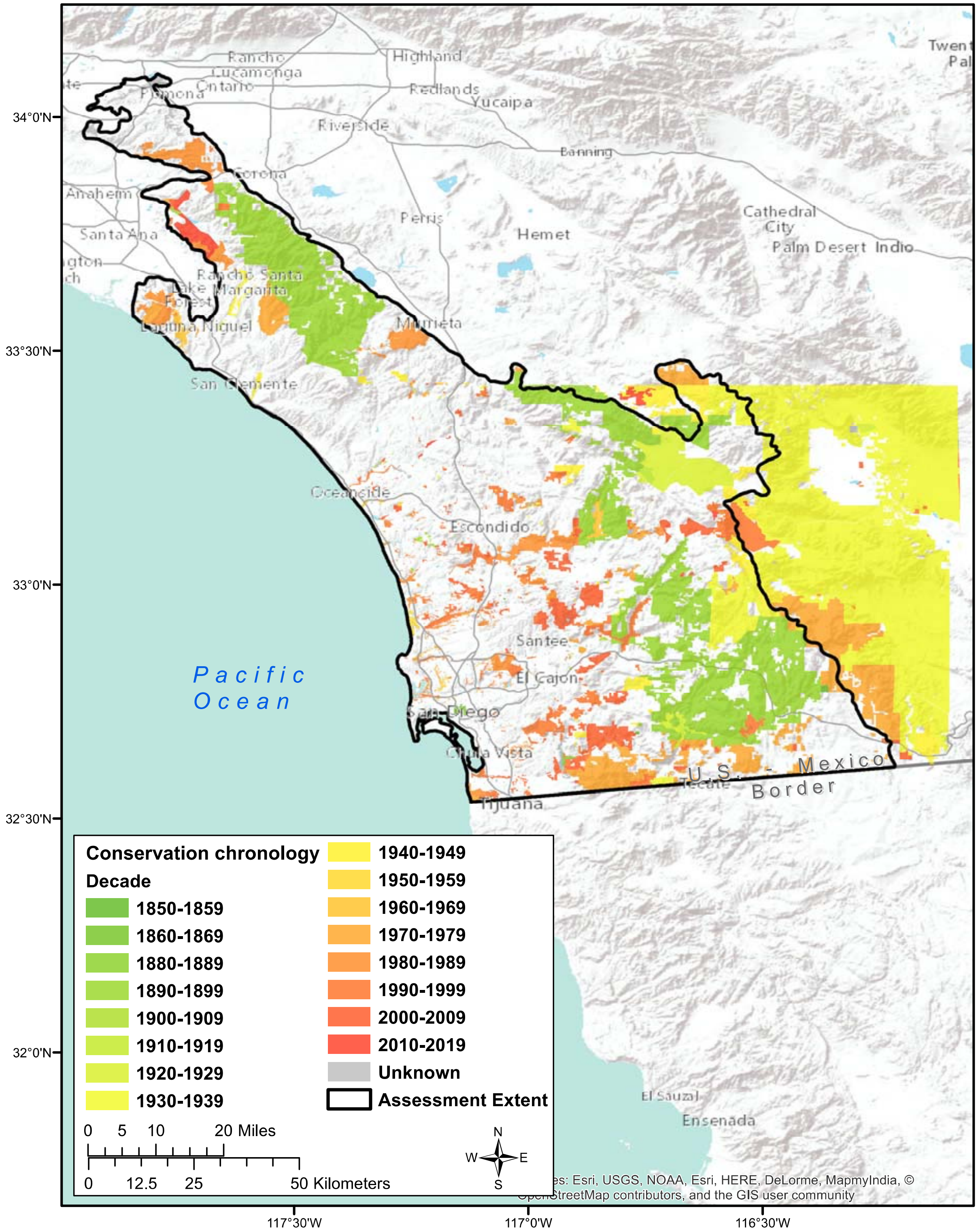

Figure 6.1: History of land conservation in the San Diego region by decade (Santos et al. 2014).

The coastal sage scrub plant community (CSS) has been especially hard hit by urban development and synergistic impacts of fragmentation, conversion to non-native grassland and agriculture, introduction of invasive species, altered fire cycles, and pollution. Once covering nearly 2.5 million acres (10,000 km^2) in California, CSS has been reduced by 85-90% of its former range (Wilcove et al. 1986, Heywood et al. 1995). CSS is now considered one of California's most endangered habitats (Barbour et al. 1993) and serves as the primary refuge for many endangered and threatened species. There are more than 100 plant and animal species closely associated with the CSS plant community that are considered to be rare, sensitive, threatened, or endangered (California Department of Fish and Wildlife 2017). One notable species is the non-migratory California gnatcatcher (*Polioptila californica*), which is entirely restricted to remnant patches of CSS located in coastal southern California and northern Baja California. California gnatcatcher occupy some of the most valuable real estate in the country and habitat loss associated with development is considered the primary factor contributing to the species' threatened status. By the early 1990s, legislators and developers became concerned that federal listing of the California gnatcatcher under the Endangered Species Act (ESA) could result in an economic and conservation clash on the scale of the listing of the northern spotted owl (*Strix occidentalis caurina)* in the Pacific northwest in 1990. The ESA was enacted in 1973 and amended in 1982 to allow the "take" of federally listed species (Endangered Species Act, Section 10a(1)(B)) on private lands under an Incidental Take Permit, which can be obtained after the applicant submits and gains approval for a Habitat Conservation Plan (HCP). Less than a decade later, California state legislators passed the Natural Community Conservation Planning Act of 1991 (NCCP) which offers a roughly parallel but more comprehensive ecosystem approach to planning for the protection of biological diversity while allowing for compatible and appropriate economic development (Pollak 2001).

The federal HCP and state NCCP approaches were designed to streamline permitting and approval processes for development projects while directing development to the lands where it will have minimal or reduced impacts, and to promote the protection of lands and waters of greatest conservation value. Rather than focusing on protection of individual species in the way mandated by ESA under a federal HCP, the NCCP approach emphasized habitat-oriented conservation efforts that encompass an entire region. Since the mid-1990s, most new land preservation efforts in San Diego County have resulted from efforts to develop regional conservation networks for multiple species through HCPs required for incidental take permits issued under the federal ESA and under the authority of California's NCCP. San Diego County led the way in these efforts between 1995 and 2005 with nine out of the ten Natural Community Conservation Plans first completed. The plans include the San Diego Gas & Electric Subregional Plan which covers a long narrow strip from southern Orange County to the Mexican border, the San Diego Multiple Habitat Conservation Plan (MHCP) covering a portion of the county's northwest, the San Diego Multiple Species Conservation Plan (MSCP) covering much of the county's southwestern quadrant, and the San Diego County Water Authority NCCP/HCP. To the north, the County of Orange Central/Coastal NCCP/HCP and the Western Riverside Multiple Species Habitat Conservation Plan (MSHCP) are also in place and being implemented (Figure 6.2). Each of these plans is designed to be implemented for four or five decades, and they have yielded protection for a suite of core protected areas and, to a more limited degree, portions of landscape linkages between them. To date, the failure to protect landscape linkages between protected areas has raised concerns in the conservation community that the wide-ranging networks of habitat necessary to support viable populations of many of the covered species may not be completed. Of even greater concern is that pinch points or barriers within linkages between core protected areas will impede migration pathways that many plant and animal species will need to survive as climate changes and their current ranges become inhospitable. In addition, specific NCCP plans can take years or even decades to develop and gain approval by the necessary parties. San Diego's North County MSCP has yet to be approved despite years of work, and the planning for east San Diego County is stalled due to budget constraints and staff reductions with little or no prospect for further progress, much less completion, in the next several years.

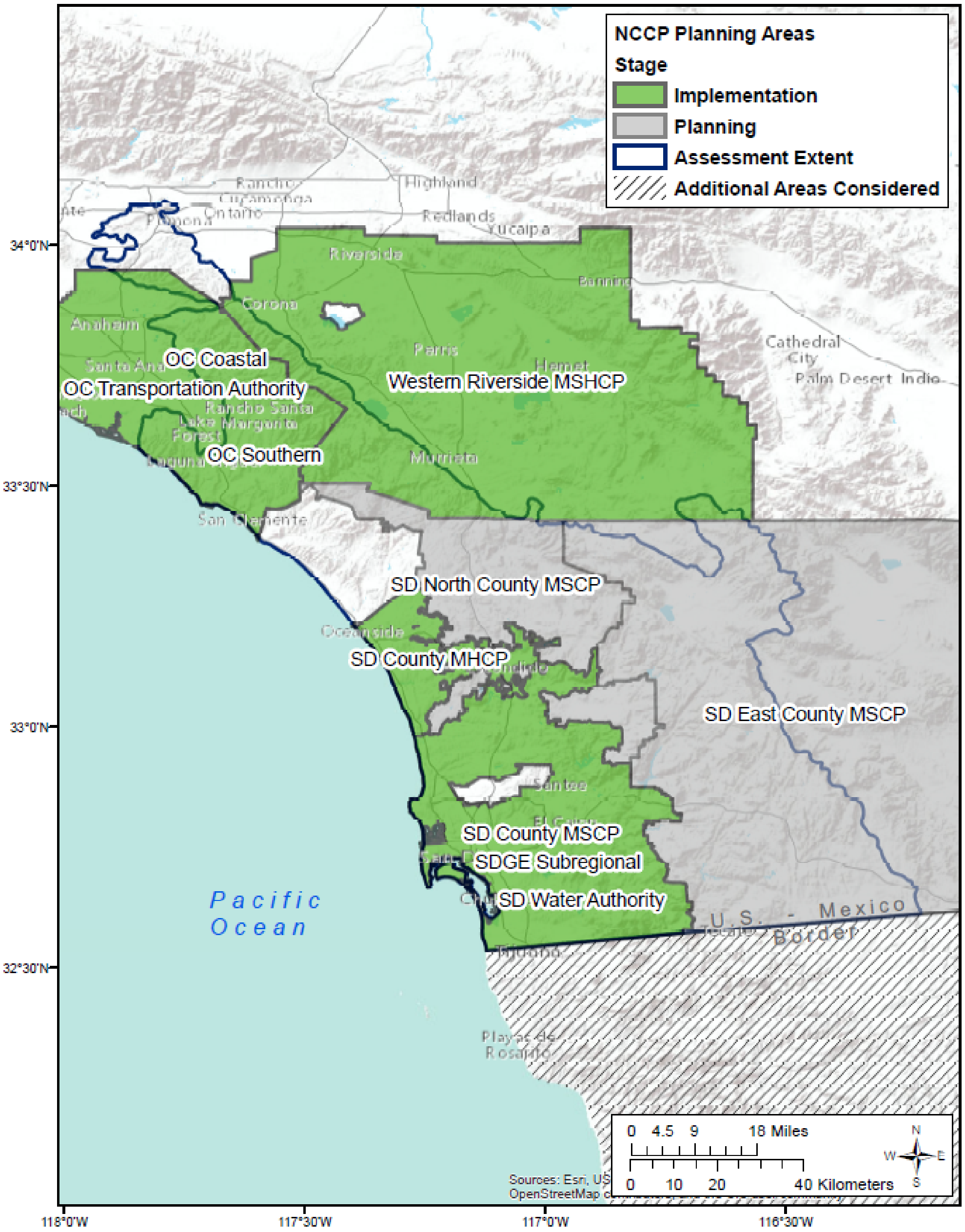

Figure 6.2: Map of NCCP and HCP planning areas (California Department of Fish and Wildlife 2017b). Completed plans that are in the implementation phase are shaded green. Plans that are in progress are identified with gray shading.

6.3 Beyond Single-Species Conservation

The unifying theme in these conservation planning efforts in San Diego County, and indeed, across much of the west, has been protection of the large number of state and federally protected species in these ecosystems. This approach has conserved lands with habitat for listed species which has also served to benefit populations of many other species. These protected lands form the foundation from which a regional network or series of networks can be built. Such a network will be necessary to establish a baseline for resistance to the impacts of climate change, to ensure the region's ecosystems can accommodate and transform in the face of change over the short-term (decades) as well as the long-term (multiple decades and centuries). More work needs to be done to improve resilience and adaptive capacity to the threats and stressors while also mitigating those impacts. This can be done by focusing attention not only on species-specific preservation, but on maintaining functional diversity at the community or ecosystem level. However, regional planning will be successful in the face of climate change only if participants take a long-range perspective that acknowledges climate change and incorporates means of facilitating dynamic shifts in species and community distribution over time as conditions change.

In San Diego, over 200 species of plants and animals are under some level of regulatory protection (Table 6.1). Specifically, specialized habitats or microhabitat requirements, rarity, poor dispersal ability, restricted thresholds of tolerance to environmental factors, and dependences on environmental triggers or interspecific interactions all describe species that are likely to be more sensitive to climate change and variability and may have low adaptive capacity or evolutionary potential to respond (Foden et al. 2013). As such, single-species-focused policies and management efforts remain vital to conservation in the San Diego region. Even within the larger landscape-scale NCCP/HCP planning and implementation efforts, much of the focus to date has been on the most imperiled species with life history traits that also put them at highest risk to the effects of climate change. However, more cooperative, coordinated planning and management for the region's preserve network is underway with the formation of SDMMP. SDMMP's MSP Roadmap is an effort to integrate complementary approaches to conservation and management at multiple scales, working toward holistic landscape-level planning, and demonstrates a shift towards recognizing the importance of various management strategies. The expansion and implementation of this type of planning with multiple biological scales in mind is likely to be most effective under shifting environmental conditions. These approaches, when implemented with entire ecological communities in mind, can result in protection for more species, natural communities (Boitani et al. 2007), and ecological processes (e.g., predation, pollination, nutrient cycles).

Despite the drawbacks, single species management plays an important role in San Diego's conservation landscape. The Federal and State ESAs in their current forms compel focus on individual listed threatened and endangered species. These efforts to protect a single species can sometimes provide ancillary benefits by protecting other species and communities that share the same habitat (Andelman and Fagan 2000). These species are commonly referred to as umbrella species, and their use was originally promoted to reduce the complexity and thus cost of management and monitoring (Simberloff 1998). The California gnatcatcher is a case in point in the San Diego region. It is federally listed as Threatened and has served as an umbrella species for the protection of coastal sage scrub communities. However, not all species benefit under an umbrella species (Roberge and Angelstam 2004), and strategic actions should be considered to conserve species requirements not met under management of priority species (e.g., Copeland et al. 2014).

Table 6.1: Taxonomic diversity of native flora and fauna in San Diego's ecosystems. Data are summarized by total taxonomic richness, as well as listing status under the Federal Endangered Species Act (ESA), State ESA, or as State Species of Special Concern (SSC), Bureau of Land Management (BLM) Sensitive and US Forest Service (USFS) Sensitive, and covered under the MSP San Diego's NCCP areas. The total of species with some listing status are also included.

	Federal ESA	State ESA	State SSC	BLM/USFS sensitive	MSP covered species	Total species with listing status
Plants	24	18	N/A	52	57	116
Invertebrate	5	0	N/A	3	7	7
Fish	2	1	2	2	1	4
Reptile	0	0	8	9	5	14
Amphibian	3	0	4	2	3	6
Bird	7	6	27	9	30	47
Mammal	3	1	15	8	8	23
Total	44	26	56	85	111	217

Ultimately, managers may be legally compelled to manage a single species or choose a single species focus to build social capital or simplify management to meet budgetary constraints. In these cases, it remains important to consider benefits to other species and conservation in general that can accrue from management aimed at an individual species so that strategic actions to maximize the benefit can be planned and implemented as resources permit (Maslo et al. 2016). Conversely, it is important not to presume benefit to other species where it may not exist (Rubinoff 2001).

Species-specific and project-by-project management have also not been fully effective at protecting or restoring upland aquatic and riparian habitats or the ecological processes they support (Kihslinger 2008). Coastal wetlands have been lost, stream corridors have been paved and fragmented, and development has encroached on floodplains. More recently, in response to these issues, there has been recognition of the importance of watershed approaches that promote more holistic and function-based restoration practices (e.g., Regional Water Board storm water permit programs). State and local policies and practices (https://www.sandiego.gov/water/conservation and http://sdirwmp.org/) are also evolving to promote increased resiliency of water supplies and decreased reliance on imported water. As these programs encourage wastewater and storm water capture and reuse, there will be a need to include requirements to consider "environmental flows" or the magnitude, timing, duration, and frequency of flows necessary to support biological communities. Including such requirements into programs and policies would ensure that potential consequences of reduced discharge on habitat and species resiliency is considered in future planning and implementation. For example, riparian habitat that supports neotropical migratory birds may depend in part on runoff from developed surfaces or wastewater discharge that has become "normal" over the past 50 years. Reduced runoff, combined with lower rainfall and hotter temperatures, may cause desiccation and loss of this habitat, further threatening species whose ranges are already restricted. On the other hand, some species such as arroyo toad require open riparian habitat provided by more natural flooding and drying regimes. Persistence of aseasonal urban flows can also support populations of invasive aquatic animals that impact amphibian and fish populations. In such complex situations, management decision-making must recognize the trade-offs in balancing species' competing needs when considering planning and prioritization.

Storm water regulations require municipalities to capture and infiltrate runoff from developed surfaces and encourage regional storm water capture for local use. Although these practices achieve conservation and water quality goals, they may result in decreased discharges to local streams and estuaries, which has the potential to affect habitat and perhaps exacerbate climate change effects. In highly urban landscapes, such as much of San Diego, restoring natural flows may not be practical given land use and water management practices and the legacy of alteration of drainage patterns, water storage, groundwater management, and floodplain encroachment. Developing "designer flows" aimed at balancing environmental, water supply, water quality, and flood control needs will require a deeper understanding of hydro-ecological relationships (including the role of groundwater) and development of an inclusive stakeholder process for determining appropriate tradeoffs.

6.4 Conservation Planning and Policy in a Changing Climate

Regardless of whether spurred by a single-species or landscape-scale approach, the primary conservation actions undertaken are habitat preservation and management. As such, land and water use planning approaches are the important tools for conserving these habitats and the biological diversity they support. Protecting habitats requires identifying the most important (ecologically valuable) land and waters to preserve, and the private lands where easements or other tools would best be used to prevent or minimize habitat damage. Protecting larger reserves and networks of reserves requires careful reserve design and appropriate management actions. For certain habitat types, such as streams and wetlands, long-term conservation also requires preservation of the physical processes necessary to maintain resilience (e.g., appropriate flow and sediment movement, periodic natural disturbance). However, decision-making regarding land acquisitions for the San Diego region's NCCP/HCPs has often presumed the environment to be static despite the fact that natural systems are inherently dynamic. The often-hard edges of land ownership boundaries, particularly in a rapidly urbanizing region like San Diego, can have profound impacts on the habitats we are trying to conserve and the populations of species those lands are intended to support. Similarly, many other conservation and land management policies were developed before the importance of climate change and its projected effects were adequately recognized and so assume a steady-state world. Shifting the baselines to which our conservation or management targets are tied may be required in a future where changes in temperature and precipitation will have cascading ecological impacts and may cause habitat distributions to change over time.

SDMMP's MSP Roadmap has begun to address these issues within the NCCP areas by outlining a strategy to address climate impacts which includes objectives to: 1) collect and analyze monitoring data on species, vegetation communities, and ecosystem processes to understand responses to weather and other potentially interacting threat and habitat covariates; 2) model the range in predicted responses of species and vegetation communities to future climate scenarios and include other threats such as land use change, invasive species, and altered fire regime; 3) manage species, vegetation communities, and ecosystem processes to increase resilience to short-term climate impacts; 4) develop longer-term strategies to facilitate adaptation of MSP species and vegetation communities to changing climate conditions; and 5) monitor resilience and adaptation management actions to determine short-term and long-term effectiveness and improve management strategies. Further, the Climate Science Alliance has worked with partners to identify research priorities that are needed to support climate adaptation in the region, identify case studies to exemplify successful adaptation implementation, and provide opportunities for peer reviews and science-management partnerships to enhance climate adaptation planning and implementation.

Although these efforts are underway and making important progress, climate change projections make it clear that more must be done to fully protect the region's biodiversity, particularly to facilitate resilience, or accommodation of change, in native species and communities over the coming decades. Integrating climate smart conservation strategies into planning and management activities will also facilitate adaptation, or transformation, of those communities to greater changes in climate expected over the long-term. Means of facilitating accommodation and transformation via conservation planning and the design of conservation reserves include:

- Creating networks of core conservation lands connected to one another through landscape linkages permeable to the largest variety of native plants and animals possible (Heller and Zavaleta 2009).
- Using spatially-explicit models to project appropriate climatic and other environmental conditions for certain species and natural communities in the future so they can be targeted for conservation. This should be considered for longer times scales (i.e., centuries) as climate change will be progressive. For example, areas projected to be suitable for a given species, such as California sagebrush (*Artemisia californica*) in 2050, may not be suitable for it by 2100 (Principe et al. 2013). Modeling for a number of sensitive species is already in progress through SDMMP coordination and could be expanded for a wider range of species.
- Prioritizing the protection of sites that can serve as the "stage" for the greatest diversity of plants and animals under any given climate regime, and corridors between them (Anderson and Ferree 2010, Beier and Brost 2010, Anderson et al. 2014, 2015, Lawler et al. 2015). Such sites characteristically encompass a wide variety of microclimates because they are topographically diverse and encompass areas with a wide variety of slopes, aspects, geological parent materials, and soils. Such sites are likely to provide refugia for a wide variety of species within a relatively small area (Morelli et al. 2016, Wilkin et al. 2016).

NCCP/HCP approaches and the plans they have spawned across the region go a long way towards these goals, but there are now additional policy efforts that may also facilitate conservation planning under climate change. Regional Conservation Investment Strategies (RCIS) are a newly available tool for regional conservation in California. This approach is similar to the existing Environmental Mitigation Program (EMP) that SANDAG has developed and funded through the TransNet Extension Ordinance and Expenditure Plan sales tax measure approved by San Diego voters in November 2004. This program supports advance planning to mitigate habitat impacts for regional transportation projects. San Diego's program is unique in that it includes funding for habitat acquisition, management, and monitoring activities to implement the region's NCCP plans. SANDAG's EMP efforts offer a potential entry for climate change considerations to enter an existing framework of infrastructure and environmental offsets already in existence. To expand the reach of this program beyond the region's NCCP areas, RCISs can be used by developers or public agencies, such as Caltrans, to mitigate habitat losses that result from development projects or maintenance and expansion of public infrastructure. The RCIS approach is touted as having the advantage of speedier development and approval of plans than NCCPs. The first RCIS has been launched in Santa Clara County, and is being considered for the San Diego region, particularly for promoting protection of linkage areas. California Assembly Bill 32, the California Global Warming Solutions Act of 2006, is influencing regional planning in a variety of ways that may serve to promote these goals as well. In particular, AB 32's focus on reducing vehicle miles traveled (VMT) to reduce greenhouse gas emissions is leading to the development of incentives that may serve to slow or deflect development from the eastern, less developed portions of our region, and direct it towards infill projects and other areas adjacent to existing development. For example, the use of Transfers of Development Rights (TDRs) have recently been recommended to local governments as one means of doing this. Locales that set up TDRs establish "Sending Areas" where protection of the land is encouraged and "Receiving Areas" where development is directed preferentially. The system allows those with development rights on properties with the "Sending Area" to transfer these rights by putting an easement or other form of protection on the land in return for rights to develop property within the "Receiving Area." "Sending Areas" may be designed to protect land for agriculture, cultural values, coastal zone values, or biodiversity conservation (Nelson et al. 2012). If adopted in California, TDRs could become another tool available to help guide siting of development and conservation protections in the future.

Planning efforts geared toward protection of water and aquatic habitat resources are largely guided by the Integrated Water Resources Management Planning (IWRMP) and associated watershed planning processes. These efforts encourage local agencies to comprehensively plan for resilient water supply and quality, including habitat quality, consistent with the State's Water Action Plan and local water quality programs (e.g., National Pollutant Discharge Elimination System or NPDES). Among other things, these efforts promote establishment and protection of intact drainage networks with connected floodplains and riparian zones. Once established, these connected systems can facilitate accommodation to climate change by providing opportunities for transgression of aquatic habitats to adjacent higher elevations or expansion to areas with more suitable soil moisture conditions as rainfall and runoff patterns change over time.

6.5 Management Considerations

For the known and expected impacts of climate change, we can develop strategies that will promote resilience and persistence of populations and community function in the short-term and the ability to adapt to even greater climatic changes that will be experienced over the long-term. Managers and planners will need to take a pragmatic approach, often termed conservation triage (McBride et al. 2007, Wilson et al. 2007), where we re-evaluate goals recognizing that we will not be able to save all species and systems in their current states (Bottrill et al. 2008). Instead, priority is focused on where to concentrate efforts and revisiting management goals to consider pragmatic options in an uncertain future.

Conservation and management decisions are typically made under high uncertainty, particularly with endangered species (Regan et al. 2003). This will only be compounded under climate change where uncertainty and variation in projections from climate models are propagated when assessing impacts to vegetation and wildlife and when scaling up to understand impacts to individuals, populations, and communities. In addition, conservation priorities are likely to shift under climate change as species are anticipated to respond in different ways (Lawson 2011). Due to uncertainties around both projections of future climate parameters and effects to species and ecosystems, cost effective decisions and management may be elusive, making adaptive management highly important. Management approaches that allow flexibility and target the three categories of adaptation introduced above—resistance, accommodation, and transformation—are key to facilitating climate adaptation in natural systems.

6.5.1 Resistance

In some, perhaps rare, cases, we may choose to intensively manage to retain certain species or systems although the climate conditions are no longer suitable habitat for the species or system. Target species for this approach would include high profile species like sugar pine (*Pinus lambertiana*) in San Diego's Cuyamaca Mountains and those with isolated populations of narrow endemics, like Cuyamaca cypress (*Hesperocyparis stephensonii*) or Tecate cypress (*Hesperocyparis forbesii*), that have little or no chance of moving on their own to newly suitable habitats as the climate changes. This concept has been referred to as living museums and we may apply it to species that are currently protected under the ESA where long-term persistence is unlikely. In these cases, translocation, habitat restoration, and captive breeding programs may be necessary to address co-occurring stressors to support long-term persistence of individual populations or an entire species. This type of intensive management has primarily been executed for federally listed species to date. One recent example is a habitat restoration, captive breeding, and re-introduction program that has been instituted for the western pond turtle (*Emys marmorata*) to re-establish a population in the previously occupied sections of the Sweetwater River in southern San Diego County (Brown et al. 2015). These populations were extirpated by non-native species (i.e., crayfish [*Procambarus clarkia*] and bullfrogs [*Lithobates catesbeianus*]), which were aggressively removed prior to the reintroduction effort and continue to be closely monitored.

6.5.2 Accommodation

Shifts in climate extremes or single events amplified by climate change, such as large, intense wildfires, may lead to extirpation or extinction of some species, and this is especially likely when climatic shifts act as compounding stressors to populations or species that are already at risk. Management of these compounding stressors is one of most tractable approaches to both resisting and accommodating climate change in natural ecosystems. For example, the early detection and rapid response (EDRR), to the introduction and spread of non-native species is already underway in San Diego. EDRR is a management approach focused on eradicating invasive plant populations before they have spread (Cal-IPC 2018). Efforts to document the flora of San Diego County by the SDNHM through their Plant Atlas project (San Diego Natural History Museum 2017) led to the identification of 240 non-native plant species between 2003 and 2017 (SDNHM Botany Department unpublished data) that had not previously been documented in the county. This data has been used by some local managers through coordination with the SDNHM Botany Department (D. Bieber pers. com., C. Wolf pers. com) and is incorporated into Calflora (http://www.calflora.org/) where it is available for EDRR planning. Due to lags in plant spread (Crooks 2005), some of these populations, even those found years ago, may still represent cost effective management targets.

Another approach to accommodating change that is particularly robust to uncertainty focuses on connecting habitats for species and processes to move across the landscape if appropriate. Habitat connectivity is essential to climate-smart landscape strategies (Heller and Zavaleta 2009) and strengthens ecosystem resilience to additional stressors such as habitat fragmentation (Beier and Gregory 2012), and other disturbances (Noss 1991, Hilty et al. 2006). Connectivity allows for wildlife movement among patches of suitable habitat, reduces the risk of extinction for small populations (Brown and Kodric-Brown 1977), and maintains gene flow in patchy landscapes (Noss 1987). Collaboratively developed regional connectivity plans, decision support tools, and feasible implementation strategies are critical to allowing planners and land managers to take proactive approaches to managing wildlife and supporting biodiversity in an uncertain future.

One such comprehensive plan recently emerged that delineated spatially-explicit linkages and wildlife road crossing locations, and considered both landscape resilience and diverse landforms (as described above) for central San Diego County (Jennings and Zeller 2017). Another regional plan is underway that will incorporate similar data products for connectivity planning but with a focus on identifying linkages to allow for adaptation in response to climatic shifts. This effort, which will prioritize linkages that will be most significant for population persistence, is currently under development. San Diego State University's (SDSU) Institute for Ecological Monitoring and Management has joined with the California Department of Fish and Wildlife (CDFW) in a science-management partnership to identify resilient linkages for landscape connectivity with a suite of complementary, innovative modeling approaches. This SDSU-CDFW partnership project builds on prior connectivity modeling efforts (Figure 6.3) by providing more detailed landscape linkages that will allow for local movements between individual preserves within NCCP plan areas in addition to landscape-scale regional connectivity. Using this approach, a regional connectivity strategy will be created by prioritizing linkages given the ability of each linkage to promote population-level persistence with consideration of the economic cost of acquisition or restoration. The end goal of this project is to develop a decision support guide based on these data-driven connectivity assessments which will prioritize conservation actions for land acquisition, habitat management, and restoration.

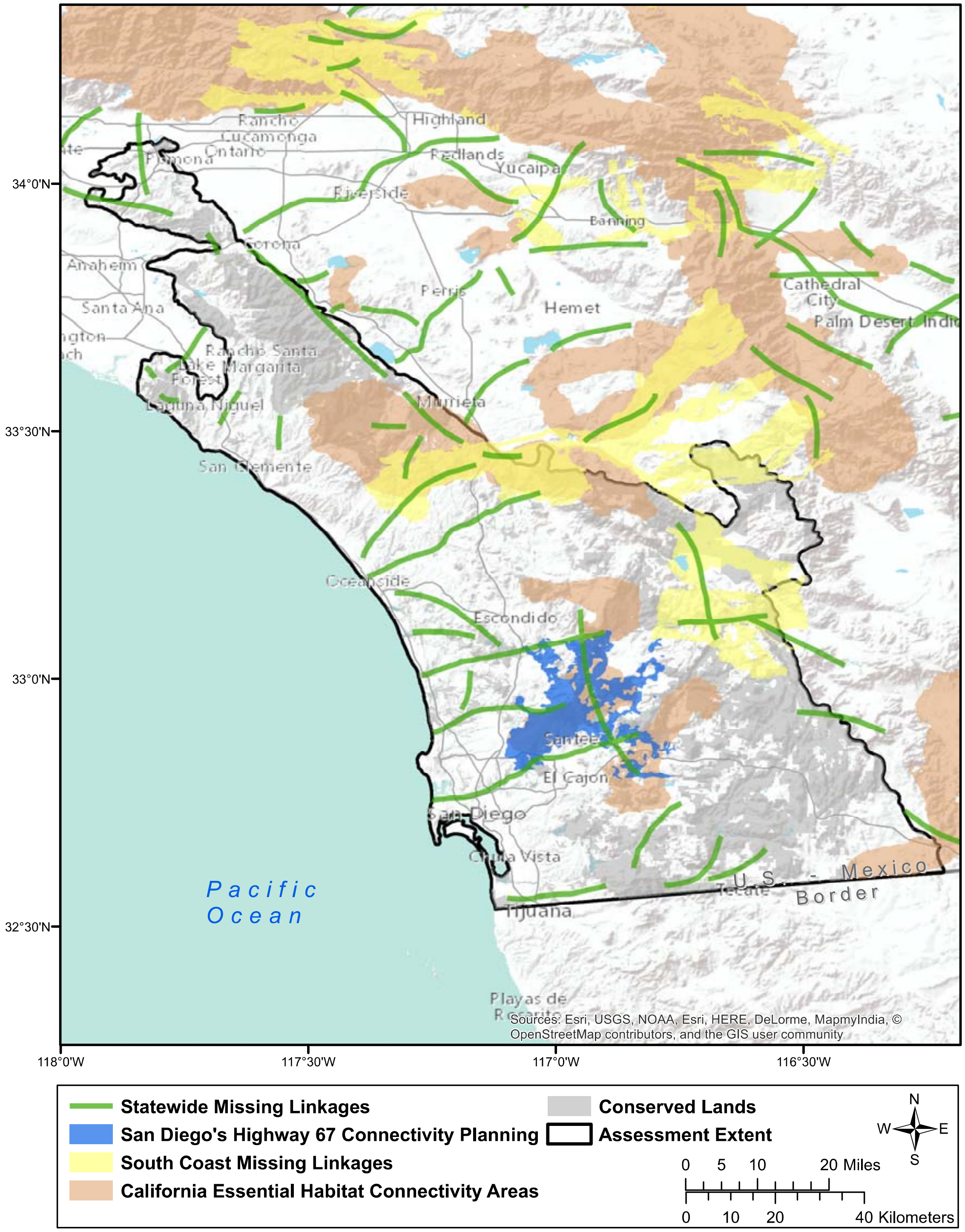

Figure 6.3: Map of existing connectivity plans for the San Diego region. Conserved lands (GreenInfo Network 2017, San Diego Association of Governments 2017) are depicted in gray. Green sticks represent proposed linkage zones from the Statewide Missing Linkages Project (Penrod et al. 2001). Spatially-explicit corridors mapped in yellow are the South Coast Missing Linkages Project (South Coast Wildlands 2008), brown are California Essential Habitat Connectivity Plan linkages (Spencer et al. 2010), and blue for San Diego's Highway 67 Connectivity Plan (Jennings and Zeller 2017).

6.5.3 Transformation

At either preserve or regional management levels, promoting resilience in our natural systems may involve guiding systems in their transformation to novel states that can be maintained and persist on their own. This management approach requires careful consideration of potential future states, potentially through scenario planning, and a thoughtful process for setting goals and management targets. Adaptive management and an active monitoring program to inform an adaptive strategy are elements that are critical to the success of managing for altered states. This type of management approach has largely been adopted across the grassland communities in the study area where non-native annual grasses have invaded native grasslands and become naturalized. Although the non-native component of the grassland system may be less resilient to climatic shifts (Seabloom et al. 2003), completely removing all non-native grasses on a large scale is not feasible. Instead, management actions that focus on ecosystem processes that promote a diverse community of species of grasses and forbs will support a system more resilient to change (LaForgia et al. 2018). Wetland and stream areas may also transform to different habitats in response to climate change. For example, coastal wetlands may become mudflats or subtidal habitat, and streams may shift to more xeroriparian habitats similar to those that currently exist in drier climates, such as Arizona. By focusing management efforts on retaining important species and dynamic processes (e.g., fire or grazing) in the system, the emphasis has been placed on preserving ecosystem function rather than on preserving species assemblages known to have existed on sites at a particular point in time.

6.6 Adaptation and Scenario Planning

Adaptation and scenario planning are the primary tools being applied to facilitate the preservation of natural systems under increasing climate variability. Adaptation planning is the process of assessing the risks and opportunities in a changing climate and taking actions to address climate change impacts by targeting those risks and leveraging the opportunities (Füssel 2007). Given that the general trajectories of climate change projected for the region are known (i.e., hotter, drier, more fires, less water), these adaptation planning efforts should begin without delay. This would involve identifying regions, habitats, and species that are conducive to supporting resistance, accommodation, and transformation and focusing planning strategies on these targets accordingly.

Scenario planning is a type of adaptation planning focused on the process of identifying several plausible futures and exploring the consequences of a management or conservation decision in each of those scenarios. Scenario planning offers a framework for deciding on when, how, and where to act in an uncertain future (Peterson et al. 2003). Scenario planning is particularly useful in informing adaptation strategies because individual climate event timelines are difficult to predict. Through this process, individual scenarios should represent alternative descriptions of how the future may locally unfold, outlining different plausible future states. The qualitative scenarios are adaptive, allowing new research to easily be incorporated into the discussion. This ensures the planning process is always directly connected to advances in scientific understanding, while allowing planners and managers to make current decisions that acknowledge the past, present, and future conditions. Identifying several plausible futures that allow land managers to take management actions to guide an area towards the plausible future increases ecosystem resiliency.

There are several ways that the threats climate change poses to biodiversity can be addressed using these tools, and several of these are already in use in San Diego, at least in limited or experimental ways. These approaches include:

- Adopting and implementing policies to:
    - Resist and accommodate change by promoting the resilience of existing native species populations and natural communities.
    - Accommodate and direct change by guiding land use decisions to foster the protection of conservation reserve networks consisting of core protected areas and landscape linkages that connect them together and facilitate the movement and migration of plants, animals, and other organisms.
- Taking land and water management actions to:
    - Resist change by promoting the resilience (persistence in place) of native species populations and natural communities where they now reside.
    - Accommodate and direct change for populations of native species by moving to new areas with suitable conditions, changing behaviors to modes suitable to new conditions in place, and/or by facilitating gene flow and genetic adaptations to modes suitable to new conditions (i.e., translocation or assisted migration).
    - Where active management is impractical or unaffordable, monitoring and recording changes in species distributions, behaviors and other adaptations over time across the region.

6.6.1 Setting Management Triggers for Action

One of the key components to successful scenario planning is the identification of management triggers (Gregory et al. 2006, West et al. 2009). When defining plausible future scenarios, managers can specify climate events or changes in the landscape that will serve as the trigger for specific management actions. Management triggers can be tied to economic drivers, degree of management intervention necessary, or based on existing thresholds that have been defined as part of other management programs. Acting on triggers may be more tractable from a management perspective than acting on timelines or trajectories that may shift over time. Establishing triggers can also help garner public buy-in for management actions since the need for action is more evident following an observable event or outcome.

In San Diego County, scenario planning has been applied to the management planning of different systems. Through the Climate Understanding & Resilience in the River Valley (CURRV) initiative, the Tijuana River National Estuarine Research Reserve used scenario planning to outline local vulnerabilities, focusing on the relationship between sea level rise and riverine flooding. The stakeholder engagement process for this project identified four potential scenarios for planning to address the potential impacts that threaten the future resiliency of important natural ecosystems, critical infrastructure, and surrounding human communities. Management triggers, such as when sediment flows close the mouth of the river multiple times in a single year, making repeated dredging prohibitively expensive, were used to ensure on-the-ground management considers future environmental changes, while continuing to address current conservation priorities. By monitoring for triggers, managers will be able to determine when the Reserve is being pushed into a new future scenario, ensuring decision-makers are able to adjust management strategies as needed.

Post-fire restoration of coastal sage scrub habitats is another example where setting management triggers may be advantageous. As described in the fire section (Section 4.4.1), weed incursion into CSS is common after fires. With repeated fires, the degree of habitat degradation can increase to a level where management intervention is necessary. On U.S. Forest Service lands surrounding the upper San Diego River, the succession of three to four fires over a 20-year period had resulted in the degradation and loss of CSS vegetation that had once been habitat for nesting California gnatcatchers. Although this was not initially identified as a management trigger, the multiple fires and degradation was a trigger that led the U.S. Forest Service to undertake a multi-year coastal sage restoration project in 2010. The objective was to recover the habitat in the hopes of gnatcatchers returning to their former nesting sites. While setting a trigger of successive fires in a limited period is a clear-cut metric for initiating management action, the potential for future fire should also be considered in designing the management response or even deciding whether to undertake the intervention. For the restoration of CSS, these considerations might include a discussion of how future high-intensity burns may affect the restoration project. Selecting plant palettes that are more resilient to fires or assembling a seed mix with greater proportions of more resilient species may be one approach to restoration when repeated disturbance is expected under shifting climatic conditions.

6.7 Conservation Through Collaboration

6.7.1 Science-Management Partnerships

To advance climate adaptation planning, there have been valuable investments in the development of climate tools, resources, databases, and training, all guided by robust climate science research. In many areas across the western U.S., most of the efforts to incorporate these resources into planning for climate change have focused on conducting vulnerability assessments and creating adaptation plans. However, the translation of assessments and plans into on-the-ground actions has lagged. Although these are important first steps in the process of responding to climate change, bridging the gap from planning to action is critical for maintaining ecosystem integrity and function. Largely, barriers to implementation arise out of the culture and constraints of land management agencies and organizations, and are associated with economic, cultural, regulatory, and political considerations. Fortunately, these barriers can largely be overcome by identifying boundary-spanning individuals that can help translate the science in real time, build trust among partners, and have enough influence to garner support for action.

In order to advance co-production of research that informs management and policy actions, researchers, managers, and decision makers must invest and participate in building strong partnerships that bring together different perspectives and expertise, drawing on advances from across the scientific spectrum (Enquist et al. 2017). However, climate science does not always reach decision makers and research is not always coordinated or integrated into existing landscape scale conservation actions. Boundary organizations connecting science with management and practice play a key role in filling these gaps and translating science into actions on the ground. In southern California, and particularly the San Diego region, the Climate Science Alliance-South Coast (The Alliance) has been formed to play that role, bringing together more than 200 organizations to support, promote, and connect climate adaptation activities with natural resource and local government planning and projects. This network has established a community of practice that offers the opportunity to leverage costs and complementary efforts, forge new and expanded climate adaptation partnerships, and be a catalyst for the kind of innovative and large-scale actions necessary to build long-term resilience to climate change.

6.7.2 Expanding Partnerships

Through San Diego's history of conservation planning and management and efforts of organizations like the Climate Science Alliance, many strong partnerships have formed among conservation planners, researchers, regulatory agencies, and land management agencies. Expanding these relationships to include important partners in the region is key to the long-term success of San Diego's conservation network under climate change.

6.7.2.1 Tribal Relationships

Climate change adaptation is a critical issue for Native American tribes throughout the United States. Although San Diego's 18 distinct tribal nations are sovereign entities with their own management goals and approaches, their climate change concerns overlap with those of other San Diego County governments and agencies. Indian reservations in San Diego include approximately 124,000 acres (500 square km) of land, or about 4.6% of the total area of the county. Although not large geographically, Indian tribal lands are significant culturally and historically, as tribes have several thousand years of indigenous land-management experience (see Blackburn and Anderson 1993), and traditional territories that include the entirety of San Diego County and beyond. In the present, management of tribal lands is complicated by the trust relationship between tribes and the federal government, which requires that tribes comply with federal environmental law. Further, much of the public funding that tribes have access to is controlled wholly or in part by federal agencies such as the Bureau of Indian Affairs, U.S. Environmental Protection Agency, and the U.S. Fish & Wildlife Service. Tribal climate change adaptation strategies are primarily tailored to addressing local impacts on land, air, and water quality, and public health within tribal communities, but there are parallels between tribal goals and the broader concerns of other local municipalities. For example, tribes seek to mitigate impacts to the health and well-being of individual tribal members but must also address impacts to the natural environment.

In San Diego County, many tribes are working on adaptation and management plans for how to address a range of climate change issues. Yet, tribes are not always included in broader regional discussions. Local governments and agencies often are not sure how to reach out to tribes, or mistakenly believe that because tribes are sovereign governments, bringing tribal representatives to the table would be inappropriate. In fact, tribes are eager to be a part of the conversation about climate change. Climate change does not recognize reservation boundaries, so for adaptation efforts to be complete, tribal lands must be considered—which means reaching out to tribal governments. The best way to do this is to start with the tribe's environmental office. Tribal environmental staff are often responsible for multiple different resources, including air, water, land, and solid waste, and could use the help of experts in integrating climate change planning into these areas. Tribes also have access to information about their own lands that could be useful to non-tribal agencies, researchers, and policymakers. Engaging with tribes means approaching them with respect for their sovereignty, their histories, and their cultures. It can take time to establish a relationship with tribal officials and staff members, but with patience and perseverance, mutually beneficial partnerships can develop.

6.7.2.2 Baja California, Mexico

Like many political boundaries, the United States–Mexico border is an artificial demarcation distinct from ecological boundaries. The international border that separates San Diego County and Baja California disrupts ecological processes including natural fire and hydrologic regimes, soil erosion and deposition, and nutrient and energy flow through food webs, as well as population dynamics, migration, gene flow, and species interactions such as predation, dispersal, pollination, and competition (Córdova and de la Parra 2007, Stallcup et al. 2015). These disrupted ecological processes create additional obstacles to climate change-driven movement and adaptation. For example, northward range shifts to cooler habitats are impeded by this physical barrier. Therefore, binational coordination is critical to developing linkages that allow movement and access to suitable habitat.

Historically, differences in the socio-economic and legal system led to challenges in cross-border coordination and conservation through programs such as Wildlife Without Borders (Stallcup et al. 2015). Disparities in financial resources have led to gaps in conservation resulting in a lack of cross-border linkages and major gaps in protection between public lands (Stallcup et al. 2015). In San Diego County, 388,750 acres (1,573 square km) are protected while only 14,373 acres (5,819 ha) are protected on the Mexican side of the border (CBI et al. 2004). In Mexico, Áreas Naturales Protegidas (ANP), lands designated by presidential decree with special protections, were originally established opportunistically and only recently have taken a more strategic approach to protecting the region's biodiversity (Stallcup et al. 2015, Comisión Nacional De Áreas Naturales Protegidas 2016). Although the San Diego side of the border has a greater amount of acreage protected and investment in a strategic approach to conservation, the construction of border security infrastructure has been exempted from adherence to environmental regulatory requirements (United States Library of Congress 2005). As such, starting in 2006, additional segments of border wall were constructed, bisecting the landscape, without a review of the actions' impacts on species and habitats.

Several goals for sharing responsibility to protect cross border ecosystems have been identified through binational collaborations (CBI et al. 2004, Stallcup et al. 2015) focused on conserving this shared landscape:

- Protect core areas of high biodiversity, which together represent the biological, topographic, geologic, and climatic diversity of the region.
- Conserve north-south and east-west linkages between these core areas and between lands that are already protected to allow biotic communities room to shift geographically in response to climate changes.
- Establish a binational park system to connect Parque Nacional Constitución de 1857 in the Sierra Juárez in Baja California to the State Parks, National Forest lands, and Wilderness Areas in the Peninsular Ranges north of the border in California.

To accomplish these goals, landscape level planning must not stop at the border and instead should foster partnerships and collaboration. One example is in the shared Tijuana River watershed where efforts to assess the impacts of cross-border patterns in land use on habitat fragmentation and connectivity have already taken place (Eaton-Gonzalez and Mellink 2015, Eaton-Gonzáles 2017). Future partnerships for cross-border planning should also consider collaborations with organizations and institutions that have shared goals that may be rooted in different values. For example, border security goals can be aligned with regional conservation goals through open space protection along the border. Conservation of open space buffers on both sides of the border can help secure landscape linkages while also facilitating border enforcement and minimizing the risk of tunneling (Stallcup et al. 2015).

6.7.2.3 Local Communities

Generating interest in conservation by the public is also critical to establishing political support and public and private resources for conservation. Carefully managed recreation in conserved lands can enhance public interest and support for conserved lands. In addition, flagship species, chosen for their public appeal (Verissimo et al. 2011), can be used to generate social capital for conservation. This social capital, in the form of interpersonal networks that facilitate societal function, has been identified as a key support for biodiversity conservation (Schwartz 2006). Researchers and research institutions can leverage partnerships with boundary spanning entities and organizations that create space for innovative cross-sector solutions and collaboration, and invest in training, capacity building, and community outreach and youth engagement. We can also embrace opportunities to promote creativity and hope in the future by identifying and sharing community-based and multigenerational solutions with the potential to shape our landscape. People are at the center of our climate adaptation decisions, so one key element to their success is to actively engage the communities in which we work to build relationships and a trust in local researchers.

There are many reasons to be hopeful. We must invest in building strong partnerships that bring together different perspectives and expertise, drawing on advances from across the scientific spectrum. To succeed at integrating climate informed research into the fabric of our culture, we must aspire to collaborate not only with other scientists but also with the broader society. Emphasizing multicultural and multigenerational leadership will support knowledge transfer and continuity and encourage leadership values around innovation and transparency to build trust (Thomashow 2017). Strong partnerships are adaptable and dynamic over time, allowing collaborators to develop and test innovative pathways that can address long-term solutions to environmental problems. These partnerships and their evolution will shape the future of natural resource management in our region.

In southern California, this framework exists from the management/monitoring and dissemination perspective in the form of manager driven networks with researchers embedded to support this type of knowledge transfer. These networks include:

- Science-management partnerships such as SDMMP and SANDAG’s EMP program, Southern California Coastal Water Research Project, San Diego State University’s Institute for Ecological Monitoring and Management, and the Climate Science Alliance
- Water management groups such as the Regional Water Management Group
- Fire management agencies such as the U.S. Forest Service and CalFire
- Planning groups such as those coordinated through SANDAG

6.8 Adaptive Management and Monitoring for San Diego's Conservation Future

Adaptive management is imperative to designing robust and successful strategies to address the impacts of climate change. Given the uncertainties associated with specific climate change effects, an adaptive management strategy informed by an ongoing, institutionally supported monitoring program will be critical to successfully managing the San Diego region's biodiversity under climate change. Adaptive management is the iterative process by which a management problem is assessed, actions or solutions are designed and then implemented to address the problem, and then monitoring is carried out and data are evaluated to assess the efficacy of the action in addressing the problem. Actions are then adjusted to achieve goals set out to address the original problem.

Below are several examples of key information needs (Section 6.8.1) and monitoring targets (Section 6.8.2) that should be addressed at a regional scale in a coordinated approach to better understand and respond to the ecological impacts of climate change in the San Diego region. Although these topics are more broad-scale than what is typically included in an adaptive management approach, we have framed them in the context of adaptive management, so they can be addressed in the same manner. These examples are not meant to be prescriptive, and as such, they will require further refinement, but by outlining them in this way, we hope they can be more readily tied to local-scale actions determined according to management agency guidance and policy. For each, we identify the following elements of the adaptive management process that are critical for addressing climate adaptation: 1) an explicit goal or objective 2) key sources of uncertainty in achieving that goal so that actions and monitoring are appropriately set and timed according to the degree of uncertainty, 3) selection of appropriate indicators or triggers, 4) an accounting of the resources available to accomplish management and monitoring goals as well as the resources needed so goals are tractable, and 5) mechanisms to connect the information gathered to changes in management. Prior to acting on these gaps and monitoring needs, we suggest review of and coordination with ongoing efforts through SDMMP, the Climate Science Alliance, and others. Monitoring data and the interpretation of data collected should be made readily available to the public and decision-makers to encourage engagement and ongoing dialogue on adaptive management. Although there are currently efforts to share these types of data and engage with managers on research results through SDMMP, the Climate Science Alliance, and others, there is a need to reach beyond existing partnerships and to ensure all data and research are widely available beyond existing science-management partnerships.

6.8.1 Filling Knowledge Gaps with Adaptive Management

- Goal: Develop a cohesive strategy through coordinated research and monitoring to understand how species and watersheds will respond to the new projected precipitation regime.
    - Management Uncertainty: The confounding effects of co-occurring stressors.
    - Actions: Expand existing partnerships, analyze existing data, determine where and how to expand/enhance monitoring, particularly with distribution of stream gauges. Further management actions to be identified once existing data are analyzed.

    - Indicators/Triggers: Flow rates and timing, water quality metrics, population trends for both sensitive and common species.
    - Available Resources: Ongoing monitoring of sensitive aquatic species, aseasonal flow monitoring, SWAMP monitoring and bioassessments.
    - Additional Resources Needed: Coordination to connect efforts and compile and integrate data and monitoring efforts, long-term funding to support continuation of these efforts, particularly stream gauge monitoring.
- **Goal:** Design and preserve spatially-explicit landscape linkages at the regional level that not only provide physical connectivity, but functional connectivity under shifting climate regimes and increased urbanization.
    - Management Uncertainty: Habitat impacts and species' responses to climate change, future development and growth in certain areas.
    - Actions: Analysis of potential landscape linkages for climate connectivity and development of supporting data to allow for prioritization during decision-making on acquisitions, restoration, etc.
    - Indicators/Triggers: Movements across monitored pinch points, movement of marked individuals, improved gene flow for segregated populations.
    - Available Resources: Ongoing Climate Resilient Connectivity project, existing monitoring and research data including occurrence, movement, and genetic data that can be further analyzed for development of additional connectivity enhancement goals.
    - Additional Resources Needed: A strategic, region-wide monitoring program for connectivity, particularly at pinch points.
- **Goal:** Design and implement a connectivity plan focused on cross-border connectivity that addresses the challenge of facilitating movement and migration for species across fenced sections of the international border.
    - Management Uncertainty: Changing policy priorities.
    - Actions: Coordinate with researchers and conservation planners on both sides of the border to determine where and how to promote cross-border connectivity for species.
    - Indicators/Triggers: Movements across monitored pinch points, movement of marked individuals, improved gene flow for segregated populations.
    - Available Resources: Las Californias Binational Conservation Initiative.
    - Additional Resources Needed: A strategic, region-wide monitoring program for connectivity, particularly at pinch points.
- **Goal:** Identify of the elements of San Diego's ecosystems that allow them to accommodate change and prioritize management actions to preserve and promote those

elements that support resilience (e.g., restoration using palettes of plant species most resistant to increased temperatures and variable precipitation).

  - Management Uncertainty: Lag times to observe impacts and responses to management shifts over time.
  - Actions: Analyze existing data where needed, target monitoring to fill gaps, and ensure findings from prior studies are being shared widely in multiple forums.
  - Indicators/Triggers: Population parameters (e.g., survival, reproduction) for focal species, other indicators of ecosystem functioning.
  - Available Resources: Existing monitoring and trend data particularly from extreme years of drought or heat (e.g., rare plant monitoring, genetic analyses on a range of species) as well as ongoing research on resilience (e.g., endemic plants, translocation efforts for butterflies).
  - Additional Resources Needed: Additional coordination for more common species and long-term monitoring to support evaluation of factors affecting resilience and response to management actions.

6.8.2 Tracking Trends Through Monitoring

- **Goal:** Implement long-term dedicated monitoring which is essential for detecting changes in habitat and community composition and relating those changes to climate-induced changes in rainfall, streamflow, sediment flux, temperature, and CLCF.
  - Management Uncertainty: Full understanding of changes and implications thereof will likely take longer than normal planning and management cycles.
  - Actions: Tracking of trends in population and reproductive status for species, habitats, and communities, particularly after disturbance events. Establish sentinel sites and probabilistic samples to capture both status and trends.
  - Indicators/Triggers: Extremes in environmental and climate data and correlated ecological data (e.g., species populations, community composition); particular climatic or environmental change thresholds may need to be investigated or set.
  - Available Resources: Some environmental data are currently available through existing monitoring networks and can be paired with existing monitoring data on sensitive species and vegetation communities.
  - Additional Resources Needed: Continued and expanded coordination among ecologists and climatologists and others gathering the environmental change data, additionally, expanded monitoring of more vegetation communities and species is needed and should be coordinated at a regional scale as it has been done for ongoing monitoring.
- **Goal:** Early detection and rapid response to invasive species to reduce their impact on native species and systems.
  - Management Uncertainty: When and where new species will emerge and at what level they become problematic.

    - Actions: Coordinate on invasive plant and animal strategies being developed by SDMMP beyond existing partners and enhance monitoring in support of these efforts at a broader geographic extent.
    - Indicators/Triggers: Emergence of new populations of species, negative impacts to native species.
    - Available Resources: Existing invasive plant strategy and an invasive animal strategy in development.
    - Additional Resources Needed: Partnerships across additional jurisdictions for monitoring, potential for expanded research capabilities when new species of invasion concern arise.
- **Goal:** Projection of areas vulnerable or resistant to future effects of climate change.
    - Management Uncertainty: Projections may not play out as anticipated.
    - Actions: Incorporate existing monitoring data into species distribution modeling, particularly for more common species that have not yet been addressed, and assessment of regions of climate refugia. Prioritize monitoring and management action in highly vulnerable areas as well as areas that will serve as refugia.
    - Indicators/Triggers: Projections of change over time under different scenarios.
    - Available Resources: Existing modeling conducted by SDMMP, San Diego State University, The Nature Conservancy, and others; monitoring data from SDMMP, USGS, and others.
    - Additional Resources Needed: Broader coordination across a wider geographic extent and jurisdictions, particularly to coordinate with Mexican counterparts on cross-border species modeling.

7: Conclusion and Directions for San Diego's Future[7]

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7.1 An Overview of Climate Impacts on a Biodiversity Hotspot

As described in the preceding sections of this assessment, San Diego County is part of a biologically diverse and unique landscape that will be impacted in various ways due to current and future climatic variability (Table 7.1). This assessment serves as an important first step in understanding the state of the science which is critical to evaluating the vulnerability of systems, communities, and populations. Such a review allows the region to take stock of what is

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known and what is unknown about potential climate impacts at the regional level. In addition, the report highlights the information needed to move forward with management and decision-making. While there is still uncertainty about exactly how some of these changes will play out across the landscape, the findings from this assessment indicate enough knowledge exists to offer insights into managing natural resources throughout the ecoregion and across jurisdictional boundaries in the face of a changing climate.

From the preceding sections, we have compiled key points that are meant to help inform land management efforts and inspire conservation practitioners to review management goals with an eye towards building resilience into our ecosystems now and into the future.

Section 1: Introduction to San Diego's Climate and Ecosystems

- San Diego's diverse ecosystems have evolved in response to a uniquely variable climate.
- The region is a biodiversity hotspot that has high levels of species richness and endemism that accords with the coast to mountain to desert topography, complex geology, and bioclimatic evolution of the region.
- There is high variability of precipitation, temperature, wind, cloudiness, and moisture associated with location on the east Pacific coast. Seasonally varying drivers at large scales include the North Pacific High and the Gulf of Alaska/Aleutian Low along with regional dynamics causing the formation of CLCF and the occasional Santa Ana wind patterns.
- San Diego's institutions are unique in southern California in forwarding conservation planning and action in the midst of very rapid urbanization and land use changes. Conservation actions have managed to protect 43% of the County's land area with goals to protect up to 55% by 2050.

Section 2: Temperature and Temperature Extremes in the San Diego Region

- Temperature in the San Diego region is spatially variable with patterns driven by elevational relief and proximity to the coast. In particular, nighttime recovery influenced by the marine layer demonstrates high coast to inland variation.
- As climate changes, the distribution of daily temperatures, along with the low and high extremes, will change.
- Shifts in mean annual temperature are most likely to be associated with range shifts for many species, resulting in novel community assemblages and biotic interactions.
- Climate change may produce more or fewer occurrences of extremes that cross particular tolerance thresholds. More frequent and intense heat waves may disproportionately affect younger age classes and reduce reproductive and survival rates in populations of species sensitive to temperature extremes.
- Warming temperatures may also create phenological mismatches.
- To prepare for likely climate change but with uncertain rates and outcomes, contiguous landscape blocks with many microclimates should be identified and protected to foster refugia.

Section 3: Precipitation and Drought in San Diego County

- The regional mediterranean climate features cool, wet winters and warm, dry summers, as well as high spatial variability in large part due to the large topographic gradients in the region.
- Year-to-year variability is very high, greater than almost any other U.S. region, and the variability is dependent on the absence or occurrence of a few large events.
- Precipitation regime is projected to become more variable with more dry years punctuated by increasingly rare extreme precipitation events. The most extreme events are projected to produce more precipitation than historical extreme events.
- Drought problems could worsen. Drought may occur more frequently due to increased occurrence of dry days and drought could intensify because of warmer temperatures. Because drought targets some species more than others, these projected changes may cause structural changes to ecosystems.
- Projected drying of spring and fall will lengthen and intensify the summer drought with possible impacts to riparian systems and plant biomass. More analysis of available data and new monitoring may be necessary to better understand these impacts.
- Gaps include soil moisture monitoring at various levels and cohesive stream monitoring, including upland habitat important for species.

Section 4: San Diego Wildfires: Drivers of Change and Future Outlook

- Regardless of changes in climate, humans will remain the major driver of fire activity in the San Diego region.
- Housing location and arrangement play a large role in fire risk and frequency.
- Increasing year-to-year variability with fewer storm events could mean increased vegetation mortality leading to increased fuel loads of dead biomass.
- Synchrony of low fuel moisture and Santa Ana winds creates ideal fire conditions annually. With longer dry spells and decreased precipitation in fall, fire conditions could extend further into the winter, which is the primary Santa Ana wind season, increasing the possibility of Santa Ana wind-driven fires.
- Increasing fire frequency has the potential to lead to type conversion from mixed conifer/hardwood to hardwood or chaparral at higher elevations, and from shrublands to more highly flammable non-native annual grasslands in the coastal zone, inland valleys, and foothills, creating a positive feedback loop.
- Land-use planning efforts that focus on infill development rather than expanding development into wildlands not only reduces fire risk to humans but can protect the landscape from too frequent fire and has the co-benefit of protecting biodiversity.

Section 5: Impacts and Influences of Coastal Low Clouds and Fog on Biodiversity in San Diego

- Coastal low clouds and fog (CLCF) are common in late spring/early summer, with a strong gradient from coast to inland and intensified occurrence during evening to early morning hours. Their high diurnal to interannual variability is driven by both local and large-scale atmospheric and oceanic conditions.

- A number of observations show declines in California CLCF, but the extent to which these are linked to anthropogenic climate change is uncertain.
- Future changes in CLCF are uncertain, but continued warming is very likely. Through shading and cooling, CLCF will help buffer warming and drying along the coastal plain.
- Through effects on ecosystem water balance, from direct water addition and shading, CLCF is an important driver of species dynamics and faunal activity along the coast.
- Local research linking CLCF to ecosystem function is sparse. Local research is needed to fill gaps to support both conservation and management under the current climate and climate change adaptation efforts. New data-sets on CLCF are facilitating this research.

Section 6: Conservation and Management for San Diego's Future Climate

- San Diego is a biologically diverse region that has been the focus of more than 20 years of conservation planning, investment, and innovation. However, much remains to be done to complete a network of protected habitats that is necessary to ensure the survival of the region's biodiversity, and through allowing for adaptability to future climate change.
- The spatial and temporal scales at which climate impacts must be considered to build resilience into natural systems require the integration of complementary approaches at multiple scales. Landscape-scale planning can build on single-species approaches that have historically driven conservation action in the region.
- Building resilience into San Diego's ecosystems is a challenge to be addressed in a cross-jurisdictional, multidisciplinary fashion by scientists, policy-makers, planners, land managers, and the broader conservation community.
- Conservation management goals and approaches need to continue to work to balance addressing near-term, regulatory requirements for single-species management with landscape-level actions necessary to build resilience and adaptability for the future under climate change across all land ownerships, jurisdictions, or planning arenas.
- Long-term monitoring and adaptive management will be critical to managing species and ecosystems into the future. This includes adaptation and scenario planning.
- Future research and planning to build resilience to climate impacts will need to focus on identifying and protecting climate refugia, understanding weather, climate, and hydrologic characteristics along protected corridors, and stronger and sustained collaborations of science, planning, policy, and implementation communities.

Anthropogenic or climate drivers of change	Projected shift	Confidence in shift*	Associated ecological impacts	San Diego or southern CA example	Availability of data to understand ecological response	Existing management options or strategies	Suggestions for future management approaches, research, or monitoring
Mean annual temperature	General increase	Very high confidence	Species range shifts, novel assemblages	Narrow endemic, gabbro-associated plants may experience unsuitable temperatures where suitable soil conditions exist	Low: strategic weather monitoring in complex topography and high gradient climatic settings and inconsistent information among species	Habitat management for persistence, protection of refugia, adaptation through connectivity or facilitated migration	Conduct trend monitoring for species of interest
Heat waves	Increase in frequency and severity	Very high confidence	Increased mortality, decreased reproductive success	Potential for exceeding thresholds for some species like the CA spotted owl with known temperature thresholds	Low: logistical and ethical issues for experimental studies of ecological response of fauna	Maintain adequate habitat to support populations that can persist. Provide connectivity for species to move to refugia	Determine if analysis of existing data can provide insight into impacts on plant and animal populations. Model climate refugia and focus conservation efforts on those areas
Spring drying	General increase	High confidence	Potential to affect biomass	Decreased reproductive success for species that breed in aquatic systems, e.g.,	Low: insufficient long-term data to understand how prolonged droughts affect ecosystem structure	Monitoring of at-risk species and recovery efforts for those that have or can be hardest hit by spring drying	Continuous long-term monitoring at a diversity of habitats

Anthropogenic or climate drivers of change	**Projected shift**	**Confidence in shift***	**Associated ecological impacts**	**San Diego or southern CA example**	**Availability of data to understand ecological response**	**Existing management options or strategies**	**Suggestions for future management approaches, research, or monitoring**
				arroyo toad (*Anaxyrus californicus*)			
Precipitation regime variability	General increase	High confidence	Impacts to ephemeral and riparian environments—less stabilizing vegetation and increased erosion can increase allochthonous input	Decrease in the shredder functional group of macroinverts reducing downstream detritus food sources for zooplankton and fish	Medium: Monitoring data can be synthesized to examine impacts of large interannual precipitation variability by using monitoring data over the last 7-10 years	SWAMP includes targeted monitoring of streams as does newer USGS Aseasonal Flows Project. Existing focus on cataloguing changes to covered species and habitats	Integration of existing monitoring programs (e.g., SWAMP and USGS aquatic species monitoring) and coordination of data on indicator sites and species; improve stream gauge monitoring
Droughts	General increase	High confidence	Potential structural shifts in ecosystems	Oak tree (*Quercus agrifolia*) stress and die off during the 2012-2016 drought	Medium: Information from recent drought show vulnerabilities of a diversity of species. Thresholds that might trigger landscape changes are unknown	Rainfall tracking available as is monitoring data, through SDMMP, on numerous plants and aquatic species that may be most sensitive to drought	Climate-quality precipitation, wind, humidity, solar radiation, and soil moisture observations in strategic locations and high-density array of precipitation gauges along topographic gradients in conjunction with habitat monitoring

Anthropogenic or climate drivers of change	Projected shift	Confidence in shift*	Associated ecological impacts	San Diego or southern CA example	Availability of data to understand ecological response	Existing management options or strategies	Suggestions for future management approaches, research, or monitoring
Pests, pathogens	Increase for some pests and vectors	Medium confidence	Increased lethal and sub-lethal effects	Bark beetle caused mortality in coniferous forest and riparian tree dieback caused by shot-hole borer and fusarium fungal pathogen	Medium: Information for some pests and pathogens are somewhat well studied, but potential for novel pathogens is unknown	Surveillance of known pests and pathogens in the region and use of early detection and rapid response efforts to address outbreaks	Expand surveillance programs to include pathogens with high probability of reaching San Diego or with potential for significant impacts to humans or ecosystems
Land use change and habitat fragmentation	General increase	Very high confidence	Habitat degradation and loss of landscape connectivity	Disconnected habitats for species like the mountain lion leading to lack of gene flow and population declines	High: Information on the effects of fragmentation on many species are known and many more are being researched to determine the population-level effects	Identification and preservation of connectivity across landscapes, including aquatic systems	Identification of spatially-explicit linkage zones for functional connectivity. Linkages should be prioritized for conservation with multi-agency stakeholders and focus on land acquisition and mitigating barriers
Fire frequency	General increase	High confidence —depends on urbanization	Type conversion to non-native grasses	Reduced habitat for shrubland species like the CA	High: Existing data supports our understanding. The major unknown is	Coordination of fire management with land management on conserved lands	Increased efforts to track type conversion or areas at risk. Fire suppression and

Anthropogenic or climate drivers of change	Projected shift	Confidence in shift*	Associated ecological impacts	San Diego or southern CA example	Availability of data to understand ecological response	Existing management options or strategies	Suggestions for future management approaches, research, or monitoring
		combined with fire		gnatcatcher that has lost nesting habitat to repeated fires	degree of population growth and land-use change		prevention efforts should be focused on these areas
Santa Ana winds	Unknown	More research needed	Plays a role in fire cycle	Longer dry periods extending into Santa Ana season may increase extreme fire events	See fire	See fire	See fire
Coastal Low Level Clouds and Fog	Unknown	More research needed	Future decreases in CLCF may result in shrub cover decrease and exotic grass cover increase degrading CSS	Future decreases in CLCF could increase shrub seedling mortality during summer	Medium: Knowledge can be gleaned from work in other regions of CA (e.g., northern CA and the Channel Islands) but research linking the impact of CLCF to biodiversity is sparse	Recent remote sensing work has made spatial CLCF data available, thus making investigating the effects of CLCF on San Diego ecosystems much more accessible	Monitoring to determine if coastal plain with CLCF can act as a climate refugium

Table 7.1: Summary of biodiversity drivers and climate impacts on San Diego's ecosystems. Examples are included as well as an assessment of the state of our knowledge about these impacts and management practices available to address each impact. *Based on IPCC definitions of confidence

7.2 Cross-Cutting Issues

The characteristics that make San Diego unique with respect to climate and ecosystems are largely the precipitation variability, coastal low clouds and fog, the region's human population and associated development, and a history of conservation planning and action to protect the region's rich biodiversity. How these key features interact to either exacerbate or damp the ecological impacts of climatic shifts and non-climate stressors have been woven throughout the report. Here, we highlight the interactions among these key characteristics, projected climate shifts, associated ecological impacts, and the ecological variables that are likely to be affected (Figure 7.1). Precipitation is projected to become more variable in the future, and, along with the projected increase in temperatures, is likely to make droughts more frequent and severe. The impacts of increased temperature on drought severity are well documented throughout the southwest (Cayan et al., 2010, Ault et al., 2016). There is a positive feedback between drought and temperature; the increased drying associated with drought also increases temperatures because less moisture is available for evapotranspiration, minimizing the cooling impact from latent heat and further enhancing temperatures. In turn, drought and increased temperatures enhance fire risk in the region by increasing the amount of available fuel to burn and prolonging fire seasons. Increasingly frequent and severe droughts are likely to cause vegetation mortality, adding dead biomass to fuel loads. Further, drying of the landscape, including fuels, is projected to begin earlier in spring and persist later into fall when Santa Ana wind events are more likely to occur. Drought can also facilitate vegetation-type conversion from shrubland dominated systems to non-native annual grasslands. Vegetation die-offs can lead to weed incursion, particularly after fire when seedlings and resprouts are particularly susceptible to drying. These highly flammable non-native annual grasses then become part of a positive feedback loop between fire frequency and type conversion. In contrast, CLCF can potentially mitigate drought and temperature extremes by provide shading, cooling, and when low enough, moisture, during San Diego's warm and dry months. During future warming, CLCF may help buffer warming and drying along the coastal plain.

Habitat loss and fragmentation caused by urbanization and land-use changes are the greatest threats to biodiversity, not only in the San Diego region, but globally. The impacts of urbanization and land-use shifts on natural ecosystems are varied and, in the case of San Diego, relatively well studied. Although these impacts are not unique to the region, our state of knowledge about how they affect San Diego's species and habitats, as well as the ongoing efforts to conserve land to combat these effects, are a key characteristic of the San Diego region. These conserved lands can act to offset some of the impacts of climate change by increasing connectivity, reducing habitat fragmentation, and reducing fire ignitions and disturbances that lead to type conversion.

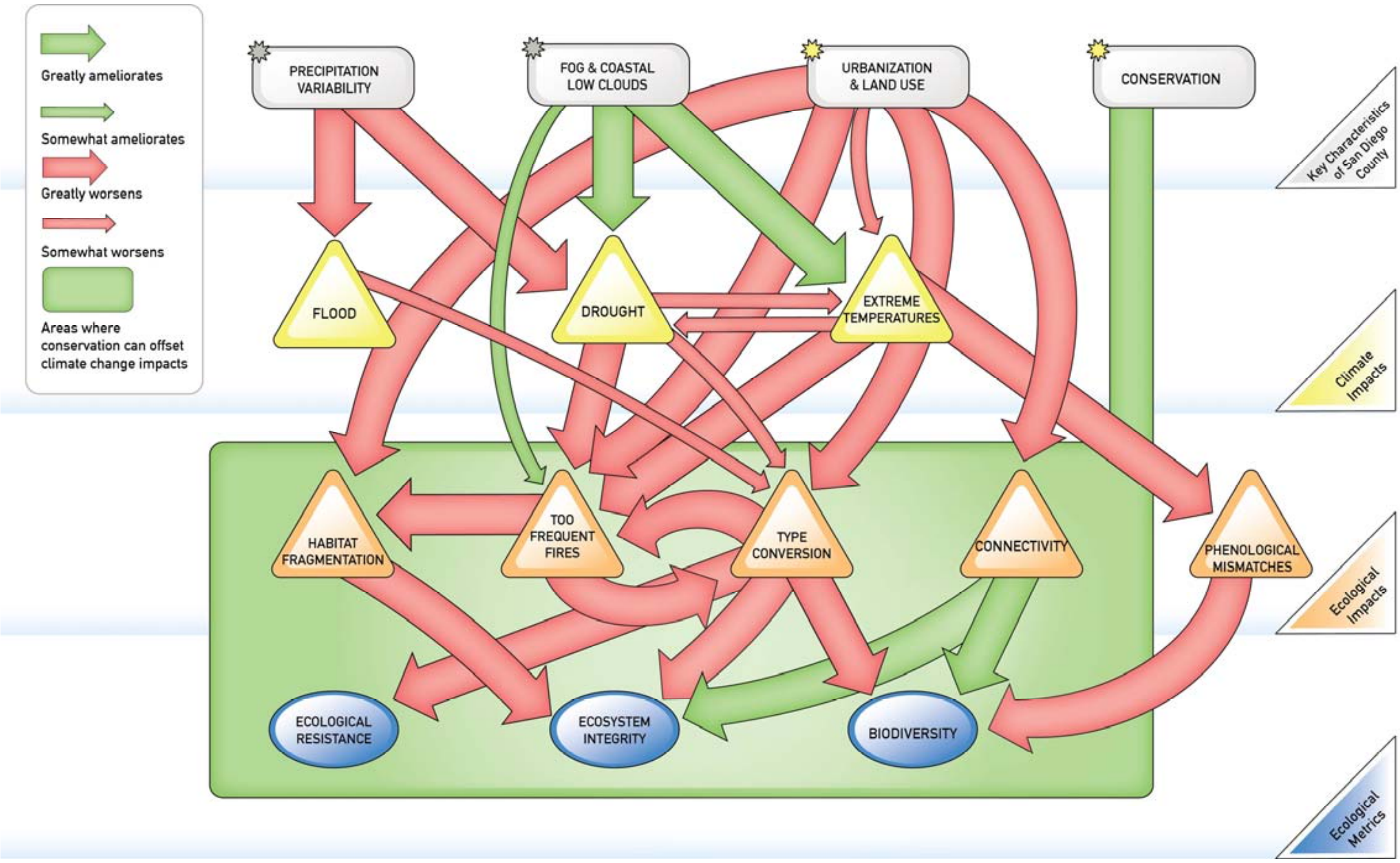

Figure 7.1: Cross-cutting issues and impacts on ecosystems and biodiversity.

7.3 Knowledge Gaps

We have broadly summarized the knowledge and monitoring gaps that have been identified throughout the report (Table 7.2). In general, these questions and research gaps cannot be filled by conducting experiments or mobilizing to collect data during climate events. Instead, ongoing monitoring to gather baseline and trend data for comparison can allow for analyses when environmental conditions create the opportunity to learn from natural experiments as they arise. Although efforts coordinated through SDMMP, as well as the Climate Science Alliance, have been initiated to address some of these knowledge gaps, given the complexity of the problem and diversity in our ecosystems, those efforts are neither comprehensive nor do they completely cover the full geographic extent we have described here. To better understand the scope and the scale of the ecological impacts of increased climate variability and develop responses to safeguard biodiversity and support ecosystem resilience will require continued efforts to ensure research and monitoring reaches across disciplines, land ownerships, and planning jurisdictions with expanded cooperation and coordination across the region. It is important that these efforts build on and coordinate with the ongoing work in the region, most notably through a review of current activities of SDMMP and Climate Science Alliance partners.

As monitoring data and the body of literature on the ecological impacts of climate change in the region expand, the distinction between new monitoring and new research can become blurred as monitoring supports and informs research. As such, we do not try to separate these two gaps in the table. The table does identify the category (or categories) that the research falls under: more ecological monitoring, more climate monitoring, research using existing data, and need to improve collaborations. All gaps would benefit from enhancements in all categories, but by identifying the most critical we hope to provide a path forward to address the gaps identified in the report.

Table 7.2: Summary of knowledge gaps that are identified throughout the report. The category that the gap best fits under is highlighted. CM – climate monitoring, EM – ecological monitoring, ED – analyses using existing data, C – collaborations. Topics for which research or monitoring efforts have been initiated are denoted with an asterisk.

CM	EM	ED	C	Targeted Actions to Fill Knowledge Gaps
				Enhance our understanding of the interaction between climate, habitat elements, populations, and interspecific interactions through modeling of biotic interactions for a broader range of the region's species.
				Identify what makes climate refugia effective though enhanced spatial resolution of temperature observations to be used in ecological modeling and to determine key elements of local refugia.
				*Continue existing studies (e.g., on rare plants and federally listed animals) and expand research to additional species on the impacts of temperature shifts, particularly temperature extremes, on demographic parameters and population dynamics by tracking populations and species with range limits within or adjacent to the region.
				Utilize phenology and population trend monitoring to identify when asynchrony is likely to lead to cascading ecological impacts (e.g., timing of resource availability, loss of pollination services).
				Evaluate how changes in precipitation regime will affect bioavailability of water. Improved observational soil moisture and hydrologic data in the region can be used to refine and validate regional hydrological modeling, which can then be used to examine future impacts.
				*Identify drought thresholds that can lead to structural changes in regional ecosystems as specific functional groups are more severely impacted. This includes field studies of the potential for drought to impede recovery of native shrublands after disturbance, particularly fire.
				*Expand data collection and analysis to evaluate the effects of an extended and more extreme dry season over several years on individual species as well as ecosystem structure and function.
				Generate a cost-benefit analysis and prioritization of where and when to conduct fire management strategies to optimize fire-risk reduction and biodiversity conservation.
				*Improve our understanding of the role of extended drought in vegetation die-back, (currently in progress for oak woodlands and riparian areas) and how that may lead to increased area burned under Santa Ana wind conditions.

CM	EM	ED	C	Targeted Actions to Fill Knowledge Gaps
				*Improve our understanding of the interaction between drought and vegetation-type conversion by building on ongoing work through quantification of the extent and rate of conversion across the region, and the primary drivers of this vegetation change.
				Improve tracking and availability of data on ignition sources of wildland fires to evaluate unknown sources and better design prevention programs. One area of needed research is the weather conditions under which powerline-caused fires are most likely to occur and how effective vegetation clearing is for mitigating that risk.
				Gather data on species' responses to low clouds and fog. Studies of individual species or groups of organisms will greatly inform our understanding of local ecosystem dynamics.
				Encourage land managers to incorporate CLCF into management planning and adaptive management (e.g., restoration efforts, out-plantings, and projecting natural disturbance, and project effects on conservation targets) by using spatial data sets derived from remote sensing.
				Establish a cohesive strategy to monitor how species and watersheds will respond to the new projected climatic conditions.
				Delineate and conserve spatially-explicit landscape linkages at the regional level, including across the U.S–Mexico border. Linkages should provide for functional connectivity under shifting climate regimes and increased urbanization. These linkages should then be integrated into reserve design and regional planning and management.
				Define thresholds or triggers for changes in management action and refine or design monitoring programs to deliver the necessary data to respond accordingly.
				Continue to coordinate research efforts to identify the elements of San Diego's ecosystems that allow them to accommodate change as understanding of these complex systems is improved and refined. Target management actions that preserve and promote those elements that support resilience (e.g., restoration using palettes of plant species resistant to increased temperatures and variable precipitation).
				*Build on existing efforts by SDMMP to make monitoring data and the interpretation of those data readily available to decision-makers and the public to encourage engagement and ongoing dialogue on adaptive management.

7.4 Future Directions

Numerous scientists and natural resource entities are working to address significant climate impacts to the natural resources in the San Diego region. However, this science does not always reach the communities that are the most affected by these impacts. This means there may be missed opportunities for the public to understand the need for climate action and/or to build trust in science coming from local researchers. The continued involvement of researchers, managers, and community members in organizations like the Climate Science Alliance is vital in developing the co-produced knowledge that is transferable and actionable to decision makers and managers.

Recognizing that people are at the center of our climate adaptation decisions requires that research needs to be actionable and delivered in a timely manner. Actionable science, or science that is intentionally created to serve society (Palmer 2012), includes activities that consider the existing regulatory, economic, legal, and social context that decision makers work within. Most decision makers do not have the luxury to wait for data to be published and instead need findings communicated in real-time to the greatest extent possible. This kind of dialogue can help encourage proactive and adaptive management, and help to leverage and coordinate regionally specific adaptation projects.

Researchers taking part in this assessment are committed to the creation of actionable science that is applicable to the myriad challenges that land managers and conservation practitioners face. From the onset of this effort, all participants made an intentional effort to think about how the results of this assessment will play out across different jurisdictional boundaries within the study region. This assessment has intentionally included perspectives and a voice for both our partners working across the border in northern Baja California, Mexico along with southern California Native American tribes, to be more inclusive of the reality in which conservation actions need to take place to appropriately address climate variability over time. In traditional conservation planning circles, tribal lands are often omitted from analysis and planning because relationships and/or mandates do not foster an environment of coordination and collaboration. This is also true for much of the planning along the U.S.–Mexico border where concrete and jurisdictional boundaries artificially separate ecosystems and species from landscape-scale planning and actions. While these boundaries may or may not manifest as physical barriers for the movement of species and ecological processes, they hinder collaborative planning for long-term landscape-scale actions.

This review, combining the knowledge of climatologists and ecologists with regional expertise and embedded in regional conservation and planning efforts, is a demonstration of what boundary spanning organizations and projects can do to inform actions that advance realistic climate adaptation planning. In this assessment, researchers have not limited themselves to the role of producing knowledge but instead are intent on working hand-in-hand with other disciplines and professions, and within communities where citizens will have a real stake in the welfare of the ecosystems that contribute richly to our societies, economies, and values. Early in the process of developing this assessment, the team engaged individuals skilled in science communication and community outreach to think about innovative ways to engage local communities and youth on the results of this work. Through the Climate Science Alliance, the results of this assessment were unveiled at the 2018 San Diego Climate Summit on March 6, 2018. This inaugural summit provided regional environmental leaders an in-depth look at climate science and related issues, while providing a forum to discuss San Diego’s regional resilience, built environment, and rich biodiversity.

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Appendix A: List of Acronyms

Acronym	Definition
AB	Assembly Bill
ac	Acre
ANP/NPA	Áreas Naturales Protegidas/Natural Protected Area
BC	Baja California, Mexico
BLM	Bureau of Land Management
BMP	Best Management Practice
C	Celsius
CA	California
CBI	Conservation Biology Institute
CDFW	California Department of Fish and Wildlife
CICESE	Centro de Investigación Científica y de Educación Superior in Ensenada
CFP	California Floristic Province
cfs	Cubic Feet per Second
CLCF	Coastal low clouds and fog
CO_2	Carbon dioxide
CONAFOR	Comisión Nacional Forestal
CONANP	Comisión Nacional de Áreas Naturales Protegidas
CSCI	California Stream Condition Index
CSS	Coastal Sage Scrub
CURRV	Climate Understanding and Resilience in the River Valley
CWD	Climatic Water Deficit
d	Day
EMP	Environmental Mitigation Program
ESA	Endangered Species Act
F	Fahrenheit
ft	Feet

GCM	Global Climate Model
GFDL	Geophysical Fluid Dynamics Laboratory
GHG	Greenhouse Gas
GOES-West	Geostationary Operational Environmental Satellite-West
GSOB	Gold Spotted Oak Borer
ha	Hectare
HCP	Habitat Conservation Plan
in	Inches
INRMP	Integrated Natural Resource Management Plan
IPCC	Intergovernmental Panel on Climate Change
IWRMP	Integrated Water Resources Management Planning
km	Kilometer
LFM	Live Fuel Moisture
LOCA	Localized Constructed Analogs
LTS	Lower Tropospheric Stability
m	Meters
mi	Mile
mm	Millimeters
MSCP	Multiple Species Conservation Plan
NASA	National Aeronautics and Space Administration
NCCP	Natural Community Conservation Plan
NPDES	National Pollutant Discharge Elimination System
NWS	National Weather Service
PDF	Probability Density Function
PRISM	Parameter Elevation Regression on Independent Slopes Model
PSI atm	Atmospheric Water Potential
RCIS	Regional Conservation Investment Strategy
RCP	Representative Concentration Pathways
RH	Relative Humidity

SANDAG	San Diego Association of Governments
SARH	Secretary of Agriculture and Hydraulic Resources
SDMMP	San Diego Management and Monitoring Program
SDNHM	San Diego Natural History Museum
SDSU	San Diego State University
SSC	Species of Special Concern
SSPM/SSPMNP	Sierra San Pedro Mártir National Park
SST	Sea Surface Temperature
SWAMP	Surface Water Ambient Monitoring Program
T	Temperature
TDR	Transfer of Development Rights
Tmax	Maximum Temperature
Tmin	Minimum Temperature
UABC	Universidad Autónoma de Baja California
US	United States
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
USFS	United States Forest Service
USFWS	United States Fish and Wildlife Service
VIC	Variable Infiltration Capacity
VMT	Vehicle Miles Traveled
WUI	Wildland-Urban Interface